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Capacity Reliability of Signalized Intersections with Mixed Traffic Conditions*

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Abstract: The reliability of capacity of signalized intersections in mixed traffic conditions involving vehicles, bicycles, and pedestrians was investigated to complete the conventional, deterministic capacity calculations. Simulations using VISSIM provided estimates of capacity distributions, and demonstrated the effects of the analysis intervals on the distributions. With the random vehicle arrivals taken into account, a capacity reliability assessment method was given as a function. Assessments were also performed regarding the effects of the conflicting pedestrian and bicycle volumes on capacity reliability. The simulation indicates that the pedestrians and bicycles result in greater random fluctuations of exclusive turning lane capacities, but have less effect on the variability of shared lane capacities. Normal distributions can be used to model the capacities for intervals not less than 10 min. At higher vehicular volumes, the capacity reliability is more sensitive to the mean and standard deviation of the pedestrian and bicycle volumes.

Key words: reliability; capacity; mixed traffic; signalized intersection; capacity distribution

Introduction

The highway capacity manual (HCM)[1] defines the traffic flow capacity as the maximum sustainable flow rate at which vehicles or persons can reasonably be expected to traverse a point or uniform segment of a lane or roadway during a specified time period for given roadway, geometric, traffic, environmental, and control conditions. For a given set of conditions, the capacity is conventionally treated as a constant. This traditional understanding of capacity is used by most capacity calculation procedures. However, in most circumstances, capacities vary over a certain range around the expectations, even for constant geometric, traffic, environmental, and control conditions. This stochastic nature of the capacity has been demonstrated by several studies of freeway traffic flow[2-5]. Since the capacity is variable, these existing deterministic methods may not be sufficient for more detailed capacity analyses.

In general, the capacities of signalized intersections are determined by a long list of determinants. The determinants include not only deterministic factors, e.g., the geometric and signalization conditions, but also random effects such as differences in traffic composition, random driver behavior, and the resulting random interactions between vehicles. Because of these random effects, the capacity is then stochastic in nature. Furthermore, in mixed traffic conditions, the randomness of the impeding effects of pedestrians and bicycles on vehicular flows, which arises from their random arrival times and behavior, further contributes to capacity variations.

However, existing methods for the capacity of signalized intersections accounting for the effects of pedestrians and bicycles in mixed traffic conditions are

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all deterministic. These methods either predict capacities based on regression models of the conflict zone occupancy[6-8] or estimate the capacity expectations based on gap-acceptance theory[9-11]. Since these methods disregard the stochastic nature of the capacities, they only yield estimates of the actual capacities. The actual capacity variations in mixed traffic conditions must be analyzed stochastically.

Stochastic analyses provide a new measure of the performance of signalized intersections in mixed traffic conditions for analysis of traffic reliability. The capacity reliability of signalized intersections is a key component of a more complete analysis of signalized intersection capacities for improved facility design and traffic operations of signalized intersections.

1 Literature Review and Objectives

The literature contains various studies regarding capacity reliability and variability. Several studies[2-5] have demonstrated the variability of freeway capacities. Minderhoud et al.[3] believed that given the dependence of capacity on traffic control, weather, and other changing conditions, there is no generally valid single capacity value, but instead capacity is a stochastic variable following a distribution function. Brilon et al.[4] proposed a stochastic analysis methodology for highway capacity analyses. Brilon et al.[5] also presented an analysis of the capacity of a typical roundabout entry as an example to illustrate that the stochastic approach is applicable to intersections. Their study indicated that the roundabout entry capacities during 1-min intervals were Weibull distributed.

Brilon et al.[4] transformed the distribution of single freeway section capacities to measure the capacity reliability in larger networks composed of freeway sections. Chen et al.[12] described the network capacity reliability as the probability that a network can accommodate a certain traffic demand at the required level-of-service (LOS), while accounting for drivers' route choice behavior. Chen et al.[13] subsequently extended the capacity reliability analysis with a comprehensive methodology to assess the performance of a degradable road network.

These results provide insights into the issues associated with capacity reliability. However, none of these studies have dealt with signalized intersections which have interrupted traffic flows, and none have explicitly taken into account mixed traffic conditions including various traffic flows (vehicles, pedestrians, and bicycles) and the complex interactions between these flows.

The objectives of this research are to apply the stochastic approach proposed by Brilon et al.[5] to signalized intersections with mixed traffic conditions to analyze the capacity variability, to present a capacity reliability assessment method accounting for random vehicle arrivals, and to analyze the effects of mixed traffic conditions on the capacity reliability.

2 Capacity Reliability of Signalized Intersections

2.1 Analysis unit for capacity reliability

The HCM defines a lane group as a set of lanes established at an intersection approach for separate capacity and LOS analysis. Lane groups are widely used as the basic analysis units of signalized intersections for facility designs and traffic operations, but the aggregation across lane groups is not always required[1,14]. Moreover, in road networks, lane groups can also be considered to be components of routes in signalized networks. Therefore, this study uses lane groups as the basic units for stochastic analyses of the capacity reliability of signalized intersections.

2.2 Definition of capacity reliability of signalized intersections

The capacity reliability of a lane group is defined as the probability that the capacity of the lane group can accommodate a certain vehicular volume at the required LOS,

$$R_c(q) = \Pr(\eta c \geqslant q) \tag{1}$$

where q is the vehicular volume and c is the capacity of the lane group, expressed in vehicles per hour (veh/h); η is a measure of the LOS, equal to the ratio of the service volume to the capacity at a specific LOS. Thus, ηc is the operational capacity at the designated LOS. When $\eta = 1$, $R_c(q)$ gauges the probability that arriving vehicles have to queue due to over-saturation.

2.3 Capacity distribution estimate

The capacity reliability of a signalized intersection must be based on the capacity distribution. For a given set of conditions, the capacity distribution can be written as

$$F_c(x) = \Pr(c \leqslant x) \tag{2}$$

where x is the independent variable of the distribution function.

The paper applies the approach given by Brilon et al.[5] for unsignalized intersections to signalized intersections. Both parametric and non-parametric methods were used to estimate the distributions.

2.3.1 Parametric methods

The normal and Weibull distributions are widely used to model lifetime distributions in reliability engineering. Then, the capacities of a lane group at signalized intersections are assumed to have either a normal distribution or a two-parameter Weibull distribution for a given set of conditions.

$$F_c(x) = \frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{x} \mathrm{e}^{\frac{-(t-\mu)^2}{2\sigma^2}}\,\mathrm{d}t \tag{3}$$

$$F_c(x) = 1 - \mathrm{e}^{-\left(\frac{x}{\beta}\right)^{\alpha}} \tag{4}$$

where μ and σ are the normal distribution parameters, while α and β are the shape and scale parameters of the Weibull distribution. These parameters can be estimated using the maximum likelihood estimation (MLE).

The Kolmogorov-Smirnov test is then used to examine whether the capacities follow the assumed distributions for the given significant level.

2.3.2 Non-parametric methods

The product limit method (PLM) by Kaplan and Meier[15] is a widely used non-parametric method for empirical cumulative distribution estimates. This statistical method is used here to provide comparisons with distributions estimated using parametric methods.

Each simulation experiment in the following sections assumed a congested traffic condition on the subject approaches. Therefore, the departing volume counts are regarded as observations of the capacity. Since these observed capacities are regarded as exact observations, the censoring Boolean vector is thus 0 for the product limit estimate.

3 Capacity Distribution Simulations

3.1 Simulations

The simulations were designed to investigate the randomness of the capacities of signalized intersections for mixed traffic conditions. The stochastic capacities of the northbound right-turn lane were analyzed for the typical four-way intersection shown in Figs. 1a and 1b.

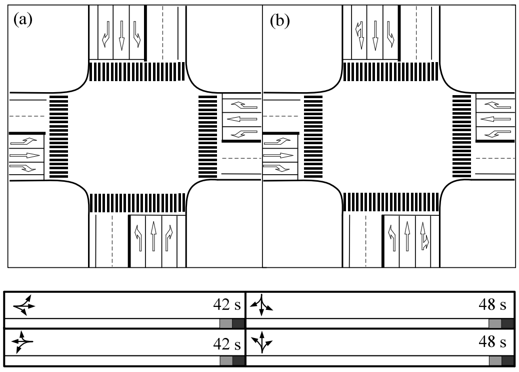


Fig. 1 Layouts and signal timing scenarios of the example intersections

Generally, the stochastic nature can be examined using random experiments conducted in the same experimental conditions. However, mixed traffic conditions have more capacity determinants that make it much more difficult to obtain a sufficient number of samples with the same experimental conditions by field observations. Therefore, VISSIM[16], a most mainstream and widely-used microscopic simulation software, was used to simulate the flows on the signalized intersections to get the capacity data. The simulations considered both exclusive and shared right-turn lanes.

3.2 Simulation inputs

3.2.1 Geometric and signalization conditions

Each approach to the intersection has a through lane, an exclusive left-turn lane and an exclusive or shared right-turn lane. The lanes are 3 m wide with a 0° grade. The crosswalks are 4 m wide.

Typical 2-phase signal timing as shown in Fig. 1 was used for the vehicles with a cycle length of 90 s, an amber light of 2 s, and an all-red of 2 s. The effective green was 45 s for the northbound right turns. Right turns on red (RTOR) were allowed. The green indications for pedestrians and bicycles were allocated together with the through vehicular movements and terminated 4 s before the vehicular green phase ended.

3.2.2 Traffic conditions

The volume ratios for the left-turn bicycles relative to the through were set to 2:8 for each approach. The bicycle volumes were set as 400 bicycles/h for all the approaches except for the northbound lane. The volume ratio of through to right-turn vehicles was set to 5:5 for the northbound shared lane in Fig. 1b.

Two pedestrian volume levels, 100 and 1400 pedestrians/h, were selected for the two crosswalks crossed by the northbound right-turn vehicular movements, with two bicycle volumes of 200 and 1000 bicycles/h selected for the northbound approach. Eight traffic conditions were then obtained as shown in Table 1. For comparison, two base scenarios a_0 and b_0 are given without the presence of pedestrians or bicycles. Here, 100 runs were made for each traffic condition with the same 100 random number seeds. Each run-time covered a period of 15 min. The input volumes for the right-turn lanes were 1300 veh/h, which created saturated conditions on those lanes.

Table 1 Input traffic conditions for the simulations

Traffic condition	Right-turn lane types	Pedestrian volumes	Bicycle volumes
a_0	Exclusive	None	None
1	Exclusive	Low	Low
2	Exclusive	Low	High
3	Exclusive	High	Low
4	Exclusive	High	High
b_0	Shared	None	None
5	Shared	Low	Low
6	Shared	Low	High
7	Shared	High	Low
8	Shared	High	High

3.3 Analysis of capacity distributions

The simulated capacities of the northbound exclusive and shared right-turn lanes are listed in Table 2 for each traffic condition.

Table 2 Descriptive statistics of the simulated capacities

Traffic condition	Mean (veh/h)	Standard deviation (veh/h)	COV	Range (veh/h)
a_0	732	12.46	0.017	56
1	595	15.13	0.025	80
2	529	17.99	0.034	68
3	375	21.03	0.056	108
4	334	18.59	0.055	100
b_0	529	20.56	0.038	104
5	517	19.83	0.038	112
6	468	22.72	0.048	112
7	468	19.43	0.041	112
8	425	22.68	0.053	116

The standard deviations, ranges, and coefficients of variance (COV) indicate that the conflicting pedestrians and bicycles markedly increase the fluctuations of the exclusive right-turn lane capacities. This phenomenon arises from the randomness of the arrivals and behavior of the pedestrians and bicycles. However, the shared lane capacities experience relatively smaller fluctuations from the effects of the pedestrians and bicycles. With right turns on red, the stochastic arrivals of through and right-turn vehicles cause the shared lane capacities to fluctuate considerably. Then, the additional effects of the pedestrians and bicycles do not significantly increase the ranges of the shared lane capacities.

The simulated capacities for 15-min intervals were analyzed for the capacity distributions using both the maximum-likelihood technique and the product limit method, with the results shown in Figs. 2 and 3. The curves estimated by the product limit method fit very well into the normal distribution functions estimated using the maximum-likelihood technique. The estimated normal distribution parameters are listed in Table 3. At a 95% significance level, the null hypothesis that the capacities during 15-min intervals have a normal distribution cannot be rejected.

The estimated Weibull distribution parameters and hypothesis testing results are also listed in Table 3. The simulation results show that the Weibull distributions have limited ability to model the capacity of signalized intersections with 15-min intervals.

3.4 Typical percentile capacities

One of the basic guidelines for intersection design is that the design capacities should accommodate the peak hour volumes. However, existing methods for predicting capacities for mixed traffic conditions either predict the capacity based on regression models or estimate the capacity expectation using the gap-acceptance model, which tend to agree with the median capacities. At peak periods or hours, these capacities may not always be able to accommodate the traffic demand, and congestion may occur. Percentile capacities from stochastic analysis can provide a better reliability-based design for signalized intersections.

The capacity distributions can yield the typical percentile capacities listed in Table 4 for each traffic condition.

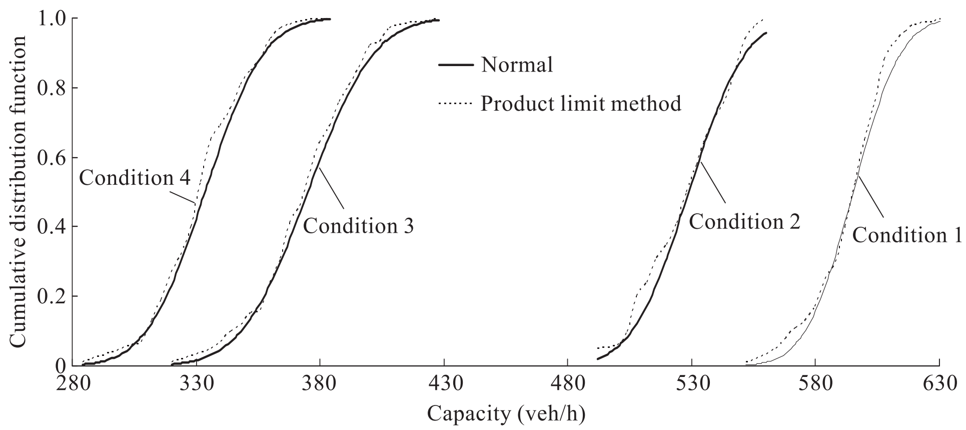


Fig. 2 Probability distribution estimates of exclusive right-turn lane capacities

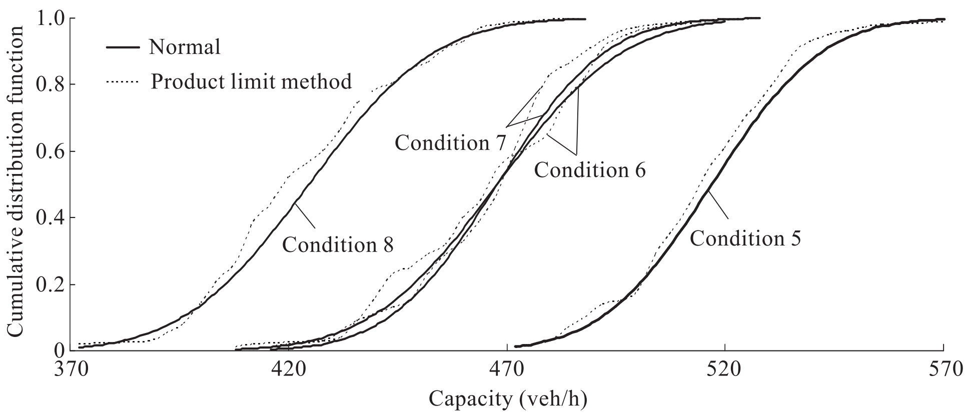


Fig. 3 Probability distribution estimates of shared right-turn lane capacities

Table 3 Estimated Weibull and normal distribution parameters

Traffic condition	Weibull distribution analysis				Normal distribution analysis			
	α	β	p	Weibull distribution	μ	σ	p	Normal distribution
a_0	64.7185	738.1281	0.0492	—	732.0800	12.4557	0.2386	√
1	44.2429	602.2162	0.2853	√	595.2000	15.1277	0.0986	√
2	34.2104	537.3536	0.2920	√	528.8800	17.9929	0.583	√
3	19.2188	384.8509	0.3907	√	375.0800	21.0270	0.4332	√
4	18.8495	342.3762	0.0255	—	333.6400	18.5894	0.2616	√
b_0	24.6142	538.9291	0.0177	—	528.8081	20.5633	0.2754	√
5	23.5920	526.6949	0.1012	√	516.9200	19.8325	0.5706	√
6	22.5919	478.4143	0.0321	—	467.7600	22.7188	0.1381	√
7	24.1704	476.9740	0.3207	√	467.8000	19.4251	0.2297	√
8	18.7108	435.6622	0.0885	√	424.6939	22.6786	0.2421	√

3.5 Capacity distributions for various analysis intervals

The capacities were also analyzed stochastically for analysis intervals of 2, 5, and 10 min.

For a 5% significance level, the 2-min capacities do not fit into any of the normal, Weibull, exponential, uniform, and Gamma or Poisson distributions. For 5-min analysis intervals, the capacities can be modeled by normal distributions for most situations except traffic condition a_0. For 10-min analysis intervals, the normal, Gamma, and Weibull distributions can be used to model the capacities. As the analysis interval increases, the capacities tend to be normally distributed

Table 4 Percentile capacities of lanes in the example intersections (veh/h)

Traffic condition	Mean	Min.	15%	Median	85%	Max.
a_0	732	700	719	732	745	756
1	595	552	580	595	611	632
2	529	492	510	529	548	560
3	375	320	353	375	397	428
4	334	284	314	334	353	384
b_0	529	484	507	529	550	588
5	517	472	496	517	538	584
6	468	408	444	468	491	520
7	468	416	448	468	488	528
8	425	372	401	425	448	488

as predicted by the central limit theorem. Thus, capacities for analysis intervals longer than 15 min will follow normal distributions.

4 Capacity Reliability with Random Vehicle Arrivals

When vehicles arrive uniformly at a constant flow rate during the analysis intervals, the capacity reliability of signalized intersections can be assessed using Eqs. (1)-(3). However, the volume rates of vehicles arriving at an isolated intersection during the analysis intervals are usually random, so their distribution depends strongly on the observation intervals.

The simulations indicated that the arrival volumes during intervals not less than 10 min have a normal distribution. Also, the volume of a lane group generally does not determine the capacity; therefore, the volume and the capacity of a lane group can be assumed to be independent.

In this paper, the reserve capacity, r, is defined as the difference between the capacity and the volume during the analysis intervals for a required LOS, $r=\eta c-q$. Since the sum of independent normal distributions is itself a normal distribution. r has a normal distribution with a mean of $\mu_r=\eta\mu_c-\mu_q$ and a variance of $\sigma_r^2=\eta^2\sigma_c^2+\sigma_q^2$, where μ_c and μ_q are the mean values of the capacity and the volume, and σ_c^2 and σ_q^2 are the variances of the capacity and the volume. Therefore,

$$\Pr(r\geqslant 0)=\phi\left(\frac{\mu_r}{\sigma_r}\right) \tag{4}$$

where $\phi(\cdot)$ is the cumulative distribution function of a standard normal distribution.

The probability of $r\geqslant 0$ is a measure of the possibility that a lane group can accommodate a certain traffic demand at a required LOS during the analysis interval. When $\eta=1$, $r<0$ indicates over-saturation during the interval and that queuing occurs. However, the queue may exist for only a short time and not result in congestion, since it may be only caused by temporary fluctuations of the capacity and the volume. Traffic congestion will occur, if the situation, for which $r<0$, lasts for a long time.

Thus, the capacity reliability of lane groups at signalized intersections can be calculated using

$$R_c(q)=\Pr(\eta c\geqslant q)=\Pr(r\geqslant 0)=\phi\left[\frac{\eta\mu_c-\mu_q}{(\eta^2\sigma_c^2+\sigma_q^2)^{\frac{1}{2}}}\right] \tag{5}$$

5 Sensitivity Analysis

Sensitivity analyses provide important implications concerning system designs in reliability engineering. The purpose of this sensitivity analysis is to investigate the effects of pedestrians and bicycles on the reliability for mixed traffic conditions.

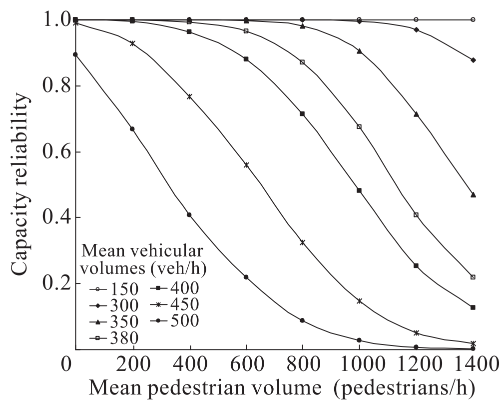
The sensitivity of the capacity reliability to a capacity determinant can be easily calculated if the analytical relationship between the capacity and the variable is known. Then, the first-order and second-order moments can be calculated using the partial derivatives of the capacity with regard to the determinant. However, existing methods cannot explicitly describe the capacity, so the partial derivatives cannot be easily calculated. Therefore, simulations were used here to analyze the sensitivity of the reliability to the capacity determinants. The means and standard deviations of pedestrian and bicycle volumes were selected for the sensitivity analysis to illustrate the characteristics of the reliability for mixed traffic conditions.

The capacity reliability of the northbound right-turn lane of intersection in Fig. 1a was used as an example for the sensitivity analysis with the capacities for 15-min intervals.

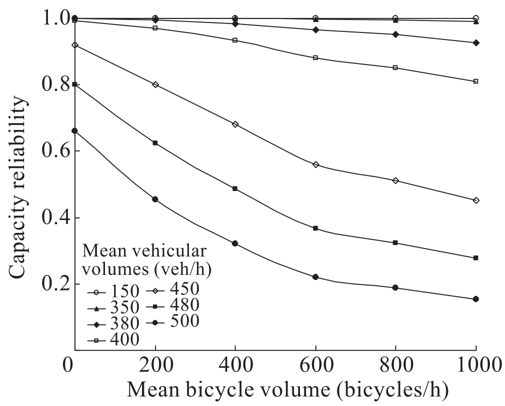
At high vehicular volumes, the capacity reliability of the northbound right-turn lane is significantly influenced by the mean volumes of pedestrians and bicycles. At low vehicular volumes, the effect of the mean pedestrian and bicycle volumes on the capacity reliability tends to be less as shown in Fig. 4 for $\eta = 1$.

Higher vehicular volumes result in higher volume to capacity ratios in the lanes due to more interactions between vehicles and non-motorized traffic. Pedestrians and bicycles then have stronger adverse effects on the vehicular flow, and hence, on the capacity reliability. At low vehicular volumes, the vehicle interactions within the vehicular traffic flows occur less frequently, so the effect of the mean pedestrian and bicycle volumes on the capacity reliability is reduced.

Similarly, the capacity reliability of the northbound right-turn lane depends strongly on the standard deviations of the pedestrian and bicycle volumes at high vehicular volumes, but the effect is insignificant at low vehicular volumes as shown in Fig. 5 for $\eta = 1$.

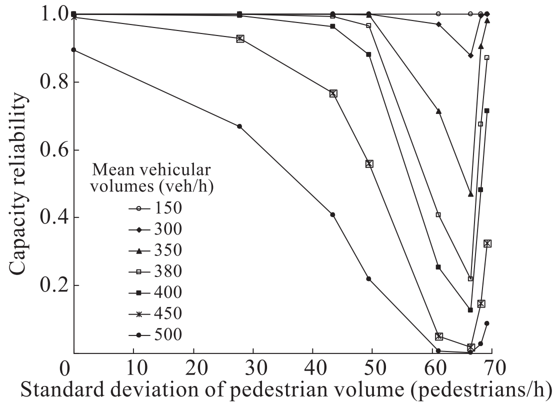


(a) Pedestrian

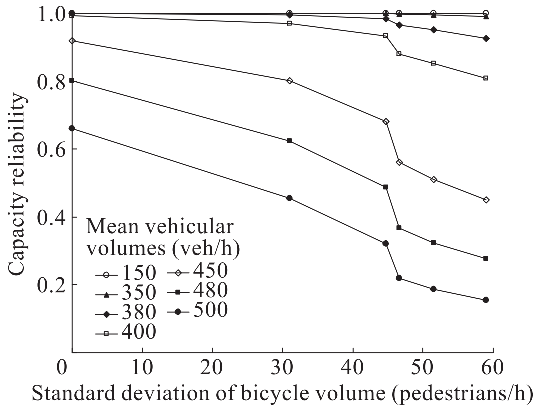


(b) Bicycle

Fig. 4 Sensitivity of the capacity reliability to the mean pedestrian and bicycle volume



(a) Pedestrian



(b) Bicycle

Fig. 5 Sensitivity of the capacity reliability to the standard deviation of the pedestrian and bicycle volume

6 Concluding Remarks

The stochastic nature of capacities of signalized intersections in mixed traffic conditions was investigated using VISSIM simulations to provide data for estimating the capacity distribution and the typical percentile lane capacities. The capacity distributions for various analysis intervals were also analyzed. With the random vehicle arrivals taken into account, a capacity reliability assessment method was given as a function. Assessments were also performed regarding the effects of the pedestrian and bicycle volumes on capacity reliability. The results are as follows:

(1) In mixed traffic conditions, the presence of pedestrians and bicycles results in greater random fluctuations of exclusive turning lane capacities, but has less effect on the random fluctuations of shared lane capacities.

(2) The capacity distribution for analysis intervals not less than 10 min can be modeled using a normal distribution. Typical percentile capacities of the lanes, calculated from the distributions, can be used to guide reliability-based intersection designs.

(3) At higher vehicular volumes, the capacity reliabilities of the turning lanes at signalized intersections are more sensitive to the mean and standard deviation of the pedestrian and bicycle volumes.

(4) Since isolated signalized intersections can be considered as "components" of a route or a network, this research provides a basis for further investigations into the capacity reliability of signalized networks in mixed traffic conditions.

(5) These distributions may have limited applicability due to the small samples of the capacities. Further work is needed to obtain sufficient amounts of empirical data for calibrations and reliability-related analyses.

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