Review of Accident Research at Roundabouts

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Abstract

Roundabouts have been a key form of junction in the UK for many years. They are used on all classes of road in both urban and rural areas for the efficient and safe control of traffic, particularly where side road flows are high. Roundabouts are the most common type of control used at motorway intersections, and are heavily used throughout the UK's trunk and principal road network, as well as on local authority roads.

Following a state-of-the-art review of international roundabout design, this paper reviews the research into accidents at roundabouts in the light of issues for the revised UK Geometric Design Standard. In order to meet the needs of modern roads, the revised Standard is likely to adopt a hierarchical approach, with different designs for roundabouts on rural and urban roads, the intention being to place much greater emphasis on the interests of vulnerable road users.

INTRODUCTION

Background

Roundabouts have been a key form of junction in the UK for many years and are used on all classes of road in both urban and rural areas for the efficient and safe control of traffic, particularly where side road flows are high. They are the most common type of control used at motorway intersections, and are heavily used throughout the trunk and principal road network, as well as on local authority roads.

The current UK Geometric Design Standard for Roundabouts (Design Manual for Roads and Bridges 6.2.3) is based on extensive research which led to predictive relationships incorporating the key variables found to influence safety and capacity. Entry width and sharpness of 'flare' were established as the primary determinants of capacity/delay whilst a combination of entry deflection and entry width was their equivalent for safety. However, it was recognized that although roundabouts performed well in terms of overall safety, the involvement in accidents of pedal cyclists and motor cyclists at this junction type was relatively high. More recently, concerns about pedestrians and horse riders, and the prevention of large goods vehicle roll-over accidents at roundabouts have become issues.

The aim of the study is to provide a state-of-the-art review of international roundabout design that will lead to a revised Design Standard to meet the needs of modern UK roads. The UK Standard is intended for high capacity trunk roads, although it is widely used by local highway authorities. Mini-roundabouts, with a central island less than 4m in diameter and capable of being driven over, and signalized roundabouts are not included as they are covered by different UK standards.

The review considers the following issues:

- The need for different roundabout designs on rural and urban roads
- Whether, and under what circumstances, designs with much greater emphasis on vulnerable road users might be introduced
- The case for outward crossfall
- The problem of large vehicle roll-over accidents

An extensive comparison of guidelines on roundabout design in various countries was summarised in Kennedy et al (2005). The current paper reviews the research into accidents at roundabouts, with particular emphasis on the above issues.

Roundabout categories

In the UK, all roundabouts have broadly the same design, whether they are mini-roundabouts or form part of a large grade separated junction. Entry flaring by adding either one or two lanes at the give-way line is recommended even if it is not required to increase capacity. There are generally two or three lanes at the give-way line. Figure 1 gives some of the basic roundabout definitions.

Guidelines in other countries tend to classify roundabouts by size:

- Single-lane roundabout - one lane entry, exit and circulatory carriageway
- Double-lane roundabout - two lane entry, exit and circulatory carriageway
- Three-lane roundabout - three lane entry, exit and circulatory carriageway

There are often separate designs or recommendations for rural and urban roads and, in some countries, for arterial and local roads. Mini-roundabouts are a possible alternative to single-lane roundabouts on local urban roads.

There is often much greater emphasis on designing primarily for safety rather than capacity in countries other than in the UK (Kennedy et al, 2005), with France, Germany and the Netherlands having smaller roundabouts with much tighter geometry. In Australia and Scandinavia, more importance is given to capacity and correspondingly, designs are more similar to the UK. US design (FHA, 2000) draws on guidelines from elsewhere, notably the UK, France and Australia. Larger single-lane and double-lane roundabouts are comparable with those in Australia and the UK, whereas "urban-compact" roundabouts are similar to single-lane urban roundabouts in Germany, France and the Netherlands (Kennedy et al, 2005).

SAFETY EFFECTS OF DESIGN

Introduction

All countries have found roundabouts to be a relatively safe form of junction. The reasons for their low accident rate were summarised in NCHRP Synthesis 264 as:

- Reduced speeds / increased awareness because of need to deflect from ahead path
- Low number of conflict points at a roundabout compared with other junction types
- Separation of conflict points
- One-way operation of circulating carriageway

However, it is noted that other countries claim a better safety record for their roundabouts than the UK.

Possible reasons for differences in the safety record are as follows:

- Higher flows at UK roundabouts
- Difference in definition of junction accident. For example, the distance at which an accident is treated as non-junction is 20m from the give-way line in the UK, but 50m at urban junctions and 100m (150m if there is an acceleration lane) at rural junctions in France. No distance is given for the exit
- Differences in the definition of injury accidents:

  fatal – e.g. death occurs within 6 days in France (30 days in the UK)

  serious – e.g. more than 6 days in hospital in France (kept in hospital in the UK)

  slight – e.g. receives hospital treatment in France (taken to hospital / reports injury in the UK)
- Cultural differences, for example, overseas drivers may be more cautious because they are still relatively unfamiliar with roundabouts and are unsure about the priority rule
- Other countries mostly use single lane roundabouts
- The main UK study (Maycock and Hall, 1984) is old (based on 1970s data). It is likely that improved roundabout design as a result of their work, reductions in two-wheeled traffic over the past 25 years, together with improved vehicle safety will have reduced the accident rates
- Although the values in the current study are similar to that by Maycock and Hall, the roundabouts involved all had high flows.

Because of the differences in driver behaviour, in accident reporting, and in sampling, it should be pointed out that the international comparison of accident frequencies and rates in the following sections needs to be treated with caution and is included for completeness. In addition to this comparison, the paper considers the effect of individual design elements on accident groups. As for all junction types, the biggest effect on accident frequency at roundabouts comes from traffic flow. However, the effect of geometric design can also be considerable.

Conversion from other junction types

In most countries, 'before-and-after' studies have been undertaken to show the effect on safety of conversion from another junction type to a roundabout. Large reductions in all types of accidents have been demonstrated (although part of the reduction may be due to site selection bias – see e.g. Hauer, 1997). The accident groups showing the smallest reductions are those involving two-wheelers.

For example, Schoon and Van Minnen (1994) in the Netherlands studied 181 junctions converted to roundabouts. The mean reduction was 51%, from 1.3 casualties per year (over 5.3 years) to 0.37 casualties per year (over 2 years), with the greatest values being for cars (63%) and pedestrians (73%). Cyclists had the lowest reduction (6%).

A study in France in which injury accidents were reduced by 78% from 1.42 per year to 0.31 per year is reported in NCHRP Synthesis 164 (1998). In the US, a mean accident reduction of 51% at 11 sites is reported in FHA (2000) following conversion to a roundabout. In Australia, the casualty accident rate decreased by 74% after roundabout installation (Arndt and Troutbeck, 1995) and by 45 to 87% in another study by Wadhwa (2003).

Accident frequency and severity

An accident study undertaken in conjunction with the current research determined the accident frequencies by severity over a five year period (Table 1) for a sample of 1162 roundabouts. The sample comprised all roundabouts in some local authorities, but only the busier roundabouts from a few others, making the study slightly biased towards busier roundabouts.

Table 1: Accident frequency at UK roundabouts by number of arms 1999 to 2003 (current study)

No. of arms	No. of sites	Accident frequency: Single cway roads	Dual cway roads	Grade separated junctions	All roads	Severity (% fatal and serious)
3	326	0.63	1.28	2.70	0.79	9.3
4	649	1.08	2.65	5.35	1.79	7.1
5	157	1.72	3.80	7.67	3.66	7.1
6	30	2.11	4.62	8.71	5.95	5.2
All	1162	1.00	2.60	6.28	1.87	7.2

As might be expected, there is a clear increase in accident frequency with number of arms (Figure 2). A similar result is reported in NCHRP Synthesis 164 (1998) for a French study in which accident frequency increases with inscribed circle diameter.

The accident frequency of 1.79 for 4-arm roundabouts is much lower than that of 3.31 obtained by Maycock and Hall (1984) – Table 2. In part, the difference may be attributed to improvements in general safety and in roundabout design over the 25 year period since data was collected for the earlier study. The Maycock and Hall sample was biased to sites with a high flow and contained a number of poorly designed roundabouts. Very few values were traced for roundabouts in other countries. Guichet (1997) gave a frequency as 11 per 100 roundabouts per year for French roundabouts. Arndt and Troutbeck (1995) predict a value of 1 accident per arm per year for a typical dual lane roundabout in an urban environment in Australia, but this includes some damage-only accidents. Harper and Dunn (2003) obtained values of 0.42 accidents per year for single lane roundabouts and 0.79 for double lane roundabouts.

Accident severity (percentage of accidents that are fatal or serious) is low, with only 7% in the current UK study, much lower than the value of 16% in Maycock and Hall (1984). This difference is likely to be due mainly to changes in vehicle design.

Table 2: Accident frequency and severity at roundabouts in different countries

Country	Reference	No. of roundabouts in study	Accident frequency	Severity (% fatal and serious)
Australia	Quoted in NCHRP 264 (1998)	290	0.6	-
Australia[1]	Arndt and Troutbeck (1995)	-	4	-
France	Guichet (1997)	12,000	0.11	25 to 38
Denmark	Jorgensen (1990)	63	1.0 to 1.25	-
New Zealand	Harper and Dunn (2003)	95	0.51	12
The Netherlands[2]	Schoon and Van Minnen (1994)	16	0.75	-
The Netherlands[2]	Van Minnen (1993)	46	0.23	-
Switzerland[3]	Spacek (2004)	32	0.85	22 to 42
UK	Maycock and Hall (1984)	84	2.36 to 4.38	16
UK	Current	1,162	1.77	7
US –	NCHRP Synthesis 264 (1998)	11	1.5	-

1 Estimated for double lane roundabouts; includes property damage only accidents

2 Casualties per roundabout per year

3 Estimated

4 Single lane roundabouts in Maryland and Florida

5

6

Accident rate

Accident rates (accidents per 100 million vehicles passing through the junction) are shown in Table 3. The UK value (Maycock and Hall, 1984) varied from an average of 23.5 per 100 million vehicles at conventional and dual-carriageway roundabouts to 34.8 per 100 million vehicles at small roundabouts. It was not possible to obtain flows for most of the roundabouts in the current study and therefore accident rates are not available.

The mean accident rate at urban roundabouts in France was 4.45 per 100 million vehicles (Alphand et al, 1991A) compared with 21.2 at conventional urban roundabouts in the UK. The accident rate in Australia (Austroads, 1993) was 8 injury accidents per 100 million vehicles at high volume and 4 per 100 million vehicles at low volume roundabouts.

In Germany, the accident rate given by Brilon (2005) ranges from 53 to 162 per 100 million vehicles, very much larger than other values as it includes damage-only accidents.

In Norway (Brown, 1995), the accident rate was 5 injury accidents per 100 million vehicles for a 4-arm roundabout, with about 36% of accidents involving a two-wheeler.

The accident rate in Denmark (Jorgensen, 1990) was 14 per 100 million vehicles. This figure is based on 38 injury accidents at 25 roundabouts, of which 7 were single vehicle accidents and 22 (58%) involved a cyclist on the circulating carriageway (16 with an entering and 6 with an exiting vehicle).

Table 3: Accident rates at roundabouts in different countries

Country	Reference	No. of roundabouts	Accident rate (accidents per 100 million vehicles)
Australia[1]	Austroads (1993)	-	4 to 8
Denmark	Jorgensen (1990)	25	14
France	Alphand et al (1991A)	179	4.45
Germany[1]	Brilon (2005)	-	53 to 162
Norway	Brown (1995)	-	5
UK	Maycock and Hall (1984)	84	21.2 to 37.1
UK	Current (high flow)	44	36.2
Sweden	Brude and Larsson (1999)	182	1.8 to 16.2
US	Quoted in Wadhwa (2003)[2]	11	8

1 Includes property damage only accidents

2 Single lane roundabouts in Maryland and Florida

Table 4 shows the percentage of accidents involved by vehicle type and their severity. Both motorcycles and pedal cycles, but particularly the former, are over-represented. The severity is much higher for motorcyclists and pedestrians than for other vehicle types.

Table 4: Accidents by type of vehicle involved (1999 to 2003)

	% of accidents	Severity
Pedal cycles	8.0%	9.5%
Motorcycles	14.4%	19.3%
Cars and taxis	76.7%	6.0%
Public Service Vehicles	2.6%	7.8%
Light goods vehicles	6.4%	5.6%
Heavy goods vehicles	9.3%	8.0%
Pedestrians	2.8%	22.6%

Accident modelling in the UK

In a major cross-sectional study of accidents at 4-arm roundabouts, Maycock and Hall (1984) developed accident predictive models based on vehicle and pedestrian flow and on geometry using the technique of generalised linear modelling. A similar study was undertaken by Kennedy et al (1998) for mini-roundabouts. Models for both are now incorporated into ARCADY and *Safe*NET software (Binning, 2000, TRL, 1999).

The relationships took the form:

$$A = kQ^{\alpha}$$

where A is the number of accidents per year, Q is the flow function and k and α are parameters to be determined by the regression. Alternatively, two flow functions, each with different exponents can be used:

$$A = k\, Q_1^{\alpha}\, Q_2^{\beta}$$

where A could be the number of entering-circulating accidents on an arm and Q_1 and Q_2 could represent the entering and circulating flows respectively and k, α and β are parameters. These models were extended to allow the effect of geometric and layout variables to be determined:

$$A = k\, Q_1^{\alpha}\, Q_2^{\beta} \exp(\sum g_i\, G_i)$$

where the G_i are geometric variables and the g_i are parameters.

The models are applicable to each arm separately.

Australian modelling approach

Arndt and Troutbeck (1995) developed models using multiple linear regression with independent variables related to driver behaviour rather than geometric design. These include flow, 85th percentile speed, vehicle path radius and changes in 85th percentile speed as the vehicle progresses through the roundabout. For example, their model for approaching rear end shunts is similar to (2) with an additional speed term:

$$A = c_1\, Q_1^{\alpha}\, Q_2^{\beta}\, S^z + c_2$$

where c_1 and c_2 are constants and S is the 85^{th} percentile speed on the approach curve, whilst that for entering-circulating accidents is similar but takes into account the relative 85^{th} percentile speeds on the approach curve and the circulating carriageway. The model for single vehicle accidents also takes into account changes in speed at the start of each geometric "element". Arndt and Troutbeck's models were later refined to include variables such as the number of approach lanes, the vehicle path radius on each geometric element and the length of the driver path on this element. The revised models are described in the Queensland Road Planning and Design

Manual, Chapter 14 (2002), including a speed prediction model, and have been incorporated into the Arndt software.

Swedish modelling approach

Brude and Larsson (1999) developed simple models for collision and injury accident rates (accidents per million vehicles entering the junction).

$$\text{Collision rate} = 0.1353 \times 0.86^{3leg} \times 1.88^{speed70} \times 1.20^{2lanes}$$

where the 3 dummy variables represent the number of arms (3leg= 1 if there are 3 arms, 0 with 4), the maximum local speed limit (speed70= 1 if the maximum local speed limit is 70km/h, 0 if 50km/h) and the number of entry lanes (2lanes= 1 if there are 2 entry lanes, 0 with 1).

Injury accidents are given by:

$$A = 0.8178 \times (\text{collision rate})^{1.6871}$$

An alternative model predicts that the accident rate increases by about 40% if the speed limit within 600m of the roundabout is higher than the local speed limit.

Accident groups

The main accident groups identified in the Maycock and Hall study were:

- *entering-circulating accidents* in which an entering vehicle collides with a vehicle already on the roundabout
- *approaching accidents* i.e. rear shunts and lane-changing accidents on the approach
- *single vehicle accidents* involving a vehicle colliding with some part of the junction layout or with street furniture
- *'other' vehicle accidents* including circulating vehicles colliding with each other, circulating vehicles colliding with vehicles exiting the junction, exiting vehicles colliding with entering vehicles and with other exiting vehicles and a few other miscellaneous accidents
- *pedestrian accidents* in which a pedestrian is hit by a vehicle

Some of the above categories are split in other countries e.g. failure to give way on entry, single vehicle accidents on the approach, rollover accidents, single vehicle collision with central island, rear shunts on exit, accidents involving two circulating vehicles etc. Accidents involving cyclists are also often handled separately.

The proportion of accidents in each group depended on the type of roundabout. Small island roundabouts (not mini-roundabouts) had a much higher proportion of entering-circulating accidents (71% compared with 20%), whilst conventional and dual-carriageway roundabouts had much higher proportions of single vehicle and approaching accidents. There were very few pedestrian accidents even at urban roundabouts.

The most important geometric variables found to affect accidents were:

- *Entry path curvature* (deflection) is an important determinant of accidents; increasing deflection had the effect of reducing entering-circulating accidents, but increasing approaching accidents and single vehicle accidents. *Entry path radius* is the inverse of entry path curvature.
- *Entry width* has the effect of increasing entering-circulating accidents but reducing approaching accidents; the entering-circulating effect is generally more important
- *Ratio factor* is a function of the ratio R of the inscribed circle diameter to the central island diameter; it was used mainly to distinguish between conventional and small roundabouts
- *Proportion of motorcycles in the flow* has the effect of increasing entering-circulating accidents; the proportion of pedal cycles was not found to be significant despite the fact that pedal cycles are also at risk.

Other variables found to have an effect on accidents were:

- *Angle with next arm*

- *Approach width*
- *Approach curvature*

Table 5 compares the percentage of accidents by accident group at French and UK roundabouts. There were notably more approaching accidents and fewer single vehicle and entering-circulating accidents at the UK roundabouts.

Table 5: Percentage of accidents by accident group at roundabouts in various countries

% of total	Single vehicle accidents	Approaching accidents	Entering-circulating accidents	'Other' vehicle accidents	Pedestrian accidents
Australia – Arndt and Troutbeck (1995)[1]	18	22	51	9	
France – Guichet (1997)	28	7	37	15	10
Germany[1] – Brilon and Stuwe (1993)	28	17	30	25	
New Zealand – Harper and Dunn (2003)	19	21	45	15	
Switzerland – Spacek (2004)	16	10	59	15	
UK – Maycock and Hall (1984)	38	19	16	19	8

1 Includes property damage only accidents

Single vehicle accidents

Maycock and Hall (1984) found that at 4-arm roundabouts in the UK, the risk of single vehicle accidents increased with wider entries and with greater entry path curvature, but decreased where there was greater approach curvature. The latter has the effect of reducing the approach speed for vehicles. If the entry speed is too great, then vehicles will not be able to negotiate the roundabout safely. Maycock and Hall also found that greater sight distance to the right (left in countries that drive on the right) was associated with an increase in single vehicle accidents, although this variable was not used in their preferred models.

There is anecdotal evidence that single vehicle accidents are more frequent where:

- there is poor delineation of the roundabout approach
- there are high speeds on the approach and the median line does not lie on an arc that is tangential to the central island

Worthington (1992) reported that the use of reflective block-paved chevrons on the central island of a roundabout, in conjunction with lighting to full standards:

- enhanced roundabout conspicuity during both night and day time conditions
- reduced approach speeds
- reduced accidents involving vehicles overrunning the central island and related damage to traffic signs.

Chevrons are now in widespread use in the UK.

In an evaluation of the effect of geometric parameters on accident rates at roundabouts in Australia, Arndt (1991) confirmed that roundabout arms with a large entry path curvature and high approach speeds tend to have more single vehicle accidents and that risk for this accident group is increased by poor recognition of the central island from the approach arms.

Robinson (1998) reported on roundabouts in New South Wales in Australia and concluded that excessive approach speed is a major cause of single vehicle accidents.

A French study by Alphand et al (1991A) found that out of 33 single vehicle accidents on the circulating carriageway, 17 involved mopeds and 5 motorcycles. These were thought to be due mainly to excessive speed for vehicles turning left (taking the third exit) and sometimes the presence of oil or gravel.

Approaching accidents (lane changing and rear shunts)

Maycock and Hall (1984) found that, at 4-arm roundabouts in the UK, wider entries had a lower risk of approaching accidents.

In an Australian study of 100 roundabouts in Queensland, Arndt and Troutbeck (1995) concluded that, in order to minimize rear shunt accident rates, it is important to limit the 85th percentile speed on the approaches to roundabouts to around 60 km/h.

Entering-circulating accidents

At 4-arm roundabouts in the UK, Maycock and Hall (1984) found that the effect of entry path curvature on entering-circulating accidents was considerable. Roundabouts with no deflection had accident rates about 8.5 times those with maximum deflection, a result that led to modern roundabout design. The same study showed that wider entries are associated with higher risk of entering-circulating accidents. The authors concluded that roundabouts with heavily flared entries should have as much entry path deflection as possible.

In Australia, Arndt (1991) observed that roundabouts with a high speed approach have increased risk of entering-circulating accidents. Arndt and Troutbeck (1995) concluded that the speed of entering relative to circulating vehicles should be limited to around 35km/h, in order to reduce entering-circulating accident rates. They suggested using a small radius approach curve, narrowing the entry, exit and circulatory lanes, better positioning of the entry and exit arms and increasing the central island diameter as ways of reducing the relative speeds between entering and circulating vehicles.

Other vehicle accidents

Literature relating to 'other vehicle' accidents includes accidents to vehicles exiting the roundabout and accidents involving the rollover of heavy goods vehicles (HGVs).

Exiting accidents

Arndt (1991) noted that exits with small deflection islands and a small exit radius can result in accidents between entering and exiting vehicles. Anecdotal evidence in the UK suggests that large exit radii are desirable.

Rollover accidents

There are about 50 to 60 injury accidents per year in the UK involving rollover of HGVs. Load shedding is frequent at some grade-separated roundabouts where large changes in crossfall are combined with tight reverse horizontal curvature on moderately steep down gradients of about 5% (Brown, 1995). Even when there is no personal injury, this type of incident is expensive and can cause considerable delay. When going ahead at a roundabout, a vehicle must follow a double bend rather than the continuous arc of a circle, which leads to load transfer and possible rollover for articulated vehicles. Unpublished research by TRL has shown that a double bend with a radius of curvature less than 50m, common at roundabouts, cannot be negotiated safely by articulated vehicles at speeds of more than 50km/hr. Articulated vehicles can overturn at speeds as low as 24km/hr on a curve of radius 20m (Kemp et al, 1978) and rollover is twice as likely as for rigid vehicles. Vehicles with high centres of gravity are most at risk.

Arndt (1991) found in Australia that large diameter elliptical roundabouts in high speed environments with adverse crossfall on the circulatory lanes can lead to instability for heavy goods vehicles.

Alphand et al (1991B) suggested that roundabouts are unsuitable where there are large numbers of HGVs, stating that rollover accidents are fairly frequent on some types of roundabout.

Unpublished research by TRL suggests that problem roundabouts have 5 main characteristics:

- Long straight high speed approach
- Little deflection before give-way line
- Low circulating flow past entry
- Good visibility to the right
- Significant tightening of turn radius part way round the roundabout

The first four characteristics all make it easy for the driver to be deceived into approaching faster than is advisable and the fifth, a tightening of the turn part way round, is a trap for the unwary.

Pedestrian accidents

UK studies (Maycock and Hall, 1984, Kennedy et al, 1998) show a relatively low proportion of accidents involving a pedestrian at both urban roundabouts (4% at small island and 8% at conventional roundabouts) and mini-roundabouts (15%). To some extent, the low proportion at UK roundabouts is due to:

- their location commonly being suburban rather than in the town centre
- pedestrians crossing beyond the flare may be outside the 20m limit of junction accidents

The latter does not apply to mini-roundabouts (which have at most a very short flare), however, suggesting that there are other reasons. Both types of junction benefit from a splitter island on the arm to assist pedestrians crossing the road. Drivers need to slow down as they approach the junction and may therefore be more alert than at other parts of the network. It is recognized, particularly in the US, that they may be harder to negotiate for people with a visual impairment than some types of junction.

Maycock and Hall did not find any design features that contributed to pedestrian accidents at roundabouts. Anecdotal evidence suggests that safety concerns are mostly related to exiting vehicles. There needs to be a balance between the geometry, which tends to push the crossing away from the roundabout if there is flaring and the increasing speed of vehicles as they leave the roundabout, pulling the crossing nearer to the exit.

Uncontrolled (zebra) crossings

In many countries, urban roundabouts have uncontrolled crossings on all arms, often adjacent to a cycle path. In the UK, their provision is relatively rare and they are often sited on only one or two arms of the roundabout. No specific distance is quoted in the Standard, but they should be beyond any flare (typically 5m in urban areas). Cycle paths in the UK commonly have a signal-controlled crossing for both cyclists and pedestrians rather than an uncontrolled crossing.

Recommended values in other countries for the distance of uncontrolled crossings from the edge of the circulatory carriageway are between 1 and 3 car lengths.

Signal-controlled crossings

Countries other than the UK mostly do not appear to use signal-controlled crossings at roundabouts, because of the potential confusion with signalised junctions. Uncontrolled crossings are preferred in the UK for the same reason, although a study showed no evidence that the presence of a pelican crossing affected accidents between entering and circulating vehicles or that pelicans were confused with signalised roundabouts (Thompson et al, 1990).

The UK Standard recommends that signal-controlled crossings are sited sufficiently far back to prevent entry capacity on the roundabout arm being limited by the capacity of the crossing (Hunt and Jabbar, 1995). If facilities do not then coincide with the routes pedestrians may wish to take (‘desire lines’), this may lead to risky behaviour as pedestrians try to minimise the time required to negotiate the roundabout. For example, a displacement of 21m allows storage for 3 vehicles per lane but increases pedestrian journey time by 35 seconds (at a walking speed of 1.2m/s).

Harper (PTRC, 1985) found that the accident rate at pelicans was lower than that at zebras (anywhere), and lower at pelicans near roundabouts than at pelicans elsewhere. It is possible that the latter is again due to lower speeds and greater alertness on the approach to the roundabout.

Accidents involving two-wheelers

Accidents to pedal cyclists were not recorded separately by Maycock and Hall (1984), but a later study of these accidents at UK roundabouts (Layfield and Maycock, 1986) based on the same data showed that the risk for pedal cyclists and motorcyclists relative to cars is higher at roundabouts than at other junction types. Pedal cycles were involved in about 13 to 16% of accidents and motor cycles in 30 to 40%. About two-thirds of the 210 cycle accidents involved a cyclist on the circulatory carriageway and, in about half, a cyclist on the circulatory carriageway was hit by an entering vehicle. Later research (e.g. Davies et al, 1997) suggests that two-wheelers are most at risk when other traffic should give way to them.

Similarly Alphand et al (1991A) found that about half of entering-circulating accidents at 194 French roundabouts involved a two-wheeler, mostly at entries with more than one lane, and Harper and Dunn (2003) recorded for New Zealand roundabouts that two-wheelers were involved in 34% of all accidents and 64% of entering-circulating accidents. Robinson (1998) found similar figures in New South Wales (Australia) - 39% and 48.2% respectively.

Layfield and Maycock (1986) developed models for pedal cyclists and motor cyclists as separate groups. The results were similar to those for all vehicles, with entry path curvature and entry width again being the dominant terms.

The various forms of provision for cyclists are:

- Mix with traffic (no special provision, cyclist mixes with other vehicles)
- With-traffic cycle lane on circulatory carriageway (1.5 to 2m wide, often coloured)
  - With / without priority for cyclists
  - With / without separation kerb
- Cycle path round outside of roundabout
  - With / without priority for cyclists

- Separate route for cyclists e.g. subway

Provision for cyclists in the UK is fairly rare, with a few exceptions (Lawton et al, 2003). It is generally recommended in other countries that cyclists should mix with the traffic where the traffic is light, but at busier roundabouts, a cycle path should be provided round the roundabout, but physically separated from it, with combined pedestrian/cycle crossings on which cyclists give way to vehicular traffic. The alternative, in which motorised traffic gives way to cyclists, is used on some urban roundabouts in the Netherlands and in Sweden, but is generally regarded as being less safe. Even where cycle paths are provided, some cyclists may continue to mix with the traffic because of the delay involved in the use of a cycle path.

Cycle lanes on the circulating carriageway itself are considered less safe than cycle paths, because they put cyclists directly into the path of entering traffic and they can result in cyclists not being in the direct line of sight of entering drivers. This concern has been addressed for a UK roundabout in York by moving the cycle lane closer to the central island.

A Swedish study by Brüde and Larsson (1999) found that, for cyclists, it is safer to use a cycle path than to travel on the circulatory carriageway. These results are in line with a German study by Brilon (1996) that concluded that designs with a cycle lane on the outer edge of the circulatory carriageway were associated with more accidents than those in which pedal cycles mixed with other traffic or had a separate cycle path.

Various Dutch authors (Botma, 1997, Minnen and Braimaister, 1994) and Weijermars, 2001) concluded from accident studies in the Netherlands that roundabouts with separate cycle paths on which cyclists have to give priority to vehicles on the arms of the roundabout were the safest solution for cyclists.

Conflict observations in Finland, where driving is on the right, (Räsänen and Summala, 2000) showed that motorists turning right onto the roundabout, frequently failed to see cyclists approaching from the right. This result supports the recommendation to allow cycle crossings on the approaches only to be used in one direction (direction of travel on the roundabout) when motorists must give way to cyclists.

Both Alphand et al (1991A) for French roundabouts and Brüde and Larsson (1996) for Swedish, Danish and Dutch ones found that single-lane small roundabouts are safest for pedal cyclists. Brüde and Larsson also found that at busier roundabouts, a separate cycle path with cycle crossings was the safest form of provision for pedal cyclists. Under low traffic flows, mixed traffic was considered acceptable. A cycle lane on the circulatory carriageway was found to be the least safe option for pedal cyclists.

Outward-sloping crossfall

Countries other than the UK recommend an outward sloping crossfall on the circulatory carriageway varying between 1.5 and 3% for all types of roundabout. This is considered to aid drainage and to make the circulatory carriageway more visible.

By contrast, roundabouts in the UK have inward crossfall close to the central island (i.e. they are dish-shaped or have a crown line), allowing drivers taking the second exit to maintain a relatively high speed through the junction. Crown lines mean that a vehicle may have to cross a 'ridge' at an angle from one camber to another, possibly leading to increased likelihood of rollover for heavy goods vehicles because of the high centre of gravity and the need to negotiate a curve at the same time as the change in camber.

A French study reported in NCHRP Synthesis 164 (1998) found that accident frequency was lower for a group of 21 roundabouts with outward sloping crossfall compared with a group of 42 roundabouts with inward sloping crossfall.

Unpublished research for the Highways Agency suggests that outward crossfall has less effect on speed than geometry and could therefore be adopted in the UK because of the increased conspicuity of the central island and easier construction. Because speeds need to be lower on roundabouts with outward crossfall, there is a concern that its use should not be advocated at rural roundabouts, or unless entry speeds are reduced at urban roundabouts; in icy or wet conditions, vehicles may start to slide at much lower values of lateral acceleration than in dry conditions and use of outward crossfall may decrease the safety margin.

It is likely that outward sloping crossfall will be allowed in urban areas, particularly for the new continental design.

Accident modelling of the effects of continental design

Using ARCADY, Davies et al (1997) studied the effects of the converting six UK roundabouts to a more 'continental' design. The key features were:

- Radial rather than tangential entries
- Single lane entries and exits
- Minimal flare on the entries
- A central island diameter of 15-25m

- An inscribed circle diameter of 25-35m
- A circulatory carriageway width of 5-7m

Although the safety benefits for pedal cyclists may not be fully reflected in the ARCADY accident prediction model, the overall safety effects were positive. The changes in geometry were considered to result in fewer entry-circulating accidents. The study concluded that ‘there seems to be scope for improving the safety for cyclists of some roundabouts by applying a “continental design” to those with total inflows below about 2,500 vehicles/hour’.

UK experiments with continental design

Lawton et al (2003) describe four UK roundabouts which were converted to a more ‘continental’ design, with tighter geometry, fewer entry and exit lanes. At one site, Toucan crossings (signal-controlled crossings for cyclists and pedestrians) were installed and cycle strips painted just ahead of the give-way lines. There appeared to be an increase in perceived safety for cyclists, but there were not enough recorded accidents for any conclusions to be statistically reliable. The cycle strips appeared to deter motor vehicles from overshooting onto the roundabout. The more radial entries were considered to make it more likely that cyclists will be in the field of vision of drivers. Single lane entering and circulating was also considered likely to improve safety for cyclists.

POSSIBLE CHANGES TO UK STANDARD

“Continental-style” design

A “continental-style” roundabout with only one entry, circulating and exit lane could be introduced. This style of roundabout would be most appropriate on local roads where there were substantial numbers of pedestrians or cyclists. Although the main use of this type of roundabout would be in urban areas, a single lane roundabout could also be used on rural roads where flaring is not required for capacity. Outward sloping crossfall would be permitted.

Entry flare

There is evidence that wider entries increase approaching and entering-circulating accidents. Flaring is used in the UK to increase capacity, but also for historical reasons, being originally intended to provide space for cars that break down at the give-way line. Allowing a design with little or no flaring and more radial entries should therefore reduce accidents where the extra width is not necessary for capacity and where approach speeds are low. It will be important to provide an entry width of 4.5 to 5m to allow sufficient space for a car to pass a broken-down vehicle.

Entry path curvature (deflection) or radius

In a number of countries, there is a maximum value of 100m for the entry path radius, which is regarded as being broadly equivalent to an entry speed of 30mph (50kph). In the UK, a minimum of 70m is currently suggested as best practice (Brown, 1995), but this might be lowered for the new design. Values in other countries tend to be lower, reducing the risk of entering-circulating accidents, but increasing that of single vehicle accidents if approach speeds are too high. Alternatively, a design speed could be specified.

Cycle provision

Cycle provision would not be required at a single lane roundabout. At larger urban roundabouts with substantial cycle flows, provision for cyclists could be either:

a) As a cycle lane on the circulatory carriageway, at least 2m from the edge of the circulatory carriageway to ensure the cyclist is in the driver’s sight line

or

b) As a cycle path round the outer edge of the roundabout, but physically separated from it, with uncontrolled crossings for pedestrians and cyclists at one or two car lengths from the give-way line, in advance of any flaring

Pedestrian provision

Pedestrian provision at the new “continental-style” roundabouts would comprise uncontrolled crossings at one or two car lengths from the give-way line. At busier roundabouts, a signal-controlled crossing may be required. This should be located within 20m or more than 50m from the roundabout.

HGV rollover

The possibility of roll-over of large vehicles should be minimized by keeping approach speeds low and ensuring that roundabouts have no abrupt changes in geometry.

Other changes

Other changes are listed below.
At rural roundabouts:

a) It should be mandatory that drivers are guided around the central island by projecting the centreline tangentially

b) On dual-carriageway roads, visibility to the right should be limited until vehicles are within 15m of the give-way line to minimize excessive entry speeds

c) In environmentally sensitive areas, reduced levels of lighting, or technologically advanced solutions such as the use of LED clusters should be permitted. Otherwise roundabouts should be lit except where there is no electricity supply and flow is very low (see Kennedy et al, 2004)

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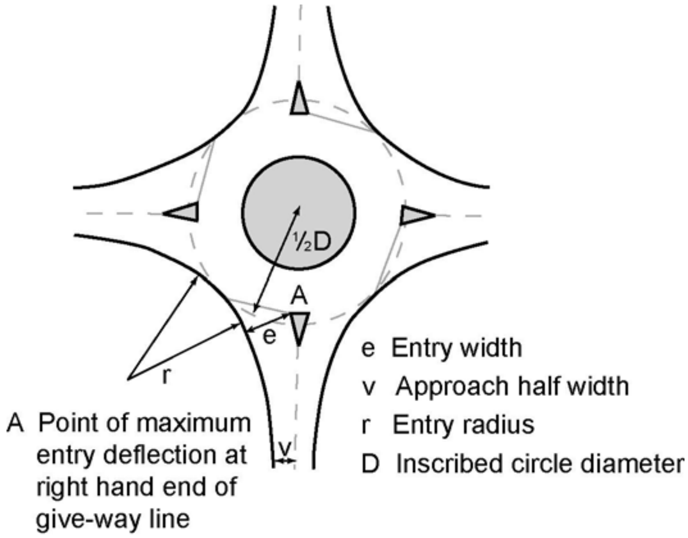

Figure 1: Some basic roundabout definitions

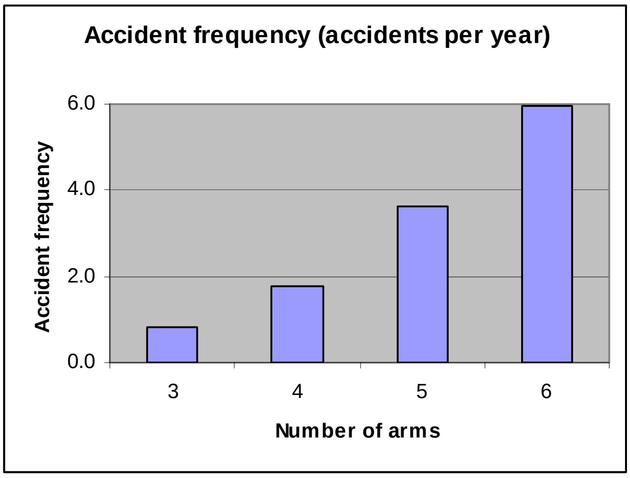

Figure 2: Injury accidents per year by number of arms for a sample of UK roundabouts