

Unsignalized Intersection Capacity with Mixed Vehicle Flows

Wenquan Li Wei Wang Dazhi Jiang

(Transportation College Southeast University, the People's Republic of China)

The corresponding author is Wenquan Li. His current affiliation, complete mailing address, telephone number, fax number, and e-mail address is

Current affiliation:

Transportation College Southeast University, the People's Republic of China

Complete mailing address:

Transportation College Southeast University, Jiangsu Nanjing 210096, the People's Republic of China

Telephone number:

86-25-3794101 or 13951613378

Fax number:

86-25-3794102

E-mail address:

wenqli@seu.edu.cn

The current affiliation, complete mailing address, telephone number, fax number, and e-mail address of Wei Wang's is

Current affiliation:

Transportation College Southeast University, the People's Republic of China

Complete mailing address:

Transportation College Southeast University, Jiangsu Nanjing 210096, the People's Republic of China

Telephone number:

86-25-3794101 or 13905170160

Fax number:

86-25-3794102

E-mail address:

weiwang@public1.ptt.js.cn or weiwang@seu.edu.cn

The current affiliation, complete mailing address, telephone number, fax number, and e-mail address of Dazhi Jiang's is

Current affiliation:

Transportation College Southeast University, the People's Republic of China

Complete mailing address:

Transportation College Southeast University, Jiangsu Nanjing 210096, the People's Republic of China

Telephone number:

86-25-3792513 or 13851573012

Fax number:

86-25-3794102

E-mail address:

i131422@hotmail.com

Unsignlized Intersection Capacity with Mixed Vehicle Flows

Wenquan Li Wei Wang Dazhi Jiang

(Transportation College Southeast University, the People's Republic of China)

Abstract

Based on the gap acceptance theory, the mixed traffic flow composed of two representative vehicle types—heavy and light vehicles is analyzed with probability theory. Capacity model of the minor mixed traffic flows crossing m major lanes, on which the traffic flows fit in with M3 distributed headway, on the unsignalized intersection is set up, and it is an extension of minor lane capacity theory for one vehicle-type and one major-lane traffic flow. More complicated case on minor stream with the composition of discretionary vehicle types is also considered and the corresponding formula is given. After being tested with field data in China, the conclusion is drawn that this model is better in analyzing Chinese traffic conditions than other existed models.

Unsignalized Intersection Capacity with Mixed Vehicle Flows

Wenquan Li Wei Wang Dazhi Jiang

(Transportation College Southeast University, the People's Republic of China)

1. INTRODUCTION

An intersection is a node of highway network, and usually a bottleneck of traffic flow in highway network. Capacity of intersections restricts the total capacity of highway network. For actions of conflicting, merging, separating caused by turning of traffic flow, the traffic characteristics of intersection are more complex than those of road section, and the data are more difficult to obtain. The plane intersection without signal control is the most common type in highway network. The capacity of such intersection is difficult to be determined and becomes a very interesting field of highway capacity study.

Two general types of capacity analysis model have been used in unsignalized intersection, empirical model based on regression technique and gap acceptance model based on probability theory. Gap acceptance model is mainly used for theory analysis, and the evaluation of traffic performance. The basic idea of gap acceptance is that a major and a minor traffic stream are supposed by their road rank, vehicles from the major stream can cross the conflict area without any delay, and vehicles from the minor stream are only allowed to cross the conflict area if the gaps of major stream are larger than t_c seconds (t_c is the critical gaps) observed by the drivers. Otherwise, they must wait. Moreover, vehicles from the minor stream can enter the intersection at least t_f seconds (t_f is the follow-up time) after the departure of the previous minor stream vehicle. Based on the gap acceptance theory, the number of vehicles in minor stream that can cross an intersection depend mainly on two variables, the distribution law of headways in major stream and the critical gap, follow-up time of drivers in the minor stream. Cowan (1975)^[1] introduced M3 distribution by using α , the proportion of free vehicles and Δ , the minimum headway between two successive vehicles in platoon. Free vehicles are defined as those vehicles whose headways are greater than Δ . When the major traffic flow rate is v_p vehicles per second (veh/sec), the M3 distribution has the following density function for major stream headway:

$$f(t) = \begin{cases} \alpha \lambda e^{-\lambda(t-\Delta)} & t > \Delta \\ 1 - \alpha & t = \Delta \\ 0 & t < \Delta \end{cases} \quad (1)$$

Where $\lambda = \frac{\alpha v_p}{1 - \Delta v_p}$, and the distribution function of M3 distribution has the following form:

$$P(h \geq t) = \begin{cases} \alpha e^{-\lambda(t-\Delta)} & t > \Delta \\ 1 & t \leq \Delta \end{cases} \quad (2)$$

The M3 distribution modifies the shifted negative exponential distribution for major stream headway. Recent researches by Sullivan and Troutbeck (1994)^[2], Akcelik and Chuing (1994)^[3] have shown that M3 distribution can provide good fitness with observed headway distributions. When the M3 distribution is allowed to estimate the headway in major stream of traffic flow rate v_p veh/sec, and the vehicles type in minor stream is idealized as the same, Troutbeck (1986)^[4] and Cowan (1987)^[5] improve on the corresponding capacity model for minor stream crossing a major road in the following form:

$$c_n = \frac{\alpha v_p e^{-\lambda(t_c - \Delta)}}{1 - e^{-\lambda t_f}} \quad (3)$$

However, there are at least two lanes on the major road of the intersection, and the flow on each lane is different. So, many scholars have studied the capacity of flow on minor lane crossing the major, which has more than one lane with different flow rate. For examples, Tanner (1967)^[6] studied the multi-lane case. Golis(1986)^[7] derived a capacity formula for the case of two major lanes with different critical gaps and with negative exponentially distribution headway. Fisk (1989)^[8] generalized Tanner's formula for m lanes when the critical gaps differ between the major lanes. Troutbeck (1986)^[4], Troutbeck(1989)^[9] derived the capacity formula for the case of two major lanes each has its own M3 distributed headway. Hagring(1998)^[10] studied the case that the headways

of m major lanes with different flow rate obey M3 distribution and that the critical gaps and follow-up time of vehicles on minor lanes change for different major lanes. His capacity formula is as following:

$$c_n = \Lambda \prod_{i=1}^m \frac{\alpha_i q_i}{\lambda_i} \frac{e^{-\sum_{k=1}^m \lambda_k (t_c^k - \Delta)}}{1 - e^{-\sum_{k=1}^m \lambda_k t_f^k}}, \quad (4)$$

where $\Lambda = \sum_{i=1}^m \lambda_i$,

$$\lambda_i = \frac{\alpha_i q_i}{1 - \Delta q_i},$$

α_i -- the proportion of free vehicles whose headways are greater than Δ in the i^{th} major lane. Δ is the minimum headway between two successive vehicles in platoon.

q_i -- the flow rate of the i^{th} major lane, veh/sec.

t_c^i -- the critical gaps of the minor road vehicle crossing the i^{th} major lane.

t_f^i -- the follow-up time of the minor road vehicle crossing the i^{th} major lane.

The formula (4) extends the result of Troutbeck and becomes so general that all results obtained by Tanner^[6], Fisk^[8], Troubeck^[4] can easily be obtained from it. Hagring has improved the capacity theory of minor stream crossing major multi-lane to a specific level. It must be pointed out that the mathematical derivation of the capacity for the minor stream in those literatures always assumed each traffic stream composed of only one vehicle type. However, this assumption is idealized because traffic flows on actual road are mixed traffic flows which consist of several vehicle types. It is very important to study the capacity of mixed traffic flows. The author replaces one type vehicle flow with the mixed flow composed of two representative types of vehicles, heavy and light vehicles. The capacity theoretical formula of this mixed flow is derived. Formula (3) and (4) becomes the corollaries of the author's formula (See section 3). More complicated case on minor stream with the composition of discretionary vehicle types is also considered and the corresponding formula is given in section 4. Our model and other existed models are tested with Chinese field data in section 5 and the conclusion is drawn in section 6.

2. BASIC HYPOTHESIS

In order to illustrate the computational process of capacity for mixed flow in minor lane crossing m major lanes on unsignalized intersection, it is useful to concentrate the following simplest case: The conflicting streams at the intersection can be simplified as shown in figure 1. Where, q_i is the flow rate of the i^{th} major lane in veh/sec. The headway distribution of the i^{th} major lane stream is M3 distribution with parameters of α_i , the proportion of free vehicles and Δ , the minimum headway between two successive vehicles in platoon. Supposing that the minor stream being composed of two representative types of vehicles, heavy and light vehicles, the proportion of light vehicles and heavy vehicles is $p:(1-p)$. The drivers who drive the same type vehicle in minor lane are homogenous and consistent, and their behaviors observe the gap acceptance theory when they cross the conflict area on unsignalized intersection. The same type vehicles crossing the different major lane have different critical gaps or follow-up time. And the different type vehicles crossing the same major lane also have different critical gaps and follow-up time. Supposing that the light vehicles crossing k^{th} major lane have constant critical gaps t_{c1}^k and follow-up time t_{f1}^k , and that the heavy vehicles crossing k^{th} major lane have constant critical gaps t_{c2}^k and follow-up time t_{f2}^k ,

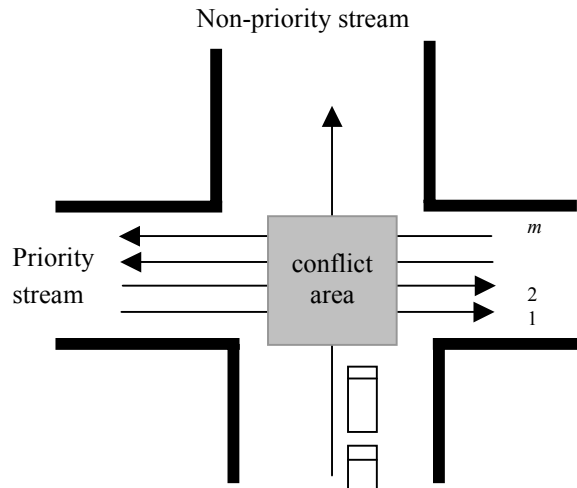


Figure 1: conflict stream

where $t_{c1}^k < t_{c2}^k$ and $t_{f1}^k < t_{f2}^k$ ($k = 1, 2, \dots, m$). Varied type vehicles are independent in arriving at the intersection. The minor road has enough space to contain those arrived vehicles in queue.

h_k is the headway of k^{th} major lane flow on unsignalized intersection. According to the gap acceptance theory, one light vehicle in minor lane will cross the k^{th} major lane on conflict area of unsignalized intersection when

$$t_{c1}^k \leq h_k < t_{c1}^k + t_{f1}^k, \quad k = 1, 2, \dots, m. \quad (5)$$

One heavy vehicle in minor lane would cross the k^{th} major lane on conflict area of unsignalized intersection when

$$t_{c2}^k \leq h_k < t_{c2}^k + t_{f1}^k, \quad k = 1, 2, \dots, m. \quad (6)$$

So the vehicle queue of A type vehicle followed by B type vehicle in minor lane would cross the k^{th} major lane when

$$t_{cA}^k + t_{fB}^k \leq h_k < t_{cA}^k + t_{fB}^k + t_{f1}^k, \quad k = 1, 2, \dots, m. \quad (7)$$

Where A type vehicle could be either light vehicle or heavy vehicle. So is B type vehicle.

With the same reason, the vehicle queue of one light vehicle followed by n_1 light vehicles and n_2 heavy vehicles in minor lane would cross the k^{th} major lane when

$$t_{c1}^k + n_1 t_{f1}^k + n_2 t_{f2}^k \leq h_k < t_{c1}^k + (n_1 + 1) t_{f1}^k + n_2 t_{f2}^k, \quad k = 1, 2, \dots, m. \quad (8)$$

The vehicle queue of one heavy vehicle followed by n_1 light vehicles and n_2 heavy vehicles in minor lane would cross the k^{th} major lane when

$$t_{c2}^k + n_1 t_{f1}^k + n_2 t_{f2}^k \leq h_k < t_{c2}^k + (n_1 + 1) t_{f1}^k + n_2 t_{f2}^k, \quad k = 1, 2, \dots, m. \quad (9)$$

Because any vehicle in the platoon of minor lane can not stop when crossing the conflict area, there must be a common gap of m major lanes for the vehicle platoon to cross. For this common gap, there is at least one major lane's gap h_i must to fit strictly one of formula (5) -- (9) and the other major lanes' gaps must fit the left of formula (5) -- (9). a_k b_k respectively represent the left and right value of formula (5) -- (9). $\{a_k \leq h_k < b_k\}$ and $\{h_k \geq a_k\}$ represents the corresponding probability event. Then the probability event of common gap for the n minor vehicles' platoon to cross the m major lanes on conflict area of the intersection is

$$\bigcup_{i=1}^m \left\{ \{a_i \leq h_i < b_i\} \bigcap_{k \neq i} \{h_k \geq a_k\} \right\} = \bigcap_{i=1}^m \{h_i \geq a_i\} - \bigcap_{i=1}^m \{h_i \geq b_i\}.$$

Where i^{th} major lane has the minimum gap h_i which must be between a_i and b_i . For other lanes h_k ($k \neq i$)

is required to be larger than a_k . $\bigcup_{i=1}^m S_i$ is the union of set S_i , $\bigcap_{i=1}^m S_i$ is the intersection of set S_i ($i = 1, 2, \dots, m$).

3. CAPACITY MODEL FOR MIXED FLOW OF TWO TYPE VEHICLES ON THE INTERSECTION

The minor mixed flow is composed of two representative types of vehicles, heavy and light vehicles. Vehicles of each type are independent to arrive at intersection. Therefore, the vehicle queue's structure and such structure's probability on minor lane should be studied before analyzing their capacity.

3.1 The structure and its corresponding probability of minor vehicle queue

The proportion of light and heavy vehicles in mixed traffic flows is $p:(1-p)$. In any case, the probability of a light vehicle in the front of the queue is p , and that of a heavy vehicle is $1-p$. So the queue whose length is only one vehicle is formed by a light vehicle or a heavy vehicle.

It is easy to know that the structures of queue with length two are given as following: light vehicle~* light vehicle, light vehicle ~ heavy vehicle, heavy vehicle ~ light vehicle, heavy vehicle ~ heavy vehicle. Because every vehicle's arriving at intersection is independent, the corresponding probability of the above queue structures is $p^2, p(1-p), (1-p)p, (1-p)^2$. It is easy to know that: $p^2 + p(1-p) + (1-p)p + (1-p)^2 = 1$.

* the symbol “~” means connecting the former and the later which are in the queue. For example “light vehicle ~ heavy vehicle” means a light vehicle is followed by a heavy vehicle.

The structures of queue with three vehicles are given as following. Light vehicle ~ light vehicle ~ light vehicle, light vehicle ~ light vehicle ~ heavy vehicle, light vehicle ~ heavy vehicle ~ light vehicle, light vehicle ~ heavy vehicle ~ heavy vehicle, heavy vehicle ~ light vehicle ~ light vehicle, heavy vehicle ~ light vehicle ~ heavy vehicle, heavy vehicle ~ heavy vehicle ~ light vehicle, heavy vehicle ~ heavy vehicle ~ heavy vehicle. Because every vehicle's arriving at intersection is independent, the corresponding probability of the above queue structures is p^3 , $p^2(1-p)$, $(1-p)^2p$, $p^2(1-p)$, $(1-p)^2p$, $p^2(1-p)$, $(1-p)^2p$ and $(1-p)^3$. We also have $p^3+3p^2(1-p)+3(1-p)^2p+(1-p)^3=1$.

In general, the structures of queue whose length is n vehicles, with i heavy vehicles and $n-i$ light vehicles respectively, could be analyzed as following. If the queue structure is a light vehicle in the head which is followed by $n-1$ vehicles, its probability could be calculated as following.

$$pC_{n-1}^i p^{n-i-1} (1-p)^i \quad (10)$$

So naturally the probability of the queue structure with a heavy vehicle in the head which is also followed by $n-1$ other vehicles could be got in the same way.

$$(1-p)C_{n-1}^i p^{n-i-1} (1-p)^i. \quad (11)$$

It is easy to know that $p \sum_{i=0}^{n-1} C_{n-1}^i p^{n-i-1} (1-p)^i + (1-p) \sum_{i=0}^{n-1} C_{n-1}^i p^{n-i-1} (1-p)^i = 1$.

3.2 The probability of major gap to cross specific n vehicles

The minimum headway Δ of vehicles in platoon on major lanes is not larger than any minor lane vehicle's critical gaps. That is $\Delta < \min(t_{c1}^k, t_{c2}^k)$. So the headway of k^{th} major lane is considered for minor flow capacity when the headway is larger than Δ . Supposing that the headway of the k^{th} major traffic stream obeys M3 distribution with parameter of traffic flow rate q_k (veh/sec), the proportion of free vehicles α_k and the minimum headway between any two successive major lane vehicles in platoon Δ . The distribution function of k^{th} major flow is

$$P(h_k \geq t_k) = \begin{cases} \alpha_k e^{-\lambda_k(t_k - \Delta)} & t_k > \Delta \\ 1 & t_k \leq \Delta \end{cases}. \quad (12)$$

When every gap h_k in k^{th} major lane is greater than the given t_k and t_k is greater than Δ ($k = 1, 2, \dots, m$), the joint distribution function of the vehicle headways on m major lanes is obtained by Hagring(1998)^[10]. That is

$$\begin{aligned} P(h_1 \geq t_1, h_2 \geq t_2, \dots, h_m \geq t_m) \\ = P(\bigcap_{k=1}^m \{h_k \geq t_k\}) = \frac{\Lambda}{Q} \prod_{k=1}^m \frac{q_k \alpha_k}{\lambda_k} e^{-\sum_{j=1}^m \lambda_j(t_j - \Delta)} \quad t_j > \Delta, \end{aligned} \quad (13)$$

where : α_k -- the proportion of free vehicles in the k^{th} major lane.

Δ -- the minimum headway between two successive vehicles in platoon

q_k -- the flow rate of the k^{th} major lane, veh/sec.

$$\lambda_k = \frac{\alpha_k q_k}{1 - \Delta q_k},$$

$$\Lambda = \sum_{i=1}^m \lambda_i$$

$$Q = \sum_{i=1}^m q_i.$$

Let $\beta_m = \frac{\Lambda}{Q} \prod_{k=1}^m \frac{q_k \alpha_k}{\lambda_k}$. When the queue structure of minor lane vehicles is one light vehicle in front of $n-1$

vehicles, the probability of the common gap among m major lanes' to allow i heavy vehicles on minor lane to cross is

$$\begin{aligned} P(\bigcap_{k=1}^m \{h_k \geq t_{c1}^k + (n+i-1)t_{f1}^k + it_{f2}^k\}) - P(\bigcap_{k=1}^m \{h_k \geq t_{c1}^k + (n+i)t_{f1}^k + it_{f2}^k\}) \\ = \beta_m e^{-\sum_{k=1}^m \lambda_k(t_{c1}^k + (n-i-1)t_{f1}^k + it_{f2}^k - \Delta)} - \beta_m e^{-\sum_{k=1}^m \lambda_k(t_{c1}^k + (n-i)t_{f1}^k + it_{f2}^k - \Delta)} \end{aligned}$$

$$= \beta_m e^{-\sum_{k=1}^m \lambda_k (t_{c1}^k - \Delta)} (1 - e^{-\sum_{k=1}^m \lambda_k t_{f1}^k}) e^{-(n-i-1) \sum_{k=1}^m \lambda_k t_{f1}^k - i \sum_{k=1}^m \lambda_k t_{f2}^k}. \quad (14)$$

The meanings of variables are the same as before.

With the same reason, the probability of the common gap among m major lanes to allow for the queue structure with one heavy vehicle in front of $n-1$ vehicles, in which there are i heavy vehicles, is

$$\begin{aligned} & P\left(\bigcap_{k=1}^m \left\{ h_k \geq t_{c2}^k + (n+i-1)t_{f1}^k + it_{f2}^k \right\}\right) - P\left(\bigcap_{k=1}^m \left\{ h_k \geq t_{c2}^k + (n+i)t_{f1}^k + it_{f2}^k \right\}\right) \\ &= \beta_m e^{-\sum_{k=1}^m |\tilde{E}_k(t_{c2}^k + (n-i-1)t_{f1}^k + it_{f2}^k - \Delta)} - \beta_m e^{-\sum_{k=1}^m |\tilde{E}_k(t_{c2}^k + (n-i)t_{f1}^k + it_{f2}^k - \Delta)} \\ &= \beta_m e^{-\sum_{k=1}^m \lambda_k (t_{c2}^k - \Delta)} (1 - e^{-\sum_{k=1}^m \lambda_k t_{f1}^k}) e^{-(n-i-1) \sum_{k=1}^m \lambda_k t_{f1}^k - i \sum_{k=1}^m \lambda_k t_{f2}^k}. \end{aligned} \quad (15)$$

The meanings of variables are the same as before.

3.3 The probability of n mixed vehicles crossing intersection

According to formula (10) in section 3.1 and formula (14) in section 3.2, the crossing probability of n vehicles queue composed of one light vehicle in front of i heavy vehicles among $n-1$ vehicles is

$$p C_{n-1}^i p^{n-i-1} (1-p)^i \beta_m e^{-\sum_{k=1}^m \lambda_k (t_{c1}^k - \Delta)} (1 - e^{-\sum_{k=1}^m \lambda_k t_{f1}^k}) e^{-(n-i-1) \sum_{k=1}^m \lambda_k t_{f1}^k - i \sum_{k=1}^m \lambda_k t_{f2}^k}. \quad (16)$$

And according to formula (11) in section 3.1 and formula (15) in section 3.2, the crossing probability of n vehicles queue composed of one heavy vehicle in front of i heavy vehicles among $n-1$ vehicles is

$$(1-p) C_{n-1}^i p^{n-i-1} (1-p)^i \beta_m e^{-\sum_{k=1}^m \lambda_k (t_{c2}^k - \Delta)} (1 - e^{-\sum_{k=1}^m \lambda_k t_{f1}^k}) e^{-(n-i-1) \sum_{k=1}^m \lambda_k t_{f1}^k - i \sum_{k=1}^m \lambda_k t_{f2}^k}. \quad (17)$$

So, the probability of n vehicles queue with i heavy vehicles after $n-1$ vehicles in minor road to cross together the major m streams conflict area on the intersection is the sum of formula (16) and (17). It is

$$\begin{aligned} p(n) &= \sum_{i=0}^{n-1} \left\{ \beta_m (1 - e^{-\sum_{k=1}^m \lambda_k t_{f1}^k}) e^{-(n-i-1) \sum_{k=1}^m \lambda_k t_{f1}^k - i \sum_{k=1}^m \lambda_k t_{f2}^k} C_{n-1}^i p^{n-i-1} (1-p)^i \right. \\ &\quad \times \left(p e^{-\sum_{k=1}^m |\tilde{E}_k(t_{c1}^k - \lceil \square \rceil)} + (1-p) e^{-\sum_{k=1}^m |\tilde{E}_k(t_{c2}^k - \lceil \square \rceil)} \right) \Big\} \\ &= \beta_m (1 - e^{-\sum_{k=1}^m |\tilde{E}_k(t_{f1}^k)}) \left(p e^{-\sum_{k=1}^m |\tilde{E}_k(t_{c1}^k - \lceil \square \rceil)} + (1-p) e^{-\sum_{k=1}^m |\tilde{E}_k(t_{c2}^k - \lceil \square \rceil)} \right) \\ &\quad \times \left(p e^{-\sum_{k=1}^m \lambda_k t_{f1}^k} + (1-p) e^{-\sum_{k=1}^m \lambda_k t_{f2}^k} \right)^{n-1}. \end{aligned} \quad (18)$$

The meanings of variables are the same as before.

3.4 Capacity model for minor mixed flow of two type vehicles on the intersection

After the analysis of section 3.1, 3.2 and 3.3 it is easy to know that when a vehicle queue cross one gap of the major lane stream its mathematical expectation of the vehicle number is

$$\sum_{n=1}^{\infty} n p(n) = \frac{\beta_m (1 - e^{-\sum_{k=1}^m |\tilde{E}_k(t_{f1}^k)}) \left(p e^{-\sum_{k=1}^m |\tilde{E}_k(t_{c1}^k - \lceil \square \rceil)} + (1-p) e^{-\sum_{k=1}^m |\tilde{E}_k(t_{c2}^k - \lceil \square \rceil)} \right)}{\left(1 - p e^{-\sum_{k=1}^m |\tilde{E}_k(t_{f1}^k)} - (1-p) e^{-\sum_{k=1}^m |\tilde{E}_k(t_{f2}^k)} \right)^2}. \quad (19)$$

Because the total traffic flow rate of major road is Q (veh/sec), there are Q gaps offered by major road in a unit time (second). The capacity model for minor mixed flow crossing unsignalized intersection is

$$\begin{aligned}
c_n &= \frac{Q\beta_m(1 - e^{-\sum_{k=1}^m \lambda_k t_{f1}^k}) \left(p e^{-\sum_{k=1}^m \lambda_k (t_{c1}^k - \Delta)} + (1-p) e^{-\sum_{k=1}^m \lambda_k (t_{c2}^k - \Delta)} \right)}{\left(1 - p e^{-\sum_{k=1}^m \lambda_k t_{f1}^k} - (1-p) e^{-\sum_{k=1}^m \lambda_k t_{f2}^k} \right)^2} \\
&= \Lambda \prod_{j=1}^m \frac{q_j \alpha_j}{\lambda_j} \frac{(1 - e^{-\sum_{k=1}^m \lambda_k t_{f1}^k}) \left(p e^{-\sum_{k=1}^m \lambda_k (t_{c1}^k - \Delta)} + (1-p) e^{-\sum_{k=1}^m \lambda_k (t_{c2}^k - \Delta)} \right)}{\left(1 - p e^{-\sum_{k=1}^m \lambda_k t_{f1}^k} - (1-p) e^{-\sum_{k=1}^m \lambda_k t_{f2}^k} \right)^2}. \quad (20)
\end{aligned}$$

The meanings of variables are the same as before.

4 CAPACITY MODEL FOR GENERALLY MIXED TRAFFIC FLOW ON THE INTERSECTION

In order to explain the derived idea of mixed flow capacity of unsignalized intersection, the simplest vehicle types of mixed flow are supposed. But, this method can be extended to mixed flow composed of discretionary vehicles.

Supposing that mixed traffic flow on minor stream is composed by r representative type vehicles of type 1, type 2, ..., type r , and the proportion of those vehicles is $p_1:p_2:\dots:p_r$, $p_1+p_2+\dots+p_r=1$. The driver who operates the same type vehicle is homogenous and consistent, that is to say, for k type-vehicle it has constant t_{ck} and t_{fk} , $k=1, 2, \dots, r$, and $t_{c1} < t_{c2} < \dots < t_{cr}$, $t_{f1} < t_{f2} < \dots < t_{fr}$. Any type vehicle is independent in arriving at the stop line of the intersection, and the minor road has enough space to contain those arriving vehicles in queue. It is easy to obtain the capacity model for this case.

$$c_n = \Lambda \prod_{j=1}^m \frac{q_j \alpha_j}{\lambda_j} \frac{(1 - e^{-\sum_{k=1}^m \lambda_k t_{f1}^k}) \left(\sum_{j=1}^r p_j e^{-\sum_{k=1}^m \lambda_k (t_{cj}^k - \Delta)} \right)}{\left(1 - \sum_{j=1}^r p_j e^{-\sum_{k=1}^m \lambda_k t_{fj}^k} \right)^2} \quad (21)$$

The meanings of variables are the same as before.

We have compiled a small program to use Equation (20) and (21) so they could easily be applied in practice. What the users need to do is just input some variables values, such as p_i (proportion of i^{th} type vehicle) q_k (the flow rate of the k^{th} major lane) and so on. It is a good outcome we all would like to see. Equation (20) and (21) bring us a better result in calculating highway capacity while not bring additional loads.

5. NUMERICAL ANALYSIS OF CHINESE EXAMPLE

The objective of capacity model research is to find out a model with which the calculating results fit relatively well with field conditions. The closer the capacity calculated by the model to the field capacity, the better the model is, and the higher the quality or “goodness of fit” is. For the capacity model tests or numerical analysis, two effective measures were given: absolute error (AE), absolute percent error (APE), mean absolute error (MAE) and mean absolute percent error (MAPE). Each is used to evaluate the quality or “goodness of fit” of each model. The AE, APE, MAE and MAPE are defined as following equation (22) – (25)^[11]

$$AE = |c_m^i - c_f^i| \quad (22)$$

$$APE = \left| \frac{c_m^i - c_f^i}{c_f^i} \right| \quad (23)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |c_m^i - c_f^i| \quad (24)$$

$$MAPE = \frac{1}{n} \sum_{i=1}^n \left| \frac{c_m^i - c_f^i}{c_f^i} \right| \quad (25)$$

Where n is the number of collecting data, c_m^i is the model capacity, and c_f^i is the field capacity.

The example intersection with two major lanes and one minor lane belongs to Xinxiang City of Henan province in China. The data come from the final report of National Highway Project of the People's Republic of China^[12]. There are few side-frictions on the intersection under investigation. The mixed traffic flow on intersection is composed of mini vehicles, medium vehicles and heavy vehicles ($r=3$). The composition split is heavy: medium: mini = 22:32:46. The ratio of turning for each arm of the intersection is left: right: through = 16:18:66. The headway distribution of the i^{th} major lane stream is M3 distribution with two parameters of $\alpha_i=0.8$ ($i=1,2$), the proportion of free vehicles and $\Delta=2$ sec., the minimum headway between two successive vehicles in platoon. The critical gap^[12], follow-up time^[12], and the value of PCU^[12] (Passenger Car Unit) for each type vehicle is given in table 1

Table 1 Parameters of different type vehicle^[12]

Parma. type	Critical gap t_c sec.			Follow-up time t_f sec.			The value of PCU (PCU)
	Lane 1	Lane 2	Mean	Lane 1	Lane 2	Mean	
heavy	7	8.0	7.5	3.5	4.5	4	3.0
medium	5.5	6.5	6	2.8	3.2	3	1.6
mini	5	6.0	5.5	2.6	2.8	2.7	1.0
	5.83*	6.83*	6.33*	2.97*	3.5*	3.23*	

Note: The number in last row of table 1 marked * is the mean of the upper data in the corresponding column.

Data were collected in eight 15-minute intervals. The total traffic flow for each major road (QMAJ1 and QMAJ2), minor road (QMIN) and total of both (QTOT) in PCU (Passenger Car Unit) per-hour is given in table 2. The average delay (sec/veh) for the major road (DMAJ), minor road (DMIN) and total of both (DTOT) is also given in table 2. The delay can be obtained by actual travel time minus reference travel time which depends on the design speed of the intersection. The field capacity is calculated with the methods given in literature [13].

Table 2 results from the eight 15-minute time intervals^[12]

data time	QMAJ1 PCU/h	QMAJ2 PCU/h	DMAJ sec	QMIN PCU/h	DMIN sec	QTOT PCU/h	DTOT sec	Field capacity PCU/h
8:30	253	251	11.00	280	4.54	784	8.70	2294
8:45	272	280	11.60	300	0.93	852	7.84	1968
10:45	268	260	12.11	304	2.25	832	8.51	1962
11:00	316	312	13.88	312	2.26	940	10.03	1823
12:30	252	252	8.02	228	0.13	532	4.64	2866
13:15	124	100	8.85	140	1.88	364	6.17	2973
14:15	166	158	9.11	188	1.32	512	5.28	2815
14:30	174	170	8.74	220	0.84	564	5.01	2680

The model capacity of Troubeck model (formula 3), Hagring model (formula 4) and our model (formula 21) is estimated with the same discounting methods given by literature. The results of model capacity, the absolute error (AE), and absolute percent error (APE) are given in table 3.

Table 3: the theoretical results for eight 15-minute time intervals

Field capacity (PCU/h)	Troubeck's model capacity (PCU/h)			Hagring's model capacity (PCU/h)			Our model capacity (PCU/h)		
	capacity	AE	APE	capacity	AE	APE	capacity	AE	APE
2294	2082	212	0.0923	2283	11	0.0049	2114	180	0.0787
1968	1886	82	0.0415	2129	161	0.0820	1989	21	0.0106

1962	1983	21	0.0109	2219	257	0.1311	2066	104	0.0530
1823	1590	233	0.1277	1896	73	0.0403	1796	27	0.0147
2866	2963	97	0.0338	2705	161	0.0561	2479	387	0.1350
2973	3340	367	0.1236	3457	484	0.1627	3091	118	0.0398
2815	2871	56	0.0198	2953	138	0.0489	2657	158	0.0561
2680	2779	99	0.0370	2869	189	0.0706	2589	91	0.0339

The mean absolute error (MAE) and mean absolute percent error (MAPE) of above models estimated with formula 24 and 25 is given in table 4.

Table 4: the MAE and MAPE of different model

Theoretical model	MAE (vehicles/hour)	MAPE (%)
Troubeck model (formula 3)	146	6.08
Hagring model (formula 4)	184	7.46
Our mixed traffic flow model (formula 21)	136	5.27

Figure 2 illustrates the results of the simple tests of the three capacity models. From table 4 and figure 2, the conclusion can be drawn that our model is fitter to the Chinese traffic condition than Troutbeck model and Hagring model.

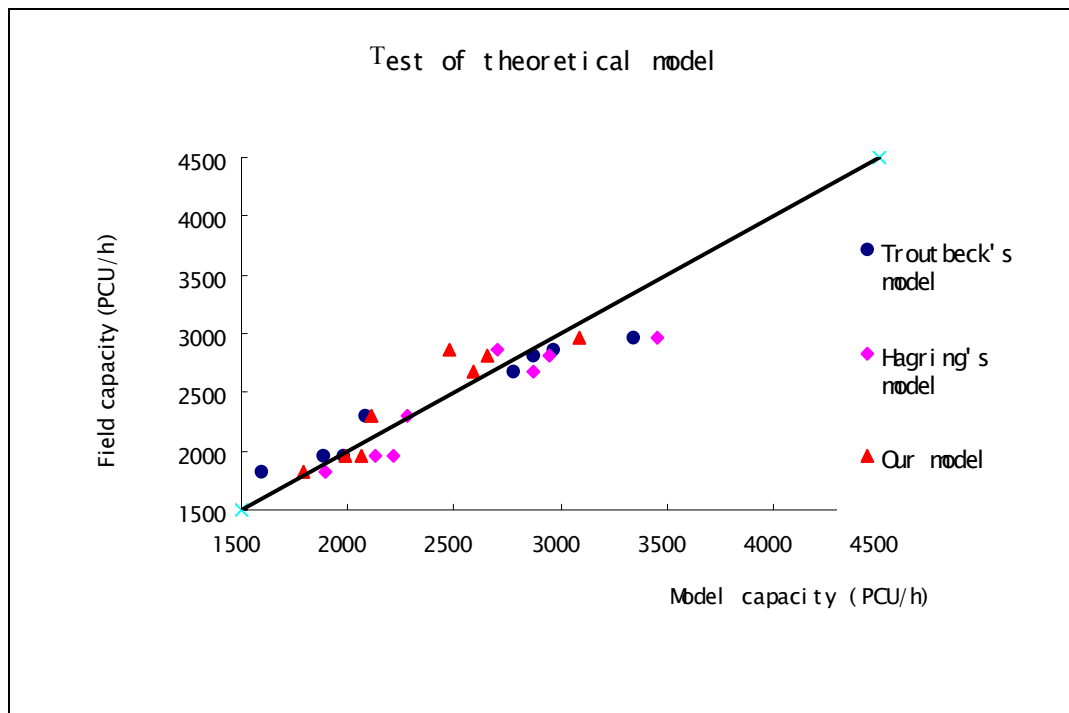


Fig. 2 Test of theoretical model

6. CONCLUSION

The capacity of minor mixed flow composed of light and heavy types of vehicles is derived in this paper, and the theoretical model of formula (20) is obtained. Model (20) is easy to be extended to generally model (21), the mixed flow composed of discretionary number type vehicles case. If the mixed traffic stream is replaced by one type vehicle, we have $t_{c1}^k = t_{c2}^k = t_c^k$ and $t_{f1}^k = t_{f2}^k = t_f^k$ ($k = 1, 2, \dots, m$). The formula (20) can become formula (4), the result of Hagring(1998)^[10]. If the intersection traffic stream is one type vehicle and the major road has only one lane, we have $m=k=1$, $t_{c1}^k = t_{c2}^k = t_c^k = t_c$ and $t_{f1}^k = t_{f2}^k = t_f^k = t_f$. The formula (20) can become formula (3), the result of Troutbeck^[4] and Cowan^[5]. So, formula (20) or formula (21) is an extension of other capacity formulae for traffic stream of one type vehicle. After being tested with Chinese data this model shows better fitness to the Chinese traffic conditions than other existed models.

ACKNOWLEDGMENT

The authors of this paper thanks for federal helps of the National Natural Science Foundation of China. This research is sponsored directly by the National Natural Science Foundation of China (50078015).

REFERENCES

1. Cowan, R J. Useful headway models. *Transportation Research*, Vol.9, No.6, 1975, PP.371-375.
2. Sullivan, D P and Troutbeck, R J. The use of Cowan's M3 headway distribution for modeling urban traffic flow. *Traffic Engineering Control*, Vol.27, 1994, PP.2-5.
3. Akeclik, R and Chung E. Calibration of the bunched exponential distribution of arrival headway. *Road & Transport Research*, Vol.3, 1994, PP.42-59.
4. Troutbeck R J. Average delay at an unsignalized intersection with two major stream each having a dichotmized headway distribution. *Transportation Science*, Vol.20, No.4, 1986, PP.272-286.
5. Cowan R J. An extension of Tanner's results on uncontrolled intersection: clarification of some issues. *Queuing System*, Vol.1, 1987, PP.249-263.
6. Tanner J C. The capacity of an uncontrolled intersection. *Biometrika*, Vol.54, 1967, PP.657-658.
7. Golias J. Towards a realistic analytical evaluation of minor-stream capacity at priority road junctions. *Traffic Engineering Control*, Vol.27, 1986, PP.2-5.
8. Fisk C S. Traffic performance analysis at roundabouts. *Transportation Research Part B*, Vol.25, 1989, PP.89-102.
9. Troutbeck R J. Unsignalized intersections and roundabouts in Australia: recent developments. In: *Intersections without Traffic Signals II*, edit by Brilon, W. Heidelberg: Springer-Verlag, 1991, PP.238-257.
10. Hagring O. A further generalization of Tanner's formula. *Transportation Research Part B*, Vol.32, No.6, 1998, PP.423-429.
11. Kyte M, Tian Z, Mir Z, et al. Capacity and level of service at unsignalized intersections. Final report, National cooperative highway research program, Project3-46,1996
12. National highway project of the People's Republic of China, World Bank loan project (Hebei & Henan), Highway capacity study (Final report appendices). 1998, 11
13. Kyte M, Clemow C, Mahfood N, et al. Capacity and delay characteristics of two-way-stop-controlled intersections. In *Transportation Research Board 1320*, TRB, National Research Council, Washington D. C., 1992, PP.123~146.

Unsignlized Intersection Capacity with Mixed Vehicle Flows

Wenquan Li Wei Wang Dazhi Jiang

(Transportation College Southeast University, the People's Republic of China)

LIST OF TABLES AND FIGURES

Figure 1: conflict stream.....	4
Figure 2: Test of theoretical model.....	10
Table 1□Parameters of different type vehicle.....	9
Table2□results from the eight 15-minute time intervals.....	9
Table 3: the theoretical results for eight 15-minute time intervals.....	9
Table 4: the MAE and MAPE of different model.....	10

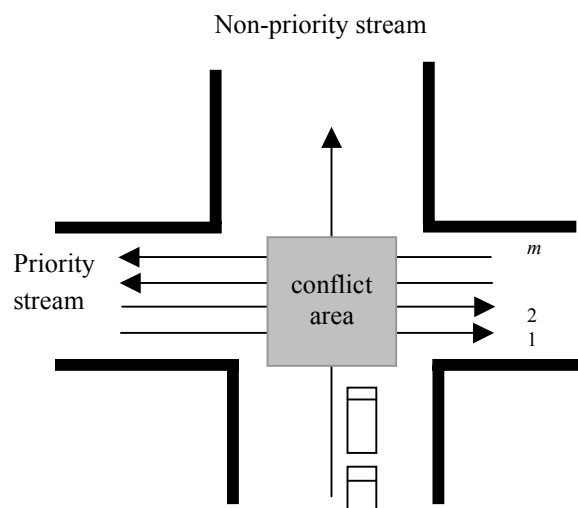


Figure 1: conflict stream

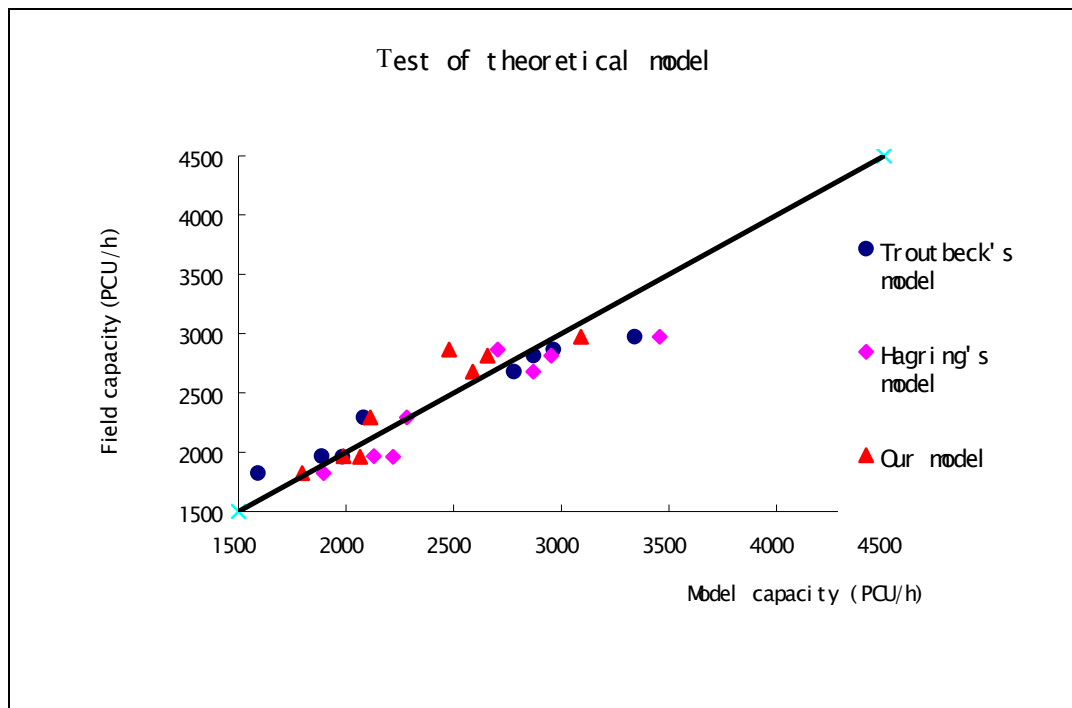


Figure 2: Test of theoretical model

Table 1 □ Parameters of different type vehicle

Parma. type	Critical gap t_c □ sec. □			Follow-up time t_f □ sec. □			The value of pcu (PCU)
	Lane 1	Lane 2	Mean	Lane 1	Lane 2	Mean	
heavy	7	8.0	7.5	3.5	4.5	4	3.0
medium	5.5	6.5	6	2.8	3.2	3	1.6
mini	5	6.0	5.5	2.6	2.8	2.7	1.0
	5.83*	6.83*	6.33*	2.97*	3.5*	3.23*	

Note: The number in last row of table 1 marked * label is the mean of heavy, medium and mini vehicle.

Table 2 □ results from the eight 15-minute time intervals

data time	QMAJ1 PCU/h	QMAJ2 PCU/h	DMAJ sec	QMIN PCU/h	DMIN sec	QTOT PCU/h	DTOT sec	Field capatiy PCU/h
8:30	253	251	11.00	280	4.54	784	8.70	2294
8:45	272	280	11.60	300	0.93	852	7.84	1968
10:45	268	260	12.11	304	2.25	832	8.51	1962
11:00	316	312	13.88	312	2.26	940	10.03	1823
12:30	252	252	8.02	228	0.13	532	4.64	2866
13:15	124	100	8.85	140	1.88	364	6.17	2973
14:15	166	158	9.11	188	1.32	512	5.28	2815
14:30	174	170	8.74	220	0.84	564	5.01	2680

Table 3: the theoretical results for eight 15-minute time intervals

Field capacity (PCU/h)	Troubeck's model capacity (PCU/h)			Hagring's model capacity (PCU/h)			Our model capacity (PCU/h)		
	capacity	AE	APE	capacity	AE	APE	capacity	AE	APE
2294	2082	212	0.0923	2283	11	0.0049	2114	180	0.0787
1968	1886	82	0.0415	2129	161	0.0820	1989	21	0.0106
1962	1983	21	0.0109	2219	257	0.1311	2066	104	0.0530
1823	1590	233	0.1277	1896	73	0.0403	1796	27	0.0147
2866	2963	97	0.0338	2705	161	0.0561	2479	387	0.1350
2973	3340	367	0.1236	3457	484	0.1627	3091	118	0.0398
2815	2871	56	0.0198	2953	138	0.0489	2657	158	0.0561
2680	2779	99	0.0370	2869	189	0.0706	2589	91	0.0339

Table 4: the MAE and MAPE of different model

Theoretical model	MAE (vehicles/hour)	MAPE (%)
Troubeck model (formula 3)	146	6.08
Hagring model (formula 4)	184	7.46
Our mixed traffic flow model (formula 21)	136	5.27