Design Optimization for Safety and Operations of Multi-Lane Roundabouts

by

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ABSTRACT

The safety and operational performance of roundabouts is predicated on how drivers receive the visual information (geometrics, signing, and markings) that is presented to them. For optimal safety and operations, this visual information must be designed to simplify decision-making and provide clear, concise information indicating the correct way to drive the roundabout. If this information does not convey the correct messages to drivers, then the operational and safety performance can be compromised. This is occurring on many multi-lane roundabout designs across the U.S.

Optimal safety and operations of roundabout design require a comprehensive design approach with a sound understanding of the underlying design principles of roundabout design. This paper will provide case studies of poorly operating roundabouts and discuss the process and design implementation elements that were applied to improve their safety and operational performance.

INTRODUCTION

Substantial operational and safety benefits can be realized with multi-lane high capacity roundabouts within the application of traffic planning, transportation, and roadway engineering. However, multiple entry and circulating lanes introduce increased complexity for a driver attempting to navigate the roundabout. Why are some roundabouts performing well and others not performing well?

Roundabouts are a performance-based intersection and their operations and safety are predicated on geometrics, signing, and marking presented in a coherent manner to drivers. For optimal operations the information must be presented (designed) to simplify decision-making and provide clear, concise information as to the correct way to drive the roundabout, taking into account driver behavior/expectancy, traffic engineering principles, and roadway engineering principles. If the information presented is contradictory or doesn’t send the correct message to drivers, then often less than optimal safety performance can result.

The emerging practice of roundabout engineering is becoming increasingly aware of how seemingly unrelated design specifications and details can affect how drivers receive and process information, and then perform driving tasks at roundabouts. The organization and arrangement of the visual information presented to drivers affects the driver behavior and the resulting safety performance.

The primary design elements of geometrics, signing, marking, and other contextual issues such as prevailing speeds and context of the roadway all play a role in how drivers interact with roundabouts. Therefore, the safety performance of a roundabout emerges from the whole system interaction of design elements. Because of this interaction, it is often difficult to quantify individual components of a design that may have the most significant effect on the overall performance. Moreover, the effect on driver behavior may seem counter-intuitive to design engineers due to the unique operational characteristics of roundabouts versus conventional intersection design.
**PRINCIPLES-BASED DESIGN**

When designing for optimized roundabout safety and operations, the whole is greater than the sum of the parts. In other words, the design elements build upon one another, and when taken as a whole have the greatest impact on driver behavior, and subsequent safety and operational performance. Figure 1 illustrates the design elements of safety and the fact that they are all tied together.

Inherent to this design process is the balancing of competing objectives that are often in sharp competition with each other. This is, in essence, the challenge of effective roundabout design. The whole is the critical consideration. How all parts interact is crucially important. Capacity and safety are holistic phenomena that emerge from interaction of the parts. This can be referred to as the overall composition of the design.

![Design Elements of Safety](image)

**FIGURE 1** Design elements of safety. Graphic: MTJ Engineering, LLC
Composition of Design Elements

Good detail and poor composition will equate to poor performance. Details are inexpensive and easy to correct, but it can be very expensive and difficult to correct poor composition. Multi-lane high-flow roundabouts require good composition and good details from design through construction for optimal safety and operations.

Often, the poor performance of a roundabout is erroneously attributed to the most easily discernible individual design components; e.g., its overall size (Inscribed Circle Diameter – ICD). However, in our experience the poor performance is less about the individual components (e.g., too big or too small) and more accurately attributed to the arrangement and relationship of all the geometric design elements; i.e., composition. The composition of geometric design elements is the most important factor when optimizing safety and operations of a roundabout. Therefore, consistent with the design principles in the FHWA Roundabout Guide (1), the individual design components, such as the ICD, are an outcome of the design process related to context and project objectives.

DESIGN ELEMENTS OUTLINE

The following outline frames the essential design components for designing optimal roundabout safety and operations. It is the composition – how all of these elements blend together – that affects how drivers process that information and then react to it.

- Operations/Geometrics: Avoiding Over-Design
  - Match capacity to demand: Meet operational requirements and objectives that allow for safe operations for near- to long-term traffic demand.
  - Minimize laneage: reduce conflict points
  - Simplify decision-making
  - Evaluate potential future expandability

- Safety Design Principles
  a. Safety – US and UK Safety Research (1, 2, 3, 4)
    - Meet Fast Path criteria
    - Maximize angle between arms: 90-degree angles preferred
    - Minimize number of arms: the fewer number of arms, the better
    - Minimize entry width: do not over-build
    - Minimize circulating width: related to entry width
    - Entry angles/angles of visibility
• **Improving Driver Messaging and Information Processing**

Design and placement of signing and pavement marking details are integral components of roundabout design. Optimization of these design elements is necessary to ensure optimal operations, safety, and public acceptance:

a. Signing  
b. Pavement Marking  
c. Landscaping/Sight Distance  
d. Illumination

**DESIGN ELEMENTS DISCUSSION**

• **Operations/Geometrics**

Research conducted in the U.K. (and supported by more recent U.S. research and reflected in the *FHWA Guide NCHRP 672* (1)) indicates that the entering-circulating conflict is a primary contributor to crashes for multi-lane roundabouts. Therefore, safety benefits can be derived from limiting the number of entry and circulating lanes to the minimum necessary while still meeting acceptable operational objectives of delay and queues (1). The reduction of entry-circulating lanes reduces the number of conflict points and therefore lowers the probability of crashes occurring.

By conducting a sensitivity analysis we gain an understanding of acceptable levels of service. The challenge lies in designing to allow for acceptable operations for short-range and long-range traffic. Acceptable measures of effectiveness, including delay and queuing, will typically vary depending on the context and project objectives.
Safety Design Principles

Fast Paths/Speed Control

The FHWA Roundabout Guide recommends that fast path speeds not exceed 20 mph for mini-roundabouts, 25 mph for single-lane, and 30 mph for multi-lane roundabouts (1). Unlike most other roadway engineering design criteria, this does not necessarily represent an upper limit, but rather may be viewed as a threshold at which the majority of safety benefits are derived. It is important to note that “fast path” speeds are a theoretical speed calculation and are, therefore, not intended or expected to reflect normal actual operating speeds. And there are other design elements, including landscaping, that affect driver speeds.

Fastest path speeds are an important measure of relative safety based on UK research (3) and adopted into US guidance as reflected in NCHRP 672 (1). Quantification of the fast path speeds in a consistent manner ensures adherence to this primary safety criteria.

Another report titled NCHRP Report 674: Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities, recommends normal vehicular speeds at the pedestrian crossing locations to be not greater than 20 mph (5). Therefore, when considering vehicular speeds for the purpose of pedestrian safety and “accessibility,” it is important to note that expected average operating speeds based on normal driving conditions should be used, versus the calculated fast path speeds.

Entry Angles/Angles of Visibility (3, 4)

- The entry angle serves as a geometric proxy for the conflict angle between entering and circulating traffic streams. The UK’s Transportation Research Lab (TRRL) determined that entry angle (Phi) for multi-lane roundabouts should be in the range of 20-40 degrees. 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.
- Small (flat) entry angles encourage higher entry speeds.
- Produce visual cues promoting ‘merging driver behavior’ vs. the desired ‘yield at entry’ message.

Sight Distance

International and U.S. research indicates that meeting minimum standard requirements and precluding excessive sight distance on each approach will aid in lowering the overall speed environment (1). Reducing drivers’ unnecessary sight distance promotes slower approach speed, versus maintaining a higher speed which can result from allowing full view to the drivers’ left.
• **Improving Driver Messaging and Information Processing**

Intersection approaches 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 (bottlenecked), drivers are required to perform a variety of different perceptual and cognitive decisions in too short a time period (6). Therefore, from an information processing perspective, workload demands in some of these tasks should be reduced by making it easier for drivers to perform these tasks (3).

A variety of factors affect sign legibility, including font characteristics, distance, and illumination/reflectance (7).

Signs should be designed and located to:
- Minimize detection, reading, and processing time
- Maximize comprehension
- Maximize ability to perform tasks of navigation, guidance, and vehicle control

Intersection navigation in general is a particularly hazardous component of driving. For example, in 2003, more than 9,213 Americans lost their lives as a result of intersection-related crashes. In total, intersection-related crashes account for more than 2.7 million crashes each year, which amounts to more than 45 percent of all reported crashes. Even though intersections comprise just a small amount of the total roadway surface area, they contribute to a relatively high proportion of crashes because they are the critical points in the roadway system where traffic movements are most frequently in conflict with each other (6).

In addition to a greater frequency of conflict points, intersections are considered more complex and difficult to navigate than most other stretches of roadway. Research findings on intersections state:

“...intersections can be visually complex, requiring that drivers scan several different areas and keep track of different elements of information to navigate the intersection. Consequently, intersection driving involves a multitude of different elements and hazards that can combine to increase the difficulty and workload that drivers face. When drivers are unable to meet these higher demands, their risk of making critical driving errors that can lead to conflicts with other road users also increases.” (6)

Pavement marking and signing complement each other. Pavement marking guidelines should be principle-based in order to:

1. Optimize pavement markings to provide clear and easily understood information
2. Effectively design line types, weight, and arrangement
3. Minimize detection, reading and processing time
4. Maximize comprehension
CASE STUDIES INTRODUCTION

In these two case studies we identified both compositional design element deficiencies and information processing challenges that drivers were facing at these roundabouts. The areas identified represented situations in which drivers may become overloaded by driving demands, which resulted in drivers conducting important driving tasks in an improper fashion; e.g., taking too quick a look at circulating traffic while entering and failing to see an oncoming vehicle, or confusing the meaning of the information presented to them, leading to skipping certain tasks altogether.

Case study #1: Lincoln, NE – Lane reductions, signing, sight distance restrictions

Case study #2: Bluffton, SC – Pavement markings only

Case Study #1: Lincoln, Nebraska – N. 14th St. and Superior Ave.

Existing Conditions

This newly opened three-lane entry roundabout experienced approximately 120 annualized crashes in the year before changes, and decreased to 34 annualized crashes after implementation of recommended modifications. This represents a 72% reduction of crashes pre- to post-modifications. We will discuss this in-service design review and the changes that were made that produced this improvement.

Superior Street is a major 4-lane arterial that runs east-west with a raised median and controlled access located in the northern section of the City of Lincoln, Nebraska (see location map in Figure 2). Superior Street is currently carrying 25,300 ADT, and has a posted speed limit of 45 mph. N. 14th Street is a north-south minor arterial that is currently carrying 11,400 ADT. N. 14th Street is a three-lane section to the south and a four-lane section with median to the north. There are commercial land uses located in the northeast and southeast quadrants, and a middle school located in the southwest quadrant.
The 14th and Superior roundabout crash types fit into the typical crash types based on U.S. and international research, and include:

- Entering/circulating crashes (between an entering vehicle and a circulating vehicle)
- Approaching crashes (mostly rear-end crashes)
- Single-vehicle crashes (a single vehicle colliding with some part of the junction layout or furniture)
- Other crashes (variety of non-pedestrian crashes)
- Pedestrian crashes (any crash involving a pedestrian casualty)

Based on a review of the crash diagrams, the pre-roundabout condition (signalized) has predominately rear-end crashes and the next most common are angle crashes. Post-roundabout there are predominantly entering-circulating crashes, and the next most common are rear-end and side-swipe crashes.

The pre- and post-roundabout crash types being experienced at this intersection are indicative of a higher speed roadway context. This higher speed context may have a direct correlation with incorrect driver decision-making leading to crashes in the roundabout. Therefore, we evaluated methods to reduce approach speeds at the intersection.

The reduction of entry-circulating lanes reduces the number of conflict points, and therefore lowers the probability of crashes occurring. The next section summarizes the operational analysis...
that was completed to determine what, if any, geometric reductions may be available to more closely match existing traffic demand.

**Recommendations provided in this roundabout review to improve safety included (not all were implemented*):**

1. Lane reductions based upon operational analysis of revised design traffic flows.

2. Modifications to assist with clarifying driver expectancy and therefore improve driver comprehension and information processing, to include:
   a. Modify existing pedestrian signal to remove resting in green condition
   b. Use standard lane-use signing and marking conventions vs. stylized fish-hook
   c. Increase size of lane-use overhead signing and use black outline*
   d. Use black outline (and wider) pavement markings to improve visibility for existing concrete paving surface*
   e. Implement exit signing*

3. Improvements aimed at influencing driver behavior related to the speed environment, to include:
   - Fencing and/or landscaping to preclude excessive sight distance.

**OPERATIONAL ANALYSIS/GEOMETRICS**

The operational analysis found that opportunities were available to reduce the number of entry and circulating lanes while still meeting acceptable operational requirements. Four primary concept level modifications were designed to reduce the entry, circulating, and exit lanes to more closely match the available capacity to existing traffic demand. The alternative chosen by the City is shown below, and this alternative maximized the reduction of conflict points from 24 in pre-change condition to 12 conflict points based on the product of entry lanes and circulating lanes.
Geometric Reduction Methods

Geometric modifications and associated lane reductions can be implemented with different construction applications allowing for differing levels of initial construction effort and costs. In this case, the City chose to first implement the lane reductions in the most cost effective manner, and then to follow up with a more permanent look dependent upon follow-up analysis as to performance. These alternatives are shown below (Figure 4), followed by recommended signing and approach visualization (Figure 5) and implemented modifications (Figure 6) in this case study.
Lane-use Symbols and Signing

“Fish-hook” style pavement markings and the associated diagrammatic lane-use designation signing may not achieve the intended driver messaging for the following reasons:

- Use of unfamiliar conventions dissimilar to all other roadway and intersection applications may be viewed to be potentially confusing to drivers.

- Providing fish-hook style markings on approaches and standard markings in the circulatory roadway do not adhere to consistency principles, creating potential driver confusion.

- Driver understanding of the diagrammatic signs and markings is not documented to improve driver comprehension of intended messaging.

Standard arrows versus the diagrammatical stylized arrows and markings (a.k.a. fish-hook style) are considered by many to be a more easily recognized convention, and therefore more clearly understood by drivers. Consequently, we recommended application of standard pavement marking arrows with the accompanying standard overhead lane-use signing to provide driver guidance as to lane use, and this was implemented as shown below in Figure 6.
FIGURE 5  Recommended signing and approach visualization.  Photo: City of Lincoln, NE

FIGURE 6  Implemented modifications.  Photo: City of Lincoln, NE
SPEED ENVIRONMENT/CONTEXT CONSIDERATIONS

- What improvements may be available to influence driver behavior related to the speed environment?
- Evaluate sight distance reductions to the minimum necessary to effect driver perceptions.

Sight Distance

As discussed earlier, U.S. and international research indicates that precluding excessive sight distance on each approach will aid in lowering the overall speed environment (1). Reducing drivers’ unnecessary sight distance promotes slower approach speed, versus maintaining a higher speed that is enabled when full view to the left is allowed.

Therefore, landscaping and/or fencing materials placed correctly based on sight distance criteria was recommended and implemented (Figure 7).
These improvements led to a 73% reduction in crashes.
Case Study #2: Bluffton, SC – SC-46 and Bluffton Parkway

As part of a requested FHWA Office of Safety Peer-to-Peer program, we worked with the South Carolina Department of Transportation to review the existing safety performance, and made pavement marking recommendations for this roundabout located at SC-46 and Bluffton Parkway near Hilton Head Island, South Carolina.

We reviewed the provided information and design data, including:
- Crash data/diagram
- Aerial of existing roundabout

FIGURE 8 Existing conditions: SC-46 & Bluffton Pkwy. Photo: Google

This roundabout was experiencing higher than anticipated or desired crashes. In this work effort we have identified low-cost pavement marking improvement recommendations aimed at improvements to driver comprehension of correct and desired driving, and navigation to provide optimal driver messaging and positive driver guidance to reduce driver confusion and improve the safety performance of this intersection.
In the pre-modification condition this roundabout experienced 34 crashes in an 18-month time frame. The crash diagram below, Figure 9, indicates many of these crashes were due to driver confusion. After recommended pavement marking modifications, there was an approximate 80% reduction in crashes. We will discuss the pre-change issues and what was completed to mitigate these issues with no geometric changes, only pavement markings.

**FIGURE 9 Pre-change crash data: SC-46 & Bluffton Pkwy.**

The crash diagrams show that the crash types occurring at this roundabout fit into the following two broad categories:

- Lane discipline crashes (incorrect lane use)
- Failure to yield at entry

The following pictures illustrate the primary issues that the improvements mitigated, and they include:

- Misalignment from entry to circulating
- Confusing line types circulating and at entry
FIGURE 10  Pre-changes showing misalignment entry to circulating and line type confusion.  Source: MTJ Engineering
Recommended pavement marking changes are shown below (Figure 12) and include:

- Providing a consistent circulating line type and entry marking modifications to improve driver comprehension for both circulating and entering driver messaging
- Realignment of circulating lane line to improve entry alignment
The photo below shows the removal of the old solid-then-skip type of circulatory lane line and its new alignment with entry by moving it approximately 3’ toward the central island (12’ from the central island). And the application of a consistent line type of a 6’ segment and 3’ gap to improve lane discipline through the circulating to exit maneuver.

**FIGURE 13 Mitigation of entry to circulating alignment.** Source: SCDOT

**Bluffton Summary**

Total crashes have been reduced by approximately 80% in the post-treatment condition due to improved driver messaging via only pavement marking changes to this roundabout, as shown in Table 1 below. The Crash Rate (CR) decreased from 4.492 to 1.16 (74% reduction). The Severity Index (SI) decreased from 5.285 to 1.16 (78% reduction).
### TABLE 1 Crash Data Before and After Modifications

**Source:** SCDOT

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CR: Crash Rate; SI: Severity Index
Case Studies Summary

Intersection safety is a challenging component of roadway and traffic engineering due to the inherent complexity of the driving tasks at intersections.

U.S. and international safety research conclude roundabouts are proven to have the least amount of serious and fatal crashes compared to signalized intersections. However, given their relative newness to drivers, some high-capacity multi-lane roundabouts are experiencing higher than anticipated and desired minor crashes.

These cases studies identified information processing challenges that drivers were facing, as well as unnecessary laneage that produced additional/excessive conflict points. The implemented changes based on roundabout design principles applied in a comprehensive manner provided for substantial improvements to the safety of these roundabouts.

Conclusion

Optimal safety and operations of roundabout design require a comprehensive design approach with a sound understanding of the underlying design principles of roundabout design. The primary design elements of geometrics, signing, marking, and other contextual issues such as prevailing speeds and context of the roadway, all play a role in how drivers interact with the multi-lane roundabouts. Therefore, the safety performance of a multi-lane roundabout emerges from the whole system interaction of design elements.
REFERENCES


Additional reference for poster case study in Richfield, MN: