Driver Behavior and Gap-Acceptance Characteristics at Roundabouts in California

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Critical headway and follow-up headway are two important parameters to perform design and operational analyses at a roundabout. This paper addresses drivers' gap-acceptance behavior characteristics at roundabouts and presents the results of critical headway and follow-up headway measurements at seven single-lane and three multilane roundabouts in California. Results indicate that the mean critical headway is consistent with the values recommended by the newly completed research NCHRP 3-65; however, the follow-up headway is significantly lower than that recommended by NCHRP 3-65. This paper also reveals that circulating flow rate and speed are two major factors affecting critical headway and follow-up headway. Results from this study enhance the existing database related to drivers' gap-acceptance behavior at U.S. roundabouts.

As an emerging intersection control type without signals, roundabouts have been gaining popularity in the United States in recent years (*1*). When design and operational analyses of roundabouts are performed, two major parameters are often involved: critical headway and follow-up headway (referred to as critical gap and follow-up time in earlier studies) (*2*). The accuracy of capacity calculations at roundabouts is dependent largely on the accurate estimation of critical headway and follow-up headway. In addition, critical headway is one major parameter used to calculate intersection sight distance in roundabout design.

Critical headway at roundabouts represents the minimum time interval in the circulating flow when an entering vehicle can safely enter a roundabout. In general, critical headway is a parameter that depends on local conditions such as geometric layout, driver behavior, vehicle characteristics, and traffic conditions (*3*). The recently completed NCHRP 3-65 report (*4*) highly recommends calibration of critical headway and follow-up headway based on local conditions to provide accurate capacity estimates. Most state departments of transportation that have developed guidelines for roundabout design and operations have adopted the recommended critical headway by the FHWA Guide (*5–8*), except Wisconsin (*9*) and Utah (*10*) for which significant deviations are noticed. This paper provides critical headway and follow-up headway measurements obtained from 10 roundabout sites in California.

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The NCHRP 3-65 study produced a new set of critical headway and follow-up headway values based on a comprehensive evaluation of roundabouts throughout the United States. The recommended operational models by NCHRP 3-65 will be incorporated into the next update of the *Highway Capacity Manual* (HCM). Although this NCHRP study contains a significant amount of data (including more than 500 h of video at various roundabout locations), the data do not include any sites from the state of California. As a result, the critical headway and follow-up headway from NCHRP 3-65 may or may not be representative of California conditions. Therefore, the results presented in this paper have significant value for roundabout design and operational analysis in California.

DATA COLLECTION AND ANALYSES

This section presents the details of data collection, data extraction, and critical headway and follow-up headway measurement results and analyses. First, field data collection efforts are described, followed by a discussion of the data extraction process. Based on time events extracted from the videos, measurements of the critical headway and the follow-up headway are conducted.

Field Data Collection

Field data collection involved mainly the videotaping of headway and gap-acceptance characteristics and measurement of geometry and vehicle speeds. Headway data were extracted later in the lab from the recorded videos, and the other field-recorded data were used for analyzing the factors that may affect critical headway and follow-up headway. Table 1 summarizes the data collection sites located in the California cities Truckee, Modesto, Calabasas, Santa Barbara, Long Beach, and Davis. Typically, videos were recorded during weekday peak periods when high traffic volumes could be observed. Speeds of circulating vehicles were recorded for each study leg in the field using a radar gun during the peak hours. The speed was recorded when a circulating vehicle was intending to pass the conflicting point with an entering vehicle.

Of the roundabouts, seven were single-lane and three were multilane facilities. Field observations revealed that most of the single-lane roundabouts were located in residential areas and were used mainly as traffic calming devices with low traffic volumes. Much higher traffic volumes were observed at the three multilane roundabouts. Pedestrian and bicycle use was light at most of the roundabout sites; therefore, the impact of pedestrians and bicyclists on a driver's critical headway and follow-up headway can be ignored.

TABLE 1 Summary of Roundabout Data Collection Sites

City	Site Name	Inscribed Circle Diameter, ft	# of Circulatory Lanes	Date	Length of Video
Truckee	Donner Pass Rd.	120	1	5/20/2006, Sat. 5/30/2006, Tue.	2 h 2 h
	I-80 EB ramps/Hwy. 89	200	2	5/20/2006, Sat. 5/30/2006, Tue.	2 h 2 h
Modesto	Bowen Ave.–Phelps Ave.	60	1	6/12/2006, Mon.	2 h
	La Loma–James St./G St.	70	1	6/13/2006, Tues. 6/13/2006, Tues.	2 h 2 h
Calabasas	Parkway Calabasas–Camino Portal	120	1	6/15/2006, Thur.	3 h
Santa Barbara	Milpas St.–US 101 NB Ramps	150	2	6/15/2006, Thur.	3 h
	Alameda Padre Serra–Salinas	90	1	6/16/2006, Fri.	2 h
Long Beach	Los Alamitos Circle	460	3	6/16/2006, Fri.	2 h
Davis	Anderson Rd.–Alvarado Ave.	95	1	6/18/2006, Sun. 6/20/2006, Tue.	2 h 2 h

Data Extraction

Data extraction involved determining specific time events, which were necessary to define various accepted and rejected headway events needed for critical headway and follow-up headway calculations. Three time events involving an entering vehicle were recorded: the time at which an entering vehicle stopped at the stop line, the passage times of circulating vehicles that directly conflicted with the entering vehicle, and the time when the entering vehicle left the stop line. The passage times of circulating vehicles defined the start and end of major stream headways that were either accepted or rejected by the entering vehicles.

The procedure of extracting video data and measuring critical headway and follow-up headway included the following steps:

Step 1. The time events as defined above were recorded using Traffic Data Input Program (TDIP) computer software. TDIP was developed at the University of Idaho and has been used in several research projects (*4, 11*) for extracting data events from videos. This paper used the same definition of headways as NCHRP 3-65. For a multilane roundabout the mixed traffic flow in all the conflicting lanes is used to define the headways that the entering drivers face.

Step 2. The accepted headways, the maximum rejected headways, and the follow-up headways were extracted from TDIP output using a macro program in Excel developed by the authors.

Step 3. On the basis of the accepted headways and the maximum rejected headways achieved in Step 2, the maximum likelihood methodology (*12*) was used to estimate the driver's critical headway. An 8-s headway was considered as the upper threshold for the driver's acceptable headways. Any accepted headways greater than 8 s were set to 8 s. The average follow-up headways were directly calculated by the macro program using the output of Step 2.

Critical Headway Measurements

The maximum likelihood methodology was used to estimate the critical headway. Critical headway cannot be obtained directly from the recorded time events. The maximum likelihood methodology provides an estimate of the average critical headway of all the drivers by assuming that a single driver's critical headway ranges between his or her largest rejected headway and the accepted headway. The rejected and the accepted headways were obtained directly from the recorded time events. Two gap acceptance cases were identified: Case 1, observations of drivers who rejected at least one gap before entering the roundabout, and Case 2, observations of drivers who accepted a lag without rejecting any gap. The majority of headway acceptance cases fell in the Case 1 category. This study counted only the vehicles of Case 1.

Results of the critical headway measurements of all the single-lane sites are summarized in Table 2. It can be seen that the critical headway varies between 4.5 and 5.3 s, with a mean value of 4.8 s. These critical headway values are within a range similar to that reported by NCHRP 3-65. Detailed comparisons are discussed later in this paper.

For a multilane roundabout, headway events can be measured using two methods. One method assumes that drivers in the right entry lane yield only to the physically conflicting vehicles in the outermost circulatory lane, and the driver in the left entry lane yields to the combination of conflicting vehicles in the inner and outer circulatory lanes (*13, 14*). An alternative method combines all conflicting vehicles in the circulatory lanes into a single conflicting traffic flow, assuming that an entering driver must wait for a gap among all

TABLE 2 Critical Headway Results at Single-Lane Roundabout Sites

	Critical Headway	
Site ID	Mean (s)	Standard Deviation (s)
CA01-S	4.7	1.1
MO02-S	5.3	1
MO03-S, a.m.	4.8	1.3
MO03-S, midday	5	1.1
TR01-W	5	1.1
SB02-NW	4.5	0.9
DA01-E	4.7	1
Average	4.8	1.1

TABLE 3 Critical Headways at Multilane Roundabouts

Site ID		Critical Headway Mean (s)	Critical Headway Standard Deviation (s)
SB01-NW	Left lane	4.8	1.1
	Right lane	4.5	1
TR02-S	Left lane	5.1	1.1
	Right lane	4.8	0.9
LB01-W	Left lane	4.4	0.9
	Right lane	4	1.1
Average	Left lane	4.7	1
	Right lane	4.4	1

conflicting vehicles. This paper used the second method to combine circulating traffic flows and assumed all the conflicting vehicles had an influence on entering drivers' behavior. NCHRP 3-65 used the same method.

Table 3 summarizes the critical headway results for the three multilane sites. As can be seen, the critical headway for the left lane varies between 4.4 and 5.1 s with a mean value of 4.7 s, and the critical headway for the right lane varies between 4.0 and 4.8 s with a mean value of 4.4 s. The critical headway is slightly higher in the left lane than that in the right lane, which is consistent with results from NCHRP 3-65.

Follow-Up Headway Measurements

Unlike for critical headway estimation, follow-up headways were obtained directly from recorded time events. By definition, follow-up headway is the minimum headway between two entering vehicles, which can be calculated by the average difference between the passage times of two entering vehicles accepting the same mainstream headway under a queued condition. Once the individual follow-up headway is obtained, the average and the standard deviation can be calculated.

Table 4 is a summary of the follow-up headway results at the single-lane roundabout sites; the mean value, standard deviation, and sample size are listed for each site. The largest follow-up headway of 2.8 s is observed at Site DA01 in Davis, which is a compact roundabout in a residential area. The smallest follow-up headway of 2.3 s is observed at Site MO03 in Modesto, which is located in the downtown area. The average for all sites is 2.5 s, which is smaller than the average follow-up headway obtained in NCHRP 3-65.

Table 5 summarizes the average follow-up headway at the three multilane roundabouts. The follow-up headway in the left lane varies between 1.8 and 2.7 s, and the follow-up headway in the right lane ranges between 2.1 and 2.3 s. A mean value of 2.2 s was obtained for the follow-up headways in both lanes.

CALIFORNIA DRIVERS' GAP-ACCEPTANCE BEHAVIOR ANALYSES

In this section the estimated critical headway and follow-up headway are compared with those from other studies. Identification and analysis of other factors affecting critical headway and follow-up headway are also provided.

Comparison with Other Studies

The results of this study have been analyzed and compared with data from other sources, including additional data reported in NCHRP 3-65 from sites in the United States, Germany, and France and guidelines from the HCM. Table 6 summarizes the critical headway and follow-up headway values from these different sources.

The following observations are made, based on the data shown in Table 6:

- The critical headway of California's sites is similar to that of other U.S. sites.
- The critical headways and follow-up headways used in the HCM and in Germany have similar values, but are generally smaller than those obtained from this research and other studies.
- The follow-up headways from this research are very similar to those used in France; however, they are generally smaller than that reported in the NCHRP 3-65 report.

Statistical analyses are conducted to determine whether California drivers have critical headway and follow-up headway statistically different from other states in the United States reported in the NCHRP 3-65 study. Figure 1 shows the comparison and statistics of critical headways at the single-lane roundabout sites. There are 16 data points from the NCHRP 3-65 study, representing the critical headways from 16 different sites (10 from Washington, three from Maryland, two from Maine, and one from Oregon). The 95%

TABLE 4 Follow-Up Headway Results at Single-Lane Roundabouts

Site ID	Mean of Follow-Up Headways (s)	Standard Deviation of Follow-Up Headways (s)	Sample Size
CA01-S	2.4	0.6	55
MO02-S	2.4	0.3	5
MO03-S, a.m.	2.3	0.7	14
MO03-S, midday	2.6	1	58
TR01-W	2.5	0.8	20
SB02-NW	2.3	0.7	63
DA01-E	2.8	0.7	15
Average	2.5	0.7	Total = 230

TABLE 5 Follow-Up Headway at Multilane Roundabouts

Site ID	Average Follow-Up Headway (s)	SD of Follow-Up Headway (s)	Sample Size
SB01-NW, left lane	2.7	0.9	109
SB01-NW, right lane	2.3	1	117
TR02-S, left lane	1.8	0.7	27
TR03-S, right lane	2.1	0.9	59
LB01-W, left lane	2.2	0.6	125
LB01-W, right lane	2.1	0.7	75
Average			
Left lane	2.2	0.7	Total = 261
Right lane	2.2	0.8	Total = 251

TABLE 6 Critical Headway and Follow-Up Headway from Different Sources

	Critical Headway (s)		Follow-Up Headway (s)	
Source	One Lane	Two Lane	One Lane	Two Lane
HCM	4.1 to 4.6	N/A	2.6 to 3.1	N/A
Germany[a]	4.4	4.4	3.2	3.2
France[a]	N/A	N/A	2.1	2.1
NCHRP 3-65				
Left lane	4.2 to 5.9 (5.1[b])	4.2 to 5.5 (4.5)	2.6 to 4.3 (3.2)	3.1 to 4.7 (3.4)
Right lane		3.4 to 4.9 (4.2)		2.7 to 4.4 (3.1)
California				
Left lane	4.5 to 5.3 (4.9)	4.4 to 5.1 (4.8)	2.3 to 2.8 (2.5)	1.8 to 2.7 (2.3)
Right lane		4.0 to 4.8 (4.4)		2.1 to 2.3 (2.2)

[a]German and French results are from NCHRP 3-65 final report.
[b]Numbers in ( ) indicate the average value.

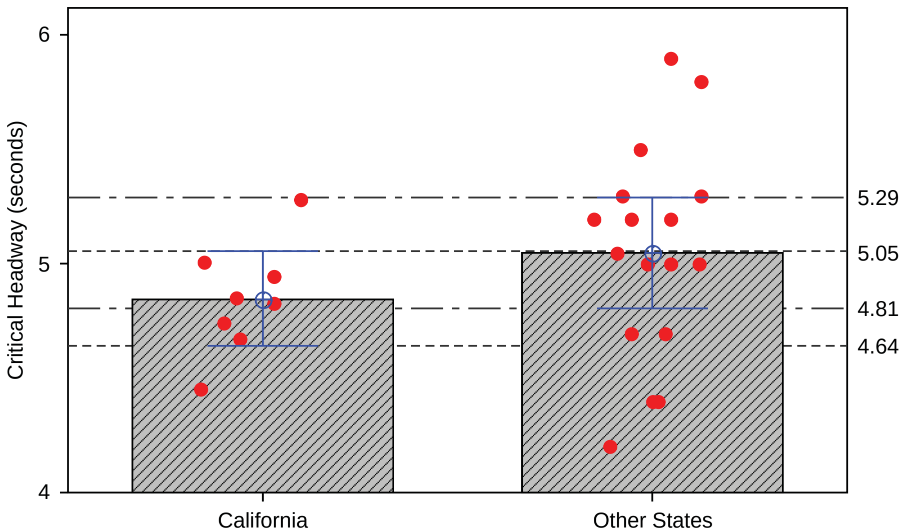

FIGURE 1 Comparison of critical headways at single-lane roundabouts in California with those in other states.

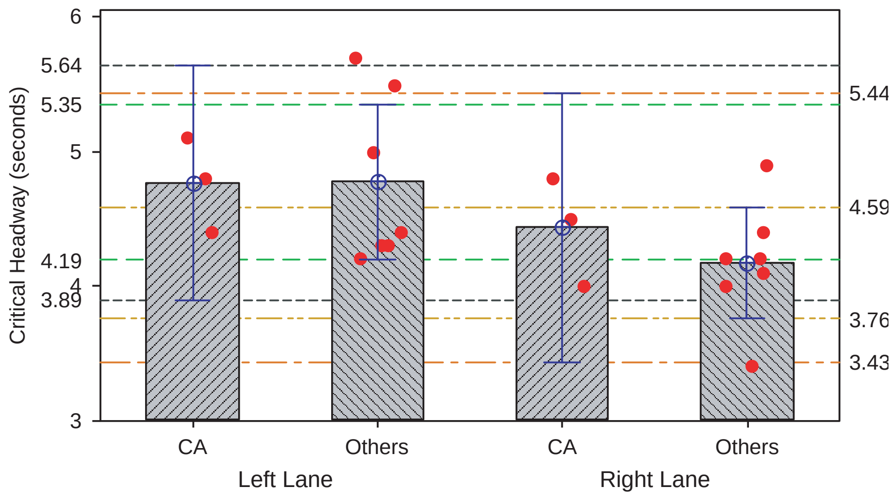

FIGURE 2 Comparison of critical headways at multilane roundabouts in California with those in other states.

confidence intervals are also plotted. Using confidence intervals for different populations is one of the means of conducting hypothesis tests in statistics. If the confidence intervals overlapped each other, it means there is no statistically significant difference between the mean values of the two populations. As shown in Figure 1, the 95% confidence interval of the California sites is (4.64, 5.05), and the 95% confidence interval of other states is (4.81, 5.29). Because there is an overlap between the two confidence intervals, it can be concluded that there is no statistically significant difference between the critical headways of California and other states.

Figure 2 shows the comparisons of critical headways at the multilane roundabout sites, with the headways for the left and right lanes shown separately. There are seven data points from the NCHRP 3-65 report, representing the critical headways from seven different sites (three from Maryland, three from Vermont, and one from Washington). Although slightly different mean critical headway values are observed, there is no statistically significant difference between the left lanes and the right lanes in California compared with those of other states, as indicated by the overlapping of the 95% confidence intervals.

Figure 3 shows the comparisons of the follow-up headways at the single-lane sites. There are 18 data points from the NCHRP 3-65 study, representing the average follow-up headways from 18 different sites (11 from Washington, three from Maryland, two from Maine, one from Michigan, and one from Oregon). As indicated by the 95% confidence intervals in the figure, California's follow-up headway is statistically significantly lower than that of other states. The mean follow-up headway in California is 2.4 s, and the mean follow-up headway in other states is 3.3 s.

Figure 4 compares the follow-up headways at the multilane sites, listed by lanes. There are seven data points from the NCHRP 3-65 study, representing the average follow-up headways from seven different sites (three from Maryland, three from Vermont, and one from Washington). As indicated by the 95% confidence intervals in the figure, California has a significantly lower follow-up headway

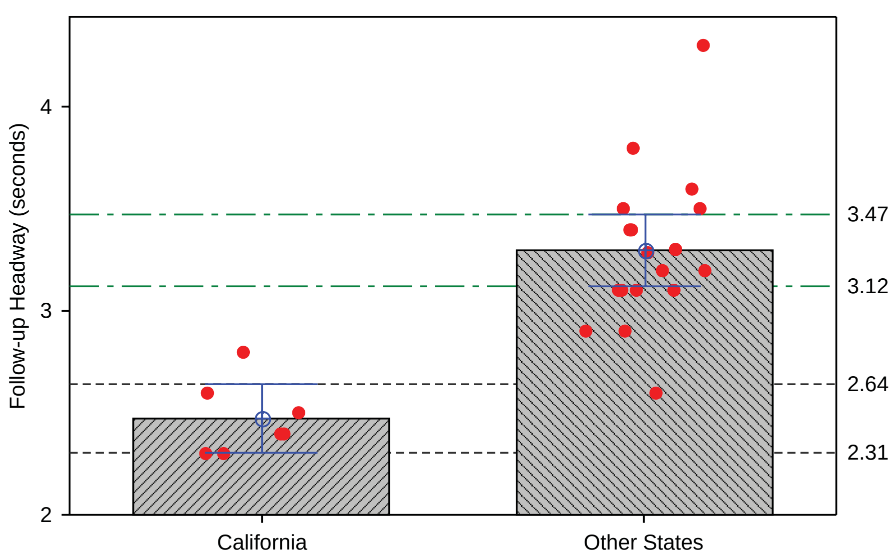

FIGURE 3 Comparison of follow-up headways at single-lane roundabouts in California with those in other states.

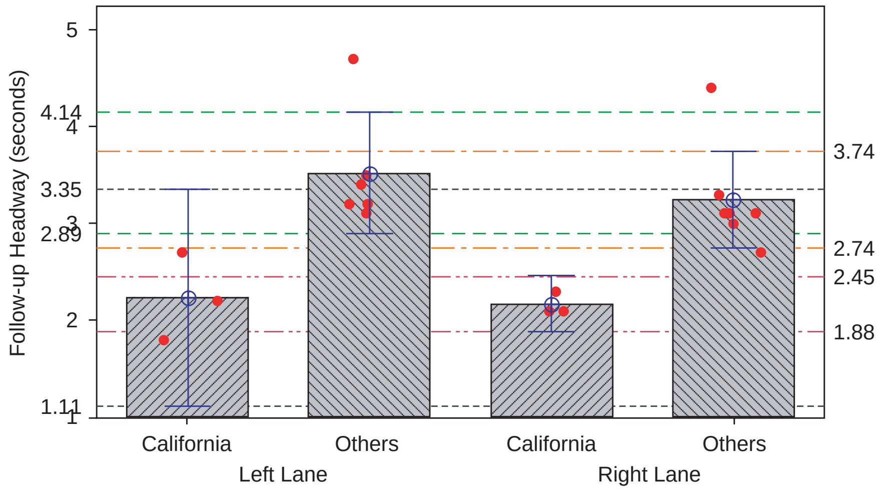

FIGURE 4 Comparison of follow-up headways at multilane roundabouts in California with those in other states.

than that of other states. Although the follow-up headway in the left lane does not show a statistically significant difference from other states, it may be due to the smaller number of samples in California for which the high variance is noticed.

Analyzing Factors Affecting Critical Headway and Follow-Up Headway

An investigation was conducted to determine the factors that may affect critical headway and follow-up headway. Previous studies have indicated that the conflicting volume and vehicle speed might affect driver's behavior at the minor traffic stream. For example, on the basis of the research in Australia (*15*), the follow-up headway at single-lane roundabouts is related to roundabout size (inscribed circle diameter) and circulating flow rate. Higher circulating flow rate resulted in much smaller follow-up headways. At low circulating flow rates the follow-up headway varied between 2.27 and 2.99 s when the inscribed circle diameter was between 60 and 240 ft. The follow-up headway was as low as 1.7 s when the circulating flow approaches 1,500 vehicles per hour (veh/h). At two-lane roundabouts with the circulating flow rate of 2,500 veh/h, the follow-up headway was as low as 1.3 s. NCHRP 3-65 reported a moderate inverse correlation between critical headway and conflicting flow rate, suggesting that the critical headway tended to decrease with an increase in conflicting flow rate. The significant influence of inscribed diameter on critical headway and follow-up headway was not observed in this paper, as shown in Table 7.

With the California data, a simple correlation analysis was applied to investigate whether the conflicting flow and the speed have any effect on critical headway and follow-up headway. This research used correlation coefficient to investigate the linear relationship between each pair of attributes by assuming that a value near 0 indicates poor linear correlation between attributes and a correlation value near +1 or –1 indicates a high level of linear correlation. The *P*-value is also used for the hypothesis test of the correlation coefficient being zero. Results of the correlation analyses are presented in Table 8.

From Table 8, the critical headway and conflicting flow had moderate negative correlation (–0.522), with a *P*-value of 6.7%, which is slightly above the normally acceptable 5% significance level. This may be characterized as marginally significant. This means that critical headway and conflicting flow had a weak inverse linear relationship; the increase in conflicting flow might result in a decrease in the critical headway as illustrated in Figure 5. Table 8 also indicates that the correlation between follow-up headway and conflicting flow was weak (correlation coefficient of –0.037 and *P*-value of .905). This is also indicated in Figure 5 in which the follow-up headway was not sensitive to the conflicting flow.

The speed of the circulating traffic had a negative correlation (–0.447) with the critical headway, indicating the circulating speed did affect critical headway, but a linear correlation between the two

TABLE 7 Influence of Inscribed Circle Diameter at Single-Lane Roundabouts

City	Site Name	Inscribed Circle Diameter, ft	Critical Headway(s)	Follow-Up Headway(s)
Modesto	Bowen Ave.–Phelps Ave.	60	5.3	2.4
Modesto	La Loma–James St./G St.	70	4.9	2.5
Santa Barbara	Alameda Padre Serra–Salinas	90	4.5	2.3
Davis	Anderson Rd.–Alvarado Ave.	95	4.7	2.8
Truckee	Donner Pass Rd.	120	5	2.5
Calabasas	Parkway Calabasas–Camino Portal	120	4.7	2.4

TABLE 8 Results of Correlation Analysis

Parameter	Critical Headway	Follow-Up Headway
Conflicting flow		
Pearson correlation	–0.522	–0.037
P-value	.067	.905
Circulating speed		
Pearson correlation	–0.447	–0.684
P-value	.126	.01

parameters is weak (*P*-value of 0.126). The speed of the circulating vehicles had a negative correlation to follow-up headway (–0.684), and the linear correlation was strong (*P*-value of 0.01). As shown in Figure 6, an increase in speed will most likely result in a decrease in critical headway and follow-up headway. That is consistent with observations in the field. At a roundabout with high circulating speed (e.g., Long Beach, LB01-W), the entering driver cannot find a large headway easily and tends to accept a smaller one. This results in a smaller critical headway than that of other sites.

Field observations also revealed that exiting vehicles were another potential factor affecting critical headway and follow-up headway; however, no data were available yet to draw any quantitative conclusions.

SUMMARY AND CONCLUSIONS

This paper presents the results of critical headway and follow-up headway measurements at 10 roundabout sites in California. The paper includes detailed information of field data collection, data extraction, and the procedures used to extract headway events and measurements of critical headway and follow-up headway. The maximum likelihood methodology was used to estimate critical headways, and the follow-up headways were obtained directly from the extracted time events. Comparisons were made between the headway results from this research and those from other resources. Analyses of the factors affecting critical headway and follow-up headway were also conducted, including the flow rate and speed of circulating vehicles. Major findings and conclusions from this research are summarized below.

Critical headway at the single-lane roundabouts in California was found to vary between 4.5 and 5.3 s, with a mean of 4.9 s. At multilane roundabouts, critical headway ranged between 4.4 and 5.1 s in the left lane and 4.0 and 4.8 s in the right lane. The average critical headways for the two lanes were 4.8 and 4.4 s, respectively. These critical headway values were within the range of that reported in the NCHRP 3-65 study. Statistical analyses did not show a significant difference between the critical headway values in California and in other states.

A total of 742 individual follow-up headways were collected at the 10 roundabout sites, among which 230 were from single-lane sites and 512 were from multilane sites. The mean follow-up headway was 2.5 s at the single-lane sites. For multilane sites, the mean follow-up headway was 2.2 s for the left and the right lanes. These follow-up headways were statistically different from those obtained in other states as reported by NCHRP 3-65 report.

The conflicting flow rate and speed were found to have a negative correlation with critical headway and follow-up headway, which means that with an increase in conflicting flow, speed, or both, the critical headway and follow-up headway tend to decrease. However, results from the correlation analyses indicate that the correlation between speed and follow-up headway was the strongest, and the correlation between conflicting flow and follow-up headway was the weakest.

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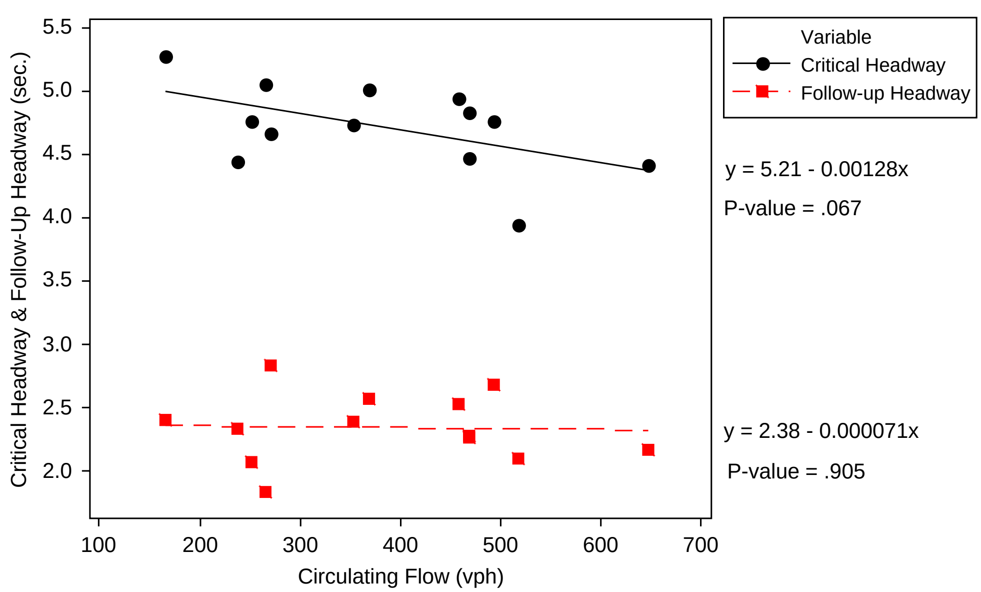

FIGURE 5 Critical headway and follow-up headway as a function of circulating flow.

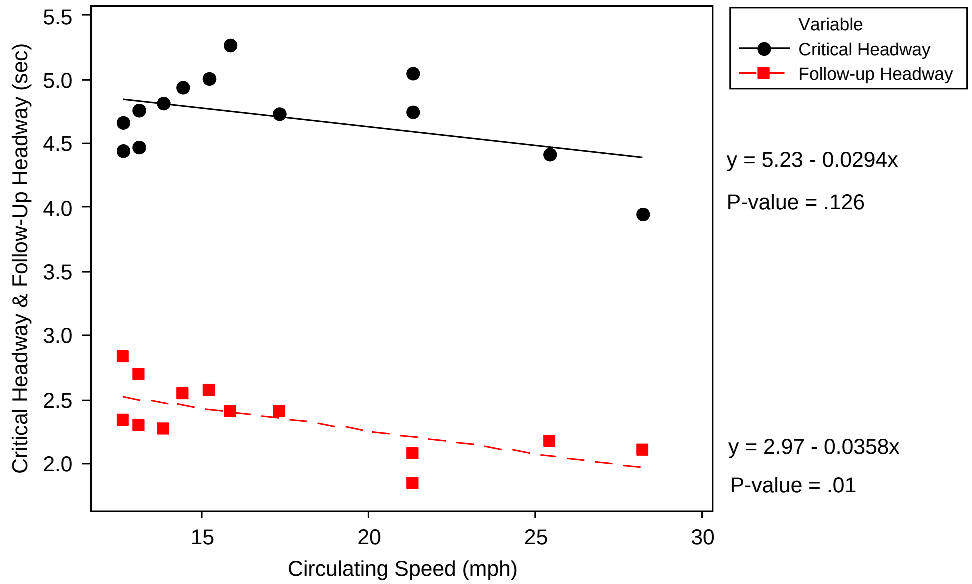

FIGURE 6 Critical headway and follow-up headway as a function of circulating speed.

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