Safety effects on pedestrians at urban roundabouts: an overview

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Abstract

Pedestrians are important users of the transportation system, but most guidelines have given them little importance in the geometric design of roads and intersections. Thus it can be difficult for vehicles and pedestrians to share the road, particularly at intersections where vehicle-pedestrian conflicts can be frequently recurring situations even with low pedestrian volume. In a sustainable safety vision, pedestrians and vehicles are required to safely share the road; thus 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.

It is well-known that modern roundabouts are safer than other intersection forms for effects on speeds and conflicts between users; several road authorities, indeed, have foreseen to convert specific types of intersections into roundabouts. To produce a better understanding of the potential impacts for the roundabout alternative, design considerations should be evaluated already at a planning level, emphasizing elements most favourable to the sharing and to use of road spaces equally distributed from a pedestrians safety perspective.

Summarizing international experience with roundabouts and pedestrians, this paper provides a review of the existing literature dealing with pedestrian safety and accessibility issues at roundabouts. First, safety aspects at modern roundabouts are presented, followed by a brief explanation of the effects of roundabouts on pedestrian safety documented in the scientific literature. Finally, this research provides an overview of the current state of practice and implications in roundabout design to maximize potential with regard to safety for pedestrians.
Keywords: road safety, pedestrian safety, roundabout.

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1 Introduction to roundabouts

Modern roundabouts are circular intersection in which vehicles circulate anticlockwise on the circulatory roadway installed around a central island and have priority. Entering vehicles, in turn, give priority and wait at the edge of the circulatory roadway until a gap in the circulating traffic flow becomes available. At approaches entering and exiting lanes are separated by raised or painted splitter islands. Raised splitter islands, as well as approach alignment, deflect vehicles into a proper entry path avoiding entry tangential to the circulatory roadway, and forcing drivers to reduce speeds as they proceed into and through the intersection. This ensures consistency between speeds of circulating vehicles and vehicles entering the roundabouts, as well as lower speed differentials with other road users. Moreover, splitter islands provide a refuge for pedestrians, allowing them to cross the street in two stages [1]. Figure 1 shows geometric design elements of a modern roundabout.

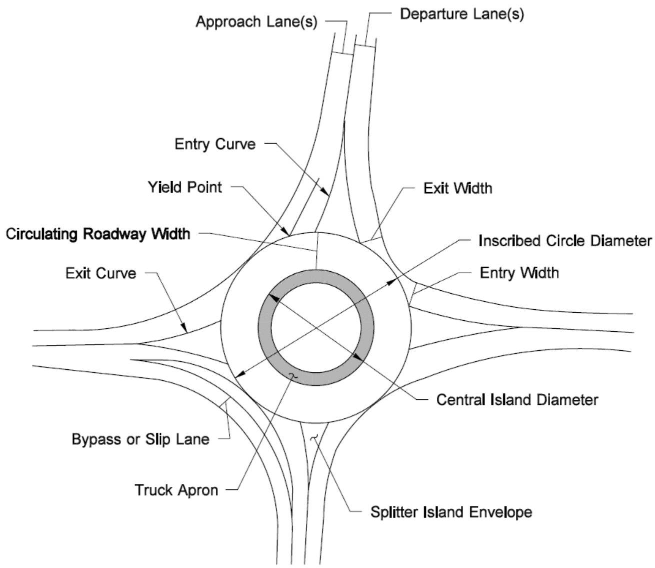


Figure 1: Roundabout elements [1].

Roundabouts can be separated into basic categories by size of the inscribed circle diameter: large, conventional, compact and mini roundabouts. Some fundamental design elements for each roundabout category, as referred in [2], are summarized in Table 1. Differently from the first three roundabout types, a mini-roundabout does not have a kerbed central island, but a (flush or domed) circular solid white road marking (1–4 m in diameter), that can be driven over where unavoidable [3]. Some standards for roundabouts also summarize design rules for grade separated roundabouts and signalised roundabouts; UK standards, in addition to this, also include the selection of roundabout types and recommended provision for non-motorised users by roundabout type [3].

Table 1: Design elements for roundabouts [2].

Roundabout category / D_i [m]	Circular roadway		Entry arms		Exit [m]
	One-lane entry [m]	Two-lane entry [m]	One-lane entry [m]	Two-lane entry [m]	
Large: $D_i > 50$	6	9	3,5	6	4,5
Conventional $40 \leq D_i \leq 50$	6	9	3,5	6	4,5
Compact $25 \leq D_i < 40$	7	8,5-9	3,5	6	4,5
Mini $14 \leq D_i < 25$	7-8	8,5-9	3,5	6	4

Note: D_i is the inscribed central diameter; to help trucks central island treatments at mini-roundabouts can be: i) partially traversable with an inscribed central diameter between 18 and 25 m; ii) fully traversable with an inscribed central diameter between 14 and 18 m. Compact roundabouts are featured by a central island with raised curbs.

A properly designed roundabout, installed at appropriate locations, has the potential to generate several benefits over other forms of traffic control (two-way stop controlled and signalized intersections) in safety, capacity, economics, aesthetics and environmental considerations [4]. Nevertheless, there are conditions under which roundabouts are not suitable either for new installations or for replacing an existing intersection: for example, where topographic or site constraints can limit the ability to provide appropriate geometry or isolated intersections are installed in a network of traffic signals. It follows that trade-offs at a planning level should be considered when a roundabout is one of the design alternatives to be considered. A summary of roundabout advantages and disadvantages is reported [5].

Many studies have proven that one of the main benefits of roundabout installations is the improvement in intersection safety performance than other intersection forms. Roundabouts slow all vehicles allowing drivers more time to react appropriately to any unexpected situation and potential conflicts, and provide refuges for pedestrians to cross a traffic stream at a time. The physical guidance and the separation of the various movements by the splitter islands and the circular central island reduce the number of conflict points. At roundabouts the conflict points, indeed, are reduced to eight of each possible type, whereas a typical four-leg right-angle intersection has the potential for a total of 32 vehicle-vehicle conflicts and 24 vehicle-pedestrian conflicts [4, 5]. Also none of these conflict points at roundabouts are at right angle; at traditional intersections, right angle crashes, indeed, are the most severe crashes and can produce an injury or fatality. Several researches have confirmed not only that the probability of a collision is lowered at roundabouts over traditional forms of intersection and traffic control, but also that any collision that can occur is likely to be less severe due to the low speeds on the roundabout [5–11]. Moreover, reduction in crash frequencies (and injury crashes) was found for a wide range of urban, suburban, and rural settings, even though the safety benefit is greater for small- and medium-capacity roundabouts than for large or multilane roundabouts [6, 7, 12, 13].

Research and observation have shown that entry geometry plays an important role in providing adequate deflection and speed control and determining, otherwise, most probable crash types: an entry tangential to the circulating vehicle path makes often more difficult to achieve speed control objectives and can be the cause of entry-circulating collisions, because entering drivers will be less inclined to yield. Conversely, an entry almost perpendicular to the circulating vehicle path can generate rear-end and loss of control collisions, because abrupt braking may be necessary; however, an alignment through the roundabout center can allow for some exit curvature encouraging drivers to maintain slower speeds through the exit [5]. The optimal design choice concerning entry alignment can also depend on antagonist traffic volumes and site characteristics.

It must be said that crash reductions are most pronounced for motor vehicle, less pronounced for pedestrians (30–40 percent reduction), bicyclists (10 percent) and motorcyclists, depending on the study and design treatments [5, 7, 9, 14]. Evaluation studies based on crash, traffic and geometric data also showed variation in crash rates at roundabouts, or particular groups of roundabouts, mainly driven by traffic exposure [13, 15]. The results of statistical crash data analysis in different countries where the roundabouts are in operation by time, particularized for individual crash categories, are reported in several studies to which it refers. Only for illustrative purposes, Figure 2 shows a comparison between US and UK disaggregated crash data [6, 12].

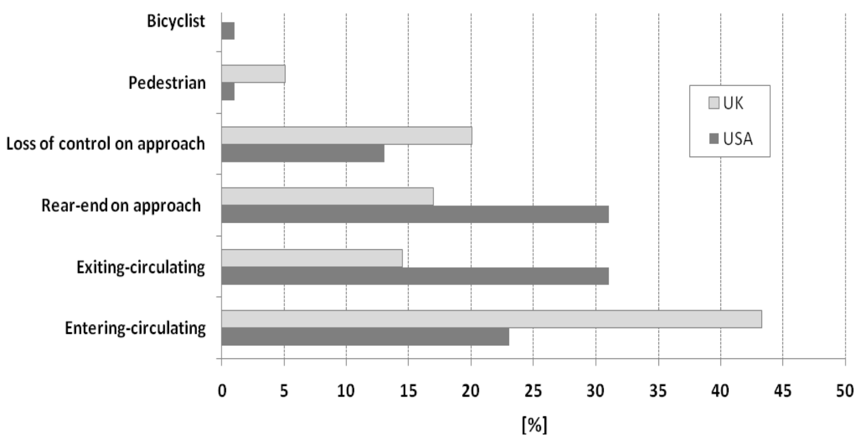


Figure 2: Disaggregated crash data in the UK and USA [6, 12].

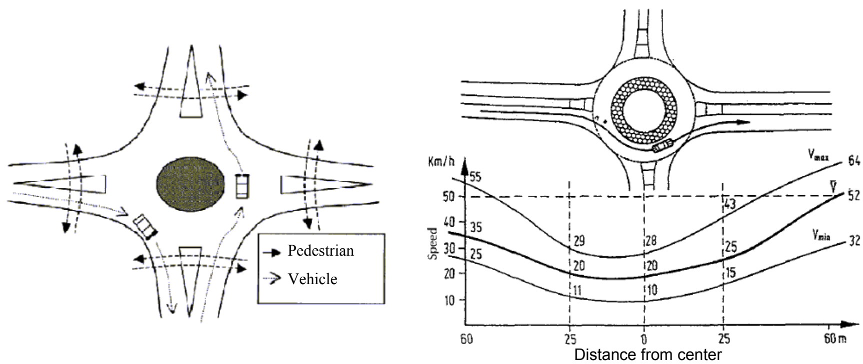
A better understanding of the safety effects of geometric design elements and traffic exposure can assist designers in optimizing the safety of all users [5]. According to [6, 8, 12, 15, 16], Table 2 summarizes elements or measures with a significant relationship with crash frequency at roundabouts for some crash categories. In particular, the entry deflection forces all vehicles to slow down, reducing the probability of crash and its severity (see Figure 3).

Table 2: Effects of design elements on road safety at roundabouts.

Measure	Crash category				
	sv	e/c	re	p	exit/c
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				**	
distance to first sight of roundabout				**	
length of vehicle path					
85th percentile speeds					
reduction in 85th percentile speed					
posted speed limit				**	

sv: single vehicle; e/c: crash between an entering and a circulating vehicle; re: rear-end crash on the approach; p: pedestrian; exit/c: crash between an exiting and a circulating vehicle at multilane roundabouts.

	an increase in this measure increases crash frequency
	an increase in this measure decreases crash frequency
**	the measure had a significant relationship with crash frequency but the relationship was not specified.



Vehicle speed at roundabouts
(German roundabout with 26m inscribed diameter)

Figure 3: Factors affecting safety at roundabouts [16].

Several efforts have been made to evaluate crash reductions at roundabouts compared to other intersection types. A review of international experience and evaluation studies on safety performances at existing roundabouts is shown in Table 3.

Understanding the relationships between roundabout design features and crash frequency through safety models can facilitate the planning and design of roundabouts, quantifying thus safety implications of design choices and determining then the effectiveness of roundabout treatments over the other

Table 3: Summary of safety studies at roundabouts.

Author and country	Sample size	Type of study	Findings
Giaever, 1992, Norway [17]	59	Comparison with 124 signalized intersections	3-arm intersections: 0,03 crash rate at roundabouts vs. 0,05 crash rate at signalized intersections; 4-arm intersections: 0,05 crash rate at roundabouts vs. 0,1 crash rate at signalized intersections; 1 pedestrian crash at roundabout vs. 20 % of injury crashes at signalized intersections; 36 % of two-wheeled vehicles at roundabouts vs. 23 % at signalized intersections
Austroads, 1993, Australia [18]	73	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*
Schoon and van Minnen, 1993, The Netherlands [19]	181	Before-and-after without control *(mostly single-lane roundabouts)*	crash reduction at roundabouts: 73% in all pedestrian injury crashes 89 % for pedestrian fatality; 63% for moped injuries; 30% for cycle injuries.
Brilon *et al.*, 1993, Germany* [20]	25	Before-and-after *(with data on traffic volume before and after)*	a 75% decrease in average vehicle pedestrian crashes for 25 intersections converted to roundabouts from stop signs or traffic signals.
Guichet, 1997, France [21]	12,000	Comparisons with rural intersections traditionally controlled and roundabouts with similar traffic flows	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.
Persaud *et al.*, 2001, USA. [9]	23	Before-after study *(conversion of 23 intersections from stop sign and traffic signal control to roundabouts)*	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.
Elvik, 2003 [20]	–	Meta-analysis of studies *(28 studies reported outside the US to obtain estimates of effects on road safety from converting intersections to roundabouts)*	a 30% to 50% reduction in the number of injury crashes ; a 50% to 70% reduction in the number of 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.

(*) 1993 Report in German as summarized by R. Elvik [20].

intersection forms. A comprehensive review of safety models is included in NCHRP Report 572 on roundabouts in the US [12]. The same report presents an overview of safety prediction models developed for intersection-level and approach-level analyses.

Considering the spread of roundabout installations, new uses have to be also analyzed both in terms of safety sensitivity of the various geometric design elements interacting with users and safety performances [22]; in this regard, an interesting summary for the French experience is reported in [23].

Starting from these considerations, the next section summarizes the international experiences with roundabouts and pedestrians trying to focus on safety-related issues for pedestrians at roundabouts. At last, starting from what is documented by technical literature, an overview of current design practices and implications for roundabout design, aimed at maximizing the potential with regard to safety pedestrians, will be presented and extensively discussed.

2 Effects on pedestrian safety at roundabouts

Several surveys and studies undertaken to explain the reduction of vehicular crashes at roundabouts highlighted that safety benefits are mainly due to low travel speeds and fewer potential conflict points, compared to many traditional intersections, between high-speeding vehicles (or right-turning vehicles or left-turning vehicles) and pedestrians crossing the street; moreover, even where crash frequencies are comparable to other intersections, crash severity is low because the severity of crashes is most directly tied to speed [5].

Several road authorities around the world have already foreseen conversions of intersections into roundabouts within geometric treatments to reduce various crashes types; however, concerns on pedestrian safety should be raised before the roundabout construction [16, 24]. It should also be noted that, although international experience also based on injury statistics confirm that pedestrian safety at roundabouts seems to be high, 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, so as to ensure sufficient stability in the results [9]. Some European safety studies provided significant results regarding pedestrian safety. In Sweden a 2000 study of vehicle-pedestrian crash data from 72 roundabouts showed that single-lane roundabouts are very safe for pedestrian compared to stop controlled and signalized intersections (about a 78% reduction in injuries); multi-lane roundabouts also resulted safe enough [16, 25]. Roundabouts usually are not signalized to provide access to pedestrians, but the possibility of this option is not excluded at crosswalks on multi-lane roundabout approaches, particularly where heavy pedestrian flow can cause long vehicular delays. An interesting research focused on the signal coordination control theory in multi-lane roundabouts and based on considering the pedestrian and bicycle crossing demand is presented in [26]. It should be added that roundabouts can be perceived as unsafe by pedestrians [16], but crash risks from left-turning vehicles, crossing the intersection during the same phase as the pedestrians, fail at roundabouts [27]; moreover, less waiting time can be attributed to the pedestrian crossing movement than at traditional intersections with many protected phases [28]. The reduced traffic speed, the simplification of conflicts, the minimization of the conflict area between pedestrians and vehicles are three reasons generally cited to maximize safety for pedestrians at roundabouts [16]. A synthesis of roundabout advantages and disadvantages for pedestrians are shown in Table 4.

Table 4: Roundabout advantages and disadvantages for pedestrians [28, 29].

Advantages	Disadvantages
– Traffic speeds are generally lower than other intersections, meaning less chance of injury in a collision.	– Entering traffic does not necessarily stop causing hesitation by pedestrians in the crosswalk.
– Drivers are more likely to see pedestrians in the crosswalk.	– Anxiety in pedestrians who are not confident in judging gaps in traffic
– Crossing distances are usually shorter due to splitter islands, allowing us to focus on one direction of traffic at a time.	– Crossing locations and set backs from the yield line often raise travel distances for pedestrians.
– Perceived risks are higher than real risks due to the absence of an exchange of the right-of-way priority by the traffic signals.	– The accommodation of visually impaired pedestrians is a challenge where roundabouts are not yet widely used.

Certain design features, as well as different engineering modifications to the built environment, were found to be important to reduce risks of pedestrian injuries and fatalities [30]. More attention in urban design is required where conversions of intersections to roundabouts are conditioned by physical and topographical constraints that can lead to compromise solutions for one or more geometric features of intersection. Design of modern roundabouts in urban traffic systems and benefits in terms of traffic safety and capacity have been addressed in several studies; see also in this regard [7, 31, 32].

Although it is undeniable the effect of the geometric design of the intersection on safety and operations, there is no consensus internationally about the specific effect of individual geometric element on safety and operational performances; nevertheless, it is generally shared the need to combine certain basic principles within the roundabout design [33]. Combinations of each element, each with its own advantages and disadvantages, are numerous; selection of the optimum combination should be based on the constraints of the site, trying to balance the need to control vehicle speeds, accommodate heavy vehicles, and meet other design objectives [5]. Micro simulation can represent a useful tool in the study of the influence of pedestrian crossings on roundabout performances; on this regard see e.g. [34]. This kind of tools allows the validation of models to interpret the actual mode of operation of the intersection under examination, in support of any strategies of conversion to other schemes or traffic control (see e.g. [35] for the case of a signalized intersection) or the choice of potential countermeasures towards specific categories of users [36].

These considerations allow us to introduce the next section focused on an overview 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 roundabout in terms of safety for pedestrians.

3 Geometric design implications to maximize pedestrians safety at roundabouts

Road design and traffic engineering can apply now a wide array of measures developed to assist pedestrians crossing roads and to minimize the risk and severity of vehicle-pedestrian crashes. Researches and studies examined under this literature review on the specific topic suggested that sharing of road space between pedestrians and vehicles can be difficult when road geometric design and the built environment assign low priority to pedestrians [37].

From a road safety perspective, two approaches are usually taken to provide safe sites for crossing roads and improve pedestrian safety. The first approach is soft type based on the promotion of appropriate behaviours by persuasion of the individual user to behave in a proper way when using road facilities (e.g. when crossing the road). Road safety educational programs, information and awareness campaigns by advertising, can be traced back to this approach. These measures are finalized to educating young people, but are also directed to drivers that may be less inclined to consider pedestrian needs. In general interventions to promote safe driver behaviours are likely to contribute to pedestrian safety whereas best driving behaviours can help to reduce pedestrian-vehicle conflicts [38, 39].

The second approach is hard type and it aims at identifying and implementing measures that result in external constraints on road users and make road space also more conducive to pedestrian traffic activities. Among the measures falling within this approach traffic enforcement measures and road engineering interventions can be cited; these measures can be regarded as aimed at containing unwary pedestrian crossings, or eliminating crossings where many collisions are experienced by pedestrians; for a review of measures see e.g. [40].

According to Retting *et al.* [37], traffic engineering countermeasures can be designed both to manage vehicle speeds and to separate pedestrians and vehicles by time and space, as well as to increase the visibility of pedestrians. A summary of current design features designed to promote pedestrian safety at modern roundabouts are reported in Table 5.

Recent research, also in progress, have suggested that measures targeted to increase pedestrian safety should be evaluated principally in terms of effects on crashes; however, further study is required to establish engineering interventions appropriate to local circumstances, and to test their actual effectiveness, also with reference to specific treatments to be taken for the site under evaluation.

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.

Table 5: Current design practices for pedestrians at roundabouts.

Measure	Design elements, rules and recommendations for accommodating pedestrians
Managing speed	*entry and exit* – Another purpose is to maximize visibility of the central island: – entry curve radii is recommended to be 10–15 m [21]; – 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); at two-lane roundabouts and larger roundabouts two-lane exits should be banned due to safety reasons [41]; – transitions between entry lane curbs and the circle should follow circles with a small radius equal to 12–16 m at entries and 14–18 m at exits [42]; – high-speed tangential exits are avoided [5].
Separating pedestrians and vehicle by time*	*installation of traffic signal* – Pedestrian activated or regular signals with exclusive pedestrian phases can be placed at least 20 m away from the yield line (at entries and exits) and signal phasing has to be set so that queues of exiting vehicles do not encroach on the circulatory roadway [5]; this must be particularly observed at high-volume sites in presence of disabled pedestrians and/or school children; – the use of measures specifically designed to separate pedestrians and vehicles by time is often site dependent [37].
Separating pedestrians and vehicle by space	*splitter island* – it acts as a pedestrian refuge island, allowing pedestrians to cross road in two stages; it is also aimed at separating traffic moving in opposing directions and slowing and deflecting entering traffic; – splitter island is cut to allow pedestrians, wheelchairs, or bicycles to pass through [5]; – it is recommended to be 1.6 to 2.5 m wide or 3.0 m [16, 43].
Increasing pedestrian visibility	*pedestrian crossings* – no pedestrian activities are allowed on the central island; in presence of flared entries, pedestrian crossing has to be placed before the flaring [3]; – location of pedestrian crossing generally recommended 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 two-lane roundabouts, because pedestrian crossings close to the circle may cause potentially longer waiting times at the entrance (so reducing roundabout capacity) and further away may increase walking distances exposing pedestrians to higher speeds [16]; – 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 [16, 43].

(*) at roundabout, the use of pedestrian hybrid beacon, more known as HAWK (High intensity Activated crossWalK), already used to warn and control traffic at an unsignalized location to assist pedestrians in crossing at a marked crosswalk, does not extend yet (for more information on this device see [44]).

Many studies on safety effectiveness of road engineering measures have experienced limits by a methodological point of view, for example, due to failure to account for regression to the mean resulting in overestimation of the effects of an intervention when high-crash locations are selected to be treated [37]. Some observational road safety studies have already considered pedestrian–motor vehicle conflicts to evaluate road countermeasures, because conflict studies can also provide information about crash causes. Traffic conflicts on the basis of empirical evidence were examined and validated by Hauer and Garder [45]. In any case, given the very large number of roads and the meagre resources available for road engineering countermeasures, these with the greatest potential for crash reduction should have priority. Further research is still needed to develop appropriate treatments to accommodate pedestrians with vision disabilities and with reduced mobility at roundabouts [46].

4 Conclusions

In a sustainable safety vision, road system planning and design must include engineering choices that help to improve the sharing of road space between vehicles and pedestrians, as well as other vulnerable users. In this view modern roundabouts represent a very safe solution compared with other types of intersections both for effects on speeds and for effects on conflicts between road users. Starting from a brief examination of the international experience on safety at modern roundabouts, as documented in the scientific literature, the paper focuses on the effects of roundabouts on pedestrian safety. This research also provides an overview of the current state of practice and implications in the roundabout design to maximize the potential with regard to safety pedestrians, highlighting that in the case of many traffic engineering measures and design patterns more definitive research is needed to establish their effects on pedestrian-vehicle crash risks.

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