Capacities of Unsignalized Intersections Under Mixed Vehicular and Nonmotorized Traffic Conditions

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Capacities of Unsignalized Intersections Under Mixed Vehicular and Nonmotorized Traffic Conditions

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Unsignalized intersections consist of three types—two-way stop-controlled, all-way stop-controlled, and uncontrolled intersections—all with different priority relationships between traffic movements according to traffic laws. A conflict technique method was used to develop capacity models for the three types of unsignalized intersections under mixed traffic conditions involving vehicular, bicycle, and pedestrian movements. With field data collected from several unsignalized intersections, the model parameters were calibrated by a comparison analysis of traffic conditions in China and were modified on the basis of actual traffic conditions. The capacities obtained by the proposed models matched well with the observed capacities and the capacities calculated by conventional methods, both of which verified the effectiveness of the proposed models. The models proved to be valuable tools for determining capacities of vehicular movements at unsignalized intersections.

Two-way stop-controlled (TWSC), all-way stop-controlled (AWSC), and uncontrolled intersections are the most common unsignalized intersection control types. The priority relationships between traffic movements are different at these three types of unsignalized intersections according to the traffic laws of different countries. A significant amount of effort has been devoted to analyzing capacities of unsignalized intersections.

Gap acceptance theory is a conventional method used to estimate the capacities of TWSC intersections according to Harders (*1*), Siegloch (*2*), Grossmann (*3*), and the *Highway Capacity Manual* (HCM 2000) (*4*). Brilon and Wu (*5*) presented a theoretical method for deriving capacities of TWSC intersections based on the traffic conflict technique. Brilon and Miltner (*6*) provided a modified method to calculate capacities of TWSC intersections.

Hebert (*7*) estimated capacities on the basis of average departure headways at AWSC T-intersections. Richardson (*8*) developed a capacity model in terms of the service time at AWSC intersections. In the 1994 HCM (*9*), an empirical approach was applied to determine capacities of AWSC intersections based on a regression of field data. In the 1997 HCM (*10*), an extended model of Richardson's work (*8*) was used to calculate capacities for AWSC intersections. The AWSC model incorporated in the HCM 2000 (*4*) was an approach-based model. Wu (*11–13*) presented a movement-based model for calculating capacities of AWSC intersections based on the method of addition-conflict-flow.

However, the previous models and methods gave little or no consideration to nonmotorized movements, and traffic characteristics at unsignalized intersections with only vehicular movements differ from those with vehicular and nonmotorized movements. A research project sponsored by the Ministry of Science and Technology in China was conducted by the authors to assess capacities of unsignalized intersections under mixed traffic conditions. As a result, models were developed to estimate capacities of vehicular movements at TWSC, AWSC, and uncontrolled intersections on the basis of the field data and a traffic conflict method.

PRIORITY RELATIONSHIPS OF TRAFFIC MOVEMENTS

According to the traffic laws in China, the priority relationships between traffic movements at TWSC, AWSC, and uncontrolled intersections can be depicted as follows:

1. At TWSC intersections, the priority rank of vehicular movements is shown in Table 1.
2. Vehicular movements at AWSC intersections are considered to be equal in priority for departure.
3. At uncontrolled intersections (unsignalized intersections without traffic signs), vehicles arriving at an intersection approach are required to yield to the vehicles on the right-side approach; through vehicles have a higher priority than left-turn or right-turn vehicles; and right-turn vehicles have to give way to conflicting left-turn vehicles. The priority relationships between vehicular movements and nonmotorized movements are ruled as follows: nonmotorized road users have to yield to through vehicles; vehicles arriving at an intersection have a higher priority than nonmotorized road users; left-turn or right-turn vehicles departing from an intersection are required to yield to nonmotorized road users.

CONFLICT TECHNIQUE METHOD

Capacities of Vehicular Movements in a Departure Sequence

Since the priority relationships between traffic movements are different at these three types of unsignalized intersections, the vehicles of different movements have to pass through corresponding conflict areas one after another according to priority rules. As a result, a conflict group (a departure sequence) is formed in the same conflict area. Each

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TABLE 1 Priority Rank of Vehicular Movements at TWSC Intersections

Rank	Priority	Vehicular Movements
1	Absolute priority	Major street through and right-turn vehicles
2	Yielding to vehicles of the first rank	Major street left-turn vehicles and minor-street right-turn vehicles
3	Yielding to vehicles of the first and second ranks	Minor street through vehicles
4	Lowest priority	Minor street left-turn vehicles

conflict group involves many conflict points that are close to each other and can be occupied by only one vehicle at a time. One conflict group usually contains traffic movements from several directions (Figure 1). Vehicles of a particular movement can pass through the conflict area if it is not occupied by other movements of equal or higher priority.

It is assumed that every vehicle of movement i occupies the conflict area for exactly t_{Bi} seconds. All movements in a conflict group can use 3,600 s all together in an hour. If all vehicular movements occur in undersaturated conditions, and the volume of movement j, Q_j, is known, the probability of movement j occupying the conflict area is given by the following equation (*11*):

$$P_{Bj} = \frac{Q_j \cdot t_{Bj}}{3{,}600} \tag{1}$$

where

P_{Bj} = probability that the conflict area is occupied by movement j,
Q_j = volume of movement j, and
t_{Bi} = average time of a vehicle crossing conflict areas for movement i.

The probability that the conflict area is not occupied by vehicles of movement j, P_{0j}, is given as follows:

$$P_{0j} = 1 - P_{Bj} \tag{2}$$

For a waiting vehicle, the conflict area is also occupied if a vehicle of a higher priority movement is approaching the conflict area. Assuming that the gaps of higher priority movements follow an exponential distribution, the probability that the conflict area is not occupied by an approaching vehicle of higher priority movement is estimated by the following equation (*6*):

$$P_{aj} = e^{-\frac{Q_j \cdot t_{aj}}{3{,}600}} \tag{3}$$

where P_{aj} is the probability that the conflict area is not occupied by vehicles of higher priority movements in advance of their arrivals, and t_{aj} is the average time of an approaching vehicle occupying the conflict area in advance of its arrival.

Vehicles of movement i can only enter the conflict area if both of the above conditions are met simultaneously. The probability that both conditions are met is given as follows in Equation 4:

$$P_{0j} = \left(1 - P_{Bj}\right) \cdot P_{aj} \tag{4}$$

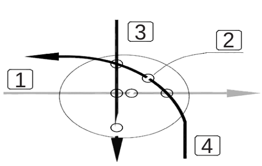

FIGURE 1 Traffic movements pass through conflict area.

The maximum capacity of movement i, $C_{\max i}$, is the maximum number of vehicles that can pass through the conflict area without being impacted by other movements:

$$C_{\max i} = \frac{3{,}600}{t_{Bi}} \tag{5}$$

According to Brilon and Miltner (*6*), the actual capacity of movement i under undersaturated traffic conditions can be expressed as follows:

$$C_i = C_{\max i} \cdot \prod_{j \in D_k} P_{0j} \tag{6}$$

where

C_i = capacity of movement i,
k = number of conflict areas related to movement i, and
D_k = set of conflict movements in the conflict group k.

If traffic flows of all vehicular movements having the same priority exceed their capacities, referred to as fully saturated conditions, all vehicular movements are supposed to have the same average capacity. The service time of higher priority movements should be subtracted from the total time in a conflict area. The capacity of vehicular movement i can then be obtained by the following equation:

$$C_i = C = \frac{3{,}600 - \sum_{s \in D_{ui}} \left(Q_s \cdot t_{Bs}\right)}{\sum_{j \in D_{ei}} t_{Bj}} \tag{7}$$

where

C = average capacity,
Q_s = volume of higher priority movement s related to movement i,
t_{Bs} = average time of a vehicle crossing conflict areas for movement s,
D_{ui} = set of higher priority movements related to movement i, and
D_{ei} = set of equal priority movements related to movement i.

If traffic flows of not all vehicular movements having the same priority are up to saturated conditions, referred to as partially saturated conditions, the remaining capacities of undersaturated vehicular movements can be distributed by other saturated vehicular movements. According to Wu (*11*) the capacity of a saturated vehicular movement i will be as follows:

$$C_i = \frac{3{,}600 - \sum_{j \in D_m} \left(Q_j \cdot t_{Bj}\right)}{\sum_{k=1}^{n} t_{Bk} - \sum_{j \in D_m} t_{Bj}} \tag{8}$$

where D_m is the set of undersaturated movements in a conflict group.

The capacity of vehicular movement i in a conflict group should be the maximum flow rate under the conditions of undersaturated, partially saturated, and fully saturated traffic flows:

$$C_i = \max \begin{cases} \dfrac{3{,}600 - \sum_{s \in D_{ui}} \left(Q_s \cdot t_{Bs}\right)}{\sum_{j \in D_{ei}} t_{Bj}} \\ C_{\max i} \cdot \prod_{j=1, j \neq i}^{n} P_{0j} \\ \dfrac{3{,}600 - \sum_{s \in D_{ui}} \left(Q_s \cdot t_{Bs}\right) - Q_j \cdot t_{Bj}}{\sum_{k \in D_{ei}, k \neq j} t_{Bk}} \\ \ldots\ldots \\ \dfrac{3{,}600 - \sum_{s \in D_{ui}} \left(Q_s \cdot t_{Bs}\right) - \sum_{j \in D_{ei}, j \neq i} \left(Q_j \cdot t_{Bj}\right)}{t_{Bi}} \end{cases} \quad j \in D_{ei},\ j \neq i \qquad (9)$$

Capacities of Vehicular Movements in More than One Departure Sequence

All vehicles have to decelerate or stop at entrances to unsignalized intersections, except for rank 1 movements at TWSC intersections. When all conflict areas are not occupied by other movements of equal or higher priority, vehicles can then enter an intersection. Figure 2 shows two cases in which movement 3, the red arrow, has to pass through two conflict areas, A and B.

If all vehicular movements in the departure sequences are in undersaturated traffic conditions, the probability that all conflict areas are free of other movements of equal or higher priority is the product of probabilities of each conflict area not being occupied. According to Brilon and Miltner (*6*), the capacity of movement i can be estimated as follows:

$$C_i = C_{\max i} \cdot \prod_{k \in D_{ni}} P_{0ki} \qquad (10)$$

where P_{0ki} is the probability that conflict area k is not occupied by other movements of equal or higher priority for movement i, and D_{ni} is the set of conflict areas that movement i needs to pass through.

If all vehicular movements related to movement i in the departure sequences are under saturated traffic conditions, then the capacity of movement i can be given as follows:

$$C_i = \frac{3{,}600}{\sum_{j \in D_{ni}} t_{Bj}} = \frac{3{,}600}{\sum_{k \in D_{ni}, h \in k} t_{Bkh} - (n_i - 1) \cdot t_{Bi}} = \frac{1}{\sum_{k \in D_{ni}} \dfrac{1}{C_{ik}} - \dfrac{(n_i - 1) \cdot t_{Bi}}{3{,}600}} \qquad (11)$$

where

t_{Bkh} = average time that vehicles of movement h occupy conflict area k related to movement i,

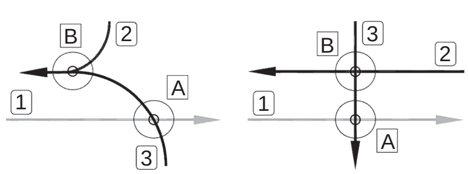

FIGURE 2 Traffic Movement 3 must pass through two conflict areas.

n_i = number of conflict areas related to movement i, and
C_{ik} = capacity of movement i passing through conflict area k.

In fact, if the capacity of movement i passing through conflict area k is adopted as the value of C_{ik} under the conditions of partially saturated or fully saturated traffic flows, then the traffic conditions of partially saturated movements have been taken into account in the calculation process. The capacity of movement i in several departure sequences should be the maximum flow rate in these three cases.

$$C_i = \max \begin{cases} \dfrac{1}{\sum_{k \in D_{ni}} \dfrac{1}{C_{ik}} - \dfrac{(n_i - 1) \cdot t_{Bi}}{3{,}600}} \\ C_{\max i} \cdot \prod_{k \in D_{ni}} P_{0ki} \end{cases} \qquad (12)$$

CAPACITY MODELS FOR UNSIGNALIZED INTERSECTIONS

Capacity Model Without Nonmotorized Movements

When nonmotorized road users are not considered, a four-leg unsignalized intersection may contain up to 12 vehicular movements. It is necessary to specify the conflict areas and conflict movements related to each movement. Assuming that each vehicular movement has its own traffic lane on all approaches, more than one conflict area must be examined for each movement. As seen in Figure 3, these conflict areas can be arranged into eight conflict groups according to the graph theory and conflict types (*11*).

Vehicles at an unsignalized intersection have to pass through several conflict areas to cross the intersection. In undersaturated traffic conditions, vehicles of movement i can enter the intersection only when all relevant conflict areas are free of other movements of equal or higher priority. In such a case, the capacity of movement i will be as follows:

$$C_i = C_{\max i} \cdot \prod_{k \in D_{ni}} P_{0ki} \qquad (13)$$

Then the capacity of movement i should be the maximum flow rate under the conditions of undersaturated, partially saturated, and fully saturated traffic flows:

$$C_i = \max \begin{cases} \dfrac{1}{\sum_{k \in D_{ni}} \dfrac{1}{C_{ik}} - \dfrac{(n_i - 1) \cdot t_{Bi}}{3{,}600}} \\ C_{\max i} \cdot \prod_{k \in D_{ni}} P_{0ki} \end{cases} \qquad (14)$$

with

$$C_{ik} = \max \begin{cases} \dfrac{3{,}600 - \sum_{s \in D_{uk}} \left(Q_s \cdot t_{Bs}\right)}{\sum_{j \in D_{ek}} t_{Bj}} \\ \dfrac{3{,}600 - \sum_{s \in D_{uk}} \left(Q_s \cdot t_{Bs}\right) - Q_j \cdot t_{Bj}}{\sum_{h \in D_{ek}, h \neq j} t_{Bh}} \\ \ldots\ldots \\ \dfrac{3{,}600 - \sum_{s \in D_{uk}} \left(Q_s \cdot t_{Bs}\right) - \sum_{j \in D_{ek}, j \neq i} \left(Q_j \cdot t_{Bj}\right)}{t_{Bi}} \end{cases} \quad j \in D_{ek},\ j \neq i \qquad (15)$$

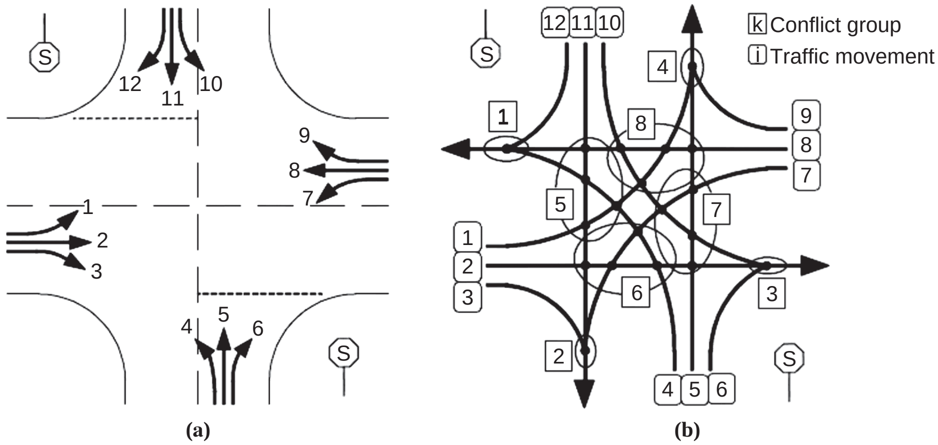

FIGURE 3 Traffic movements and conflict groups at TWSC intersection without nonmotorized road users.

where

D_{uk} = set of higher priority movements in conflict group k related to movement i,

t_{Bs} = average time of a vehicle crossing conflict areas for movement s, and

D_{ek} = set of equal priority movements in conflict group k related to movement i.

Capacity Model with Nonmotorized Movements

In addition to the vehicular movements, a four-leg unsignalized intersection can have up to eight pedestrian movements and 12 bicycle movements. The four right-turn bicycle movements can be ignored, however, due to their lack of conflicts with other movements. To take all the other 28 movements into account at the intersection, it is necessary to specify the conflict areas and conflict movements related to each movement. Assuming that each vehicular movement has its own traffic lane on all approaches and each nonmotorized road user has his or her own path, more than one conflict area has to be examined for each vehicular movement. All conflict areas can be arranged into 12 conflict groups at an unsignalized intersection with pedestrian and bicycle movements arranged according to graph theory and conflict types (*11*).

Conflict groups and relevant traffic movements are shown in Figures 4 and 5 and are listed in Table 2, in which 1 through 12 denote vehicular movements; F1 through F8 denote pedestrian movements; and R1 through R8 denote bicycle movements.

According to Brilon and Miltner (*6*), a so-called conflict matrix is used to express the priority relationships based on traffic laws. If one movement conflicts with another one, the corresponding cell of the matrix is given a value of A_{ij}. By definition, $A_{ij} = 1$ if movement i has higher priority than movement j; $A_{ij} = 0$ for movement i yielding to movement j; and $A_{ij} = 0.5$ for movement i and movement j having the same priority. Since conflicts among pedestrians and bicyclists are minor, both conflict types are not taken into account.

In undersaturated traffic conditions, vehicles of movement i can enter the intersection only when all relevant conflict groups are free of other movements of equal or higher priority. In such a case, the capacity of vehicular movement i will be as follows:

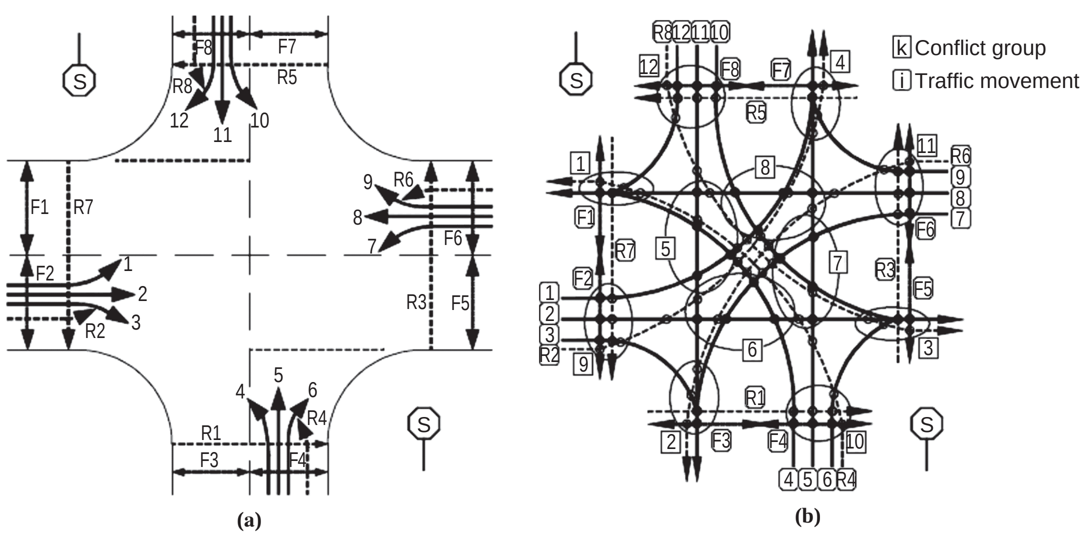

FIGURE 4 Traffic movements and conflict groups at TWSC intersection with nonmotorized road users.

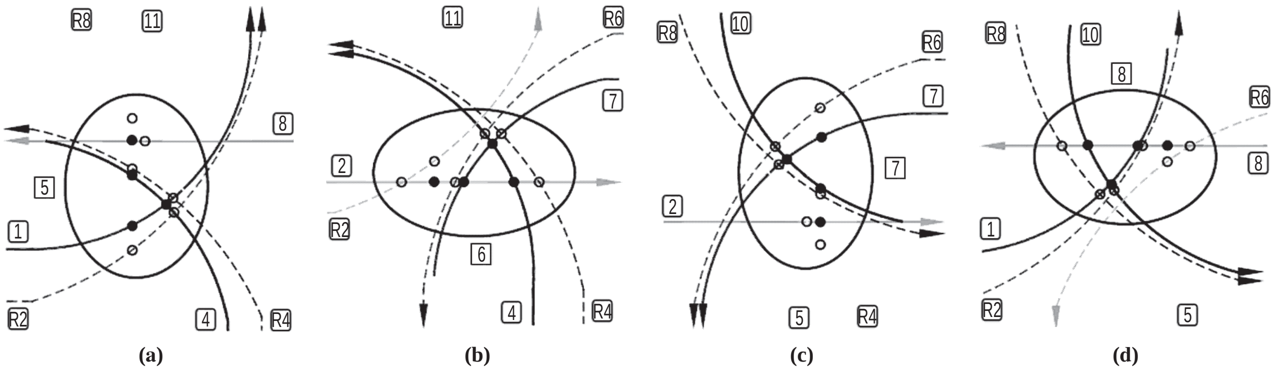

FIGURE 5 Conflict Groups 5, 6, 7, and 8.

$$C_i = C_{\max i} \cdot \prod_{k\in D_{ni}} P_{0ki} = \frac{3,600}{t_{Bi}} \cdot \left\{ \prod_{k\in D_{ni}} \left[1 - \frac{1}{3,600} \cdot \sum_{l\in D_k} \left(A_{li} \cdot Q_l \cdot t_{Bl} \right) \right] \right\} \cdot e^{-\frac{1}{3,600} \cdot \sum_{r\in D_{sk}, k\in D_{ni}} \left(A_{ri} \cdot Q_r \cdot t_{ar} \right)} \qquad (16)$$

where

- A_{li} = cell value of conflict matrix between movement l and movement i,
- A_{ri} = cell value of the conflict matrix between movement r and movement i,
- Q_l = volume of movement l,
- t_{Bl} = average time of a unit of movement l crossing conflict areas,
- Q_r = volume of movement r,
- t_{ar} = average time of a vehicle occupying conflict areas in advance of its arrival for movement r, and
- D_{sk} = set of higher-priority vehicular movements in conflict group k related to movement i.

For vehicular movement i, the service time of higher priority movements must be subtracted from the total time. The capacity of vehicular movement i should be the maximum flow rate under the conditions of undersaturated, partially saturated, and fully saturated traffic flows.

$$C_i = \max \begin{cases} \dfrac{1}{\sum_{k\in D_{ni}} \dfrac{1}{C_{ik}} - \dfrac{(n_i - 1)\cdot t_{Bi}}{3,600}} \\ \dfrac{3,600}{t_{Bi}} \cdot \left\{ \prod_{k\in D_{ni}} \left[1 - \dfrac{1}{3,600} \cdot \sum_{l\in D_k} \left(A_{li} \cdot Q_l \cdot t_{Bl} \right) \right] \right\} \\ \cdot\, e^{-\frac{1}{3,600} \cdot \sum_{r\in D_{sk}, k\in D_{ni}} \left(A_{ri} \cdot Q_r \cdot t_{ar} \right)} \end{cases} \qquad (17)$$

with

$$C_{ik} = \max \begin{cases} \dfrac{3,600 - \sum_{g\in D_{pb}} \left(A_{gi} \cdot Q_g \cdot t_{Bg} \right) - \sum_{r\in D_{sk}} \left(A_{ri} \cdot Q_r \cdot t_{Br} \right)}{\sum_{j\in D_{ek}} t_{Bj}} \\ \dfrac{3,600 - \sum_{g\in D_{pb}} \left(A_{gi} \cdot Q_g \cdot t_{Bg} \right) - \sum_{r\in D_{sk}} \left(A_{ri} \cdot Q_r \cdot t_{Br} \right) - Q_j \cdot t_{Bj}}{\sum_{h\in D_{ek}, h\neq j} t_{Bh}} \\ \qquad\qquad j \in D_{ek},\ j \neq i \\ \cdots \\ \dfrac{3,600 - \sum_{g\in D_{pb}} \left(A_{gi} \cdot Q_g \cdot t_{Bg} \right) - \sum_{r\in D_{sk}} \left(A_{ri} \cdot Q_r \cdot t_{Br} \right) - \sum_{j\in D_{ek}, j\neq i} \left(Q_j \cdot t_{Bj} \right)}{t_{Bi}} \end{cases} \qquad (18)$$

where

- D_{pb} = set of pedestrian and bicycle movements in conflict group k related to movement i,
- t_{Br} = average time of a vehicle crossing conflict areas for movement r,
- A_{gi} = cell value of the conflict matrix between pedestrian or bicycle movement g and vehicular movement i,
- Q_g = volume of pedestrian or bicycle movement g, and
- t_{Bg} = average time of pedestrians or bicyclists crossing conflict areas for pedestrian or bicycle movement g.

Equation 17 is a general model for estimating capacities at these three types of unsignalized intersections. The second part of Equation 17 can be used directly to calculate the capacities of

TABLE 2 Conflict Groups and Traffic Movements

	i				i			i		
k	Veh	Ped	Bike	k	Veh	Bike	k	Veh	Ped	Bike
1	4, 8, 12	F1	R7, R4	5	1, 4, 8, 11	R2, R4, R8	9	1, 2, 3	F2	R7, R2
2	3, 7, 11	F3	R1, R6	6	2, 4, 7, 11	R2, R4, R6	10	4, 5, 6	F4	R1, R4
3	2, 6, 10	F5	R3, R8	7	2, 5, 7, 10	R4, R6, R8	11	7, 8, 9	F6	R3, R6
4	1, 5, 9	F7	R5, R2	8	1, 5, 8, 10	R2, R6, R8	12	10, 11,1 2	F8	R5, R8

NOTE: i = traffic movements involved in conflict group k, veh = vehicular movements, ped = pedestrian movements, and bike = bicycle movements.

TWSC intersections. At AWSC intersections, since all vehicular movements have the same priority, the part of higher priority vehicular movements in Equation 18 can be ignored, and the probability that conflict areas are not occupied by higher priority vehicles in advance of their arrivals should be cancelled in the second part of Equation 17.

GROUP CALCULATION OF NONMOTORIZED MOVEMENTS

Pedestrians and bicyclists usually pass through the intersections group by group. Thus, group volume and group occupation time of pedestrian and bicycle movements should be adopted in the models.

Group Calculation of Pedestrian Movements

In order to determine group volume and group occupation time, the analyst must observe in the field or estimate the group size of pedestrians waiting to cross the intersection (*4*):

$$N_{ci} = \frac{V_{pi} \cdot e^{V_{pi} \cdot t_{ci}} + V_{pvi} \cdot e^{-V_{pvi} \cdot t_{ci}}}{\left(V_{pi} + V_{pvi}\right) \cdot e^{\left(V_{pi} - V_{pvi}\right) \cdot t_{ci}}} \quad (19)$$

with

$$t_{ci} = \frac{W_{Bi}}{S_{Pi}} + 1.1 \quad (20)$$

$$V_{pvi} = \sum_{j \in D_k} \left(A_{ji} \cdot Q_j\right) \quad (21)$$

where

N_{ci} = group size of pedestrians waiting to cross the intersection for pedestrian movement *i*,
V_{pi} = flow rate of pedestrian movement *i*,
V_{pvi} = total flow rate of vehicular movements conflicting with pedestrian movement *i*,
t_{ci} = average time of pedestrians crossing conflict areas for pedestrian movement *i*,
W_{Bi} = total width of one-way lanes and bicycle paths, and
S_{Pi} = average walking speed.

The spatial distribution of pedestrians can then be obtained by using Equation 22 (*4*). If no platoon is observed, spatial distribution of pedestrians is assumed to be 1:

$$N_{pi} = \text{int}\left[\frac{0.75 \cdot \left(N_{ci} - 1\right)}{W_{Ei}}\right] + 1 \quad (22)$$

where N_{pi} is the spatial distribution of pedestrians for pedestrian movement *i* and W_{Ei} is the effective crosswalk width.

Group occupation time of pedestrian movement *i*, t_{Gpi}, can be determined as follows:

$$t_{Gpi} = t_{ci} + 2 \cdot \left(N_{pi} - 1\right) \quad (23)$$

Group flow rate of pedestrian movement *i*, n_{pi}, can be expressed as follows:

$$n_{pi} = \text{int}\left(\frac{V_{pi}}{N_{pi}}\right) \quad (24)$$

Group Calculation of Bicycle Movements

Similar to the analytical method for pedestrians, group volume and group occupation time of bicycle movements can be obtained. The group size of bicyclists waiting to cross the intersection can be obtained through field observation or estimation methods:

$$N_{si} = \frac{V_{bi} \cdot e^{V_{bi} \cdot t_{bi}} + V_{bvi} \cdot e^{-V_{bvi} \cdot t_{bi}}}{\left(V_{bi} + V_{bvi}\right) \cdot e^{\left(V_{bi} - V_{bvi}\right) \cdot t_{bi}}} \quad (25)$$

with

$$t_{bi} = \frac{W_{Bi}}{S_{bi}} + 2.5 \quad (26)$$

$$V_{bvi} = \sum_{j \in D_k, k \in D_{ni}} \left(A_{ji} \cdot Q_j\right) \quad (27)$$

where

N_{si} = group size of bicyclists waiting to cross the intersection for bicycle movement *i*,
V_{bi} = flow rate of bicycle movement *i*,
V_{bvi} = total flow rate of vehicular movements conflicting with bicycle movement *i*,
t_{bi} = average time of bicyclists crossing conflict areas, and
S_{bi} = average speed of bicyclists.

The spatial distribution of bicyclists can then be obtained as follows:

$$N_{bi} = \text{int}\left(\frac{N_{si} - 1}{W_{bi}}\right) + 1 \quad (28)$$

with

$$W_{bi} = \bar{D}_b \cdot N_{bfi} \quad (29)$$

$$N_{bfi} = \frac{W_{Zi}}{D_0} \quad (30)$$

where

N_{bi} = spatial distribution of bicyclists for bicycle movement *i*,
W_{bi} = actual width of bicycles occupying the road when bicyclists are crossing the intersection,
$\bar{D}_b$ = average actual width of a bicycle occupying the road,
N_{bfi} = platoon size of bicyclists at the first row,
W_{Zi} = effective width of the bicycle path, and
D_0 = average immobile width of a bicycle occupying the road.

Group occupation time of bicycle movement *i*, t_{Gbi}, can be determined as follows:

$$t_{Gbi} = t_{bi} + 2 \cdot \left(N_{bi} - 1\right) \quad (31)$$

Group flow rate of bicycle movement i, n_{bi}, can be expressed as follows:

$$n_{bi} = \text{int}\left(\frac{V_{bi}}{N_{bi}}\right) \tag{32}$$

DATA COLLECTION AND MODIFIED CONFLICT MATRIX

Data Collection

Traffic data used in this study were obtained by videotaping TWSC and four-leg uncontrolled intersections in Wuhu and Maanshan, China. The intersections selected for observation had different configurations and relatively heavy traffic of all kinds of road users. All videos were taped during the morning (6:30 to 9:30 a.m.) and evening (4:30 to 7:30 p.m.) peak hours for five weekdays at each intersection. The data were gathered by a video-image system and were analyzed by a program package, SPSS. The capacities of vehicular movements were observed at the intersections by using Kyte's method (*14*). The model parameters can be calibrated by the field data, and the models can also be evaluated by comparing the observed capacities with the calculated capacities. In addition, an important aspect of the survey was to observe the behaviors of vehicular drivers and nonmotorized road users in the cases of conflicts and to determine the types and proportion of priority rule reversals.

Modified Conflict Matrix

Since not all road users always have a clear idea about the priority hierarchy at these three types of unsignalized intersections, they do not usually completely comply with the priority rules. The field data showed many cases of priority reversal.

The observed priority of traffic movements can be reflected by a modified conflict matrix. The modified conflict matrix expresses to which degree, A_{ij}, the movement i has priority over movement j. These A_{ij} values are rounded averages over all observed intersections. The modified conflict matrix indicates that all the priorities are limited in real-life situations at unsignalized intersections. Since the limited priority behaviors significantly influence the capacities and delays of traffic movements, the assumption that the traffic priority rules are obeyed completely is unpractical at unsignalized intersections. The actual capacities of vehicular movements can be obtained by using the modified conflict matrix in the proposed models.

CALIBRATIONS OF MODEL PARAMETERS

Before the proposed models can be used to calculate the capacities of vehicular movements at these three types of unsignalized intersections, it is necessary to calibrate the values of the model parameters for different vehicular movements. Since conflict areas cannot be partitioned clearly in practice, the model parameters cannot be calibrated directly by observing traffic movements. Therefore, a comparison method is presented to calibrate the model parameters approximately by comparing the results produced by different methods.

Calibrations of Model Parameters at TWSC Intersections

At TWSC intersections, the model parameters are estimated by comparing the capacities obtained by the proposed models with the observed capacities (*14*) and the capacities computed by gap acceptance theory (*4*) at several typical observed intersections. Ultimately, the presented values of the model parameters can be given by comprehensively considering the calibration results (see Table 3).

Calibrations of Model Parameters at AWSC and Uncontrolled Intersections

Similar to the analytical method for TWSC intersections, at AWSC and uncontrolled intersections, the model parameters are estimated by comparing the capacities obtained by the proposed models with the observed capacities (*14*) and the capacities obtained by the relevant model from HCM 2000 (*4*) and the motorcade analysis method. The motorcade analysis method was recommended by Gao (*15*) for estimating vehicular capacities of uncontrolled intersections on the basis of characteristics of vehicles alternately crossing uncontrolled intersections in terms of motorcades. The presented values of the model parameters can be given by comprehensively considering the calibration results:

Vehicular Movement i	t_{Bbi} *(s)*	t_{ai} *(s)*
1, 4, 7, 10	3.5	3.8
2, 5, 8, 11	3.3	4.0
3, 6, 9, 12	3.1	3.5

Determination of Model Parameters

Since basic values of the model parameter t_{Bbi} are given for passenger cars, the influence of heavy vehicles, approach grade, and T-intersections on the model parameter t_{Bi} is not considered in the process of calibration. Adjustments are made to account for these impact factors (*4*). The model parameter t_{Bi} is computed separately for each vehicular movement as follows:

$$t_{Bi} = t_{Bbi} + t_{BH} \cdot P_H + t_{BG} \cdot G - t_{3LT} \tag{33}$$

TABLE 3 Presented Values of Model Parameters at TWSC Intersections

Vehicular Movement i	t_{Bbi} (s)	t_{ai} (s)
1, 7	3.3	3.2
2, 8	2.2	3.5
3, 9	2.4	3.0
4, 10	3.6	4.0
5, 11	3.5	4.3
6, 12	3.2	3.8

NOTE: t_{Bbi} = the basic average time of a vehicle crossing conflict areas for vehicular movement i.

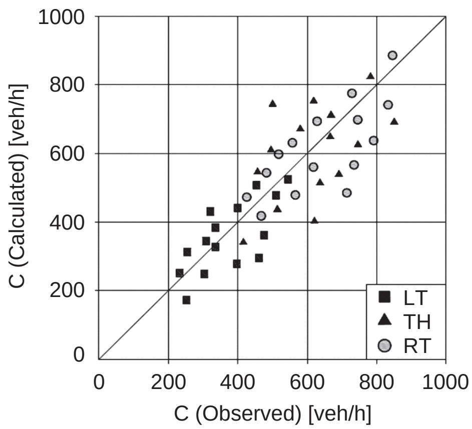

FIGURE 6 Comparisons of observed capacities and capacities calculated by proposed models at minor street TWSC intersections (C = capacity, LT = left turn, TH = through, and RT = right turn).

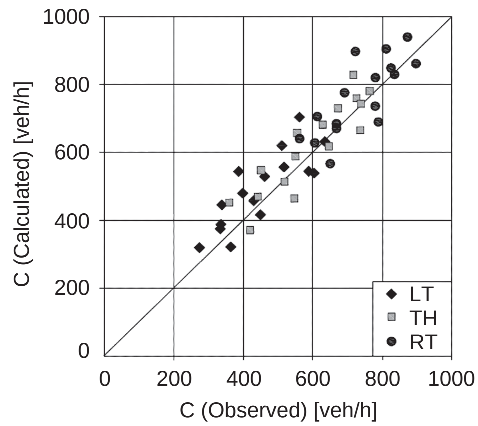

FIGURE 7 Comparisons of observed capacities and capacities calculated by the proposed models at uncontrolled intersections.

where

t_{BH} = adjustment factor for heavy vehicles (1.0 for two-lane streets and 2.0 for four-lane streets),
P_H = proportion of heavy vehicles for vehicular movement i,
t_{BG} = adjustment factor for approach grade (0.1 for right-turn movements and 0.2 for left-turn and through movements),
G = percent grade divided by 100, and
t_{3LT} = adjustment factor for the intersection geometry (0.7 for left-turn movements at T-intersections; 0.0 otherwise).

EVALUATIONS OF CAPACITY MODELS

To check whether the proposed models yield realistic results, the calculated capacities are compared with the observed capacities at typical TWSC (Figure 6) and uncontrolled (Figure 7) intersections. On average, there is a good correspondence between the observed capacities and the calculated capacities. Furthermore, the calculated capacities of the proposed models are compared with the calculated capacities of both gap acceptance theory (*4*) (Figure 8) and the motorcade analysis method (*15*) (Figure 9) to assess the effectiveness of the proposed models. Since conventional methods do not consider pedestrians and bicyclists, the comparisons are limited to vehicular movements. The results indicate that the calculation methods yield similar values. Figures 6 and 8 present capacities of minor street movements, while Figures 7 and 9 present major street capacities.

CONCLUSIONS

This paper presents a series of models for determining capacities of vehicular movements at TWSC, AWSC, and uncontrolled intersections. The models extend the capabilities of existing models by incorporating pedestrian and bicycle movements. This aspect of operation is especially important for urban intersections with mixed traffic movements. The models for obtaining the capacities of vehicular movements have been derived by the conflict technique method under mixed traffic conditions. The model parameters have been calibrated for traffic conditions in China on the basis of the field data.

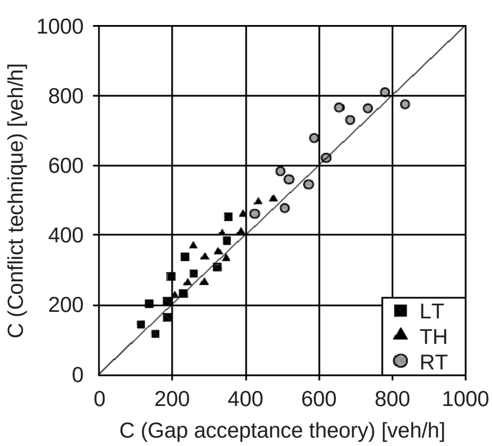

FIGURE 8 Comparisons of capacities calculated by proposed models and capacities obtained by gap acceptance theory at TWSC intersections.

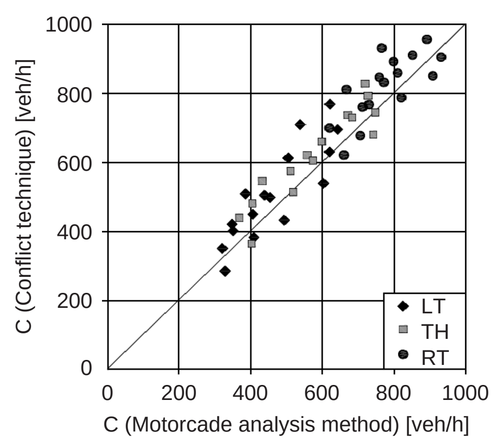

FIGURE 9 Comparisons of capacities calculated by proposed models and capacities obtained by motorcade analysis method at uncontrolled intersections.

The model evaluations show that the proposed models yielded realistic capacity estimations of vehicular movements, although more comprehensive data for calibration and validation are desirable. The research shows that realistic capacity estimations can be achieved if noncompliance with traffic rules is regarded in the models. The model results indicate that the influence of pedestrian and bicycle movements on the capacities of vehicular movements cannot be ignored. In conclusion, the proposed models provide valuable tools for determining capacities at unsignalized intersections under mixed traffic conditions, typically seen in developing countries like China.

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