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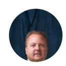
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ABSTRACT

VISSIM roundabout models have been widely applied in practice to facilitate analyzing the operational performance of roundabouts. To prepare a VISSIM roundabout model for analysis, an essential prerequisite is to calibrate the model by adjusting parameters until real-world roundabout operations are reproduced in the simulation model. Previous calibration research has used qualitative analysis to study the impact of VISSIM parameters on roundabout capacity. Comprehensive calibration guidelines, parameter values based on field data, and quantitative sensitivity analyses of parameters are necessary to facilitate accurate modeling of roundabouts. This paper addresses these important needs. Speed trajectories of free-flow entering vehicles were collected in the field using a radar sensor. Analysis identified that the approach to a roundabout entrance can be divided into four speed zones reflecting different stages of drivers' deceleration maneuver. Location, length, speed distribution, and deceleration rate parameters for the VISSIM Reduced Speed Areas (RSA) were determined through the analysis of the radar data. Comparisons between Conflict Areas (CA) and Priority Rules (PR) were also investigated, and revealed that using PR can result in more consistent and repeatable gap acceptance behavior. In addition, the impact of VISSIM parameters on critical gap and follow-up headway was quantitatively analyzed through sensitivity analysis of minimum gap for PR, speed distribution and deceleration rate for RSA, and additive and multiplicative settings for the Wiedemann 74 model. Numerical recommendations for calibrating VISSIM roundabout models were ultimately developed, and validated via a case study.

INTRODUCTION

In recent years, as many intersections in the U.S. have been converted to, or originally built as roundabouts, analyzing roundabout operations and safety has drawn extensive attention from practitioners and researchers. Most commercial microscopic traffic simulation software packages offer the capability of building roundabout simulation models. VISSIM roundabout models have been heavily discussed as one of the most widely applied microscopic simulation packages for modeling roundabouts (*1-12*). In order for a simulation model to provide useful output, an essential prerequisite is to prove that the established simulation model can accurately mimic real-world traffic operations. In other words, the simulation model has to be calibrated through adjusting model parameters and be validated through comparison with field ground truth data before the model can be used for analysis.

Previous studies have summarized that the settings of three elements in VISSIM have critical impact on the operational performance of roundabout simulation models (*3-5, 9-12*). These elements include: (1) Priority Rules (PR) or Conflict Areas (CA), which control the yielding logic; (2) Reduced Speed Areas (RSA), which provide temporary speed control over a short roadway distance; and, (3) Wiedemann 74 and 99 car following models, which can fine-tune the simulated car-following behavior.

Much research has been conducted to explore methods for calibrating VISSIM roundabout models. The primary method of calibration was repeatedly adjusting parameter settings of VISSIM elements until a calibration goal was reached (*3-5*, *9-12*). The typical calibration goal used in previous studies was to match the capacity curve obtained from the simulation model to the field-observed capacity curve (*3-5*), while some other studies matched simulated travel time or speed to field data (*10-12*). Most of these studies focused on different VISSIM settings for calibration. Only a few studies investigated using field collected data as input into the roundabout simulation model with regard to calibration, and discussed the model validation using field data. In summary, previous research has not adequately fulfilled the need for comprehensive calibration guidelines, recommended simulation parameter values based on field data, or in-depth sensitivity analyses that quantify the impact of changing various VISSIM parameter settings on simulated capacity.

In this context, the objective of the paper is two-fold: (1) quantitatively investigate the sensitivity of change of roundabout capacity under different settings of VISSIM elements; and, (2) provide quantitative guidance on selection of VISSIM elements during the calibration process, and recommend field-estimated parameter values for calibration.

LITERATURE REVIEW

The earliest documented study on calibration of VISSIM roundabout models was a paper back in 2003, in which Trueblood and Dale gave a good overview of the basics of how VISSIM works with regards to modeling single and multilane roundabouts (*2*). However, most information provided was qualitative. Particularly, the validation of PR settings was based on trial and error only by viewing the animation file produced by VISSIM (*2*). Instead of PR, Schroeder investigated CA in his study, and described a methodology for calibrating the roundabout simulation model through sensitivity analysis of CA's gap parameters (*3*). Schroeder's sensitivity analysis gives qualitative results of the impact on the intercept and slope of the capacity curve when changing the inputs of various VISSIM parameters. Schroeder's analyses were based on one simulation run per experiment with varied volume inputs during different periods of the experiment. Although this single run approach can save calibration time (*3*), fewer observations were collected than in other studies (*4*), and circulating flows above 1400 veh/hr were not obtained.

Cicu et al. used PR to model a two-lane roundabout in VISSIM (*5*). No sensitivity analysis was conducted. The major contribution of this study is that researchers tried to find proper parameter estimates using field-collected data, including critical gap and speed. However, only the simulation output capacity was compared with the capacity curve recommended by National Cooperative Highway Research Program (NCHRP) Report 572 (*6*). Validation may have been stronger if they had compared the capacity output from the calibrated VISSIM model to field-observed capacity.

Wei et al. experimented with both PR and CA in VISSIM (*4*) and concluded that both can be applied in VISSIM roundabout models. However, they mentioned that CA can occasionally produce situations where a circulating vehicle yields to an entering vehicle (*4*). Multiple runs with different random seeds were used (*4*). Wei et al. analyzed the impact of VISSIM parameters on critical gap, follow-up headway, and eventually the capacity curve, although the method of estimating critical gap and follow-up headway was not discussed in detail. The results were mostly limited to the qualitative level by only describing whether an increasing or decreasing trend was observed. Also, the selection of parameter values was based on the default values recommended by VISSIM rather than from field observations. Overall, the study is one of the most comprehensive studies with regard to VISSIM model calibration in the literature. Wei et al. finally suggested that in future research more detailed investigation into critical gap and follow-up headway should be conducted (*4*).

From a methodology perspective, Duong et al. developed a general framework for any simulation model calibration, including VISSIM (*7*). Duong et al. used time to collision (TTC), rather than the capacity, as the performance measure to calibrate a roundabout simulation model, which made the methodology more appropriate for model calibration from a safety perspective.

In addition to the aforementioned research efforts, which were dedicated to VISSIM roundabout model calibration, other studies were conducted using VISSIM roundabout simulation models. Bared and Afshar investigated roundabout capacity using a multilane roundabout model in VISSIM (*8*). No calibration of the simulation model was mentioned in the paper. Fortuijn investigated capacity for turbo roundabouts using VISSIM (*9*). Calibration was achieved by modifying the Wiedemann car-following model and PR to achieve a fit between the distributions of accepted gaps, rejected gaps, follow-up headways, and headways in circulating traffic. Valdez et al. investigated roundabout delay with unbalanced approach volumes using a two lane roundabout from the NCHRP Report 572 dataset coded in VISSIM (*10*). Calibration was performed by adjusting the CA gap times until the travel time distribution in VISSIM matched the travel time distribution of the field data. Gallelli and Vaiana also conducted research on delay with VISSIM by evaluating the effects of roundabout geometry on delay (*11*). In another study conducted by them, the simulation model was calibrated by using speed as the performance measure (*12*). Gagnon et al. investigated the calibration abilities of different software packages, including PARAMICS and VISSIM (*13*). Al-Ghandour et al. used the VISSIM roundabout model to develop conflict models to predict crashes at single-lane roundabouts (*14*). Lu et al. studied the impact of the pedestrian crosswalk on the capacity of a roundabout using VISSIM simulation (*15*).

In summary, although considerable research has been conducted on VISSIM roundabout models, there is still a lack of a comprehensive calibration guideline with quantitative recommendations on the selection of different parameter values in term of calibrating VISSIM roundabout models.

METHODOLOGY

Data Collection

Field data collection is of great importance to provide reasonable field estimates for VISSIM parameters as well as observed ground truth capacity data. The chosen study site was a congested two-lane roundabout in De Pere, Wisconsin. As shown in the top portion of Table 1, the De Pere roundabout is located at the intersection of State Trunk Highway 32 and 57.

Video cameras were set up in field to capture vehicle events including arrival, entry, and exit, as well as conflicts between entering and circulating vehicles of the NB and EB approaches. Based on the recorded time stamps of these events, one-minute circulating, and entering flow, as well as critical gap and follow-up headways were then derived. Specifically, the estimation of critical gaps was based on the maximum likelihood (ML) method (*16-18*), assuming that the critical gap follows a log-normal distribution. As a result, the top portion of Table 1 summarizes the observed critical gaps and follow-up headways for passenger car and heavy vehicles for the NB approach, which is the major study approach of this research due to its high congestion level.

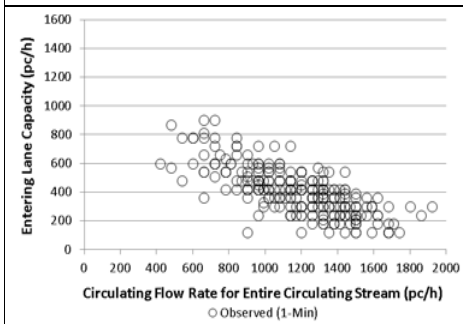
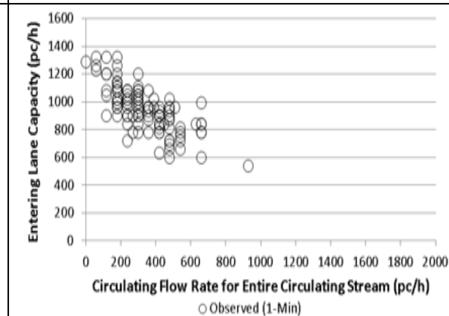
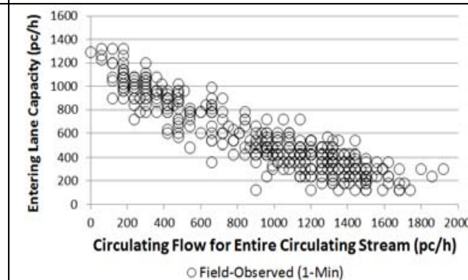
The middle portion of Table 1 summarizes the capacity data collected at the left lanes of the NB and EB approaches of the De Pere roundabout. All capacity data are 1-minute-based, and were collected under queuing conditions and then converted to passenger car equivalent using the conversion factor of one heavy vehicle equivalent to two passenger cars. Due to the traffic pattern at the roundabout during the data collection period, no circulating flows below 400 pc/hr were observed at the NB left lane, while no circulating flows above 1000 pc/hr were observed at the EB left lane. Since the validation of a roundabout simulation model requires the ground truth capacity data to have a full range of circulating flows, all capacity data from EB (low circulating flows) were merged into the NB capacity data in order to prepare a complete dataset of ground truth capacity, as shown in the right middle portion of Table 1. The merge is based on the fact that the EB left lane has similar critical gap and follow-up headway with the NB left lane.

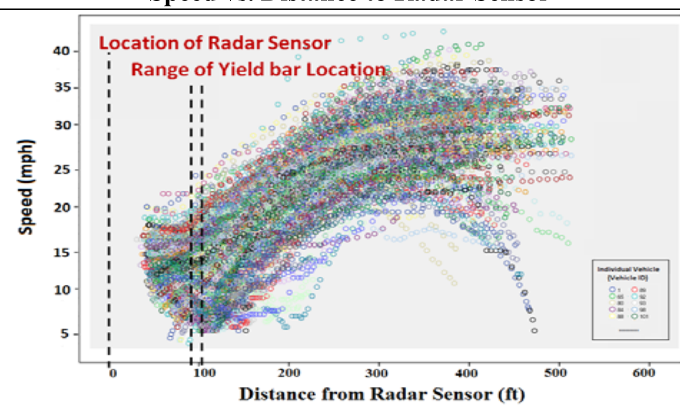
In addition to the capacity and gap acceptance data, free-flow speed data were collected at a roundabout approach in Oshkosh, WI using a microwave radar sensor. The purpose of collecting the speed data is to provide field estimation for input parameters of the RSAs in VISSIM. This roundabout approach was selected for speed data collection because it has similar entrance 85th percentile speed with that of the De Pere roundabout. Also, there is no horizontal curve on the approach to the roundabout (upstream of the roundabout). Hence, the geometric effect on the speed is minimized. The radar sensor scanned the approaching traffic every 0.3 sec covering distances up to 500 feet from the sensor. The corresponding location and speed data were recorded. Note that all data pertaining to the non-free-flow vehicles, which are vehicles that stopped during the entire course of approaching and entering the roundabout, were dropped during the data reduction process. The bottom portion of Table 1 shows the observed speed profiles of free-flow entering vehicles. The mean and 85th percentile entry and upstream speeds of a total of 539 observed free-flow vehicles are summarized in the bottom portion of Table 1.

TABLE 1 Summary of Field Collected Data

Top Portion	Acceptance Data		NB Left Lane n*	NB Left Lane t_c^* (s)	NB Left Lane n	NB Left Lane t_f^* (s)	NB Right Lane n	NB Right Lane t_c (s)	NB Right Lane n	NB Right Lane t_f (s)
		Passenger Car	648	4.3 (1.0)	638	3.1 (1.2)	428	3.6 (0.9)	406	3.0 (1.2)
		Truck	58	5.2 (1.2)	36	3.7 (1.2)	15	4.8 (2.0)	15	3.4 (0.8)

* *n denotes the sample size; t_c denotes critical gap; t_f denotes follow-up headway; ()denotes standard deviation.*

Middle Portion	Capacity Data	Critical Lane (Left Lane)	NB	EB	Combined
					

Bottom Portion	Speed Data	Free-Flow Entering Vehicles (0.3 s-based data)	Speed vs. Distance to Radar Sensor
			

Statistics of Free-flow Entering Vehicles	
Sample Size (veh)	539
Mean Upstream Free-flow Speed (mph)	28.7
85th Percentile Upstream Free-flow Speed (mph)	32.0
Mean Entry Free-flow Speed (mph)	12.1
85th Percentile Entry Free-flow Speed (mph)	16.0

Critical Gap and Follow-up Headway Based Sensitivity Analysis

Most previous studies used capacity curve based sensitivity analysis when exploring the calibration guidelines for VISSIM roundabout model. Typically, the output capacity cloud from VISSIM (i.e., dots representing entering flow versus circulating flow) or the cloud's regression curve was used as the only performance measure in the sensitivity analysis. Due to the fact that the capacity cloud is a distribution, most results of these sensitivity analyses were hard to quantify other than qualitatively describing the change of the capacity curve's intercept and slope.

According to the Highway Capacity Manual 2010, the capacity of the critical lane of a multilane roundabout is an exponential function of critical gap (t_c) and follow-up headway (t_f), as expressed by the following equation (*19*).

$$C_{pce} = Ae^{(-Bv_c)}$$
$$A = \frac{3600}{t_f} \quad (1)$$
$$B = \frac{t_c - (t_f / 2)}{3600}$$

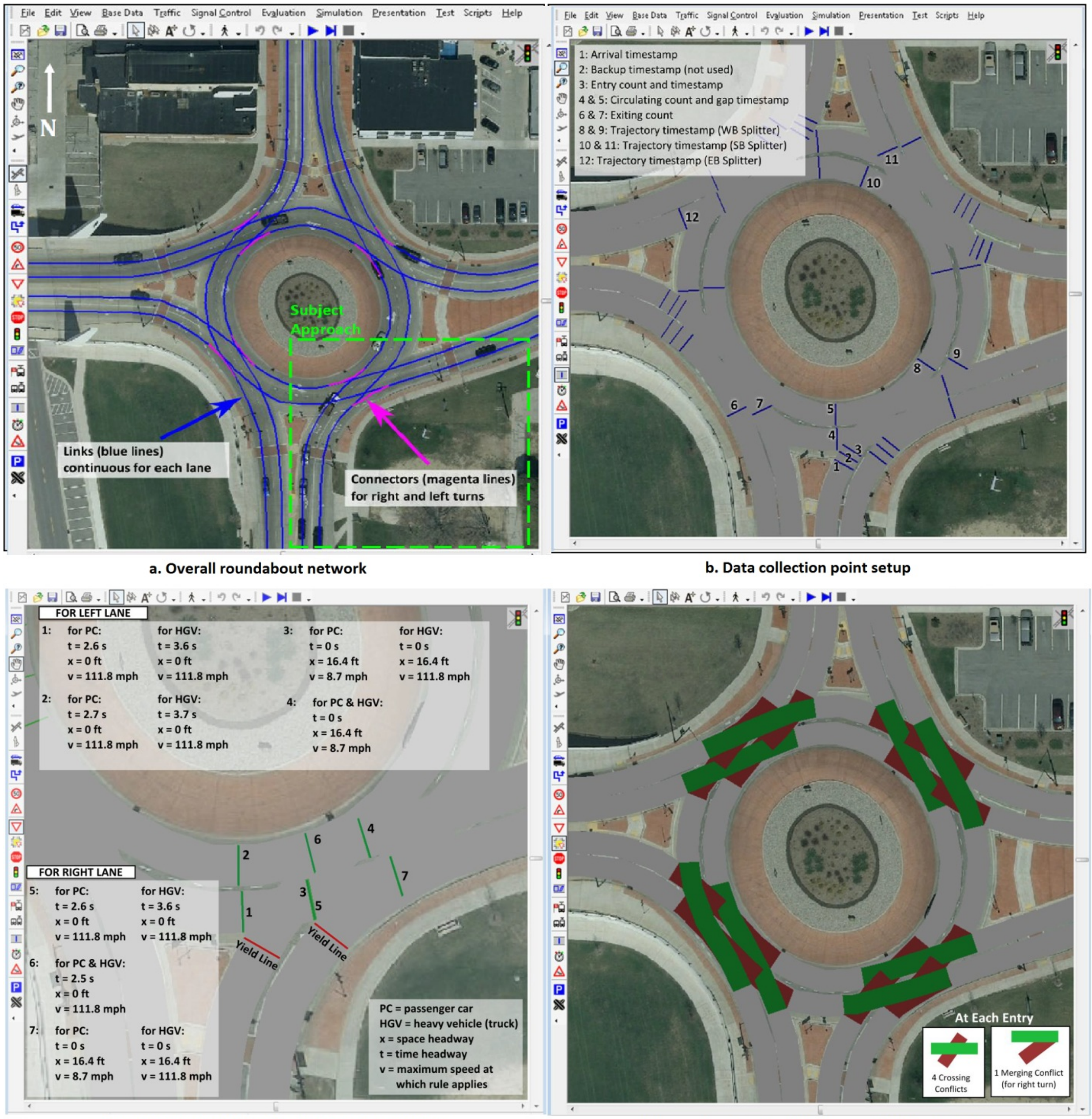
Where, C_{pce} = lane capacity, passenger car equivalent (pc/hr)
v_c = conflicting flow (pc/hr),
t_c = critical gap (s), and,
t_f = follow-up headway (s) .

Since t_c and t_f are the only parameters of the capacity model, the roundabout capacity can hence be simply determined by these two parameters. Considering that t_c and t_f are much easier to describe quantitatively than the capacity cloud, they are a better quantitative performance indicator in sensitivity analysis, replacing the traditional capacity cloud. Based on this fact, in this research, t_c and t_f were estimated from VISSIM's output data using similar methods as used in field data collection. They were used as the major performance measure in the sensitivity analysis and the calibration process.

Setup of the Roundabout Model in VISSIM

As shown in Figure 1.a, the De Pere roundabout model was coded in VISSIM based on its aerial map. The desired speeds for all links were set to a distribution ranging from 22 to 36 mph, with 26 mph and 29 mph as the 50th and 85th percentile speeds, which matched expectations for a 25 mph speed limit. Figure 1.b illustrates the locations of the data collection points that were placed to facilitate collection of traffic flow data as well as timestamps of vehicles' gap acceptance events. The timestamps were used to estimate the critical gap and follow-up headways.

In order to investigate the performance difference between PR and CA, two default network scenarios using PRs and CAs were created. One used PRs and the other used CAs to define the yielding logic. All other VISSIM parameters were identical. In all cases, the NB approach was used for the study approach, and data from the left lane was specifically chosen for sensitivity analysis. Figure 1.c shows the layout of the PRs defined for the NB study approach, using the priority rule settings recommended in the VISSIM User's Manual (*20*). One exception is that the setting of the minimal gap for the right lane was changed to 2.5 sec from the recommended 1.8 sec to obtain more realistic yielding behavior. Note that all these default settings were temporary, and were changed in the sensitivity analyses, which are to be discussed in detail in the following section.



a. Overall roundabout network

b. Data collection point setup

c. Scenario using Priority Rules with default settings

d. Scenario using Conflict Areas with default settings

FIGURE 1 VISSIM roundabout model setup.

All simulation experiments performed in this research were based on simulation runs of 1800 sec (30 minutes) at a resolution of 10 time steps per simulation second. A five minute warm-up time was included in each run to allow traffic to stabilize before collecting data between 300 sec and 1,800 sec (25 minutes). Each run was used to obtain the entering flow under one regime of circulating flow. A total of fifteen flow regimes were used to generate data throughout a range of practical circulating flows, with 10 simulation runs using different random seeds per regime, resulting in a total of 150 simulation runs per experimental trial. The first two flow regimes correspond to circulating flows of 25 veh/hr/ln and 100 veh/hr/ln, respectively. For each subsequent regime, 100 veh/hr/ln were added starting from flow regime #3. Flow regime #15 has a circulating flow of 1400 veh/hr/ln.

Because the NB approach was selected as the study approach, the entry volume demand of NB was fixed at 2500 veh/hr in each lane to ensure that there was always sufficient entering demand at this approach. The circulating flow was only from the EB approach (adjacent entry) to allow an easy control of circulating flow rate. Considering that VISSIM provides options to model the operations of cars and heavy vehicles separately, such as establishing separate PRs and reduced speed areas, the critical gaps and follow-up headways for cars and heavy vehicles can therefore be calibrated separately. Based on this consideration, all simulation runs in this research used vehicle composition of 100% passenger cars in order to simplify the process of exploring the calibration approach. The difference between cars and heavy vehicles is that the heavy vehicles have larger critical gaps and follow-up headways. Therefore, the calibration recommendations developed based on cars can be simply used for calibrating heavy vehicles by setting the calibration goals of longer critical gaps and follow-up headways.

Method for Estimating Critical Gap and Follow-up Headway in VISSIM

Gaps were calculated as the time difference between timestamps of vehicles crossing data collection points 4 and 5 as shown in Figure 1.b. Locations of points 4 and 5 matched the PR conflict markers for the left lane. Gaps were then indexed chronologically. Finally, characteristics of the gaps accepted and rejected for each vehicle were computed in order to find maximum likelihood method estimates of critical gap. Headway between two entering vehicles was considered as a follow-up headway if the two vehicles accepted the same gap. The differences between timestamps of vehicles crossing data collection point 3 (See Figure 1.b) during a single gap were used to estimate average follow-up headway. In summary, the same method for estimating the field-observed critical gap and follow-up headway was used for VISSIM data.

ANALYSIS AND RESULTS

Analysis of Driver's Speed Reduction Behavior

While the placement of RSAs has been investigated previously, most suggested placing RSAs on the entrances of roundabouts (*2-4, 12*). However, how far from the yield line the RSA should be placed, and what speed distribution and deceleration rate should be used was not specified; rather they were based on experience. This research tried to give recommendations on the placement and settings of RSAs based on speed trajectory data collected in field.

Figure 2.a shows the speed profiles of 65 free-flow entering vehicles as they approached the roundabout. Different colors are used to represent different vehicles. These 65 vehicles were randomly selected from a total of 539 observed free-flow vehicles to achieve an easier recognition of speed patterns. However, in the detailed data analysis, the full sample of 539 vehicles was used. In Figure 2.a, a relatively level speed profile was observed when the distance from yield line was greater than 160 feet, which indicated that constant speeds were maintained by vehicles. A distinct change in slope in the speed profile began at around 160 feet from the yield line and continued smoothly, which indicated a continuous and consistent deceleration

maneuver by drivers. The slope became less steep when the distance reached about 25 feet from the yield line. This indicated a trend that drivers started to end the deceleration and tried to maintain a constant speed. When the distance reached around 8 feet from the yield line, speed of nearly half of the vehicles started to increase, indicating that vehicles began to accelerate to enter the roundabout. Based on these patterns, the entire roundabout approach could be approximately divided into four speed zones, namely:

- Constant Speed Zone (>160 feet from yield line),
- Deceleration Zone (25-160 feet from yield line),
- Reduced Speed Zone (8-25feet from yield line), and
- Speed Up Zone (0-8 feet from yield line).

Assuming that the deceleration rate within the Deceleration Zone is fixed (similar assumption used in VISSIM RSAs), each vehicle's deceleration rate can be computed using the following equation:

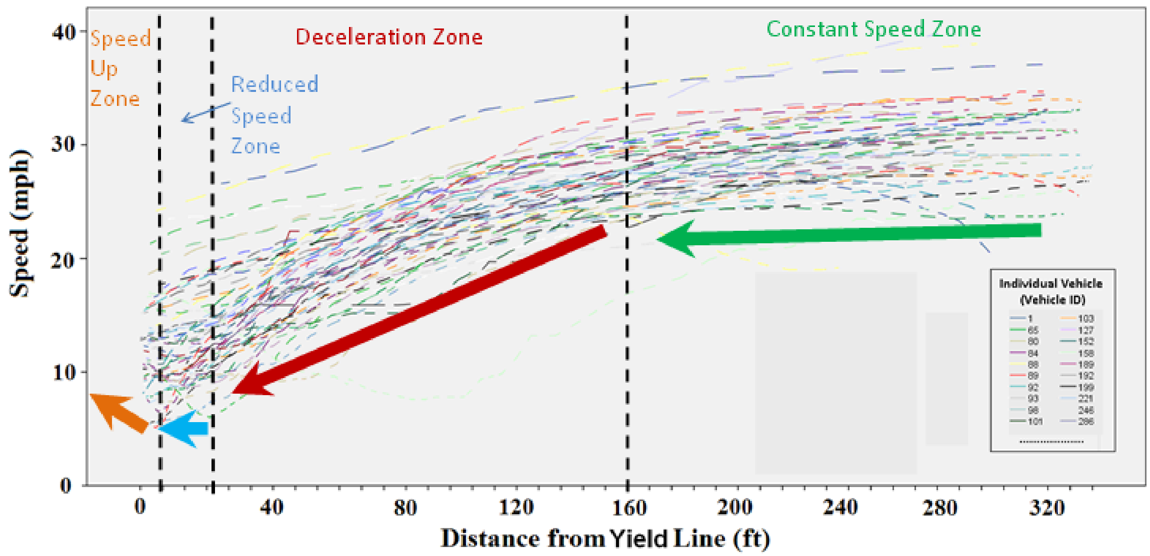
$$a = \frac{v_e - v_0}{t_e - t_0} \qquad (2)$$

Where, α = deceleration rate (ft/s^2);
v_e = exiting speed (ft/s);
v_0 = entering speed (ft/s);
t_e = exiting timestamp (t); and,
t_0 = entering timestamp (t);

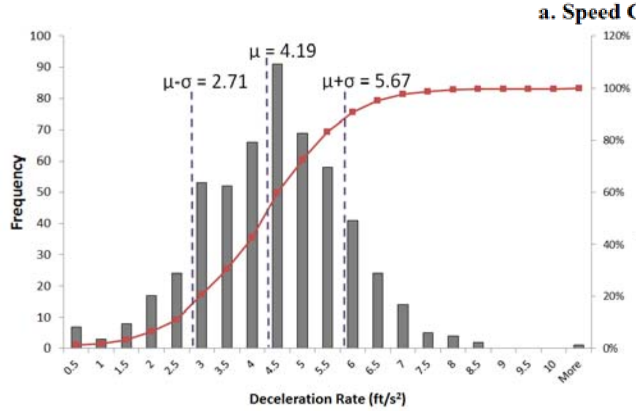
Figure 2.b shows the distribution of deceleration rate in the Deceleration Zone for all observed free-flow vehicles. The mean deceleration rate and standard deviation were found to be 4.19 ft/s^2 and 1.48 ft/s^2, respectively.

According to Figure 2.a, vehicle speeds in the Reduced Speed Zone vary slightly at different distances; however they are relatively stable when compared to the speeds in the Deceleration Zone. Therefore, the assumption was made that each vehicle maintained near constant speed in the Reduced Speed Zone (similar assumption used by VISSIM RSA), and the constant speed (termed as travel speed) for each vehicle could be computed by taking the average of each vehicle's speed measurements within the Reduced Speed Zone. Figure 2.c shows the distribution of travel speed in the Reduced Speed Zone. The mean travel speed and standard deviation were found to be 13.15 mph and 3.97 mph.

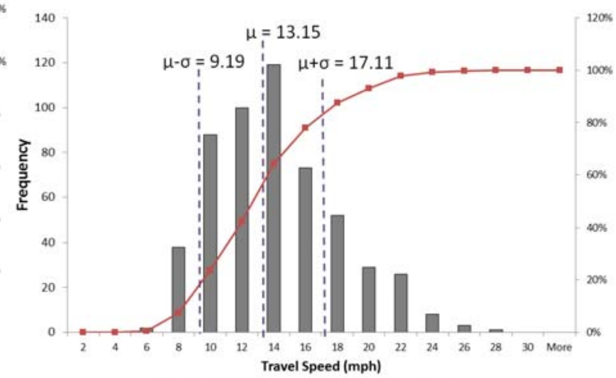
According to the definition of RSA in VISSIM user's manual (*20*), the location of the entrance RSA should exactly overlap with the Reduced Speed Zone as shown in Figure 2.a. Deceleration rate and speed distribution parameters therefore correspond to the observed deceleration rate in the Deceleration Zone and the travel speed distribution in the Reduced Speed Zone, respectively. Figure 2.d illustrates the layout of the entrance RSA in the VISSIM roundabout model. Based on the findings from Figure 2.a, the length of the RSA equals the length of the Reduced Speed Zone, i.e., 17 feet. The end boundary of the RSA is located at 8 feet from the yield line. The speed distribution in the RSA conforms to the cumulative speed curve as shown by the red curve in Figure 2.c. The default deceleration rate has been changed to 4.19 ft/s^2 as it is the mean deceleration rate observed in field.



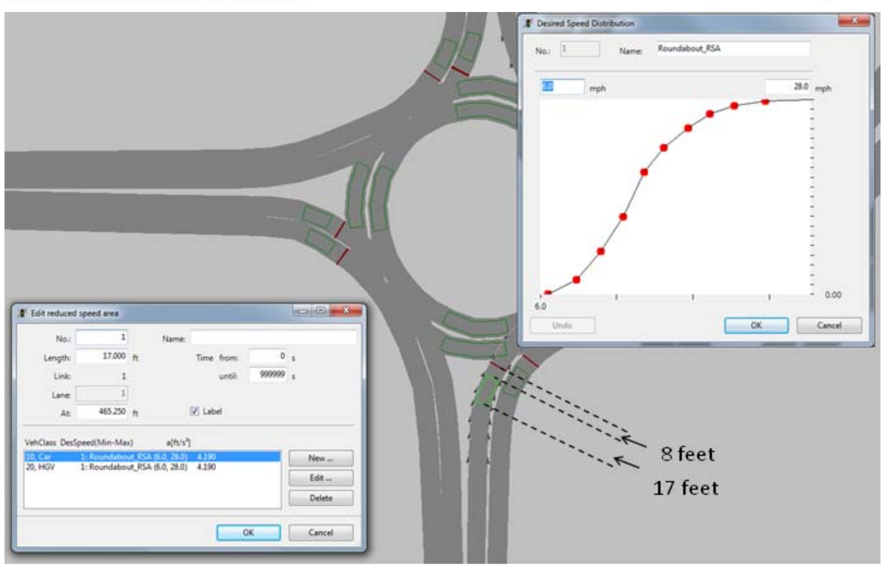
a. Speed Change Profiles



b. Distribution of Deceleration Rate in Deceleration Zone



c. Distribution of Speed in Reduced Speed Zone



d. placement of RSA

FIGURE 2 Parameters for VISSIM reduced speed areas.

In addition to the placement of the entrance RSA, recommendations by Trueblood and Dale were also taken into account in this research in regards to placement RSAs within the circulatory roadway (*2*). Instead of having large, continuous RSAs, smaller RSAs at the splitter islands were defined to enable vehicles to realistically travel at speeds typically observed within roundabouts (*2*). The placement of these circulatory RSAs is illustrated in Figure 2.d.

Analysis of Performance of Conflict Areas and Priority Rules

VISSIM provides two options for modeling roundabout's right-of-way, namely PR and CA. VISSIM user's manual gives examples of using both PR and CA for modeling roundabouts. This section aims at providing assistance to the practitioners and researchers on which to choose between these two alternatives through analyzing the difference in yielding behavior resulting from the use of PR and CA.

Wei et al. found that the use of CA may cause the situation where a circulating vehicle yields to an entering vehicle (*4*). In this research, it is revealed that the occurrence of the yielding behavior of circulating traffic under CAs can be eliminated through careful placement of the links and connectors in the outer lane. Specifically, the placement of the right turn connector was the key. If the right turn connector was drawn such that it started before the yield line, so that only the front part of the first vehicle waiting in queue would be on the right turn connector, the yielding phenomenon of the circulating traffic was alleviated.

Considering that the yielding issue has been fixed for the CAs, a further comparison of the gap acceptance distributions between CA and PR was performed to analyze their performance from the perspective of consistency in driver's gap acceptance behavior. Figures 3.a and 3.b show the distributions of the accepted gaps and the largest rejected gaps under PR and CA scenarios. Note that the CA scenarios were adjusted to eliminate the yielding phenomenon of the circulating traffic). Distributions were compared by the two-sided Kolmogorov-Smirnov (K-S) statistic to test for statistically significant differences between the distributions, measured by the distance, D, statistic. For accepted gap distribution, low circulating flows were similar between PR and CA. However, differences in accepted gap distribution increased with the increasing circulating flow, which is indicated by the increasing D statistic. For the largest rejected gap distribution, significant differences were observed at all circulating flows. PR can also be seen to have narrower distributions, indicating more uniform behavior in accepting and rejecting gaps. CA on the other hand, showed a wider distribution, even rejecting large gaps of 6 sec or more regardless of conflicting flow regime. All these facts indicate that driver's gap acceptance behavior under PRs is more consistent and repeatable than under CAs. The consistency and repeatability under PRs concurs with the field-observed normally distributed accepted and rejected gaps which are reported in the previous studies (*17, 18, 21*).

In summary, PR produced traffic behavior that is consistent with field observations, hence the preferred alternative in this research to define yielding logic for roundabouts. Therefore, all remaining analyses used PR.

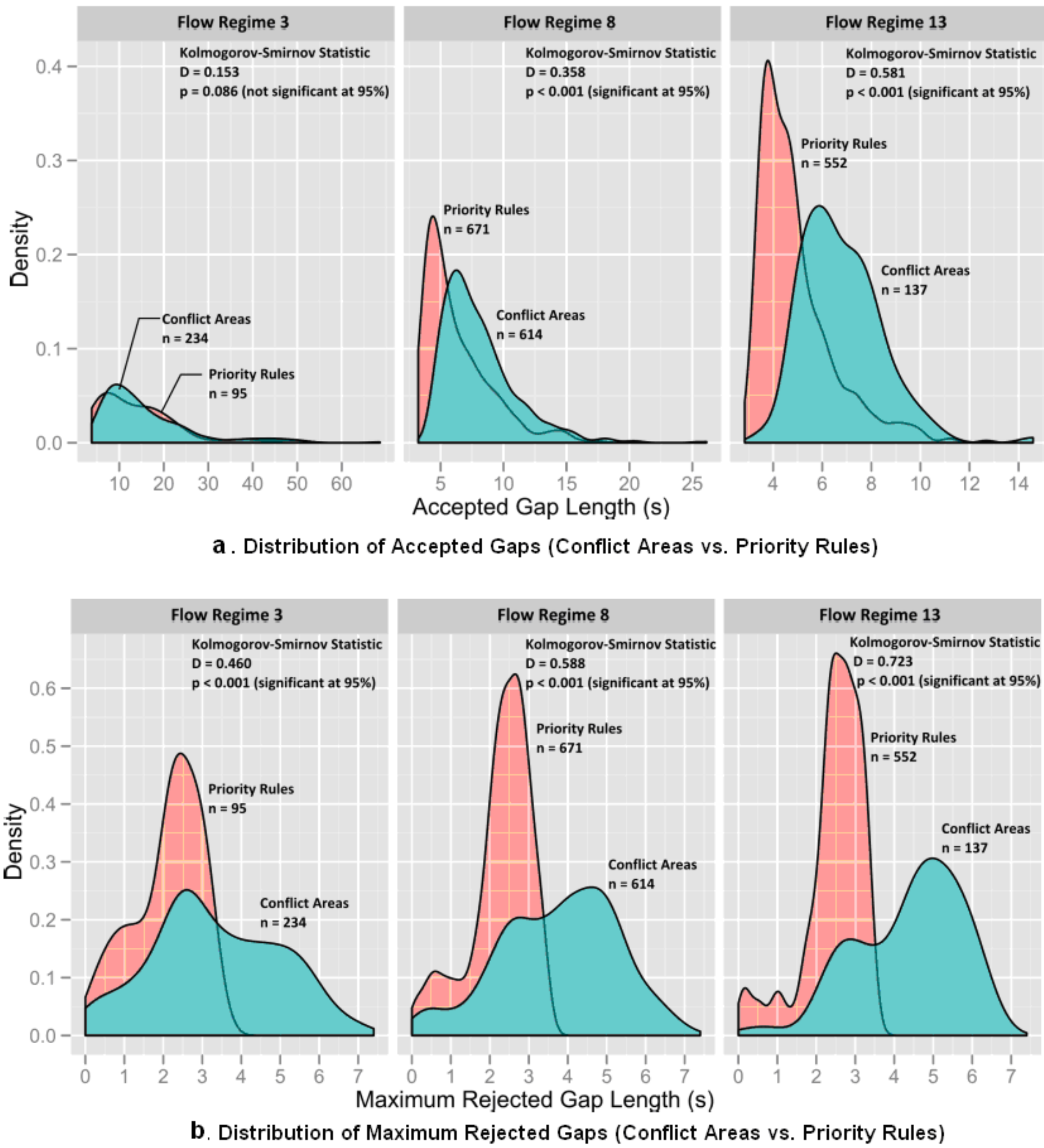


FIGURE 3 Comparison between conflict area and priority rule.

Sensitivity Analyses

The following subsections are dedicated to sensitivity analyses of settings of different VISSIM elements to investigate their impact on the roundabout model's capacity (i.e., t_c and t_f). The results of the sensitivity analysis are expected to provide quantitative reference for calibrating the roundabout simulation model. Specifically, the VISSIM elements that are considered in this section include:

- PR: minimum gap;
- RSA: speed distribution and deceleration rate;
- Wiedemann 74 Model (W74M): safety distance factors: additive and multiplicative.

TABLE 2 Settings of Parameters and Results of the Sensitivity Analyses

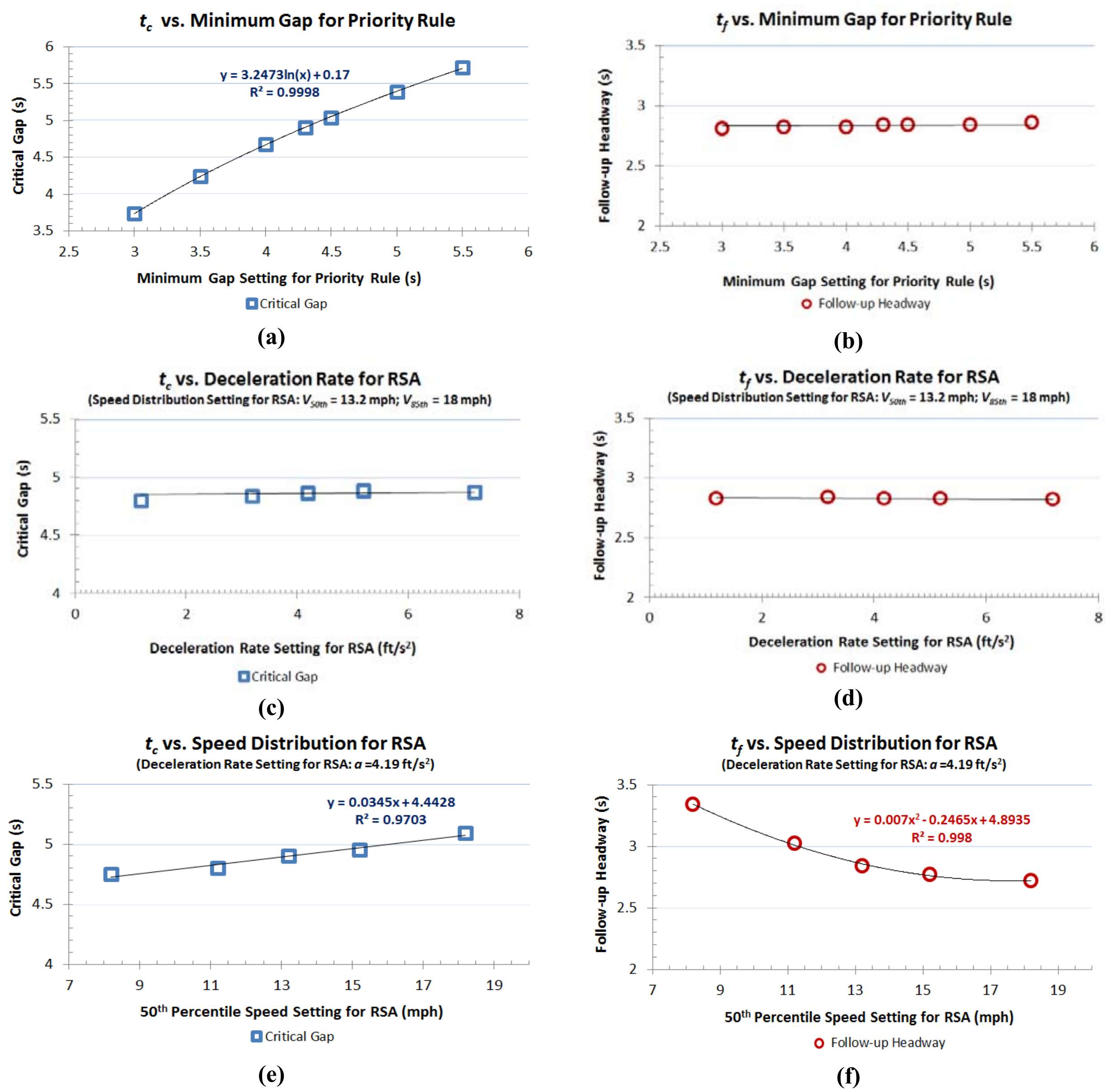
Priority Rules			Parameter	Result	
			Minimum Gap (s)	**t_c (s)***	**t_f (s)***
Default Value			4.3		
Value in Sensitivity Analysis	**Experiment ID**	**1**	3.0	3.74 (0.13)	2.81 (0.45)
		2	3.5	4.24 (0.16)	2.82 (0.44)
		3	4.0	4.68 (0.18)	2.82 (0.44)
		4	4.3	4.90 (0.19)	2.84 (0.43)
		5	4.5	5.04 (0.22)	2.84 (0.45)
		6	5.0	5.39 (0.29)	2.84 (0.44)
		7	5.5	5.72 (0.43)	2.86 (0.49)

Reduced Speed Areas			Parameter		Result	
			Speed Distribution (mph)	**Deceleration Rate (ft/s^2)**	**t_c (s)**	**t_f (s)**
Default Value			V_{50th}* = 13.2; V_{85th}* =18.0	4.19		
Value in Sensitivity Analysis	**Experiment ID**	**11**	V_{50th} = 13.2; V_{85th} =18.0	1.19	4.84 (0.26)	2.84 (0.45)
		12	V_{50th} = 13.2; V_{85th} =18.0	3.19	4.88 (0.28)	2.84 (0.44)
		13	V_{50th} = 13.2; V_{85th} =18.0	4.19	4.90 (0.19)	2.84 (0.43)
		14	V_{50th} = 13.2; V_{85th} =18.0	5.19	4.92 (0.29)	2.84 (0.44)
		15	V_{50th} = 13.2; V_{85th} =18.0	7.19	4.91 (0.31)	2.83 (0.43)
		16	V_{50th} = 8.2; V_{85th} =13.0	4.19	4.75 (0.15)	3.34 (0.58)
		17	V_{50th} = 11.2; V_{85th} =16.0	4.19	4.80 (0.18)	3.02 (0.50)
		18	V_{50th} = 13.2; V_{85th} =18.0	4.19	4.90 (0.19)	2.84 (0.43)
		19	V_{50th} = 15.2; V_{85th} =20.0	4.19	4.95 (0.21)	2.77 (0.45)
		20	V_{50th} = 18.2; V_{85th} =23.0	4.19	5.09 (0.26)	2.72 (0.47)

Wiedemann 74 model			Parameter		Result	
			Additive Part of Safety Distance	**Multiplicative Part of Safety Distance**	**t_c (s)**	**t_f (s)**
Default Value			2.0	3.0		
Value in Sensitivity Analysis	**Experiment ID**	**21**	2.0	1.5	4.89 (0.21)	2.60 (0.40)
		22	2.0	2.5	4.87 (0.20)	2.76 (0.43)
		23	2.0	3.0	4.90 (0.19)	2.84 (0.43)
		24	2.0	3.5	4.88 (0.19)	2.92 (0.45)
		25	2.0	4.5	4.90 (0.19)	3.08 (0.47)
		26	1.0	3.0	4.84 (0.20)	2.53 (0.43)
		27	1.5	3.0	4.85 (0.20)	2.68 (0.42)
		28	2.0	3.0	4.90 (0.19)	2.84 (0.43)
		29	2.5	3.0	4.93 (0.21)	3.01 (0.44)
		30	3.0	3.0	4.93 (0.20)	3.17 (0.44)

** t_c denotes critical gap; t_f denotes follow-up headway; () denotes standard deviation; V50th denotes 50th percentile speed; V85th denotes 85th percentile speed.*

The main idea of the sensitivity analysis was to test how sensitive the changes in critical gap (t_c) and follow-up headway (t_f) were when changing parameter values of a subject VISSIM element. Since the left lane of the NB entrance was selected as the study lane in this research, changes in parameter settings only applied to the NB left lane in the sensitivity analyses, except changes in some global settings like the W74M. In each analysis, only the parameter values of the subject VISSIM element were changed. The parameter values of other elements remained at defaults. For RSA and PR, the default parameter values were the field-observed values. For W74M, the default parameter values were values that are recommended by VISSIM (*20*). Each analysis included multiple experiments. Table 2 summarizes the settings of VISSIM parameters and the results of the sensitivity analyses.



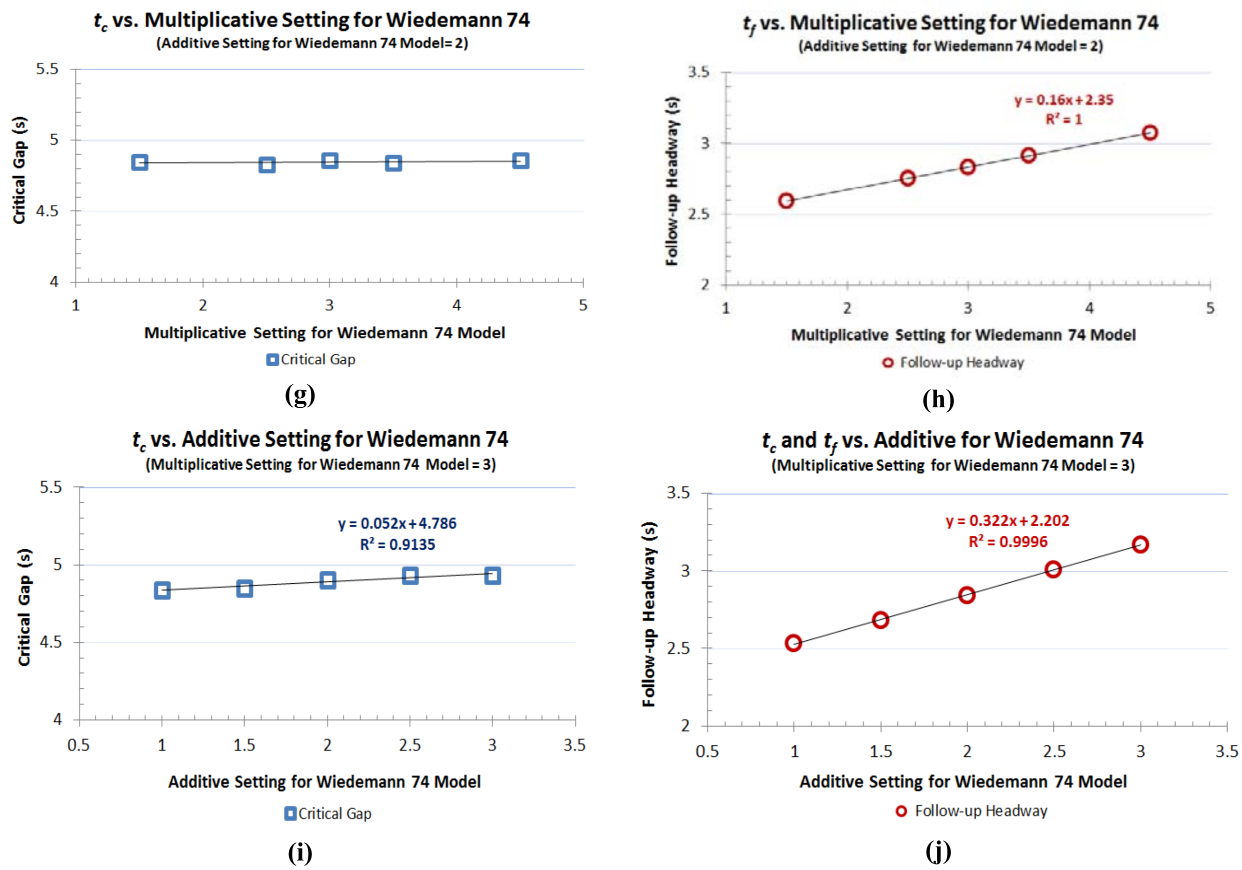


FIGURE 4 Numerical illustrations of sensitivity analysis results.

Results of Priority Rule

The sensitivity analysis for PR was designed to quantify the impact of the PR's minimum gap setting on the roundabout capacity. The setting of minimum gap in the PR is a close reflection of the critical gap. Before running the analysis, it was expected that linear relationship lies between the minimum gap and the critical gap. For instance, increasing the minimum gap by 0.1 second would also increase the critical gap by 0.1 second. The sensitivity analysis aimed at verifying this expectation.

Seven different minimum gaps, ranging from 3.0 sec to 5.5 sec, were tested in the analysis. Figures 4.a and 4.b illustrate the results of the minimum gap's impact on critical gap and follow-up headway, respectively. As expected, increasing the minimum gap significantly increased the critical gap according to Figure 4.a. And, all critical gaps were observed being greater than the minimum gaps. For instance, when inputting the minimum gap as 4.3 sec, a critical gap of 4.9 sec was observed. However, the difference between the input minimum gap and the resulted critical gap was not constant through all the tested minimum gaps, which suggests that the minimum gap input and the resulting critical gap are not linearly correlated. Regression analysis also identified the best-fit numerical relationship between the minimum gap and the resulted critical gap (under default settings summarized in Table 2) to be logarithmic rather than linear as initially expected. Numerically, the relationship is represented by the following equation:

$$t_c = 3.2473\ln(g_{\min}) + 0.17$$
$$R^2 = 0.9998 \tag{3}$$

Where, t_c is critical gap (sec), and g_{min} is minimum gap setting for the PR (sec).

Increasing the minimum gap did not change the follow-up headway according to Figure 4.b. The regression line was quite flat, indicating that the minimum gap did not have a significant impact on the follow-up headway as expected.

Results of Reduced Speed Area

Although the location, speed distribution, and deceleration rate of RSA have been determined using field observation in the previous section, sensitivity analyses of RSA settings were still required to investigate how these settings would quantitatively impact the roundabout capacity. The analysis was comprised of two sets of sensitivity analyses. The first set was designed to test the impact of RSA's deceleration rate on the roundabout capacity. In the analysis, the RSA's speed distribution remained the default value (i.e., 50th percentile speed = 13.2 mph and 85th percentile speed = 18.0 mph). Five different deceleration rates, ranging from 1.19 ft/s^2 to 7.19 ft/s^2, were tested in the analysis. Figures 4.c and 4.d illustrate the results of the deceleration rate's impact on critical gap and follow-up headway, respectively. According to Figure 4.c, increasing the deceleration rate did not change the critical gap significantly. In other words, the deceleration rate only controlled the starting distance of drivers' deceleration maneuver. It did not impact drivers' critical gap. Similar result was found for follow-up headway according to Figure 4.d. The regression curve was flat, indicating that the deceleration rate did not have significant impact on drivers' follow-up headway, either.

The second set of analysis was designed to test the impact of RSA's speed distribution setting on the roundabout capacity. In the analysis, the RSA deceleration rate remained at the default value (i.e., deceleration rate = 4.19 ft/s^2). Five different speed distributions with 50th percentile speed ranging from 8.2 mph to 18.2 mph were tested in the analysis. Figures 4.e and 4.f illustrate the analysis results. Figure 4.e showed that increasing the 50th and 85th percentile speeds in the speed distribution significantly increased the critical gap. Through regression analysis, a linear relationship between the 50th percentile speed and the critical gap (under default settings summarized in Table 2) was identified, and was represented by the following equation:

$$t_c = 0.0345 v_{50th} + 4.4428$$
$$R^2 = 0.9703 \tag{4}$$

Where, t_c is critical gap (sec), and v_{50th} is 50th percentile speed in the RSA's speed distribution setting (mph).

In regards to follow-up headway, increasing the 50th and 85th percentile speeds in the speed distribution for RSA was found to significantly reduce the follow-up headway as shown in Figure 4.f. Rather than in a linear form, the increment in the 50th percentile speed tended to reduce the follow-up headway in a polynomial form. The magnitude of reduction was high in the lower speed range (8.2-11.2 mph) and was low in the higher speed range (15.2-18.2 mph). Through regression analysis, the relationship between the 50th percentile speed and the follow-up headway (under default settings summarized in Table 2) was represented by the following equation:

$$t_f = 0.007{v^2}_{50th} - 0.2465 v_{50th} + 4.8935 \qquad (5)$$
$$R^2 = 0.998$$

Where, t_f is follow-up headway (sec), and v_{50th} is 50th percentile speed in the RSA's speed distribution setting (mph).

Results of the Wiedemann 74 Model

In VISSIM, the W74M includes two important adjustable parameters. Namely, the additive and multiplicative parts of the safety distance. Therefore, the analysis of the W74M was comprised of two sets of sensitivity analyses. The first set was designed to test the impact of the multiplicative setting on the roundabout capacity. In the analysis, the additive setting remained the default value (i.e., additive = 2.0). Five different multiplicative settings, ranging from 1.5 to 4.5, were tested in the analysis. Figures 4.g and 4.h illustrate the results of the multiplicative setting's impact on critical gap and follow-up headway, respectively. According to Figure 4.g, increasing the multiplicative setting did not change the critical gap significantly. In other words, the multiplicative setting had no impact on driver's critical gap. However, it did have significant impact on the follow-up headway according to Figure 4.h. The follow-up headway increased linearly with the multiplicative setting. Generally, for one unit increment of the multiplicative setting, the follow-up headway increased by about 0.16 sec. Regression analysis summarized the relationship between the multiplicative setting and the follow-up headway (under default settings summarized in Table 2) using the following equation:

$$t_f = 0.16m + 2.35 \qquad (6)$$
$$R^2 = 1$$

Where, t_f is follow-up headway (sec), and m is the multiplicative part of the safety distance for the W74M.

The second set of analysis was designed to test the impact of the additive setting on the roundabout capacity. In the analysis, the multiplicative setting remained the default value (i.e., multiplicative = 3.0). Five different additive settings, ranging from 1.0 to 3.0, were tested in the analysis. Figures 4.i and 4.j illustrate the analysis results. It was identified from Figure 4.i that increasing the additive setting slightly increased the critical gap. Through regression analysis, a linear relationship between the 50th percentile speed and the critical gap (under default settings summarized in Table 2) was identified, and was represented by the following equation:

$$t_c = 0.052a + 4.786 \qquad (7)$$
$$R^2 = 0.9135$$

Where, t_c is critical gap (sec), and a is the additive part of the safety distance for the W74M.

Increasing the additive setting was found to increase the follow-up headway in a linear form according to Figure 4.j. The magnitude of increment in follow-up headway is 0.32 sec per unit increment in the additive setting. Through regression analysis, the relationship between the 50th percentile speed and the follow-up headway (under default settings summarized in Table (2) was represented by the following equation:

$$t_f = 0.322a + 2.202$$
$$R^2 = 0.9996 \quad (8)$$

Where, t_f is follow-up headway (sec), and a is additive part of the safety distance for the W74M.

CALIBRATION RECOMMENDATIONS

The following recommendations have been made for calibrating VISSIM roundabout models based on the sensitivity analysis results:

- The entrance RSA is recommended to be placed at approximately 8 feet from the yield line, and the length of the RSA is 17 feet. The speed distribution setting is recommended to conform to the speed cumulative curve shown in Figure 2.c. Since the RSA's deceleration rate setting does not impact the roundabout capacity, the deceleration rate can vary to adapt the actual approach speed of a specific roundabout. For example, higher speed approach can use a higher deceleration rate. The chosen deceleration rate is recommended to fall within the field-observed distribution shown in Figure 2.b.
- PRs rather than CAs are recommended to model the yielding logics to achieve consistent and repeatable gap acceptance behavior.
- Speed distribution of RSA and the additive setting for W74M are *not* recommended to be used in calibrating the roundabout model, as they impact both the critical gap and follow-up headway simultaneously. Using these two parameters will make the calibration hard to control. Therefore, the RSA's speed distribution and the additive setting for W74M are recommended to remain default values (i.e., Figure 2.c for speed distribution, and 2.0 for additive setting) during the calibration.
- Minimum gap for PR impacts the critical gap only, and hence is recommended to be used in calibrating the critical gap. The critical gap can be calculated by inputting the minimum gap into Equation (3).
- Multiplicative setting for W74M impacts the follow-up headway only, and hence is recommended to be used in calibrating the follow-up headway. The follow-up headway can be calculated using Equation (6) and a multiplicative input.

VALIDATION OF THE CALBRATION RECOMMENDATIONS

Using the study site as a case study, the effectiveness of the calibration recommendations developed in the previous section is validated in this section.

According to Table 1, the study entrance lane (i.e., NB left lane of De Pere roundabout) had a field-observed critical gap of 4.3 sec and follow-up headway of 3.1 sec. In the validation process, the study lane's critical gap and follow-up headway were attempted to be calibrated following the calibration recommendations. Specifically, the minimum gap of 3.6 sec and the multiplicative value of 4.7 were used based on Equations (3) and (6) in order to obtain the 4.3 sec critical gap and the 3.1 sec follow-up headway. All other VISSIM parameters remained default values as summarized in Table 2. Validation results obtained from 150 simulation runs showed that the resultant critical gap and follow-up headway after calibration were 4.31 sec and 3.09 sec, respectively. Both numbers were almost identical to the calibration goal. Figure 5 further illustrates the validation of the calibrated simulation model by comparing the simulated capacity cloud (i.e., plots of entering flow vs. circulating flow) with the field-observed ground-truth capacity cloud.

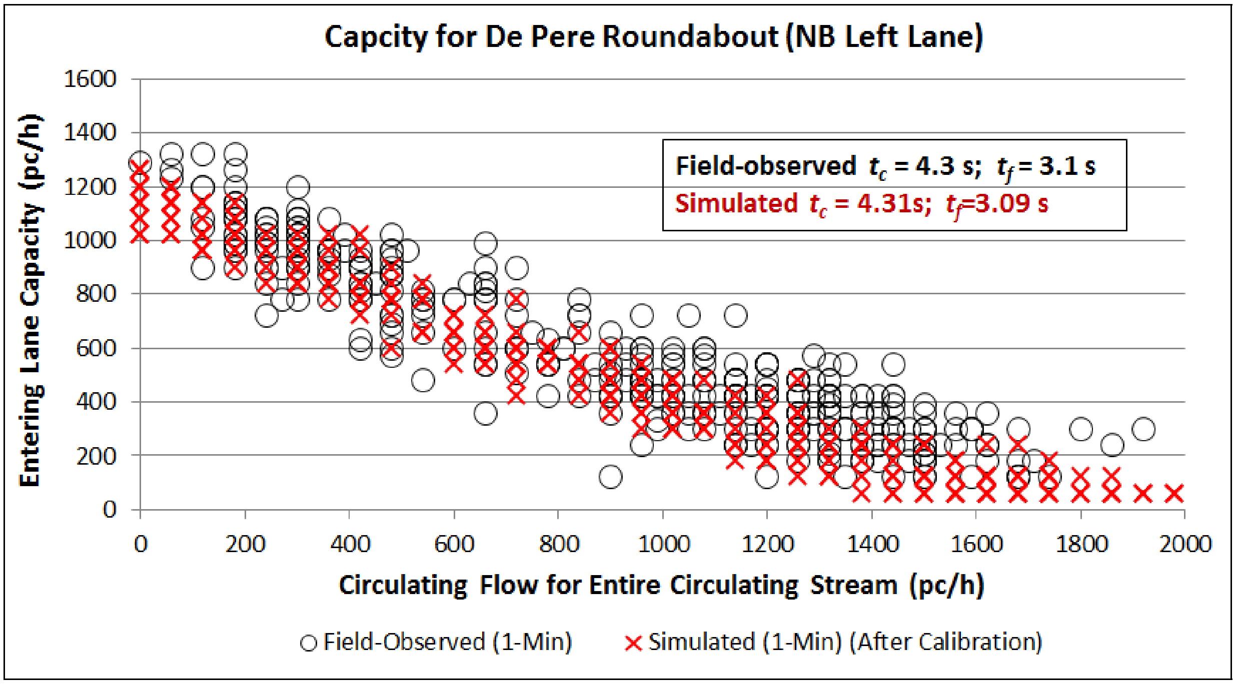


FIGURE 5 Validation of the roundabout simulation model.

According to Figure 5, the capacity cloud obtained from the calibrated simulation model matches very well with the field-observed capacity cloud, which indicates that the VISSIM roundabout model was successfully calibrated. By calculating the root-mean-square-error, the difference between the average VISSIM data and field data was about 116 pc/hr/ln. At very high circulating flows above 1400 pc/hr, field data, although sparse, showed slightly more capacity than the simulated data. Based on these validation results, the proposed calibration recommendations for VISSIM roundabout models demonstrated their applicability in calibrating VISSIM roundabout models. .

CONCLUSIONS

Based on the findings presented in the previous sections, the following conclusions were reached:

- *Field estimates of RSA parameters*: location and length for RSAs have been determined through analyzing the four stages of drivers' deceleration maneuver based on field speed data. The estimates for RSA deceleration rate and speed distribution have also been determined as shown by Figure 2.b and Figure 2.c.
- *CA vs. PR*: using CAs may result in circulating vehicles yielding to entering vehicles, while using PRs may not. The finding concurs with Wei et al.'s finding (*4*). However, when the links and connectors are modeled properly, the yielding behavior of the circulating traffic can be eliminated. Compared with PRs, CAs have wider and inconsistent distribution of accepted gaps and largest rejected gaps, which indicates using

PR can result in more uniform and repeatable behavior in accepting and rejecting gaps. Therefore, PRs are recommended for modeling roundabouts.

- *Sensitivity analyses of VISSIM parameters*
    - *Minimum gap for PR*: critical gap increases as minimum gap increases, the numerical relationship between them is logarithmic; and, follow-up headway is not impacted by minimum gap.
    - *Deceleration rate for RSA*: both critical gap and follow-up headway are not impacted by RSA's deceleration rate; and, deceleration rate only controls the starting distance of driver's deceleration maneuver in VISSIM.
    - *Speed distribution for RSA*: critical gap increases as RSA's 50th and 85th percentile speeds increase; the numerical relationship between 50th percentile speed and critical gap is linear; follow-up headway decreases as RSA's 50th and 85th percentile speeds increase; and, the numerical relationship between 50th percentile speed and follow-up headway is polynomial.
    - *Multiplicative setting for the W74M*: critical gap is not impacted by the multiplicative setting; follow-up headway increases as multiplicative increases; and, the numerical relationship between multiplicative and follow-up headway is linear;
    - *Additive setting for the W74M*: critical gap slightly increases as additive increases; the numerical relationship between additive and critical gap is linear; follow-up headway increases as additive increases; and, the numerical relationship between additive and follow-up headway is linear;

In summary, the paper tries to develop simple and numerical calibration recommendations based on the comprehensive discussion of the calibration process. Despite the complex process of developing such recommendations, the final product is simple and it provides formulated solutions to researchers and practitioners to simplify their calibration of VISSIM roundabout models. The limitation is that the calibration recommendations were validated based on the data from only one roundabout. Future research will focus on investigating the transferability of the proposed calibration recommendations via exploring more study sites in the validation process.

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