

Simulation-Based Study of Traffic Operational Characteristics at All-Way-Stop-Controlled Intersections

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Traffic operational characteristics at all-way-stop-controlled intersections were investigated by using AWSIM, a microscopic simulation model. The effects of vehicle arrival distribution and traffic volume split on intersection operations were studied. Traffic operations were analyzed from delay, capacity, and queue length perspectives. Empirical models were developed on the basis of simulation results for delay and queue length estimations. It was found that longer delays and queues resulted from platoon arrivals. Higher intersection capacity or lower control delay can be achieved with even volume splits on all the approaches. A generalized form of the delay model showed a better correlation compared with those for exponential-form models used by other studies. A nonlinear relationship was found to exist between the 95th percentile queue length and the average queue length. An empirical model was developed on the basis of the simulation results for estimation of the 95th percentile queue lengths. The model proves to be reliable and easy to use on the basis of field studies, and it fulfills one of the major shortcomings in queue estimation, which is currently unavailable in the *Highway Capacity Manual*.

All-way-stop-controlled (AWSC) intersections are commonly used intersection control types in the United States. Under certain traffic volume and geometric conditions, AWSC provides safe, efficient, and economical traffic control compared with the traffic control at signalized intersections and two-way-stop-controlled (TWSC) intersections (1, 2). Although significant research has been conducted on signalized intersections and TWSC intersections, the understanding and study of AWSC intersections are somewhat limited. The purpose of this paper is to continue the effort from an earlier study (3) to address the traffic operational characteristics at AWSC intersections by using microsimulation as a tool.

The 1997 update to the *Highway Capacity Manual* (HCM) (4) provides guidelines for the analysis of capacity and level of service (LOS) at AWSC intersections. An enhanced analytical procedure was introduced to estimate capacity at AWSC intersections. The procedure involves iterative calculations, which would be possible to perform only with microcomputers. The procedure also relies on the saturation headways classified under eight cases under a normal traffic volume distribution and turning movement proportion. One of the major shortcomings of the HCM is the absence of a queue length estimation procedure, which is a parameter usually desired by traffic engineers for the purpose of design and operational studies.

Simulation models provide alternative means for transportation studies when analytical models cannot provide satisfactory solutions. Although several simulation models currently available have features for modeling of AWSC intersections, an earlier study (3) found that AWSIM, specifically developed for AWSC intersections, provides the most reliable results on the basis of field studies. Details on the model structure and the modeling features of AWSIM can be found in the same study. As a result, the present study was continued by using AWSIM as the primary model.

The study tends to address the effect of vehicle arrival and traffic volume split on intersection delay, queue, and capacity. Empirical delay and queue length models are developed for easy practical applications and analyses of traffic operational characteristics. Because the current version of AWSIM is still limited to the modeling of single-lane-approach intersections, the conclusions of this study are to be derived primarily on the basis of the results for single-lane-approach intersections.

EMPIRICAL DELAY MODELS

The purpose of developing empirical models is to provide traffic engineers with an easy means of quickly deriving a solution based on certain traffic conditions. On the other hand, empirical models would also provide insights into how delay is associated with traffic flow conditions. Because capacity is not a direct output of simulation models, the study focused on the development of empirical delay models based on simulation results.

Before the publication of HCM 1997, empirical capacity and delay models were the primary tools for analysis of traffic operations at AWSC intersections. Simulation provides a means of conducting multiple runs and gathering the results from various scenarios. Simulation makes it possible to cover a much broader range of traffic volume conditions compared with the range that can be covered by use of data collected in the field.

Previously developed empirical delay models (5) were primarily in the exponential form, as shown in Equation 1:

$$d = e^{a_i V} \quad (1)$$

where

d = average vehicle delay [s/vehicle (veh)],

a_i = constant of regression analysis based on volume split i , and

V = total intersection volume (veh/h).

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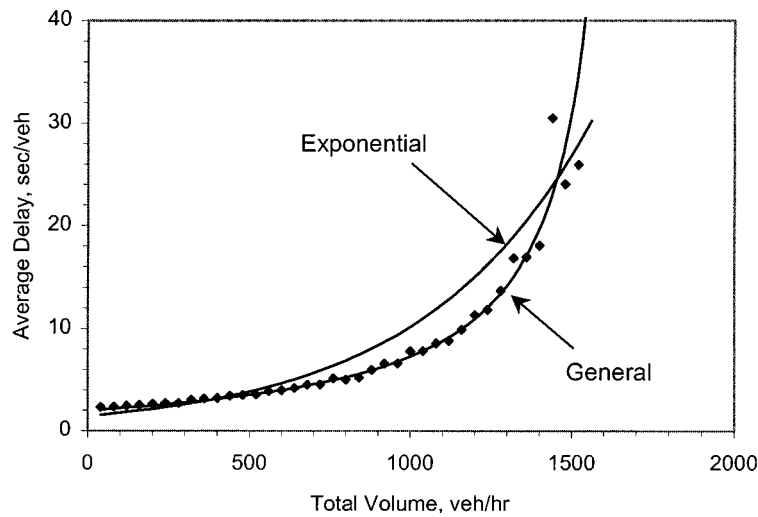


FIGURE 1 Generalized-form versus exponential-form delay model.

Although the exponential form of the delay model is easy to derive, it may not be suitable under certain traffic flow conditions. A generalized form of the delay model, as proposed in the present study and as shown in Equation 2, might provide better delay estimates.

$$d = D_{\min} \left(1 + \frac{a_i V}{1 - b_i V} \right) \tag{2}$$

where

D_{\min} = minimum delay when traffic is present (2.0 s was found to be reasonable); and

a_i and b_i = constants of regression based on volume split i , a ratio between traffic volumes on two directions of intersection.

The two forms of delay models were tested on the basis of simulation runs, and the results are shown in Figure 1. The total inter-

section volume ranged between 40 and 1,600 veh/h. Each datum point represents an average delay value for four runs, with 4-h simulation times used for each run. Figure 1 was based on a volume split of 70% (i.e., 70 percent in the east-west direction and 30 percent in the north-south direction), with an even volume distribution on the two approaches of the same direction. The proportions of turning movements on each approach were assumed to be 20, 60, and 20 percent for the left-turn, through, and right-turn movements, respectively. Regression analyses were conducted by using the two forms of delay models, and both are illustrated in Figure 1.

A general observation from Figure 1 reveals that the generalized form of the delay model provides a better fit to the datum points obtained from simulation. Statistical results were calculated on the basis of a regression analysis of the two models, and the standard errors and the R^2 values are given in Table 1.

The data indicate that use of the generalized form of the regression model (Equation 2) gives better results than the exponential form (Equation 1), as shown by the standard error and R^2 values.

TABLE 1 Statistical Results Between Types of Regression Equations

Volume Split	Standard Error		R^2	
	General	Exponential	General	Exponential
50/50	1.0	1.7	0.98	0.94
60/40	1.4	2.8	0.96	0.87
70/30	2.1	4.1	0.95	0.83
80/20	1.1	8.6	1.00	0.78
90/10	3.7	12.0	0.99	0.82
100/0	3.4	9.6	0.97	0.84

Note: Standard Error = $\sqrt{\frac{1}{n} \sum_{i=1}^n (simulation_i - model_i)^2}$

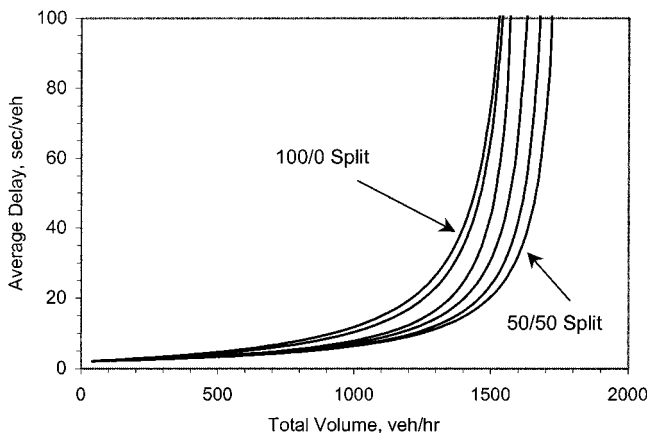


FIGURE 2 Regression delay models with 20, 60, and 20 percent left-turn, through, and right-turn movements, respectively.

The regression lines under various traffic volume splits are shown in Figures 2 and 3. The 20, 60, and 20 percent turning movement proportions were assumed for Figure 2, whereas 100 percent through movement was used for Figure 3. The regression parameters are summarized in Tables 2 and 3.

CAPACITY ESTIMATION

Capacity estimates for AWSC intersections have been reported in several studies (5–9). This section attempts to provide comparisons of the capacities given by various models. It is important to understand how capacity has been defined at AWSC intersections and what assumptions were used in various studies while reporting capacities.

Hebert (6) was probably the first researcher who studied traffic operational characteristics at AWSC intersections. In 1963, Hebert proposed an empirical capacity model for AWSC intersections based on the saturation headway values collected at three single-lane-approach intersections in the Chicago area. He defined capacity as

the maximum traffic flow that the entire intersection can process under certain traffic volume splits in each direction. It is noted that excessive vehicle delay could result from conditions when the traffic volume is equal to capacity.

Richardson (7) developed an analytical model based on the saturation headway data collected by Hebert (6). Richardson’s study did not recognize the effect of turning movements. His capacity definition was similar to Hebert’s, which is the maximum flow rate that the entire intersection would handle under certain traffic volume splits.

Kyte and colleagues (5, 8) extended the studies of both Hebert (6) and Richardson (7). They developed empirical capacity and delay models that were incorporated into the 1994 update to the HCM (9) and enhanced Richardson’s model, which is included in HCM 1997 (4). In both the HCM 1994 and the HCM 1997 models, the capacity is reported for each approach, which is defined as the maximum flow rate of that approach while the traffic volumes on the other approaches are held constant. It is important to realize that the intersection capacity equivalent to those reported by use of the models mentioned above cannot be obtained by simply adding the individual capacities of each approach.

Wu (10) developed a theoretical model based on the addition-conflict-flow method, which can be used to analyze capacity and delay under most lane configurations and traffic flow conditions. He presented the capacity results on the basis of the concepts used by both Hebert (6) and Kyte and colleagues (5, 8).

Unlike theoretical models or empirical models, simulation models generally do not provide capacity estimates directly. To provide a fair comparison among different models, the following approach was used to derive the capacities for the AWSIM model and the HCM models:

- Capacity from AWSIM was obtained on the basis of the maximum traffic flow rate when the average control delay does not exceed 60 s/veh. This delay threshold represents a condition just beyond LOS F and is believed to be close to true capacity.
- Capacities from both HCM 1994 (9) and HCM 1997 (4) were obtained on the basis of the total service volume when the highest degree of saturation on each approach is approximately equal to 1.0. The corresponding delay is usually just above 50 s/veh, which represents LOS F conditions.

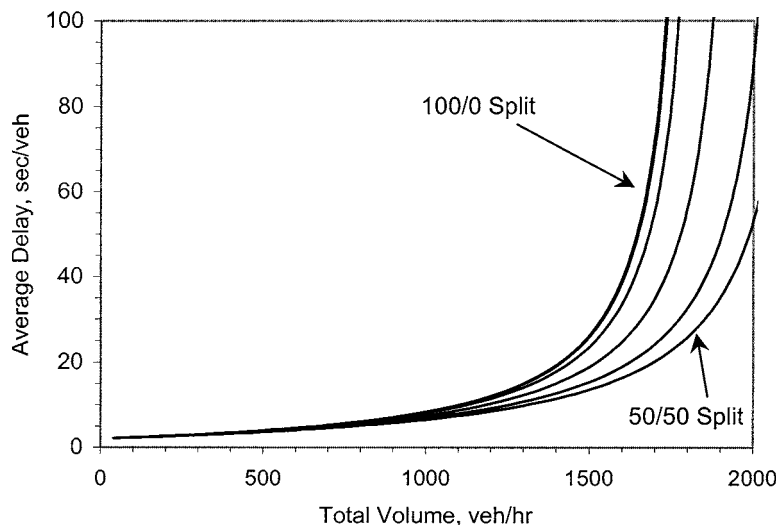


FIGURE 3 Regression delay models with 100 percent through movements.

TABLE 2 Regression Parameters (Equation 2) Under Volume Splits

Volume Split	a_i	b_i
50/50	0.00097	0.00056
60/40	0.00098	0.00058
70/30	0.00108	0.00059
80/20	0.00115	0.00061
90/10	0.00161	0.00062
100/0	0.00191	0.00062

Table 4 shows the capacity of a single-lane AWSC intersection from various models. On the basis of the results presented in Table 4, the following conclusions can be made:

- The AWSIM, HCM 1994 (9), HCM 1997 (4), and Wu (10) models predict the highest intersection capacity under an even volume split (50%). Capacity tends to decrease with uneven volume splits.
- Both Hebert (6) and Richardson (7) predicted similar capacity results, in which the highest capacity is achieved with even volume splits. However, the capacity under a 100% split shows a slight increase compared with that under a 60% split, which contradicts the results from the AWSIM, HCM 1994 (9), HCM 1997 (4), and Wu (10) models.
- The capacities given by both the HCM1994 (9) and the HCM 1997 (4) models are not sensitive to turning movements and volume splits. The reason is that perhaps both models were based on saturation headways measured in the field, which would reflect only normal traffic flow conditions.
- The result from Wu's model indicates that the capacity is irrelevant to the volume split when all traffic movements are through movements (10).
- AWSIM predicts capacities with 100 percent through movements similar to those given by Hebert (6), Richardson (7), Wu (10), and HCM 1994 (9). With 20 percent left-turn movements, the capacity given by AWSIM is similar to that from HCM 1997 (4).

EMPIRICAL QUEUE LENGTH MODEL

Queue length is an important performance measure for both intersection operations and design purposes. In practice, traffic engineers

TABLE 3 Regression Parameters (Equation 2) Assuming All Through Movements on Each Approach

Volume Split	a_i	b_i
50/50	0.001239	0.000451
60/40	0.001298	0.000471
70/30	0.001350	0.000506
80/20	0.001401	0.000536
90/10	0.001421	0.000547
100/0	0.001426	0.000549

often use the 90th or 95th percentile queue length as the design criterion. It is noted that there are fundamental differences in how the percentile queue length is calculated at signalized and unsignalized intersections. At signalized intersections, the queue length is usually measured on the basis of the start of the green interval, and the percentile queue length is derived from these queue length measurements. At unsignalized intersections, however, queue length is measured at equal time intervals, and the percentile queue length is derived from these queue length measurements (5).

Although the HCM provides a model for estimation of 95th percentile queue lengths at TWSC intersections, it provides no guidelines on how to estimate the 95th percentile queue lengths at AWSC intersections (4, 9). The queue length model for TWSC intersections was developed on the basis of complicated mathematical procedures and may not be suitable for applications at AWSC intersections. Therefore, the present study attempts to develop an empirical queue length model based on simulation results.

It has been found from both queuing theory and field data that the average queue length at AWSC intersections is directly related to the average vehicle delay (5), which can be represented by Equation 3:

$$L = \frac{V}{3,600} \times d \quad (3)$$

where L is the average queue length on an approach (veh).

Although the average queue length can sometimes provide useful information, it is not a parameter that is generally used in practice for design purposes. However, if a relationship between the percentile queue length and the average queue length can be established, the 95th percentile queue length can be estimated from the more easily obtainable average queue length estimate. This section focuses on the study of such a relationship and the development of an empirical queue length model.

To conduct the study, simulation runs were made by using a wide range of traffic flow conditions. The average queue length as well as the 95th percentile queue length was recorded from each simulation run. Traffic flow conditions used in the simulation included

- A total intersection volume ranging from 400 to 1,800 veh/h, with an increment of 40 veh/h;
- Volume splits of 50%, 60%, and 70%;
- Twenty percent left turns, 60 percent through movements, and 20 percent right turns; and
- Natural bunching arrival headway (Cowan's M3 distribution; see description in next section).

Figure 4 is a plot of the average queue length and 95th percentile queue length from the simulation runs.

Regression analysis was conducted, and the relationship between the average queue length and the 95th percentile queue length was found and is shown in Equation 4. The regression line is also shown in Figure 4.

$$L_{95\%} = 2.3L + 2.1\sqrt{L} + \frac{L}{L + 4.6} \quad (4)$$

where $L_{95\%}$ is the 95th percentile queue length (veh).

The queue length model was further verified by using the database established during the NCHRP 3-46 project, Capacity and Level of Service at Unsignalized Intersections (8). The database used in the test included data from 11 intersections with single-lane approaches and

TABLE 4 Comparison of Capacities Obtained by Different Studies

Volume Split	Model					
	Hebert	Richardson	HCM94	HCM97	Wu	AWSIM
50/50	1900	1900	2200 (2100)	1600(1600)	1960 (1881)	2000(1650)
60/40	1700	1650	2100 (2100)	1560(1540)	1960 (1789)	1900(1600)
100/0	1800	1800	2000 (1900)	1520(1520)	1960 (1470)	1650 (1400)

NOTE: The results obtained with the models of both Hebert (6) and Richardson (7) are based on 100 percent through movements. Results obtained with the HCM 1994 (9), HCM 1997 (4), Wu (10), and AWSIM models were based on 100 percent through movement and 20, 60, and 20 percent for left-turn, through, and right-turn movements, respectively (numbers in parentheses).

7 intersections with multilane approaches. Data were summarized on the basis of 15-min intervals, which included traffic volume, average delay, and 95th percentile queue length on each approach or lane. Figure 5 illustrates the results of the test.

Figure 5 shows that there is a fairly good correlation between the field data and the model estimation under short queue length conditions; however, the empirical queue length model tends to overestimate queues lengths when the queue length is longer than four vehicles. To better match the field data, the original queue length model from simulation was further modified:

$$L_{95\%} = 1.3L + 2.1\sqrt{L} + \frac{L}{L + 4.6} \tag{5}$$

Notice that the only change is the constant for the first term (which was changed from 2.3 to 1.3). Figure 6 shows the results after a modification of the model.

As can be seen, the modified model improves the results, with the mean absolute error (MAE) reduced from 0.6 to 0.4 veh. Therefore, Equation 5 is recommended for practical applications. This model applies to both single-lane and multilane intersections.

EFFECT OF VEHICLE ARRIVAL HEADWAY DISTRIBUTION

In the AWSIM model, vehicle arrivals are generated on the basis of various headway distributions. Cowan’s (11) M3 headway distribution model, the headway distribution model adopted for use in AWSIM, has been widely used in Australia to study traffic opera-

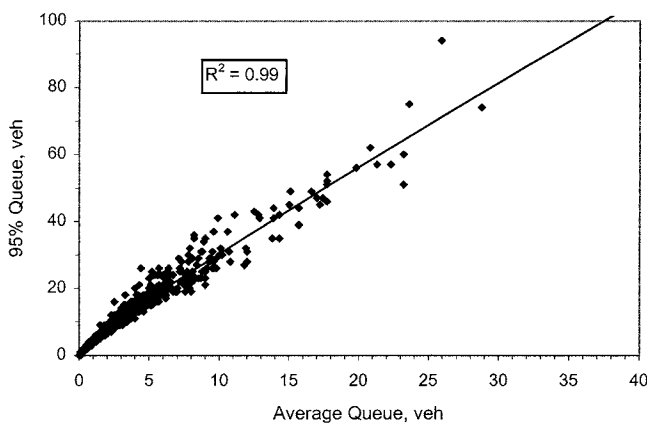


FIGURE 4 Ninety-fifth percentile queue length versus average queue length (from simulation).

tions at unsignalized intersections (12). The cumulative distribution function is given in Equation 6:

$$F(t) = 1 - \alpha \cdot e^{-\lambda(t-t_m)} \tag{6}$$

where

- $F(t)$ = cumulative probability function;
- t = vehicle headway;
- t_m = minimum headway (s);
- α = proportion of free vehicles (i.e., proportion of vehicles with headways larger than t_m); and
- λ = average arrival rate (veh/s), calculated by Equation 7:

$$\lambda = \frac{\alpha \cdot \frac{V}{3,600}}{1 - t_m \cdot \frac{V}{3,600}} \tag{7}$$

A random headway for an arrival vehicle (t_i) can then be obtained by Equation 8:

$$t_i = -\frac{1}{\lambda} \ln \frac{1-R}{\alpha} + t_m \tag{8}$$

where R is a random number between 0 and 1.

Sullivan and Troutbeck (12) found that α can be calculated on the basis of Equation 9 under an equilibrium state without interrupted facilities:

$$\alpha = e^{-A \cdot V/3,600} \tag{9}$$

where A is a coefficient that ranges between 3.7 and 7.5 and is related to the lane width and lane type, and V is the traffic flow rate (veh/h).

Cowan’s M3 model can represent a wide range of vehicle arrival conditions (11). In AWSIM, three vehicle arrival conditions were analyzed: random, natural bunching, and platoon. The random arrival condition, which is normally represented by a negative exponential distribution, was obtained from Cowan’s M3 model by assuming that α is equal to 1 and that t_m is equal to 0 in that model. The natural bunching headway was obtained from Cowan’s M3 model by assuming that A is equal to 6.5 under normal traffic volume and geometric conditions. The platoon arrival is obtained by using 0.9 times the value of α obtained from the natural bunching condition.

The effect of vehicle arrival distribution on vehicle delay and queue length was investigated on a subject approach while traffic volumes on the other approaches were kept constant. Other assumptions used in the simulation included the following:

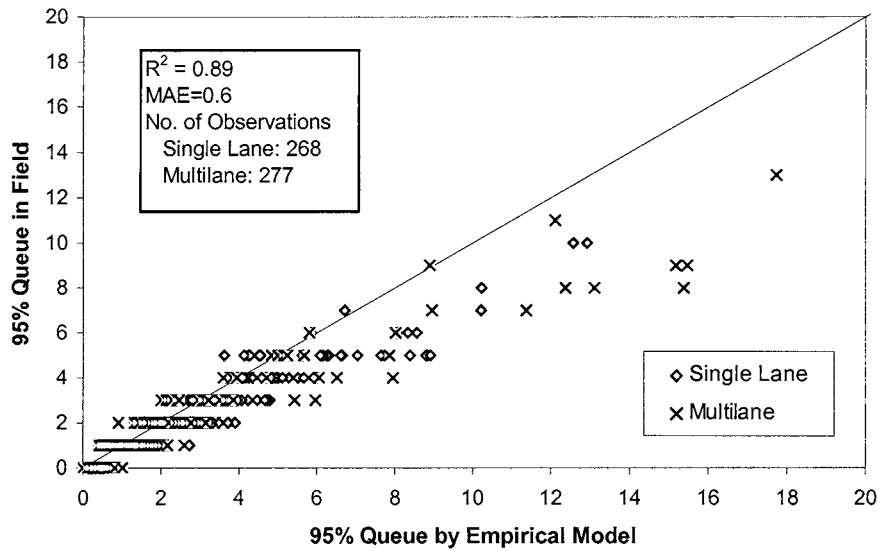


FIGURE 5 Comparison of original queue length model with field data.

$$MAE = \frac{1}{n} \sum_{i=1}^n |model_i - field_i|$$

- The subject approach volume ranged from 20 to 500 veh/h, with an increment of 20 veh/h;
- The volume for the other approaches was 200 veh/h; and
- On all of the approaches there were 20 percent left-turn movements, 60 percent through movements, and 20 percent right-turn movements.

Figure 7 shows the regression lines from the delay results, and Figure 8 shows the regression lines from the queue length results. It can be seen that random arrivals resulted in the minimum delay and that platoon arrivals resulted in the maximum delay. An implication of this is that an AWSC intersection close to traffic signals, where platoon arrivals likely exist, would increase approach delays compared with those for an isolated intersection far from the influence

of upstream signals. Similarly, longer queues resulted from platoon arrivals than from random arrivals.

SUMMARY AND CONCLUSIONS

This paper addresses traffic operational characteristics at AWSC intersections by using the AWSIM microscopic simulation model, specifically developed for modeling of AWSC intersection operations. Traffic operational characteristics were analyzed from both a delay perspective and a queue length perspective. A generalized form of the delay model was developed and recommended for better estimation of delays. The capacities estimated from AWSIM were compared with those estimated from other models. An empirical queue length model was also developed for estimation of the 95th percentile

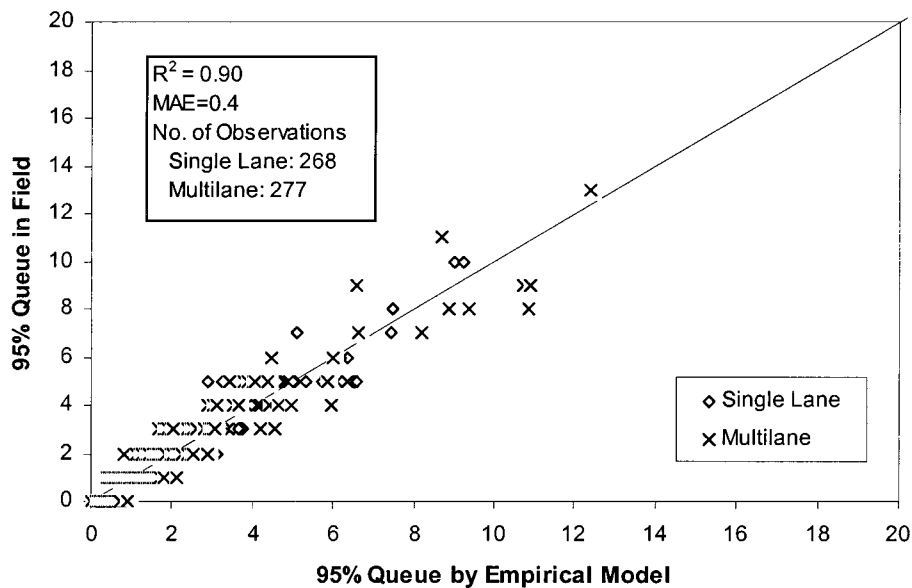


FIGURE 6 Comparison of modified queue length model with field data.

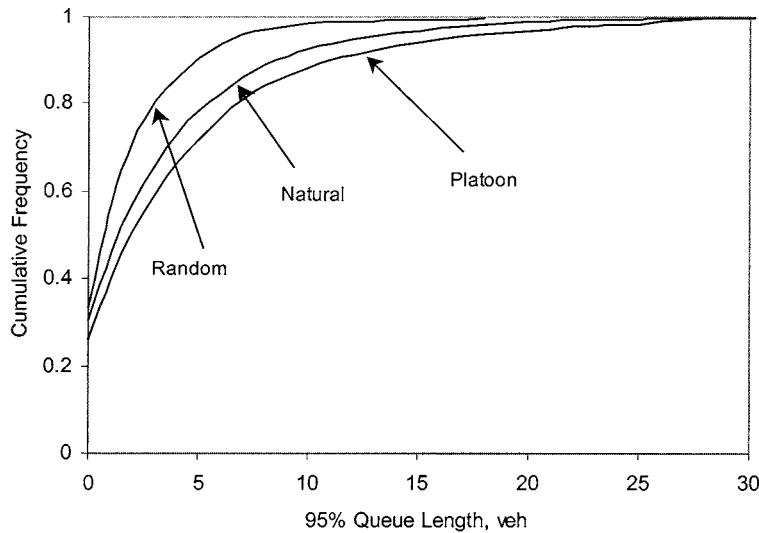


FIGURE 7 Effect of vehicle arrival headway distribution on delay (vph = veh/h).

queue length based on the average queue length. The study reached the following conclusions:

- Simulation models make it possible to develop empirical models with the consideration of a wide variety of traffic flow conditions. A generalized form of the delay model proposed in the present study improved the delay estimates compared with those obtained from the exponential form of the delay model used by other studies.
- Volume split has a significant effect on intersection operations at AWSC intersections. The results obtained with AWSIM have shown that an even volume split would result in the best intersection operations, which is consistent with the HCM (4, 9) and the studies by Hebert (6) and Richardson (7). However, the present study investigated in more detail the volume split of 100%, and the results do not support the conclusions of Hebert (6) and Richardson (7).
- Vehicle arrival headway distribution affects intersection delay and queue length. When more vehicles arrive in platoons, as is the case when a traffic signal exists nearby, longer delays and longer queues result.
- The 95th percentile queue length model developed in the present study seems to provide reliable estimates of queue lengths on the basis

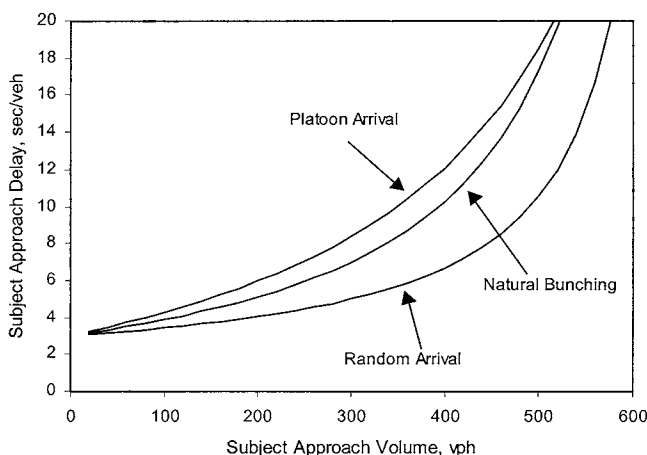


FIGURE 8 Effect of vehicle arrival headway distribution on queue length (vph = veh/h).

of the results of field studies. This model fulfills one of the major shortcomings of the HCM and provides traffic engineers with an easy tool for queue length estimation.

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