Exploration of Pedestrian Gap Acceptance at TWSC Intersections using Simulation

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ABSTRACT

Pedestrian behavior plays an important role in analyzing the operations of two-way stop-controlled intersections because pedestrian travel creates complex interactions at such locations. This study focuses on modeling pedestrians and analyzing their gap acceptance behavior at two-way stop-controlled intersections. Simulation models are established using VISSIM and CORSIM micro-simulation environment because of their maneuvers of modeling interactions between vehicles and pedestrians. Vehicle and pedestrian yielding behaviors, critical gaps as well as volume data are recorded at study sites and used for model calibration and validation. Based on the model output, the pedestrian accepted and rejected gap thresholds are put forward. Further, statistical analyses are conducted to figure out the probability distribution of pedestrian gap acceptance. The analysis of the model output indicates that the established simulation models can reflect the pedestrian behavior at two-way stop-controlled intersections well.

Key Words: Two-way Stop-controlled Intersection; Pedestrian Behavior; Gap Acceptance; Micro-Simulation.

1 INTRODUCTION

Two-way stop-controlled (hereafter referred to as TWSC) intersections are one of the most common intersection types within the United States and abroad. They are also among the most complex to analyze with respect to their capacity and delay characteristics (*1*). This is because TWSC intersection provides a high degree of discretion to individual drivers and pedestrians in how they react to conflict traffic streams. In order to investigate the characteristics of pedestrian behavior at TWSC intersections, rational pedestrian gap-acceptance at such locations is one critical factor that needs to be studied. The 2010 Highway Capacity Manual (HCM) defines critical gap or headway as "the time in seconds below which a pedestrian will not attempt to begin crossing the street. If the available gap is greater than the critical gap, it is assumed that the pedestrian will cross, but if the available gap is less than the critical gap, it is assumed that the pedestrian will not cross" (*2*). The term adequate gap is used in the Manual on Uniform Traffic Control Devices (MUTCD) and is assumed to be the same as the critical gap in HCM (*3*). The gap can also be defined as available gap, accepted gap or rejected gap dependent on the conditions present at the time a pedestrian attempts to cross (*4*). This study focuses on pedestrians' acceptable gaps.

According to previous researches, several methodologies have been developed to determine pedestrian acceptable gap. Mainly, two modes are summarized consisting behavioral analysis and statistical analysis. On one hand, researchers tend to establish mathematical or simulation models to demonstrate interactions between pedestrians and vehicles at studied locations and the corresponding driver and pedestrian acceptable gaps can be extracted or calculated. On the other hand, based on assumptions with respect to the distribution of arriving vehicles and pedestrian movements, further calculations were conducted to obtain the probability of accepting a particular gap.

For instance, in the research work conducted by Schroeder E.I. et al., simulation models based on Cellular Automata was proposed (5). Later, they come up with pedestrian gap utilization models for micro-simulation applications in another research study (6). Moreover, Wilson and Grayson analysed the proportion of pedestrians accepting gaps of less than 2 seconds in a two way traffic flow (7). They made conclusion that the proportion of those accepting such small gaps on the far side traffic was higher than those from near side. Later, Hunt and Abduljabbar discussed in more detail the phenomenon of pedestrian gap-acceptance in two way traffic streams (8). It can be indicated that for gaps smaller than 4.5 seconds, fewer people would cross the wider road showing the effect of road width on choice of acceptable gap. In another previous study, DiPietro and King also studied on pedestrian gap-acceptance in two way traffic. Their results show that as the waiting time on the curb increases the accepted gaps become longer (9, 10).

There is a wide variation in pedestrian behavior studies as demonstrated in the literature. The complexity is reflected in the various modeling approaches adopted to study pedestrian behaviors. In previous studies, several variations were put forward to describe pedestrian movement characteristics which are valuable reference for this study, such as pedestrian free-flow speeds, speed-density relationships, spatial and temporal compliance etc. (11). This study will focus on modeling the interactions between vehicle and pedestrian at TWSC intersections and measure pedestrian acceptable gaps.

2 PEDESTRIAN GAP ACCEPTANCE

At a TWSC intersection, the pedestrian blockage is formed when a pedestrian tends to cross. Pedestrian will cause major-street vehicles to yield or stop, or even eliminate the opportunity for a minor-street vehicle to seek gaps. However, current HCM assumes major street vehicles have higher priority than the pedestrians crossing the major street. That means major-street movements do not have to yield to pedestrians which is against the right-of-way law in real life. It also assumes that pedestrian must always use the same gap as minor-street vehicle which is not necessarily true in real-world condition. Consequently, no delay on major street vehicles would occur according to HCM procedure. However, field observations indicate that major street vehicles may yield to pedestrians crossing, especially when pedestrian volumes are high and major street speed is low (e.g., near schools). Vehicle yielding to pedestrians is not consistent, but if they do yield, delays would occur to the main street vehicles and the acceptable gap or critical gap would be quite different, which the HCM procedure does not take into consideration. To conclude, two circumstances may occur to pedestrians crossing major-street at a TWSC intersection. On one hand, when major-street vehicles do yield to pedestrians, very small acceptable gaps should be found for pedestrians since they have higher priority. On the other hand, if vehicles partially or even do not yield to pedestrians, they are in the similar condition as minor-street vehicles and have to seek acceptable gaps among those conflicting traffic streams. Both conditions should be taken into account while modeling interactions between vehicles and pedestrians.

3 MODEL CONSTRUCTIONS

This study chooses VISSIM and CORSIM micro-simulation environment to model interactions between vehicles and pedestrians at TWSC intersections. The following sections will introduce details in data collection and model construction.

3.1 Data Collection

Two typical TWSC intersections in Reno Nevada, namely Bell Street & W 1st Street and Ralston Street & W 1st Street are chosen as study intersections. West 1st Street is the major street with four lanes on eastbound and westbound directions. Both Bell Street and Ralston Street are minor streets with single shared lane. The detailed information of study sites are presented in Table 1.

Field data collection was conducted on 6th July 2011 and 18th March 2012. Basically, video cameras were used to record traffic and pedestrian volumes, vehicle travel time, gaps and vehicle against pedestrian behaviors. Video cameras were set up at each location with their clocks synchronized. The complete pedestrian movements from curb to curb on and near the pedestrian crosswalk were captured as well. Vehicle number plates were matched from both camera outputs to give vehicle travel times. The pedestrian peak hours were chosen based on pedestrian ADT data collected in Reno area. The vehicle and pedestrian volumes from each approach during PM peak hours were recorded as well. The details of data collected at study sites are presented in Table 2-5.

Table 1 General Information of Study Sites

Intersection Information	1st & Bell St. Intersection	1st & Ralston St. Intersection
Geometry Layout of Intersection	4-Leg TWSC	4-Leg TWSC
Median Type	No Median	No Median
Pedestrian Crosswalk	Unmarked Crosswalk	Marked Crosswalk Width 3.5m
Vehicle Speed Limit (mph)	35 mph	35 mph
Number of Travel Lanes (major street)	4 Lanes	4 Lanes
Pedestrian Related Crashes (2007-2010)	2 acc./year	1 acc./year
Surrounding Land Use Pattern	Residential and Recreational	Residential and Recreational

Table 2 Traffic Volumes and Pedestrian Volumes

Wed., July 6th, 2011 4:00-5:00PM	W 1st Street & Ralston Street											
Traffic Volume (vph)	NBL 56	NBT 23	NBR 44	SBL 78	SBT 32	SBR 12	EBL 93	EBT 334	EBR 77	WBL 112	WBT 436	WBR 43
Heavy Vehicles (vph)	0	0	0	0	0	0	0	25	0	0	14	5
Pedestrian Volume (ped/h)		MA-WB 28			MA-EB 25			MI-NB 12			MI-SB 22	
Wed., July 6th, 2011 4:00-5:00PM	W 1st Street & Bell Street											
Traffic Volume (vph)	NBL 22	NBT 23	NBR 32	SBL 161	SBT 89	SBR 198	EBL 278	EBT 311	EBR 34	WBL 120	WBT 286	WBR 98
Heavy Vehicles (vph)	0	0	0	3	0	9	8	16	0	0	21	0
Pedestrian Volume (ped/h)		MA-WB 22			MA-EB 19			MI-NB 6			MI-SB 5	
Sun., March 18th, 2012 4:00-5:00PM	W 1st Street & Ralston Street											
Traffic Volume (vph)	NBL 39	NBT 18	NBR 41	SBL 101	SBT 51	SBR 22	EBL 65	EBT 200	EBR 39	WBL 139	WBT 534	WBR 46

Heavy Vehicles (vph)	0	0	0	0	1	0	2	1	0	0	0	0
Pedestrian Volume (ped/h)	MA-WB 46			MA-EB 37			MI-NB 32			MI-SB 45		
Sun., March 18th, 2012 4:00-5:00PM	W 1st Street & Bell Street											
Traffic Volume (vph)	NBL	NBT	NBR	SBL	SBT	SBR	EBL	EBT	EBR	WBL	WBT	WBR
	20	18	30	209	142	369	195	187	17	149	350	104
Heavy Vehicles (vph)	0	0	0	0	0	0	0	0	0	0	0	0
Pedestrian Volume (ped/h)	MA-WB 36			MA-EB 28			MI-NB 20			MI-SB 28		

Note: NBL=Northbound Left-Turn; NBT=Northbound Through; NBR=Northbound Right-Turn and so forth. MA-WB=Pedestrians crossing western side of major street; MA-EB=Pedestrians crossing eastern side of major street; MI-NB=Pedestrians crossing southern side of minor street; MI-SB=Pedestrians crossing northern side of minor street.

Table 3 Network Travel Times

Data Collection Date	Number of Vehicles Captured	Capture Duration (min)	Average Travel Time (sec)
Wed., July 6th, 2011	36	15	22
Sun., March 18th, 2012	42	34	16

Table 4 Available Gaps and Pedestrian Accepted Gaps

Data Collection Date	Number of Observations	Available Gaps (sec)			Accepted Gaps (sec)		
		Max.	Min.	Mean	Max.	Min.	Mean
Wed., July 6th, 2011	35	16	1	4.6	6.5	2.6	3.5
Sun., March 18th, 2012	50	12	2	5.2	5.3	1.8	3.0

Table 5 Vehicle and Pedestrian Yielding Behaviors

Data Collection Date	Number of Observations	Vehicles Yield to Pedestrians (%)	Pedestrians Yield to Vehicles (%)
Wed., July 6th, 2011	30	75.44%	24.56%
Sun., March 18th, 2012	35	78.46%	21.54%

3.2 Model Coding

VISSIM provides a default mechanism to simulate pedestrian movements; however, it does not adequately replicate pedestrian behavior and the related data, such as pedestrian gap acceptance and pedestrian travel time etc., are relatively hard to extract. Therefore, this study defines pedestrians as vehicles and calibrates various parameters within VISSIM as pedestrians. Since critical gap is the most important parameter to represent the interaction between pedestrian and vehicle, the field minimum acceptable gap was coded into the model. Compared with VISSIM, CORSIM model containing both NETSIM and FRESIM models does not explicitly model pedestrian movements at TWSC intersections; however, it is possible to indirectly model pedestrian movements. The pedestrian volumes can be input directly into the model and they are divided into three categories, namely, light pedestrians, moderate pedestrians and heavy pedestrians. Additionally, certain input parameters can be used to calibrate traffic performance at TWSC intersections in CORSIM. These parameters include the start-up lost time for calibrating follow-up time, acceptable gaps in near-side cross-street traffic, and acceptable gaps in far-side cross street etc. The default acceptable gap values can be changed under NETSIM setup dialog easily.

The simulation procedure was conducted for ten replications with various random seed for each new run. In all runs, one hour of simulation is performed, preceded by ten minutes initializing period. The pedestrian walking speed was recorded and input as 3.8 ft/s. In the simulation models, key parameters are coded as control variables so that they can be easily changed to test different scenarios. These parameters can be classified into three categories, namely input vehicle and pedestrian demands, basic geometric properties of the study TWSC intersections, and vehicle against pedestrian behavior attributes. In addition, the acceptable gaps and rejected gaps were recorded and extracted based on actual simulation data. For each run, the time each pedestrian arrived at the front of crosswalk, and the time each vehicle entered the crosswalk were recorded correspondingly. Then, the length of each gap was calculated from the differences between the arrival times of consecutive vehicles.

3.3 Model Calibration and Validation

For simulation models, it is critical that the model output can match the observed field data. In addition to this, the model should also be validated against independent data. Therefore, field data collected on July 6th 2011 were used to calibrate the model and field data collected on March 18th 2012 were used for validation. The correlations of volume data between field counting and calibrated models are presented in Table 6. Since the p-values (this study assumes 95% confidence interval) are all smaller than significance level, the correlations between field data and calibrated model output are significantly different from zero. And it can be seen that the correlation coefficients are very close to one which indicates that the calibrated models can reflect field traffic and pedestrian volume.

Table 6 Correlation between Field Data and Model Output

Pearson Correlation Coefficient	Traffic Volume (vph)		Pedestrian Volume (ped/h)	
	Field Data vs. VISSIM Output	Field Data vs. CORSIM Output	Field Data vs. VISSIM Output	Field Data vs. CORSIM Output
$t_r = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}}$	0.974	0.998	0.966	0.895
P-value (95% confidence interval)	0.000	0.000	0.000	<0.001

Note: Assume t_r follows a T distribution $t_{(n-2)}$ with degree of freedom equals (n-2), $t_r \sim t_{(n-2)}$.

On the other hand, the vehicle travel time plotted based on field data collected on Wednesday, 6th July 2011, and results from ten runs of the calibrated VISSIM and eight runs of calibrated CORSIM models are compared and shown in Figure 1 and 2. Travel time is another critical factor in the model calibration procedure which combines travel speed and volume information. According to 20 observations from field recording, the total travel time of study network was in the threshold of [5.10, 32.39] seconds. However, most of vehicles (around 68%) were traveling within [8.50, 15.62] seconds. A few vehicles (less than 10%) were travelling less than 10 seconds during peak hour. Therefore, the travel time data versus the corresponding percentages of recorded vehicles are plotted in the Figures as the basis of comparisons. The accuracy of calibration can be visually assessed since the fluctuate tendency of the percentages of vehicles travelling in the network are approximately same. Also, the results from VISSIM model are steadier than those from CORSIM model even though both average values of model output could meet the field observation. Figure 3 and 4 further indicate the correlation between two datasets is monotonic linear regression with positive slope nearly 1. There are some outliers in CORSIM model output, but they are not influential since the average travel time from the model could meet the field observation.

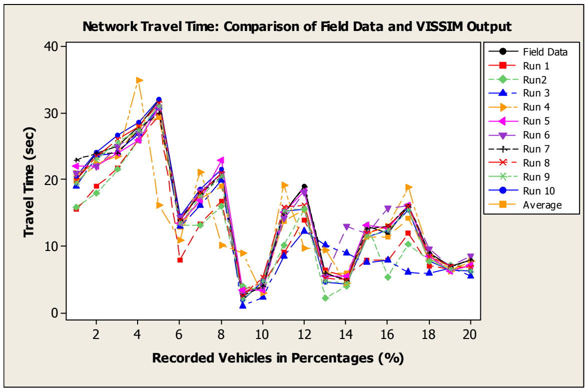

Figure 1 Travel Time: Field Data vs.VISSIM

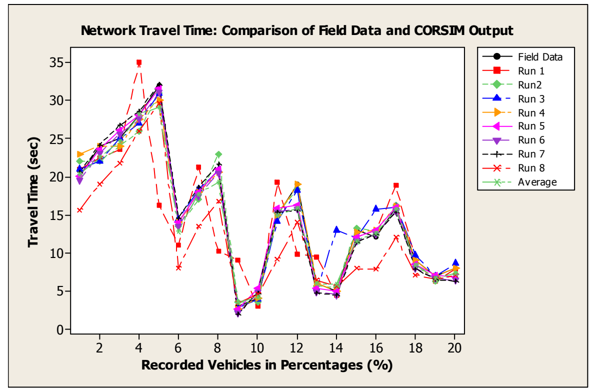

Figure 2 Travel Time: Field Data vs.CORSIM

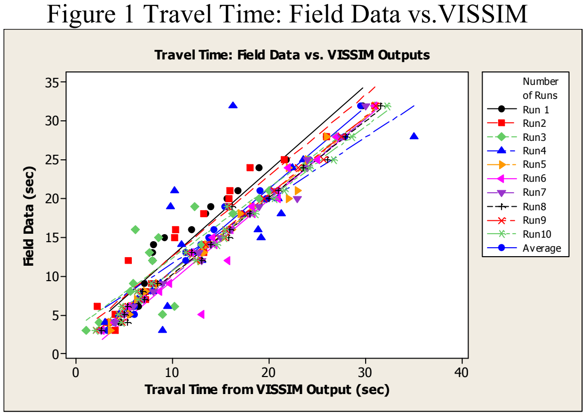

Figure 3 Correlation between Field and VISSIM Data

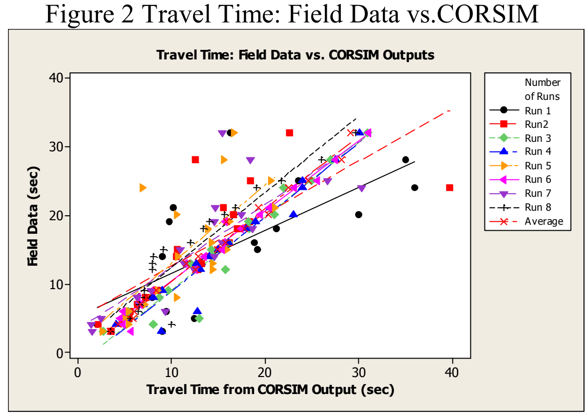

Figure 4 Correlation between Field and CORSIM Data

Data collected on Sunday, March 18th 2012 were used for model validation. The difference between data collected on weekday and weekend are the traffic and pedestrian flows as well as the vehicle composition. Relatively more heavy vehicles were observed on weekday. On the contrary, more pedestrians were recorded on weekend. Similar analysis procedure was conducted for vehicle and pedestrian flows as presented in the model calibration section. Comparison of model output and field data is shown in Table 7. Although fine-tuning of the volumes was conducted, the model output can still match with the field data. The comparison of means indicates that there was no statistically significant different in the averages between field data and model output. The sound results from validation of volumes suggests that the models were robust enough to predict vehicle travel times and delays that would result from changes in vehicle fleet compositions.

Table 7 Comparison of Field Data and Model Output

Pearson Correlation Coefficient	Traffic Volume (vph)		Pedestrian Volume (ped/h)	
	Field Data vs. VISSIM Output	Field Data vs. CORSIM Output	Field Data vs. VISSIM Output	Field Data vs. CORSIM Output
$t_r = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}}$	0.922	0.946	0.862	0.815
P-value (95% confidence interval)	0.000	0.000	0.000	0.002

Since pedestrians were coded as vehicles in VISSIM model, pedestrians should obey the car-following algorithm. Therefore, the calibrated VISSIM should be able to provide and predict the well-known pedestrian/vehicle speed-flow relationships. The coefficients from Fruin model

$q = 3.729u - 0.0467u^2$ are referenced in this study and plotted as black dots in Figure 5. In the established simulation models, the pedestrian crosswalk width was assigned as 1.0m, 2.0m and 3.5m, respectively to calibrate and validate the model. Correspondingly, the flow-speed correlation is output and demonstrated separately in Figure 5. Pedestrian flows were increasing from 0 to 140, and yet the pedestrian speed was decreasing as shown at the right side of the figure. Generally speaking, the model output results are following the assumed flow-speed correlation even though there are several outliers. The crosswalk width 1.0m provides more reasonable results in this model. To sum up, according to model calibration and validation results, the established simulation models can provide reasonable and meaningful results for this study.

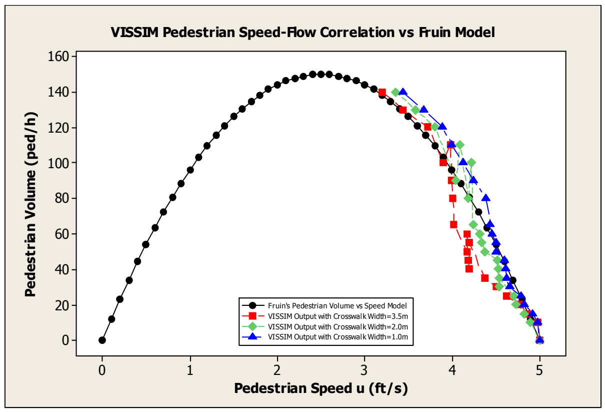

Figure 5 Pedestrian Speed-Flow Correlation

5 ANALYSIS

5.1 Delay Analysis

The major street delay and pedestrian delay are extracted in Table 8. In VISSIM model, two conditions, i.e. pedestrian yielding and vehicle yielding, are considered proportionally whereas CORSIM model follows pedestrian full yielding behaviors. Therefore, major street vehicles will have nearly zero delay from CORSIM model which accounts for HCM gap acceptance theory.

Table 8 Vehicle and Pedestrian Delay from Simulation Models

Minimum Acceptable Gap (sec)		VISSM: 3.2 sec	CORSIM: 1.1 sec
Bell St & 1st St	Delay of Major-street Approaches (sec/veh)	8.1682	1.5013
	Pedestrian Delay (sec/ped)	3.9512	4.3746
Ralston St & 1st St	Delay of Major-street Approaches (sec/veh)	10.2344	1.0206
	Pedestrian Delay (sec/ped)	3.4082	5.1241

The pedestrian delays at two study intersections are relatively small. The CORSIM results show higher pedestrian delay. Although CORSIM model uses a smaller acceptable gap, it is assumed that vehicles have full priority. Pedestrians will yield to vehicles no matter what the conditions are. However in VISSIM model, pedestrians were coded as vehicles and 20% of vehicles were coded to have higher priorities than pedestrians whereas the rest 80% vehicles would have lower priorities. So it would expect higher vehicle yielding behavior in VISSIM model, correspondingly greater vehicle delay and lesser pedestrian delay.

5.2 Gap Acceptance

In this study, three categories of gaps including available gap, accepted and rejected gap are discussed below. Available gaps are calculated as headways which is the time difference between the head of consecutive vehicles in major-street. Additionally, both accepted and rejected gaps are recorded and analyzed. The accepted gaps recorded from the near-side of pedestrian crossing direction are considered as near-gap of the vehicle lane. Similarly, the far-side gap time from the vehicle lane is considered as far-gap time.

Table 9 Accepted and Rejected Gap Thresholds

		VISSM	CORSIM
Accepted Gap Threshold (sec)	Near-Gap (sec)	[2.678, 10.961]	[3.812, 12.026]
	Far-Gap (sec)	[2.587, 5.254]	[2.630, 6.710]
Rejected Gap Threshold (sec)	Near-Gap (sec)	[0.960, 4.719]	[2.311, 5.671]
	Far-Gap (sec)	[0, 1.960]	[0.656, 1.997]

In VISSIM model, the accepted gaps are approximate 3 to 11 seconds. The average gap acceptance is 5.1 seconds which is higher than the field data 3.2 seconds in the model. In CORSIM model, the average gap is 8.53 seconds. To sum up, the acceptable gap is range from 4 to 12 seconds under both simulation environments. The rejected gaps are around 0 to 5.5 seconds. It can be indicated that shorter far-side gaps are accepted in both models. The default far-side acceptable gap in VISSIM model is the same with near-side value. And in CORSIM model, the far-side acceptable gap is equal to near-side gap plus additional 1.2 seconds. However, the simulation results show that the accepted far-side gap is smaller than near-side gap. This is because the near-gap and far-gap are recorded simultaneously when the pedestrians make the decision to cross. The result also reflects the phenomenon that some pedestrians pay little attention to the far-side incoming vehicles when they start to cross the first vehicle line. Although this is a potential dangerous behavior, pedestrians hardly consider it seriously.

Moreover, the accepted and rejected gap thresholds are not separated completely as shown in Figure 6. There is approximate 2 seconds overlap between them. This result means that the time space between 3 to 5 seconds can be both accepted and rejected depending on other possible factors. Although there is difference between VISSIM and CORSIM results, the variance is not significant. Also, according to the cumulative distributions in Figure 7, cumulative line is a pattern of rejected gaps, available gaps followed by accepted gaps from left to right side in both model output results. This mainly indicates that the mean of rejected gaps is smaller than available gaps followed by accepted gaps. The shapes of cumulative lines are not exactly congruent but alike so that the variances of the extracted data are similar.

Further, considering gaps as random variables, statistical analysis are conducted focusing on available gap and accepted gap. Basically, probability analysis and empirical CDF plots are conducted assuming one of the common distributions like Normal, Lognormal and Exponential etc. It is found that both available gap databases from simulation models fit shifted Log-normal distribution pretty well although there will be subtle difference with the location and scale properties of the distribution from location to location. Similar analysis are conducted for accepted gaps afterwards. It is found that the accepted gaps from both simulation models and field data follow normal distributions. As shown in Figure 11, when large sample size is collected, the probability distribution of accepted gap will be symmetric bell-shaped density curves with a single peak. Therefore, it is pretty easy to obtain the probability of accepting a particular gap.

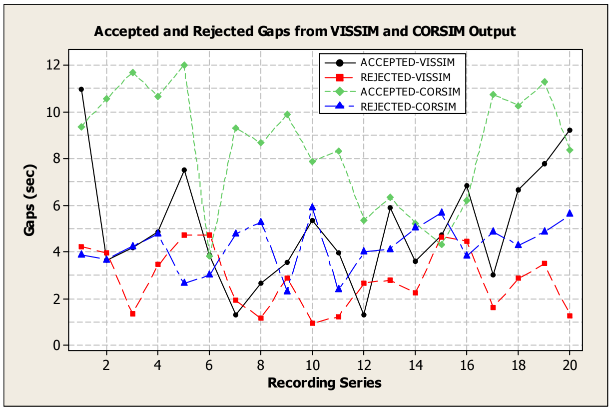

Figure 6 Accepted and Rejected Gaps from VISSIM and CORSIM Models

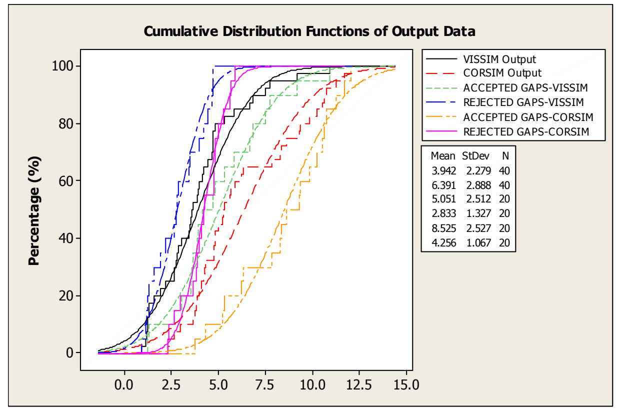

Figure 7 Cumulative Distribution Functions (CDF) of Output Gap Data

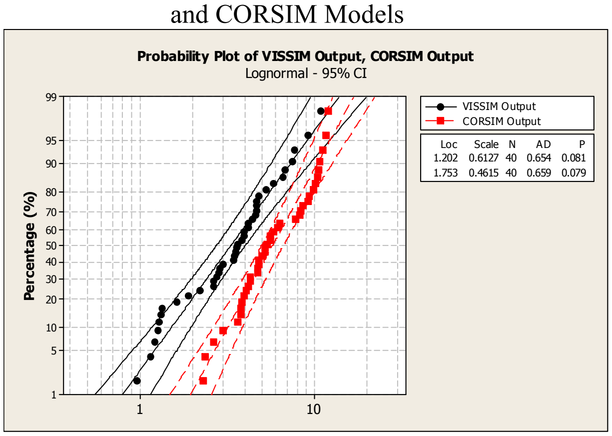

Figure 8 Hypothesis Test of Available Gap

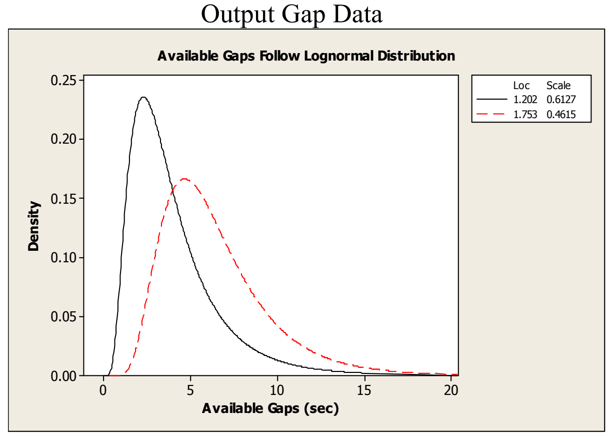

Figure 9 Shifted Log-normal Distribution of Available Gaps

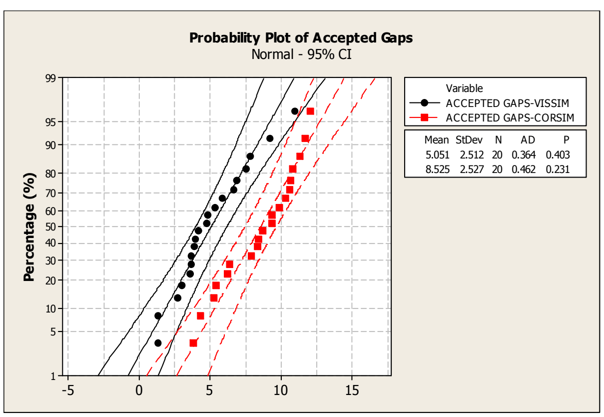

Figure 10 Hypothesis Test of Accepted Gap

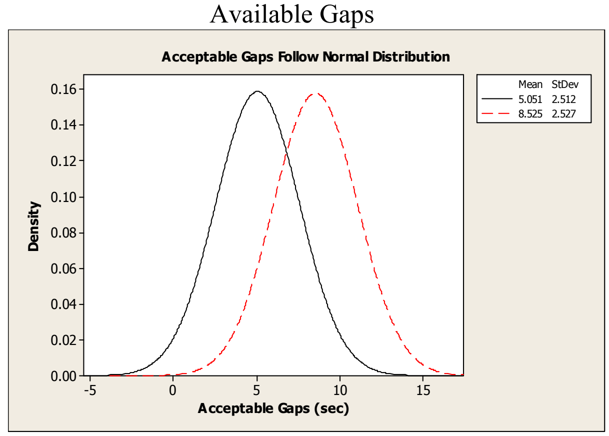

Figure 11 Normal Distribution of Accepted Gaps

5 CONCLUSIONS

This study focuses on pedestrian gap acceptance behavior which is a crucial factor pertaining to both mobility and safety performance of a TWSC intersection. Simulation models within VISSIM and CORSIM environments are established based on field data. The following conclusions can be drawn based on the analysis. First of all, at a typical TWSC intersection, pedestrians who intend to cross the major-street are in the similar circumstances with minor-street vehicles. This study puts forward that acceptable gap at TWSC intersections is range from 4 to 12 seconds, and the rejected gaps are around 0 to 5.5 seconds. Approximately 2 seconds overlap time space is pointed out between accepted and rejected gap thresholds. This means the acceptable and rejected gaps are not separated completely. Based on both field data and model output, it is found out that available gaps follow shifted Log-normal distribution and accepted gaps follow symmetrical normal distribution which provides a way to calculate the probability of accepting a particular gap. Last but not least, compared to CORSIM model, the VISSIM model environment provides more detailed coding platform and information, such as the individual pedestrian characteristics and behavior, the length of crosswalks, and even the marking length on the crosswalks. Therefore, it is recommended to apply VISSIM model for pedestrian behavior analysis in the future studies.

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