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Exploring the Pattern of Platoon Dispersion Caused by Traffic Signal

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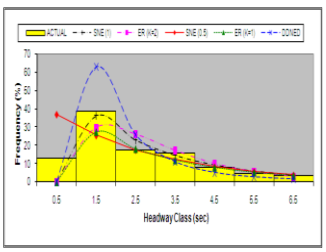
Graphical abstract



Abstract

Platoon dispersion is an essential phenomenon to be studied for determining the traffic arrivals at downstream intersections to access the need for signal coordination and to optimize the signal timing plans in coordinated signal systems. However, platoon dispersion is difficult to determine compared with other traffic flow parameters such as traffic volume, saturation flow, and speed. This paper explores the pattern of platoon dispersion caused by traffic signal, in which the focus are given on vehicle headway, intra-platoon headway and inter-platoon headway. Field investigation was made by means of videotapes which record traffic flows at selected location at Senai, Johor. After processing the data, vehicle headway at several consecutive points downstream of traffic signal were obtained and used for the platoon dispersion analysis. The dispersion patterns obtained from the observation during peak and off-peak periods were fitted with the theoretical distribution models. It was observed that vehicle headways follow the Erlang and Shifted Negative Exponential Distribution, intra-platoon headways have Normal Distribution and inter-platoon headways do not fit the tested distribution model.

Keywords: Platoon dispersion, traffic signal, vehicle platoon, headway, theoretical distribution model

1.0 INTRODUCTION

A platoon of road traffic can be defined as a set of vehicles or pedestrians travelling together as a group, either voluntarily or involuntarily, because of signal control, road geometry or other factors [1]. In the Highway Capacity Manual (HCM), a vehicle platoon is defined as a group of vehicles travelling together [2]. It can also be defined temporally and spatially by selecting major parameters of the vehicle platoon characteristics such as platoon headway, inter-platoon headway, platoon size and platoon speed as fundamental variables. With respect to these parameters, platoon behaviours and distribution patterns could be identified.

Platoon dispersion is the common phenomenon on urban arterial road in which vehicular traffic released from an upstream signal. According to Denny, traffic departing a traffic signal initially moves as a tight platoon with short vehicle headways [3]. However, platoons do not remain in a compact bunch but gradually spread out as they move downstream [4-6]. This situation occurs due to differences in vehicle speeds, vehicle interactions (lane changing and merging), and other interferences (parking, pedestrians, and other frictional effects) [3]. While other study state most of the dispersion is caused by interaction among vehicles entering and exiting the roadway [6].

Field observations of platoon dispersion have been noted by researchers as early as in the 1950s [5]. It is because the amount by which a platoon spreads out or disperses as it travels downstream at any point along a road has a major implication in traffic flow analysis, modelling, and also traffic engineering design. According to Smelt, the study of platoon dispersion is important in the design of traffic engineering facilities, such as (i) intersection design, (ii) traffic signal linking systems, (iii) the location and design of access facilities for traffic to enter arterial roads from uncontrolled points, and (iv) in the traffic modelling field such as in simulation modeling in order to increase accuracy in traffic arrival distribution [7]. As a consequence, the traffic management of those locations can be improved and at the same time it will provide benefit for road users who always want to travel fast and safe.

The study of platoon dispersion is quite related to driver behavior and car following is one key element of driver behaviour. Driver's car following behaviour is the process of following drivers attempt to adjust to the behaviour of the leading vehicle [8]. Normally, the driver in the car following stage is assumed to move forward without the intention of changing lane or overtaking. Michael *et al*. had stated that time gap and headway are two measures which are widely used to assess such driver behaviours [9]. In 1983, Evans and Wasieleweki showed that headway increased with driver age and they also reported that males are choosing shorter headways than females [10]. However, vehicle headways were rarely less than 0.5s or over 10s at different traffic volumes [11].

The arrival pattern at the downstream signal is affected by the platoon dispersion [12]. The platoon dispersion model used in the Highway Capacity Manual assumes that the effects of platooning from an upstream signal will disperse at about 152.4 to 182.9m downstream from the signal [13]. Skabardonis and Geroliminis suggest that the platoon dispersion analysis is engaged for distance longer than 152.4m which platoon ratio is smaller than 0.9 [12]. While, according to Transportation Research Institute, platoon dispersion models shows that greater dispersion occurs over a distance of 402m [14].

Nowadays, management of transportation networks especially in major cities is impossible without traffic signals and it is widely accepted that many practical problems remain to be solved. In Malaysia, it is realized that there is a lack of information on the platoon dispersion characteristics. Thus, this study aims to explore the pattern of platoon dispersion caused by traffic signal, in which the focus are given on vehicle headway, intra-platoon headway and inter-platoon headway.

2.0 MATERIALS AND METHOD

The single carriageway Federal Highway FT001 Senai, Kulai in the Johor State of Malaysia has been selected for the study after careful considerations. The study was carried out at downstream of signalised three-arm intersection under dry weather and daylight conditions located at Saleng as shown in Fig. 1. Within the purview of study objective and boundary, three video cameras (each attached with a character generator) were used to record the movement of each vehicle from stop line up to 402m as illustrated in Fig. 2. A video camera was positioned on the overhead pedestrian footbridge adjacent to the observed site and the other two were located at edge of the road at distance 263 and 402m respectively. Note that in this study, traffic data were collected during weekday's periods during morning peak and off-peak periods and the intersection operates solely as a pre-timed signalised intersection.

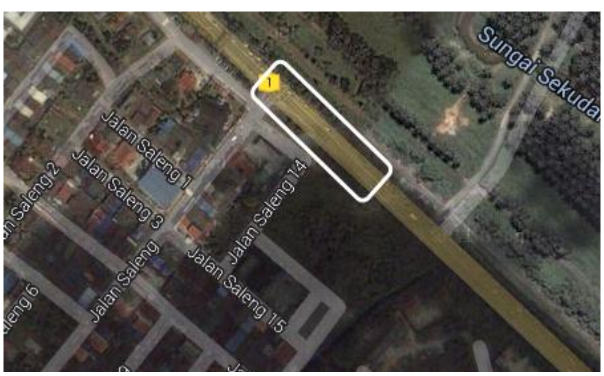


Figure 1 Selected study site at Saleng, Senai

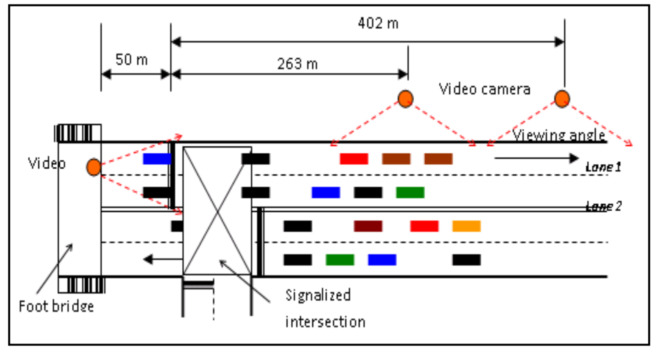


Figure 2 Layout of study site

In general, Senai Highway has the average traffic volume of 1125 vehicle per period per lane (vphpl) and the spot speed observed using radar gun at 0, 263 and 402m were 35, 47 and 56 km/h, respectively. Based on the following equation [15], there were 1003 vehicles that satisfied the sample sizes of the study.

$$N \geq \frac{1.96^2 \times s^2}{e^2} \qquad (1)$$

where,

1.96^2 = used only for 95% confidence
s = standard deviation
e = tolerance

In this study, traffic data were analyzed using data per carriageway lane in order to obtain critical headway for determining the platoon size and the headway distribution. In order to choose a proper value of the critical headway, the relationship between the proportion of platooned vehicles and the dispersion of the platoon size were examined.

Then, the histograms were produced for vehicle headway, intra-platoon headway and inter-platoon headway on a per lane basis at distance 0, 263 and 402m during peak and off-peak periods. These give a good visual appreciation of the extent by which platoon disperse. Each of observed vehicle headway histograms was fitted to theoretical distribution models including Shifted Negative Exponential (SNED), Erlang and Double Displaced Negative Exponential Distribution (DDNED). While for intra-platoon headway, the histogram was fitted to Normal Distribution, and Lognormal Distribution was selected to fit inter-platoon headway histogram.

The functions of mathematical distribution model used in this study are shown below:

Shifted Negative Exponential Distribution

$f(t) = 0$, if $t < c$

$$f(t) = \frac{1}{\left(\bar{t} - c\right)} . e^{-\left[(t-c)/\left(\bar{t}-c\right)\right]}, \text{ if } t \geq c \qquad (2)$$

where,

$\bar{t}$ = mean headway = $\frac{3600}{Q}$ (s)
c = minimum headway (s)
Q = traffic flow (veh/h)

Erlang Distribution

$$f(t) = 0 \text{, if } t < 0$$

$$f(t) = \frac{b^k}{(k-1)!}.(t-c)^{k-1}.e^{-b(t-c)} \quad k = 1, 2, 3, \ldots \qquad (3)$$

where,

c = minimum observed headway (s)

k = the shape parameter

$\bar{t}$ = mean headway = $\frac{k}{b}$

Double Displaced Negative Exponential Distribution

$$f(t) = 0 \text{, if } t < d$$

$$f(t) = \phi\lambda_1 e^{-\lambda_1(t-d)} + (1-\phi)\lambda_2 e^{-\lambda_2(t-d)} \text{, if } t \geq d \qquad (4)$$

where,

ϕ = weighting factor, $0.5 \geq \phi > 0$

d = the displacement parameter

λ_1, λ_2 = constants associated with the traffic flow

Normal Distribution

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\left[\frac{(x-\mu)^2}{2\sigma^2}\right]} \qquad (5)$$

where,

x = normally distributed statistic

μ = true mean of the distribution

σ = true standard deviation of the distribution

Lognormal Distribution

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln x-\mu}{\sigma}\right)^2} \qquad (6)$$

where,

μ = log mean

σ = log standard deviation

The intra-platoon headways could also be represented by the Lognormal Distribution [16]. However, it is advisable to choose a model that can simplify the analysis procedure without sacrificing the accuracy. Therefore, Normal Distribution is selected because it is simpler to use than the Lognormal Distribution. Goodness of fit with 0.05 significance level was used to evaluate the data sets. With the hypothesis that:

$H_0 : D_{observed} = D_{theoretical}$

$H_1 : D_{observed} \neq D_{theoretical}$

where D represents distribution, the null hypothesis will be accepted if it satisfies $\chi^2_{cal} < \chi^2_{0.95}$.

3.0 RESULTS AND DISCUSSION

3.1 Vehicle Headway

Fig. 3 shows typical vehicle headway frequency distribution observed during peak period at 402m downstream of traffic signal. This distribution shows a large number of small headways with long tails to the distribution. The same trend is observed to be constant for all vehicle headway distributions. Large numbers of small headways were contributed by the influence of cyclic flows from traffic control facilities. While longer tails of the observed distributions were caused by the absence of vehicles after the queue were released at traffic signal and also caused by the absence of vehicles during the red stage of the signal cycle. Besides, the large headways between vehicles were influenced by buses stopping at bus stop which is approximately 100m upstream of the stop line. The presence of HGV (a vehicle having more than two axles or having more than two wheels on the rear axle) also created larger headways especially when it travels in slow speed and obstruct other vehicles to overtake.

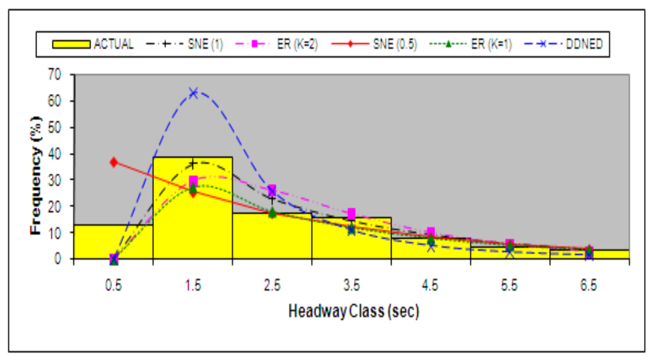


Figure 3 Distribution of vehicle headways at distance 402m in lane 2 during peak period

The statistical analysis results of vehicle headway distributions are summarized in Table 1 and Table 2. During peak period, the test results show that the Erlang Distribution (k=2) is a better fit than others. It was followed by Shifted Negative Exponential Distribution (1.0s). While, the results of the analysis during off-peak period show that Shifted Negative Exponential Distribution (1.0s) and then Erlang Distribution provide a good fit to the observed vehicle headway distributions. These results were not similar as reported by previous studies which there is poor agreement with distributions [17-19]

Table 1 χ^2 – Tests for vehicle headway distributions during peak period

Lane No.	Dist. (m)	Shifted Negative Exponential 0.5	Shifted Negative Exponential 1.0	Erlang k=1	Erlang k=2	DDNE
		Accepted null hypothesis?				
1	0	No	Yes	No	Yes	Yes
	263	No	No	No	Yes	No
	402	No	No	No	Yes	No
2	0	No	Yes	No	Yes	No
	263	No	Yes	Yes	Yes	Yes
	402	Yes	Yes	Yes	Yes	No

Table 2 χ^2 – tests for vehicle headway distributions during off-peak period

Lane No.	Dist. (m)	Shifted Negative Exponential 0.5	Shifted Negative Exponential 1.0	Erlang k=1	Erlang k=2	DDNE
		Accepted null hypothesis?				
1	0	No	Yes	Yes	Yes	No
	263	No	No	No	No	No
	402	Yes	Yes	Yes	No	No
2	0	No	Yes	No	Yes	No
	263	No	Yes	Yes	Yes	No
	402	Yes	Yes	Yes	Yes	No

3.2 Determination of Critical Headway

It is of great importance to select a proper value of the critical headway since a small change in the critical headway will generate tremendous changes in the resultant platoon characteristics [16]. The proper value of critical headway is used to decide whether vehicles included in platoons or not and this value can be determined based on the traffic data collected at selected intersections.

Platoon sizes range from two to any number of consecutive vehicles with headways less than the chosen critical headway. In this study, platoon size was classified based on critical headway values of 1.5, 2.0, 2.5, 3.0 and 3.5s for each lane during peak and off-peak periods at 0m. It is similar with critical headway values used by Jiang et al. [16]. The distribution of platoon size by critical headway gain from data extracted is shown in Fig. 4 and 5. It is obvious that this road dominated by the two-vehicle platoons. The frequency of two-vehicle platoons decreased as the critical headway increased. Besides, it also demonstrates that the frequency of large size platoons increased and the frequency of small size platoons decreased as the critical headway increased. The average headways observed for peak and off-peak periods are 3.55 and 3.58s, respectively.

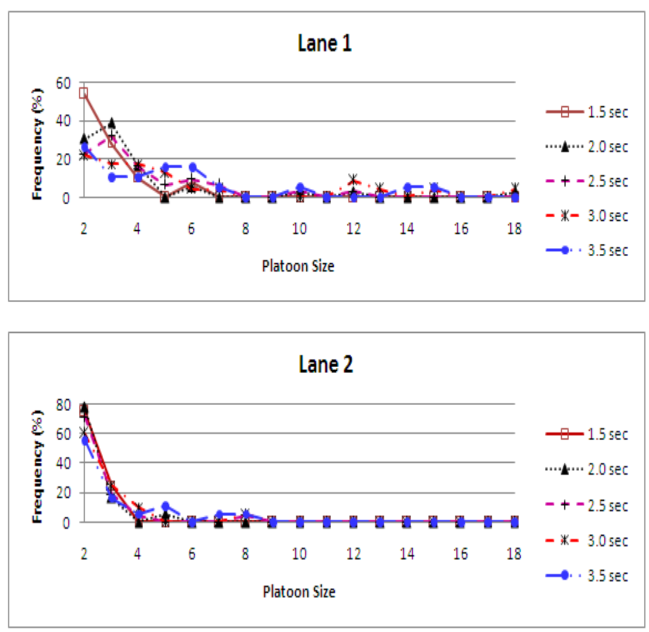


Figure 4 Distributions of platoon size by critical headway during peak period

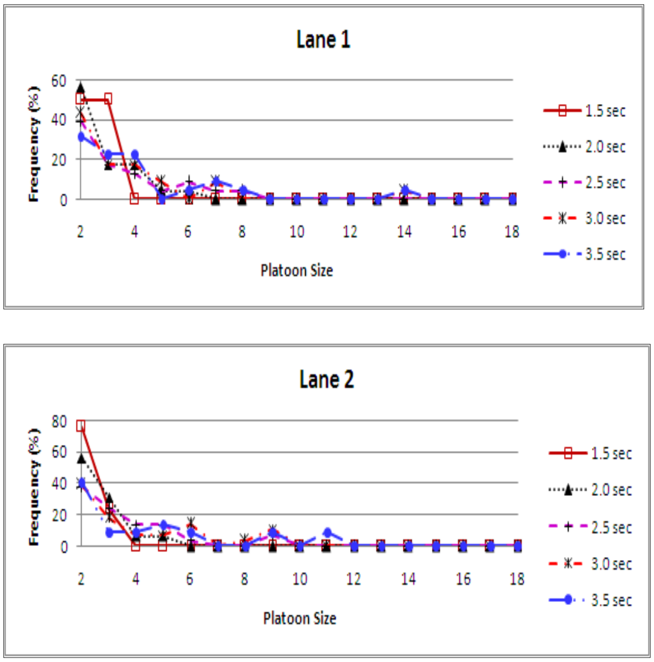


Figure 5 Distributions of platoon size by critical headway during off-peak period

This information is very useful to examine a proper value of critical headway which is through the relationship between the dispersion of platoon sizes and the proportion of platooned vehicles with the selected critical headways. The dispersion of platoons was measured in terms of coefficient of variation (COV) and the platooned vehicles in terms of the percent of the total traffic volume [20]. An example of this relationship is presented in Fig. 6. As illustrated in this figure, the proportion of platooned vehicles and the dispersion of platoon sizes increased as the critical headway increased. However, it shows that 2.5s critical headway is a turning point for both curves. Hence, 2.5s is utilized as the critical headway for the purpose of platoon determination in the data analysis. It was also determined that the critical headway of other lanes during peak and off-peak periods was found to be 2.5s.

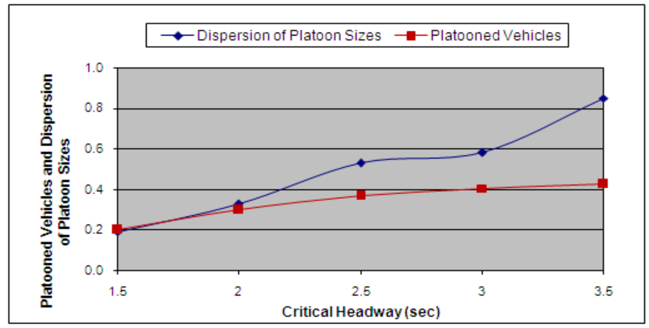


Figure 6 Proportions of platooned vehicles and dispersion of platoon sizes at selected critical headway in lane 2 (off-peak period)

3.3 Intra-Platoon Headway

Intra-platoon headway is defined as the average of individual headways within a vehicle platoon. These headways have distributed around the mode of 1.50s (Fig. 7) and this trend is observed nearly similar for all intra-platoon headway distributions. As shown in this figure, the intra-platoon headway distribution exhibits almost a symmetrical pattern. Based on the analysed distribution pattern, Normal Distribution has been fitted to intra-platoon headway distribution. As presented in Table 3, the Normal Distribution model gives the similar results reported by Jiang *et al*. [16].

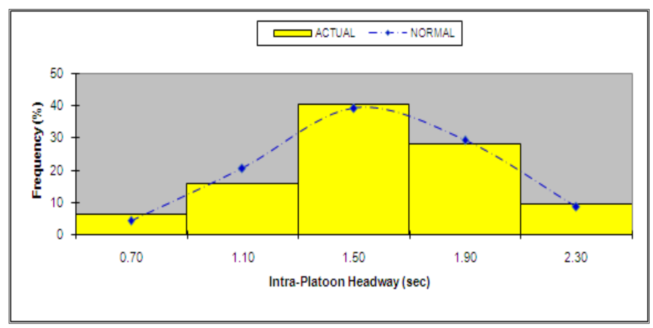


Figure 7 Distribution of intra-platoon headways at 263m in lane 2 (off-peak period)

Table 3 Summary of results of normal distribution analysis for intra-platoon headway distributions

Lane No.	Distance (m)	Normal Distribution	
		Peak Period	Off-peak Period
		Accepted null hypothesis?	
1	0	Yes	Yes
	263	Yes	Yes
	402	No	Yes
2	0	Yes	Yes
	263	No	Yes
	402	Yes	Yes

3.4 Inter-Platoon Headway

Inter-platoon headway is defined as the headway between the last vehicle of a vehicle platoon and the first vehicle of the following vehicle platoon. Generally, inter-platoon headway is influenced by the movement of individual vehicle. A studied by Jiang *et al*. have found that the inter-platoon headway follow the Lognormal Distribution [16]. For that reason, Lognormal Distribution was selected in order to found the best descriptor of inter-platoon headway under peak and off-peak periods for each lane at 0, 263 and 402m. The statistical results summarized in Table 4 showed that all the computed χ^2 values exceeded the corresponding critical χ^2_{cal} and therefore, Lognormal Distribution model is rejected for inter-platoon headway distribution. An example of inter-platoon headway distribution obtained from the data analysis is illustrated in Figure 8.

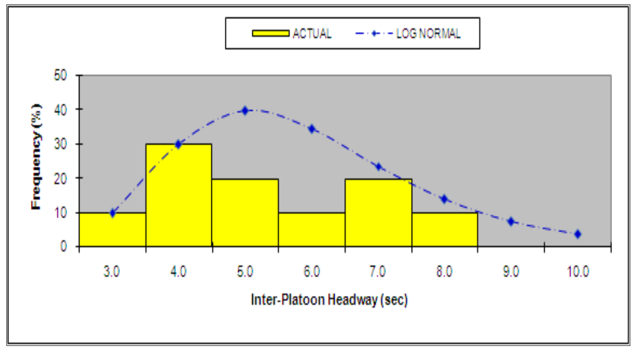


Figure 8 Distribution of inter-platoon headways at 0m in lane 1 (off-peak period

Table 4 Summary of results of lognormal distribution analysis for inter-platoon headway distributions

Lane No.	Distance (m)	Lognormal Distribution	
		Peak Period	Off-peak Period
		Accepted null hypothesis?	
1	0	No	No
	263	No	No
	402	No	No
2	0	No	No
	263	No	No
	402	No	No

4.0 CONCLUSION

In the light of the discussion so far, findings from the study have shown the distribution pattern for vehicle headway, intra-platoon headway and inter-platoon headway during weekday's peak and off-peak periods. Based on the analysis of empirical data, the following conclusions can be drawn:

- Vehicle headway distribution skews to the left and spreads over a wide range. Erlang Distribution and Shifted Negative Exponential Distribution are a better fit to the observed vehicle headway distributions than other distributions during the peak and off-peak periods.
- The distribution of intra-platoon headway exhibits almost a symmetrical pattern. Normal Distribution model provides a good fit to the observed intra-platoon headway distribution.
- The tail of the inter-platoon headway skews to the left. Fitted Lognormal Distribution model did not provide a good fit to the observed data.

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