Application of Safety Design Principles for Urban Multi-lane Roundabouts

Keys to Improving Driver Comprehension and Reducing PDO Crashes

by

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ABSTRACT

U.S. and international research confirms that roundabouts provide substantial safety benefits with respect to injury and fatal crashes. However, many multi-lane, high-flow roundabouts in North America are experiencing higher numbers of vehicular property-damage-only (PDO) crashes than models predict. Whereas, others roundabouts similar in design, context and traffic flows are preforming with low and closer-to-predicted numbers of PDOS. Many of the high crash roundabouts exceed 90 PDOS annually (and some up to 150 or more PDOS per year), while other roundabouts similar in context and traffic flows that are experiencing only 15-30 PDOS per year are within expected predictions for crashes based on U.S. crash data.

While safety research and analysis points to the substantial safety benefits derived from roundabouts in terms of injury and fatal crashes, the high occurrence of excessive PDOS is viewed as problematic.

This paper reviews research and practice that indicates that a comprehensive, principles-based design approach is necessary to achieve expected safety performance and avoid high amounts of PDOS. A comprehensive and integrated design approach – that includes operational analysis, safe geometrics, signing, and pavement markings working together as a unified whole – is necessary for a driving experience that results in the expected amount of vehicular PDO crashes.

INTRODUCTION

The field of road safety has endeavored to achieve zero deaths originating in Sweden, FHWA is committed to the vision of eliminating fatalities and serious injuries, as per there strategic plan, which articulates the goal of "working toward no fatalities across all modes of travel". Indeed, the introduction of roundabouts has been revolutionary in reducing fatal and serious injury crashes at high flow intersections.

The substantial safety benefits of roundabouts with respect to fatal and injury crashes has been widely documented both in North America and internationally. The central problem complicating the safety benefits is a wide variation in rates of vehicular property-damage-only (PDO) crashes among roundabouts of similar capacity and similar measured flow.

As the number of multi-lane, high-flow roundabouts has increased in North America, some are experiencing high numbers of PDO crashes. Despite following U.S. design guidelines, some are exceeding 90 PDOS annually; yet other roundabouts similar in context and traffic flows are experiencing expected amounts in the range of 15-30 PDOS per year (Figure 1).

The two predominant crash types occurring at roundabouts are entering-circulating (failure-to-yield) and lane discipline crashes, and they represent the majority of the PDO crashes (1, 2).

Established transportation research supports the use of a multi-disciplinary, comprehensive, principles-based design approach to achieve maximum safety (3, 4, 5). This paper discusses why a comprehensive design approach – to include operational analysis, geometrics, signing, and pavement marking, working together as a unified whole – is necessary to reduce crashes at roundabouts.
Roundabout design is of paramount importance. Design elements include: speed limit, sight distance, radius, traffic signs, and pavement markings. But these are just elements. Ultimately, good design requires bringing all of the elements together into a coherent whole. Staging information delivery such that a roundabout is easily interpretable by the driver is key. The objective geometry, visual cues, signage and other elements have to be delivered in a way that conforms to the driver's knowledge, experiences, and understanding.

The goal of good design is optimization. Design optimization is about making all the constituent parts work together in a unified way that minimizes crashes while maintaining efficient function. In this review of literature, combined with experience in the field, we have found that optimally-performing roundabouts (i.e., those that experience minimal crash rates), have this in common: a well-integrated, systematic, and multi-disciplinary approach to geometrics, signing, markings, and speed control.

We have found that problematic roundabouts with excessive crashes appear to lack the implementation of safety principles associated with safe geometrics, or may have confusing signage and/or pavement markings, or a combination of these design elements. On the other hand, roundabouts that are performing within anticipated PDO crash ranges include roundabout and roadway geometric and traffic safety principles for geometry, signing and markings. Figure 1 compares PDOs at several multi-lane roundabouts. The left-hand column shows roundabouts with excessive crashes vs. similar roundabouts (right-hand column) with crash rates within expected range, as predicted by U.S. and U.K. crash prediction models (5, 6).
<table>
<thead>
<tr>
<th>Roundabouts with &gt; 85 PDOs per Year:</th>
<th>Roundabouts with &lt; 20 PDOs per Year:</th>
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<tbody>
<tr>
<td>~90 PDOs per year (40k ADT)</td>
<td>Avg. 15 per year (40k ADT)</td>
</tr>
<tr>
<td>Region of Waterloo, ON</td>
<td>New Berlin, WI (4 years of data)</td>
</tr>
<tr>
<td>~85 PDOs per year (~30k ADT)</td>
<td>Avg. 10 PDOs per year (28k ADT)</td>
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<tr>
<td>Joplin, MO</td>
<td>Monona, WI (5 years of data)</td>
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<tr>
<td>~150 PDOs per year (35k ADT)</td>
<td>Avg. 18 PDOs per year (~30k ADT)</td>
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<tr>
<td>Ann Arbor, MI</td>
<td>Waunakee, WI (1st year of data)</td>
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FIGURE 1 Comparison of annual PDOs at multi-lane roundabouts.
It is common for engineers and research to attempt to attribute performance of a roundabout to separate and easily discernable individual design components; for example, “it’s too big” or “it’s too small;” or to lack of education about how to drive roundabouts. However, research and practice are confirming that poorly performing roundabouts are a function of the arrangement and relationship of many design elements – to include combinations of geometrics, signing and markings, and the speed context of an application (7). More so than individual design components or driver education or lack of familiarity, driver behavior is influenced by the designs they are driving.

Multi-lane roundabout design objectives for safety and operations compete sharply, making adherence to safety criteria and principles more challenging; e.g., speed control criteria versus entry angle criteria. Optimal design requires the synthesis of geometric design to meet traffic operational objectives within available site constraints. Conformance with design guides implies design consistency, but does not ensure optimal safety. NCHRP 672 is a principles-based design guide aimed at achieving the underlying safety design principles (4). However, design flexibility provided by these principles may inadvertently give the wrong impression that this relieves engineers from the understanding of and adherence to proven multi-disciplinary design principles for safety.

LITERATURE REVIEW

U.S. Highway Safety Methodology

U.S. safety research is focused on: understanding the expected numbers of crashes for a given design, traffic volumes, and speed considerations – Safety Performance Functions (SPFs); allowing for predicting crash numbers and frequency for designs; and determining potential contributing crash factors (Accident Modification Factors, AMFs), and/or countermeasures (8). There are two primary crash prediction models for roundabouts in the Highway Safety Manual (HSM):

1) “Intersection level roundabout crash prediction methodology:” intended to evaluate the safety performance of an existing roundabout relative to other similar roundabouts. This model includes number of legs (3 to 5), number of circulating lanes, number of crashes annually, and the AADT.

2) “Approach level crash prediction methodology:” used to predict three crash types – entering-circulating, existing-circulating and approach crashes, and utilizes both AADT for entering and circulating traffic and geometric parameters including Entry Width, Approach Width, Angle between Arms, ICD and Circulating Width. (4). These equations utilize this information along with an Empirical Bayes (EB) methodology to predict expected crashes or to compare results at an existing roundabout to other similar roundabouts.

Chiu et al. conducted safety research on approximately 30 roundabouts in Wisconsin and found that Wisconsin roundabouts have better safety performance (intersection level) than
aggregated U.S. data reported in the NCHRP 572 model \((I, 5)\). The researchers concluded that reasons could be varied, but that the most plausible reason is attributed to “driving behavior, especially in terms of drivers’ familiarity of roundabouts” \((I)\). However, we find the attribution of improved safety record due to primarily driver familiarity questionable. The roundabouts studied were all constructed prior to or by 2008 and often represented the first roundabouts in communities throughout Wisconsin. Also, there is no attribution to design guidance that informed these designs. The Wisconsin Department of Transportation was an early adopter of a principles-based, comprehensive approach to roundabout design anchored in proven safety principles.

An interesting finding of the Wisconsin research was the safety benefits of flared entry roundabouts \((I)\). This finding is consistent with U.K. safety research for flared entry roundabouts. The roundabouts studied addressed driver expectancy and conspicuity through design features for central islands and implemented roadway and roundabout geometrics for safety, and include easily recognized conventions for traffic signing and pavement markings. The roundabouts had standard lane-use signing and marking arrows (versus fish-hooks), consistent line types for circulatory markings, and a single, clear yield line (without shark’s-teeth markings).

**International Safety Research**

Brown states that important experiments on roundabouts were carried out in the U.K. during a 25-year period \((9)\). This comprehensive work on roundabout safety by the U.K. government collected data on 84 roundabouts with an average of more than five years of crash data per site – a total of 431 junction years of crash data \((5)\). These studies sought to understand the principles of roundabout layout to maximize traffic flow and safety simultaneously, and to produce a practical design method for the highway engineer \((9)\). These accumulated results have been implemented and refined in the U.K. with considerable success \((9)\). This research aimed to develop an integrated design approach that related fatal and injury accidents to traffic volumes and the roundabouts’ geometry. By regressing observed crashes against traffic flow and geometry, they found that different types of crashes related to different variables. Among the key variables were:

- traffic volumes
- approach width \((V)\)
- entry width \((E)\)
- entry path curvatures (deflection)
- angle between arms
- diameter \((D)\)

The result was a geometric crash prediction model: a series of equations to predict crash types and injuries based on geometry and traffic flow \((9)\). The objectives of the U.K. study were to provide insight to the main crash problems and derive relationships between crash frequency,
traffic flows, speeds, and geometric design principles to optimize designs and predict mean crash
distributions.

Other variables found to have relevance to roundabout accidents include (5):

- Intersection sight distance – with excessive sight distance having a negative effect on
  safety
- Inadequate deflection
- Acute (flat) entry angles which encourage merging behavior
- Poorly designed and/or positioned warning and advance directional signing
- Signs and markings
- Cross fall design

The 2010 U.S. Roundabout Guide (NCHRP 672) reflects many of the key U.K. safety criteria
and advice related to safety, including angle between arms, speed control, sight distance, and
excessive visibility to left (for right-hand drive), and view angle – to mention a few of the
primary design elements (4, 5).

Research in Italy set out to determine crash contributory factors at urban roundabouts (7).
The research was based on site inspections and analysis performed by a team of specialists with
relevant road safety engineering experience. The poorly performing roundabouts were inspected
annually from 2004 to 2009. They found that in many crashes road users’ wrong behavior was
significantly affected by a combination of roundabout geometric design, markings and signs,
which gave wrong indications to the speed context of the application (7).

This research reviewed geometric data and included: inscribed circle diameter, circulating
roadway width, entry width, exit width, entry angle, deviation angle, eccentricity, entry radius,
exit radius, radius of deflection of the right turn maneuver, and radius of deflection of the
crossing maneuver. Findings showed that the most common geometric design factors were
related to speed control, entry angles and combinations of geometrics, signing and markings (7).
Geometrics were found to be a contributory factor in 60% of all crashes. Pavement markings
were a contributory factor in more than 50% of the crashes. And signs were a contributory factor
in nearly 50% of the crashes. This research reflects the challenges with associating specific
causes and countermeasures with a key finding, stating: “Even though the identification of
contributory factors was based on rigorous analyses and on sound road safety engineering
experience, it was a subjective task and some degree of uncertainty existed. Many combinations
of contributory factors related to markings, signs, and geometric design were associated with
angle crashes at entry. Furthermore, it should be noted that each crash was the result of a
unique chain of events and that it might not be possible to identify all of the links for each chain”
(7).

Speed-Focused Studies

Recent studies focus on speed as a surrogate for safety. Chen et al. examined sight distance
preclusion as a means of effecting slower speeds (10). A study by Zirkel et al. supports the
importance of speed control, focused on different sight distance parameters related to operating
speed data on approaches, and concluded that drivers have a tendency to drive faster when they have a greater range of vision \((11)\). Isebrands et al. also found that speed can increase the risk of injury-producing crashes, especially at intersections where vehicles may be approaching and entering the intersection with high speed differentials \((12)\).

Another speed-focused study by Mandavilli et al. supports previous research regarding speed as a safety factor, and states that “high approach speeds were an important driver crash factor” \((13)\). The study found that increasing the conspicuity of upcoming roundabouts could be achieved through larger "roundabout ahead" and "yield" signs which could reduce speeds by alerting drivers ahead of time, enhanced landscaping of central islands, and reflective pavement markers and yield signs at the entrance to roundabouts \((13)\).

Roundabout research and subsequent design guidelines from the U.K. reference the slowing effect of visibility restrictions. Their guidance states that “excessive visibility to the right (left for right-hand drive) can result in high entry speeds, potentially leading to accidents” \((5)\). U.K. guidance also suggests the potential use of visibility screens at least 2m high to reduce excessive approach speeds, but has limited the scope to only multi-lane roundabouts where the speed limit is greater than 40 mph \((5)\).

APPLICATION OF SAFETY DESIGN PRINCIPLES TO IMPROVE DRIVER COMPREHENSION AND REDUCT PDO CRASHES

1. Operational analysis/laneage requirements
2. Roundabout geometric design principles
3. Signing and marking

1. Operational Analysis/Laneage Requirements

Most safety research indicates that the entering-circulating conflict is a primary contributor to crashes for multi-lane roundabouts (as is traffic volume). Therefore, macro-level safety benefits are derived from limiting the number of entry and circulating lanes to the minimum necessary while still meeting acceptable operational objectives of delay and queues \((5)\).

Operational performance analysis is necessary to avoid over-design (excessive laneage) and to provide appropriate laneage to meet operational objectives for queue and delay for the entire design life. In high-flow multi-lane conditions higher v/c ratios are prevalent, and if the tools used are too conservative and indicate the need for and determination of additional lanes this will effect safety, feasibility, and costs. High traffic flow multi-lane roundabout applications require sophisticated operational analysis (software) tools.

A thorough understanding of the relative strengths and weaknesses' of available operational tools (gap, empirical, micro-simulation) is necessary in high-flow applications, and using multiple tools is often beneficial. Deterministic software tools in use include Sidra, Arcady and Rodel – robust software tools that offer distinct advantages for high-flow, multi-lane
applications over less robust tools such as spreadsheets that incorporate various equations or HCM (I4).

The capacity methodology from the U.K.’s Transport Research Lab (TRL) as implemented by both Arcady and Rodel includes “high definition” queuing theory (15). High definition queuing theory allows for accuracy and understanding of queuing and delay at high v/c ratio conditions up to and exceeding 1.0, which can make a substantial difference in lane decisions at high-flow and high v/c ratio conditions. The high definition models use seven “time-dependent” equations to predict queue lengths and delays. Each equation is selected depending on whether the v/c ratio is less than or greater than 1.0, and if the queues are growing, reducing, or stable. This methodology provides for accurate estimates of queues and delays over the full range of v/c ratios, especially for high v/c ratios including those exceeding 1.0. Queues and delay depend on time and the evolution of flow and capacity. These are described fully in TRL Report 909 (16).

HCM and other gap-based methodologies lack this necessary fine-tuning for optimal design outcomes. Gap-based methodologies utilize a “low definition” model that incorporates a single average v/c ratio in a single queuing equation. This simplified time-dependent model gives good queue and delay predictions at lower v/c ratios. But as v/c ratios approach and exceed 0.9, error rates rapidly increase, particularly in predicted queue and delay. This can result in a call for unnecessary laneage, reducing desired safety outcomes. Ultimately, a good, sound, safe roundabout design might be rejected based on faulty output at high v/c ratios.

Thus, it is important to utilize high-definition models. The detailed look at the full spectrum of v/c ratios allows appropriate matching of capacity to demand. Avoiding unnecessary laneage while still meeting operational requirements and objectives allows the designer to explore safer geometric layouts. Most importantly, the driver's decision-making requirements are simplified. Adherence to safety design principles within the context of a junction include: Speed Control (Fast Path criteria), maximization of angle between arms (90-degree angles are optimal), minimize the number of arms (the fewer, the better; double roundabouts are preferable to a single large 5- or 6-leg roundabout).

2. Roundabout Geometric Design Principles

The two predominant PDO crash types in North America are entry-circulating crashes or “failure-to-yield” crashes, representing approximately 50-70% of all crashes, and lane discipline related crashes. A recent roundabout questionnaire by Washtenaw County Road Commission (Ann Arbor, MI) found that over 1/3 of the respondents believe that one ‘merges’ into a roundabout on entry (incorrect), as opposed to waiting for an appropriate gap (correct) (17).

This mistaken merging behavior is thought to be influenced by roundabout entry angles and the messages they send to drivers. Many North American roundabouts have an overly flattened entry angle, well below desired thresholds as indicated in U.K. guidance.

The U.K. safety research found that flat entry (Phi) angles promote incorrect merging behavior, the result of geometries that send incorrect yield messages at entry. The importance of
entry/Phi angle cannot be overstated. It is a major factor in speed control and fast path measurements.

The entry angle (Phi) serves as a geometric proxy for the conflict angle between entering and circulating traffic streams. The U.K.’s TRL determined that entry angle (Phi) for multi-lane roundabouts should be in the range of 20-40 degrees. It is stated that entry angles below 20 degrees force drivers to strain to look over their left shoulders, creating poor view angles that make it difficult to see circulating traffic. These smaller (flatter) entry angles encourage higher entry speeds due to the visual cues promoting ‘merging driver behavior’ versus the desired priority message of ‘yield’ at entry to circulating traffic.

For multi-lane entries with 3 or 4 RT lanes, the Phi for each lane can be very different from the mean Phi for the whole entry, with the outside lanes (3rd or 4th lanes) having a very small unacceptable Phi even when Phi for the other lanes, and for the entry as a whole, is within the accepted range. Therefore, it is important to check Phi for all lanes (Figure 2), illustrating the design changes necessary to adhere to Phi angle for all lanes. The Phi angle for an entry is the angle between the mean path of the entering traffic and the mean path of the circulating traffic.

Measuring Phi – Two Methods (18)

There are two methods for measuring Phi:

1. Method 1: The most common for modern roundabout application due to the smaller ICDs with a nearby exit, as the entering traffic first conflicts with the exiting traffic that has diverged from the circulating traffic. In this case, the angle between the two streams is 2Phi, so Phi is the angle/2.

2. Method 2: Used if the mean path of the entering traffic first conflicts with the mean path of the circulating traffic (before exiting traffic has diverged), typical of older large-ICD roundabouts, and therefore not common in North America. The angle between the two streams is Phi (not the 2Phi of method 1).

Along with Deflection, Entry angle, or Phi angle, may also affect entry speed. Speed control is achieved as a function of the deflection, angle between arms combined with entry/phi angle in a geometric relationship. Neither the fast path nor Phi angle are on their own a controlling criteria as per NCHRP 672 (4). But in combination, they are decisive in influencing safe driver behavior. Thus, it is imperative that the designer adhere to these fundamental, geometric safety design principles in combination with one another. Figure 2 contrasts non adherence geometry with a design which adheres to these fundamental geometric principles that result in a safe roundabout.
FIGURE 2 Application examples of meeting and not meeting primary geometric design principles: Phi angle for all lanes and intersection angle.
3. Signing and Pavement Markings – Driver Messaging and Information Processing

Roundabouts involve high visual and perceptual demands arising from information acquisition and processing requirements. When signing and other roadway information is presented in too compressed a manner or is incongruent for the design or context, driver comprehension is reduced (19).

Therefore, from an information processing perspective, workload demands in some tasks should be reduced by making it easier for drivers to perform these tasks (9). Signs and pavement markings should be designed and located to minimize detection, reading, and processing time, maximize comprehension, and maximize ability to perform tasks of navigation, guidance, and vehicle control (20). The role of the designer is to simplify messaging and make safe travel as intuitive as possible.

Context and system considerations will affect the design and placement of signing. Too little information, information overload, and sign clutter are undesirable. Optimizing signing and pavement markings requires clarity. Line types, weight, and arrangements are all important to minimize detection, reading and processing time and maximize comprehension.

The first examples in Figure 3 illustrate information overload. The ensuing driver confusion actually works against the design goal of speed reduction upon approach to the roundabout. The large system-to-system style overhead (OH) style signs give incongruent messages to drivers. These types of signs cue drivers that this is a high-speed facility, exactly the opposite of the design intent – speed reduction. Moreover, the unnecessary duplication of information forces larger, competing signs but does not increase drivers’ ease of recognition.

A better way is to stage information delivery by separating destination and lane use information. This hews to our information processing principles. Appropriately scaled signing also mutually reinforces the design intent of slower speeds upon approach.

The second set of illustrations in Figure 3 appropriately separate destination from lane use information. The smaller signs and simplified information improve messaging to the driver. There may be instances when combined information is necessary and desirable, but those would be on a case by case basis, versus a standard.
The three case studies presented here focus on existing roundabouts which were experiencing excessive PDO crashes. The results make clear that drivers were facing significant information processing challenges.

Contributory crash factors were identified through an in-service design review (safety audit). Driver confusion was suspected as the culprit and mitigating features targeted this issue. In each of these cases the designers took a comprehensive and integrated approach. The operational analysis kept fundamental roundabout design principles front and center. The group settled on low-cost mitigation measures that included: sight preclusions and lane reduction in one project; and signing and marking changes (consistent circulatory markings, standard lane-use assignment arrows for signing and pavement marking) for all three projects. These solutions resulted in dramatic 60-80% reductions in PDO crashes (21, 22, 23).
Case Study #1: N. 14th and Superior Ave. Roundabout, Lincoln, NE

This 2x3-lane roundabout intersection had experienced approximately 120 crashes in its first year of operation. An in-service design review identified driver comprehension issues and made recommendations to clarify driver information delivery. The mitigation recommendations were implemented with low-cost temporary improvements. Post-modification data showed a 73% reduction in crashes (21, 24).

Issues:

• Failure-to-yield (entering/circulating), side-swipe and rear-end crashes
• Context is a 6-lane suburban arterial roadway (posted speed: 45 mph) 85% speeds ~55 mph therefore higher prevailing speeds
• Low entry (Phi angle) and excessive view angle left
• Lane discipline and priority confusion as to who yields to whom at entry

Recommended countermeasures:

• Lane reductions – based on operational analysis of existing traffic flows, reduce laneage to 2x1 roundabout (reduced entry-circulating conflicts by ~50%)
• Implement standard (and oversized) lane-use signing and marking conventions vs. stylized fish-hook markings.
• Induce speed reduction via preclusion of unnecessary sight distance to left using approaches (6’ high non-see-thru fence)
• Modify existing pedestrian signal to remove resting in green condition.

Results:

73% reduction in crashes (21).

Discussion:

The project team used a comprehensive approach to implementing recommended countermeasures aimed at improving driver comprehension. Each design element mutually reinforced other elements, resulting in less conflicts, improved driver comprehension and a safer roundabout.

Before Changes: Diagrammatical Lane Use Signing and Markings
After Changes: Conventional Overhead Signing and Markings and Sight-Preclusion Fencing

FIGURE 4 Before and after changes: diagrammatical vs. conventional signing and marking. Photos: City of Lincoln, NE.
Case Study #2: 66th and Portland Aves. Roundabout, Richfield, MN

An in-service design review recommended signing and pavement marking changes aimed at improving driver comprehension. The specific crash type targeted was incorrect lane use. The results of these changes were studied by the University of Minnesota Traffic Observatory (22).

Issues:
- Lane discipline – outside lane incorrectly circulating, causing crashes with inside lane exiting vehicles, ~ 45%
- Failure-to-yield crashes, ~ 45% (22)

Recommended countermeasures:
- Circulatory markings from solid lines and skips through exit replaced with 6" white “consistent/strong” 6’ line, 3’ gap.
- Change from fish-hook to standard style lane-use signing (oversized) and markings. Added additional series of two sets further upstream of the roundabout entrance.
- Solid white channelization lane line extended (250’) from yield line, lane line 10’ skip and 10’ gap (150’).
- Replace W11-2 standard “pedestrian crosswalk warning” sign with the R1-6 “yield to pedestrians in crosswalk” sign, with lowered placement height (driver eye level), making signs clearer and more visible to drivers.

Results: (22)
- 80% reduction in lane-discipline issues (left turn from outside lane).
- 20% reduction in lane changes at entrance and exits.

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Solid-then-skip, as per MUTCD 2009  
Consistent line type, as per 672

FIGURE 5 Circulating line types: MUTCD 2009 and NCHRP 672.

Discussion
The original design included the solid-then-skip circulatory markings, as per the Manual on Uniform Traffic Control Devices (MUTCD), and diagrammatical lane-use signage (fish-hook style) and pavement marking arrows (25). The assumption behind implementation of fish-hook style signing and markings was to help prevent the possibility of drivers making wrong-way left turns. Therefore, it is important to note that the change to conventional lane-use signing and
pavement markings produced no evidence of increased wrong-way left turns (22). Similarly, lane discipline was improved with implementation of consistent circulatory markings (22).

Before Changes: Diagrammatical Lane Use Signing and Markings

After Changes: Conventional Overhead Signing and Markings

Before Changes

After Changes

Case Study #3: SC 46 and Bluffton Pkwy. Roundabout, Bluffton, SC

The predominant crash types at this poorly performing roundabout were lane discipline and failure-to-yield at entry crashes. An in-service design review conducted in conjunction with the FHWA Office of Safety and SCDOT’s Office of Safety identified ways to improve the safety record. The review resulted in a comprehensive set of pavement marking recommendations. The goal was to improve driver comprehension via positive driver guidance and optimal driver messaging. The post-modifications crash data showed an 80% reduction in crashes (23).

Issues:
• Solid-then-skip circulatory line type reduces driver recognition of correct lane use
• Misalignment from entry to circulating roadway – poor entry angles, confusing priority message (who yields to whom)
• Multiple line types at entry – dotted edge line extended was tangent to down-stream exit leg encouraging merging due to very flat entry angle
**Recommended countermeasures:**

1. Provide a consistent circulating line type (8” white, 6 seg., 3’ gap)
2. Realign entry to circulating lane to improve entry alignment and view angles
3. 11’ inside circulatory lane width and wider (17”) outside lane width (vs. equal 14’ lane widths)
4. Remove shark’s-teeth and dotted edge line extension markings at entry
5. Realign placement of new singular and bolder yield line (dotted edge line extended) to clearly delineate yield condition to entry drivers

**Results:**

80% reduction in crashes (23).

<table>
<thead>
<tr>
<th>Before Changes: Misaligned Entry to Circulating</th>
<th>After Changes: Aligned Entry to Circulating</th>
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<tbody>
<tr>
<td><img src="image1" alt="Before Changes: Misaligned Entry to Circulating" /></td>
<td><img src="image2" alt="After Changes: Aligned Entry to Circulating" /></td>
</tr>
<tr>
<td>Before Changes: Confusing line types at entry</td>
<td>After Changes: Clarified priority with heavy yield line</td>
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<td><img src="image3" alt="Before Changes: Confusing line types at entry" /></td>
<td><img src="image4" alt="After Changes: Clarified priority with heavy yield line" /></td>
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**FIGURE 7** Before and after lane marking changes: misaligned vs. aligned; confusing vs. clarified entry lines.
Discussion

The 2009 MUTCD shows circulatory pavement markings of a solid-then-skip line through the exit area (to allow entry to cross), but these recommendations contradict international guidance for circulatory markings. It is becoming evident through these safety retrofits that the solid-then-skip line type reduces driver recognition of correct lane use, resulting in increased lane discipline crashes. Also the 2009 MUTCD indicates that the yield line is called a dotted edge line extended, which gives the erroneous impression that circulating drivers utilize this line thus promoting tangential placement with the downstream leg.

CONCLUSION

We have found that problematic roundabouts with excessive PDO crash rates appear to have several issues in common, including:

- Entry angle issues: overly flat entry angles, and corresponding excessive view angle to left at entry
- Clarity of message issues: confusing signs and pavement markings that may have excessive amounts of information that are confusing and not consistent with drivers’ expectations
- Design element congruity issues: combinations of design elements that work against the design purpose; e.g., large overhead signs that promote excessive speed at roundabout entry
- Speed/context issues: lacking incorporation of design elements to address speed characteristics, such as conspicuity, safer geometrics, and unnecessarily wide sight distances.

We now have a large body of research and designs in practice which show that comprehensive, integrated roundabout design can keep crash rates negligibly low. This requires a design that adheres to roundabout, roadway, and traffic safety principles. Geometrics, signing and markings anchored in these safety principles, and designed to work one with the other, bring about significant safety benefits.

Roundabout design is principles-based. It is also predicated on design flexibility. Adherence to rigid standards that do not take into account safety and operational outcomes results in a less safe roadway. Of course, this design flexibility does not relieve the engineer from understanding and adhering to proven multi-disciplinary safety design principles. But there must always be an eye toward constant improvement in design. Otherwise, the extraordinary safety benefits of roundabouts — the drastic reduction in death and injury — could be obscured by unnecessarily high PDO crash rates.

Our review of relevant research and state-of-the-art roundabout design practice points to improved driver comprehension via design elements as the key to reducing PDO crash rates at high-flow, multi-lane roundabouts. A comprehensive and integrated design approach is critical. This includes operational analysis, geometrics, signing, and pavement markings — working together as a unified whole. And each element must be anchored in roadway, traffic and roundabout-specific safety design principles.
REFERENCES


