An Exploratory Hazard-based Analysis of the First Discharge Headway

Ming-Jun LIU\textsuperscript{a,b}, Bao-Hua MAO\textsuperscript{b}*, Shao-Kuan CHEN\textsuperscript{b}, Li-Ping GAO\textsuperscript{c}, Quan-Xin SUN\textsuperscript{b}

\textsuperscript{a} Institute of Comprehensive Transportation, National Development and Reform Commission, Beijing 100038 P.R.China
\textsuperscript{b} MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, Beijing Jiaotong University, Beijing 100044
\textsuperscript{c} PLA Beijing Military Area Command Headquarters, Beijing 100041

Abstract

The discharge headway is an important parameter in determining intersection capacity. However, it is difficult to quantify the discharge headway of individual queuing vehicle because of the great difference in the vehicle characteristics and traffic conditions. The current research aims at analyzing the first discharge headway at signalized intersections in Beijing. It introduces a hazard-based model to analyze the first discharge headway of queuing vehicles, and proposes the parameter estimation method. The model has been calibrated and validated on the basis of data collected from Beijing. It has been found that the first discharge headway, which is much longer than that in other cities, is very much dependent on the vehicle type and complexity of the intersection. It also indicates that disturbances during the starting and moving of the first vehicle increase the first discharge headway drastically. Without regard to other independent factors of traffic conditions, the starting disturbance is expected to increase the average value of the first discharge headway from to 3.99 s to 5.47 s, while the moving disturbance prolongs it from 4.15 s to 6.65 s.

© 2011 Published by Elsevier Ltd.

Keywords: Headway; The first discharge headway; Signalized intersections; Hazard-based model

1. Introduction

Discharge headway on a signalized intersection is a critical microscopic traffic flow characteristic that affects the safety, level of service, driver behavior and intersection capacity. Under pure vehicle traffic flow conditions, there is very little interaction between vehicles and extraneous interference from other traffic participants; and then, it’s relatively easy to determine the discharge headway of queuing vehicles. However, in some developing countries such as China and India, mixed traffic flow consisting of motorized vehicles and non-motorized vehicles (including pedestrians) is prevalent for urban traffic (Gao et al., 2008). The interactions between motor vehicles and other...
motor vehicles, also between motor vehicles and non-motorized vehicles seriously restrict the throughput and the efficiency and put strains on headway determination. Therefore, it is necessary to study the effect of interaction between motor vehicles and non-motor vehicles on the properties of discharge headway.

The discharge headway has attracted extensive concerns from researchers in developed countries over the years, but it is unwise to adopt the values from those developed countries to fit traffic conditions in developing countries. The current study focuses on the first discharge headway at some signalized intersections with heterogeneous traffic in Beijing, P.R. China. As of yet, very few researches have been devoted to the discharge headway in China. This study attempts to investigate the first discharge headway at intersections in Beijing. More specifically, the first discharge headway is estimated in this study by introducing the hazard-based model.

The remainder of this paper is organized as follows. In the next section, the definitions of the first discharge headway and disturbance are given and major recent developments of headway are reviewed. Section 3 is devoted at the description of the survey data used for empirical analysis and provided a descriptive analysis of the variables. Next, the methodology to use a hazard-based model for the first discharge headway with heterogeneous traffic is developed and the estimation procedure is presented. Then, a numerical analysis is performed and the results and discussions are given. Finally, the paper discusses the results and concludes with some important aspects of this application and topics for future research applications.

2. Background

2.1 Definitions

Generally, when vehicles in a queue start crossing a stop line (or any other reference line) at a signalized intersection after the signal turns green, the discharge headway is the time that elapses between consecutive vehicles (Transportation Research Board, 2000). Teply et al. (1991) pointed out that the exact definition varies from one research to another with research condition and need, and the critical point focuses on definitions of the reference line and/or vehicle discharge criteria.

The vehicle discharge headway may be defined as the interval between passage moments at which the front or rear bumpers of successive vehicles cover the stop line. If the front bumper is used, the discharge headway of the following vehicle relies on the preceding vehicle type (Huang et al., 2008). Affected by visual range, the following vehicle will adjust the safety distance, then, the larger the preceding vehicle type, the longer the discharge headway of the following vehicle. If the rear bumper is used, the discharge headway mainly depends on the type of the subject vehicle. Therefore, a passenger car may have shorter discharge headway than a bus does. In this paper, the rear bumper is employed and the queue discharge headway is defined as the elapse time between the two moments the rear bumpers of a pair of successive vehicles cover the stop line.

Apropos of the first vehicle in the queue, there is a little difference when referring to the discharge headway because there is no preceding vehicle. It is determined not only by the reference point selected in the vehicle (the front bump, the rear bump, or others), but also by the signal plan from which the start moment of the headway is determined. For example, the indication sequence of Hong Kong’s traffic signal is “red”, “red/amber”, “green” and “amber”, so Tong et al. (2002) defined the first discharge headway as the time elapse between the start moment of red/amber indication and the moment at which the rear bumper of the first vehicle covers the stop line. In Beijing, the indication sequence of traffic signal is “red”, “green” and “amber”, and then the first discharge headway is regarded as the time between the initiation of the green indication and the moment at which the rear bumper of the first vehicle crosses over the stop line. Concretely, the first discharge headway, as illustrated in Fig. 1, is composed of three parts:

1. The driver’s reaction time to green indication,
2. Starting time, counted from the driver accepting the green message to the vehicle starting up, and
3. Operation time, counted from the vehicle starting up to the rear bumper passing the stop line.

Where, (1) and (2) are jointly called the "vehicle response time".

Under the condition of pure motorized traffic flow, for vehicles of the same type theoretically, the operation time don't vary and the first discharge headway of a queue mainly depended on the vehicle response time. So, the longer the response time is, the greater the first discharge headway will be. However, it is not necessary the same in many cities of China as a lot of pedestrians and bicycles compete with vehicles at crosswalks and intersections. Once the
traffic signal is not reasonably timed between motorized and non-motorized traffic, serious chaos will occur, which will inevitably lead to notable decline in traffic efficiency and safety. Unfortunately, it’s often the case in practice, especially at some complicated intersections. In this case, pedestrians and bicycles are usually observed disturbing motor vehicles movement. Then, the vehicle's discharge headway is often enlarged by this kind of disturbance. The more disturbances occur, the greater discharge headway becomes. Therefore, the disturbance of pedestrians and bicycles must be taken into account when we analyze on vehicle's discharge headway in Beijing.

Fig. 1. Components of the first discharge headway

This paper divides the disturbance into two categories, named starting disturbance and moving disturbance. Though the signal turns green, vehicles’ startup time will be delayed if there are pedestrians or/and bicycles at the crosswalk. The disturbance taking place during this time is defined as the starting disturbance. Even worse in traffic, there are some aggressive walkers or/and bicyclists that frequently occupy motor lanes in front of moving or starting up vehicles. In order to deal with this emergency, the driver has to reduce the speed or just drive idly. Undoubtedly, the discharge headway will be extended. This paper calls this kind of disturbance as moving disturbance. To simplify the matter, this paper just distinguishes the starting and the moving disturbances and merely pay attention on whether the two kinds of disturbance happen or not, rather than analyze the severity of them.

2.2 Literature Review

Discharge headway is of fundamental importance to traffic engineers because of its strong relationship with other parameters of operation at signalized intersections, such as capacity, saturation flow rate, starting delay, and lost time (Liu, 2010). As against researches on headway, there are relatively few studies on the discharge headway, let alone the first discharge headway. Actually, under the heavy mixed-traffic condition in China, the queuing vehicles are frequently disturbed by bicycles and pedestrians (Chen et al. 2005), which bring much uncertainty to the determination of discharge headway. Then, it’s a meaningful work to study the first discharge headway in estimating the prevailing saturation flow as well as the capacity of the intersection in China.

Greenshields et al. (1947) and Sadoun (2003) investigated the average vehicle discharge headway at intersections. They found the discharge headway is closely related with queue positions. The first discharge headway will be relatively longer since it includes the reaction time of the driver and the time necessary to accelerate, and it will get to 3.8 s generally. The second headway will be comparatively lower because the second driver can overlap his/her reaction time with that of the first driver’s. After few vehicles, the headway will become constant. This constant headway which characterizes all headways beginning with the fourth or fifth vehicle is defined as the saturation headway.

Moussavi et al. (1990) and Parker (1996) studied on the discharge headway of passenger car making straight-through movements and heavy vehicles respectively. It was found that the vehicle size influences significantly the discharge headway and passenger cars induce a smaller headway to the following vehicles than heavy vehicles. Their researches also indicated that the first queuing vehicle needs a longest time to clear the intersection and the discharge headway of successor vehicle will progressively decrease. And then from the fifth, it tends to be constant.

Tong et al. (2002) proposed a neural network approach to simulate the discharge headway of individual queuing vehicle at intersections. They found the geometrical variables have significant effect on the discharge headway, for example, the discharge headway is proportional to the lane width. Besides, it’s found from field data that discharge headway of curb-side lane is significantly larger than the one on the off-side lane.
Hung et al. (2003) reported the analysis and comparisons of departure headways at a typical signalized junction in Hong Kong. The result indicated that the factors such as the lane position, vehicle type, queue position, interactions between vehicles influence the departure headway.

González (2006) investigated the discharge headway at intersection in Monterrey, Nuevo Leon, Mexico. The general result of his study is that average headway for Monterrey conditions is slightly higher than that in United States. The lane used by drivers was shown to affect headway as well, because the discharge headways of left-turn-only-lane vehicles result a 0.2 s higher than that of the adjacent through-only-lane while that of the off-side straight lane is longer than curb-side straight lane in PM peak period.

Jin et al. (2009) proposes a car-following model to explain why the time intervals between two successive vehicles passing the stop line of the signalized intersection follow position-dependent log-normal distributions except the first one. The results showed that the statistics of these departure headways are intrinsically determined by the interactions of the queuing vehicles.

An overall review of previous studies demonstrates that discharge headways are influenced by various kinds of factors, which in turn causes the varieties of discharge headways in different cities and places. Accordingly, those results and conclusions may be difficult to consistent with conditions in China.

The hazard-based analysis is referred to statistical methods for analyzing duration data. It has been used in biometrics, industrial engineering, social sciences fields as a means of determining causality in duration data and it has recently been applied in the transportation field (Wang et al., 2005). In transportation field, it has been used in accident analysis (Jovanis et al., 1989), traffic congestion analysis (Stathopoulos et al., 2002), pedestrian crossing risk analysis (Tiwari et al., 1998), travel behavior (Chen, 2007) and vehicle ownership (Yamamoto et al., 2000). And so far, there is little application in discharge headway analysis. As this paper will show, hazard-based analysis can play an important role in the first discharge headway analysis.

3. Data acquisition and variable selection

3.1 Data Acquisition

Data collection is a critical step for the first discharge headway analysis, and all the data used in the paper are from Beijing. In order to reflect comprehensively the traffic situation of Beijing, we follow the pluralism principle of intersection location, types and lane function; meanwhile, we keep intersections away from bus stop or stop parking place to avoid internal interference. The general characteristics for the five study sites selected are presented in TABLE 1.

For all selected intersection approaches, data collection occurred by placing a high-definition digital video camera on high-rise buildings or pedestrian bridges nearby. Of course, we also kept detailed records on vehicle queued in entrance driveway, behavior characteristic of pedestrians or bicycles and the signal periodic changing.

### TABLE 1. Intersections for Collecting the First Discharge Headway Data

| Intersection No. | Intersection Type | Approach       | Phase Number | Lane Number |
|------------------|-------------------|----------------|--------------|-------------|
| 1                | 4-arm             | Eastbound      | 5            | 5           |
| 2                | 4-arm             | Eastbound      | 4            | 4           |
| 3                | 4-arm             | Eastbound      | 4            | 3           |
| 4                | 3-arm             | Northbound     | 3            | 3           |
| 5                | 4-arm             | Eastbound      | 2            | 2           |

Videotape data were coded in the laboratory. Frame by frame progress of tapes was monitored by research assistants manually, and values entered in a pre-designed format. During data extraction and analysis, we defined three kinds of situation for data censoring, namely (1) U-turning queued head vehicle by left turn only lane, (2) queued vehicles in right turn only lane without signal control, and (3) queued vehicles had passed the stop line partly or completely before green on.
3.2 Variable Selection

Generally, queue vehicle discharge headway relies on a series of potential explanatory variables such as physical characteristics of intersection, vehicle and traffic flow characteristics. Additionally, there are a lot of external factors influencing vehicle discharge headway (Guo et al. 2008). Restricted by realistic conditions, some variables such as driver's character are excluded from the model on account of difficult to collection and calibration. Based on the main factors affecting discharge headway as discussed in previous sections and the characteristics of mixed traffic flow in Beijing, six variables have been chosen to be the explanatory variables for estimation of the first discharge headway. As TABLE 2 shows, $X_1$, $X_3$ and $X_4$ are categorical variables.

| Variables | Definition | Description |
|-----------|------------|-------------|
| $X_1$     | Type of the head vehicle | 0 for passenger car & taxi, 1 for vans & medium vehicles, 2 for buses & heavy goods vehicles |
| $X_2$     | Phase number of intersection | 0 for 2-phase intersection, otherwise 1 |
| $X_3$     | Lane type | 0 for exclusive left-turn lane, 1 for curb-side straight lane, 2 for off-side straight lane, 3 for exclusive right-turn lane |
| $X_4$     | Location of intersection | 0 for residential district, 1 for business district, 2 for political district |
| $X_5$     | Starting disturbance | 1 if disturbed when starting up, otherwise 0 |
| $X_6$     | Moving disturbance | 1 if disturbed during the operation time, otherwise 0 |

Among the variables, type of the head vehicle is a three categories variable, it can be divided into car (e.g. passenger car and taxi), medium-sized vehicle (e.g. vans and medium vehicles) and large-sized vehicle (e.g. buses and heavy goods vehicles) by geometrical dimensions (Liu et al. 2008). Lane type is split into exclusive left-turn lane, curb-side straight lane, off-side straight lane and exclusive right-turn lane according to approach function and allocation. Phase number and Location of intersection was used to reflect its complexity on the effects of the first discharge headway. It is remarkable vehicles to be or have been started up are easily subjected to interference by pedestrians or bicycles, so we adopt the 2 binary variables, starting disturbance and moving disturbance, to depict the phenomena.

4. Methodology

There are three basic types of the discharge headway prediction models, namely, deterministic model proposed by Briggs (1977) to predict the average queue discharge headway at signalized intersection, Booneson model (Bonneson, 1992), and neural network model (Tong et al., 2002). In this paper, we develop a hazard-based model to estimate and analyze the first discharge headway for individual vehicle.

4.1 Model Framework

The deal of duration time is the most important part in hazard-based analysis. More generally, duration time refers to a variable which measures the time from a particular starting time (e.g., time initiated the treatment) to a particular endpoint of interest (e.g., attaining certain functional abilities) in proportional hazard model (Cox, 1972). In this paper, the duration time is defined as the length of time that elapsed from the beginning of the green to the first queue vehicle’s rear bumper crossing over the stop line.

Suppose the cumulative distribution function of last time $T$ (in this research, it’s named first discharge headway while named duration time in hazard-based analysis) of the first vehicle is:

$$F(t) = p(T < t)$$  \hspace{1cm} (1)

where $p$ denotes the probability, $T$ is a random variable, and $−\infty < t < \infty$.

Then the probability density function of $T$ is

$$f(t) = \frac{dF}{dt}$$  \hspace{1cm} (2)

The survival function, $S(t)$, gives the probability that the duration will be larger than or equal to some specified time $t$:
The hazard function, \( h(t) \), which represents the conditional probability density that the first vehicle will pass stop line between time \( t \) and \( t + \Delta t \), given that it has not passed up to time \( t \), is given as

\[
0 \lim_{\Delta t \to 0} p(t \leq T < t + \Delta t | T \geq t) = \lim_{\Delta t \to 0} \frac{S(t) - S(t + \Delta t)}{\Delta t \cdot S(t)}
\]

Then, we obtain

\[
h(t) = -\frac{S'(t)}{S(t)}
\]

And thus, the survival function can be rewritten as

\[
S(t) = e^{-\int_0^t h(t) dt}
\]

Several distributions are available to describe the hazard rate as a function of time. In the paper, Cox proportional hazard model is adopted because it’s robust to approximate the results of a correct parametric model without needing to assume a specific functional form in advance. The Cox regression model is comprised of two parts: the baseline hazard and an exponential component (Cox, 1972). Its functional form can be expressed as

\[
h(t | X, \beta) = h_0(t)e^{\beta^T X}
\]

where \( h_0(t) \) is the baseline hazard function and \( X \) and \( \beta \) are vectors of the independent variables and the corresponding parameters, respectively.

In order to compare the relative hazard contribution of two independent variable vectors, \( X_1 \) and \( X_2 \), we constructed the hazard ratio function from equation (7). According to Cox proportional hazard assumption (Cox, 1972), the hazard ratio is constant since \( h_0(t) \) cancels out of the equation and \( \beta \) is estimated parameters (the estimation method will be presented in the next section).

\[
HR = \frac{h(t | X_1, \tilde{\beta})}{h(t | X_2, \tilde{\beta})} = e^{(X_1 - X_2)^T \beta}
\]

If \( HR > 1 \), then the conditions described by \( X_1 \) are more likely to terminate the first discharge headway than the conditions given by \( X_2 \). In other words, the first discharge headway is shorter under \( X_1 \).

### 4.2 Model Estimation

Suppose a sample with size is \( n \), including three variables, \( T_i \), \( \delta_i \) and \( X_j(t) \), \( (j = 1, 2, \cdots, n) \). Where \( T_i \) denotes the last time of the \( j \)th individual; \( \delta_i \) is an event identify variable, if the event occurs, \( \delta_i = 1 \), else, it will be right-censoring, then \( \delta_i = 0 \); \( X_j(t) = (X_{j1}(t), \cdots, X_{jn}(t))^T \) represents the covariate variable vector or influencing factors of individual \( j \) at time \( t \), and we also suppose covariate variable doesn’t vary with time, i.e. \( X_j(t) = X_j = (X_{j1}, \cdots, X_{jn})^T \).

Then, assumption there are \( n+1 \) categories for categorical variable \( Y \). In order to get a full-rank matrix with \( n \) dummy variables \( y_1, y_2, \ldots, y_n \) and assure the unity of likelihood estimation, we have to assign 0 to the coefficient of a random dummy variable. The design for fixed referential level is shown in TABLE 3.

| \( Y \) | Designing matrix |
|---|---|
| \( y_1 \) | 1 | 0 | 0 | 0 | 0 |
| \( y_2 \) | 0 | 1 | 0 | 0 | 0 |
| \( \cdots \) | 0 | 0 | \( \cdots \) | \( \cdots \) | 0 |
| \( y_n \) | 0 | 0 | 0 | 1 | 0 |
| \( y_{n+1} \) | 0 | 0 | 0 | 0 | 0 |
For convenience of description, let the category, \( n + 1 \), as the reference level. Coefficients \( \theta_1, \theta_2, \ldots, \theta_n \) represent the logarithmic hazard ratio of level 1, 2, \ldots, \( n \) relative to level \( n + 1 \), respectively. For instance, level 1’s logarithmic hazard ratio to level 2 is

\[
(1 \times \theta_1 + 0 \times \theta_2 + \cdots + 0 \times \theta_n) - (0 \times \theta_1 + 1 \times \theta_2 + \cdots + 0 \times \theta_n) = \theta_1 - \theta_2
\]

Let \( R(t_j) \) denote the set of vehicles at risk at time \( t_j \) for occurred events, which represents the set of vehicles are not cross over the stop line before \( t_j \). Then, the hazard function will be

\[
h(t) = h_0(t) \exp\left( X_i \beta_i + \sum_{s=1}^{n} \left( \sum_{\theta_s} y_s \theta_s \right)^d \right)
\]

Thus, The partial likelihood function for proportional hazard model with categorical variable will be:

\[
L(\beta, \theta) = \prod_{r \in R(t)} \frac{\exp[X_i \beta_i + \sum_{s=1}^{n} \left( \sum_{\theta_s} y_s \theta_s \right)^d]}{\exp[X_i \beta_i + \sum_{s=1}^{n} \left( \sum_{\theta_s} y_s \theta_s \right)^d]}
\]

And then, the parameter, \( \beta \) and \( \theta \), are the value that maximizes the log-likelihood function. The log-likelihood function, obtained by taking the log of the likelihood (11), is

\[
LL(\beta, \theta) = \sum_{i=1}^{k} \left[ \beta_i X_i + \sum_{s=1}^{n} \left( \sum_{\theta_s} y_s \theta_s \right)^d \right] - \sum_{i=1}^{k} \ln \sum_{j \in R(t)} \exp[\beta_i X_i + \sum_{s=1}^{n} \left( \sum_{\theta_s} y_s \theta_s \right)^d]
\]

We obtain the maximum partial likelihood estimator by differentiating the right hand side of (12) with respect to \( \beta \) and \( \theta \) respectively. By setting the derivative equal to zero and solving for the unknown parameter, we can obtain the maximum likelihood estimation value, \( \hat{\beta}_1, \hat{\beta}_2, \ldots, \hat{\beta}_n \), and \( \hat{\theta}_1, \hat{\theta}_2, \ldots, \hat{\theta}_n \).

### 5. Empirical Analysis

#### 5.1 Estimation Results

The first discharge headway is measured from the moment that green on to the time the head vehicle’s rear bumper crosses over the stop line. According to the video survey, 694 cases of the queuing head vehicles are sampled. Six variables including vehicle type, phase number of intersection, lane type, sites location, starting disturbance, and moving disturbance are take account into explanatory variables. And vehicle type, lane type, and sites location are multi-categorical variables. TABLE 4 shows the estimation results for hazard-based analysis model. In interpreting the signs of the coefficients presented in this table, a negative sign decreases the hazard and thus increases duration while a positive signs increases the hazard and decreases duration.

| Independent variable | \( \beta \)  | SE    | \( t \)-test | \( \text{Exp}(\beta) \) |
|----------------------|------------|-------|--------------|------------------------|
| \( X_1 \)            |            |       |              |                        |
| \( X_1(1) \)         | -0.256     | 0.1305| -1.96*       | 0.77                   |
| \( X_1(2) \)         | -0.853     | 0.1751| -4.87**      | 0.43                   |
| \( X_2 \)            | -0.707     | 0.1726| -4.10**      | 0.49                   |
| \( X_3 \)            |            |       |              |                        |
| \( X_3(1) \)         | 0.043      | 0.0218| 1.97*        | 1.04                   |
| \( X_3(2) \)         | 0.267      | 0.1327| 2.01*        | 1.31                   |
| \( X_3(3) \)         | -0.469     | 0.2304| -2.04*       | 0.63                   |
| \( X_4 \)            |            |       |              |                        |
| \( X_4(1) \)         | 0.258      | 0.1285| 2.01*        | 1.29                   |
According to the t-test value shown in TABLE 4, we can found all the six variables have significant influence on the first discharge headway. Additionally, Suppose null hypothesis $H_0: \beta_1 = \beta_2 = \cdots = \beta_k = 0$ submit to $\chi^2_{0.05}(10)$. As $-2(\ln L(0) - \ln L(\beta)) = 5150.047 - 5031.082 = 119.585 > \chi^2_{0.05}(10) = 18.307$, then null hypothesis is rejected and the test results indicate that the variables have significant effect on the first discharge headway. The hazard function is:

$$h(t) = h_0(t) \exp(PI)$$

where the prognostic index:

$$PI = -0.256 \times x_1(1) - 0.853 \times x_1(2) - 0.707 \times x_2 + 0.043 \times x_3(1) + 0.267 \times x_3(2)$$

$$- 0.469 \times x_3(3) + 0.258 \times x_4(1) - 0.252 \times x_4(2) - 0.296 \times x_5 - 0.696 \times x_6$$

Survival function $S(t): S(t) = S_0(t)^{\exp(PI)}$

The baseline survival rate: $S_0(t) = S(t)^{1/\exp(PI)}$

### 5.2 Description of the First Discharge Headway

After estimating for the sample by hazard-based analysis model, the average first discharge headway is 4.54 s, and the value is obviously longer than 3.6 s in Hong Kong (Tong et al. 2002), 3.85 s in Los Angeles metropolitan area (Gerlough et al. 1967), 3.3 s in Mexico (González 2006), and 3.2 s in Riyadh (Al-Ghamdi 1999). There seem to be two reasons for this. On the one hand, the problem relates to mixed-traffic characteristics that result in conflicts between motor vehicle and non-motorized traffic (mostly bicycle and pedestrian) in at-grade, signalized intersections, which lead to a higher discharge headway. On the other hand, the relatively poor performance of vehicles also prolong the vehicle reaction and start-up time, which, in turn, leads to an increase in the first discharge headway, indirectly.

![Fig. 2. Distribution of the first discharge headway by hazard-based analysis](image-url)
stop line in 2.0 s, and 4.0 s later, cum survival has reduced to 54.1%, which means 45.9% queue head vehicles’ discharge headway are lower than 4.0 s. A cum survival of discharge headway in the 15th percentile is 6.04 s, i.e. 15% queuing vehicles’ first discharge headway exceeds 6.04 s at intersection, Beijing.

5.3 Quantify Analysis of Influencing Parameters

On the Basis of estimation results, the partial regression coefficients of vehicle type $X_1(1)$ and $X_1(2)$, phase number $X_2$, lane type $X_3(3)$, site location $X_4(2)$, starting disturbance $X_5$, moving disturbance $X_6$ are all less than 0, i.e. $\exp(\beta_i x_k) < 1$. It indicates the probability of head vehicle crossing over stop line in a given time $t$ (i.e. the probability of first discharge headway is less than $t$) will decrease from baseline hazard rate $h_0(t)$ to $\exp(\beta_i x_k) \times h_0(t)$, furthermore, the smaller the coefficients, the smaller the probability, the greater the first discharge headway. Similarly, the positive partial regression coefficients of lane type $X_3(1)$ and $X_3(2)$, site location $X_4(1)$ represent the probability of head vehicle crossing over stop line in a given time $t$ will rise to $\exp(\beta_i x_k) \times h_0(t)$, moreover, the greater the coefficients, the greater the probability, the smaller the first discharge headway.

The estimation results of hazard-based model allow us to quantify the impact of significant variables on the first discharge headway, so as to provide the theory basis for the intersection capacity analysis and parameter determination of micro simulation model in Beijing.

(1) Physics characteristics of intersection

Phase number, lane type and location are introduced to describe the physics characteristics of intersections.

Phase number reflects the complexity of intersection indirectly. In general, the more the phase number is, the more complex the intersection will be. The calibration value is -0.707 and the relative hazard rate is $\exp(-0.707) = 0.49$, which indicates, among other things, the first discharge headway of multi-phase interaction is greater than two-phase interaction. Moreover, the average first discharge headway, which is 2.98 s at two-phase intersection and 4.71 s at multi-phase intersection, also corroborated it.

Lane type is a multi-categorical variable, and it is divided into exclusive left-turn lane, off-side straight lane, curb-side straight lane and exclusive right-turn lane. Referring to the variable of exclusive left-turn lane, the estimations of curb-side straight lane, off-side straight lane and exclusive right-turn lane are 0.043, 0.267, and -0.469 respectively, and corresponding relative hazard rates are 1.04, 1.31, and 0.63. This phenomena represent the first discharge headway of off-side straight lane is shorter than the curb-side straight lane, and this is approximately like Mexico (Gonzalez, 2006) and Hong Kong (Tong et al., 2002). The results also indicate the first discharge headways of the straight lanes are shorter than exclusive left-turn lane while that of exclusive right-turn lane is longer than exclusive left-turn lane, other conditions being the same. To explain the phenomena, we must focus on lane function and vehicle direction, Compared with straight-through vehicles, turning vehicles may travel at a relatively lower speed and induce a longer headway under safety constraint. As previously mentioned, the left-turning and right-turning vehicles have different first discharge headway. Under Beijing’s right-hand driving system, the exclusive right-turn lane is next to the bicycle lane and pavement, therefore, the right-turning vehicles prone to be disruptive.

Similar to variables of phase number and lane type, the location variable will no longer be deeply analyzed here.

(2) Vehicle characteristics

We adopt vehicle type to reflect the vehicle characteristics in this paper. Vehicle type is a three-categorical variable, including small vehicle (e.g., taxi), medium-size vehicle (e.g., vans) and oversize vehicle (e.g., bus). When the other conditions are alike, the first discharge headway of them will be 4.41 s, 4.78 s and 4.68 s, respectively. In the model, the coefficients for medium-size vehicle and oversize vehicle are -0.256 and -0.853, which indicate that the greater the vehicle type, the smaller the probability of vehicle passing the stop line in a given time $t$, the longer the first discharge headway. To be specific, the probability of medium-size vehicle passing the stop line in the same period of time is $\exp(-0.256) = 0.77$ with respect to small vehicle. And the relative hazard rate of oversize vehicle is $\exp(-0.853) = 0.43$, namely, about 43% of the oversize vehicles will pass the stop line while all the small vehicles pass it in a given time $t$, which indicate that the first discharge headway will get longer with vehicle type.

(3) Traffic flow characteristics

Starting disturbance and moving disturbance, which are used to depict traffic flow characteristics, are dichotomous variables. The estimation results reveal that the average first discharge headway is 3.99 s for non-
starting-interfered vehicle, while the starting-interfered vehicle is 5.47 s. And similarly, the average first discharge headway of non-passing-interfered is 4.15 s, while passing-interfered vehicle is 6.65 s.

The values of the traffic flow characteristic parameters, starting disturbance $X_5$ and moving disturbance $X_6$, are estimated at $-0.296$ and $-0.696$, then the relative hazard rate are $\exp(-0.296) = 0.74$ and $\exp(-0.696) = 0.50$, respectively. They demonstrate that the probability of starting-disturbed vehicle pass the stop line in given time $t$ is 74% of non-starting-disturbed vehicle, that is, the first discharge headway of starting-disturbed vehicle is 1.35 times of non-starting-interfered vehicle. Moreover, the probability of moving-disturbed vehicle pass the stop line in given time $t$ is 50% of non-moving-disturbed vehicle among other things, therefore, its first discharge headway is twice as non-moving-disturbed vehicle. Fig. 3 illustrates cum survival distribution of the first discharge headway using starting disturbance as control variable. We can found that the interference curve is above on the no disturbance curve, which indicate the first discharge headway of the starting-disturbed vehicle is longer than non-starting-disturbed vehicle.

![Fig. 3. Distribution of the first discharge headway by starting disturbance](image)

6. Conclusions

The first discharge headway is influenced by physics characteristics of intersections, vehicle characteristics and traffic flow characteristics. Based on these factors, a hazard-based analysis model was adopted to study the first discharge headway of queuing vehicle at intersections in Beijing. By analyzing the influencing factors of the first discharge headway, we proposed estimation methods for model according to whether or not a categorical variable is contained and estimated the parameters. Finally, we depicted the distribution of the first discharge headway and qualified the impact of influencing factors on the first discharge headway. The results of analytical modeling show:

1. Owing to the high-density mixed traffic condition and vehicle characteristics, the average value of the first discharge headway for queuing vehicles at signalized intersection in Beijing is 4.54s, which is 1.0s to 1.5s longer than foreign similar cities.

2. According to the estimation results, the first discharge headway is directly proportional to vehicle type and phase number. Greater dimension of the vehicle and more division of the signal phase will respectively lead to longer discharge headway of the first vehicle.

3. The results demonstrate that vehicles in exclusive left-turn lane or right-turn lane have longer first discharge headway than straight-through vehicles in curb-side straight lane or off-side straight lane. Moreover, with right-hand driving systems, the right-turning vehicles’ first discharge headway is longer than that of left-turning vehicles.

4. The paper distinguishes the disturbance factor into starting disturbance and moving disturbance and finds they are significant factors to determine the first discharge headway. On account of starting disturbance, the average first discharge headway is prolonged from 3.99 s to 5.47 s, while the moving disturbance leads it to lengthen from 4.15 s to 6.65 s.

Discharge headway is an important parameter in traffic engineering. The findings of this study will contribute to capacity analysis at signalized intersections in developing cities. As for future research, we will focus on the disturbance of pedestrians and bicycles to headway, and then introduce it to build a revised capacity model under mixed traffic.
Acknowledgements

We gratefully acknowledge the financial assistance of the program for New Century Excellent Talents in University of China (NCET-05-0094), the National Basic Research Program of China (No.2006CB705507) and the National Natural Science Foundation of China (70571005, 70631001). The authors thank anonymous referees for their valuable comments that resulted in a significant improvement of this paper.

References

[1] Al-Ghamdi, A.S. (1999). “Entering headway for through movements at urban signalized intersections.” Transp. Res. Rec., Transportation Research Board of the National Academies, Washington, D.C., 1678, 42-47.
[2] Bonneson, J.A. (1992). “Study of headway and lost time at single-point urban interchanges.” Transp. Res. Rec., Transportation Research Board of the National Academies, Washington, D.C., 1365, 30-39.
[3] Briggs, T. (1977). “Time headways on crossing the stop line after queuing at traffic lights.” Traffic Eng Control, 18(5), 264-265.
[4] Chen, S.K., Guo, J.Y., Wang, X., and Mao, B.H. (2005). “Analysis and simulation on signalized intersection delay.” Beijing Jiaotong Daxue Xuebao, 29(3), 77-80.
[5] Chen, T.S. (2007). “Travel behavior characteristics analysis for commuter.” Doctoral dissertation, Beijing Jiaotong University, Beijing, China.
[6] Cox, D.R. (1972). “Regression models and life tables.” J. Roy. Statist. Soc. Ser. B, 34, 187-220.
[7] GAO, L.P., Liu, M.J., Sun, Z.Z. and Mao, B.H. (2008). “Simulation on Impact of Information Guidance on Regional Traffic Flow.” J. Transp. Syst. Eng. Inf. Technol., 8(4), 63-69.
[8] Gerlough, D. L., and Wagner, F.A. (1967). “NCHRP Report 32: Improved Criteria for Traffic Signals at Individual Intersections.” TRB, National Research Council, Washington, D.C., 38–42.
[9] González, L.F.C. “Discharge headway at signalized intersections in Monterrey, Nuevo Leon, Mexico.” Doctoral dissertation, University of Texas, USA, 2006.
[10] Greenshields, B.D., Schapiro, D., and Ericksen, E.L. (1947). “Traffic performance at urban intersections.” En� Foundation for Highway Traffic Control, 23-30.
[11] Guo, J.Y., Mao, B.H., Liu, M.J., and Gao, L.P. (2008). “Study on Actuated Signal Controlled System in Isolated Intersection.” Chinese Contr. Decis. Conf., CCDC. Yantai, China, 2177-2181.
[12] Huang, R., Guo, M., Chen, S.K., and Liang X. (2008). “Modeling capacity of signalized intersections with congestion.” J. Transp. Syst. Eng. Inf. Technol., 8(3), 58-65.
[13] Hung W.T., Tian F., and Tong H.Y. (2003). “Discharge headway at signalized intersections in Hong Kong.” J. Adv. Transport., 37(1), 105-113.
[14] Jin X.X., Zhang Y., Wang F., Li L., Yao D.Y., Su Y.L., and Wei Z. (2009). “Departure headways at signalized intersections: A log-normal distribution model approach.” Transp. Res. C-Emer, doi:10.1016/j.trc.2009.01.003
[15] Jovanis, P., and Chang, H.L. (1989). “Disaggregate model of highway accident occurrence using survival theory.” Accid. Anal. Prev., 21(5), 445-458.
[16] Liu, M.J. (2010). “Modelling on Discharge Headway with Heterogeneous Traffic at Signalized Intersections.” Doctoral dissertation, Beijing Jiaotong University.
[17] Liu, M.J., Mao, B.H., Huang, Y., Zhang, J.P., and Chen, S.K. (2008). “Comparison of pre- & post-Olympic traffic: A case study of several roads in Beijing.” J. Transp. Syst. Eng. Inf. Technol., 8(6), 67-72.
[18] Luo, X., Du, J.Y., and Huo, Y.M. (2001). “Study on the distribution patterns of time headway of vehicles.” Xinan Jiaotong Daxue Xuebao, 36(2), 113-116.
[19] Moussavi, M., and Tarawneh, M. (1990). “Variability of departure headways at signalized intersections.” Compred Tech Pap Annu Meet Inst Transp Eng, Orlando, Florida, 313-317.
[20] Parker, M.T. (1996). “The effect of heavy goods vehicles and following behavior on capacity at motorway roadwork sites.” Traffic Eng Control, 37(9), 524-531.
[21] Sadoun, B. (2003). “An efficient simulation methodology for the design of traffic lights at intersections in urban areas”. Simulation, 79(4), 243-251.
[22] Stathopoulos, A., and Karlafis, M.G. (2002). “Modeling duration of urban traffic congestion.” J. Transp. Eng-ASCE, 128(6), 587-590.
[23] Teply, S., and Jones, A.M. (1991). “Saturation flow: Do we speak the same language?” Transp. Res. Rec., Transportation Research Board of the National Academies, Washington, D.C., 1320, 144–153.
[24] Tiwari, G., Mohan, D., and Fazio, J. (1998). “Conflict analysis for pedestrian of fatal crash locations in mixed traffic streams.” Accid. Anal. Prev., 30(2), 207-215.
[25] Tong, H.Y., and Hung, W.T. (2002). “Neural network modeling of vehicle discharge headway at signalized intersection: model descriptions and results.” Transp. Res. A-Pol., 36(1), 17-40.
[26] Transportation Research Board. (2000). “Highway capacity manual, fourth edition.” National Research Council, Washington, DC, USA.
[27] Wang, W.Q., Chen, H.B., and Bell, M.C. (2005). “A review of traffic incident duration analysis.” J. Transp. Syst. Eng. Inf. Technol., 5(3), 127-140.

[28] Yamamoto, T., and Kitamura, R. (2000). “An analysis of household vehicle holding durations considering intended holding durations.” Transp. Res. A-Pol., 34(5), 339-351.