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AN EMPIRICAL STUDY ON THE TIME GAP AND ITS
RELATION TO THE FUNDAMENTAL DIAGRAM

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ABSTRACT

The fundamental diagram is an important element in a variety of transportation studies. While various shapes of the fundamental diagram have been proposed and numerous debates on the best-fit fundamental diagram have been made, why the fundamental diagram has many different shapes has not been well explained. This study introduces time gap as a key parameter to understand drivers' behavioral differences at different locations and traffic conditions, then relate it to the shape of the fundamental diagram. From I-80 freeway event detector data, it is shown that time gap follows a certain probabilistic distribution and its mean value varies along locations. When downstream congestion is expected, drivers tend to take larger time gap than otherwise. It also turns out that drivers take different time gaps for different travel speeds. Three different types of time gap-speed diagrams are identified and matched to Greenberg, reversed-lambda, and inverted-V types of fundamental diagrams, respectively.

1. INTRODUCTION

The relationship among macroscopic traffic flow parameters, such as flow rate, speed, and density has been of major interest to a variety of transportation studies such as planning, design, and operations. While various traffic stream models that describe the relationship among those parameters have been proposed, there still exist ongoing debates regarding which model best fits the real traffic data. The earliest traffic stream model found in literature dates back to Greenshields' linear model [1]. From a ground photographic data, he found that the speed is a linearly decreasing function of density. The flow(q)-density(k) relationship (fundamental diagram) derived from Greenshields' linear speed-density model is a single parabolic curve, which is symmetric to the critical density at which the maximum flow rate is gained. Another traffic stream model was developed by Greenberg [2]. Greenberg derived a non-linear speed-density relationship from a hydrodynamic analogy and showed that this non-linear speed-density relationship fits well with Lincoln Tunnel data. The fundamental diagram derivable from Greenberg's speed-density relationship is an asymmetric parabolic curve such that the critical density is about one thirds of the jam density(Fig. 1 (a)). Because of their simplicity and connection with General Motors car-following model, Greenshields and Greenberg's single-regime models are generally accepted and widely used up-to-date. However, a careful investigation of the flow-density scatter plots has led to the so-called dual-regime traffic stream model. Edie and Foote [3] first noticed that two different sets of scattered points are in the flow-density diagram (one for free flow and the other for congested flow) and a discontinuity exists between them. Edie [4] studied the same Lincoln Tunnel data as in Greenberg and represented the flow-density scatter plot with two distinctive curves one for free flow and one for congested flow(Fig. 1 (b)). Edie's dual-regime model was supported by several other researchers e.g. [5] [6] [7]. The characteristic feature of the dual-regime fundamental diagram is the existence of the discontinuity, which represents the capacity drop: the maximum flow rate achievable in the congested flow regime is significantly lower than that in the free flow regime. There have been numerous arguments regarding the existence of the capacity drop and the value of freeway capacity [8] [9] [10]. Recently, driver's behavioral models have been developed to explain the capacity drop phenomenon [11] [12].

Another remarkable feature of the fundamental diagram was revealed from Japanese highway data. Koshi et al. [13] analyzed traffic data from the Tokyo Expressway and proposed 'the mirror image of a reversed λ '-type fundamental diagram, where the free flow branch is downward concave and the congested flow branch is upward concave. A discontinuity exists between those two curves(Fig. 1 (c)). The reverse-lambda type fundamental diagrams are also found in other sites as well [14] [15]. Banks [16] has mentioned that the reverse-lambda and inverted-V shapes usually are found in the inside lane. When data are aggregated across all lanes, the inverted-V

shape is most commonly encountered. The inverted-V shape is initially mentioned by Athol [17] and Hillegas et al. [18](Fig. 1 (d)). Hall et al. [8] have studied 5-min average data from a section of Queen Elizabeth Way between Oakville and Toronto, concluding that discontinuity is not convincing. Rather, an inverted-V shape is a logical choice for the fundamental diagram. Banks [14], from San Diego traffic data, has also confirmed that the overall flow-density relationship is well described by the inverted-V shape. The inverted-V shape holds a linear relationship between flow and density for both free flow and congested flow branches. Because the linearity in the congested flow branch implies that drivers have constant time gap (the time separation between the rear of the leading vehicle and the head of the following vehicle) a much simpler and direct interpretation is possible on the inverted-V shape fundamental diagram. Due to the simplicity and behavioral backing of the inverted-V shape model, it is adopted in many recent traffic flow studies [19] [20].

There has been a great number of research regarding the flow-density relationship. However, a consistent and globally-applicable flow-density relationship has not been developed, and we still do not fully understand the implications of various features in the fundamental diagram. This complexity of the fundamental diagram is mainly due to the fact that drivers behave differently at different locations and traffic conditions. Accordingly, to uncover drivers' behavior hidden in the fundamental diagram, we must gain a better understanding of the fundamental diagram. However, most of the empirical studies of the fundamental diagram mainly relied on visual investigation, and no attempt is made to use a microscopic approach to explain the features of the fundamental diagram. In this paper, we introduce the time gap of individual vehicles as a key parameter to explain the fundamental diagram. We investigate the time gap distribution and by relating it with the fundamental diagram we attempt to explain various features of the fundamental diagram from drivers' behavior.

2. TIME GAP AND FUNDAMENTAL DIAGRAM

In congested traffic, the concern of a driver is mainly to avoid collision with the vehicle in front. For safe driving, the driver usually need to maintain adequate spacing (the distance between the rear of the leading vehicle and the head of the following vehicle). If we assume that the leading and following vehicle's deceleration performance is the same and there is no reaction time for the following driver, no spacing is needed between the rear of the leader and the head of the follower. If a following driver has a reaction time, the minimum spacing required to avoid collision is speed times the reaction time assuming steady state flow. When the actual time gap is much bigger than the reaction time(minimum required time gap), the following driver can drive in a more relaxed mood. In reality, due to the uncertainty of the deceleration performance and individual preference for relaxation, the actual time

gap tends to be bigger than the reaction time. Field measurements show that the actual time gap varies across driver population and time of a day for an individual driver [21].

Different time gaps lead to different fundamental diagrams. Forbes [22] has shown that a constant time gap corresponds to a linear relationship between flow and density (Fig. 1 (e)). Zhang and Kim [12] have postulated that the time gap (h), also called response time, could be a function of spacing (s). They have shown that different types of fundamental diagrams are derived from different functional forms of time gap vs. spacing. For example, a single parabolic fundamental diagram is obtained when the time gap of vehicle n at time t follows Eq.1 (refer to [12] for the derivation of fundamental diagram from time gap-spacing function).

$$h_n(t) = h_0 + \frac{1}{v_f} s_n(t) \quad (1)$$

where, v_f is the free flow speed and h_0 is a constant.

Substituting $s_n(t)$ with $v_n(t) \cdot h_n(t)$, the time gap can be represented as a function of speed.

$$h_n(t) = \frac{h_0}{1 - \frac{v_n(t)}{v_f}}. \quad (2)$$

In Fig. 2, the continuous parabolic type fundamental diagram (a), its corresponding h - s relationship (b) and h - v relationship (c) are drawn.

The reverse lambda fundamental diagram (Fig. 3(a)) can be obtained when the time gap is constant for the congested traffic and a linearly increasing function of spacing for the free flow traffic.

$$\begin{aligned} h_n(t) &= \frac{s_n(t)}{v_f} && \text{if } S_1 \leq s_n(t), \\ &= h_1 && \text{if } 0 \leq s_n(t) < S_0. \\ &= \frac{s_n(t)}{v_f} && \text{if } S_0 \leq s_n(t) < S_1, \text{ and } v_n(t) = v_f \\ &= h_1 && \text{if } S_0 \leq s_n(t) < S_1, \text{ and } v_n(t) < v_f \end{aligned}$$

The time gap-spacing function can be transformed into a time gap-speed function as follows.

$$\begin{aligned} h_n(t) &\geq h_0 && \text{if } v_n(t) = v_f, \\ &= h_1 && \text{if } v_n(t) < v_f \end{aligned}$$

The time gap-spacing and time gap-speed functions corresponding to the reverse lambda fundamental diagram is drawn in Fig. 3(b) and (c). For congested traffic, if time gap is a decreasing function of speed, the right leg of the reverse lambda would be convex to the origin, which is much similar to the original reverse lambda

fundamental diagram proposed by Koshi et al [13].

Analytically, it has been shown that various types of fundamental diagrams can be matched to corresponding time gap-spacing(speed) functions, from which it is easier to decipher drivers' behavior. In the next section, we study empirical freeway traffic data and investigate the fundamental diagrams obtained from the data and their interpretations in terms of drivers' behavior.

3. STUDY SITE AND DATA GATHERING

The traffic data are collected on a stretch of I-80 in Berkeley, California(Fig. 4 (a)). This stretch of I-80 is a flat and straight 10-lane freeway. The westbound leads to Bay Bridge, which is often crowded due to the large amount of traffic entering San Francisco. During weekday morning and evening peaks, the congestion generated in the vicinity of the Bay Bridge entrance propagates far upstream to the study site. The eastbound traffic is to Richmond. Congestion is also commonly found in the eastbound traffic, but it is milder than the westbound. The HOV lanes are lane 0 and lane 5, and they are used exclusively by HOVs during AM 5:00 ~ AM 10:00 and PM 3:00 ~ PM 7:00. There are 8 detector stations. At each station, each lane has a pair of loop detectors. The size of a detector is $6ft \times 6ft$ ($1.83m \times 1.83m$) and the pair of detectors are $14ft$ ($4.27m$) apart(Fig. 4(b)). The raw detector data used in this study is the event detector data. In other words, vehicles' on/off time records for a pair of loop detectors are used. The on/off times are recorded in 1/60 second unit. This event data provides more appropriate information to compute the time gap of individual vehicles than the aggregated data such as flow or occupancy.

The on-time of a detector is the time that the head of a vehicle hits the upstream edge of the detector and the off-time of a detector is the time that the rear of a vehicle leaves the downstream edge of the detector(Fig. 4(b)). Some mechanical bias or error of the detector is not considered in this study. Let the on and off time of n -th vehicle at upstream detector be t_n^{11} and t_n^{12} , and the on and off time of n -th vehicle at downstream detector be t_n^{21} and t_n^{22} , respectively. Assuming steady state condition, the speed of the n -th vehicle is computed as

$$v_n = (D + d)/(t_n^{21} - t_n^{11}). \quad (3)$$

where, d is the length of a detector ($6ft$) and D is the distance between the pair of detectors ($12ft$).

The time gap of n -th vehicle(h_n) is computed as the time difference that the rear of $(n - 1)$ -th vehicle and the head of n -th vehicle passes the upstream edge of the detector

$$h_n = t_n^{11} - (t_{n-1}^{12} - d/v_{n-1}). \quad (4)$$

The flow rate, speed, occupancy, and density, unless otherwise stated in this paper, are pooled for every 60 seconds. Flow rate is computed by counting the number of vehicles that activated the upstream detector during every 60 seconds and transformed into hourly unit. The speed(space-mean speed) is the harmonic mean of the vehicles' speeds that are computed as in (3). The occupancy is the percentage of the time(60seconds) that the upstream detector is activated. The density is computed as

$$k = (\% \text{ occupancy})/(\bar{L} + d) \quad (5)$$

where, \bar{L} is the average length of vehicles and assumed to be $5m$ (the actual length of some midsize vehicles are considered here, e.g. Ford Taurus: $5.02m$, Honda Accord: $4.81m$).

The traffic data were collected during AM 0:00 ~ PM 12:00 on December 7, 2001. For all lanes at Station 3 and 8, Lane 0 at Station 5, detectors were not functioning during some time of the day and we do not include these measurement sites in further analysis. For the other measurement sites, the validity of individual vehicle's data are checked according to the following criteria.

- on-time should be always earlier than off-time: $t_n^{11} > t_n^{12}$ and $t_n^{21} > t_n^{22}$
- the upstream detector's on/off time should be earlier than the downstream detector's on/off time for the same vehicle: $t_n^{11} > t_n^{21}$ and $t_n^{12} > t_n^{22}$
- for vehicles n and $n - 1$ that satisfy $t_n^{11} > t_{n-1}^{11}$, following inequalities should also hold: $t_n^{12} > t_{n-1}^{12}$, $t_n^{21} > t_{n-1}^{21}$, and $t_n^{22} > t_{n-1}^{22}$
- the speeds should not be too high: $v_n^{on} < 60m/s$ and $v_n^{off} < 60m/s$, where v_n^{on} is computed by (3) and v_n^{off} is computed by $(D+d)/(t_n^{22} - t_n^{12})$.
- the difference of the speeds computed using on/off times should not be too large: $|v_n^{on} - v_n^{off}| < 10m/s$
- the time gap should be positive: $h_n > 0$

A vehicle's on/off time data that violates the above criteria is taken as an error. And if a vehicle's data turns out to be an error its follower's data is also dropped from the analysis, because the following vehicle's computed time gap could also be wrong. After screening all the data using the above criteria, the error rate(the rate of erroneous data to the total number of raw data) are computed for each measurement site. Most of the measurement sites has error rate less than 1.0%, while some of them showed very high error rate. The measurement sites that have error rate higher than 5% are excluded from further analysis. They include Lane 2 (8.72 %) and Lane 3 (45.94 %) at Station 4, Lane 1 (11.29 %) and Lane 2 (99.66 %) at

Station 6, Lane 9(18.84%) at Station 7. In addition, Lane 0 and Lane 6 at Station 7 are also excluded. Because, in the flow-density plots drawn from these data, the former has no measurement points with density over 9 veh/km and the latter has many measurement points with low flow rate(under 1000vph) corresponding to low density(under 30veh/km). Finally, a total of 51 measurement sites are used for the data analysis.

4. ANALYSIS

To overview how traffic on the freeway section has changed during the day, we draw speed diagrams for Lane 1 and Lane 6 at Station 4. The speed is a space-mean speed pooled for 60 seconds. The other eastbound lanes at other stations have much similar patterns as Fig. 5(a) and westbound lanes as Fig. 5(b). For the eastbound lanes, congestion did not happen during morning hours and a significant major congestion began around 14:00 and continued until 20:00. During the congestion the speed dropped to as low as 20~60km/hr. For the westbound, a mild morning congestion occurred during 6:00 ~ 10:00 and then a strong afternoon congestion occurred during 14:00 ~ 20:00. The speeds during the congestion periods were 60~80km/hr and 10~50km/hr, respectively. The free flow speeds varied between 120km/hr(for left lanes) and 100 km/hr(for shoulder lanes).

In this paper, we limit our time gap study to the congested flow. Because in light traffic(free flow), the time gap is much dependent on flow rate rather than drivers' behavior. Accordingly, in light traffic, the time gap distribution and driver's behavior cannot be directly related. Traffic data during 14:00 ~ 20:00 for the eastbound traffic, during 6:00 ~ 10:00 and 14:00 ~ 20:00 for the westbound traffic are therefore used to get the time gap values.

To investigate how time gap varies across location, the mean time gaps at all the measurement sites are shown in Fig. 6 (a). The mean time gap is obtained by taking the arithmetic mean value of the vehicles' time gaps. The mean time gap varies between 1.7sec(Station 4 Lane 1) and 2.94 sec(Station 2 Lane 4). Both eastbound and westbound traffic show similar patterns. The first-left lanes(Lane 0 and 5) have relatively larger time gap values. We contemplate two reasons for the large time gap values in HOV: 1) The traffic volume in HOV lanes is relatively less than the other lanes 2) The concrete barrier that is close to the HOV lane may force the drivers to take larger time gaps for psychological comfort. The second-left lanes(Lane 1 and 6) have relatively smaller time gap values, which implies that the aggressive drivers prefer the second-left lane. We also notice that time gaps in westbound traffic have relatively larger values than those of the eastbound traffic. This may be explained by the recurrent congestion existing far downstream to the Bay Bridge. It may not be desirable for the westbound drivers to drive close to the leader because they

know that the downstream freeway is already congested. On the contrary, for the eastbound traffic, the congestion usually ends somewhere downstream of Powell St. In this situation, drivers seem to prefer smaller time gap to travel fast. The similar phenomenon is also found on the shoulder lanes at Stations 2, 6, 7. The time gap at these sites have distinctively larger values. Referring to Fig. 4, we can notice that these sites are just downstream of an exit of the freeway. When some vehicles exit the freeway, the following vehicles have more gaps but they do not reduce the gap because they know that the downstream is already congested. Note that the shoulder lanes at Stations 4, 5 have smaller time gaps, the extra time gap produced at Station 2 is reduced when new vehicles merge into the freeway. In conclusion, it turns out that drivers take different time gaps at different freeway locations, and when congestion at downstream is expected, the drivers tend to prefer larger time gaps. The standard deviation of time gap is shown in Fig. 6(b). Except Station 5, the pattern of standard deviation is much similar to that of mean time gap: where the mean time gap is larger, the standard deviation is also larger. However, why Station 5 has the largest standard deviation is not clear here.

For all the westbound traffic, the time gap distributions of the vehicles at the speeds $10m/sec$, $20m/sec$ and $30m/sec$ are plotted in Fig. 7. The vertical axis represents the normalized sample number: the number of samples with a certain time gap value divided by the total number of the samples for a given speed. It is shown that the distribution of time gap is asymmetric with a long tail to the right. The mode values differ at different speeds. The lower value is obtained for speed $20m/sec$. When speed is $30m/sec$, more samples are found for higher time gap. This diagram implies that time gap is stochastic and its probabilistic distribution differs for different travel speeds. In the following, we investigate in detail about the variations of time gap with respect to speed and reveal its relationship to the fundamental diagram.

For Station 4 Lane 6, the mean time gap is plotted with respect to travel speed (upper left diagram in Fig. 8). The mean time gap is taken as the arithmetic mean of the time gap values of the vehicles that passed that lane at a given speed. The time gap is larger at speeds under $10m/sec$ and over $30m/sec$. In the middle range of speed, the mean time gap lies between $1.5sec$ and $2sec$. The smallest time gap values are obtained in the speed range of $20m/sec$ to $25m/sec$ and the time gap continuously decreased until the speed reaches $20m/sec$. As discussed in the previous section, the decrease of time gap with respect to speed produces a convex flow-density curve. On the contrary, the time gap increases as speed increases at the speed over $25m/sec$, which produces a concave flow-density curve. The fundamental diagram which can be derived from this time gap-speed diagram would comprise a convex curve and a concave curve. For comparison, we overlapped the flow-density scatter points diagram with the flow-density curve derived from the mean time gap-

speed diagram (upper right diagram in Fig. 8). The flow-density scatter points are drawn by the 60-seconds pooled flow, density data for the whole measurement time, 24 hours. The flow-density curve is obtained by transforming time gap(h)-speed(v) pairs in the time gap-speed diagram into density($\frac{1}{vh+L}$) and flow ($\frac{v}{vh+L}$) pairs. The scatter plot here clearly shows the reversed-lambda shape and the flow-density curve is almost centered in the scatter, showing a convex-concave shape. The flow-density curve in the congested regime is a convex curve, which corresponds to the right leg of Koshi's reversed-lambda. This fact indicates that Koshi's reversed-lambda type fundamental diagram is produced when the drivers reduce the time gap as the speed increases in a congested traffic.

The other pattern is obtained for Station 7 Lane 4. In the same manner, the mean time gap-speed curve and flow-density scatter plot are drawn in Fig. 8 (b). The flow-density scatter plot here clearly shows the inverted-V pattern. The time gap value at the speed range of $7 \sim 25m/sec$ is $2sec$ except for the sharp drop at speed $19m/sec$. This constant time gap value corresponds to the right straight leg of the inverted-V. Above interpretation on Fig. 8 reveals that various features of the fundamental diagram is a result of drivers' time gap choice with respect to travel speed.

To identify the differences of time gap-speed diagram across stations and lanes, we aggregated the traffic data by stations and lanes. By aggregating, we could get smoother time gap-speed curves and could identify three types of time gap-speed relations and their corresponding fundamental diagrams: Greenberg type, reversed-lambda type, inverted-V type. Fig. 9 (a) depicts the time gap-speed, fundamental diagram for Station 1, aggregated for all the lanes. The flow-density scatter plot in Fig. 9(a) is drawn by overlapping the flow-density scatter plots of every 10 lanes at Station 1. The time gap-speed diagram is a smooth U-shape that comprise a decreasing curve and an increasing curve, the minimum value located at $15m/sec$. The decreasing curve indicates that people tend to take larger time gap when the vehicles slow down close to stop. This is reasonable considering that at a very low speed, the vehicle in front can stop immediately and a late response of the following vehicle can lead to a collision. On the contrary, when the speed is high, the spacing between the two vehicles is large and a late response of the following vehicle to the deceleration of the vehicle in front does not necessarily lead to a collision. Therefore drivers take a larger time gap at a very low speed. The increasing curve at the speed range over $15m/sec$ can be explained by: 1) if a passenger car that leads a lower performance vehicle such as a truck accelerates, the time gap increases as they speed up 2) for a traffic on transition from congestion to free flow state, the time gap increases when a driver with lower desired speed follows a driver with higher desired speed. The flow-density curve drawn from this time gap-speed diagram is a convex-concave curve. The existence of these two portions(concave and convex) implies that two reciprocal wave propagation characteristics co-exist in a congested traffic.

For the convex portion, corresponding to the speed under $15m/sec$, the acceleration wave in downstream is faster than the acceleration wave in upstream and the waves coalesce to form an acceleration shock. On the contrary, if the traffic is decelerating, a rarefaction wave is created. For the concave portion, wave propagation is in a reciprocal way: deceleration shock and acceleration rarefaction. This finding implies that the concavity assumption that most of the fundamental diagrams employ may not be applicable for a very congested traffic and the convex portion should also be considered. The flow-density curve located at the density under $50veh/km$, much like the Greenberg's single-regime fundamental diagram as the flow-density scatter plot also looks similar. The critical density, that gives the maximum flow rate, is located around $35 veh/km$.

The reversed-lambda type is found in Station 4 (Fig. 9(b)). The time gap-speed diagram is also a smooth U-shape, but the minimum value is located at $20 m/sec$, which is higher than at Station 1. In this case, convexity dominates in the flow-density curve and the fundamental diagram resembles Koshi's reversed-lambda. The critical density is about $20 veh/km$ and there exists a slight increase in flow rate from the right side. This slight increase in flow rate is thought to contribute partly to the head of the reversed-lambda. Station 2 and 7 also show similar patterns as in (Fig. 9(b)) and they also have a slight increase in flow rate in the vicinity of critical density.

The inverted-V type is found in Stations 5 and 6 (Fig. 9(c)). The mean time gap is almost constant for the speed range of $10 m/sec$ to $23 m/sec$ producing a U-shape with a flat bottom. The inverted V-shape is clearly identified in the flow-density curve for the density under $50veh/km$: the flat bottom of the U-shape corresponds to the right straight leg of inverted V. As in Station 1, a convex curve is drawn for the density over $50veh/km$. The critical density is $20 veh/km$ as is in the reverse lambda type but significantly less than that of the Greenberg type. These three types of time gap-speed diagrams are also clearly identified when we aggregated the data by lanes. Lanes 2, 3, 4, and 9 produced Greenberg type fundamental diagrams and corresponding time gap-speed diagrams (Fig. 10(a)), while Lanes 5 and 6 produced Koshi's reversed-lambda type diagram (Fig. 10(b)). Lanes 0,1,7, and 8 produced inverted-V type diagrams (Fig. 10(c)).

In conclusion, the U-shape seems to be a common feature of the time gap-speed diagram. The critical factor that determines the type of the fundamental diagram is the shape of the bottom of the U, which varies according to the time gap values at the speed range $20m/sec \sim 25m/sec$. From the time gap-speed diagrams in Fig. 9 and Fig. 10, we can notice that the time gap values at the speed range $20m/sec \sim 25m/sec$ are under 2 seconds for reversed-lambda, 2 seconds for the inverted-V, and over 2 seconds for the Greenberg type fundamental diagram. The slope of the bot-

tom of the U is slanted downward, flat, slanted upward corresponding to those time gap values and are related to the three types of fundamental diagrams, respectively. This conclusion is also in accordance with the findings that on the left side lanes, where more aggressive or higher performance vehicles tend to travel, the reverse lambda or inverted-V type are usually found and the Greenberg type is common in the shoulder lanes. .

5. SUMMARY AND CONCLUSIONS

Time gap is an important parameter that is closely related to the driver's behavior and also connected to the features of the fundamental diagram. Despite its importance and capability of describing traffic flow, the literature on time gap is quite few. Recently, significant attention is paid to the time gap by researchers and several interesting studies are presented. Banks [23] has discovered that the mean time gap is constant for most speed ranges from San Diego freeway data. Banks' finding is consistent with the mean time gap-speed diagram produced in this paper that corresponds to inverted-V type fundamental diagrams. In this paper the mean time-gap is obtained from event loop detector data of the I-80 freeway. The distribution of mean time gap and its relationship with speed is investigated. The time gap and speed relationship is transformed into the flow-density relationship and compared with the flow-density scatter plot. Three different types of time gap-speed relationships are identified, which correspond to the Greenberg, reversed-lambda, and inverted-V types of fundamental diagrams. It is found that these different features of the fundamental diagrams resulted from the fact that drivers apply different time gaps for different speeds in three different patterns. It is also demonstrated that time gap study could be an effective approach in traffic stream model studies. Time gap study reveal distinctive features of the flow-density relationship, which could not be obtained by usual visual inspection of the scattered flow-density plot.

Some interesting features of drivers' behavior is also discussed in relation with traffic condition and roadway geometry. When congestion is predicted at the downstream, drivers tend to prefer larger time gaps and the extra time gap obtained by the exit of a leading vehicle is not filled out immediately by the following vehicle. The mean time gap is smallest for the second left lane and larger for the HOV lane and shoulder lane. These findings confirms that drivers have different time gap preferences for different traffic conditions and locations.

This paper explains the variations of time gap with respect to speed. However, we believe that there could be other traffic flow parameters as well as speed, which are also closely related to drivers' determination of time gap. To identify them and reveal their relationships in a systematic way is left for future studies.

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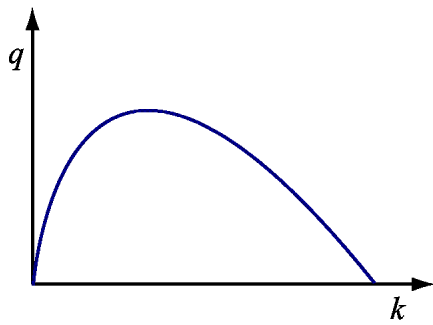
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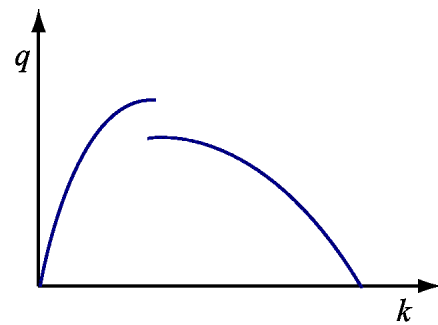
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LIST OF FIGURES

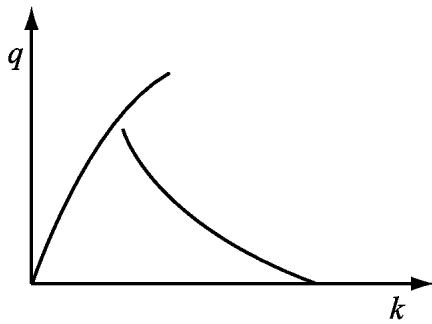
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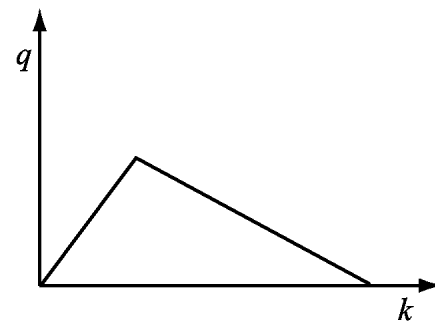
(a) Greenberg's single regime model



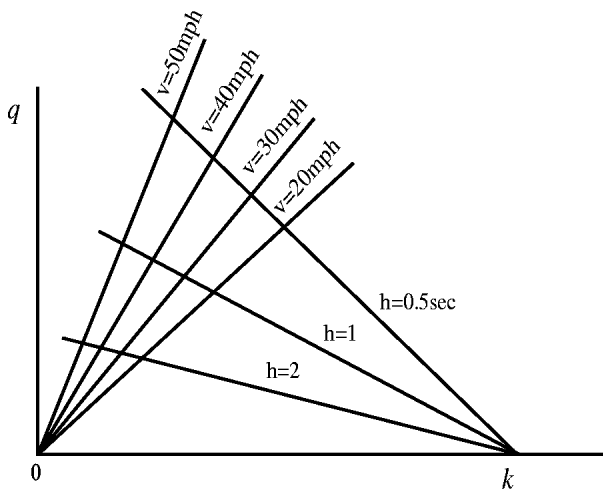
(b) Edie's dual regime model



(c) Koshi's reverse lambda model

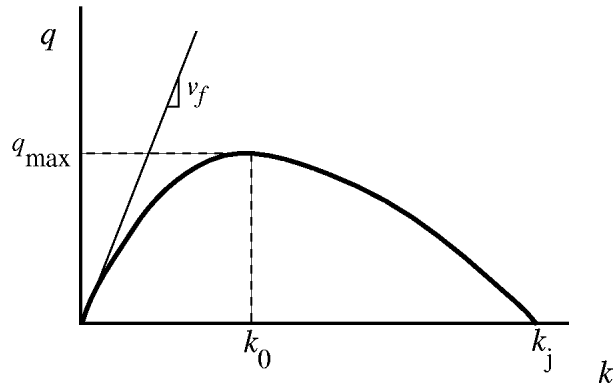


(d) Inverted-V model

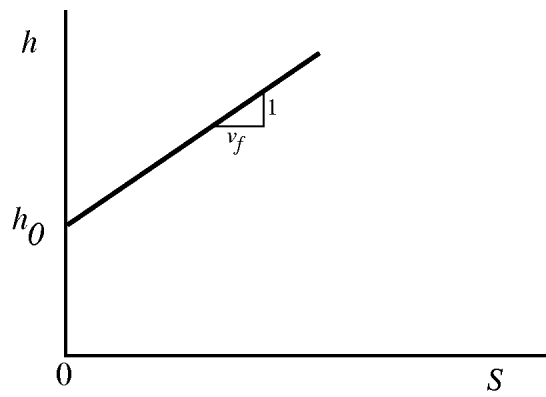


(e) Flow-density relationship for various time gap and speed (Forbes, 1963)

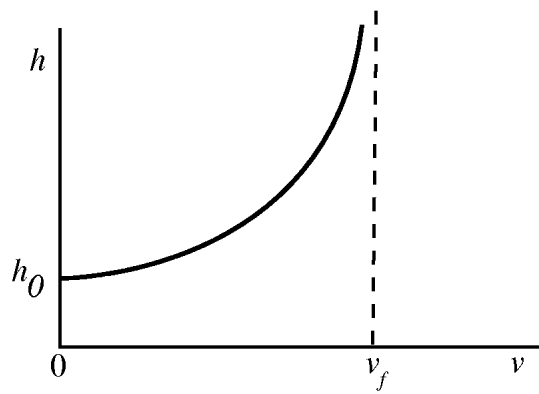
Figure 1: Fundamental diagrams (reproduced)



(a) Fundamental diagram

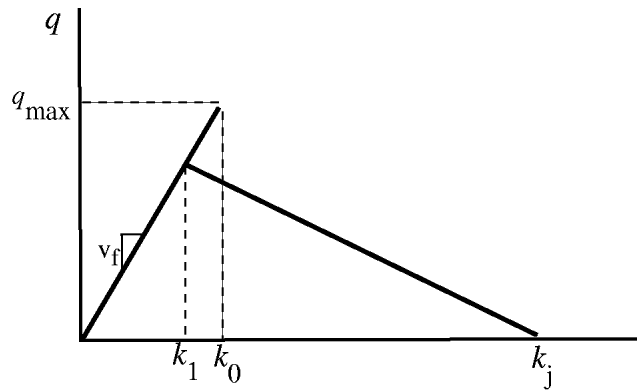


(b) h - S relationship

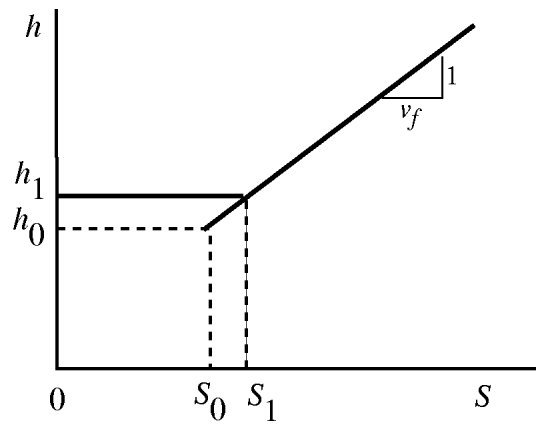


(c) h - v relationship

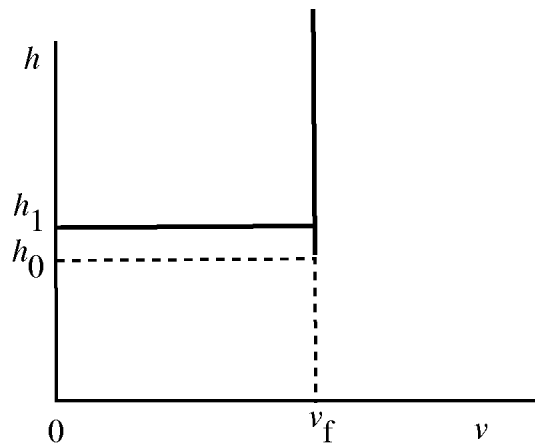
Figure 2: Greenberg type fundamental diagram



(a) Fundamental diagram

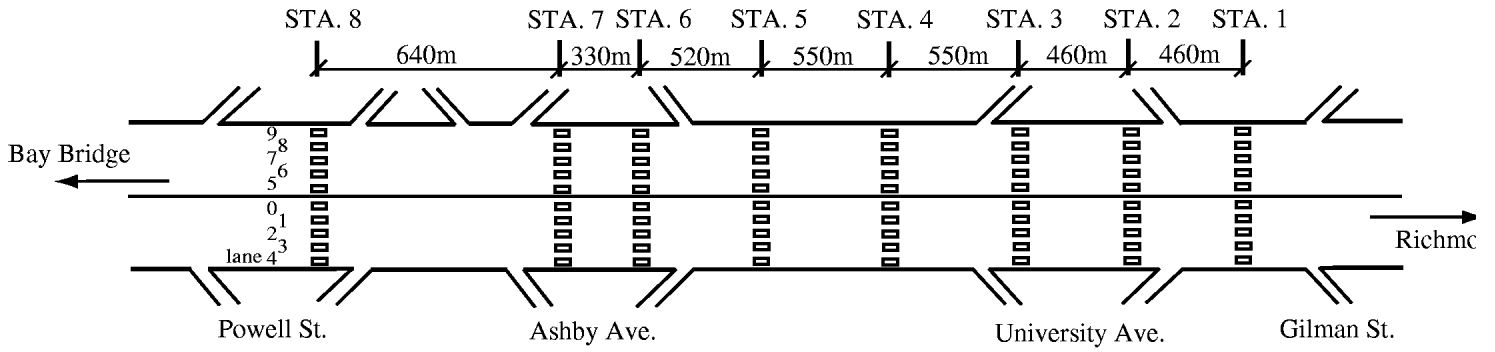


(b) h - S relationship

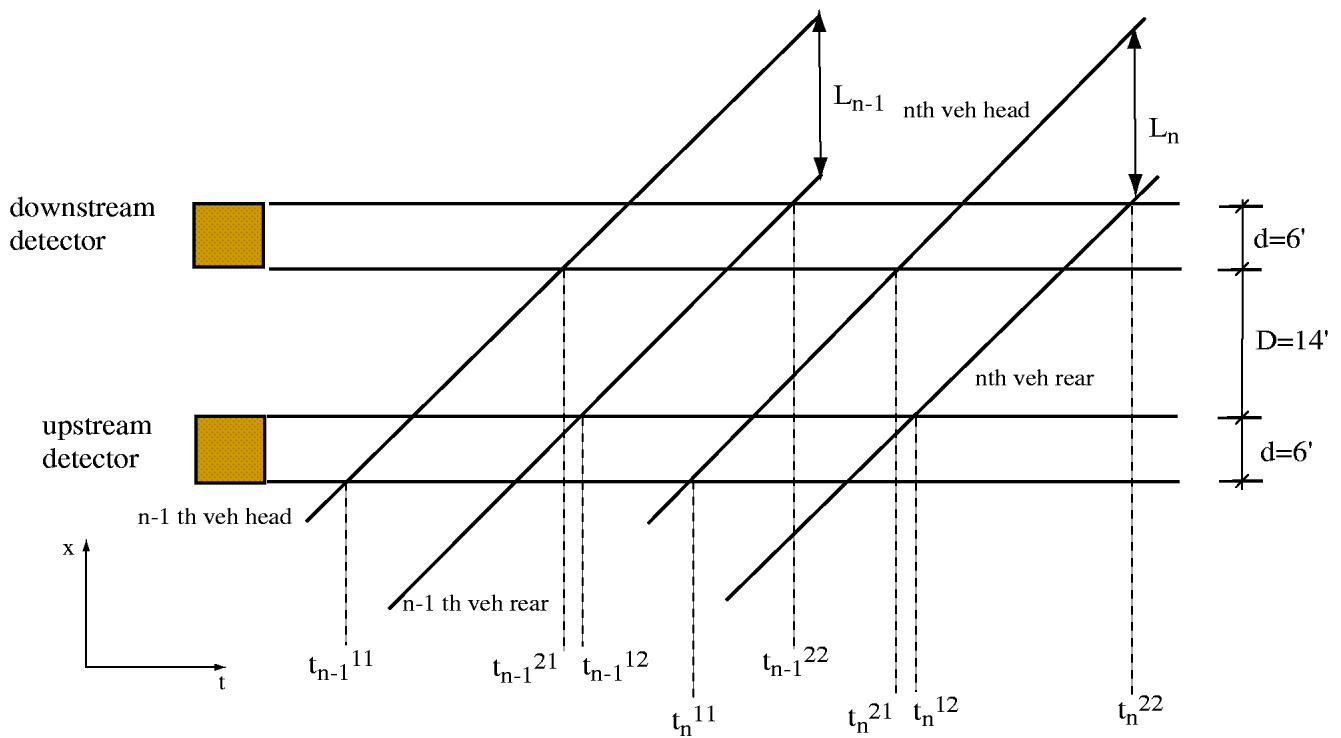


(c) h - v relationship

Figure 3: Reversed-lambda type fundamental diagram

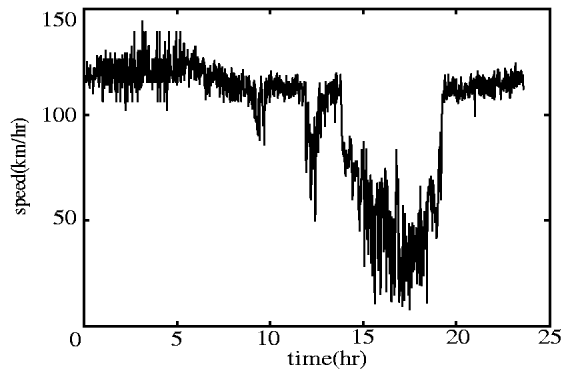


(a) Detectors location

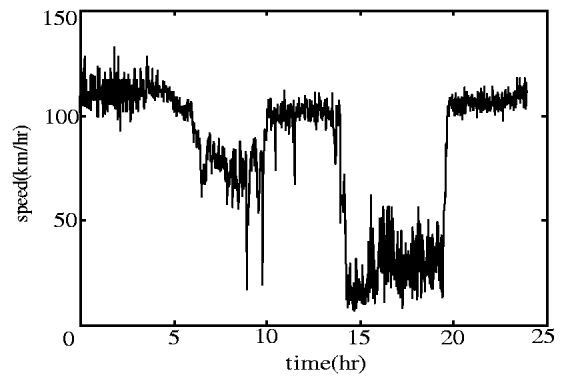


(b) On/Off time of a detector

Figure 4: Study site and detector configuration

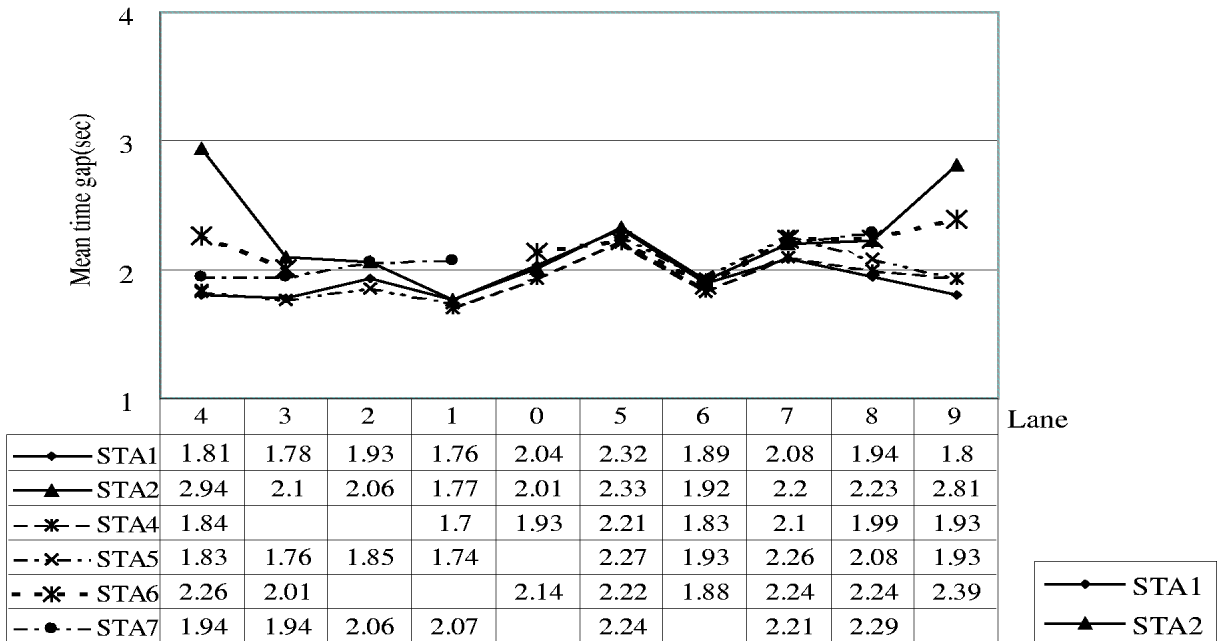


(a) Lane 1 at Station 4

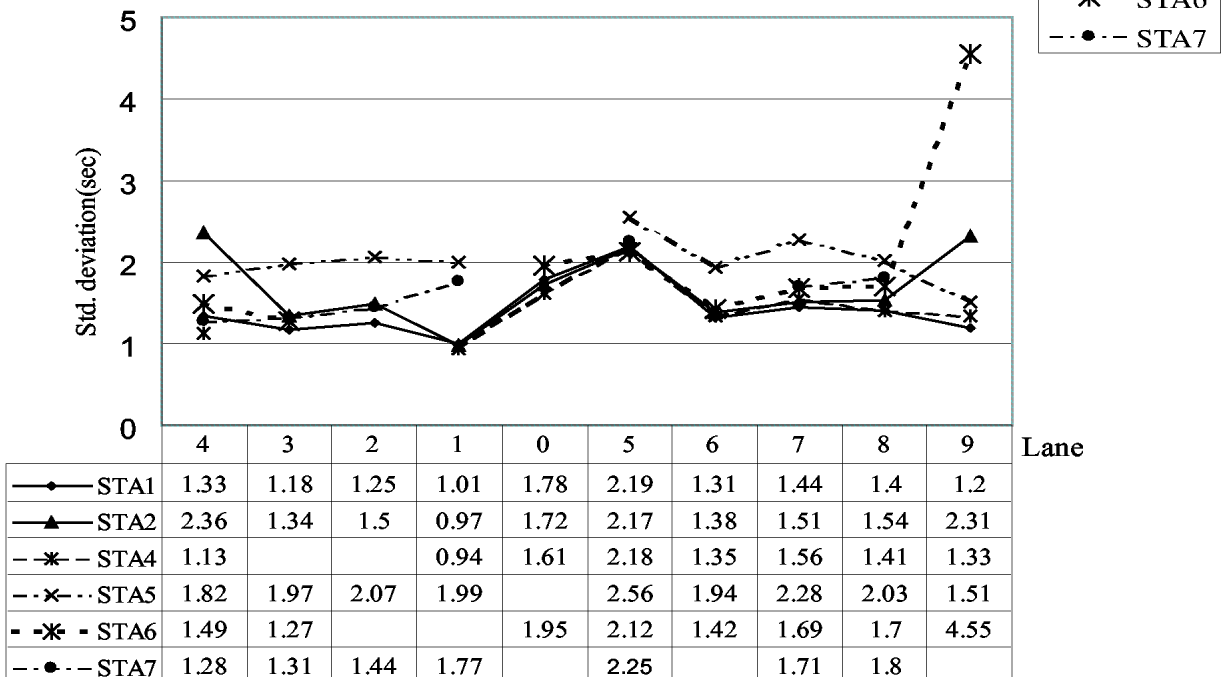


(b) Lane 6 at Station 4

Figure 5: Speed transitions at Station 4 for a day



(a) Mean time gap



(b) Standard deviation of time gap

Figure 6: Mean and standard deviation of time gap

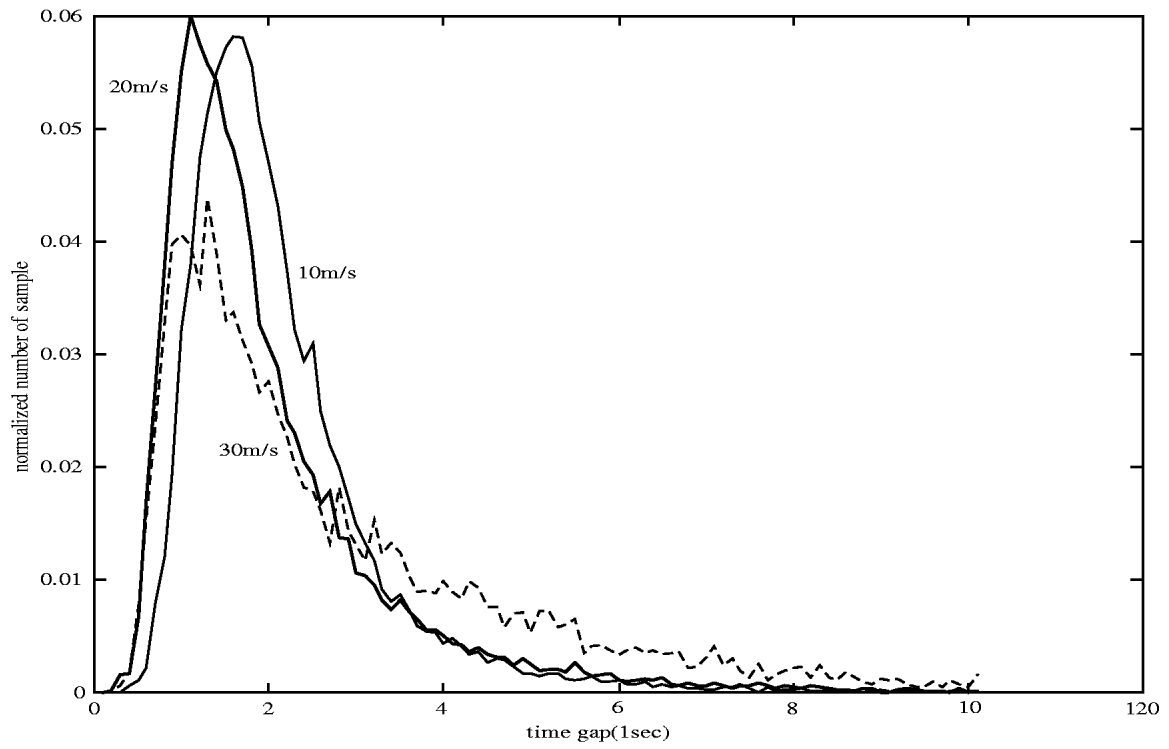
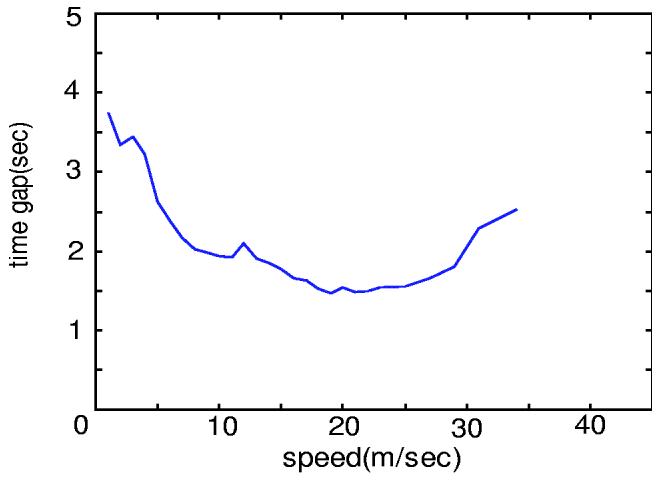
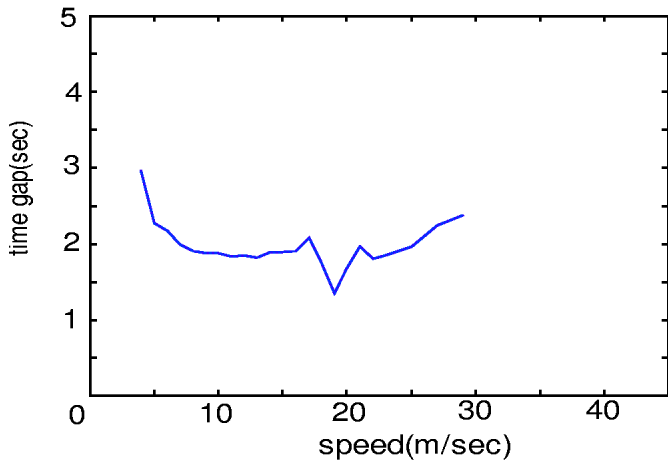
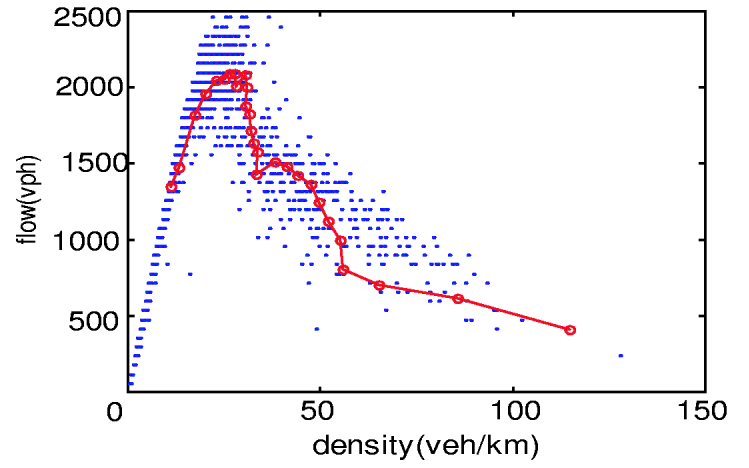


Figure 7: Normalized distribution of time gap(Westbound total traffic)



(a) Station 4 lane 6



(b) Station 7 lane 4

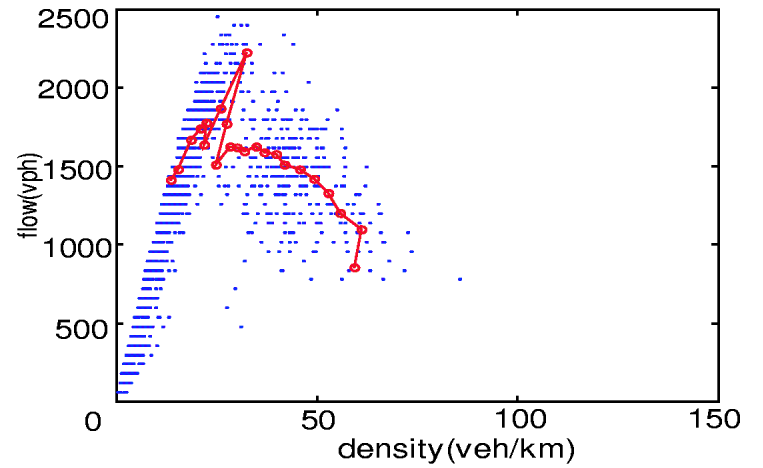
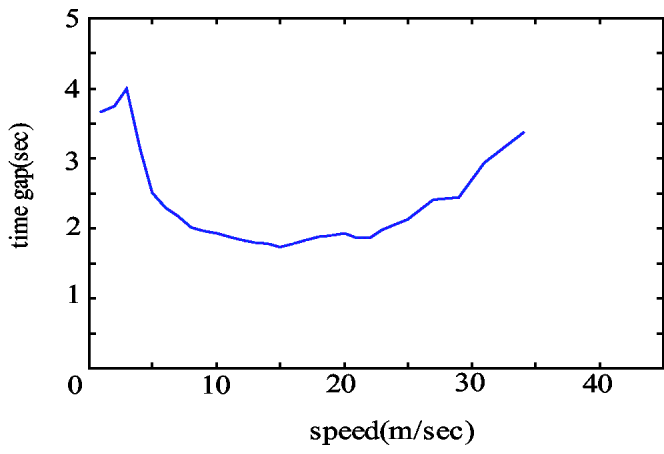
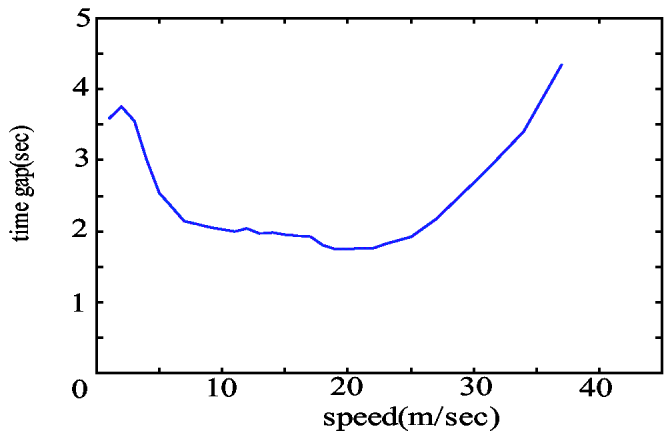
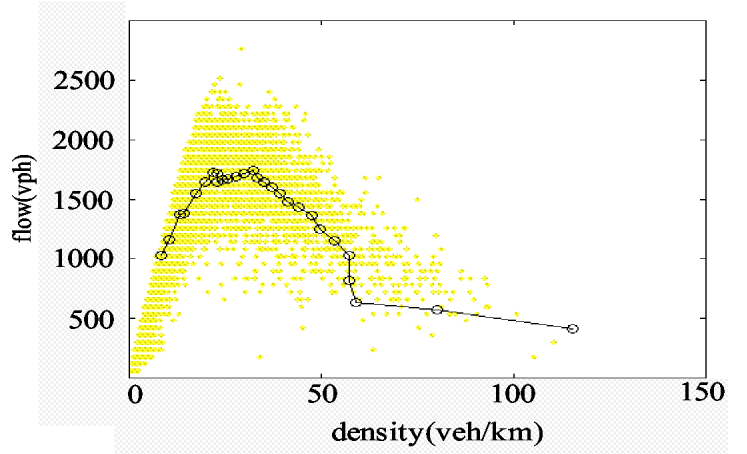


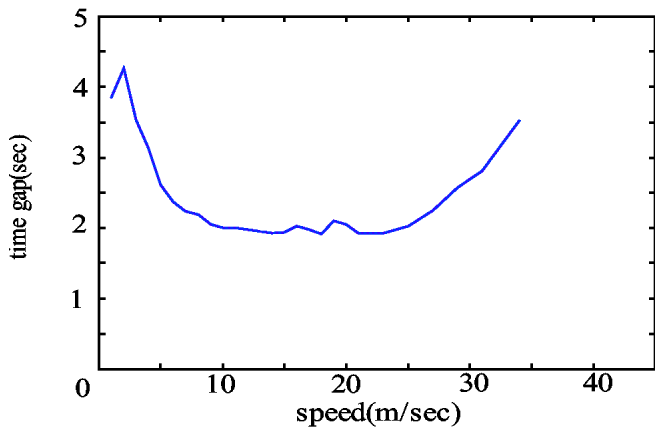
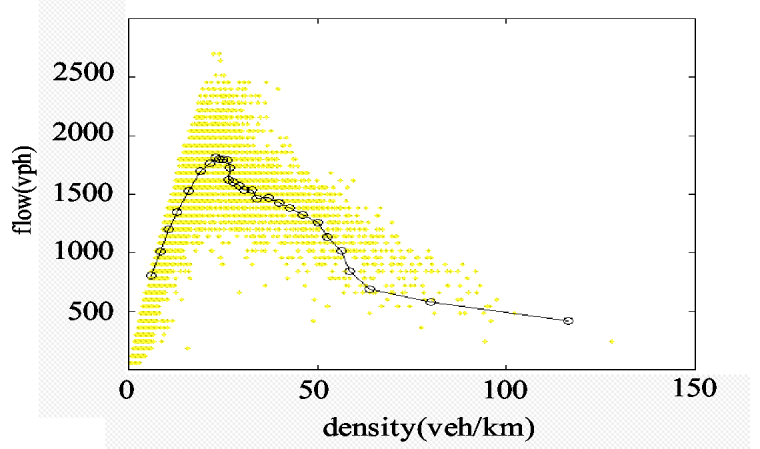
Figure 8: Time gap and fundamental diagram for selected sites



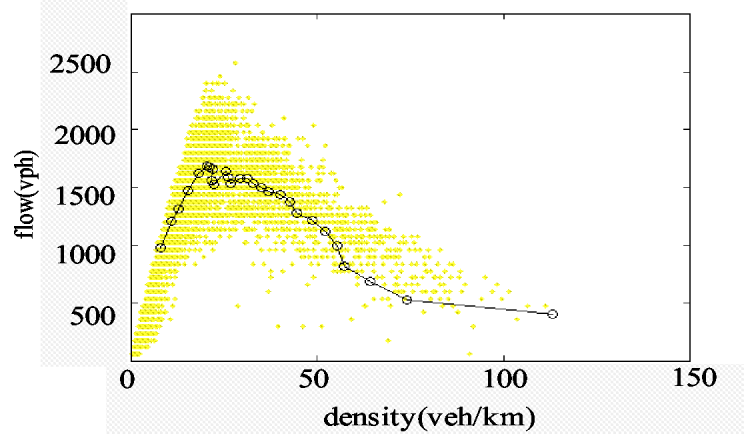
(a) Station 1

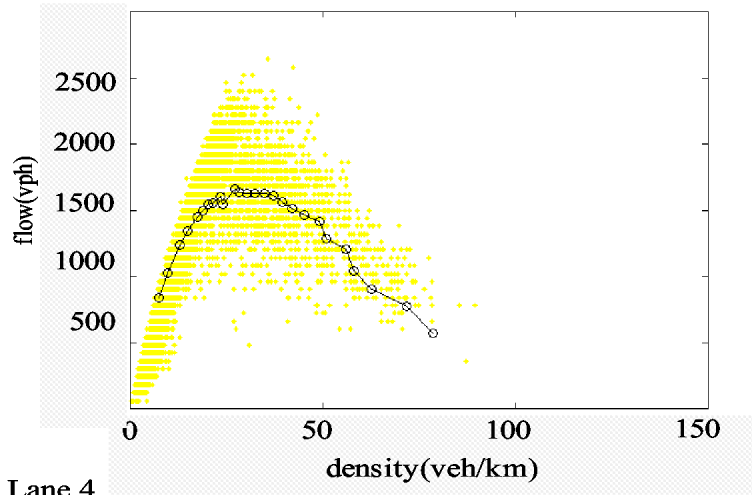
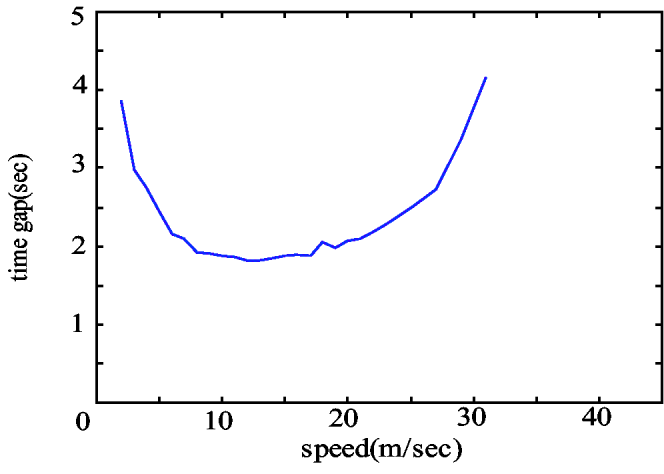


(b) Station 4

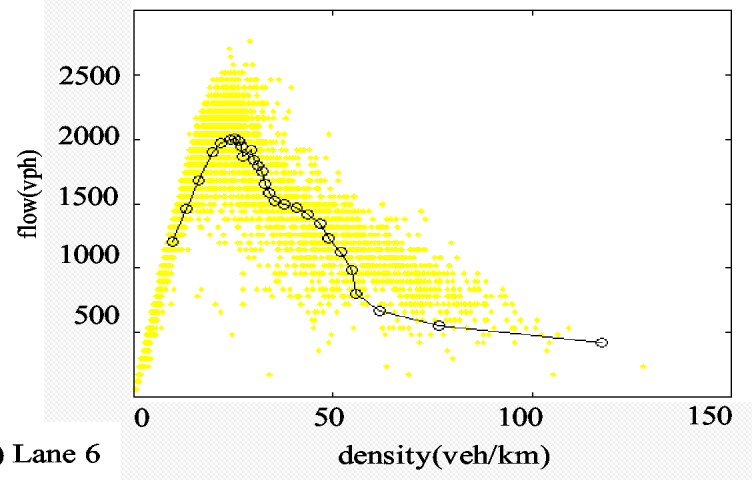
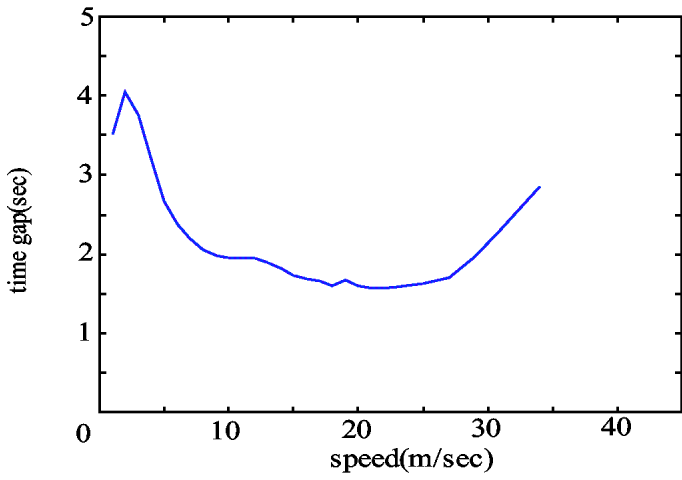


(c) Station 5

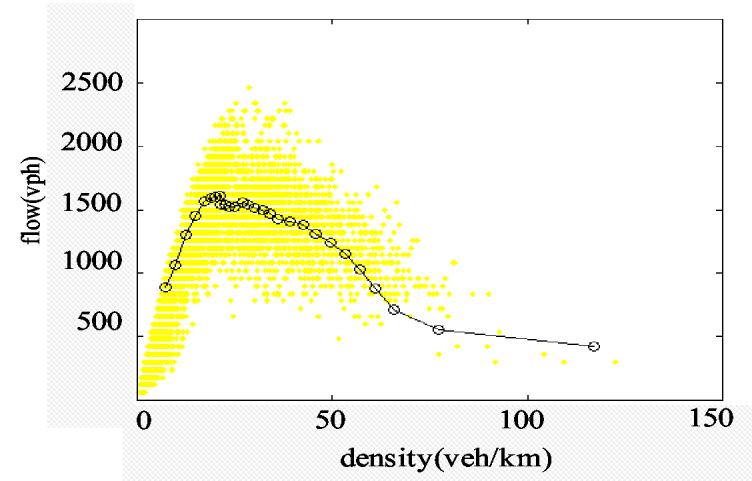
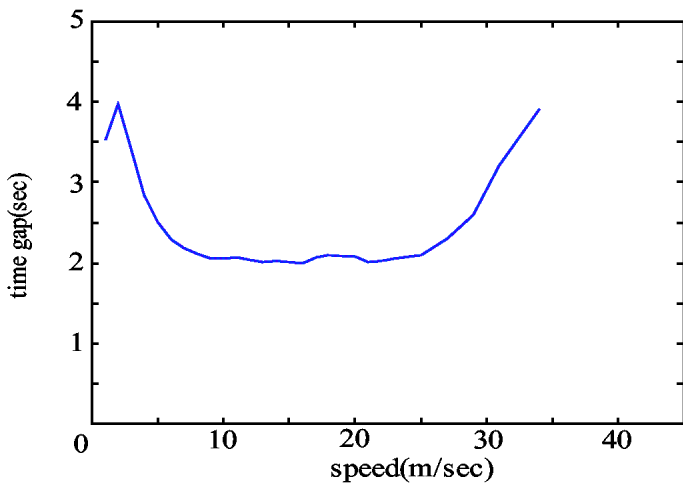




(a) Lane 4



(b) Lane 6



(c) Lane 8