

Alternate Design Methods for Pedestrian Safety at Roundabout Entries and Exits: Crash Studies and Design Practices in Australia, France, Great Britain and the USA

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The paper and presentation discuss study results of pedestrian/vehicle crashes and design practices at roundabouts in Australia, France, Great Britain and the USA. There are conflicting roundabout design practices among transportation engineers in the USA, with alternate opinions and claims about the safe design of entries and exits for both single-lane and multi-lane roundabouts. This paper compares two recent designs constructed in the USA using alternate design methods to reduce travel speeds. The meeting presentation will illustrate various alternate design applications at roundabouts currently operating in the USA.

This paper came about as the result of the authors observing roundabout designers in the USA who, in an attempt to slow exiting traffic to protect pedestrians, have constructed roundabouts with excessively tight exit radii. This practice has resulted in roundabouts with unnecessarily low capacity and high vehicle crash rates in some cases. This paper is an opportunity to make the case for the design of high capacity roundabouts that are safe for pedestrians.

1. Introduction

Roundabouts should be designed to provide adequate vehicle capacity while reducing vehicle entry, circulating, and exit speeds. Reduced speeds in roundabouts benefit both vehicles and pedestrians. Pedestrian safety at roundabouts is a function of crash probability and severity. Crash probability relates to user attentiveness, decision time, stopping sight distance, and exposure. Severity relates to vehicle speed at impact.

Adequate speed reduction is essential prior to crosswalks. Curvature of the entry path (R1) reduces speeds prior to the approach crosswalk, and offers the main opportunity to physically constrain speed at that location. For exits, both the entry path curve (R1) and the circulating roadway (R2) are prior to the exit crosswalk, as is part of the exit curve (R3). When speeds are reduced prior to entry and on the circulating roadway, speeds also tend to be lower at the exits. See Figure 1.

FHWA Roundabout Informational Guide According to the FHWA informational guide “achieving appropriate vehicular speeds through the roundabout is the most critical design objective. A well-designed roundabout reduces the relative speeds between conflicting traffic streams by requiring vehicles to negotiate the roundabout along a curved path. Recommended design speeds vary from between 15 mph for an urban compact single lane roundabout (SLR) to 30 mph for a rural Multi Lane Roundabout (MLR).” The design speed of a roundabout is determined from the smallest radius along the fastest available path. The entry path radius R1, the circulatory path radius R2 and the exit path radius R3 are shown in Figure 1. The smallest radius usually occurs on the circulatory roadway as the vehicle curves to the left around the central island. (1)

The Informational Guide states that at “single-lane roundabouts with pedestrian activity, exit radii may still be small (the same or slightly larger than R2) in order to minimize exit speeds. And at multi-lane roundabouts where pedestrians are present, tighter exit curvature may be necessary to ensure sufficiently low speeds at the downstream pedestrian crossing.”

Australian Recommendations Australian pedestrian crash studies have been cited as the motivation to build tight exit radii in the United States. In particular, the following statement from Tumber 1997 has been used as a rationale for tight exit radii: “The design of roundabouts should ensure adequate that

reduction of vehicle speeds is achieved prior to pedestrian crossing points, to assist in reducing the severity of injury in the event of a crash with a pedestrian.” The same study found that nearly twice as many pedestrian crashes (45% vs. 27%) occurred at entries as at exits. This shows that the probability of a pedestrian collision (in Melbourne) is nearly twice as high at entries than at exits, and suggests that speed reduction at entries is most critical. (2)

British Roundabout Design

“Adequate” speed reduction leaves room for interpretation. The designer should consider the driver’s stopping sight distance and pedestrian decision and crossing time. The pedestrian needs to interpret the drivers’ intentions (to exit or circulate) with adequate time to complete the crossing. With a relaxed exit path, the driver’s intentions are apparent to the pedestrian earlier. The pedestrian crossing is also visible to the driver earlier, so the stopping sight distance is improved. If vehicle speed is reduced prior to the entry, and the Inscribed Circle Diameter (ICD) is smaller, cars will tend to circulate slower, and if the pedestrian is clearly visible (as they are on a more tangential exit), reasonable drivers do not accelerate at them as they begin their exit.

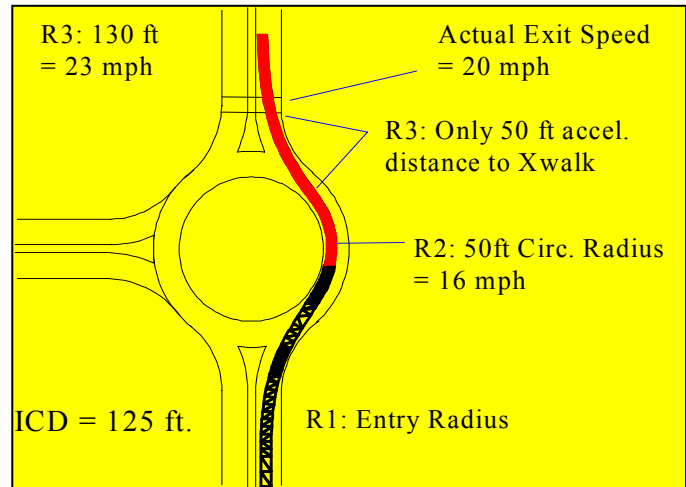


Figure 1: Fastest Vehicle Path and R1, R2 and R3

Exit speed can be calculated based on circulating speed and acceleration rate, starting from the circulating speed at the point where drivers round the central island and begin their exit path curve. A 125 ft. ICD SLR is illustrated in Figure 1 where R2 slows traffic to 16 mph. The R3 is 130ft. which suggests a speed of 23 mph at the exit crosswalk. However, after vehicles pass R2 they have only 50 ft. to reach the exit crosswalk and are only able to reach a speed of 20 mph. The speed reduction to 20 mph at the exiting crosswalk is due to R1 and R2 and not R3.

The exit radius (the mean radius of the exit) of a MLR determines the exit speed during peak-period operation when traffic is plentiful, and people stay in-lane. However, the fastest path ignores lane markings and the fast path exit radius R3 is usually very much larger than the mean exit geometry. On a Single Lane Roundabout (SLR) with a narrow exit width, R3 and the fastest path exit radius are nearly the same. However, if it is a wider single lane exit (to accommodate trucks) R3 can be surprisingly larger than the radius of the exit geometry.

On a Multi-Lane Roundabout (MLR) with a two or three-lane exit, R3 is much larger than the exit geometry radius. Consequently, during peak-periods with lots of traffic (when most pedestrians are present) drivers stay in their lanes on MLR exits, and speeds are low. Speeds are usually greatest during fast-path operation at off-peak periods when vehicles are scarce (and pedestrians are scarce).

Off-peak, the fastest-path exit speed depends not on R3 (too large to have any effect) but on the following:

- The circulatory radius, R2 ;
- The distance from the end of the R2 radius to the exit crosswalk; and
- The acceleration from the end of R2 to the exit crosswalk.

This assumes that drivers accelerate immediately as they reach the end of R2. (This is very aggressive and usually there is a time lag.) The acceleration rate is about 3.5 ft/sec/sec (it may vary depending on the initial R2 speed).

Using Newton's' equation for speed and acceleration:

$$V_f^2 = U^2 + 2aS$$

Where:

V_f = Final Speed

U = Initial R2 Speed

a = Acceleration

S = Distance

Sometimes the R1 speed can be so low that R2 speed is not achieved, so this will be lower than the speed indicated by the R2 radius, especially if the ICD is small as the distance from R1 to R2 is small.

The smaller the ICD, the harder it is to keep R1 small. More interestingly, R2 is strange because with a small ICD, R2 can be large as it skims the central island on a flat trajectory. As the ICD is increased, the enlarged central island bends R2, so it gets smaller. Further increasing the ICD reduces R2 until the point is reached when R2 is the same as the central island radius. From this point onwards, increasing the ICD increases R2, which increases the overall design speed. (3)

2. Roundabout Entry/Exit Design Examples in the USA

The following two examples illustrate critical differences in design of roundabout entries and exits. The Okemos roundabout was designed first with tight exit methods, but with British design methods carried forward to construction. The Clearwater Beach roundabout was designed using tight exit methods through construction, with later changes using British methods to reduce crashes.

Okemos Roundabout – Ingham County, Michigan

Exit speed can be calculated based on circulating speed and acceleration rate, starting from the circulating speed at the point where drivers round the central island and begin their exit path curve. The Okemos, Michigan roundabout shown below was designed following tight exit guidelines shown in Figure 3 and following British guidelines shown in Figure 4. The calculated exit speed at the eastbound exit for both designs is 18 MPH. The constructed roundabout, shown in Figures 5 and 6, followed the British design with exit speeds measured at 15-20 mph. The crossing "feels" very safe, and there have been no pedestrian crashes or complaints between 2000 and 2003.

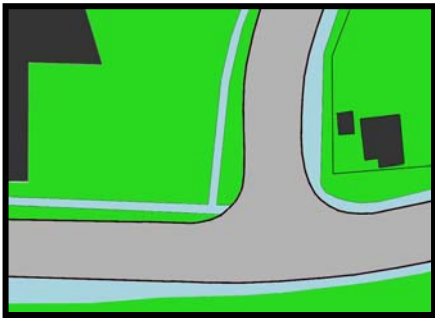


Figure 2. Okemos: Existing Intersection – Traffic Signal

- Old Stop –controlled intersection had delays on side street.
- Installation of a signal resulted in injury crashes and poor signal coordination with nearby signal (to the west), due to high left-turn percentage.
- Move roundabout as far south as possible to:
 - Provide adequate stopping sight distance;
 - Remove see-through problem.
- Large deflection on approach minimizes speeds inside the circle.
- Small ICD has short acceleration distances to the exits.
- Low exit speed (18 mph) for pedestrian safety.

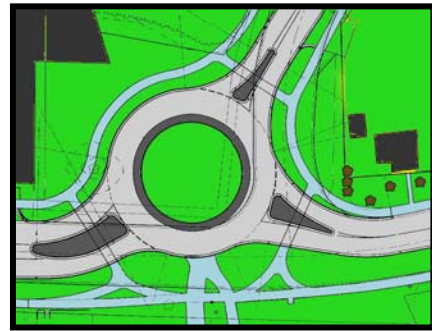


Figure 3. Okemos: Tight Exit Radii Design

- Low circulating flows.
- Minimal queues and delays predicted.
- Stopping sight distance west to east is sub-standard.
- Dangerous “see-through” problem.

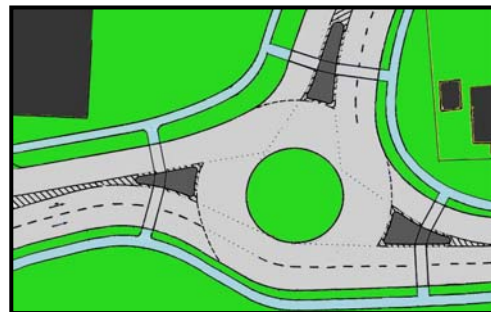


Figure 4. Okemos: British Style Re-Design
Large Deflection, 2-Lane Entry and Tangential Exits



Figure 5. Okemos: Looking Westbound
(Photo courtesy Ingham County Road Commission)



Figure 6. Okemos: Looking Southbound
(Photo courtesy Ingham County Road Commission)

Clearwater Beach Roundabout - Clearwater, Florida

The Clearwater Beach roundabout is described here because it has received a significant amount of negative publicity and is often referred to by roundabout naysayers when explaining why roundabouts will not work in heavy traffic. It is also a classic example of tight exit radii design.



Figure 7. Clearwater Beach Roundabout After Striping and Curb Changes
(Photo courtesy Ken Sides)

I. The Original Design

The design of the Clearwater Roundabout completed in 2000 was uncommonly complex. It converted 5 intersections into one intersection that had to accommodate Spring Break traffic volumes of 56,000 vehicles and 6,000 pedestrians per day. The desires of the Landscape Architects and the Fountain Designers also contributed to the design complexity. The design sought to find the best balance between these unavoidably conflicting aims.

II. Resulting Crash Experience

The roundabout had a large number of vehicle crashes at the 2-lane exits onto the Causeway and at the exit onto Coronado Drive. Many of those crashes involved cars continuing around the circle in the right lane colliding with drivers exiting from the left lane. However, there have been no pedestrian crashes at the roundabout. This clearly reveals that the best balance between vehicle capacity and pedestrian safety was not initially achieved.

III. Striping Changes and Reduction in Crashes

In July 2001, the revisions shown in Figure 7 were made following British practices. The changes included revisions to curbs, signing, striping, and lane arrows were introduced that resulted in a significant drop in number of crashes. For example, at the Causeway exit crashes dropped from a high of 25 per month. At last report, there have been no crashes at this location since the changes were made. This clearly demonstrates that the fault was with design detail and not the drivers. To resolve the crash problem at the Causeway exit and the Mandalay exit the curbs were realigned to create wider and more relaxed exit radii.

3. Review of Pedestrian Crash Studies: *in France, Australia, and Great Britain*

Pedestrian Crash Study in France

In 1990, 202 crashes were investigated at 179 urban roundabouts in France. Table 2 shows the relative frequency of the different causes of these crashes. (4)

The major design recommendations derived from the above study are:

- Ensure motorists recognize the approach to the roundabout;
- Avoid entries and exits with two or more lanes except for capacity requirements;
- Separate the exit and entry by a splitter island;
- Avoid perpendicular entries or very large radii;
- **Avoid very tight exit radii**; and
- Avoid oval-shaped roundabouts.

Cause of Crash	Percent of Crashes
Entering traffic failing to yield to circulating traffic	36.6%
Loss of control inside the circulatory roadway	16.3%
Loss of control at entries	10.0%
Rear-end crashes at entries	7.4%
Sideswipe, mostly at two-lane exits with cyclists	5.9%
Running over pedestrians at marked crosswalks, mostly at two-lane entries	5.9%
Pedestrians on the circulatory roadway	3.5%
Loss of control at exits	2.5%
Head on collision at exits	2.5%
Weaving inside the circulatory roadway	2.5%

Pedestrian Casualty Study in Australia

A 1982 Victorian Pedestrian Casualty Study reported by Jordan evaluated 31 pedestrian crashes from 1980-1983. The study found one pedestrian crash per 100 roundabout years. Of crashes that occurred in crosswalks, 78% occurred as the pedestrian began the crossing, with 22% as they left the splitter island. Of all pedestrian crashes, 39% were on entries, 35% were on exits, 16% were on the circulating roadway and 10% other. (5)

Jordan offers several recommendations for pedestrian crossings (paraphrasing):

- **Reduce vehicle approach speeds by providing adequate deflection on each approach.**
- Provide splitter islands as large as the site allows.
- Provide clearly defined carriage and splitter island crossings.
- Prohibit parking on approaches to improve visibility of pedestrians.
- Assure street lighting illuminates the roundabout and the approaches.
- Locate signs so users perceive an easily recognizable intersection layout.
- Locate signs and landscaping so that signs, pedestrians and bicyclists are not hidden.

A 1997 study by Tumber evaluated 64 pedestrian crashes at 38 Melbourne roundabouts from 1987-1994. The study found 45% of the pedestrian crashes were at entries, 27% at exits, 17% on the circulating roadway, 3% on the footpath or splitter, and 8% at other locations. (This data suggests that vehicle speed reduction is nearly twice as important at entries as at exits). No data was available for pedestrian or vehicle volume, however pedestrian crashes were more common in commercial precincts where pedestrians were most frequent. Pedestrian injuries were less severe at roundabouts than at all other intersection types. (2)

Tumber offers six recommendations for pedestrian safety:

- **Assure adequate vehicle speed reduction prior to pedestrian crossings.**
- Set pedestrian crossings one-to-two car lengths back from yield lines so drivers encounter pedestrian and vehicle conflicts as separate tasks.
- Provide space on the splitter island for carriages, wheelchairs, etc., and make crossings flush with the pavement or as low as possible.
- Assure curbs cuts and splitter island crossings are in alignment.
- Assure visibility for pedestrians to see oncoming vehicles from all crossing points, and for drivers to see all crossing points from each approach.
- Use physical measures to discourage inappropriate pedestrian movements and direct pedestrian to crosswalks.

Pedestrian Crash Studies in Great Britain

A 1975 study by Lalani reported before-and-after crash experience from 38 intersections converted to roundabouts between January 1970 and May 1975. **Pedestrian crashes within 50 meters (165') of the intersection were included in the study, and these dropped 46.2% after conversion to roundabouts, with fatal and serious pedestrian crashes down 70.0%.** At mini-roundabouts, pedestrian crashes dropped 37.5%, and fatal/serious pedestrian crashes dropped 60%. The study did not provide data on pedestrian or vehicle volumes, and did not offer specific design guidance, but recommended roundabouts as an intersection safety measure, with raised islands where practical. (6)

In 1984, the Transport and Road Research Laboratory and Southampton University evaluated 431 junction-years of injury crash data, encompassing 1,427 crashes at 84 four-leg roundabouts. Data was collected on pedestrian and traffic volumes, intersection geometry, and crash type, and analyzed through multivariate regression to determine the variables which predicted crashes of each type -

including pedestrian crashes, which were 5.5% of the total (78 crashes). Pedestrian volume data was available for 60 pedestrian crashes, at fifty roundabouts within 30-40 MPH speed zones.

The TRL study found no significant relationship between geometry and pedestrian crashes. They developed a formula for pedestrian crashes related only to traffic and pedestrian flows:

$$A = .029 (Q_v Q_p)^{0.5}$$

Where:

A = Annual Pedestrian Injury Crashes for a Roundabout Leg

Q_v = Entering + Exiting vehicle ADT (in thousands)

Q_p = Average Daily Pedestrian Crossing Volume (in thousands)

Although the report relates crashes to volume only and does not provide design recommendations for roundabout pedestrian crossings, some geometric factors are implicit in the TRL formula. For example, vehicle entering and exiting volumes strongly relate to entry and exit width. Since higher volume roads tend to be wider, pedestrians require more time to walk across. Therefore, the TRRL equation relates pedestrian crashes to both vehicle volume and pedestrian crossing time (exposure). This does not state that other relationships between geometry and pedestrian crashes do not exist, only that the crash data did not reveal a significant relationship between pedestrian crashes and roundabout geometry. (7)

4. Conclusions

1. Tight-exit versus relaxed-exit designs were compared at the Okemos and Clearwater Beach roundabouts.
2. Tight-exit design shows little benefit for pedestrians by reducing speed, and in some cases may endanger them by limiting sight-distance for drivers.
3. Studies in both Australia and France show that most pedestrian crashes occur at roundabout entries, not exits.
4. No relationship has been reported between pedestrian crashes and exit radius.
5. Both British and Australian roundabout accident studies show significant reduction in pedestrian accidents after roundabouts are installed. Pedestrian accident rates increase with traffic volumes and pedestrian volumes. As pedestrian/vehicle crossing conflicts increase, crosswalk treatments should be improved accordingly and may warrant grade separation for some roundabout locations.
6. Designed correctly, easy roundabout exits can improve roundabout capacity and reduce vehicle crashes, without increasing exit speeds or harming pedestrians.

Since 1990, about 300 modern roundabouts have been built in the United States. Almost all have been unqualified successes. A study by the Insurance Institute for Highway Safety determined that roundabouts in the United States have reduced all crash types by 40% and injury crashes by 80%, at sites where they replaced other types of intersections. We do not know of any other type of highway improvement that has such a high success rate.

Considering that USA traffic engineers are very inexperienced at roundabout design, it is to our credit that the failure rate so far has been only a few percent. This is exemplified by public opinion in the USA:

typically 80-90% against building a roundabout when it is proposed, but 80-90% in favor after construction. The lesson to be learned from the few failures in the USA is not that roundabouts in general do not work here, but that roundabout design is difficult, errors can lead to failure, and good design produces roundabouts that are safer than any other type of at-grade intersection. "Would-be" roundabout designers should be well advised get experienced assistance before attempting to design a roundabout.

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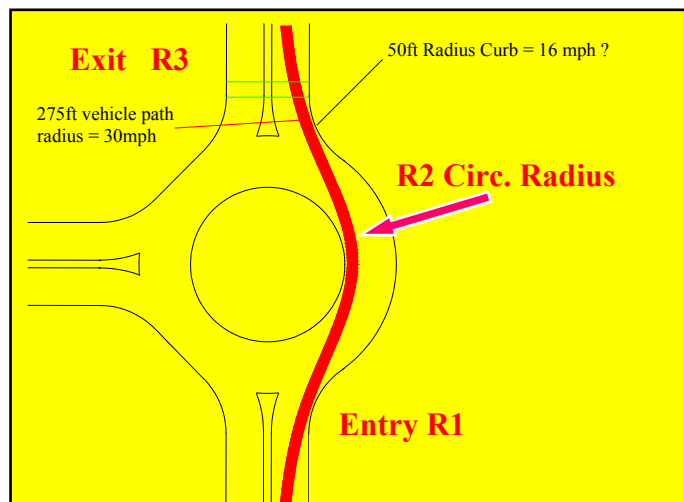
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Exit Speeds and R1, R2, and R3

Exit speed needs to be controlled
 Fast exit speed is dangerous for pedestrians
 How can exit speed be controlled?

It is generally accepted:
 -that small exit radii controls exit speed
 -says so in most literature
 -it is very plausible
However things are not always as they seem



Single Lane Roundabout - 125 ft. ICD

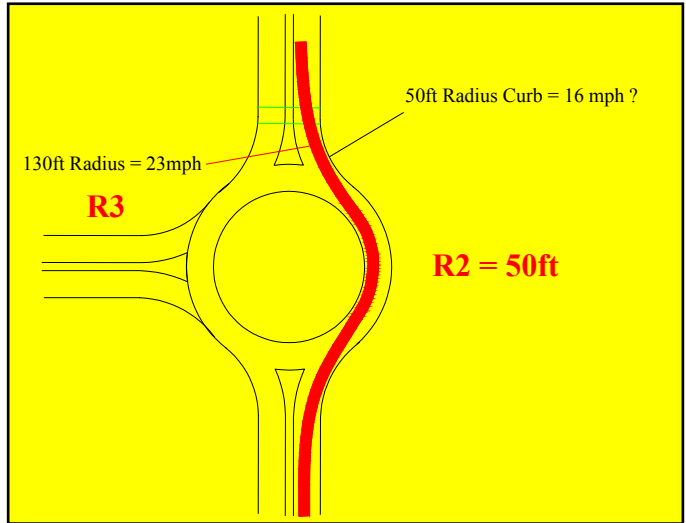
Medium sized 125 ft. ICD single-lane roundabout
If exit width (curb face to curb face) is small (13ft.)

- Small exit radius will control exit speeds
 - R3 the exit path radius is similar to the exit radius
- However if trucks are to be accommodated
Exit width needs to be at least 17 ft. wide
The exit radius is now not so effective
The exit path radius R3 is larger than the exit radius

The exit radius suggests a 16mph speed.
R3 suggests a 23 mph exit speed.
However the central path radius R2 has an effect.
R2 is 50 ft and suggests 16 mph.

The acceleration distance, R2 to crosswalk is 50ft.

- FHWA Guide gives 3.4 ft /second acceleration.
- This gives an exit speed of only 20 mph.
Exit speed on wide single exits is controlled by R2 .
Not controlled by the exit radius or by R3.



2 Lane Roundabout - 165 ft. ICD

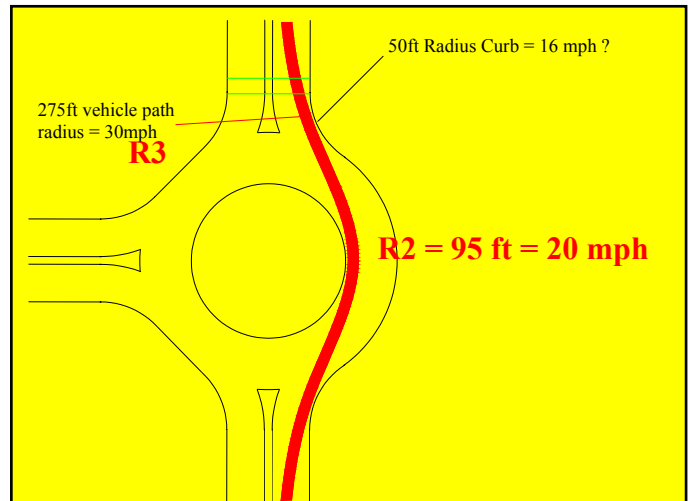
- If exit width curb face to curb face large (23-28ft.).
 - Small exit radius will not control exit speeds.
 - R3 the exit path radius much larger than the exit radius.
- When vehicles exit two abreast speeds are lower.
Small exit radii causes exit overlap and exit crashes.
Small exit radii must not be used on MLRs.

MLR Exit Speed - 165 ft. ICD

The exit radius suggests a 16 mph exit speed.
R3 suggests a 30 mph exit speed.
Again the central path radius R2 has an effect.
This is 95ft and suggests 20 mph.
There is 80ft acceleration distance to the crosswalk.
FHWA Guide gives 3.4 ft/second acceleration.
This gives an exit speed of 25 mph.

Exit speed is therefore controlled by R2.
NOT by the exit radius or R3.

They do not control exit speeds effectively.
Cause exit crashes.



Exit Path Overlap

On a two-lane exit two vehicles can exit together. They must therefore stay in-lane and speeds are low. Small exit radii cause exit lane overlapping. This causes exit crashes.

Clearwater Roundabout had 600 exit crashes

Exit path overlap was one of the causes.

Relaxing exit radii has reduced exit crashes dramatically

BALANCE IS NEEDED

Larger exit radii to avoid vehicle crashes

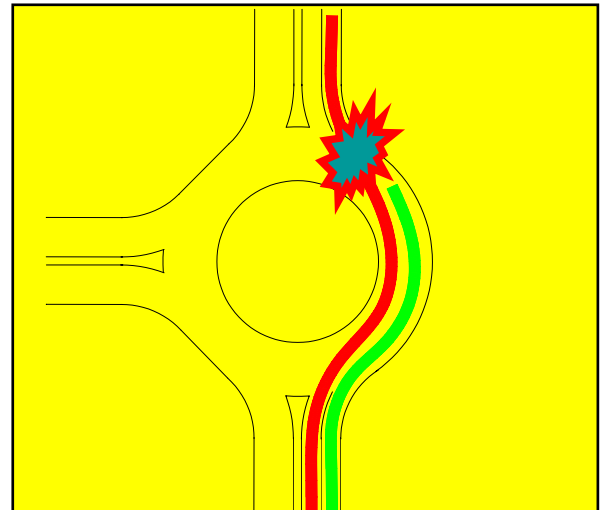
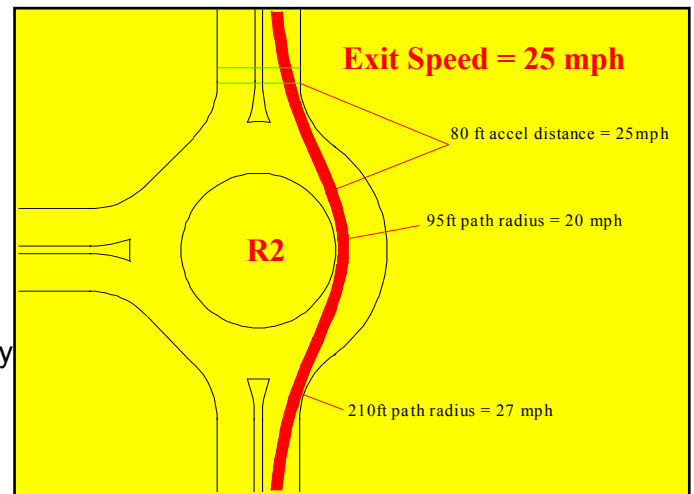
Slow speeds on entry at R1

Slow speeds into exit with R2

Small ICD makes distance between R2 and crosswalk short

Larger radius gives good view: Ped <====>Car

Exit speeds = about 25 mph with good visibility



Crosswalks

UK roundabouts have ~50% less pedestrian crashes than traffic signals.

There is a UK warrant for installing a Signalized crosswalk. PV^2

P is pedestrians crossing/hr, V is vph

If $PV^2 > 10^8$ then a signalized crossing is warranted.

At a roundabout with a splitter Island there are two crosswalks so each has to satisfy the warrant criteria.

The pedestrians cross both so P is the same, but V will be different, the entry flows on one and the exit flows on the other.

When pedestrian volumes are significant they can hamper the roundabout capacity on a un-signalized crosswalk as single pedestrians stop the traffic.

Signalized crosswalks can be set to give a good split for both vehicle traffic and pedestrians.

Crossing the pedestrians in groups is more visible also.

With signalized crosswalks drivers tend to watch the signals rather than the pedestrians just like at normal traffic signals.

Clearwater Beach Mother of All Roundabouts Today as of March 2003:

During Spring Break, traffic approaches 4,000 vph and around 1,000 pedestrians/hour use the two major crosswalks shown below. Photo at left shows new crosswalk location and old location in faint paint.

