A SPATIAL AND TEMPORAL ANALYSIS OF DRIVER GAP ACCEPTANCE BEHAVIOR AT MODERN ROUNDABOUTS

Daniel S. Abrams
Undergraduate Research Assistant
Department of Civil and Environmental Engineering
University of Massachusetts
139B Marston Hall
Amherst, MA 01003-92993
Email: dsabrams@student.umass.edu

Cole D. Fitzpatrick (corresponding author)
Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Massachusetts
139B Marston Hall
Amherst, MA 01003-92993
Email: colefitzpatrick@ecs.umass.edu

Yue Tang
Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Massachusetts
139B Marston Hall
Amherst, MA 01003-92993
Email: yuet@engin.umass.edu

Michael A. Knodler., Ph.D.
Associate Professor
Department of Civil and Environmental Engineering
University of Massachusetts Amherst
142B Marston Hall
Amherst, MA 01003
Email: mknodler@ecs.umass.edu

Paper Number: 13-3237  Review Committee: ANB70 Truck and Bus Safety Committee
Prepared for the 92nd Annual meeting of the Transportation Research Board, Washington, D.C.
January, 2013

Length of Paper:
156 word abstract; 4,573 words; 9 figures and tables @ 250 equivalent words
Total Word Count = 6,979
ABSTRACT
Despite an increasing acceptance of modern roundabouts in the United States, there is still a widespread unfamiliarity with this type of intersection. This unfamiliarity results in more unpredictable gap acceptance decisions by drivers increasing the difficulty of design decisions. Here, the relationship between the spatial and temporal critical gaps accepted by drivers in modern roundabouts was explored via gap acceptance data taken on over 1,500 vehicle interactions at the roundabout on the University of Massachusetts Amherst campus. The critical gap was found to be 42 feet spatially and 2.2 seconds temporally, which correlated directly with the average speed of the circulating flow. An increase in critical gap time was observed for heavy vehicles in the traffic stream. Although the unidirectional flow of the circulating traffic creates a potentially unpredictable environment for the driver, careful and precise analysis to obtain an accurate and reliable value of the critical gap will allow for improved design of future roundabouts.
INTRODUCTION
The functionality of a roundabout is directly related to the ability of entering drivers to select an appropriate gap within the circulating traffic stream (1). The critical gap refers to a specific gap size that if it were larger a driver would accept, and if it were smaller a driver would reject it (2). Unfamiliarity with modern roundabouts has the potential to cause drivers to reject large gaps, thus reducing the efficiency of a roundabout. Misjudging the size of the gaps in traffic that drivers are willing to accept can cause traffic engineers to make poor design decisions. If an excessively passive driver (i.e., large critical gap value) is used in the design, it is likely that the roundabout will be overdesigned, and in turn minimizing the operational efficiency. By comparison, if an overly aggressive driver (i.e., small critical gap) is chosen for the design, the intersection will be undersized and potentially lack the capacity to function properly. In the latter case, the safety of the intersection is jeopardized when drivers are forced to operate under smaller tolerances. A timid driver will be forced to either make an aggressive decision or not enter the intersection, causing a significant queue to develop. These design implications make it essential for engineers to gain a better understanding of driver gap acceptance behavior at roundabouts.

Although the topic of gap acceptance has been widely studied (3–5), there is a need to better understand the relationship between spatial and temporal critical gaps. Drivers may misjudge the circumferential distance and time of a roundabout resulting in a different critical gap of vehicles in a circulating roadway than a typical perpendicular intersection. In this study, the spatial and temporal critical gaps accepted by drivers in modern roundabouts were compared to provide an improved understanding of driver behavior in this roadway environment, which impacts operational and design decisions by traffic engineers.

BACKGROUND
Roundabout Function and Safety
The modern roundabout has gained a more widespread acceptance across the United States over the course of the past decade due in part to both operational and safety benefits. Advancement with regard to the overall understanding of roundabout operation was demonstrated by the 2010 Highway Capacity Manual (6). Unfortunately, there is still a large learning curve for drivers as modern roundabouts display many features that separate them from other types of traffic circles. In a true modern roundabout, drivers in the circulating traffic have complete priority over the entering vehicles, which must yield before entering the traffic stream. Roundabouts also have a smaller diameter and steeper entry deflection, thus forcing lower speeds. The characteristic splitter island also helps promote low speeds while improving the ease and safety of pedestrian crossings. Due to their small size, parking is not allowed in roundabouts, whereas it is allowed in some larger traffic circles (7).

Roundabouts are often installed because they consistently perform better than signalized or stop-controlled intersections based on the criteria of delay, capacity, safety, costs, aesthetics, and accommodation for pedestrians and bicyclists (7,8). In a 1998 survey of all roundabouts in the United States, respondents were unanimous in reporting only positive or neutral impacts based on the aforementioned criteria after the installation of roundabouts. These roundabout installations decreased the peak-hour delay by about 75% in all cases (8). In isolation, the capacity of a roundabout is almost always greater than that of a signalized intersection. This is largely due to the complete omission of loss-time (7).
Perhaps the biggest advantage of the roundabout are the safety benefits. Many features inherent in the design make roundabouts significantly safer than other types of intersections. Stop controlled intersections have 24 points of decision and 28 points of potential conflict (7,9). Roundabouts only have 4 decision points and 8 conflict points, making the likelihood of a crash occurring decrease significantly (7,9). Drivers only need to scan one direction at a roundabout to find an acceptable gap, while drivers traversing stop-controlled intersections must scan, at minimum, two traffic streams to safely cross the intersection (9). With the simplified decision system of roundabouts, driver are able to pay more attention to driving safely (7). Even though the decision is simplified, the design of the intersection forces the driver to assume a higher level of responsibility. The driver must slow down due to the decrease in lane width caused by the splitter island and yield to the circulating traffic. The driver must then negotiate the roundabout as an “obstacle” that obstructs the normally straight path of the roadway (7). The combination of these factors causes a significant decrease in the number of accidents and in the severity of these accidents. All movements in a roundabout are equivalent to right-turn movements resulting in virtually no instances of right-angle, head-on, or left-turn accidents. Almost all collisions are bumper-to-bumper, which decreases the number of injury accidents and virtually removes fatalities (3-5). Concern has been expressed that older drivers may have trouble adjusting to this new type of intersection; however, the mean age of drivers involved in crashes does not increase with the addition of a roundabout, suggesting this is not a problem (10). A potential disadvantage of roundabouts could be that these drivers may re-route themselves and cause traffic congestion at a nearby intersection.

In addition to an increase in vehicle safety, roundabouts are also safer for pedestrians and bicyclists (10). At any given crossing, a pedestrian needs to be aware of vehicles coming from only one direction at a time. The splitter island acts as refuge for the pedestrians between traffic streams (7,10), decreasing the distance a pedestrian must cross. Combined with the decreased vehicle speeds, pedestrians are much more protected from collisions; some studies show up to an 89% reduction in pedestrian injuries. Low speeds also decrease bicycle injuries by up to 44% (8).

There are other advantages to the installation of a roundabout. Unlike other traffic control measures, roundabouts have the unique ability to improve the aesthetics of an area. The central island can be landscaped or include a sculpture, thus breaking the monotonous visual corridor of the roadway in a positive way (8). Additionally, roundabouts show a significant reduction in vehicular emissions due to the reduction in delay and queue times. Emissions of CO, CO$_2$, and hydrocarbons are all significantly reduced with roundabout installation (11). Although the construction costs of roundabouts are higher than other types of intersection, they save money in the long run due to the low cost of operation and the decreased emissions (7).

Despite its advantages, roundabouts are only appropriate in certain situations. Roundabouts should be installed in areas with high incidents of vehicular accidents, especially those related to crossing and turning movements, as these are completely eliminated. Roundabouts are also appropriate for intersections where there are high delays, where U-turns are frequent, where the speed of the road changes, and where a traffic signal is not warranted by the Manual on Uniform Traffic Control Devices (MUTCD). Roundabouts should not be installed in locations of uneven terrain, locations with space restrictions that do not allow for the proper diameter of the roundabout, locations where a nearby signalized intersection may have a queue that backs up into the roundabout, or at a location where a networked signal may be more appropriate. Roundabouts do not perform well when placed in those conditions. Additionally,
intersections of major and minor roads are not ideal roundabout candidates as the minor traffic can cause significant delays on the major roadway (8).

**Gap Acceptance Background & Analysis Methods**

The Highway Capacity Manual (HCM) procedure defines the critical gap as the median gap time accepted by driver in a given situation (6). This method often leads to misestimates and is inconsistent with the methods commonly used by traffic engineers (12). The HCM assumes the critical gap is constant, when in fact it varies with many variables, such as the time of day, maneuver being made, queue time, driver wait time, number of gaps rejected/time spent waiting for an acceptable gap, vehicle classification, point of departure, driver demographics, and presence of a passenger (5,12,13). Depending on the intersection, an engineer will use different methods to analyze the gap acceptance data. While a detailed description of every method is beyond the scope of this study, the pertinent methods are outlined.

Proposed by Raff in the late 1940’s, the Raff method is a very logical and computationally simple method for determining the critical gap. With this method, the critical gap is defined as the intersection of the cumulative distribution of the accepted and rejected gaps (2,4). Due to using both accepted and rejected gap data, only a small sample size is needed (2). Steven Tupper et al. demonstrated the Raff method as one of the best data analysis methods for the critical gap.

Tupper et al. also compared critical gap methods, including the cumulative acceptance method, the equilibrium of probabilities method, and the fit maximization method. The cumulative acceptance method finds the gap acceptable to 85 percent of drivers. Unlike the Raff method, this method requires a larger set of data because it only uses the accepted gaps. The equilibrium of probabilities method is computationally derived from another method known as the Troutbeck method. In these methods, a maximum likelihood of acceptance decision is determined by organizing the gap data by length. Similar to the Raff method, these methods use all of the data and thus a smaller set is required. Additionally, the Troutbeck method gives critical gap values closest to that of the HCM. The fit maximization method, based on a small data set, uses the logic that most gaps larger than the critical one are accepted and smaller than critical are rejected (2).

![FIGURE 1 Summary of different gap acceptance techniques used in practice and research. (14)](image-url)
Gap Acceptance in Roundabouts

There is extensive literature on the general topic of gap acceptance. However, there is little research on gap acceptance in the modern roundabout. This proves problematic, as the median accepted gap is often used as the critical gap for input into the widely accepted HCM capacity-prediction model for roundabouts (6). While gap acceptance at roundabouts has been modeled (15,16), a chasm exists in the research regarding empirical observations to estimate an accurate critical gap value. Furthermore, while temporal critical gaps are used in practice, there is no research that recommends whether a temporal or spatial critical gap is a better predictor for roundabouts.

One report asserts that the critical gap of a roundabout is in constant flux. As the queue, or waiting time increases at a roundabout, the accepted gap decreases asymptotically to the minimum gap. Additionally, for short time intervals, the capacity changes as the critical gap is constantly affected by the building queue. Over larger periods, though, the capacity value converges to an intermediate average leading to the counter-intuitive conclusion of higher queues leading to a higher capacity (1). This conclusion was further supported by another study where the critical gap decreased during the peak-hour, a time at which queues are likely to be larger (17). Xu et al examined roundabout gap acceptance and concluded that speed and circulating flow rate heavily influence the critical gap (18). Research suggests that this phenomena is not unique to roundabouts (3).

Johnson et al. investigated the critical gap at roundabouts in relation to control delay and compared the different NCHRP methods used to find the critical gap (19). Ruijun Guo also examined the different methods of obtaining critical gap in a similar fashion as Tupper et al. but this time at roundabouts (20). Mensah et al. performed a before and after study of two newly constructed roundabouts. Significant reductions in the critical gap were observed indicating the capacity of the roundabout improves as people become more familiar with the intersection (21). Finally, a study performed on the state of Wisconsin’s roundabouts concluded that trucks had higher critical gaps and motorcycles had smaller critical gaps in comparison to critical gaps of cars (22). In each of the preceding studies, only temporal gaps were used and spatial gaps were either ignored or not mentioned.

OBJECTIVES

There are three primary objectives for this research. The first objective is to explore the relationship between spatial and temporal critical gaps in modern roundabouts and to evaluate whether one type of critical gap is a better indicator of the overall gap acceptance of entering drivers. The next aim of this study includes investigating a connection between heavy vehicles and increased critical gap values. The final objective is to determine an accurate and reliable value of the critical gap to help improve future design of roundabouts.

METHODOLOGY

Empirical observation data was taken at a roundabout located on the University of Massachusetts Amherst campus at the intersection of North Pleasant Street, Eastman Lane, and Governors Drive. This roundabout is similar in geometry and vehicle volumes as a typical suburban roundabout. Drivers may be more familiar with the roundabout operations than a typical suburban roundabout as it is located on a university campus.

Cameras were strategically placed on the rooftop of a nearby building to provide an overhead vantage point that was ideal for data analysis. FIGURE 2 shows a typical frame from the video analysis. In this example, the Governors Drive approach was being analyzed. When a
vehicle arrives at the intersection, the driver begins the decision making process which will ultimately lead to them accepting or rejecting a gap. The moment the decision making vehicle arrives at the yield line, the location of the gap vehicle (the vehicle in the circulating traffic stream) along the center line of the roadway is recorded. When the gap vehicle crosses the first line, the gap closes and the time it took for the gap vehicle to traverse the intersection is recorded. The gap opens again when this ceases to be blocking the approach. The gap is considered accepted if the decision car entered the intersection (defined as crossing the dashed pavement marking) before the gap vehicle closed the gap.

![Image of roundabout with labeled parts: Gap Vehicle, Gap Closes, Gap Re-opens, Decision Vehicle](image)

**FIGURE 2** Example frame from roundabout video analysis.

The previously described gap situation is for actual gaps, where the gap vehicle in fact closed the gap, thus preventing the decision vehicle from entering the intersection. However, due to the inherent nature of roundabout intersections, there are situations where a vehicle appears as though it may continue in the circulating traffic and eventually close the gap, but instead exits the intersection before doing so. While in this situation the gap was technically never closed, the driver may have perceived this car as a potential threat to close the gap; therefore they may have chosen to yield even though the gap technically never terminated. These “perceived” gaps were also recorded and used within the analysis.

For every observation made during this study, the length of each gap both spatially and temporally was recorded for every interaction. The video data was analyzed frame-by-frame using the free analysis software, Forevid®, to determine the time and distance of each gap, both accepted and rejected. This data was also used to determine the circulating speed of each vehicle. The type of vehicle was also recorded as one of five categories: passenger car, bus, utility vehicle, tractor trailer, and bicycle.

In addition to exploring the relationship between the temporal and spatial aspects of the critical gap, the exit behavior of the decision vehicle was also recorded on each interaction. Specifically, the drivers making an immediate right turn could be compared to those fully
engaging the roundabout as circulating traffic. It was hypothesized that drivers that enter the roundabout only to make an immediate right turn do not have to fully become part of the circulating flow and therefore do not engage the roundabout in the same way that drivers making other movements do. This difference might allow drivers to accept a smaller gap because they are in the intersection for a shorter amount of time.

**FINDINGS AND RESULTS**

**Critical Gap Values**

For the analysis, data was taken from the Governors Drive and North Pleasant Street (southbound) approaches. More than 10 hours of video footage was captured during both morning and afternoon peak hours in February of 2012. All observations were made in daylight and with favorable weather conditions. Over the duration of the analysis, data was taken on over 1,500 vehicle interactions.

The Raff method was selected for analysis because of its small sample requirements, non-robust calculations and favorable view in past research (2,14). The simplicity of the Raff method also makes it a good candidate for widespread use in the field of Transportation Engineering. Using the Raff method, the value of the critical gap is defined as the value at which the cumulative distribution functions (CDFs) of the accepted gaps intersects with the cumulative distribution of the rejected gaps. At this value, the probability of a driver rejecting a gap becomes less than that of accepting a gap, thus it is the critical gap value. This value is found graphically by plotting the data for each scenario and finding the point of intersection. The overall critical gap of this roundabout was found to have a value of 42 feet spatially and 2.2 seconds temporally. The CDFs that yielded these two values can be seen in Figure 3. A summary of the critical gaps can be found in Table 1.

![Figure 3: CDFs for the temporal (left) and spatial (right) critical gaps.](image)

Statistical testing could not be conducted comparing the critical gaps because the value of the critical gap is aggregated from the data and thus does not contain a standard deviation. Rather, statistical testing compared whether the difference in means for accepted gaps was statistically significant. It was also found that on average, vehicles making right turns are willing to accept a gap that is 0.3 seconds longer and 1 foot longer than those making other movements. This conclusion does not support the original hypothesis, as both numbers would need to be smaller for the results to be conclusive. However, both values are statistically insignificant with regards to the average accepted/rejected gaps, indicating that no definitive conclusion can be
made as to whether drivers making right turns act no differently than those intending other movements. Additionally, subjective observation of the video data supported the conclusion that drivers making right turns were just as cautious as those heading straight through or making left turns.

When entering vehicles were faced with a gap created by a heavy vehicle, the drivers tended to act more timidly. The critical gap for drivers facing a heavy vehicle was 0.6 seconds longer, but 6 feet shorter than when entering vehicles faced a passenger vehicle. The spatial aspect of this conclusion, while statistically significant, may say more about spatial critical gaps than it does about driver behavior. Conversely, the temporal aspect is quite significant – when faced with a heavy vehicle, drivers needed an additional six-tenths of a second to feel comfortable entering the roundabout. These values do make sense intuitively, although the correlation would be much stronger if both spatial and temporal gaps were statistically significant and supportive. Additional research is warranted to verify these results.

As expected, the data supports the notion that heavy vehicles required larger gaps. The critical gap accepted by larger vehicles is 0.6 seconds longer than the critical gap accepted by passenger vehicles. No conclusion regarding the spatial critical gap could be reached due to the small sample of heavy vehicles.

### TABLE 1 Summary of Spatial and Temporal Critical Gaps

<table>
<thead>
<tr>
<th></th>
<th>Overall</th>
<th>Right Turns</th>
<th>Other Movements</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial (ft)</td>
<td>42</td>
<td>42</td>
<td>41</td>
<td>1*</td>
</tr>
<tr>
<td>Temporal (s)</td>
<td>2.2</td>
<td>2.3</td>
<td>2.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Passenger Gap Vehicle</td>
<td></td>
<td></td>
<td>Heavy Gap Vehicle</td>
<td>Difference</td>
</tr>
<tr>
<td>Spatial (ft)</td>
<td>42</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Temporal (s)</td>
<td>2.2</td>
<td>2.8</td>
<td>-0.6</td>
<td></td>
</tr>
<tr>
<td>Facing Passenger Vehicle</td>
<td></td>
<td>Facing Heavy Vehicle</td>
<td>Difference</td>
<td></td>
</tr>
<tr>
<td>Spatial (ft)</td>
<td>41</td>
<td>35</td>
<td>6*</td>
<td></td>
</tr>
<tr>
<td>Temporal (s)</td>
<td>2.6</td>
<td>2.0</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

Note: (*) represents the difference not statistically significant.

**Evaluating Spatial Gaps vs. Temporal Gaps**

The speed of the circulating traffic was chosen to examine the correlation between gap time and distance. Figure 4 is a graph of the gap distance vs. gap time for every vehicle interaction. The average speed is interpreted from the best fit line. With the obvious outliers excluded, the slope of data is 20.3 ft/sec (13.8 mph). Dividing the spatial critical gap into the temporal critical gap yields a speed of 21.6 ft/sec (14.7 mph). The 6% error suggests the two measures are highly correlated, and both of them can be used in predicting critical gap. Thus, a statistical comparison is required to evaluate whether space or time is a better measure of the critical gap.

Figure 5 and Figure 6 shows the CDF of accepted and rejected temporal and spatial gaps, respectively. The CDF of the temporal gaps is much smoother for both accepted and rejected gaps, which indicates that driver decisions are more consistent temporally than spatially.
Furthermore, the difference in slopes of the temporal measure is smaller than that of the spatial measure, and the trend is apparent at the 50% critical gap. This indicates a more precise predictor of the temporal measure than spatial measure. Looking at the frequency distribution of accepted gaps of the two measures, as shown in Figure 7 and Figure 8, the temporal gaps presents a normal distribution. In contrast, the majority of spatial gaps are relatively evenly distributed between 50 and 150 feet and do not yield a classic normal distribution. The mean and standard deviation of the temporal gaps are 3.7 and 2.4 seconds respectively, while those of the spatial gaps are 71.3 and 37.4 feet. Moreover, the insignificance of the spatial aspect of the difference in critical gaps for cars facing heavy vehicles and passenger vehicles is another indicator that the critical gap is better indicated temporally.

FIGURE 4 Gap distance vs. gap time for every interaction.
FIGURE 5 CDF of accepted and rejected temporal gaps.

FIGURE 6 CDF of accepted and rejected spatial gaps.
FIGURE 7 Histogram of accepted temporal gaps.

FIGURE 8 Histogram of accepted spatial gaps.
DISCUSSION
The challenge of measuring or identifying the critical gap is that it includes elements of subjectivity, which is further complicated within roundabouts. Both the spatial and temporal analysis methods are valuable tools in understanding the inner workings of this unique type of intersection. With a reliable value of the average speed, both measures can be used to accurately frame the critical gap. That said, the temporal analysis of the critical gap appears to be a more appropriate predictor of the critical gap estimate and starting point for design. Measuring the critical gap in units of time was found to be a more significant indicator of the gap in this study as there were no significant findings regarding spatial gaps. Whereas, it was found that passenger cars accept a gap 0.6 seconds shorter than heavy vehicles. Additionally, temporal gaps are already the standard measure of gap acceptance at most other types of intersections.

Despite the initial successes documented herein, further research is required to fully understand gap acceptance behavior in roundabouts. This analysis was performed at only one roundabout out of thousands across the country. Further research could compare these results to those of a roundabout located at another location – perhaps one not on a college campus, where there are more experienced drivers and lower instances of heavy vehicles. This highly contrasting example would give additional insight on critical gap value determined in this research. Ideally, there would be a multitude of gap acceptance studies, such as this one, at roundabouts across the country. Then, these critical gap studies could be used by engineers when designing new roundabouts.

Roundabouts present interesting challenges in gap acceptance. The unidirectional nature of the circulating traffic creates a potentially confusing environment for the driver to decide on an acceptable gap. In many cases, drivers act excessively timid due to inexperience with this relatively unfamiliar type of intersection and with the unpredictability of the circulating traffic behavior in relation to perceived versus actual gaps. However, with careful analysis and an exacting method for obtaining the gap acceptance data, an accurate and reliable value of the critical gap can be determined.

REFERENCES


