Synthesis of Roundabout Design and Operations with Flared Entries

by

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Word Count: 4,119 words text + 13 tables/figures x 250 words (each) = 7,369
Submission: November 12, 2014
ABSTRACT

There has been confusion among traffic researchers and practitioners when evaluating and designing flared entry roundabout design. In some cases, researchers and practitioners have concluded that flares and their associated analysis methodologies do not work since either (a) they were not able to measure the capacity effects created by a flared entry or (b) drivers were not utilizing the available entry width created with a flared entry. Subsequently, researchers erroneously concluded that flared entry roundabout design is therefore unsuitable for their drivers, regions, or countries.

However, what was not understood in these cases was that these roundabouts are either not designed for additional capacity as in the case of a single-lane entry that has been widened only to accommodate trucks and the additional width beyond the single-lane capacity width is “non-effective width” not intended for additional capacity, or where additional capacity effects were clearly expected, as in the case with a two-lane entry marked with two entry lanes, however the necessary design elements to achieve the expected and predicted operational effects were not present.

The successful design and implementation of flared entry roundabouts is predicated on Professor Rod Kimber’s empirical capacity equations. Kimber’s equations provide operational prediction capabilities for flared entry roundabout design with three primary geometric parameters: Entry Width (E), Approach Roadway Width (V), and Flare Length (L’); with secondary geometric variables that include the Entry Radius, Entry Angle (Phi), and Diameter (D). These six geometric variables represent what is referred to as the unified capacity formula for Kimber’s equations.

The design and subsequent driver behavior and field-measured operations of multi-lane flared entry roundabouts are strongly interrelated. To achieve the predicted operations and substantial safety benefits, the flared entry multi-lane roundabout design requires correct geometrics and appropriate pavement markings and signage to facilitate effective lane utilization. Only then will predicted operations closely match field-measured operations.

INTRODUCTION

This synthesis will discuss the design components and traffic distributions necessary to facilitate efficient lane utilization, to ensure that model predictions are consistent with actual roundabout operations for multi-lane flared entry design application. Case studies will be utilized to demonstrate multi-lane flared entry roundabouts with the necessary design elements for efficient lane utilization, producing model predictions consistent with field measurements. We will also review case studies without the correct design elements and/or traffic attributes to illustrate how these design attributes create conditions that preclude correct operations, leading to underutilization of available entry width and the associated capacity reductions that result from these designs. In summary, we will discuss the following:

- Definition of flared entries,
- Research basis for multi-lane flared entry analysis and design,
• Design elements necessary for multi-lane flared entries to work correctly, and
• Transferability of multi-lane flared entry design to the US and other countries.

BACKGROUND

Properly designed and applied flared entry multi-lane roundabouts can utilize the unique operational characteristics of roundabouts to provide significant advantages to our roadway and transportation infrastructure, by precluding expensive roadway and structure widening necessary with our current traffic planning standards that are predicated on signalization and its operational characteristics. Urban arterial Average Daily Traffic (ADT) volume thresholds and the associated roadway cross-section standards are largely derived based on the needs of signalized intersections to allow the signalized system to operate most efficiently and safely including lane saturation rates, intersection spacing, and access control.

The 2000 FHWA Roundabout Guide (1) as well as the 2010 FHWA Roundabout Guide Second Edition (2) provide useful information and qualitative discussion on this topic and this is shown below. The following is an excerpt from the FHWA Roundabout Guide Second Edition (2) that provides a very good qualitative description of the effects that roundabouts may have on our roadway traffic planning compared to current roadway planning standards in practice in the US:

1. FHWA Roundabout Guide 2010 Second Edition – 2.2.4 SPATIAL REQUIREMENTS (2)

Roundabouts present opportunities to shape the cross section of a corridor in ways that are perhaps different from those afforded by signalized intersections.

Signalized intersections operate most efficiently when they progress platoons of traffic, allowing the maximum number of vehicles to pass through on green without stopping. These platoons maximize the use of green time by promoting shorter headways. However, lane continuity between signals is needed to sustain these platoons through a series of signals, and the links tend to be underused between platoons.

Roundabouts can be designed to accommodate node capacity, keeping the links between nodes more narrow. The resulting flow between roundabouts tends to be more random and makes more efficient use of the links between intersections.

FIGURE 1 Flaring and additional lane design (1).
Flared entry roundabout analysis and design represents a significant change from conventional US traffic planning analysis and design that is predicated on signalization and stop control analysis and design procedures. Current traffic planning procedures rely on adding lanes at the intersection along with widening of the associated roadway links to add system capacity as a function of lane saturation to meet the needs of signalized intersections along a roadway. More research into this area is necessary. US capacity research provides limited to no explicit quantitative guidance on methods to correctly analyze a flared entry roundabout or the correlation between its design and analysis.

To date, there has been no US research on capacity equations for flared entries. The US-based Highway Capacity Manual 2010 (HCM 2010) (3) equations only apply to either a single-lane approach or a two-lane approach roadway. However, it is important to note that the HCM 2010 (3) provides discussion regarding other analysis tools that can be utilized that do include flared entry analysis procedures based on Kimber’s equations.

**FLARED ENTRIES CAPACITY DERIVATION**
(Crown, B. Unpublished data.)

The UK has been building roundabouts for the last 70 years. The first UK roundabouts were similar to the US traffic circles built from the 1930s to the 1950s. Entering traffic had priority over circulating traffic, or had equal priority with traffic circulating in the adjacent lane. The two streams had to weave to either exit or proceed around the roundabout.

Traffic circles were inefficient, with poor capacity and safety. Long weaving sections made them large and expensive. At high traffic flows they were in danger of locking, sometimes requiring police intervention before traffic movements could resume.

In 1966 the UK changed the traffic regulations, giving priority to the circulating traffic. Yield lines were introduced and approach traffic was required to yield to the circulating traffic. Locking ceased and capacities dramatically increased. It was the introduction of this priority rule that led to the subsequent radical improvements in UK roundabout design pioneered by Frank Blackmore.

The resulting increases in capacities were welcome, but the capacities of some approaches were unexpectedly low. The reason for this was not clear, as geometry, flow levels, and turning proportions were similar in some cases. A new method for estimating yield-line capacities was needed, as the existing method that estimated the weaving capacity of traffic circles was now obsolete. As the new roundabouts superficially appeared to be a series of T-junctions, it was natural for designers to unofficially use T-junction techniques for estimating yield-line capacity, as nothing better was available.

Capacity estimation for T-junctions used a mathematical model that considered the probability of a side road vehicle entering a gap in the main road traffic. This method, called ‘gap theory,’ was pioneered in 1962 by J.C. Tanner, a researcher at the UK’s government agency called the Transport and Road Research Laboratory (TRRL). However, their current gap-based procedures turned out to be disappointingly unsuitable for estimating roundabout
entry capacities. The comparison between the existing gap theory predictions and the observed capacities at saturated roundabouts revealed substantial disagreement. This was discouraging, as many congested roundabouts needed to be improved immediately. How to do this was uncertain, especially in urban locations where extra land was limited and expensive. To bypass this considerable uncertainty the usual practice was to over-design and incur the extra cost. It was not discovered until several years later that over-design substantially increased accidents.

At this time, the UK had the unique advantage of having many saturated roundabouts of different sizes and traffic flows. The TRRL, a government agency, began an extensive research project into driver behavior and capacity at roundabouts.

**Development of the UK Capacity Estimation to Include Flared Entries**

In the late 1970s, Professor Rod Kimber, then Head of Junction Design Section at TRRL, spearheaded a series of experiments on the TRRL test track, accompanied by extensive field measurements at sites on the UK road network. On the TRRL test track, 35 different geometric parameters were tested for their effect on capacity. Six parameters per leg were found to be significant.

Saturation capacity was observed and detailed geometry was collected at 86 public road roundabouts. This data, together with other data from various universities, was used to refine and calibrate the capacity model. The roundabouts were selected as they operated at saturation capacity and included a wide range for each of the six geometric parameters. A linear model was selected, as the non-linear gave no better fit to the data. The field data included 11,000 minutes of at-capacity operation of about 500,000 vehicles. The statistically significant predictive variables are shown in Table 1 (4).

**TABLE 1 The Six Statistically Significant Variables of Roundabout Design (4)**

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Symbol</th>
<th>Data Range</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Width(^2)</td>
<td>e</td>
<td>3.6 - 16.5</td>
<td>Meters</td>
</tr>
<tr>
<td>Approach Half Width</td>
<td>v</td>
<td>1.9 - 12.5</td>
<td>Meters</td>
</tr>
<tr>
<td>Effective Flare Length</td>
<td>l(^1)</td>
<td>1.0 - (\infty)</td>
<td>Meters</td>
</tr>
<tr>
<td>Inscribed Circle Diameter</td>
<td>D</td>
<td>13.5 - 171.6</td>
<td>Meters</td>
</tr>
<tr>
<td>Entry Radius</td>
<td>r</td>
<td>3.4 - (\infty)</td>
<td>Meters</td>
</tr>
<tr>
<td>Entry Angle</td>
<td>(\phi)</td>
<td>0.0 - 77</td>
<td>Degrees</td>
</tr>
<tr>
<td>Circulating Flow (Not Geometric)</td>
<td>Q(_c)</td>
<td>0 - 4,700</td>
<td>PCUs/hr</td>
</tr>
</tbody>
</table>
The final version of the TRRL regression equation achieved a known $r^2$ of .78; (i.e., the independent variables explain 78% of variation in entry capacity).

Between-site variation leaves a statistically irreducible standard error of about 200 vehicles per hour due to variation in network location, local conditions, driver behavior, weather, and other random factors. This statistic is critically important, because it is essential for designers to know not just the mean capacity, but also the probability that actual capacity varies from the mean. This can then be allowed for in the design process, producing robust designs that allow for the unavoidable error in capacity estimation.

In 1992, the TRRL conducted follow-up field studies on 26 specifically chosen sites to update the empirical capacity model believing that this would be necessary. However, this study confirmed the existing equations and no revision was necessary, illustrating the robustness of the original research from which the equations were derived.
The six geometric parameters can be separated into primary capacity variables and secondary capacity variables, as each have differing influences on capacity and these are shown below. The approach roadway width \( V \), entry width \( E \), and the distance over which this widens from \( V \) to \( E \), assuming it does, are the primary capacity variables. The entry angle \( \Phi \) and Radius \( R \) are secondary, along with the Diameter \( D \).

FIGURE 3  Capacity influence of each of the six geometric parameters (4).
DEFINITION OF FLARED ENTRY

Flare length ($L'$) is the distance from the entry to the halfway point in the approach. Figure 4 below shows the method from which a flared entry is derived. When entry width ($E$) is greater than the approach roadway width ($V$), increasing the effective flare length ($L'$) will increase capacity. The increase in capacity is proportional to the area ($E-V$) multiplied by $L'/2$. The increase in width from $V$ to $E$ should be at a uniform rate.

Consequently, if $E-V$ is very small, even a large $L'$ will produce only a small increase in capacity. Even widening $V$ to match the slightly larger $E$ only increases capacity a small amount.

When $E$ is significantly greater than $V$, increasing $L'$ produces large increases in capacity that level out at about 300 feet. With $L' = 312$ ft (100 m) the capacity can be as high as 95% of the capacity achieved by widening the entire roadway link $V$ to match $E$. Entry width ($E$) in this definition as applied to US design will be in most cases full lanes, either two- or three- lane entries, not partial lane widths. However, while often debated, Kimber’s equation will give lower capacity for two 10’ entry lanes vs. two 14’ entry lanes. It is also important to clarify that ‘Flaring ‘and ‘Deflection’ are two completely different design issues. These have been in some presentations and papers confused as being associated, and therefore erroneously one and the same, when in fact they are mutually exclusive.

FLARED ENTRY DESIGN ELEMENTS

Correct visual information predicated on roundabout design principles, together with the principles underlying pavement marking and signage, form the foundation for the design elements that address the human factors to help drivers to correctly utilize a flared entry roundabout design. If incongruent visual information is present this will send incorrect and contradictory messages to drivers, resulting in the ineffective use of the approach geometrics, and field-measured operations will not match predicted operations.
The geometrics, signing, and pavement marking must all provide a congruent and consistent message to inform the driver correctly to facilitate effective use of the available entry width provided with the multi-lane flared entries. Next we will look at a few examples in which one or more of these design elements was missing. The resulting operations of these projects did not match predicted operations, with the erroneous conclusion that “flared” entries do not work for their region and/or drivers. When in fact, after reviewing the specific designs, the true cause of the inefficient and incorrect operations is missing or wrong visual information, which communicated incongruent information to the drivers.

Figure 5 below clearly shows, via the tire patterns, that drivers are not utilizing the inside approach lane. This is caused by incorrect alignment of entry to circulating roadway, making it physically difficult, or in this case nearly impossible, to utilize the entry available with the two-lane entry width. The resulting driver behavior will more closely match a single-lane entry and subsequent operations as reflected in Queue and Delay measurements.

FIGURE 5 Ineffective entry width; West Vail, CO (source: MTJ Engineering).
Figure 6 below shows the effects of a combination of geometrics and pavement markings that result in an underutilized right lane of this two-lane flared entry roundabout (95% left lane, 5% right lane). Traffic distribution was not the cause, as major flow is in the through movement (8).

The above example illustrates that it is important for design elements and the associated visual message to drivers to be congruent, and if they are not, it leads to ineffective lane utilization of the flared entry:

1) The approach marking is developed in a manner that does not provide indication of two through lanes, but rather the markings are more indicative of what a driver would expect to see when a designated exclusive right-turn lane is the correct lane use.

2) The alignment at entry to circulating is poorly aligned in a manner that creates entry path overlap that further reduces the visual cues and associated message to help drives to utilize both lanes.
A summary of the design elements and traffic conditions necessary for flared entries to work correctly include:

**Geometrics**

- Gradual smooth flaring from V to E
- Proper entry to circulating alignment
- Correct circulating to exit alignment with sufficient receiving distance and taper length as a function of speeds and volumes

**Pavement Markings**

Providing earlier indication and correct message to drivers to split/stagger from the single approach stream of traffic into two streams to achieve the associated resultant increase in capacity is a key component. Figure 7 at right is an adaption of UK guidance to accomplish this.

Providing at least one skip in advance of the channel line provides drivers with a subtle but very effective visual cue to drivers that both lanes are available for the thru-movement in this case. Providing early indication sub-full lane width provides for a smooth transition from the single approach stream of traffic into the two lanes at roundabout entry and therefore is more effective at splitting the single stream into two.

It is noted that this pavement marking application is often met with trepidation in the US, since traffic operations engineers used to their procedures that were established for the differing operational characteristics associated with signal- and stop-controlled intersections. Without a clear understanding of the reasons for the flared entry pavement marking application, it would otherwise seem inadvisable.

**Signing**

Signing must relate to the overall design and lane assignment needs corresponding with both the geometrics and pavement markings. The information must be clear, easily detected, and congruent; and too much or insufficient information is equally not good.

**Traffic Distribution**

The traffic distribution must be accounted for in the operational analysis and also followed through to the design and construction to facilitate utilization of entry lanes. If, for example, there was a distribution of 90% through left-turn volume and 10% right-turning volume, and
the left lane was assigned the through and left volumes, and the right lane the right volumes, these two lanes would result in unbalanced entry lane use since the inside lane would contain 90% of the traffic.

The photo in Figure 8 below illustrates a flared entry design for the eastbound through movement (north is assumed up) with the appropriate lane assignment to accommodate the major through movements (thru-left, thru-right). This compact hybrid type of design mixes dual-lane, single-lane, and differing lane use assignments to meet the operational objectives of the specific design traffic for this intersection.

FIGURE 8 State Highway 18 and Commercial Drive, Wales, WI (source: MTJ Engineering).
There has been some confusion among traffic researchers and practitioners when evaluating what appears to be a flared entry and the associated capacity effects of zippering/staggering and doubling up at entry are not present they have in some cases erroneously concluded that flaring and therefore the associated analysis methodologies do not work. However, what was not realized in these single-lane cases is that wider flared entry applied to US single-lane roundabouts are not designed with flare to elicit the capacity mechanisms of zippering or doubling up, as the circulating width and exit width are not designed in this manner. Rather, the entry has been widened only to accommodate large design vehicles, not for the operational effects that would be achieved with a multi-lane flared entry. It is noted that Kimber’s equations show residual increases in capacity with a wider single-lane entry vs. a narrower single-lane entry (e.g., 12’ vs. 15’); but the capacity effect of the wider entry in these single-lane-only entry designs will effectively max out, since in most cases no zipping or doubling up will occur.

The pictures side-by-side in Figures 9 and 10 below illustrate this issue and identify the fact that the roundabout on the left is a single-lane entry design (widened for trucks) with single circulating and exit lanes and therefore drivers will not zipper or double up, whereas the roundabout design on the right is clearly designed as a “flared” entry with correct and effective geometrics, including correct alignment entry to circulating and circulating to exit. In addition to the geometrics, the corresponding pavement markings clearly elicit the driver behavior of zippering and then doubling up at entry, achieving effective lane utilization of the entry which enables predicted and field measurements to then match.
The following illustrations in Figure 11 illustrate the above issues by stepping through an exercise whereby we have taken a properly designed roundabout with a two-lane flared entry, but then graphically modified it to change the geometrics to US single-lane design practices that will preclude drivers from using the flared two-lane entry.
Geometry necessary for a correct flared two-lane entry:
Base Condition

Geometry modified:
- Single-lane circulating width
- Results in single-lane entry utilization

Effective lane utilization at flared entry:
- Dual-lane circulating width restored
- Dual-lane entry utilization achieved

FIGURE 11 Examples of the effects of geometry on operations of flared entry designs.
(source: MTJ Engineering)
Video taken from the location indicated in Figure 12 below shows how vehicles approach in the single-approach lane and smoothly begin to zipper or stagger and then divide into each available lane at the entry, creating balanced lane use at entry. This movement exhibits the design elements and traffic distribution necessary for correct operations, which will therefore allow for correct analysis that will match prediction and measured field operations.

TRANSFERABILITY OF FLARED ENTRY ROUNDABOUT DESIGN TO OTHER COUNTRIES

Early US research concluded that international models over predict US roundabout capacities. This has raised questions about the transferability of non-US models to US conditions. Such questions include: Are non-US drivers more experienced with roundabouts? Is their driver behavior different than US drivers? Does the different size of cars and trucks have an effect? Will such differences persist into the future? Some have assumed that UK field capacity measurements may not apply to the US because UK drivers are more experienced with roundabouts and drive smaller cars and trucks. However, recent US capacity research shows very good correlation with Kimber’s equations (5). More recent
data presented at the 2014 TRB 4th International Conference on Roundabouts on saturated roundabout data collection conducted by FHWA further corroborates and supports the transferability of these equations to US drivers and conditions (6).

Kimber’s equations have been found to be statistically sound for approximately 25 years (5). This robustness is attributed to the large statistical database on which the original work was predicated. It has been discussed that it will be difficult to replicate this original work in other countries given the unique conditions available to them at that time, which included: wide variation in geometrics and fully saturated flow conditions over the entire range of flow conditions (9, 10). But with improved understanding of the importance of the necessary data collection efforts, and stronger understanding of the original underpinning of the research that forms the basis for Kimber’s equations, together with the design elements, research will then be able to, with more certainty, substantiate and validate Kimber’s equations to drivers outside of the UK.

CONCLUSION

Multi-lane flared entry roundabouts provide significant advantages to our roadway and transportation infrastructure, with the potential to provide solutions to congestion that avoid or minimize expensive roadway widening and the impacts and costs associated with current traffic planning with signals (11).

However, multi-lane flared entry roundabout analysis and design represent a significant change from conventional US traffic planning analysis methodologies that are based on signalization and stop-control procedures. Existing procedures rely on adding lanes at the intersection and widening the associated roadway links to add system capacity.

When analyzed, designed, constructed, and maintained properly with inclusion of essential design elements for the specific traffic distribution, multi-lane flared entry roundabouts are shown to operate as discussed in UK research literature that forms the basis for Kimber’s equations. This is thought to occur because the inherent and natural driver behavior is elicited with these design elements applied, irrespective of country of origin, and drivers respond correspondingly as predicted by Kimber’s equations.

US capacity research provides limited and mostly qualitative guidance on methods to correctly analyze a flared entry roundabout or the correlation between the design and analysis. With improved understanding of the design elements and the underlying research conducted in the UK, future researchers can more accurately assess the full potential of multi-lane flared entry roundabout design and its potential positive effects on our current traffic planning paradigm.
REFERENCES


