MICROSCOPIC SIMULATION AND EVALUATION OF THE ROUNDABOUT CAPACITY MODEL IN HIGHWAY CAPACITY MANUAL

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ABSTRACT

Shown to be an effective intersection design, the roundabout is receiving increasing attention and popularity. Several models, described in this work, have been developed to predict roundabout capacity. One of them, the roundabout capacity model included in the Highway Capacity Manual (HCM), is widely used in the US, using a gap-acceptance foundation based on data collected in US roundabouts.

This study explored the accuracy of the two-lane variants of the roundabout capacity models in HCM 6th Edition and HCM 2010 by comparing them with an exponential regression model fitted on flow rate measurements collected at a two-lane roundabout in Richfield, Minnesota. Based on the same gap-acceptance foundation proposed in HCM, two other models were developed by recalculating coefficients. Each followed a different calibration strategy and compared with the Richfield model. It was found that calibration can significantly enhance the accuracy of the default HCM model and calibrating only the intercept of the default HCM model can produce a model with similar accuracy as the model resulting by calibrating both coefficients.

To further assist traffic engineers, this work validated the capability of the popular traffic simulator AIMSUN to build a roundabout model with realistic capacities. A sensitivity analysis, exploring the impact of different simulation parameters, further assisted in proposing an efficient and reliable simulation calibration methodology. Initial safety margin, visibility along main stream, reaction time at stop, and max acceleration were selected to calibrate driver’s gap acceptance behavior. The result showed that if a calibrated model in AIMSUN could produce the same critical headway and follow-up headway as those in the HCM6 model, it will also result in similar capacities as the HCM6 model.

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CHAPTER 1

1 INTRODUCTION

1.1 Problem Statement and Objectives of Study

Roundabout is a type of circular intersection where the traffic flows in a single direction around a center island. The installation of the roundabout can effectively enhance the safety of the intersection by reducing the number of conflict points as well as travel speed. Introducing any new facility into the road network, especially one as fundamentally different as a roundabout, requires accurate prediction of its capacity.

In the US, as is the case with several other road designs, the Highway Capacity Manual (HCM) has been the most used source for capacity and Level of Service (LOS) estimation and prediction. The roundabout capacity models in HCM are based on empirical information and formulations developed from actual observations. Given the relative recent introduction of roundabouts as a road facility in the US, the HCM roundabout model is still in flux. The latest HCM 6th Edition, has revised the proposed capacity model with observations of capacities higher than the ones used in HCM 2010. Although both resources recommend that the user calibrates the model with local data using the formulas provided, most use the default model as it is. All HCM models reflect an average condition based on observations from several roundabouts in the US. Given the still low number of roundabouts in-service over the variety of design features as well as differences in driver population, the average may poorly reflect local conditions. The model foundation and in extend the formulas used are based on driver's gap acceptance behavior while ignoring specific design features of the roundabout like speed limit, deflection angles, number of approaches, etc. Although it is not possible to cover all design alternatives, capitalizing on a unique set of information from a local roundabout, this work evaluates the accuracy and calibration potential of the HCM models. The Richfield roundabout, represents a popular design that has been replicated all around the US. It was developed as an early case study to inform or formulate design standards.

Towards that goal, this work collected both, critical and follow-up headways as well as flow rates at capacity reaching events.

Traffic simulation is an important tool to study complex traffic problems, especially when the traffic network in question is too complicated to be explained by mathematical models. Traffic simulation is often used to assess the performance of road facilities and help with the design of new ones. Using traffic simulation software packages, users can easily build a virtual road network and observe the effect of different demand level and traffic control strategies. Before a roundabout is built, traffic engineers often introduce it in simulation to predict its performance and effects on the greater system. Most existing projects utilize the VISSIM simulation application for modeling roundabouts. This has resulted in several studies discussing its accuracy and pros/cons of its underlying models. Other simulation packages, such as AIMSUN and PARAMICS, are rarely discussed by researchers in the context of roundabouts. From these two, AIMSUN has risen in popularity due to its ability to handle larger more complicated networks than VISSIM. Unfortunately, the validity of its modeling foundation in accurately emulating roundabout capacities is still lacking. This study wishes to alleviate this by exploring the capability of AIMSUN to replicate the capacity model in HCM 6. Sensitivity analysis is used to figure out key parameters for the calibration in AIMSUN. These parameters are used to calibrate the driver's gap acceptance behavior in the simulation model before the flow rates generated by the calibrated simulation model are compared with the observed ones as well as the default roundabout capacity model in HCM 6.

1.2 Thesis Organization

Chapter 2 introduces two types of mathematical roundabout capacity models, including the empirical model and the analytical model. It also presents three traffic simulation software packages used for the simulation of the roundabout simulation and their relevant studies.

Chapter 3 shows the data collection and data processing of traffic flow rate and gap acceptance data. Exponential regression model is applied to fit the traffic flow rate data from a roundabout in Richfield, Minnesota. Critical headway is estimated using maximum likelihood method and follow-up headway estimated using averaging method.

Chapter 4 compares the roundabout capacity model for the roundabout in Richfield with two default roundabout capacity models in HCM and two calibrated HCM models using different calibration strategies.

Chapter 5 applies sensitivity analysis to figure out important parameters to model calibration in traffic simulation software AIMSUN. These parameters are used to calibrate driver's gap acceptance behavior in roundabout simulation model. After the calibration, the traffic flow rates produced by the simulation model are compared to the default roundabout capacity model in HCM 6.

CHAPTER 2

2. BACKGROUND

This chapter offers basic knowledge about roundabout capacity models and roundabout simulation models. In the first part, popular roundabout capacity models like the empirical and gap acceptance models, are introduced. The second part focuses on the microscopic simulation of roundabout traffic by frequently-used simulation tools and relevant studies about roundabout simulation.

2.1 Mathematical Roundabout Capacity Models

The capacity of a roundabout approach is the maximum number of entering vehicles in a time interval. To predict the capacity of the roundabout, researchers developed various mathematical capacity models. There are mainly two types: the empirical model, and the analytical model.

2.1.1 Empirical Models

Empirical model builds the relationship between the capacity and other factors based on empirical data using regression method. This type of models often consider the circulating flow and the geometry characteristics of the roundabout.

LR942 Linear Regression Model is a fully empirical-based linear regression model. It was developed by The Transport Research Laboratory (TTRL) in UK. It is also known as the TRL (UK) linear regression model or TRL (UK) empirical model. This model was based on an empirical study at 86 public roundabout entries in UK [1]. Users can calculate the capacity with the input of roundabout geometry data and circulating traffic rates. The input geometric data includes lane characteristics (lane width, flair, radius, and angle), circle diameter, and turning flows [2]. This model is widely used in UK and is the theoretical basis of two software packages: ARCADY/Junctions 8 and RODEL [3]. But this model does not specify the number of lanes, which may result in biased results if it is applied to multilane roundabout.

2.1.2 Analytical models

Most analytical models aim to represent the underlying relationship between the capacity and the traffic flow. Gap acceptance model is a type of the most common analytical models, which is often used to analyze the capacity of an unsignalized intersection or a roundabout.

In a roundabout, circulating vehicles have higher priority, while entering vehicles have lower priority. Gap acceptance model is based on the behavior that an entering vehicle waits at the stop line until the gap between two circulating vehicles is large enough for them to enter the roundabout safely. Most of the gap acceptance models assume that the gaps between two consecutive circulating vehicles follow one of the three distributions: negative exponential (M1), shifted negative exponential (M2), and bunched exponential (M3) [4].

There are many analytical gap-acceptance models, such as SIDRA model in Australia [5], Tanner Wu's model in German [6], and Arem and Kneepkens's model in Netherlands [7]. The roundabout capacity model used in this thesis is from highway capacity manual (HCM), which is a gap acceptance model developed in the united states.

Highway Capacity Manual Model

The roundabout capacity model in HCM 2010 is based on a study of multiple roundabouts in the US in 2003, which is part of project NCHRP 3-65. The full description of the results of this project can be found in NCHRP Report 572 [8].

The roundabout capacity model in HCM 6th edition (HCM 6) keeps the form in earlier models but is based on a new dataset collected in 2012 as a part of FHWA supported project, presented in "Accelerating Roundabout Implementation in the United States – Volume II" report [9]. HCM 6 includes one capacity model for a single lane roundabout, and three models for three types of multilane roundabouts.

HCM uses exponential models to represent the relation between the circulating flow rates and the entering flow rates. Formula 1 presents a general form of the roundabout capacity model in HCM.

$$c_{pce} = Ae^{(-Bv_c)} \quad (1)$$

Where:

c_{pce} = capacity of an entry lane

$v_{c,pce}$ = circulating flow rate (total of both lanes)

Table 1 summarizes two parameters of all roundabout capacity models in HCM 2010 [10] and HCM 6 [11].

Table 1. Roundabout Capacity Model in HCM

Lane Numbers		HCM2010		HCM 6	
Entering lanes	Circulating Lanes	A	B	A	B
1	1	1130	1.0×10^{-3}	1380	1.02×10^{-3}
2	1	1130	1.0×10^{-3}	1420	0.91×10^{-3}
1	2	1130	0.7×10^{-3}	1420	0.85×10^{-3}
2 (Left lane)	2	1130	0.75×10^{-3}	1380	0.92×10^{-3}
2 (Right-Lane)	2	1130	0.7×10^{-3}	1420	0.85×10^{-3}

The roundabout capacity models in HCM reflect an average level of the roundabout capacity all over the country. As the condition at a local area is probably different, HCM provides two formulas (Formula 2, Formula 3) to calibrate the default capacity model with two gap acceptance parameters: the critical headway and the follow-up headway.

$$A = \frac{3600}{t_f} \quad (2)$$

$$B = \frac{t_c - (t_f/2)}{3600} \quad (3)$$

Where:

t_c = critical headway

t_f = follow-up headway

There are several studies testing and validating the roundabout capacity model in HCM or relative projects.

Xu and Tian (2008) collected the critical headway and follow-up headway from seven single-lane roundabouts and three multilane roundabouts in California. The critical headway and follow-up headway collected in the field were compared with those in project NCHRP 3-65. The result showed that the critical headway in California was close to that in the project, while the follow-up headway was smaller than that in project NCHRP 3-65 [12].

Zheng et al. (2011) collected critical headways and follow-up headway in congested roundabout in Wisconsin and compared them with the critical headway and the follow-up headway in report NCHRP 572. They indicated that the critical headway and the follow-up headway collected under congested condition were much smaller than that in report NCHPR 572 [13].

Wei and Grenard (2012) calibrated the capacity model in HCM 2010 using gap-acceptance data from three single-lane roundabouts in Carmel, Indiana. The result indicated that the calibrated model accurately predicted the capacity under low-to-moderate circulating flow but overestimated the capacity under heavy circulating flow [14]. Another study of Wei in 2011 compared actual flow rates with the capacity model in report NCHRP 572, and found that it significantly underestimated the capacity of roundabouts in Carmel, Indiana [15].

Gazzarri et al. (2013) used field data at seven roundabouts in Italy to explore if the default values of two parameters in the roundabout capacity model in HCM 2010 were still appropriate in Italy. The results showed that the critical headway at selected roundabouts was smaller than the average critical headway in California, and HCM 2010. The follow-up headway was also smaller than the follow-up headway suggested in HCM 2010, but was larger than that in California [16].

Fitzpatrick et al. (2013) measured the critical headway at roundabouts in University of Massachusetts. The measured critical headway was 2.2 second, which was significantly smaller than that in HCM 2010 [17].

Ren et al. (2016) calibrated the default roundabout capacity model in HCM 2010 with the gap acceptance data at nine roundabouts in Gold Coast, Australia. The calibrated model was compared with actual flow rates in the field. The result showed the calibrated model underestimated the capacity by 4.62% to 16.14% [18].

Mensah et al. (2010) used a before-and after study to test the change in driver behavior by comparing the critical headways in 2005 and in 2009. The data were collected at two single-lane roundabouts in Maryland. The result showed that the critical headway reduced from 3.88 to 2.55 second in four years. The study concluded that the critical headway reduced as drivers became more experienced with the roundabout [19].

2.2 Microscopic Simulation Models

Microscopic traffic models simulate single vehicles and use car-following and lane-changing models to regulate the behaviors of drivers. It models the traffic system in high resolution and has considerable popularity among traffic practitioners. There are various traffic simulation software packages used to simulate the roundabout in existing studies, such as PARAMICS, VISSIM, and AIMSUN.

2.2.1 PARAMICS

PARAMICS is a simulation software package developed by Quadstone Limit. It was based on a project in University of Edinburgh in the early 1990's. This software is made of six parts (Modeller, Processor, Analyser, Programmer, Monitor, and Estimator), which provides various functions for users. It uses a series of yield-controlled T-shape intersections to represent the roundabout [20].

Its viability to simulate the operational performance of a single-lane roundabout was proved in a study of Robinson et al (2004). This study concluded that PARAMICS could model the effect of various geometry factors and traffic characteristics on driving behaviors except the effect of lane width as it used a lane-based model. [21]

Car-following algorithm and gap acceptance algorithm in PARAMICS are used to get a calibrated roundabout model. In car-following algorithm, users can adjust the trajectories of vehicles on the roundabout. In gap acceptance algorithm, users can decide the yield behaviors of drivers [20].

2.2.2 VISSIM

VISSIM was developed by PTV Group in Germany. It uses Wiedemann model's model to control the behavior of the vehicle [22].

Compared with other simulation packages, most people use VISSIM to model a roundabout. Trueblood proved that VISSIM had the capability of simulating drivers' behavior at a roundabout [22]. Gallelli et al. [23] analyzed the performance of a single-lane roundabout under three scenarios in VISSIM, but the simulation model was not calibrated with field data. Valdez et al. [24] used speed data to calibrate a two-lane roundabout model in VISSIM, and this model was used to get the average control delay and level of service. Cicu et al. [25] calibrated a roundabout model with two entering lanes and two circulating lanes in VISSIM using field estimated headways and speed. Wei et al. [26] built a roundabout model with VISSIM and calibrated it with three capacity-based strategies. Li et al. [27] calibrated a multilane roundabout model in VISSIM using speed trajectories of free-flow entering vehicles and gap acceptance data. Sensitivity analysis was conducted to build the quantitative relationship between VISSIM parameters and generated headways. Bared [28] calibrated roundabout model with gap acceptance data and developed new formulas for two multilane roundabouts.

In some studies, the researchers used VISSIM to evaluate the performance of non-standard roundabout designs. Lochrane et al. [29] [30] used VISSIM to model and evaluate the capacity of mini roundabouts. Fortuijn [31] used VISSIM to model a turbo roundabout in Dutch. The simulated capacity of turbo roundabouts was compared with standard roundabouts.

According to existing studies, three sets of parameters could be used to calibrate the roundabout model in VISSIM. One is Priority Rules (PR) and Conflict Areas (CA), which control the gap acceptance behavior. But there is still a question about which of them can better depict the gap acceptance behavior. Wei [26] and Li [27] gave opposite advices on using PR or CA in their studies. The second set is Reduced Speed Areas

(RSA) and Desired Safety Distance (DSD), which controls the distribution of speeds on a short segment or a long segment respectively. The third one is Wiedemann 74 and 99 car-following models. Wiedemann 74 is mainly applied to urban traffic while Wiedemann 99 is mainly applied to interurban traffic [26].

2.2.3 AIMSUN

AIMSUN is a microscopic simulation software developed by TSS-Transport Simulation Systems (TSS) in Barcelona, Spain. The car-following model and lane-changing model in AIMSUN are from Gipps's models [32]. There are few studies about simulation with AIMSUN, let alone any study using AIMSUN to model a roundabout.

Silva et al. (2015) used AIMSUN to model the effect of replacing a traditional roundabout with a turbo-roundabout on a corridor. In this study, speed acceptance and the reaction time were used to calibrate the model. The queue length and the travel time were compared with the field data to check model's accuracy after the calibration [33].

AIMSUN uses Gipp's model to simulate the driver's behavior, which is significantly different with the car-following model and the lane-changing model in VISSIM. And the parameters to be calibrated are also different from those in other simulation software. From the literature search conducted for this study, there is no existing research that provide a detailed guidance about what parameter should be used to calibrate a roundabout model in AIMSUN.

2.2.4 Studies About Microscopic Simulation Models

A few studies compared the results of microscopic simulation with mathematical roundabout capacity models. In the studies of Stanek [34], Yin et [35], Kinzel et al. [36], Bared et al. [37], Ambadipudi [38], Chen and Ming [39], and Gagnon et al. [40], the simulation results of VISSIM were compared with analytical roundabout capacity models, such as RODEL and SIDRA. In other studies, the author compared the simulation results between microscopic simulation packages. Nikolic [41] built three roundabout models with PARAMICS, AIMSUN, and VISSIM and compared them with the field data. The result indicated that microscopic simulation models had advantages in simulating non-standard roundabout design. AIMSUN and VISSIM were likely to be more realistic than PARAMICS and building a roundabout model in AIMUSN was easier than in VISSIM. Stanek [34] compared the output of roundabout capacity models including HCM 2000 model, HCM 2010 model, SIDRA INTERSECTION, SimTraffic, VISSIM, and PARAMICS with their default settings. And he recommended the roundabout model to be calibrated to local condition.

CHAPTER 3

3 HCM ROUNDABOUT CAPACITY MODEL EVALUATION

In this chapter, roundabout capacity models in HCM were evaluated using the field data at a multilane roundabout in Richfield, Minnesota. The actual flow rates and gap acceptance data in this roundabout were extracted from videos. The actual flow rates were used to produce an exponential regression model to represent the local condition. Gap acceptance data were used to produce two calibrated HCM models using Formula (2) and (3).

3.1 Field Data Collection

Video data were collected from a roundabout at Portland Avenue South and East 66th Street. The roundabout had two entry lanes and two circulating lanes. An omni-directional camera mounted on a mast at the center of the roundabout was used for the data collection, then the drivers' behaviors on four approaches can be captured at the same time. Figure 1 shows a specific view of the omni-directional camera. The data collection was conducted on four days: October 10, 2016, March 16, 2017, March 17, 2017, and March 20, 2017. A total of five hours of traffic observations were collected on each of the roundabout approaches during the afternoon peak hours in four days.

Figure 1. Omni-directional Camera View

Two set of information were extracted from the video. The first set included the times of four events (Figure 2): the entry of a vehicle to the roundabout on the right lane (E_R), the left lane (E_R), the passage of a circulating vehicle through the conflict point on the right lane (C_R), and the passage of a circulating vehicle through the conflict point on the left lane (C_L). And vehicle type was also recorded to help translate traffic flows to PCE per hour. The second set of information extracted included the times of queue initiation and suspension. A queue period was defined as the time interval between the first occurrence of an entering vehicle yielding to a circulating one and the time the last queued vehicle entered the roundabout.

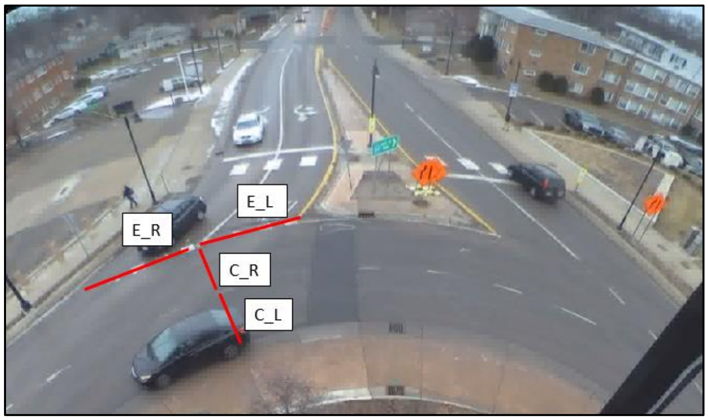


Figure 2. First Set of Data

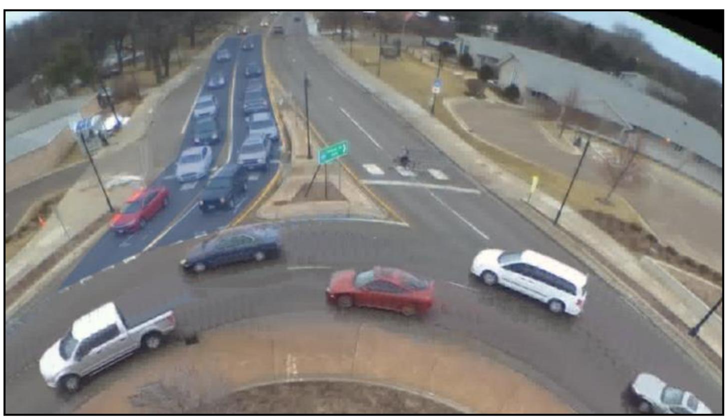


Figure 3. Second Set of Data

Events of interest were collected by hand. At each occurrence or event, a corresponding key in the keyboard was pressed. A keystroke recording program, which was developed using Python, recorded the press times. Further, the press times were saved in a text file.

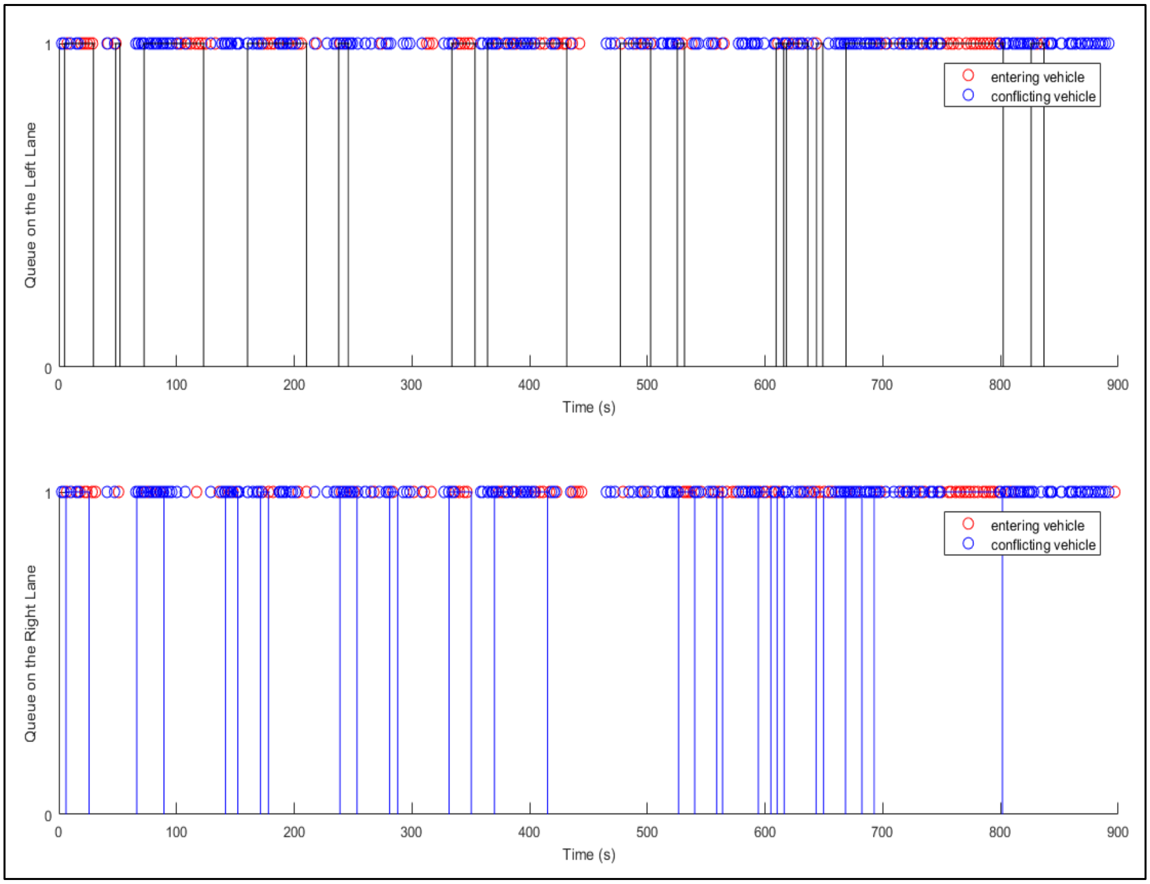


Figure 4. Visualization of Traffic Flow and Queue Time

Figure 4 shows the collected the events of interest for both lanes of an approach during a 15-minute interval. The blue and black lines illustrate occurrences of queue initiations and suspensions (Use of horizontal lines illustrate durations of queues; lines are covered by densely distributed points). A red point represents an entering vehicle and a blue point represents a circulating vehicle. Only the observation in a queue was interested. For example, there are many points between 415 s and 525 s marked by two blue lines. But, there was no queue at the approach of the roundabout during that period. So these points would not be used for flow rate data extraction and gap acceptance data extraction.

3.2 Flow Rate Data Extraction

Traffic volumes at capacity condition were collected for both lanes of the roundabout. For purpose of this study, "at capacity" is defined as the condition when the duration of the queue on the left or right entry lanes is longer than 30 seconds. Then traffic volumes were converted to hourly flow rates in pc/hour. In total, there were 159 data points and

227 data points for the left entry lane and the right entry lane extracted. Figure 5 shows all the data points collected. Blue points represent vehicles on the left entry lane while the red points represent vehicles on the right entry lane. In Figure 5, the clouds of data points for the left lane and for the right lane are partially overlapped and the cloud of data points for the right lane is higher than that for the left lane, which indicates that the capacity of the right entry lane is higher than the capacity of the left entry lane.

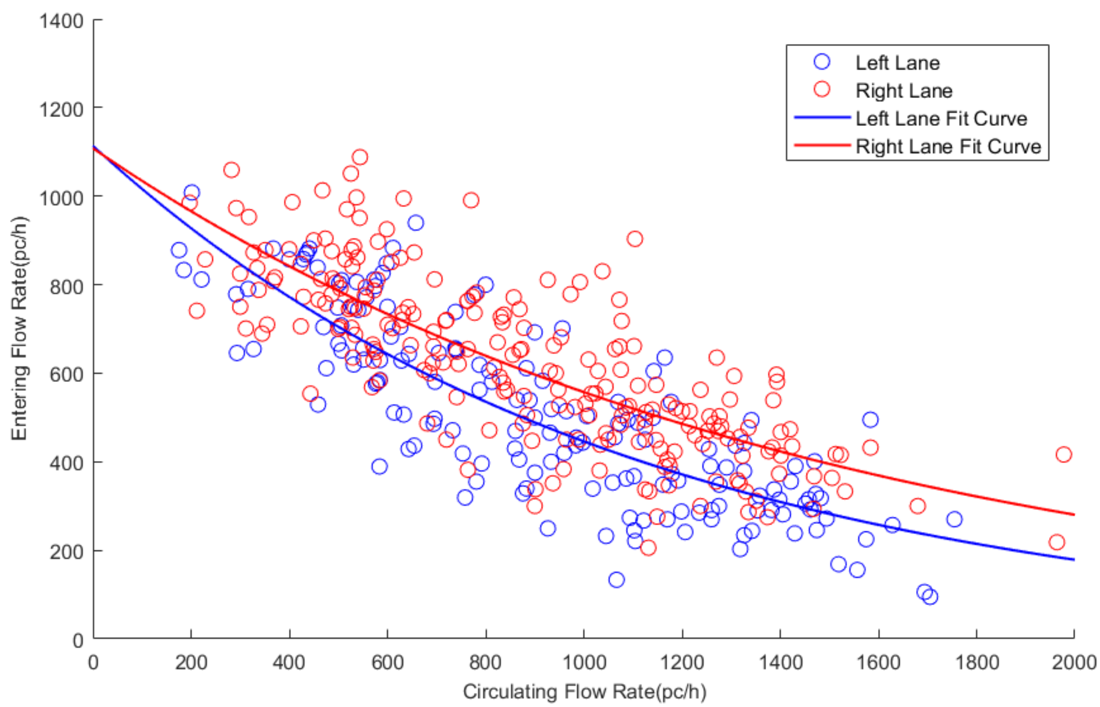


Figure 5. Capacity Curves of Field Data

3.3 Gap Acceptance Data Extraction

The critical headway and follow-up headway were extracted from the video to calibrate the HCM roundabout capacity model. The critical headway is the minimum headway between two consecutive circulating vehicles that an entering driver can use to enter the roundabout safely. The follow-up headway is the average time between two consecutive queued vehicles entering the roundabout before interrupted by a circulating vehicle.

3.3.1 Estimation of Critical Headway

The critical headway cannot be measured directly, so there are lots of methods used to estimate the critical headway. Two most common methods are Raff's Method and Maximum Likelihood Method. Both methods require accepted headways and rejected headways. An accepted headway is any headway utilized by a driver to enter the roundabout while the rejected headway is any headway not utilized by a driver to enter the roundabout. The accepted headway and reject headway vary among drivers and locations as they are based on driving behaviors.

In Raff's method, the critical headway is the headway that is equally likely accepted or rejected by drivers. To apply this method, two cumulative frequency distributions curves for accepted headway and rejected headway should be developed. The value on the horizontal axis which corresponds to the intercept of two cumulative distributions is the value of the critical headway [42].

The Maximum Likelihood Method was used in the analysis described in report NCHRP 572. This method assumes that the size of the critical headway of any driver is between his/her accepted headway and his/her largest rejected headway. The distribution of the critical headway is assumed to be log-normal [43]. To employ this method, observations of vehicles entering the roundabout are used if they meet three requirements; 1) the vehicle should be in a queue, 2) the vehicle should have rejected at least one headway before it accepts one to enter the roundabout, and 3) the largest rejected headway should be smaller than the accepted one [43].

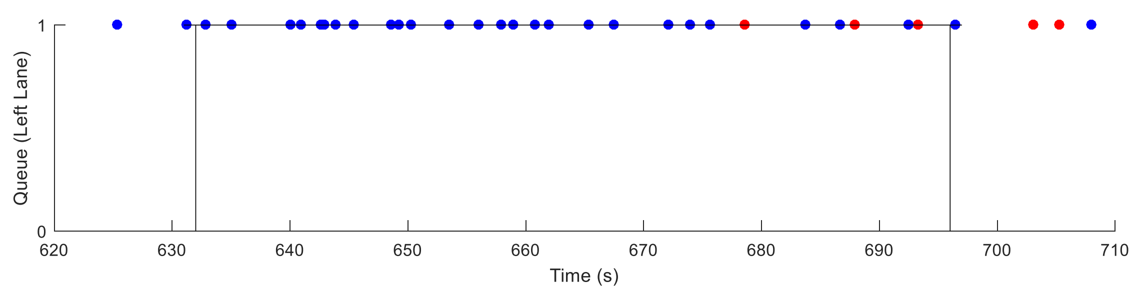


Figure 6 Qualified Observations in Critical Headway Data Extraction

In Figure 6, red points represent the entering vehicles and the blue points represent the circulating vehicles. If an entering vehicle meets three requirements mentioned above, it is a qualified observation. In Figure 6, the fourth and the fifth red points are not qualified because they are not in a queue. The third red point is not qualified because it does not reject any headway before it enters the roundabout. Only the first and the second red points are qualified observations.

After filtering out unqualified observations in the dataset, there were 627 and 833 observations on the left and right lanes respectively. Figure $8a_L$ and Figure $8a_R$ show the histograms of the largest rejected and corresponding accepted headways for the left and right lanes respectively. Blue bars represent accepted headways and orange bars represent largest rejected headways. The most frequent largest rejected headways are between 2 and 3 seconds while the most frequent accepted headway is between 4 and 6 seconds.

In the Maximum Likelihood method, if the i_{th} driver has an accepted headway e^{y_i} and a largest rejected headway e^{x_i}, then a dataset with n drivers has a maximum log likelihood L [44] given by Formula 4:

$$L = \sum_{i=1}^{n} \ln(F(y_i) - F(x_i)) \qquad (4)$$

Where:

y_i = the logarithm of the gap accepted by the i_{th} driver;

x_i = the logarithm of the largest gap rejected by the i_{th} driver; and

$F(\ )$ = the cumulative distribution function of the normal distribution.

The cumulative distribution function of a normal distribution is described by its mean μ and variance σ^2. The parameters of the normal distribution that describes critical headway are the ones that maximize L. The mean t_c and variance s^2 of the critical headway can be calculated with formulas (5) and (6).

$$t_c = e^{\mu + 0.5\sigma^2} \qquad (5)$$

$$s^2 = t_c\left(e^{\sigma^2} - 1\right) \qquad (6)$$

Estimates for μ and σ^2 were computed using the Python Package “scipy”. The critical headway on the left lane had a mean of 4.428 seconds and a standard deviation of 0.985.

The critical headway on the right lane had a mean of 3.992 seconds and a standard deviation of 0.905. Raff's method, not described here in detail, was also applied and resulted in estimates of 4.30 and 3.90 seconds for the left and right lanes respectively.

Formula 7 was used to test whether the sample size available was large enough to reach an accurate estimation. For a confidence interval of 95%, and a 0.1 margin of error, the left and right lanes required sample sizes of 373 and 315 observations respectively, which are much smaller than the available observations used in this study: 627 for the left lane and 833 for the right lane.

$$n = \left\lceil \frac{Z_{\alpha/2}\sigma}{E} \right\rceil \qquad (7)$$

Where:

n = sample size;

σ = population standard deviation;

E = Margin of the error; and

$Z\alpha/_2$ = Z value for a given confidence interval α.

Figure $8b_L$ and Figure $8b_R$ presents the cumulative distribution functions of the largest rejected headway, the accepted headway, and the estimated critical headway for the left and right lanes respectively. For the left lane, 95% of the largest rejected headways were smaller than 5 seconds while only 22% of the accepted headways were smaller than 5 second. 70% of the drivers had a critical headway smaller than 5 seconds. For the right lane, 97% of the largest rejected headway were smaller than 5 seconds while 30% of accepted headways were smaller than 5 seconds. 87% of the drivers had a critical headway smaller than 5 seconds.

3.3.2 Estimation of Follow-up headway

The estimation of the follow-up headway is much simpler than the critical headway. In Figure 7, the time interval between two red points in the red circle is an observation of follow-up headway because these two entering vehicles use the same headway to enter the roundabout. The estimate of the follow-up headway is the mean of all collected observations.

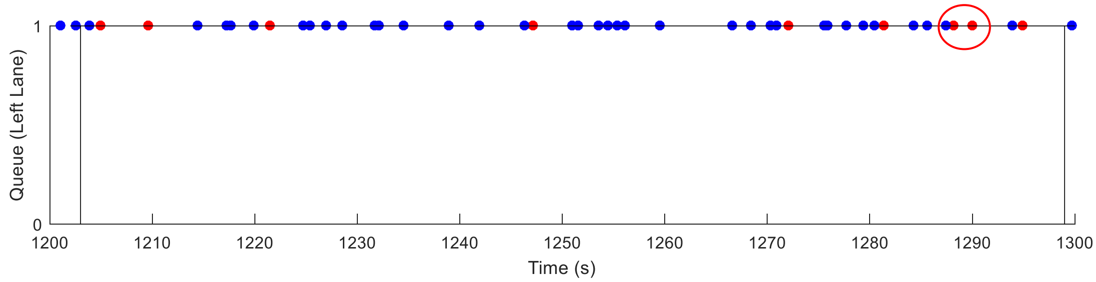


Figure 7 Observations in Follow-up Headway Data Extraction

There are 802 and 1127 follow-up headways on the left lane and on the right lane respectively. The required sample sizes for a 95% confidence were 508 and 406, so the dataset was large enough to provide accurate estimates. The estimate of the follow-up headway on the left and right lane is 3.05 seconds and 2.96 seconds respectively. Drivers on the left lane have larger follow-up headways than drivers on the right lane. The distributions of the follow-up headways in different sizes are illustrated in Figure 9.

3.4 Capacity Model for the Roundabout in Richfield

Both Linear and Exponential regression model forms were tested for goodness of fit to the collected capacity flows. Table 2 shows the parameter estimation and goodness-of-fit scores. The exponential model provided a better fitting to the flow rate data than the linear model as suggested by a larger R^2 and a smaller RMSE. The correlations of two exponential models here were not ideal, but they still had RMSE values smaller than those in the studies that developed roundabout capacity models in HCM 6 and HCM 2010, which had RMSE values of 167 and 183 respectively [9].

Table 2. Fitted Regression Models of Flows at Capacity

	p_1	p_2	SSE	R^2	RMSE
Linear Model (Left lane)	925.4	-0.4540	2.226e+06	0.674	119.08
Linear Model (Right lane)	989.3	-0.4157	3.268e+06	0.615	120.52
Exponential model (Left lane)	1114	-0.0009151	2.151e+06	0.685	117.10
Exponential model (Right lane)	1108	-0.0006874	3.269e+06	0.615	120.50

The formulas for the exponential models, referred to in the rest of the thesis as the Richfield Model, for the left and right lanes are as follows:

$$C_{e,R,pce} = 1108e^{(-0.687\times10^{-3})v_{c,pce}} \quad (6)$$

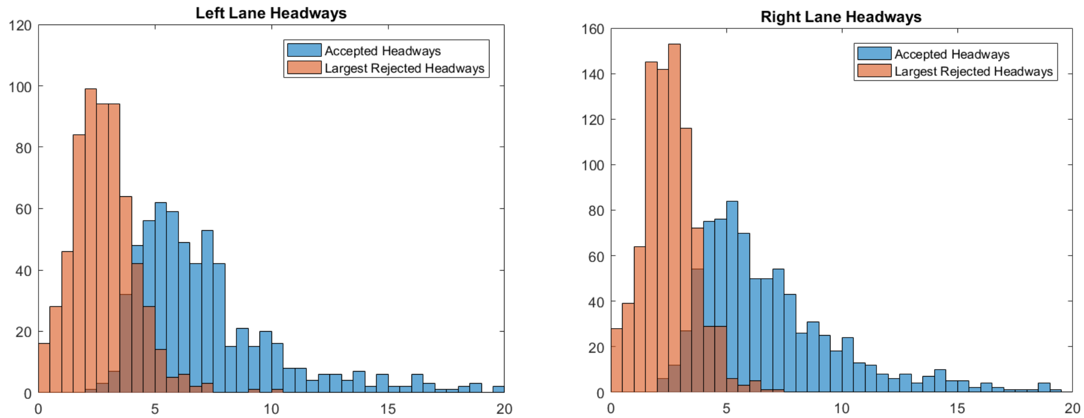
$$C_{e,L,pce} = 1114e^{(-0.915\times10^{-3})v_{c,pce}} \quad (7)$$

3.5 Comparison of parameters in the field data and in HCM

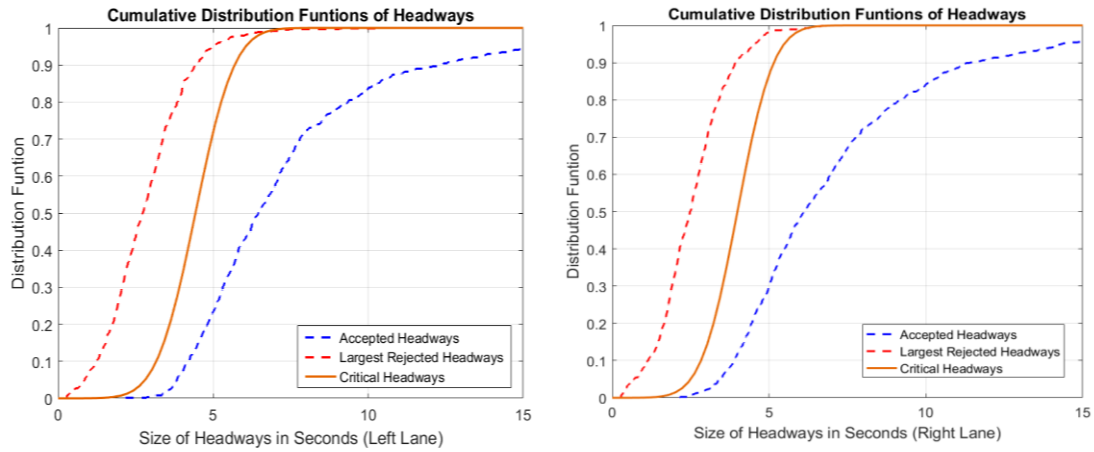
HCM provides two formulas (Formula 2 and Formula 3) to recalculate the coefficients of its default capacity model. In these two formulas, coefficient A is the intercept of the curve, which only relates with the follow-up headway. A smaller follow-up headway produces in a larger intercept. Table 3 presents different headways resulting from different models as well as the ones observed in the field. The follow-up headway in HCM6 is the shortest, resulting in the highest capacity as the circulating flow approaches zero. Coefficient B is the slope which controls the rate of change. A long critical headway and a short follow-up headway can lead to a rapidly decreasing capacity. Among the three models, the model in HCM 6 has the greatest rate of change.

Table 3. Comparison of Headways in Field Data and HCM

		Critical headway	Follow-up headway
Richfield Model	Left Lane	4.910	3.232
	Right Lane	4.099	3.249
Field Observed	Left Lane	4.428	3.049
	Right Lane	3.992	2.964
HCM 6	Left Lane	4.650	2.667
	Right Lane	4.320	2.536
HCM 2010	Left Lane	4.293	3.186
	Right Lane	4.113	3.186



(aL) (aR)



(bL) (bR)

Figure 8. Observations of Accepted and Largest Rejected Headways. Histogram of the Critical Headway (a_L and a_R) and Fitted Cumulative Distributions (b_L and b_R)

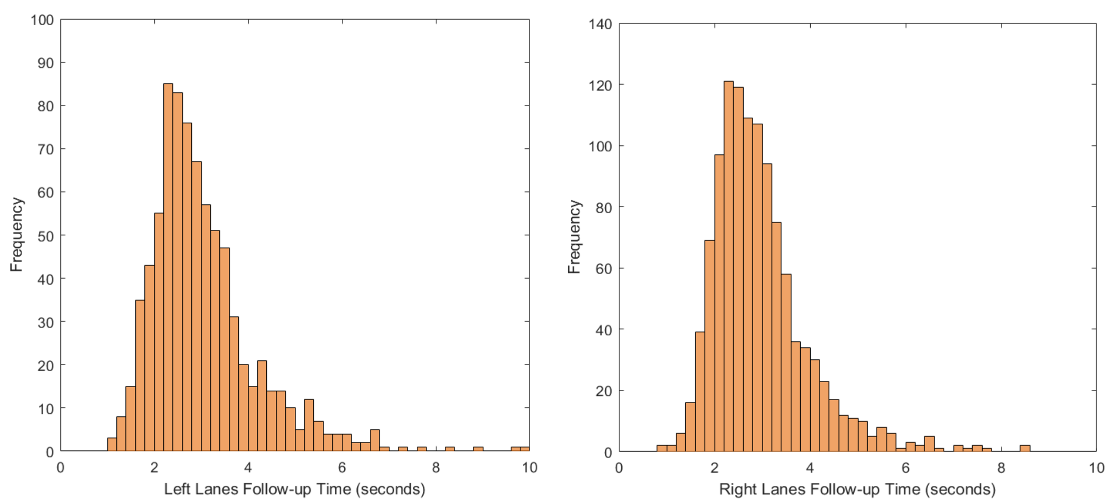


Figure 9. Histogram of the Follow-up Headways

3.6 Summary

In this chapter, traffic flow rates were extracted from the video records. Two exponential models (Richfield Model) for the right entry lane and the left entry lane were built based on 159 data points and 227 data points. Besides, the critical headways on two entry lanes at Richfield roundabout was estimated using the maximum likelihood method. The critical headways on the left lane and right lane were 4.428 and 3.992 seconds. The follow-up headways were estimated with mean of all observations. The follow-up headway on the left lane and the right lane were 3.05 and 2.96 seconds.

CHAPTER 4

4 EVALUATION OF ROUNDABOUT CAPACITY MODEL IN HCM

In this chapter, two default roundabout capacity models in HCM and two calibrated roundabout model using different calibration strategies were compared with the Richfield model. Two measurements were used to quantify the difference between two models. The formulas of two measurements are as follows:

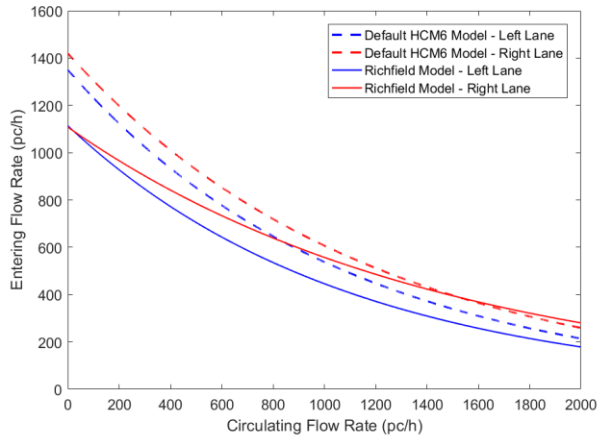
Capacity Difference = Model 1 – Model 2 (8)

Relative Difference = (Model 1 – Model 2) / Model 2 (9)

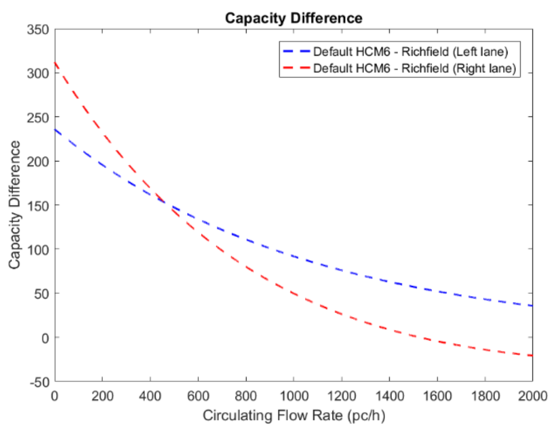
4.1 Default HCM 6th Edition Model vs Richfield Model

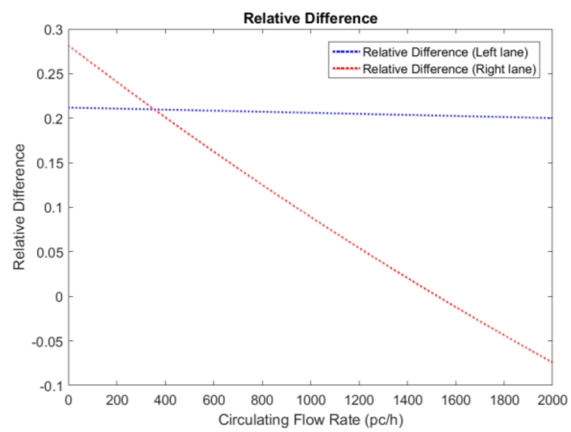
The comparison between the default two-by-two roundabout capacity models in HCM 6 and Richfield model are presented in Figure 10a. In Figure 10a, the capacities estimated by the Richfield model are in general lower than the capacities produced by HCM 6. For the right lane specifically, under the same circulating flow rate, the roundabout capacity in HCM 6 is higher than the one estimated by the field data. When the circulating flow rate is higher than 1600 pc/h, the difference between the two models reduces. For the left lane, the capacity in HCM 6 is always higher. Figure 10b shows the differences in capacity estimation under different circulating flow rates while Figure 10c shows the relative difference of the model in HCM 6 as compared to the Richfield model.

Specifically, on the right lane, the difference in estimated capacity has a highest value of about 310 pc/h when the circulating flow rate is zero. The relative difference starts at 30%, which means the capacity model in HCM 6 overestimates the capacity of the roundabout in Richfield by 30% when the circulating flow rate is zero. As the circulating flow rate increases, the capacity difference between two models as well as the relative difference drops and both reach zero when the circulating flow is about 1600 pc/h. On the left lane, the difference between capacity models starts at 240 pc/h and drops to 40 pc/h as the circulating flow rate reaches 2000 pc/h. According to the graph of relative difference, the capacity model in HCM 6 overestimates the capacity of the roundabout in Richfield by approximately 20% regardless of the level of circulating flow.



(a)



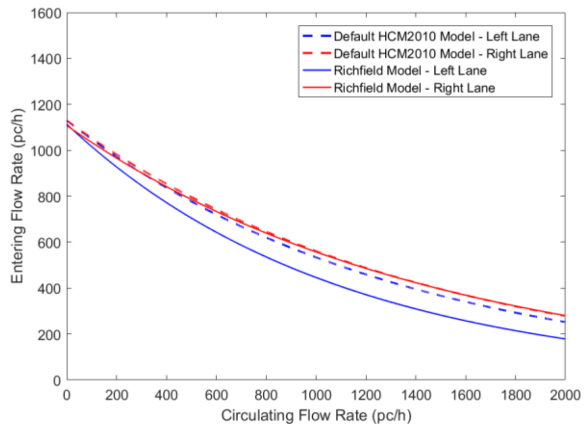


(b) **(c)**

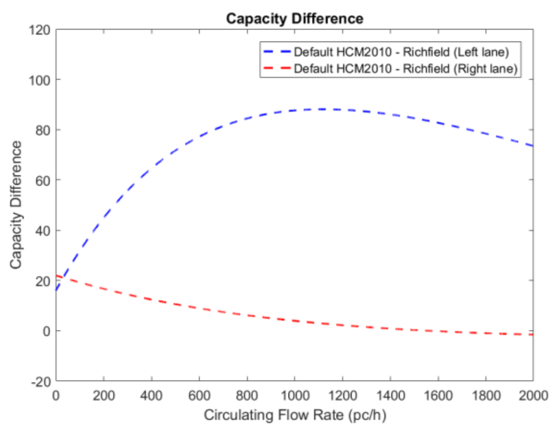
Figure 10. Comparison between the HCM 6th Edition and Richfield Models

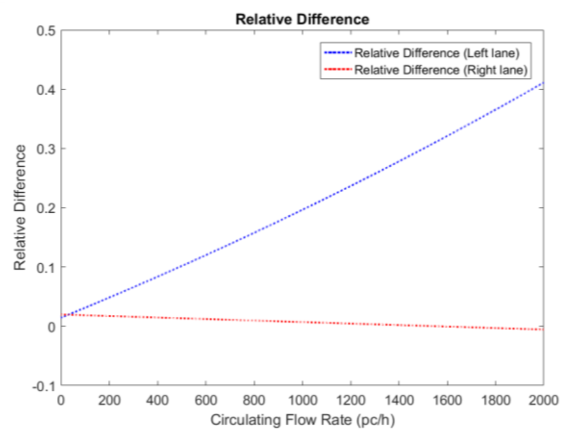
4.2 Default HCM 2010 Model vs Richfield Model

The comparison between the default two-by-two roundabout capacity models in HCM 2010 and the Richfield model are presented in Figure 11. In Figure 11a, the capacities estimated by the Richfield model and the HCM 2010 model are almost identical for the right lane. The difference in capacity decreases from 20 pc/h to 0 pc/h and the relative difference decrease from 2% to 0% when the circulating flow increases from 0 to 2000 pc/h. For the left lane, HCM 2010 overestimates the capacity of the Richfield roundabout by 2% to 41% as the circulating flow increases from 0 to 2000 pc/h. And the difference in capacity increases from 18 to 89 pc/h when the circulating flow increases from 0 to 1000 pc/h, and then it drops to 74 pc/h when the circulating flow reaches 2000 pc/h.



(a)





(b) (c)

Figure 11. Comparison between the HCM 2010 and Richfield Models

4.3 Default HCM 6 Model vs Fully Calibrated HCM Model

Figure 12 compares the values produced by the default HCM 6 model with the fully calibrated HCM model. In fully calibrated model, both coefficients in default HCM model were recalculated with the estimated critical headway and the follow-up headway using Formula 2 and 3.

According to Figure 12, when the circulating flow rate is low, the fully calibrated model for the right lane experiences less difference with Richfield model. The capacity difference between the calibrated model and Richfield model under low circulating flow rate (< 300 pc/h) is between 80 to 110 pc/h, with a relative difference no larger than 10%. In Figure 10b, the capacity different between the default HCM model and Richfield model under low circulating flow rate is between 200 to 310 pc/h, which is much larger than that in Figure 12. Under moderate-to-high circulating flow rate (> 300 pc/h), the capacity different between calibrated model and Richfield model is between 25 to 80 pc/h. Therefore, the calibrated model for the right lane is closer to the Richfield model than the default HCM 6 model.

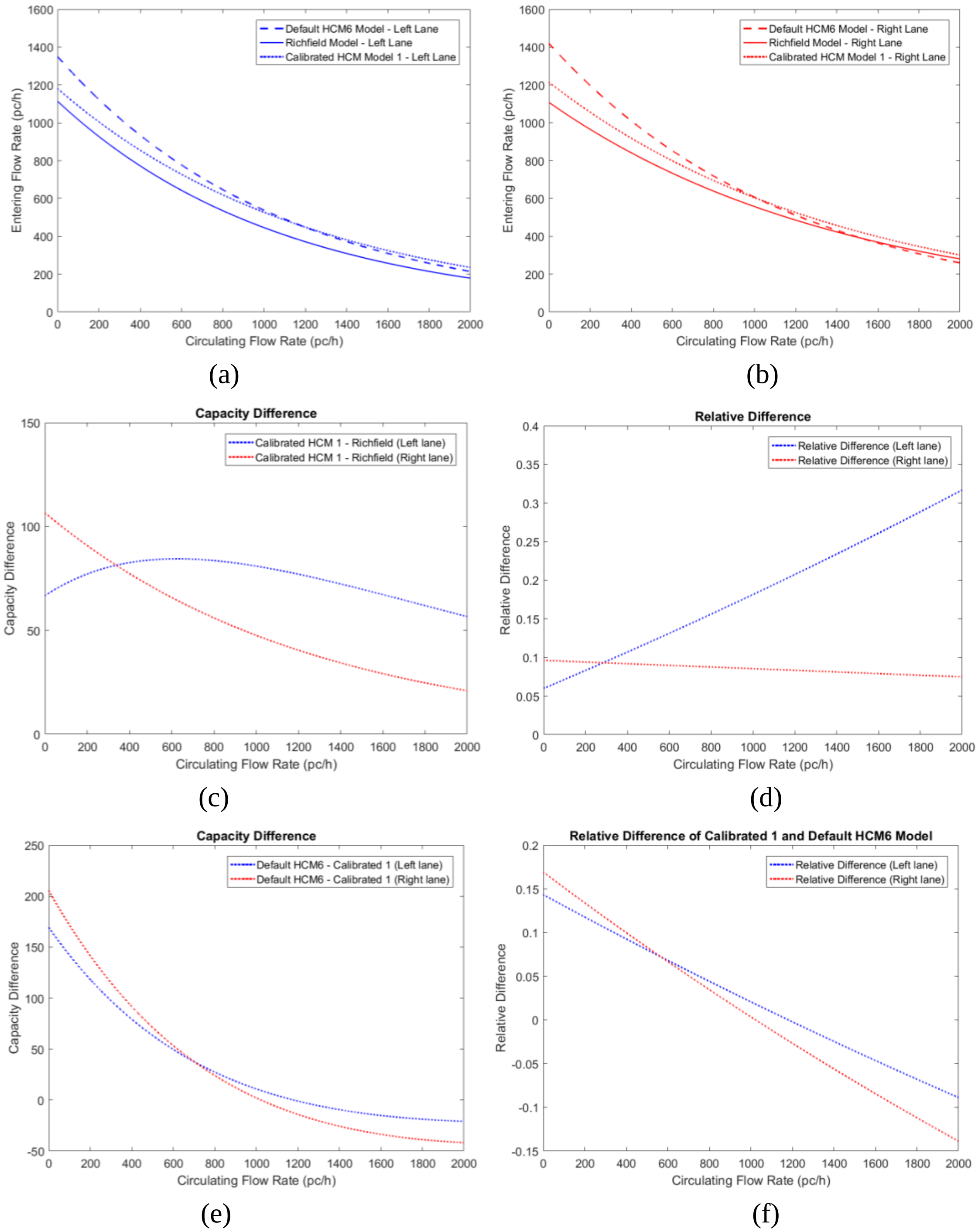


Figure 12. Comparison between Default HCM6 and Fully Calibrated HCM Models

For the left lane, the capacity difference between calibrated model and Richfield model is always between 50 to 80 pc/h while the capacity difference between default HCM 6 model and Richfield model is between 40 to 240 p/h. Therefore, the calibrated model for the left lane is also closer to the Richfield model than the default HCM 6 model. Figure 12e and Figure 12f shows the difference between the default HCM model and fully calibrated model, which reflect how much the model calibration changes the default model.

The accuracy of the calibrated model can also be compared with HCM 2010 model. These two models have similar accuracy for the left lane while HCM 2010 model has higher accuracy for the right lane. The capacity difference between the HCM 2010 model and Richfield model is only about 15 pc/h no matter how large the circulating flow is.

4.4 Default HCM 6 Model vs Partially Calibrated HCM Model

Figure **13** compares the values produced by default HCM 6 model with the partially calibrated model. Partially calibrated model only recalculates coefficient A with estimated follow-up headway, which involves much less effort than calibrating both coefficients. Surprisingly, the partially calibrated model produces results that are even closer to Richfield model than the fully calibrated model.

For the right lane, under low circulating flow rate (<300 pc/h), the capacity difference between partially calibrated model and Richfield model is about 45 to 110 pc/h, and the partially calibrated model overestimates the capacity by about 5% to 10%. Under moderate circulating flow rate (300 to 800 pc/h), these two models are nearly equivalent. Under high circulating flow rate (800 to 2000 pc/h), the capacity different is between -30 to -60 pc/h, and the partially calibrated model underestimates the capacity by 4% to 20%. For the left lane, the capacity different between partially calibrated model and Richfield model is between 50 to 70 pc/h under low circulating flow rate (< 300 pc/h). The capacity different is between 10 to 50 pc/h when the circulating flow rate is moderate or high (> 300 pc/h). The calibrated model for the left lane overestimates the capacity by 7%. Therefore, the partially calibrated model can produce better prediction than the fully calibrated model and the default HCM 6 model.

When comparing the partially calibrated model with default roundabout capacity model in HCM 2010, it is found that default HCM 2010 model has higher accuracy for the right lane. But default HCM 2010 model has worse accuracy for the left lane than the partially calibrated model. Overall, the partially calibrated model is closer to the Richfield model than the HCM 2010 model.

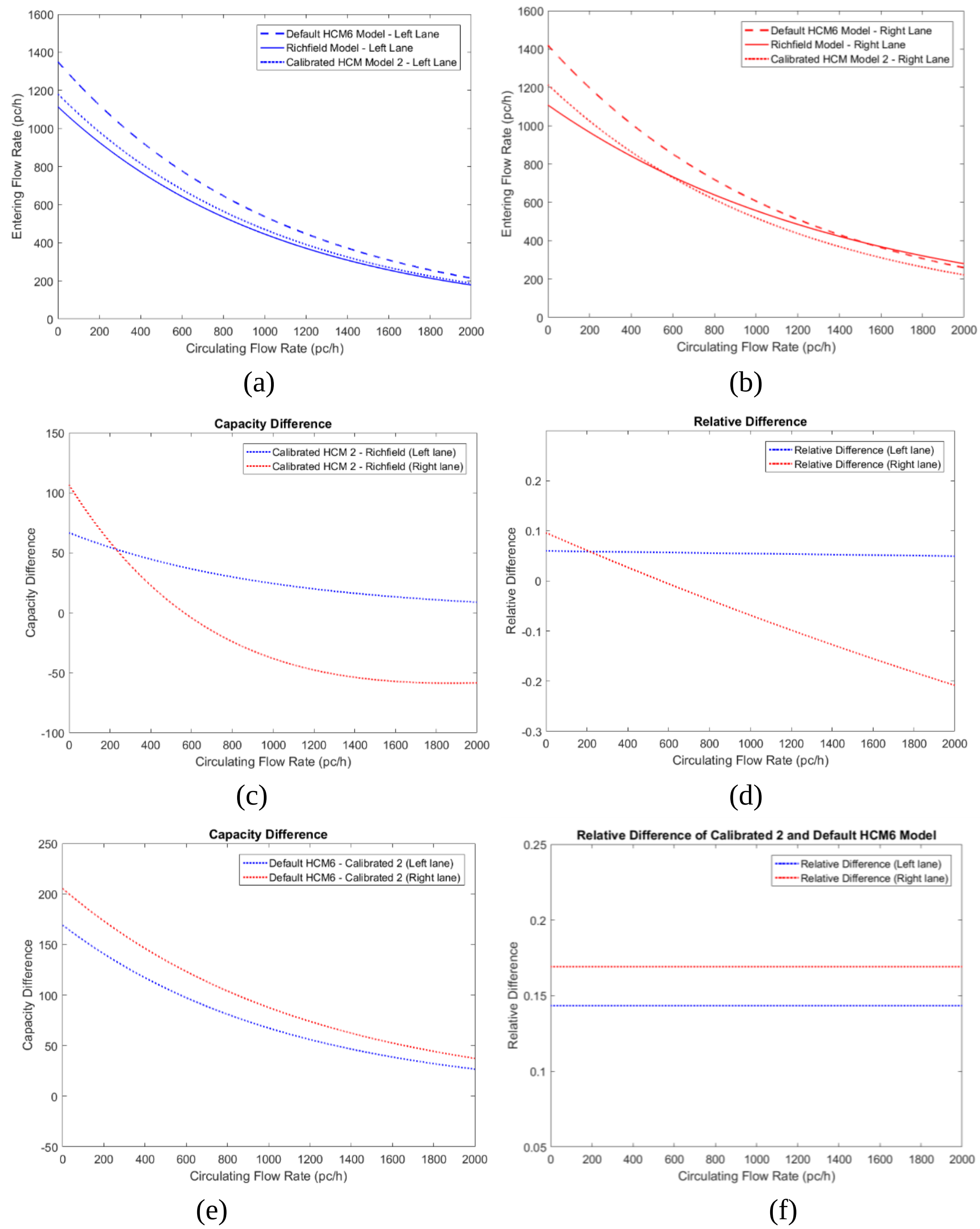
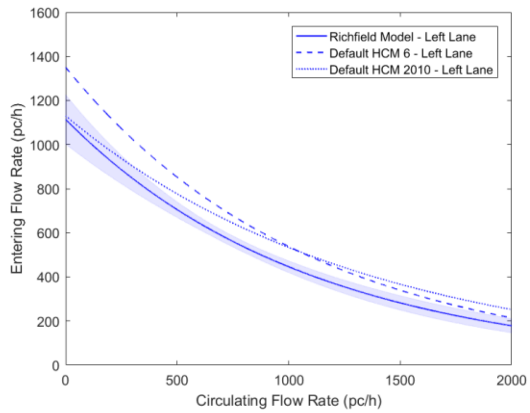


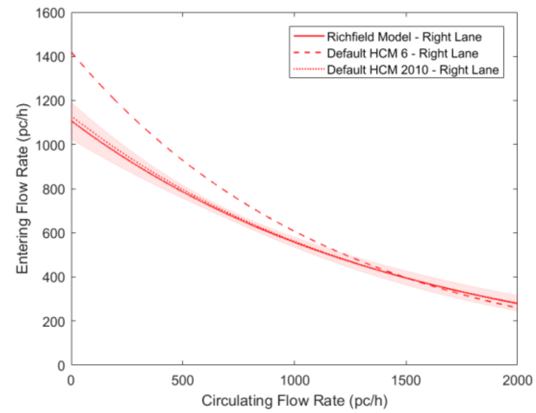
Figure 13. Default HCM 6 Model VS Partially Calibrated HCM models

4.5 Confidence interval and Prediction Interval of Mean Function

In Figure 14, 95% confidence intervals and prediction intervals were built based on the flow rate data in the field. In each graph, the dashed line is the default HCM 6 model, the dotted line is the default HCM 2010 model, and the solid line is the Richfield model. Figure 14a and Figure 14b shows the confidence interval of Richfield model at the left lane and the right lane while Figure 14c and Figure 14d shows the prediction interval of Richfield model at the left lane and the right lane.



(a)



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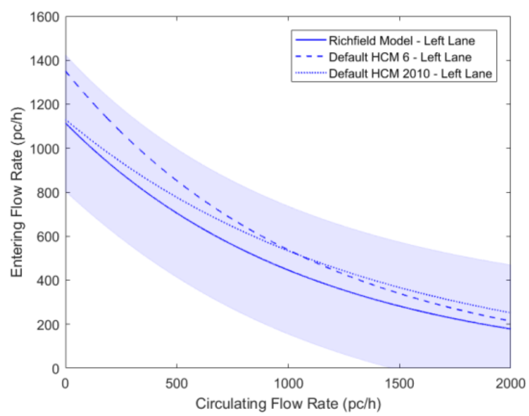

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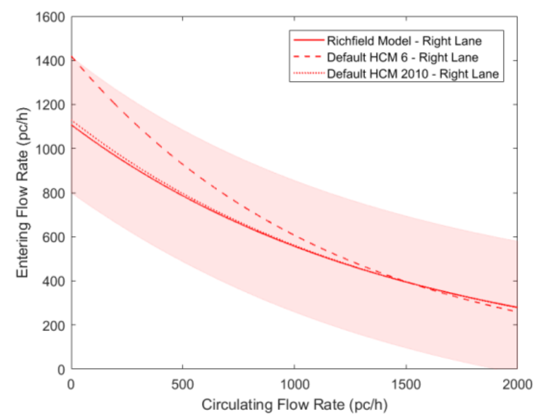


(d)

Figure 14 Confidence Interval and Prediction Interval of Mean Function

The confidence interval represents the range of the expectation of the response, which is E(Y|X=x). In this case, confidence interval indicates the range of the expectation of the entering flow rate given a circulating flow rate. The area of the confidence interval means there is 95% probability that a true mean function is inside this area. If there is another model that lays inside the confidence interval of the Richfield model, then this model and Richfield model can be regards as the same model and this model can also be used to represent the condition at the local roundabout. According to Figure 14a, part of the default 2010 model is inside the confidence interval of Richfield model for the left lane, while the remaining part of the default HCM 2010 model and the HCM 6 model is outside of the confidence interval of Richfield model for the left lane. It means neither default HCM 2010 model or default HCM 6 model can be an adequate representative of the actual condition at the roundabout in Richfield. In Figure 14b, the default HCM 2010 model is completely inside the confidence interval while most part of the default HCM 6 model is outside of the confidence interval of the Richfield model, which means default HCM 2010 model of the right lane can represent the condition at the roundabout in Richfield while the default HCM 6 model cannot.

The prediction interval is used when there is a need to predict the response given an observed value of the predictor using the estimated mean function. For example, if a value of entering flow rata is observed, and this value is imported to the mean function to get a prediction of the entering flow rate, the true value of the entering flow rate has 95% probability of being inside of the prediction interval. Figure 14c and Figure 14d show the prediction intervals of Richfield models for the left lane and right lane respectively. The prediction intervals of Richfield models have large width because the collected data have a large variance. The regression model assumes a constant residual variance, which means the average magnitude of the residual does not change no matter how large the predicter is. Although inconstant residual variance can be observed in Figure 5, the exponential regression model still assumes that the magnitude of the residual is fixed when the circulating flow rate increases from 0 to 2000 pc/h. That is the main reason why the width of the prediction interval does not change much in Figure 14c and Figure 14d, even though the variance of the data points changes a lot when the circulating flow increases from 0 to 2000 pc/h. Due to the large prediction interval, if default HCM 6 model is used for predicting the entering flow, there is still possibility that the value predicted is the true value of the entering flow as this value is inside the 95% prediction interval. But it is relative safer to use the Richfield model instead of the default HCM 6 model to predict the capacity of the local roundabout because Richfield model is closer to the center of the data.

There are two main reasons resulting in the large variance in entering flow rates. The first reason is that the maximum entering flow of a roundabout approach is not stable. Besides circulating flow rate, it can be affected by many other factors, such as the acceleration or deceleration of heavy vehicles. The second reason is that a short time-interval was used here and any queue lasting longer than 30 seconds was used to extract the flow rate, as there were few queues that can last longer than several minutes. On the other hand, there is a need for a new type of model instead of the regression model to represent the capacity of a roundabout. Because it is not reasonable enough to use a line to illustrate a cloud of data points.

4.6 Summary

HCM recommends users to calibrate the default roundabout capacity model. In this case, both calibrated models had higher accuracy than the default HCM 6 model, which indicates that model calibration is useful. HCM also mentioned that only calibrating the intercept of the default model with estimated follow-up headway can get a model as good as the model calibrating both coefficients. In this thesis, the partially calibrated model using the follow-up headway had a slightly higher accuracy than the fully calibrated model, which verifies the statement in HCM.

CHAPTER 5

5 MICROSCOPIC SIMULATION OF THE ROUNDABOUT

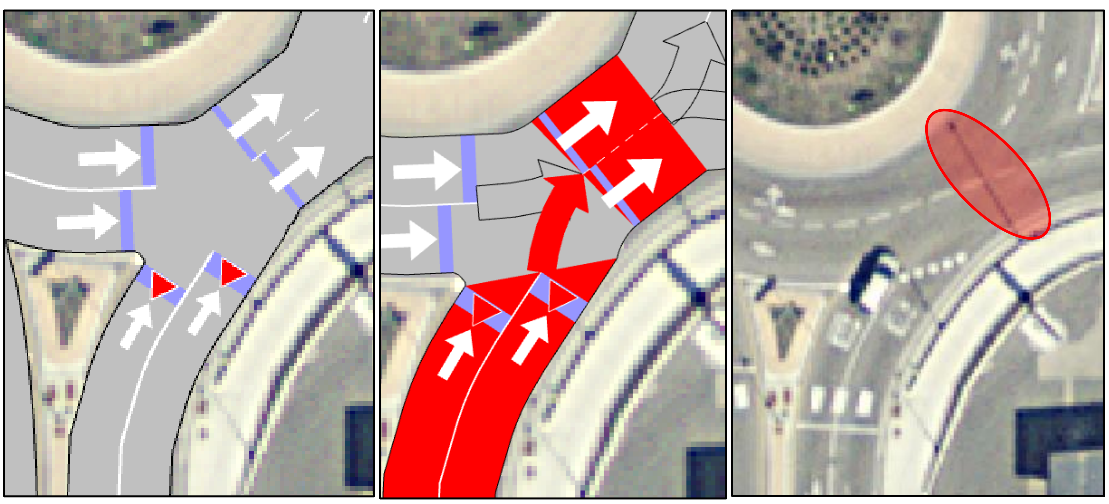
In this chapter, the capability of AIMSUN to conduct a realistic roundabout simulation was explored. The calibrated model should produce a similar roundabout capacity curve as that in HCM 6. It was assumed that if the roundabout model could produce the same critical and follow-up headways as those in HCM 6, this model would also generate the same capacities as the default roundabout capacity model in HCM 6. To find the important parameters for model calibration in AIMSUN, a sensitivity analysis was conducted.

5.1 Simulation Model Build-up

A roundabout simulation model was set up in AIMSUN. The network Editor was first used to build the geometry of the roundabout. The study roundabout with two entering lanes and two circulating lanes is located at Portland Ave and 66th Street (Figure 15)

Figure 15. Geometry of the Roundabout

The model was built on a high-resolution base map so that the geometry of the roundabout model can follow the roundabout in Richfield. There were loop detectors placed on two circulating lanes and two entry lanes to record the traffic flow rate data and gap acceptance data. After the roundabout model was built roughly, more attention was paid to adjust the geometric parameters. Because geometric parameters control the physical characteristics of the roundabout, which have important effects on the vehicles' behaviors in the roundabout. The geometric parameters of the roundabout simulation model are radius, entry angle, entry length, entry width, turning length, length of the weaving section, etc. In AIMSUN, these parameters affect the behavior of the vehicle by modifying the travel distance and the travel speed of the vehicle. Setting geometric parameters properly is a prerequisite to make vehicle behave normally and to get a realistic roundabout model. The geometric parameters of the roundabout simulation model should be close to the actual design of the roundabout. It means the radius, the entry angle, entry length, and entry width should be identical to a roundabout in the field, the stop line on the entry lane should be where it is, and the conflict zone in the simulation model need to be close to the conflict point in the field. Besides, the length and the shape of the turning for entering vehicles should be modified carefully. Because turning length and turning angle affect the time that a vehicle entering the roundabout and affect the gap acceptance behavior of the vehicle.



a. the stop line   b. the tuning of the entering vehicle   c. the conflict zone

Figure 16. Geometric Parameter of the Roundabout Simulation Model

There are some factors existing in the field but are ignored in AIMSUN. For example, the distance between the entry lane and the exiting lane, and the flow rates on exit lanes can affect the critical headway of the entering vehicle, but neither of them are considered by AIMSUN.

5.2 Sensitivity Analysis

To calibrate the roundabout model to an extent that it can generate the same critical headway and follow-up headway as those in HCM 6, the parameters used for calibration should be explored first. Even though the user's manual of AIMSUN provides some information about simulation parameters, it is still unclear whether and how these parameters affect the critical headway and the follow-up headway. Therefore, sensitivity analysis is necessary.

Sensitivity analysis is the study exploring how the uncertainty in the model input effects the uncertainty in the model output [45]. In sensitivity analysis, the relation between the output (the critical headway and the follow-up headway) and several parameters in AIMSUN was analyzed. To test the main effect of each parameter, one-factor-at-a-time (OFAT) experiment was first conducted. To test the interactions between parameters, full factorial experiment was then conducted. After the sensitivity analysis, two linear models for the critical headway and the follow-up headway were built respectively.

In the process of the sensitivity analysis, hundreds of combinations of parameters should be imported into AIMSUN to run the simulation. It is time-consuming if all these works are accomplished by hand. To enhance the efficiency and accuracy of the simulation work, a tool called 'RSIM' was developed with MATLAB. It was utilized to adjust the values of simulation parameters, run simulation in AIMSUN console, export the gap acceptance data, and save headway data to a database. To use this tool, two files should be prepared in advance: a CSV file including all combinations of parameters that need to be tested, an AIMSUN file (ANG) in which a roundabout model has been built.

Figure 17 shows the work flow of the tool. At first, it opens the prepared CSV file and selects a combination of parameters. Then it generates a CSV file which includes the combination of parameters to be imported. Then this tool imports parameters to AIMSUN model and run the simulation in AIMSUN console. During the simulation, an API script (see Appendix A1) in the simulation model exports all the gap acceptance data and save them to a CSV file. After the simulation, the critical headway and the follow-up headway are estimated using maximum likelihood method. After each simulation run, the combination of parameters used in this run is saved to the database, along with the estimated critical headway and the follow-up headway. All the steps mentioned above are repeated until all combinations of parameters are tested. Using this tool, the time needed for one run of simulation is about 28 seconds, which is much shorter than finishing all these works by hand.

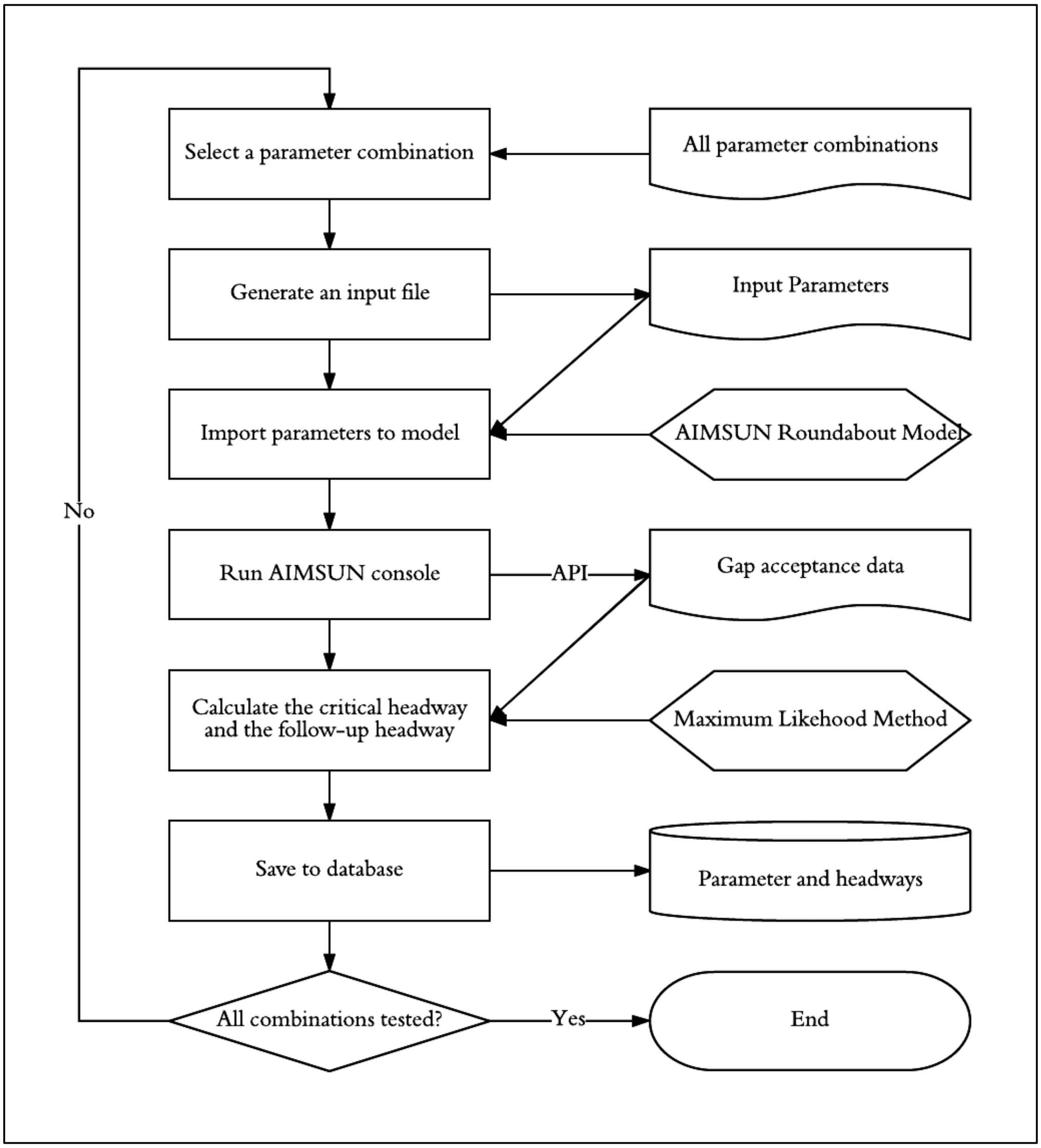


Figure 17. The Work Flow of 'RSIM'

The sensitivity analysis only focused on the conflict zone at one approach of the roundabout. During the simulation, the model generated two groups of vehicles from southbound and northbound and there was no vehicle from westbound or eastbound. In Figure 18, all the vehicles from the southbound go to eastbound and all the vehicle from northbound go to southbound. The vehicle from southbound (marked by orange area) has higher priority and may block the way of the vehicle from northbound. The vehicle from northbound (marked by blue area) has lower approach and need to wait at the entry until a large headway appears. These vehicles can never block vehicles from southbound.

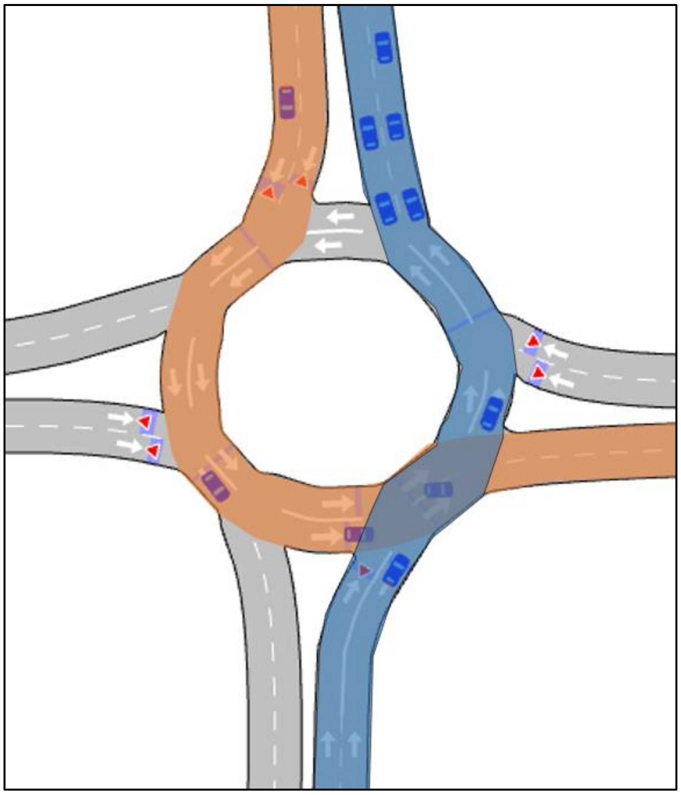


Figure 18 Two Conflicting Travel Trajectories

Table 4. Values for Parameters in OFAT Analysis

Parameters	Notation	Unit	Base	Values									
Initial Safety Margin	ISM	sec	1.2	0	0.3	0.6	0.9	1.2	1.5	1.8	2.1	2.4	2.7
Final Safety Margin	FSM	sec	0.5	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Visibility to Give Way	VDA	ft	75	15	30	45	60	75	90	105	120	135	150
Visibility along Main Stream	VDM	ft	155	15	50	85	120	155	190	225	260	295	330
Clearance	CLE	ft	4.1	0.82	1.64	2.46	3.28	4.10	4.92	5.74	6.56	7.38	8.20
Speed Acceptance	SA	NA	1	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20	1.25
Max Give-way Time	MGT	sec	110	90	95	100	105	110	115	120	125	130	135
Max Acceleration	MA	ft/s2	8.2	1.64	3.28	4.92	6.56	8.20	9.84	11.48	13.12	14.76	16.40
Max Deceleration	MD	ft/s2	16.4	3.28	6.56	9.84	13.12	16.40	19.68	22.96	26.24	29.52	32.80
Sensitivity Factor	SF	NA	1	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Gap	GAP	sec	1	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Section Reaction Time at Stop	RAS	sec	1.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Section Maximum Speed	MSP	mph	25	5	10	15	20	25	30	35	40	45	50
Turning Speed	TS	mph	17	5	8	11	14	17	20	23	26	29	32

5.2.1 One-factor-at-a-time Analysis

In one-factor-at-a-time (OFAT) analysis, only one parameter is varied at a time while all the other parameters are fixed at their baseline values. The change in the dependent variable is ascribed to the change in one parameter. However, this analysis cannot identify the interactions between parameters and may produce biased results if parameters have interactions. In this study, OFAT was used to explore the usefulness of parameters for model calibration. Before the analysis, fourteen parameters that potentially affect drivers' gap acceptance behaviors were selected. Each parameter had ten levels. Table 4 lists all the levels for parameters and their baseline values. Therefore, in this analysis, there were 127 different combinations of parameters. Each combination was imported in model and run in five replications to get a robust result. In total, there were 635 simulation runs.

Among all the fourteen parameters, Initial safety margin, Final Safety Margin, Visibility to Give Way, and Visibility along Main Stream control driver's behavior on a turning. Clearance, Speed Acceptance, Max Give-Way Time, Max Acceleration, Max Deceleration, Sensitivity Factor, and Gap control the car-following model or dynamic model for a vehicle type. Section Reaction Time at Stop, and Section Maximum Speed control driver's behavior on a section.

Gap acceptance model in AIMSUN

The gap acceptance model in AIMSUN plays the most important role in controlling the drivers' gap acceptance behavior. Figure 19 shows how the gap acceptance model works and its related parameters. In gap acceptance model, the vehicle with lower priority (VEHY) adjusts its driving condition according to the condition of circulating vehicle in the roundabout (VEHP), only when its distance to VEHP along the main road is shorter than the visibility along main stream of the turning. When the distance of VEHY to the end of the entry lane is shorter than the distance of visibility to give way, the gap acceptance model will start to be applied to this vehicle. Then VEHY will calculate the time it needs to reach the conflict zone (TP1), and the time it needs to pass the conflict zone (TP2). It will also estimate the time that VEHP needs to reach the conflict point (ETP1), and the time pass the conflict point (ETP2).

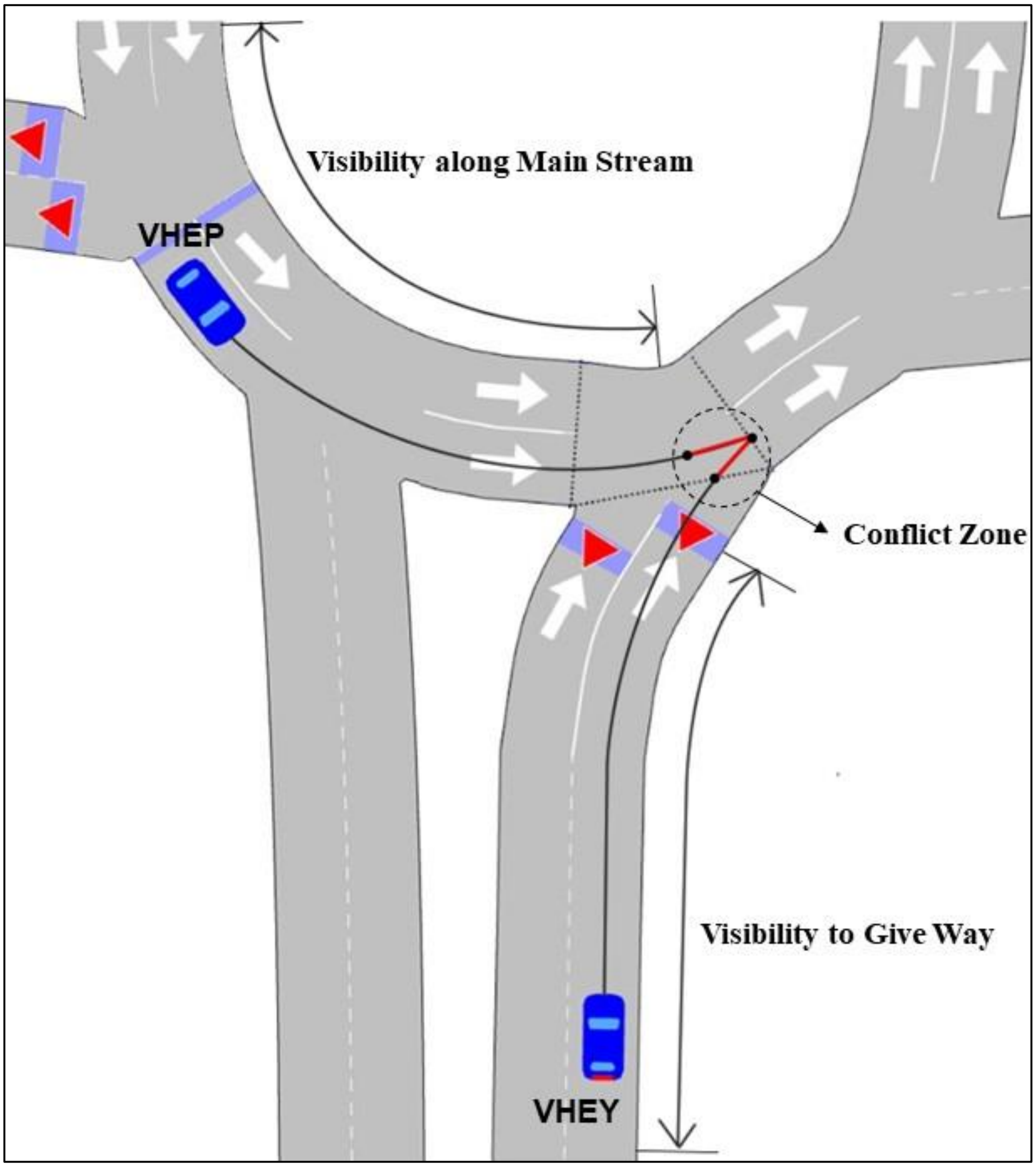


Figure 19. AIMSUN's Gap Acceptance Model at a Roundabout

If TP2 plus the safety margin time is less than ETP1, which means VEHY can cross the intersection before VEHP arrives, then VEHY will accelerate and enter the roundabout. If ETP2 plus the safety margin time is less than TP1, which means VEHP passes the intersection before the arrival of VEHY, then VEHY will search for the next vehicle on the main stream. For all the other conditions, VEHY will decelerate and stop before the stop line.

Results of Initial Safety Margin

Initial safety margin affects the gap acceptance behavior of VEHY. If the initial safety margin is small, TP2 plus the safety margin is more likely to be smaller than ETP1, then the yielding vehicle can accelerate and enter the roundabout, which results in a small critical headway. The result is consistent with this effect. When the initial safety margin increases from 0 to 2.7 seconds, the critical headway increases from 3.5 to 6.2 seconds.

Results of Final Safety Margin

After VEHY waits at the stop line for a long time, the safety margin will start to decrease from the initial safety margin to the final safety margin. As the give-way time was set to be 90 seconds, few vehicles in the simulation can wait for this long, so the safety margin did not decrease and this parameter was not used. According to the result, the critical headway and the follow-up headway did not change when the safety margin increased from 0.1 to 1 second.

Results of Visibility to Give Way

Visibility to give way controls the distance of VEHY to the stop sign when the gap acceptance model starts to be applied. The length of the visibility includes both the lengths of sections and turnings. The result shows that visibility to give way has little effect on the critical headway and the follow-up headway. These two headways are nearly unchanged when the visibility to give way increases from 15 to 150 ft.

Results of Visibility Along Main Stream

Any VEHY waiting at the stop line only considers the VEHP within its visibility along main stream. If this parameter is set to be 0, VEHY cannot see any VEHP on the main road, then it will enter the roundabout and force VEHP to stop. The user manual of AIMSUM mentions that this distance can extend to the preceding section of main stream [46], but it should be clarified that the visibility distance does not extend to other entry lanes. According to the result, visibility along main stream has little effect on the follow-up headway, but it has relatively large effects on the critical headway when its value is between 15 to 85 ft.

Results of Additional Reaction Time at Stop

This parameter sets the reaction time for a road section, which is different from a global parameter called 'reaction time at the stop' in Experiment Editor. According to the result, additional reaction time at stop only affects the follow-up headway. As it increases from 0.2 to 2 seconds, the follow-up headway increases from 1.9 to 2.2 seconds. Because when the reaction time increases, the following vehicle spends more time to react to the preceding vehicle before it accelerates. But it is unclear that why an increase of 1.8 seconds in reaction time at stop results in an increase of only 0.3 second in the follow-up headway.

Results of Gap

Gap is a parameter used in car-following model. It describes the minimum headway between the preceding vehicle and the following vehicle. In this analysis, gap did not show significant influence on the critical headway nor the follow-up headway. When the gap increased from 0.2 to 2 seconds, the follow-up headway increased by only 0.1 second and the critical headway had no increase.

Results of Clearance

Clearance controls the distance between a vehicle and its preceding vehicle when they are stopped. It is unknown if this parameter controls the distance of two vehicles when they are moving. According to the result, this parameter has small effect on the follow-up headway but has no effect on the critical headway.

Results of Sensitivity Factor

Sensitivity factor is a parameter in car-following model. It determines whether the following vehicle overestimate or underestimates the deceleration of the preceding vehicle. It has little effect on the critical headway and the follow-up headway.

Results of Max Deceleration

Max deceleration is the largest deceleration a vehicle can have under emergency braking. But in this simulation, emergency braking can hardly happen inside the roundabout or on the entry lane. The result shows that max deceleration has very small effect on the critical headway and the follow-up headway.

Results of Max Acceleration

This parameter sets the maximum acceleration of a vehicle under any condition. An entering vehicle accelerates to a value that is close to its preceding vehicle so that it can enter the roundabout safely. When the max acceleration increases from 1.64 to 6.56 ft/sec^2, the critical headway drops from 8.6 to 4.9 seconds, which reflects that most entering vehicles use an acceleration rate larger than 6.56 ft/sec^2. Therefore, when the maximum acceleration is smaller than this value, many vehicles cannot accelerate to a normal speed in time, which results in the delay of the circulating vehicle and a large critical headway. Once the maximum acceleration is larger than a normal level, it is not a key factor to the critical headway anymore. When the max acceleration increases from 6.56 to 16.4 ft/sec^2, the critical headway decreases from 4.9 to 3.6 seconds. Max acceleration also had effects on the follow-up headway. When it increased from 1.64 to 16.4 ft/sec^2, the follow-up headway decreases from 3.3 seconds to 2 seconds.

Results of Speed Acceptance

Speed acceptance determines the perspective of drivers to the speed limit. If it is larger than 1, drivers overestimate the speed limit and follow a maximum speed larger or than the speed limit, otherwise they underestimate the speed limit. According to the result of the analysis, speed acceptance had little effect on the critical headway and the follow-up headway.

Results of Max Give-way Time

Max give-way time controls the moment when the safety margin starts to decrease from initial safety margin. In this analysis, all levels of max give-way time were larger than 90 seconds. But as few vehicles had a waiting time larger than 90 seconds in the simulation, this parameter has no effect on both headways.

Results of Maximum Speed at the Approach Section

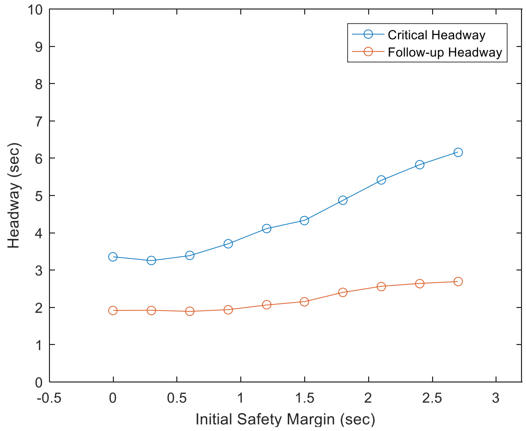
The maximum speed at the approach section has no effect on the critical headway, but has significant effect on the follow-up headway when the maximum speed is set to be a small value. In the result, when the maximum speed is 4 ft/sec, the follow-up headway is 3.1 seconds. The follow-up headway is relatively large because the speed of the following vehicle is restricted by a low speed limit. It takes a following vehicle longer to move toward and cross the stop line.

Results of Turning Speed

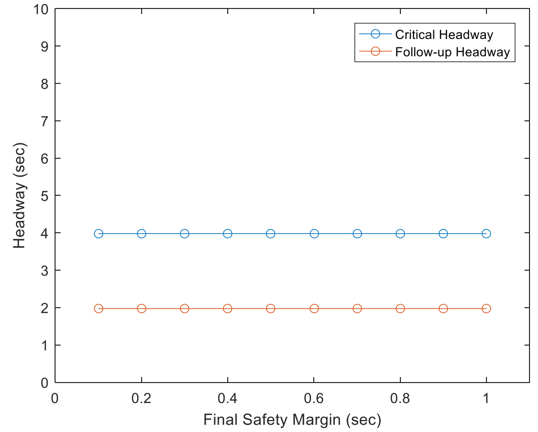
Turning speed affects both the critical headway and the follow-up headway. Because the edge of the conflict zone is close to the stop line of the entry lane, so a following vehicle need to wait until its preceding vehicle pass the conflict zone. If the turning speed is smaller, the preceding vehicle spends more time to pass the conflict zone, which makes the following vehicle wait for a longer time at the stop line. Because of the small turning speed, the acceleration of the following vehicle is restricted, which leads to a large follow-up headway.

From Figure 20, it was difficult to figure out whether each parameter had effects on the critical headway or the follow-up headway, especially for those parameters that make small differences. Therefore, one-way ANOVA test was conducted to figure out the main effect of each parameter. If a parameter had a statistically significant effect on the depend variable, the p-value of this parameter in the test should be smaller than 0.05. According to

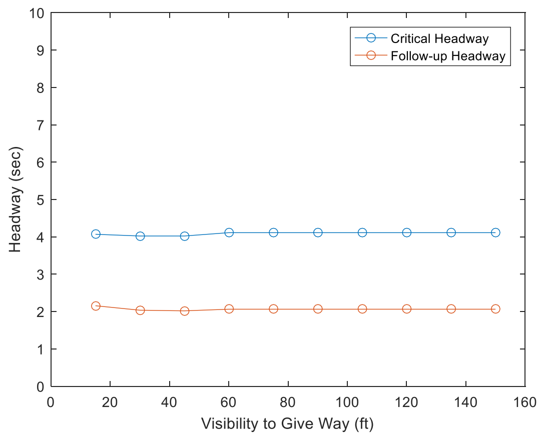
Table 5, there are twelve parameters that have significant effects on the critical headway or the follow-up headway. If a parameter has significant effect on any one of the two headways, it will be included in the analysis in next step. Two parameters, which were the final safety margin and the max give-way time, had no effect on the critical headway nor the follow-up headway. They were excluded from the analysis in next step.



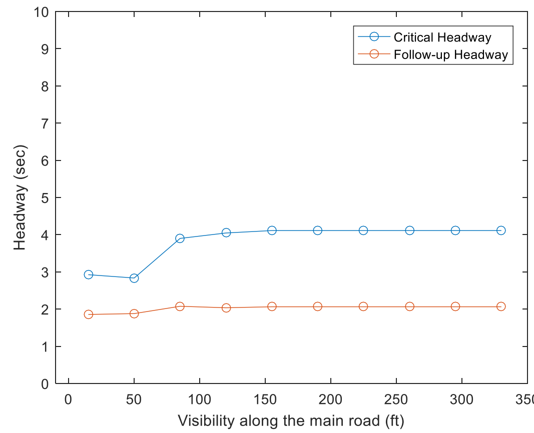
a) Initial Safety Margin



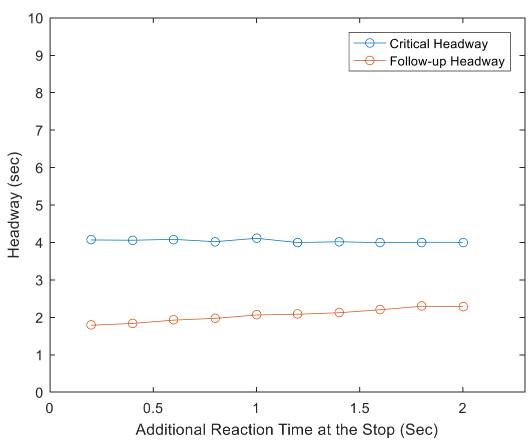
b) Final Safety Margin



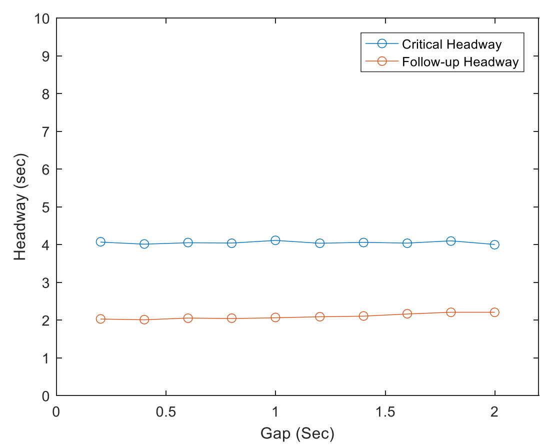
c) Visibility to Give Way



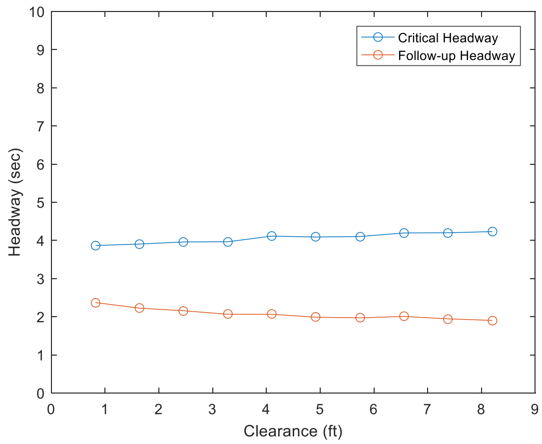
d) Visibility Along Main Stream



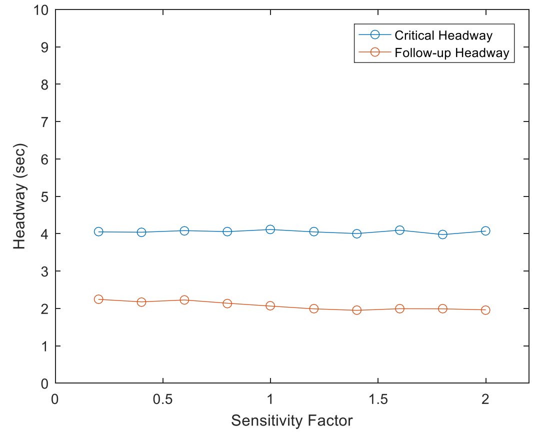
e) Additional Reaction Time at Stop



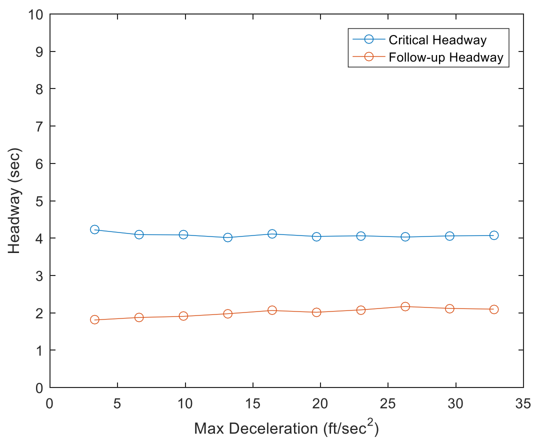
f) Gap



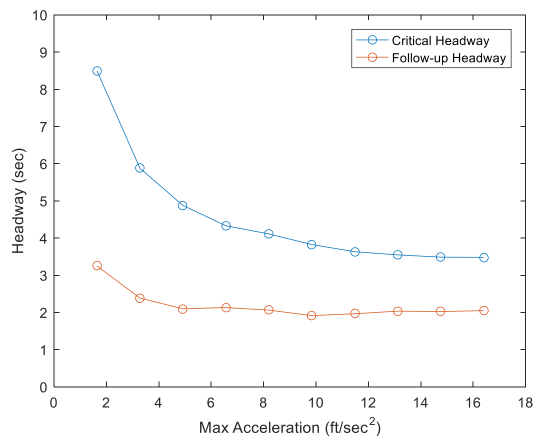
g) Clearance



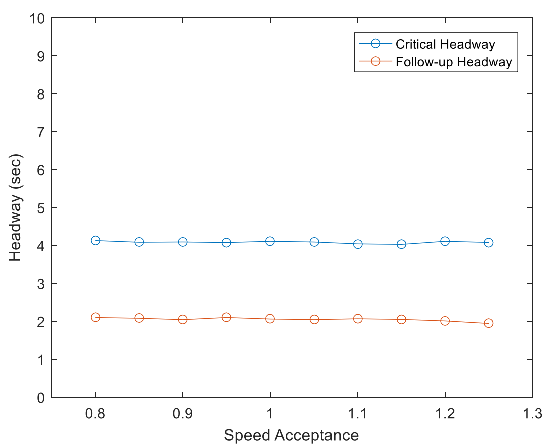
h) Sensitivity Factor



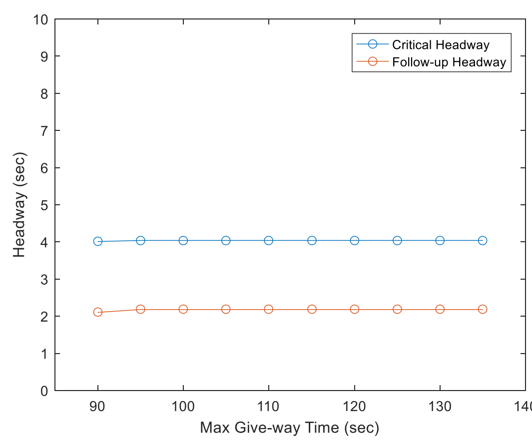
i) Max Deceleration



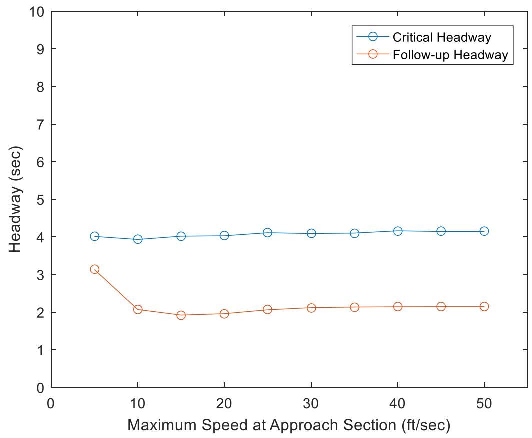
j) Max Acceleration



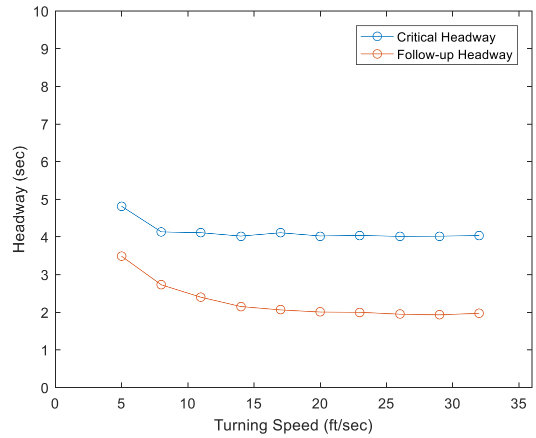
k) Speed Acceptance



l) Max Give-way Time



m) Maximum Speed at Approach Section



n) Turning Speed

Figure 20. Results of OFAT Analysis

Table 5. P-value in One-way ANOVA Test

Notation	Parameters	Critical headway	Follow-up headway
ISM	Initial Safety Margin	< 10-6	< 10-6
FSM	Final Safety Margin	0.1215	0.1215
VDA	Visibility to Give Way	0.02194	0.5289
VDM	Visibility along Main Stream	0.01218	0.02309
RAS	Section Reaction Time at Stop	0.03144	< 10-6
GAP	Gap	0.9786	< 10-6
CLE	Clearance	< 10-6	0.0001087
SF	Sensitivity Factor	0.0804	0.0002148
MGT	Max Give-way Time	0.1215	0.1215
MD	Max Deceleration	0.8315	0.0001291
MA	Max Acceleration	0.003218	0.03463
SA	Speed Acceptance	0.2173	0.007145
MSP	Section Maximum Speed	0.0005729	0.3122
TS	Turning Speed	0.0524	0.004265

5.2.2 Two-level Full Factorial Analysis

In this section, factorial analysis was used to figure out the potential interactions between parameters. This analysis explored how one parameter and how the combination of parameters affects the output. Twelve parameters that were proved effective in OFAT analysis were included here.

At first, two-level full factorial analysis was conducted to figure out the potential interaction between parameters and to screen out the useless parameters. Each parameter had two levels: low and high. R package 'FrF2' was applied to design the two-level full factorial experiment, in which there were 2^{12} combinations of parameters. Each combination of parameters was run in three replications, so there were 12288 runs in total.

Table 6 lists two levels of each parameter in this analysis. The values chosen for both levels should guarantee that the simulation model can operate normally and realistically. For example, the speed limit on the entry lane, the tuning speed and the max acceleration of the vehicle were not allowed to be extremely small values, or the entering vehicle in a low-speed would force the circulating vehicle to stop inside the roundabout.

Figure 21 and Figure 22 show the main effect of each parameter in two-level full factorial analysis. Each graph has two points, representing the average values of the output when the parameter is set to a low level or a high level. There is a line connecting two points in each graph. A large slope of the line indicates a significant main effect of the parameter. In Figure 21, initial safety margin, visibility along main stream, clearance, and max acceleration show relatively large effects on the critical headway. In Figure 22, initial safety margin, visibility along main stream, reaction time at stop, and gap show large effects on the follow-up headway. Reaction at stop and gap have nearly identical effects on the follow-up headway according to the plots. All the other parameters have no effect or relatively small effects on the critical headway or the follow-up headway.

Referring to the results of OFAT and two-level full factorial analysis comprehensively, parameters with small or zero main effect were removed. The remaining parameters were used to build two linear models for the critical headway and the follow-up headway in the next step. The model for the critical headway included initial safety margin, visibility along main stream, and the max acceleration. All three parameters had large effects in OFAT and two-level factorial experiment. Among three parameters, max acceleration was a global parameter for the vehicle type while the other parameters were local parameters for the turning. In the model calibration, the local parameter was preferred because it only modified a specific part of the model without affecting other part of the model. Besides, clearance was not used here because this parameter only showed its effect in factorial analysis but was not effective in OFAT experiment, which reflected that this parameter influenced the critical headway indirectly. The model for the follow-up headway included initial safety margin, visibility along main stream, and the additional reaction at stop. Gap was not used because it produced similar effects as the reaction at stop, and it was a global parameter while the reaction at stop was a local parameter for the entry section, which was preferred in simulation model calibration. Therefore, only four parameters were included in five-level full factorial experiment.

Table 6. Values for Parameters in Two-level Full Factorial Analysis

Notation	Parameters	Unit	Low Level	High Level
A	Initial Safety Margin	sec	0.5	2.5
B	Visibility to Give Way	ft	30	150
C	Visibility along Main Stream	ft	75	135
D	Section Reaction Time at Stop	sec	0.1	2.0
E	Gap	sec	0.4	2.8
F	Clearance	ft	0.82	7.38
G	Sensitivity Factor	NA	0.6	1.4
H	Max Deceleration	ft/s2	8.20	26.24
I	Max Acceleration	ft/s2	8.20	14.76
J	Speed Acceptance	NA	0.9	1.1
K	Section Maximum Speed	mph	14	20
L	Turning Speed	mph	12	18

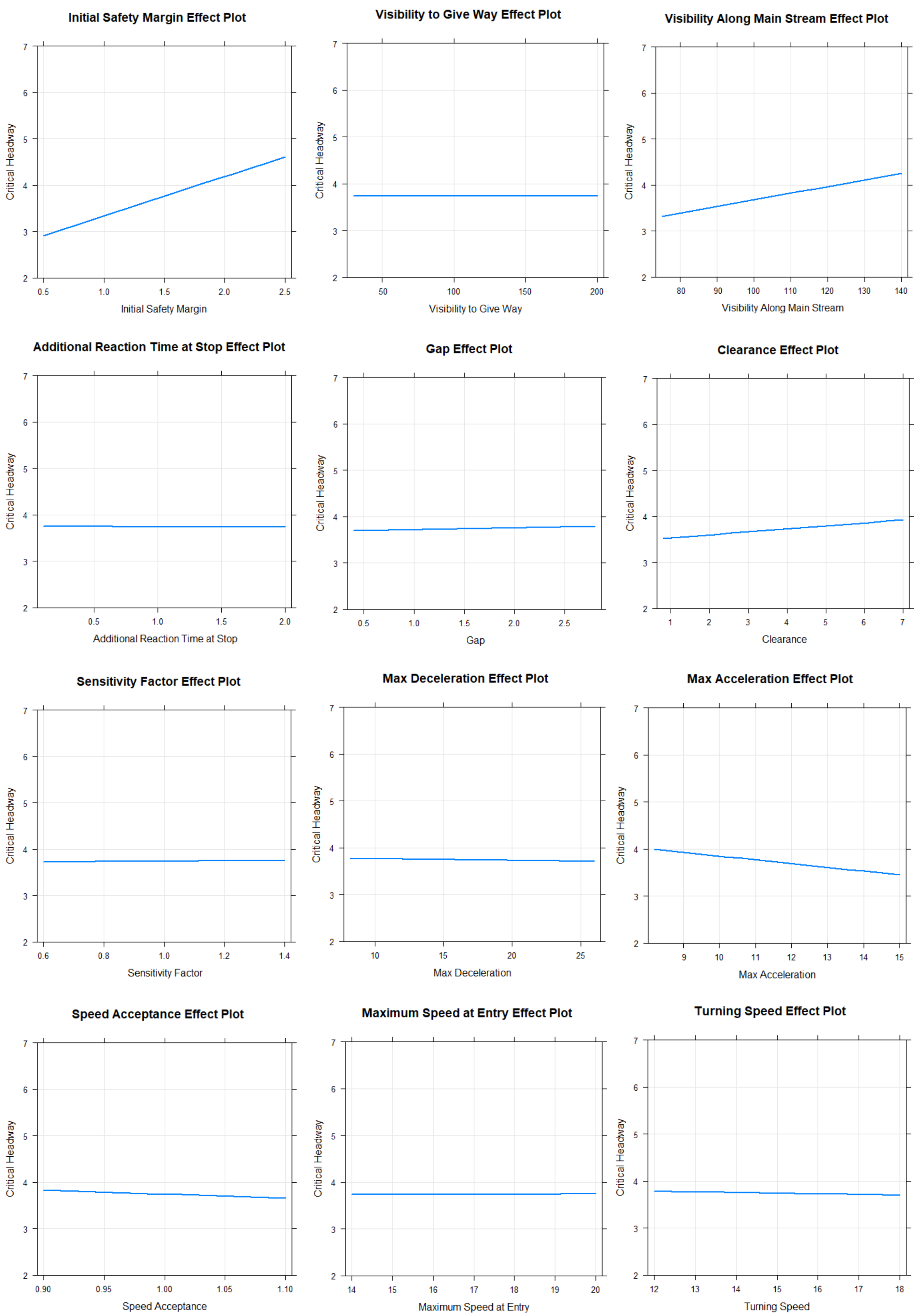


Figure 21. Main Effect on Critical Headway in Full Factorial Analysis

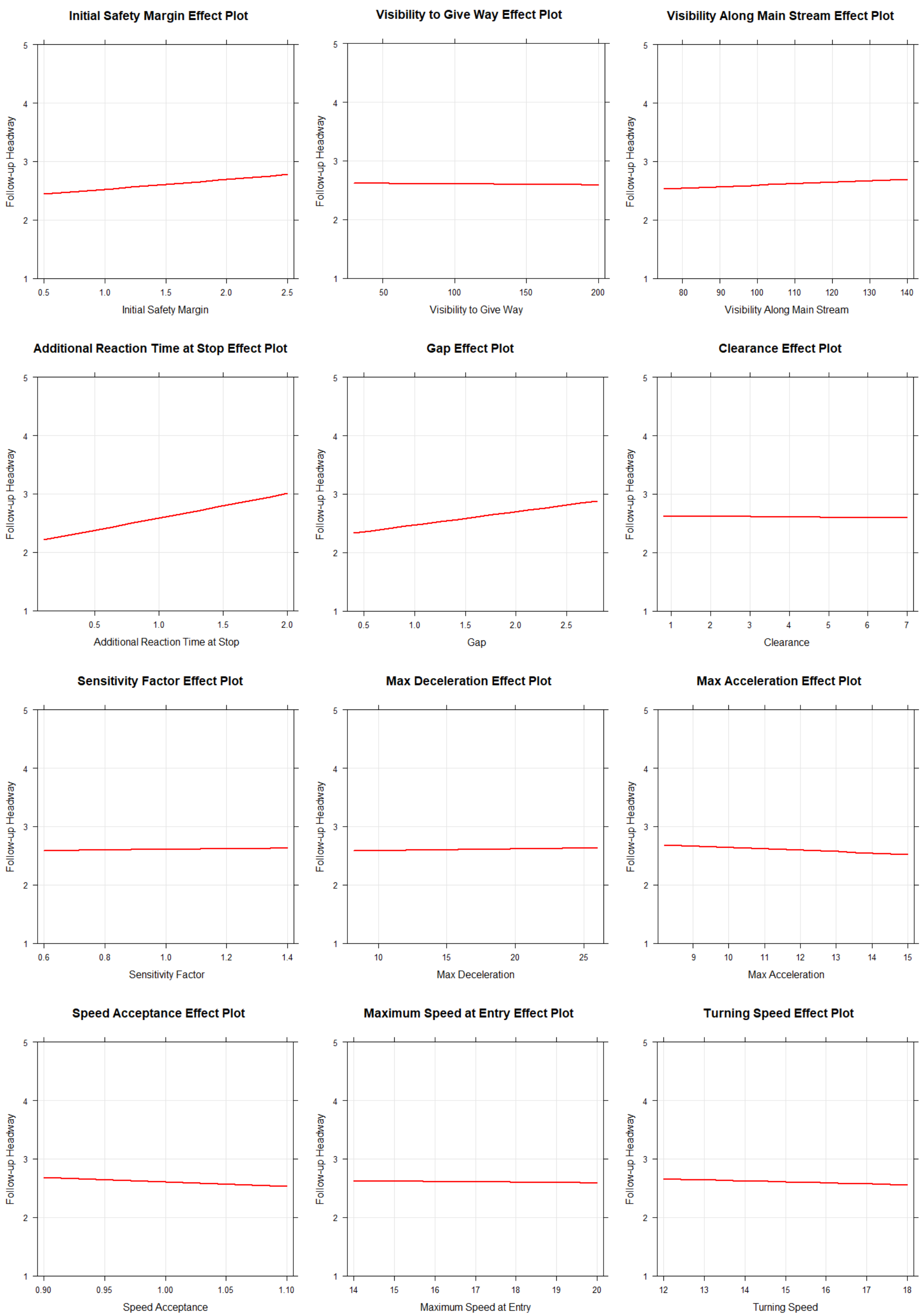


Figure 22. Main Effect on Follow-up Headway in Full Factorial Analysis

5.2.3 Five-level Full Factorial Analysis

After screening out unneeded parameters in two-level factorial analysis, five-level full factorial analysis was applied to capture the interactions between four parameters in higher resolution. In five-level factorial analysis, each parameter had five levels, so there were 625 combinations of parameters. Each combination of parameters was run in three replications, and there were 1875 simulation runs in total. At same time, all the other unused parameters were fixed at their baseline values. Table 7 lists all the values for parameters in five-level full factorial analysis.

Table 7. Values for Parameters in Five-level Factorial Analysis

Parameter	Notation	Parameters	Unit	Levels				
				1	2	3	4	5
Has Effects	A	Initial Safety Margin	sec	0.6	1.2	1.8	2.4	3.0
	C	Visibility along Main Stream	ft	90	105	120	135	150
	D	Section Reaction Time at Stop	sec	0.5	1.0	1.5	2.0	2.5
	I	Max Acceleration	ft/s2	8.2	9.84	11.48	13.12	14.76
No Effects	B	Visibility to Give Way	ft	85	\	\	\	\
	E	Gap	sec	1	\	\	\	\
	F	Clearance	ft	4.1	\	\	\	\
	G	Sensitivity Factor	NA	1	\	\	\	\
	H	Max Deceleration	ft/s2	16.4	\	\	\	\
	J	Speed Acceptance	NA	1	\	\	\	\
	K	Section Maximum Speed	mph	23	\	\	\	\
	L	Turning Speed	mph	18	\	\	\	\

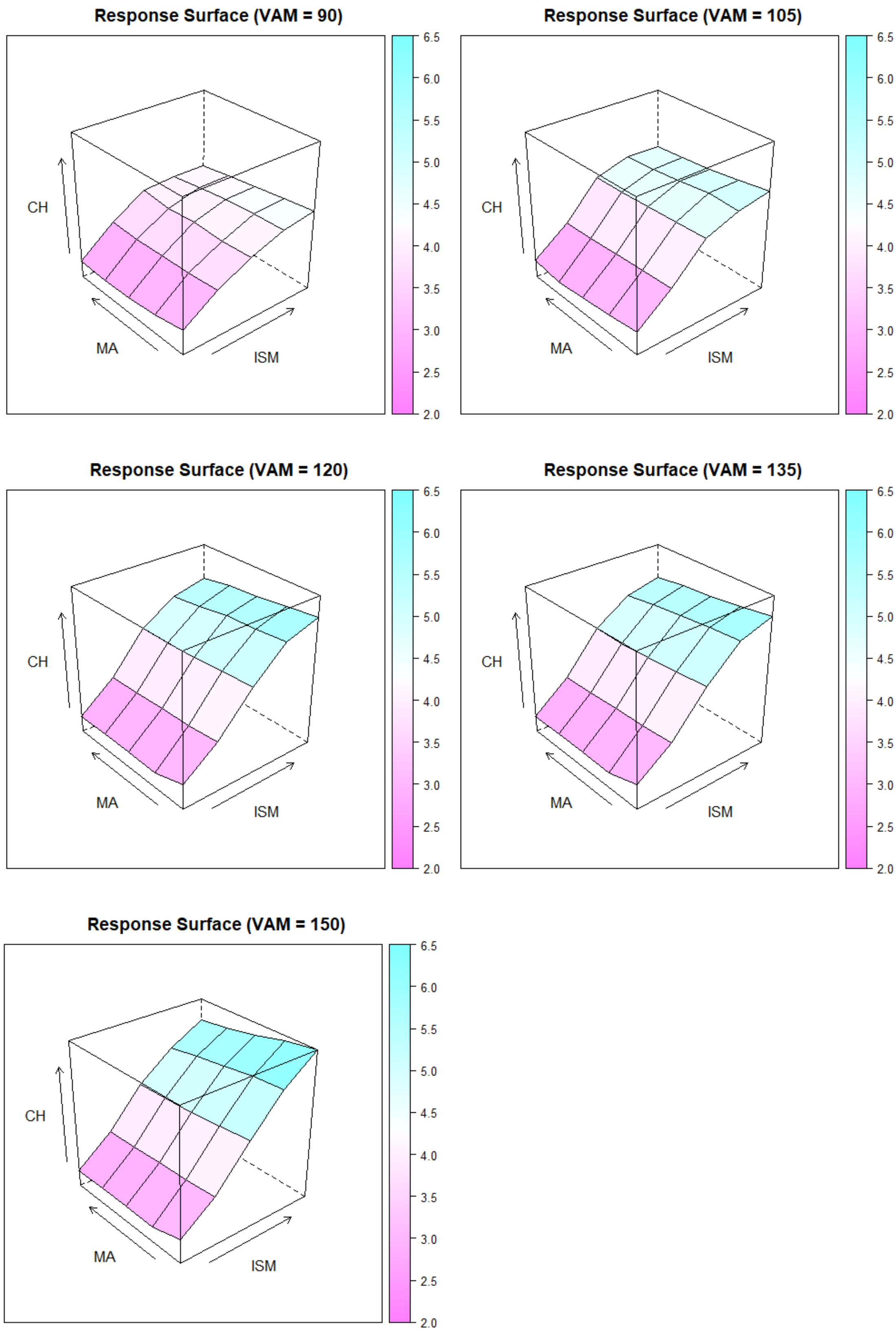


Figure 23. Response Surface of Critical Headway Model

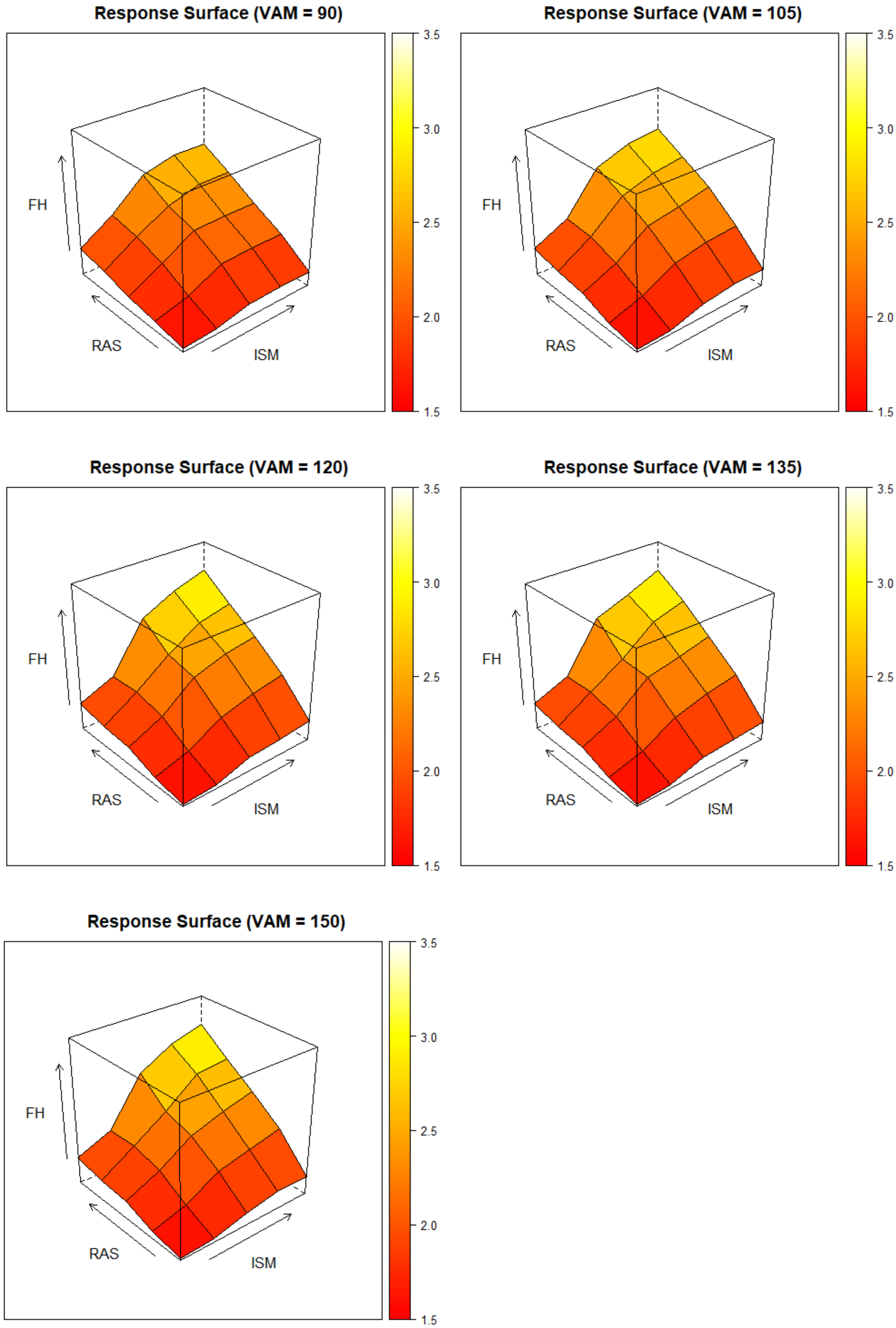


Figure 24. Response Surface of Follow-up Headway Model

Figure 23 and Figure 24 illustrate the response surfaces of two models. Figure 23 shows how the changes in initial safety margin, visibility along main stream, and max acceleration affect the critical headway. In each graph, X axis represents the initial safety margin, Y axis represents the max acceleration, and Z axis represents the critical headway. The values of visibility along main stream in five graphs are different, which are 90 ft, 105 ft, 120 ft, 135 ft, and 150 ft respectively. In Figure 23, an increase in initial safety margin and a decrease in the max acceleration lead to an increase in the critical headway. An increase in visibility along main stream lead to an increase in the maximum value of the critical headway.

Figure 24 shows how changes in initial safety margin, visibility long main stream, and reaction time at stop affects the follow-up headway. An increase in initial safety margin or reaction time at stop results in an increase in the follow-up headway. As the visibility along main stream increases from 90 to 105 ft, the maximum follow-up headway increases. But when it increases from 105 to 150 ft, the response surface does not make big changes.

After the five-level full factorial analysis, two regression models were built for the critical headway and the follow-up headway. Formula (10) shows a general form of the regression model, which includes quadratic terms and the interaction terms.

$$y = \beta_0 + \sum_{i=1}^{p} \beta_i x_i + \sum_{i=1}^{p} \beta_{ii} x_i^2 + \sum_{i<j} \sum \beta_{ij} x_i x_j \qquad (10)$$

Where, y = the critical headway, the follow-up headway

x_i = parameter i

p = the number of parameters

After the establishment of two regression models, Bayesian Information Criterion (BIC) was used to simplified the model. However, no variable was deleted during the model simplification process. At last, each model had nine parameters, as showed in Table 8 and Table 9. Two models had R^2 of 98.17% and 96.87% respectively. In the model for the critical headway, initial safety margin is the most important parameter as it has the largest coefficient (β_1). The quadratic term of initial safety margin (β_4) and the interaction term of initial safety margin and the visibility along main stream (β_7) also have relatively large values. In the model for the follow-up headway, the reaction time at stop is the most important parameter as its coefficient (β_3) was the largest.

Table 8. Critical Headway Model

Term	Coefficient		P-value
	Notation	Estimate	
Constant	β_0	-8.48E-01	3.53E-01
A	β_1	8.51E-01	6.63E-02
C	β_2	5.20E-02	4.24E-03
I	β_3	-3.11E-02	3.54E-02
A^2	β_4	-3.20E-01	1.02E-02
C^2	β_5	-2.51E-04	1.64E-05
I^2	β_6	2.32E-03	1.37E-03
A:C	β_7	1.38E-02	3.43E-04
A:I	β_8	-1.22E-02	3.13E-03
C:I	β_9	-3.49E-04	1.25E-04

Table 9. Follow-up Headway Model

Term	Coefficient		P-value
	Notation	Estimate	
Constant	β_0	7.29E-01	1.01E-07
A	β_1	8.94E-02	0.00322
C	β_2	1.09E-02	3.77E-07
D	β_3	1.49E-01	4.68E-05
A2	β_4	-7.69E-02	< 2e-16
C2	β_5	-6.13E-05	2.42E-12
D2	β_6	-8.17E-02	< 2e-16
A:C	β_7	1.92E-03	< 2e-16
A:D	β_8	2.06E-01	< 2e-16
C:D	β_9	1.20E-03	3.54E-08

5.3 Roundabout Simulation Model Calibration

In this section, the roundabout simulation model was calibrated with four parameters: initial safety margin, visibility along main stream, reaction time at stop, and max acceleration. These parameters of the simulation model were adjusted until the critical headway and the follow-up headway at the left entry lane were the same as those in HCM 6. (The gap acceptance behavior on both lanes cannot be calibrated at the same time, so only the gap acceptance behavior of the left entry lane was calibrated here). As showed in Table 3, critical headways in roundabout capacity model of a two-by-two roundabout in HCM 6 are 4.65 seconds and 4.32 for the left lane and the right. The corresponding follow-up headways in HCM 6 are 2.67 and 2.54 seconds for the left lane and the right lane.

The first task is to find a combination of parameters that can produce a critical headway of 4.650 seconds and a follow-up headway of 2.667 seconds for the left entry lane at the same time. Two models built in five-level full factorial experiment were used to find the optimal combination of the parameters. The formula set below illustrates this optimization problem.

Minimize: $$(t_c - 4.650)^2 + (t_f - 2.667)^2$$

Subject to:

$$t_c = \beta_0 + \beta_1 A + \beta_2 C + \beta_3 I + \beta_4 A^2 + \beta_5 C^2 + \beta_6 I^2 + \beta_7 AC + \beta_8 AI + \beta_9 CI$$

$$t_f = \beta_0 + \beta_1 A + \beta_2 C + \beta_3 D + \beta_4 A^2 + \beta_5 C^2 + \beta_6 D^2 + \beta_7 AC + \beta_8 AD + \beta_9 CD$$

$$0.6 \le A \le 3$$
$$90 \le C \le 130$$
$$0.5 \le D \le 3$$
$$6.56 \le I \le 14.76$$

By adjusting feasible domains of parameters, multiple solutions can be computed. Python package "scipy" was used to solve this problem. Table 10 lists five combinations of parameters which can produce a critical headway close to 4.65 second and a follow-up headway close to 2.667 second. Among these five combinations, the fifth one produced the best performance in AIMSUN, which produced a critical headway of 4.66 seconds and a follow-up headway of 2.60 seconds. Therefore, this combination of four parameters was used to calibrate the roundabout model, and all the other parameters were set to be their baseline values listed in Table 7.

Table 10. Several Solutions to the Optimization Problems

Combination					Predicted		Simulated	
No.	ISM	VMA	RAS	MA	CH	FH	CH	FH
1	2.0	129.6	2	13.12	4.75	2.59	4.87	2.53
2	1.9	129.7	2	11.48	4.70	2.54	4.68	2.52

3	1.8	129.9	2	9.84	4.57	2.50	4.62	2.53
4	1.8	130	2.3	9.84	4.65	2.59	4.61	2.76
5	1.9	130	2.3	9.84	4.78	2.65	4.66	2.60

After importing the combination of parameters to the simulation model, the capacities of the left and right entry lanes on the northbound approach were simulated under sixteen circulating flow rates (from 200 pc/h to 2000 pc/h). The arrival of vehicle follows Poisson distribution and the time interval between two consecutive vehicles follows exponential distribution. The simulation time was set to be 30 minutes for each of the circulating flows. The model was run in 25 replications to reduce errors.

Figure 25a illustrates the capacity model in HCM6 and two capacity curves produced by the simulation model. The capacity curves for both lanes are very close to those in HCM 6. For both entry lanes, the simulation model overestimates the capacity when the circulating flow rate is small, and underestimate the capacity when the circulating flow is large.

Figure 25b and Figure 25c show differences of two models in detail. For the left lane, when the circulating flow rate is from 0 to 400 pc/h, the simulation model overestimated the capacity by 12.5% to 3%. When circulating flow rate is from 400 to 700 pc/h, the simulation model can predict the capacity accurately. When the circulating flow is from 700 to 2000 pc/h, the simulation model underestimated the capacity by 2.5% to 24%. For the right lane, when the circulating flow is from 0 to 500 pc/h, the simulation model overestimated the capacity by 7.5% to 2%. The simulation model is accurate when the circulating flow is from 500 to 800 pc/h. It will underestimate the capacity by 2% to 15% when the circulating flow is from 800 to 2000 pc/h.

5.4 The Procedure of Calibrating a Roundabout Model in AIMSUN

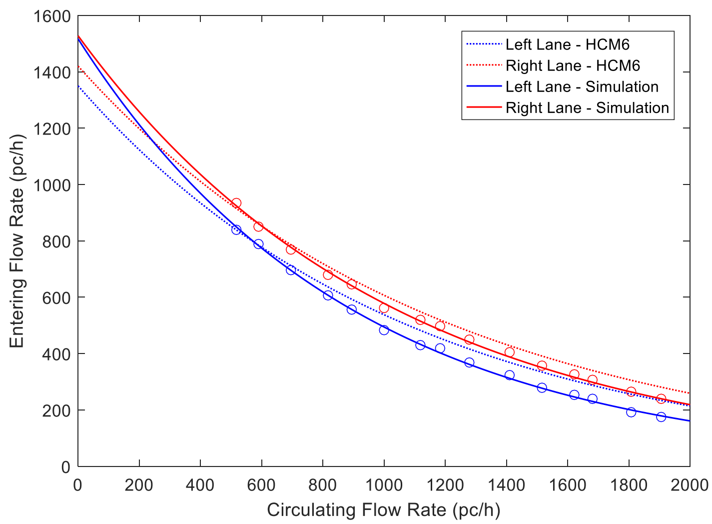
This chapter figures out key parameters used for calibrating a roundabout model in AIMSUN and validates the capability of AIMSUN to build a realistic roundabout model. A procedure of calibrating a roundabout model in AIMSUN can be proposed.

Step1: Build a roundabout model on a high-resolution base map and correctly set the geometry of the roundabout, especially the turning length and turning speed.

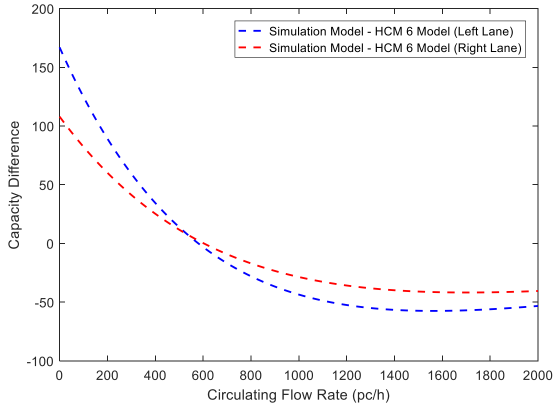
Step 2: Adjust the values of four parameters (Initial Safety Margin, Visibility Along Main Stream, Reaction Time at Stop, and Max Acceleration) to calibrate the roundabout model.

Step 3: Export gap acceptance data for the left entry lane of one approach using API and calculate the critical headway and the follow-up headway of the vehicles.

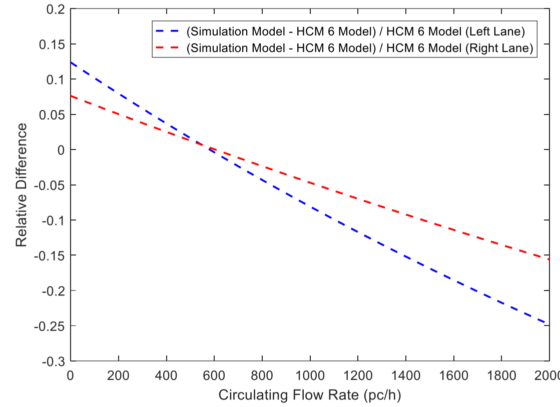
Step 4: Compared the critical headway and the follow-up headway with those in the target model. Target model can be a default or calibrated HCM roundabout capacity model or an exponential regression model based on flow rates at a local roundabout. If they are not close to each other, go back to step 2. If they are close to each other, set the entire roundabout in the same way.



(a)



(b)



(c)

Figure 25. Capacity of Simulation Model vs Capacity in HCM 6

5.5 The Effect of Model Calibration to the Network Model

If the roundabout simulation model is a part of a simulation model for a large network, then calibrating the roundabout model may affect the network simulation model. In AIMSUN, the parameters that relate to the vehicle behaviors are classified: the global parameters, local section parameters, and local turning parameters.

The global parameter affects the behavior of vehicles in the whole network. Local section parameters influence vehicles driving on a specific section or a turning without affecting other part of the network. In the calibration of the roundabout model, two parameters (Initial safety margin, Visibility along main stream) are local turning parameters, additional reaction time at stop is local section parameter, and Max acceleration is the global parameter. It means the change of the value of max acceleration during the calibration of the roundabout model will result in the change in the behavior of vehicles for the whole network.

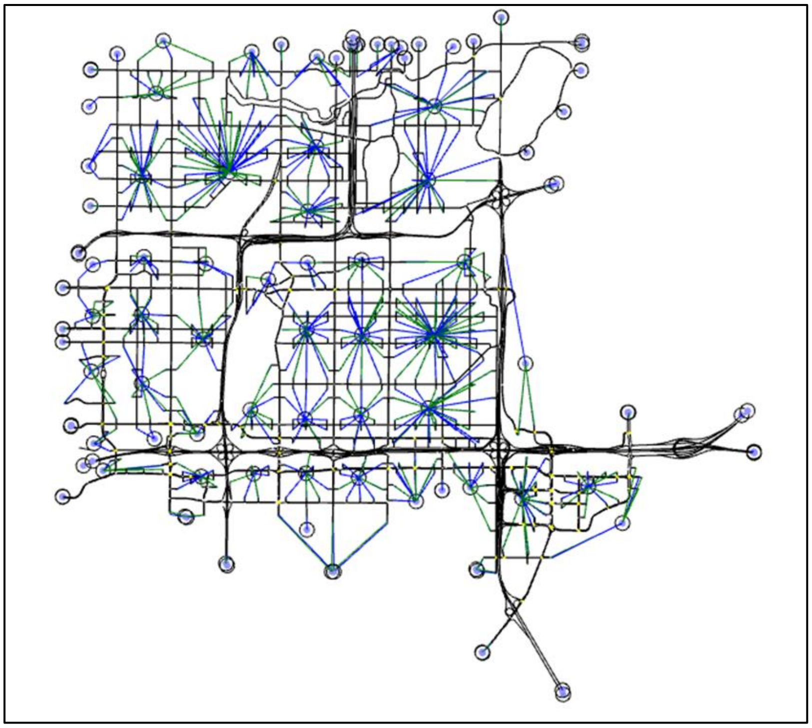


Figure 26. A Simulation Model for the Road Network

In this study, to calibrated roundabout model, the value of max acceleration was changed from 11 to 9.8 ft/sec2. A simulation model for a large road network was used to test the effect of changing the max acceleration. This model, which is a part of a project funded by NSF, includes the all the arterials and minor roads in the city of Richfield as well as part of the arterials in the city of Bloomington, Edina, and Minneapolis. Figure 26 shows the road network of this network. There are two roundabouts in this network, which are located at 66th Street. The result the test shows that the change in max acceleration does not change the overall performance of the whole network.

5.6 Summary

In this chapter, the capability of AIMSUN building a realistic roundabout model was validated and a standard procedure of calibrating a roundabout model in AIMSUN was proposed. Sensitivity analysis was conducted to find the important simulation parameters to the critical headway and the follow-up headway in the simulation model. It was found that initial safety margin, visibility along main stream, and max acceleration can be used to calibrate the critical headway of the model, and initial safety margin, visibility along main stream, and reaction at stop can be used to calibrate the follow-up headway of the model. To calibrate the capacity curve of the simulation model, AIMSUN users should first build a roundabout with reasonable geometry, and then calibrate the critical headway and follow-up headway for the left entry lane.

CHAPTER 6

6 CONCLUSIONS

In the first part, default roundabout capacity models in Highway Capacity Manual (HCM) were evaluated. Two formulas provided by HCM were used to calibrate the default roundabout capacity model using the gap acceptance data from a local roundabout. Two calibrated roundabout capacity models were built with two strategies: calibrate both coefficients using the critical headway and the follow-up headway (fully calibrated), and calibrate only one coefficient using the follow-up headway (partially calibrated). A regression model based on actual flow rate data was used as the real condition.

The default model in HCM 6 overestimated the roundabout capacity on left lane by about 10% and on the right lane by about 20 % on average. The default 2010 model accurately predict the capacity on the right lane but overestimated the capacity on the left lane by about 20% on average. The fully calibrated model overestimated the capacity by 9% on average and by 18% on average. The partially calibrated model overestimated the capacity on the right lane by 5% when under low circulating flow (< 800 pc/h) but underestimated the capacity by 10% under moderate or heavy circulating flow (> 800 pc/h). It also overestimated the capacity on the left lane by about 8%.

Several conclusions were made:

1) It is useful to calibrate the default HCM model because calibration enhances the accuracy of the model. In this study, both calibrated models produced better prediction than the default HCM 6 model.
2) Traffic practitioners can calibrate the default HCM model only using the follow-up headway as the data collection of the follow-up headway is much easier than that of the critical headway. In this study, the partially calibrated model only using the follow-up headway produced better prediction than the fully calibrated model that using both critical and follow-up headway.

In the second part, the capability of AIMSUN to build a roundabout simulation model was validated. Sensitivity analysis was first used to find important parameters that control the gap acceptance behavior of the model. Then two models for the critical headway and the follow-up headway were built to find values of parameters for calibration. These values made the model produce the same critical headway and the follow-up headway as those in default HCM 6 model. At last, the capacity curve of the calibrated AIMSUN simulation model was compared with the default capacity curve.

Several conclusions were made:

1) AIMSUN has the capability of building a realistic roundabout model.
2) To calibrate drivers' gap acceptance behaviors in AIMSUN simulation model, Initial safety margin, Visibility along main stream, Reaction time at stop, and Max Acceleration are four most important parameters.
3) If a simulation model in AIMSUN can produce the same critical headway and follow-up headway as those in default HCM6 model, it can also produce similar capacities to the HCM 6 model.

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APPENDICES

A1. AIMSUN API for Exporting Gap Acceptance Data

```
from AAPI import *
import sys
import datetime
from PyANGBasic import *
from PyANGKernel import *
from PyANGConsole import *
from PyANGAimsun import *

DetAct = [0,0]
ActType = 0
ActTime = [0,0
GapList = []
DetList = [777,778]
DetList1 = 785
Entrance = [4043,4043]
Occupy = 785
filename = 'Critical_Headways.csv'
filename1 = 'Follow_up_Headways.csv'
Output = open(filename, 'w')
Output1 = open(filename1, 'w')
Follow_up_activation = 0
Follow_up_activation_time = 0
Speed1 = 0
MaxRej = []

print 'Hello'
def AAPILoad():
    return 0
def AAPIInit():
    global Output,Output1
    AKIPrintString("Init")
    Output.write("Gaptime,AR\n")
    Output1.write("Follow-up\n")
    return 0
def AAPIManage(time, timeSta, timeTrans, acycle):
    global DetAct, ActTime,ActType, GapList, DetList, Entrance, Occupy, Output, Output1, Follow_up_activation,Follow_up_activation_time,Speed1,MaxRej

    ################## critical headway ###################

    timenew = float(time) ## current time
    NbDet = len(DetList)  ## the total number of detectors
    def OCC(id):  ## get the condition of the detectors at the approaches
        if (id == 777):
            O = AKIDetGetNbintervalsOccupedCyclebyId(785,0)
        elif (id == 778):
            O = AKIDetGetNbintervalsOccupedCyclebyId(785,0)
        else:
            print "OCC Function Error!"
        return O
    for i in range(NbDet):
            detectorId = DetList[i]  ## detector ID
            InfDet = AKIDetGetPropertiesDetector(i) ## detector information
            sectionId = AKIDetGetPropertiesDetectorById(detectorId).IdSection
            DetLoc = AKIDetGetPropertiesDetectorById(detectorId).InitialPosition
```

```
            DetLoc1 = AKIDetGetPropertiesDetectorById(detectorId).FinalPosition
            Lane = AKIDetGetPropertiesDetectorById(detectorId).IdFirstLane
            InsNb = AKIDetGetNbintervalsOccupedCyclebyId(detectorId,0)
            if InsNb == 0:  ## if the detector is not occupied
                DetAct[i] = 0
            elif InsNb == 1 and InsNb - DetAct[i] == 1:
                nb = AKIVehStateGetNbVehiclesSection(sectionId,True)
                NoVeh = 0
                D = 1000
                DetAct[i] = 1
                for j in range(nb):
                    infVeh =AKIVehStateGetVehicleInfSection(sectionId,j)
                    Pos=AKIVehStateGetVehicleInfSection(sectionId,j).CurrentPos
                    VehLane=AKIVehStateGetVehicleInfSection(sectionId,j).numberLane
                    D1 = abs(Pos-DetLoc)
                    if D >= D1 and Lane == VehLane:
                        ToDec = Pos
                        NoVeh = j
                        D = D1
                infVeh = AKIVehStateGetVehicleInfSection(sectionId,NoVeh)
                FROM = AKIVehInfPathSection(sectionId,NoVeh).entranceSectionId
                Speed = AKIDetGetSpeedCyclebyId (detectorId, 0)
                if (FROM == Entrance[i]):
                    if detectorId == 777:
                        ActType = 'Enter'
                        print ActType
                        if (len(MaxRej) > 0):
                            print MaxRej
                            GapList.append(str(max(MaxRej)) + ", rejected")
                            Output.write("%f,rejected\n"%max(MaxRej))
                            MaxRej = []
                            print ", Gaptime " + str(round(timenew - ActTime[0],3)) + " , rejected"
                        else:
                            Output.write("0,rejected\n")
                            print 'This car enter the roundabout without rejecting any gap.'
                elif (FROM != Entrance[i]):
                    OCCUPY = OCC(detectorId)
                    if ActType == 'Enter':
                        if (timenew - ActTime[0]) < 15 and Speed > 10:
                            GapList.append(str(round(timenew - ActTime[0],3)) + " , accepted")
                            Output.write("%.3f,accepted\n"%(timenew - ActTime[0]))

                            print ", Gaptime " + str(round(timenew - ActTime[0],3)) + " , accepted"
                    if ActType == 'Circle':
                        if ActTime[1] > 0 and OCCUPY > 0:
                            MaxRej.append(round(timenew - ActTime[0],3))
                        else:
                            MaxRej = []
                    ActTime = (timenew,OCCUPY)
                    ActType = 'Circle'
                    print ActType
            else:
                DetAct[i] = 1


        ################## follow-up headway ###################

```

```
        detectorId = int(DetList1)
        InsNb1 = AKIDetGetNbintervalsOccupedCyclebyId(detectorId,0)
        if InsNb1 == 1:
            Follow_up_activation = 1
            Speed1 = AKIDetGetSpeedCyclebyId(detectorId,0)
        elif InsNb1 == 0 and Follow_up_activation - InsNb1 == 1:
            Follow_up_activation = 0
            if ActTime[0] < Follow_up_activation_time and timenew - Follow_up_activation_time <= 10:
                print ", Followup Time " + str(round(timenew - Follow_up_activation_time,3))
                print "##########################################"
                Output1.write("%.3f\n"%(timenew - Follow_up_activation_time))

            Follow_up_activation_time = timenew
        return 0
    def AAPIPostManage(time, timeSta, timeTrans, acycle):
        return 0
    def AAPIFinish():
        global Output,Output1
        Output.close()
        Output1.close()
        return 0
    def AAPIUnLoad():
        return 0
    def AAPIPreRouteChoiceCalculation(time, timeSta):
        return 0
    def AAPIEnterVehicle(idveh, idsection):
        return 0
    def AAPIExitVehicle(idveh, idsection):
        return 0
    def AAPIEnterPedestrian(idPedestrian, originCentroid):
        return 0
    def AAPIExitPedestrian(idPedestrian, destinationCentroid):
        return 0
    def AAPIEnterVehicleSection(idveh, idsection, atime):
        return 0
    def AAPIExitVehicleSection(idveh, idsection, atime):
        return 0
```