APPENDIX C
ROUNDABOUT CRITICAL HEADWAY MEASUREMENT
BASED ON HI-RESOLUTION EVENT-BASED DATA FROM
WIRELESS MAGNETOMETERS

by

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ABSTRACT

Critical headway is an important parameter for roundabout design, particularly in regards to analytical modeling approaches. Those models have been developed over the past 30 years and were typically developed using data obtained from manually reduced video and/or field observations. This paper reports on the application of wireless magnetometers to collect point presence detection used to calculate the rejected critical headways. Data was collected at a single lane roundabout in Carmel, IN. Carmel, IN is a community with over 60 roundabouts in operation for several years, representing a community highly experienced in using roundabouts. Over 260,000 entering vehicles were observed at one of the single lane roundabouts over a two week period with over 45,000 rejected headways analyzed. For the roundabout studied, 75% of the rejected headways were found to be less than 3.0 seconds. The rejected headways values were somewhat less than reported in NCHRP Report 572 and is perhaps due to the evolving driver familiarity with using roundabouts. Although this community has a particularly large number of roundabouts, the rejected headway characteristics observed suggest that as roundabouts become more common throughout the U.S., it may be appropriate to revisit some of the basic traffic engineering parameters used for analysis, much like the traffic signal community did with saturation flow rate in the 1990s. The techniques presented in this paper could be scaled to several roundabouts with varying geometrics and traffic to diversify the data set necessary to update some of the values developed in the last decade before roundabouts were common in the U.S.
INTRODUCTION

Roundabouts are growing in popularity. Although the number of roundabouts in existence continues to grow, engineering experience with roundabout operations in the US is still developing. Critical headway (sometimes referred to as headway acceptance) is a very important parameter with regards to roundabout operation and design. At a roundabout, entering vehicles are faced with a decision to enter or wait (yield) depending upon the circulating traffic. Each driver must make a decision based on their own acceptable level of risk. Often, this decision comes down to how much time the driver needs to feel comfortable to enter versus the amount of time available which is a function of the circulating traffic (1). Specifically, the amount of time between vehicles (effectively the gap time, although headway is more commonly measured) is a finite time that drivers can make a decision based on their intuition.

With a known demand volume (or perhaps historical volume counts) and some reasonable planning logic, flow rates expressed in vehicles per hour can be calculated. Based on the turning movements from each flow rate, the number of vehicles passing in front of each approach (the circulating volume) can also be determined, usually during a design period of 15-minutes or 1-hour. With this information, the probability of headways can be determined (1).

Modeling techniques in the 2010 Highway Capacity Manual have converged on headway acceptance procedures and several studies have been done to define the design values of headway acceptance (2). As roundabout usage grows, the headway acceptance characteristics will likely evolve. A similar evolution in traffic signal analysis occurred when the saturation flow used in the Highway Capacity Manual was increased from 1,800 to 1,900 vehicles per hour.

This paper reports on a roundabout instrumented with 16 wireless magnetometer point sensors that collected data over a two week period observing more than 265,000 entering vehicles. Figure 1 shows a map of Carmel, IN from 2010 with nearly 50 roundabouts in place, making residents of this community perhaps some of the most experienced roundabout users in the United States.

OBJECTIVES

The objective of this paper is to examine the headway acceptance characteristics in a community of highly experienced roundabout users. This data is useful for providing a lower bound on headway acceptance to provide a frame of reference to agencies on how conservative current modeling techniques are. Also, the data should stimulate dialog in the roundabout community on how headway acceptance characteristics are maturing in the United States as roundabouts become more prevalent. In addition, the techniques presented in this paper can be used to develop headway acceptance models for varying conditions such as weekday/weekend, dry/rain, and dry/snow.
MODELING TECHNIQUES AND PREVIOUS STUDIES

Models of roundabout performance may be categorized into two groups: statistical models and analytical models (1). Statistical models use regression analyses of field observations to develop mathematical relationships primarily between roundabout geometry, and performance measures. The seminal work on this subject comprised a vast body of field observations, and was carried out in the UK in the 1970s (4), and a family of analysis tools has since emerged from that approach. Analytical models began to emerge more recently, from the 1990s and after (5,6). These types of models use traffic flow theory concepts to explain and predict roundabout performance, leading to another group of analysis tools.

In the US, the most widely used document for establishing intersection performance measures is the Highway Capacity Manual (HCM) (2). The current HCM approach, based on outcomes from NCHRP Report 572 (1), uses a combination of statistical and analytical tools to incorporate various intersection parameters. Several adjustment factors for various properties are based on regression, while the delay equation is based on traffic flow theory, similar to the handling of other intersection types in the HCM. Although headway acceptance factors are not directly used in the HCM analysis, the capacity formula recommended in NCHRP Report 572 has the basic form

\[
\begin{align*}
    c &= A \cdot \exp(-Bv_c) \\
    A &= \frac{3600}{t_f} \\
    B &= \left(\frac{t_c - t_f}{2}\right) / 3600
\end{align*}
\]

[Equation 1]

where the entry capacity \( c \) is a function of the conflicting flow \( (v_c) \), follow-up headway \( (t_f) \), and critical headway \( (t_c) \). The recommended values for these formulas in the HCM are thus ultimately based on calibration of \( t_f \) and \( t_c \). As the use of roundabouts continues to expand in the United States, it is likely that driver characteristics, and therefore \( t_f \) and \( t_c \), will also evolve.

The largest observational study in the US carried out to date to characterize \( t_f \) and \( t_c \) was done as part of NCHRP report 572 (1) to establish calibrated values of \( A \) and \( B \) in Equation 1. Using 11,581 observations from 18 sites, average critical headway values of 4.5, 5.0, and 5.1 s are suggested (using different estimation methods) for single-lane roundabouts. Another investigation of headway-acceptance behavior in the US is presented by Xu and Tian (8). A total of 28 hours of video from nine roundabouts in California is used to analyze relationships between \( t_c \), \( t_f \), and circulating flow and circulating speed. The reported values of \( t_c \) and \( t_f \) are similar to those found in NCHRP Report 572. A 2002 study by Polus, et al. (9) at seven roundabouts in Israel investigated the evolution of critical headway with respect to waiting time. The observations show critical headways shrinking by up to 2.0 seconds for waiting times up to 40 seconds.
INSTRUMENTATION

To conduct a detailed analysis of driver behavior with a very large data set, a single lane roundabout at Spring Mill Rd and W 106th St in Carmel, IN was instrumented with 16 wireless magnetometers in the entering, exiting, and circulating lanes on all four legs of the intersection according to the process shown in Figure 2. The magnetometers give an “on” time and “off” time for each vehicle, thus allowing for occupancy to be calculated between these two events for each vehicle (10). Also, headway (the time from the “on” event of vehicle $n$ to the “on” event of vehicle $n+1$) and gap (the time from the “off” event of vehicle $n$ to the “on” event of vehicle $n+1$) could be calculated. All events were transmitted locally to an access point and then to an SQL database over cellular communication networks.

The instrumentation of the intersection is part of continued research by the project team applying discrete event logging to analyze microscopic traffic behavior characteristics. In 1999, the first instrumented signalized intersections were constructed by the Indiana Department of Transportation to evaluate video detection technology (11). Detector and signal phase status were recorded in real-time using industrial control equipment. This infrastructure was later migrated to video detection equipment (12), and then finally encapsulated in data loggers embedded in controller firmware (13). Because of enhanced performance measurement capabilities offered by deployment of discrete event data collection, it has been possible to assess the impact of adverse weather and other conditions on signal operation (14). Similar findings are anticipated should additional roundabouts be instrumented.

ANALYSIS

Originally, this roundabout was selected because of its unbalanced flow characteristics. Figure 3 shows a sample day of volume entering on each approach for every 15 minutes. With Indianapolis to the south, there is a heavy southbound (SB) entering volume in the AM from the north approach (as seen in Figure 3) and similarly strong northbound (NB) entering volume in the PM from the south approach as drivers return home.

The headway was calculated from the sensor data. Table 1 (similar to Table 34 in NCHRP Report 572) shows a sample set of data for an entering vehicle (E1) that rejected two headway intervals including:

1. Headway 1 between circulating vehicle 1 and circulating vehicle 2 which was 1.9 seconds
2. Headway 2 between circulating vehicle 2 and circulating vehicle 3 which was 1.8 seconds
The headway 3 interval between circulating vehicle 3 and circulating vehicle 4 was 3.2 seconds which exceeded the $t_c$ for this particular entering driver. A graphical representation of this is shown in Figure 4 with the rising edge (“on” event) and falling edge (“off” event) for each of the two detectors used in the analysis. Figure 5a shows this as a schematic for the intersection and Figure 5b shows this based on the recorded video data used for post-processing verification.

During the two week study from July 11, 2012 to July 25, 2012, there were 265,483 entering vehicles observed at the study location. Of these, 241,023 entered without having to yield while 24,460 vehicles rejected one or more headways. A total of 45,457 headway rejections were observed as many vehicles will reject multiple headways during peak periods. Figure 6 shows the sample sizes of headways analyzed from headways 1-10 for each approach (a-d) and for the whole intersection (e). Figure 5 is a conceptual figure explaining how sensor events generate traffic data. Headway and gap times can be calculated and the number of headways each driver rejected can be determined.

Figure 7 characterizes the cumulative distribution from the two week study period for rejected headways. Headway 1 can operate in two different modes depending on the driver’s decision at what may be thought of as a roundabout “dilemma zone”. If an entering driver chooses to slow down and arrives on the entering sensor just before the circulating vehicle triggers the circulating sensor, and then proceeds to vacate the entering sensor, this would appear as a nearly zero-second headway rejection. To eliminate some noise from the data and be more conservative, a 2.5 second look-ahead time was used to analyze entering vehicle decisions. This looks at the status of the circulating sensor up to 2.5 seconds before the entering sensor turns on, perhaps indicating that a driver is looking to the left for circulating traffic (the 2.5 second time may be conservative, but was based on headways rejection times for headways 2-n). While headways 2-7 are hard to distinguish on the graph, this demonstrates that the headway rejection by headway sequence appear quite similar.

Figure 8 characterizes headways by sequence and compares the four approaches. It should be noted that the west approach has the shortest headway rejection time for headways 2-7, due to the high circulating volume from the southbound entering traffic from the north approach. With a lack of opportunities, drivers typically accept shorter headways. Again, most of the curves are very similar. Headways 6 and 7 have lower sample sizes, so the curves are not as smooth.

Figure 9 characterizes the quartiles of each headway in sequence. The trend of drivers accepting lower headways due to self-calibration as they wait and reject sequential headways at the intersection is evident in the monotonically decreasing median headway rejection time from about 2.2 seconds for headway 2 to about 1.9 seconds for the median rejected time of headway 10. Figure 10 compares weekdays to weekends and it is clear that drivers are willing to accept shorter headways during the weekdays as the headway rejection times are lower in most cases.
Finally, Figure 11 shows the quartiles of the headway time by time-of-day for all the circulating sensors in the roundabout. As previously mentioned (and shown in Figure 3), there is a heavy southbound entering volume from the north approach. These vehicles immediately pass over the circulating sensor for the west approach where the headways are very tight as shown by callout “ii” in Figure 11d. This is likely the reason that drivers entering from the west approach have a lower headway rejection as they are forced to be opportunistic and accept a smaller headway. A similar trend is shown for the east approach in the PM (callout “i”) to a lesser extent. For both Figure 11b-i and Figure 11b-ii, the circulating headway is approaching a lower bound of about 1.7 seconds for the 25th percentile and the median is approaching 2.2 seconds.

CONCLUSIONS

This paper examines the most robust set of headway acceptance data collected at a roundabout to date with over 45,000 headway rejections over a two week study period. Under heavy circulating volumes, drivers are less likely to reject shorter headways. Drivers are likely to reduce their headway rejection threshold the longer they wait at the yield line rejecting vehicles. For an experienced community of roundabout drivers, the median critical headway was 2.2 seconds and the 75th percentile was 2.8 seconds. The median critical headway was about 2.1 seconds during the weekday and 2.2 seconds during the weekend. The west approach in general had a lower critical headway, likely due to the strong entering volume from the north approach which immediately functions as circulating traffic for the west approach. This suggests that as roundabouts become more congested, the critical headway reduces. Finally, critical headway monotonically reduced from 2.2 seconds to 1.9 seconds between the 2nd rejected headway and the 10th rejected headway. These numbers are substantially lower than those reported in NCHRP Report 572, showing that driver experience is important to consider with regards to capacity. This is very important since the 20-year design life will operate more similar to a population familiar with roundabouts (such as the dataset in this paper) rather than the drivers inexperienced with roundabouts (such as the dataset which NCHRP Report 572 is based). Furthermore, adjustments to capacity may need to be considered.

Future work will include looking at headway acceptance during rain, snow, or other inclement weather and also instrumenting a multi-lane roundabout. This corridor will be monitored over a long term period to observe seasonal variations in headway acceptance and to compare with other local traffic characteristics to account for local behavior adjustments. This information along with the new technological approach gives a great precision and understanding of driver decisions with regards to headway acceptance at roundabouts.

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REFERENCES


a) Roundabouts in Carmel, IN

b) Study roundabout at Spring Mill Rd / W 106th St in Carmel, IN with instrumentation shown

Figure 1 Carmel, IN
a) Core drill the hole for the sensor

b) Clear the hole and remove asphalt core

c) Remove debris

d) Torch dry the hole for epoxy

e) Place the magnetometer and epoxy in place

f) Finished installation at yield line

Figure 2  Installation of wireless magnetometer for entering vehicle
Figure 3  Sample volumetric data denoting AM/PM peak trends for Ve at each approach
Table 1 Sample Hi-Resolution Event-Based data from the server

<table>
<thead>
<tr>
<th>SENSOR</th>
<th>STATUS</th>
<th>VEH-ID</th>
<th>CODE</th>
<th>TSTAMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entering</td>
<td>ON</td>
<td>1</td>
<td>E1</td>
<td>09:47:13.0</td>
</tr>
<tr>
<td>Circulating</td>
<td>ON</td>
<td>1</td>
<td>C1</td>
<td>09:47:13.1</td>
</tr>
<tr>
<td>Circulating</td>
<td>OFF</td>
<td>1</td>
<td>C1</td>
<td>09:47:14.2</td>
</tr>
<tr>
<td>Circulating</td>
<td>ON</td>
<td>2</td>
<td>C2</td>
<td>09:47:15.2</td>
</tr>
<tr>
<td>Circulating</td>
<td>OFF</td>
<td>2</td>
<td>C2</td>
<td>09:47:16.0</td>
</tr>
<tr>
<td>Circulating</td>
<td>ON</td>
<td>3</td>
<td>C3</td>
<td>09:47:17.0</td>
</tr>
<tr>
<td>Circulating</td>
<td>OFF</td>
<td>3</td>
<td>C3</td>
<td>09:47:17.7</td>
</tr>
<tr>
<td>Entering</td>
<td>OFF</td>
<td>1</td>
<td>E1</td>
<td>09:47:18.5</td>
</tr>
<tr>
<td>Circulating</td>
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<td>4</td>
<td>C4</td>
<td>10:47:20.2</td>
</tr>
<tr>
<td>Circulating</td>
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<td>4</td>
<td>C4</td>
<td>11:47:20.8</td>
</tr>
</tbody>
</table>

Example Code: “C21” indicates the Circulating sensor for vehicle 2 turned on (1=On/0=Off)

Figure 4 Graphical representation of sensor status based on hi-resolution event-based data
a) Overhead schematic of headway intervals

![Overhead schematic of headway intervals](image)

- Headway_1 = 1.9 sec
- Headway_2 = 1.8 sec
- Headway_3 = 3.2 sec

b) Field collected video verification of timestamped hi-resolution data

![Field collected video verification](image)

Figure 5  Headway acceptance as related to the roundabout
a) North approach

b) South approach

c) West approach

d) East approach

e) Entire roundabout with all approaches

Figure 6  Number of headways analyzed
Figure 7  Distribution of headway rejection times (* Indicates 2.5 second look ahead)
Figure 8  Distribution of headway rejection times

NCHRP Report 572

Average Headway ranges from 4.0 to 5.1 seconds

Rejected Headway Time (Seconds)
Figure 9 Quartile plots of headway rejection times by approach and headway sequence (summary of Figure 8)
a) North approach
b) South approach
c) West approach
d) East approach
e) Entire roundabout with all approaches

Figure 10  Weekday vs. weekend distributions of headway rejection times
a) North circulating sensor

b) East circulating sensor

c) South circulating sensor

d) West circulating sensor

Figure 11  Circulating sensor headway (corollary to saturation)