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16. Abstract Since the 1980s, traffic volumes have experienced a rapid growth of approximately 30% in Indiana. Traffic data indicates that more than 70% of vehicles travel in platoons on Indiana highway corridors in the vicinity of urban areas. At a rural highway intersection consisting of a major road with high traffic volume and a minor road with low traffic volume, it is very common that the green time cannot be used efficiently, especially when the vehicle detectors on the major road are imbedded close to the intersection. In Indiana, most of the traffic signal timing systems operate well. However, these systems do not allow for considering the presence of vehicle platoons on major roads. For a semi-actuated or fully actuated signal control, the green on the major road is often terminated at the intersection due to the arrival of vehicles on the minor road. Vehicle platoons are often stopped to give the right-of-way to the minor traffic, even only a single vehicle. As a result, vehicle platoons are delayed, and the green time is not efficiently used. If this can be improved, traffic delay will be reduced. This study, as the second phase of a two-phase study of vehicle platoons, was conducted to improve traffic control at intersections on Indiana rural corridor. Major parameters of the vehicle platoon characteristics include platoon headway, inter-platoon headway, platoon size and platoon speed. Platoon behaviors and distribution patterns were identified with respect to these parameters. A platoon-based adaptive algorithm was derived for traffic signal timing. A simulation computer program was developed for analyzing the performance of platoon-based traffic control systems and effects of the key platoon related traffic measurements.					
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**DEVELOPMENT OF VEHICLE PLATOON DISTRIBUTION MODELS  
AND SIMULATION OF PLATOON MOVEMENTS ON INDIAN RURAL  
CORRIDORS**

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## CHAPTER 1. INTRODUCTION

Intersection related traffic problems include traffic delay, safety and pollution. Traffic control at highway intersections is to provide safe passages for conflicting vehicle flows with the lowest traffic delay possible. At an intersection, vehicle flows are frequently interrupted due to traffic signs or signals in order to give the necessary right-of-way to the conflicting vehicle flows. As a result, vehicles are often slowed down or stopped in front of the intersection, resulting in a rise in travel time, consumption of fuel and pollutant emission. Therefore, much effort has been made to develop new technologies, such as Intelligent Transportation Systems (ITS) technologies, to make vehicle movements more efficient, safer and environmentally friendly at intersections.

Due to the tremendous advancement in ITS technologies, Urban Traffic Control (UTC) has evolved to be a promising solver to urban traffic problems. An UTC system is usually developed for a coordinated control of traffic signals in a particular urban street network. It consists of mathematical models to simulate traffic flows; objective functions to determine cycle length and allocate green time; and vehicle detectors to identify the presence or passage of vehicles. Therefore, successful implementation of an UTC system depends on the performance of basic models and reliability and deployment of detectors. For the past decades, TRANSYT is perhaps the most popular simulation model. Its latest version TRANSYT-7F has been reported to deliver a great deal of power to traffic engineers and planners (Wallace et al. 1991). TSIS 4.2 is another software package for performing traffic simulation. It combines two traffic simulation models, NETSIM and FRESIM, into one called CORSIM. CORSIM has expanded the capacities of NETSIM

and FRESIM, and can be used to simulate traffic and traffic control conditions in a combined street and freeway network (FHWA 1998).

Both TRANSYT-7F and CORSIM simulate vehicle flows based on the distributions of individual arriving vehicle at the intersections. These two simulation packages can be employed to time traffic signals for both urban streets and rural highways. However, there exist certain special scenarios in which the individual-vehicle-based traffic simulation software does not work well. On Indiana highway corridors, many isolated intersections in rural areas consist of intersecting major and minor roads. The major road usually has a much higher high traffic volume than the minor road. It was observed that due to the intermittent interruption of traffic signals, vehicles on the major road usually traveled in platoons. It was also observed that, under the current traffic control, the green time was often granted to the few vehicles on the minor road at the expenses of stopping a long vehicle platoon on the major road. This research was conducted to analyze the platoon characteristics, such as platoon distribution, platoon size and headway within a platoon, in order to improve the current traffic control and reduce traffic delays at highway intersections.

### **1.1 Problem Statement and Research Objectives**

A realistic traffic signal system arises from knowledge of the real world traffic conditions, such as vehicle arrival patterns. There are hundreds of signalized intersections on Indiana highway corridors, of which many intersections are isolated intersections of major roads with minor roads. Since 1980s, traffic volumes have experienced a rapid

growth of approximately 30% in Indiana. Consequently, vehicles may undergo traffic delays at intersections not only in urban streets, but also on rural highways to some extent. In addition, it is not uncommon that vehicles may travel and arrive at intersections in platoons. Traffic data indicates that about 70% of vehicles travel in platoons on Indiana highway corridors in the vicinity of urban areas. Many vehicle platoons were halted at signalized intersections so as to give the right-of-way to vehicles on the intersecting minor road, even though there were only one or two vehicles on the minor road. This led to a great rise in traffic delays. At the intersection of US-52 with Ducan Drive in West Lafayette, for example, it was observed that on the major road, the average queue length was about eleven vehicles and the average stop delay was 200 vehicle-seconds per cycle (about 70 sec) in one direction. If this can be improved, the reduction of traffic delay on the major road will be tremendous.

At a rural highway intersection consisting of a major road with high traffic volume and a minor road with low traffic volume, it is very common that the green time cannot be used efficiently, especially when the vehicle detectors on the major road are imbedded close to the intersection. In Indiana, the traffic signal timing systems are designed in accordance to Indiana Design Manual (INDOT 1995) and most of the current systems operate well. However, these systems do not allow for considering the presence of vehicle platoons on major roads. For a semi-actuated or fully actuated signal control, the green on the major road is often terminated at the intersection due to the arrival of vehicles on the minor road. Vehicle platoons are often stopped so as to give the right-of-way to the minor traffic, even for only a single vehicle. As a result, vehicle platoons are

delayed, and the green time is not efficiently used. If this can be improved, traffic delay will be reduced.

A vehicle platoon is defined as a group of vehicles traveling together in the Highway Capacity Manual (HCM) (TRB 1998). HCM uses a platoon ratio,  $R_p$ , to take into account the presence of platoons.  $R_p$  in HCM is utilized as a measure of traffic progression quality at intersections. However,  $R_p$  values are not considered in signal design and timing. Furthermore, the fundamental of  $R_p$ , as discussed in HCM, is so simplified that the essential characteristics of vehicle platoons are omitted. As observed in the field, the portion of vehicles traveling in groups changes from time to time, and is not a constant. An arbitrary value of platoon ratio cannot represent the real platoon characteristics. It is desirable to identify major variables of vehicle platoons and to represent their characteristics mathematically.

To take into account the vehicle platoons in traffic signal timing, it is essential to investigate the vehicle platoon characteristics on Indiana highway corridors. Major parameters of the vehicle platoon characteristics include platoon headway, inter-platoon headway, platoon size and platoon speed. Platoon behaviors and distribution patterns could be identified with respect to these parameters. A platoon-based adaptive algorithm would be derived for traffic signal timing. It would then be necessary to experiment the proposed algorithm and evaluate platoon parameters. While it would be desirable to conduct experiments on the existing signal systems, there exist many difficulties in practice. To test different traffic and road conditions, a number of intersections should be

employed; and accordingly, suitable instrumentation, such as vehicle detectors, should be installed. It may also take days or weeks to repeat a specific condition. In addition, field experiments may disturb signal operations and cause traffic accidents. As a result, field experiments become very expensive and time consuming, and it is natural for us to utilize simulation technologies to test the proposed algorithm. It is necessary to develop a special purpose simulation program to address this traffic platoon problem.

The objectives of this project were to investigate vehicle platoon characteristics and to develop control logic for timing actuated traffic signals at isolated intersections, in light of the presence of platoons on the major road based on the real conditions of rural highway corridors in Indiana. In addition, efforts were to be made to determine an appropriate deployment of detectors that would enable traffic signal systems to identify platoons and to develop a computer program to simulate traffic movements with significant platoon characteristics at isolated intersections. It was expected that if vehicle platoon behaviors were predictable, the derived control algorithm would significantly enhance the performance of signal systems.

## **1.2 Research Scope and Approach**

This research project was carried out by focusing on (1) examination of current signal control systems; (2) platoon data collection and analysis; (3) appropriate deployment of vehicle detectors; (4) derivation of a signal control logic taking into account platoon characteristics on major roads; (5) derivation of a platoon generating

model; (6) derivation of appropriate procedures for general signal timing; and (6) simulation of platoon related signal control.

In order to achieve the research objective, the following research approach was adopted in the course of performing this project. An extensive review of relevant literature was conducted to examine current methods for timing traffic signals and schemes for deploying vehicle detectors. Emphasis was given to signal control logic, especially those related to vehicle actuated control system. Secondly, field data were collected at selected intersections in Indiana in order to better understanding characteristics of vehicle platoons. The findings from both the literatures and field data were summarized to serve as fundamentals for the research, and combined to determine deployment of vehicle detectors. An equation was derived to determine the position of vehicle detector for obtaining platoon characteristics. A computer program was developed to simulate vehicle platoons. Four variables, such as size, headway between vehicles within a platoon, speed and time interval between consecutive platoons, were employed to characterize a vehicle platoon. This simulation program allows users to generate random numbers for these four variables on the basis of five different probabilistic distribution functions, including constant, normal, lognormal, Poisson, and negative exponential distributions. Following the aforementioned work, a platoon based adaptive logic was recommended for traffic signal timing and the issues associated with implementation of the proposed control logic were identified.

## **CHAPTER 2. PLATOON CHARACTERIZATION, PLATOON DETECTOR PLACEMENT, AND DATA COLLECTION**

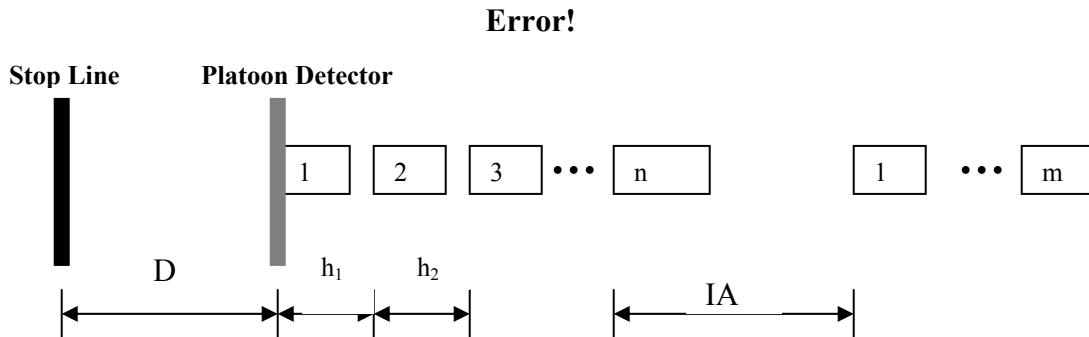
Vehicle platoon is defined in the Highway Capacity Manual as a group of vehicles traveling together. To take into account the presence of vehicle platoons in signal timing effectively, the existing macroscopic and microscopic flow characteristics are not sufficient and specific information on vehicle platoons is required. In order to define a vehicle platoon temporally and spatially, this study selected four fundamental variables such as platoon size, platoon headway, platoon speed, and inter-arrival between consecutive platoons to characterize the platoon. The concept of critical headway was used to screen collected field data so as to identify vehicle platoons and determine platoon characteristics. This study also addressed issues associated with the placement of the detectors for detecting vehicle platoons, and an empirical algorithm was proposed to estimate optimal platoon detector locations. Tremendous amount of data was collected over selected highway corridors statewide. Statistical analysis was performed to determine the distribution patterns of the four platoon variables.

### **2.1 Characterization of Vehicle Platoons**

#### **Measurements of Platoon Characteristics**

For the purpose of this study, the intersections for platoon data collection were specified as isolated intersections of a major road and a minor road with significant platoon presence on the major road. Tube traffic counters were used to obtain vehicle platoon data. As traffic variables include traffic flow rate, speed and density in the conventional traffic signal timing, four fundamental variables were selected in this study

to analyze the characteristics of platoon-based traffic flows. Figure 2.1 shows a graphical illustration of the four vehicle platoon variables: platoon size, platoon headway, platoon speed, and inter-arrival between consecutive platoons.



**Figure 2.1. Illustration of Platoon Variables**

As shown in the figure,  $D$  is the distance between the stop lane and the platoon detector, the platoon size  $n$  is the number of vehicles in a platoon, the platoon headway  $h_i$  is the headway between vehicle  $i$  and vehicle  $i+1$  within a platoon, the platoon speed  $V$  is the average speed of the vehicles in a platoon, the inter-arrival between consecutive platoons  $IA$  is the headway between the last vehicle of the front platoon and the first vehicle the following platoon. Apparently, headway value is essential for determining whether a vehicle belongs to a platoon. That is, if a headway  $h_i$  is “small”, then vehicle  $i$  and vehicle  $i+1$  belong to the same vehicle platoon. Otherwise, they are not in the same vehicle platoon. To quantify this “small” headway, a pre-determined headway value, or the critical headway as defined by Athol (1965), should be selected. As discussed in the following section, the value of critical headway was determined based on the traffic data collected at selected intersections along Indiana highway corridors.

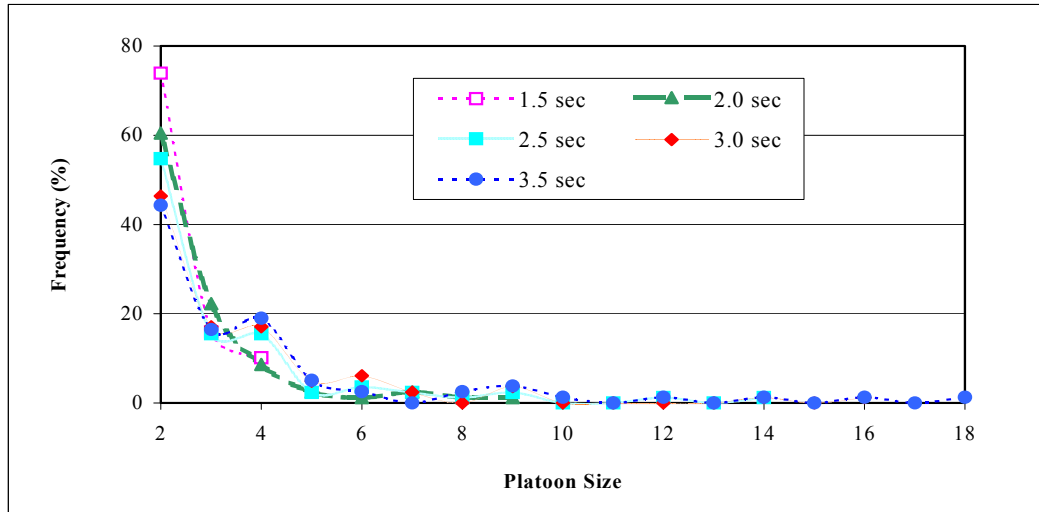
## Determination of Critical Headway

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. May (1965) investigated individual headway distributions and concluded that vehicle headways were rarely less than 0.5 seconds or over 10 seconds at different traffic volumes. Athol (1965) investigated the effects of critical headways of 1.2, 1.5, 2.1 and 2.7 seconds on platoon behavior and selected a critical headway of 2.1 seconds corresponding to a traffic volume of 1500 vehicles per hour per lane (vphpl).

In order to identify an appropriate critical headway, approximately 30,000 headway measurements at the selected Indiana intersections were examined with respect to critical headway values of 1.5, 2.0, 2.5, 3.0 and 3.5 seconds. Figure 2.2 shows the frequencies of the resultant vehicle platoon sizes ( platoons with two or more vehicles). It shows that vehicle platoons were dominated by the two-vehicle platoons. The two-vehicle platoons increase as the critical headway decreases. When the critical headway is 3.5 seconds, two-vehicle platoons account for about 45% of total number of platoons with two or more vehicles. This percentage increases to 74% when the critical headway drops to 1.5 seconds.

As the critical headway increases, more vehicles will be included in platoons. Use of a large critical headway will result in too large platoon sizes and too large variances of platoon variables. In addition, detecting large vehicle platoons requires a large detection area, leading to a significant rise in the costs of detector installation and maintenance. The extreme end of a very large critical headway is that every vehicle belongs to a vehicle platoon. On the other hand, use of a small critical headway will

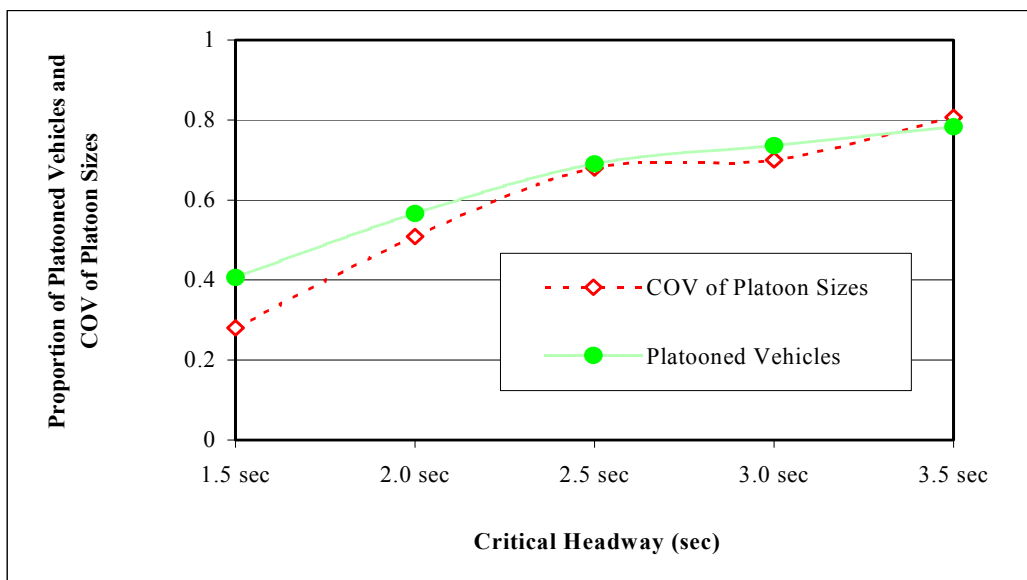
result in small platoon sizes and insufficient platoon information. The extreme end of a very small critical headway is that no vehicle belongs to a vehicle platoon, or no platoons can be identified. Therefore, use of either a too large or a too small critical headway will not serve the purpose of an effective traffic control in terms of vehicle platoons.



**Figure 2.2. Distributions of Platoon Size by Different Critical Headways**

To choose an appropriate value of the critical headway, the variance of platoon size should be kept at a reasonable level so that traffic data contains sufficient and accurate platoon information for signal timing. Therefore, the relationship between the platoon size and the coefficient of variation of the platoon size was examined to determine a proper value of critical headway. The coefficient of variation (COV) of platoon size is defined as the ratio of the standard deviation of platoon size to the average platoon size. The definition of COV implies that COV is actually the relative standard deviation of platoon sizes in terms of the average platoon size. That is, COV takes into account the effects of the variations of platoon sizes as well as the magnitude of the average platoon size. Figure 2.3 shows the proportions of platooned vehicles and COV

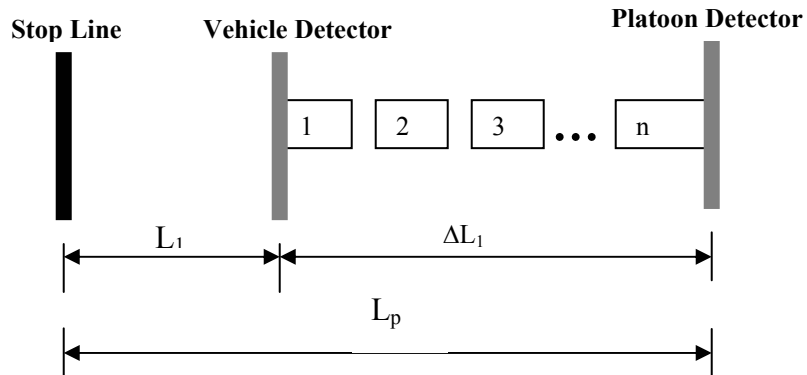
values corresponding to different critical headways. It is observed that both proportion and COV values increase as the critical headway increases. As illustrated in Figure 2.3, the two curves join and inflect at the 2.5-second critical headway. Both curves become flat beyond the inflection point at the 2.5-second critical headway. This implies that use of the 2.5-second critical headway would make the proportion of vehicles in platoons and the COV relatively stable. Consequently, 2.5 seconds is utilized as the critical headway for platoon determination in the data analysis. This critical headway seems to be practically reasonable as it is right in the middle of the commonly assumed saturated headway (2.0 seconds) and the desired allowable gap (3.0 seconds).



**Figure 2.3. Proportion of Platooned Vehicles and COV at Various Critical Headways**

## 2.2 Determination of Appropriate Platoon Detector Location

In conventional signal timing, vehicle detectors should be placed at an optimal distance of  $L$  upstream of the stop line. These detectors are used to determine arrivals of vehicles at the intersection. To acquire platoon information, an additional detector is required on each main approach. Figure 2.4 illustrates the placement of both conventional vehicle detector and the additional platoon detector. In the figure,  $L_p$  is the distance for the platoon detector,  $L$  is the distance for the conventional detector, and  $\Delta L$  is the distance between the two detectors.



**Figure 2.4. Platoon Detector Placement**

The location of a vehicle detector is a function of vehicles' approach speed. The Institute of Traffic Engineers (ITE) (ITE 1976) recommended the detector Distance for large-area individual vehicle detection with high-speed approaches as listed in Table 2.1.

**Table 2.1. Length of Large-Area Detection with High Approach Speed**

Approach Speed (mph)	Detector Length (feet)
30	175
40	250
45	300
50	350
60	450

*(Courtesy of ITE South Section 1976)*

ITE (1974) also provided the following equation to determine the detector distance for small-area detection of individual vehicles with low-speed approaches (less than 25 mph).

$$L = 1.47V(3 - UE) - 18 \quad (2.1)$$

where  $L$  = detector distance (ft);  $V$  = vehicle speed (mph);  $UE$  = vehicle interval (sec); 18 = average vehicle length (ft); 3 = desired allowable gap (seconds); and 1.47 = factor converting the vehicle speed from mph to feet/second.

To determine the appropriate location of the platoon detector, the distance between the conventional vehicle detector and the platoon detector  $\Delta L$ , should be large enough to provide sufficient space for detecting a vehicle platoon. Based on similar concept as in Equation 2.1,  $\Delta L$  can be estimated in terms of platoon speed, and headway as shown in Equation 2.2.

$$\Delta L = 1.47V_p(N_p - 1)h_p + 18 \quad (2.2)$$

where the units for  $\Delta L$ ,  $V_p$  and  $h_p$  are feet, mph, and seconds, respectively.

For highway corridors with high approach speed, adding a proper value of  $L$  to  $\Delta L$  gives the total setback of the platoon detector,  $L_p$ . For low-speed approaches,  $L_p$  is the summation of Equation 2.1 and Equation 2.2, which can be simplified as:

$$L_p = 1.47V_p N_p h_p \quad (2.3)$$

where the units for  $L_p$ ,  $V_p$  and  $h_p$  are feet, mph, and seconds, respectively.

To use Equation 2.3, the values of  $L_p$ ,  $V_p$  and  $h_p$  must be determined. However, the values of these variables are not constant and their representative values should be utilized to determine the detector location. With a given significant level, the platoon variables can be estimated with their statistical values, such as sample means and standard deviations. A random variable's mean,  $\mu$ , can be estimated using the sample mean  $\bar{x}$ , the sample standard deviation  $S$ , and the sample size  $n$  with a  $100(1-\alpha)\%$  confidence interval (Neter, Wasserman, and Kutner 1985):

$$\bar{x} - t_{\alpha/2, n-1} \frac{S}{\sqrt{n}} \leq \mu \leq \bar{x} + t_{\alpha/2, n-1} \frac{S}{\sqrt{n}} \quad (2.4)$$

where  $t_{\alpha/2, n-1}$  denotes the percentage point of the  $t$  distribution with  $n-1$  degrees of freedom.

With Equation 2.3, the upper and lower bounds of  $L_p$  can be estimated in terms of the sample mean values of  $V_p$ ,  $N_p$  and  $h_p$ . Set  $\alpha = 0.05$  and  $\lambda = t_{\alpha/2, n-1}$ , then  $\lambda = 1.96$  when sample size  $n \geq 120$ . Thus, the upper bound of the detector distance  $UL_p$  (in feet)

can be estimated by substituting  $V_p = \bar{V}_p (1 + \lambda \frac{S_{V_p}}{\sqrt{n}})$ ,  $N_p = \bar{N}_p (1 + \lambda \frac{S_{N_p}}{\sqrt{n}})$ , and

$h_p = \bar{h}_p (1 + \lambda \frac{S_{h_p}}{\sqrt{n}})$  into Equation 2.3:

$$UL_p = 1.47 \bar{V}_p \bar{N}_p \bar{h}_p (1 + \lambda \frac{S_{V_p}}{\sqrt{n}}) (1 + \lambda \frac{S_{N_p}}{\sqrt{n}}) (1 + \lambda \frac{S_{h_p}}{\sqrt{n}}) \quad (2.5)$$

where  $\bar{V}_p$ ,  $\bar{N}_p$  and  $\bar{h}_p$  are the mean values of the platoon speed (mph), size (number of vehicles), and headway (seconds) from  $n$  measured platoons, respectively; and  $S_{V_p}$ ,  $S_{N_p}$  and  $S_{h_p}$  are their corresponding standard deviations.

Similarly, the lower bound of the detector distance  $LL_p$  can be estimated as:

$$LL_p = 1.47 \bar{V}_p \bar{N}_p \bar{h}_p (1 - \lambda \frac{S_{V_p}}{\sqrt{n}}) (1 - \lambda \frac{S_{N_p}}{\sqrt{n}}) (1 - \lambda \frac{S_{h_p}}{\sqrt{n}}) \quad (2.6)$$

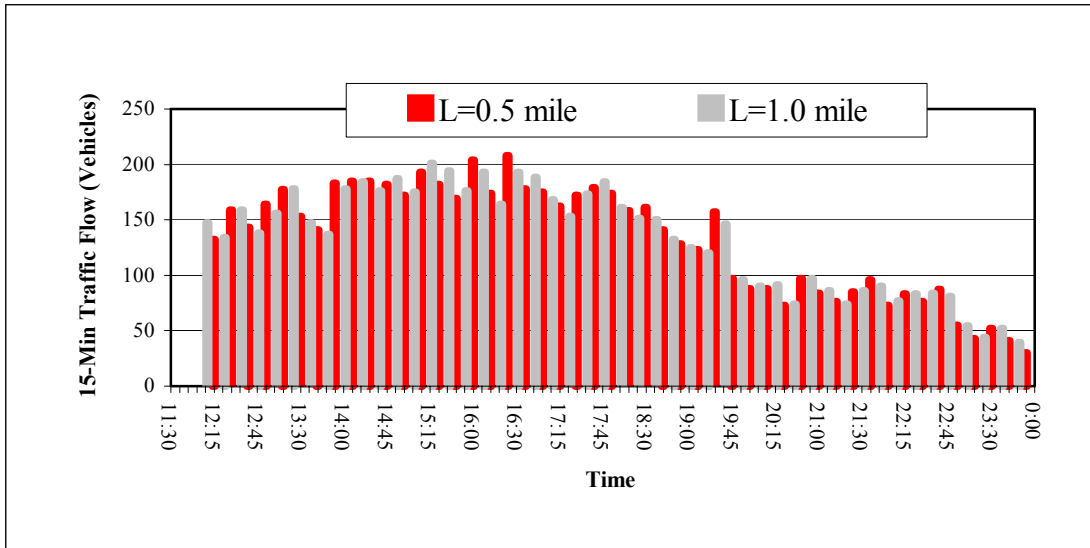
Using Equations 2.5 and 2.6, the platoon detector distances were calculated with collected traffic platoon data at eight highway intersections. Table 2.2 presents the  $UL_p$  and  $LL_p$  values at the intersections.

**Table 2.2. Estimated Platoon Detector Locations**

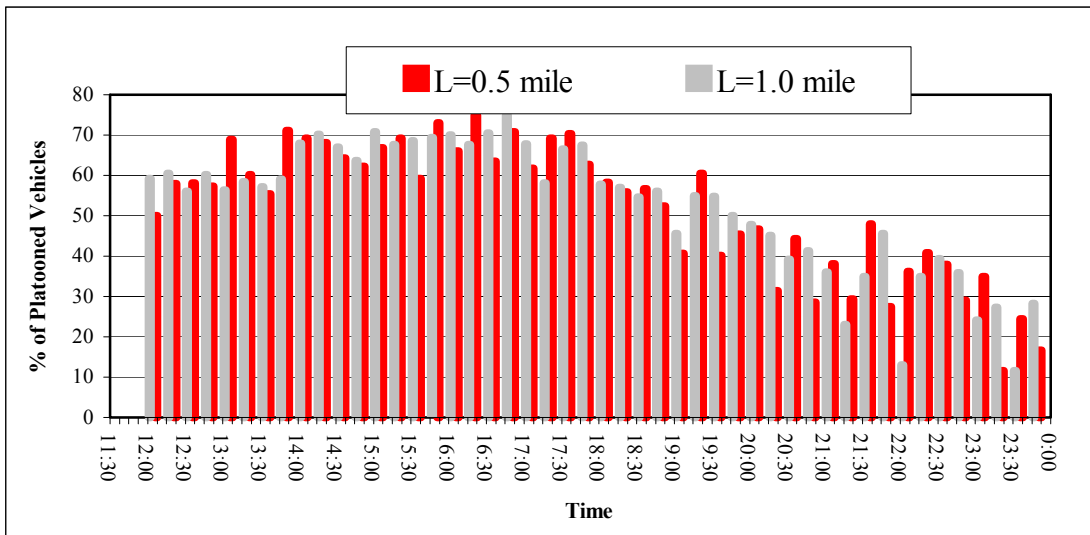
Parameters		US52	US31	SR2	SR332	SR37	SR66	US27	US30
Platoon Detector Location	$LL_p$ , (ft)	2620	2680	1320	1352	1300	1300	1340	1960
	$UL_p$ , (ft)	5000	5450	2850	3180	2810	2920	2740	4090
85 <sup>th</sup> Percentile Platoon Speed	Mean	61	62	61	61	60	60	63	61
	COV	0.15	0.2	0.17	0.24	0.17	0.20	0.13	0.14
85 <sup>th</sup> Percentile Platoon Size	Mean	6	6	4	4	4	4	4	6
	COV	0.65	0.7	0.50	0.50	0.50	0.50	0.50	0.50
85 <sup>th</sup> Percentile Platoon Headway	Mean	2	2	1.5	1.5	1.5	1.5	1.5	1.5
	COV	0.3	0.3	0.5	0.5	0.5	0.5	0.5	0.5

(1 mile = 1609 meters)

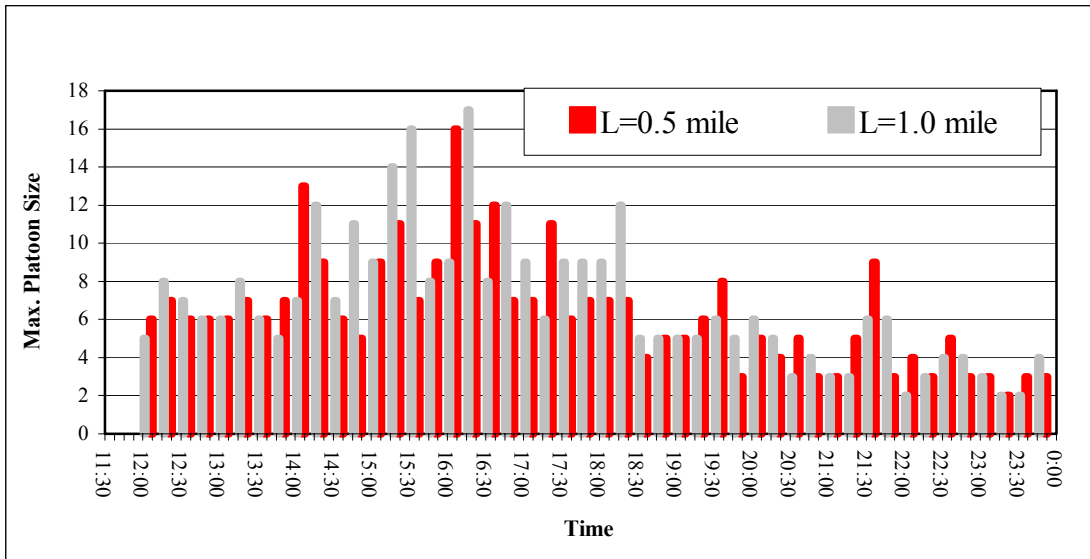
The pair of  $LL_p$  and  $UL_p$  values at each intersection provides a range of platoon detector distance values that can be utilized to provide sufficient platoon-based traffic information. That is, a platoon detector placed at a distance between the calculated  $LL_p$  and  $UL_p$  should be able to obtain statistically sufficient and stable platoon data. To verify this, platoon-based traffic data was collected at the intersection at US-31 with two vehicle counters. As shown in Table 2.2 the  $LL_p$  is 2680 feet and  $UL_p$  is 5450 feet at the intersection. Thus, one traffic counter was placed at about 0.5 mile from the stop line and the other traffic counter was placed at about 1.0 mile. That is, both counters were within the range formed by  $LL_p$  and  $UL_p$  with one near the lower boundary and the other near the upper boundary. There are no minor roads between these two locations. The measured data is summarized in Figures 2.5, 2.6 and 2.7. Figure 2.5 illustrates the traffic volumes measured during a 12-hour period at the two counter locations. It shows that the volume measurements at these two locations follow the same pattern. Similarly, Figures 2.6 and 2.7 show that at the two counters the proportions of platooned vehicles and the maximum platoon sizes also exhibit the same trend. This implies that a platoon detector placed within the interval between  $LL_p$  and  $UL_p$  can provide consistent and steady platoon information.



**Figure 2.5. Traffic Flows at Two Counter Locations**



**Figure 2.6. Percentage of Platooned Vehicles at Two Counter Locations**



**Figure 2.7. Maximum Platoon Sizes at Two Counter Locations**

## 2.3 Data Collection

### Selection of Intersections

Two major concerns were taken into consideration in the process of choosing intersections for platoon data collection. First, the intersections should be isolated intersections on highway corridors and have experienced significant platoon presence. Next, the driveway condition should be sufficient to place vehicle detectors. Based on the traffic surveys conducted statewide, four isolated intersections were selected for platoon data collection on the following state roads:

US-30 in Valparaiso,

US-31 in Kokomo,

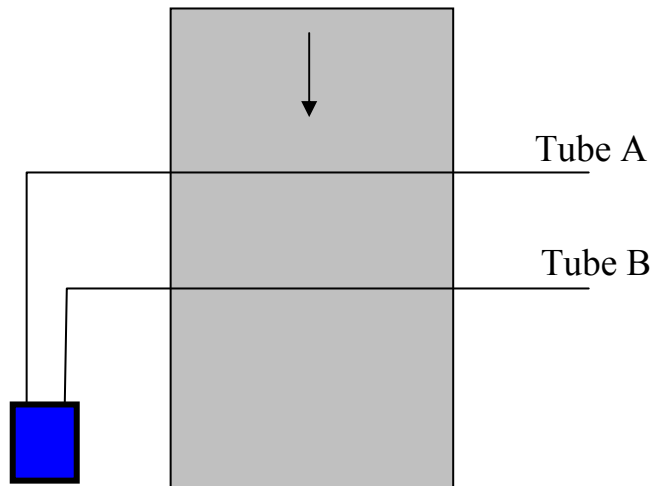
US-52 in Lafayette, and

US-52 in West Lafayette

### **Data Measurements**

Two types of vehicle counters were purchased for this study. Jamar traffic counters, TRAX I (Jamar Technologies 1998), were used to measure general traffic data. Inasmuch as MetroCount (Microcom Pty Ltd 2000) counters can provide detailed individual headway data at an accuracy of up to 10ths of a second, they were used to measure platoon data. Original data was exported as Microsoft Excel worksheets, and then sorted with respect to the selected critical headway of 2.5 sec.

During data collection, two tubes (i.e. two sensors) were used. Each tube was sixty feet long and the two tubes were of equal length. Tube layout depends on the information to measure. In this study, such information as vehicle speed, classification, and headway was acquired. Accordingly, a typical tube layout used is given in Figure 2.8. The spacing between the two tubes depends on the requirement of a specific vehicle counter. It is eight feet for TRAX II counters and one meter (3.28 feet) for MetroCount counters.



**Figure 2.8. Illustration of Tube Layout**

### CHAPTER 3. FUNDAMENTALS OF PLATOON CHARACTERISTICS

As discussed above, the key platoon variables were selected; the critical platoon headway was chosen; and the method for determining detector locations was developed. The selected platoon variables, along with the appropriate critical platoon headway and detector location, provide a basis for platoon-based traffic data collection and analysis. To study the characteristics of the platoon variables, isolated intersections were selected for platoon data measurements on Indiana highway corridors based on a statewide traffic survey. For the purpose of this study, each of the selected intersections includes a major road with relatively high traffic volume and a minor road with very low traffic volume. A large amount of platoon-based traffic data was collected at the intersections with traffic counters placed at calculated locations. Vehicle platoons were characterized using platoon size, platoon headway, platoon speed, and inter-arrival time between consecutive platoons as previously defined. Based on the frequency distributions of the four platoon key variables, three mathematical distributions were selected to fit the traffic data, including the negative exponential distribution, the normal distribution, and the lognormal distribution. Detailed descriptions of various mathematical distributions can be found in many books on probability and statistics, such as Walpole and Myers (1972) and Neter, Wasserman and Kutner (1985). An excellent reference on modeling traffic flows with the mathematical distribution models is Gerlough and Huber (1975).

The negative exponential distribution has the following form:

$$P(x \geq s) = e^{-s/S} \quad (3.1)$$

where  $P(x \geq s)$  is the probability of a random variable  $x$  equal to or greater than a specified value  $s$ , and  $S$  is the mean of the observed values of variable  $x$ .

The normal distribution  $N(\mu, \sigma)$  is characterized by the mean  $\mu$  and standard deviation  $\sigma$  of a random variable  $x$ . With the following conversion, the normal distribution  $N(\mu, \sigma)$  can be transformed into the standard normal distribution  $N(0, 1)$ , with mean 0 and standard deviation 1.

$$Z_i = \frac{x_i - \mu}{\sigma} \quad (3.2)$$

where  $\mu$  and  $\sigma^2$  can be estimated with observed  $x$  values:

$$\hat{\mu} = \bar{x} = \frac{\sum_{i=1}^N x_i}{N} \quad (3.3)$$

$$\hat{\sigma}^2 = S_s^2 = \frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N - 1} \quad (3.4)$$

The lognormal distribution is used to describe systems where the logarithm of the measured variable is normally distributed. If the measured variable is  $x_i$ , then  $s_i = \log x_i$  is assumed to be normally distributed with estimated mean  $\hat{\mu}$  and variance  $\bar{\sigma}^2$ :

$$\hat{\mu} = \bar{s} = \frac{\sum_{i=1}^N s_i}{N} = \frac{\sum_{i=1}^N \log x_i}{N} \quad (3.5)$$

$$\hat{\sigma}^2 = S_s^2 = \frac{\sum_{i=1}^N (s_i - \bar{s})^2}{N - 1} = \frac{\sum_{i=1}^N (\log x_i - \bar{s})^2}{N - 1} \quad (3.6)$$

### 3.1 Platoon Sizes Distribution

When analyzing vehicle platoons, a vehicle is usually classified either as a platooned vehicle or as a non-platooned vehicle. This would make it inconvenient for platoon analysis because of the random positions of the platooned vehicles and non-platooned vehicles within a traffic stream. It is therefore desired to analyze platoon-based traffic flows without separating platooned vehicles from non-platooned vehicles. This can be achieved by treating non-platooned vehicles as single-vehicle platoons. That is, each non-platooned vehicle is considered a special vehicle platoon with platoon size equal to one. Consequently, no vehicles are excluded from the platoon-based traffic flows and vehicle platoon sizes range from one to any number of consecutive vehicles with headways less than the critical headway of 2.5 seconds. By introducing single-vehicle platoons, it significantly simplifies the procedures for analyzing and simulating platoon behaviors because a single mathematical distribution model can represent both platoon and non-platooned vehicles.

Figure 3.1 illustrates the observed platoon size distributions at two intersections during peak hours based on the critical headway of 2.5 seconds. Two distribution curves are shown for each intersection, one including and the other excluding single-vehicle platoons. The two curves for each intersection indicate that the platoon size distributions have a similar pattern either including or excluding single-vehicle platoons. This implies that treating non-platooned vehicles as single-vehicle platoons will not change the platoon variable's mathematical distribution. Figure 3.1 also exhibits that approximately 70% of the vehicles traveled in groups (with platoon size of two or more). Based on the

shape of the platoon size distribution curves in Figure 3.1, two possible mathematical distributions, the negative exponential and lognormal distributions, were selected to fit the measured platoon size data.

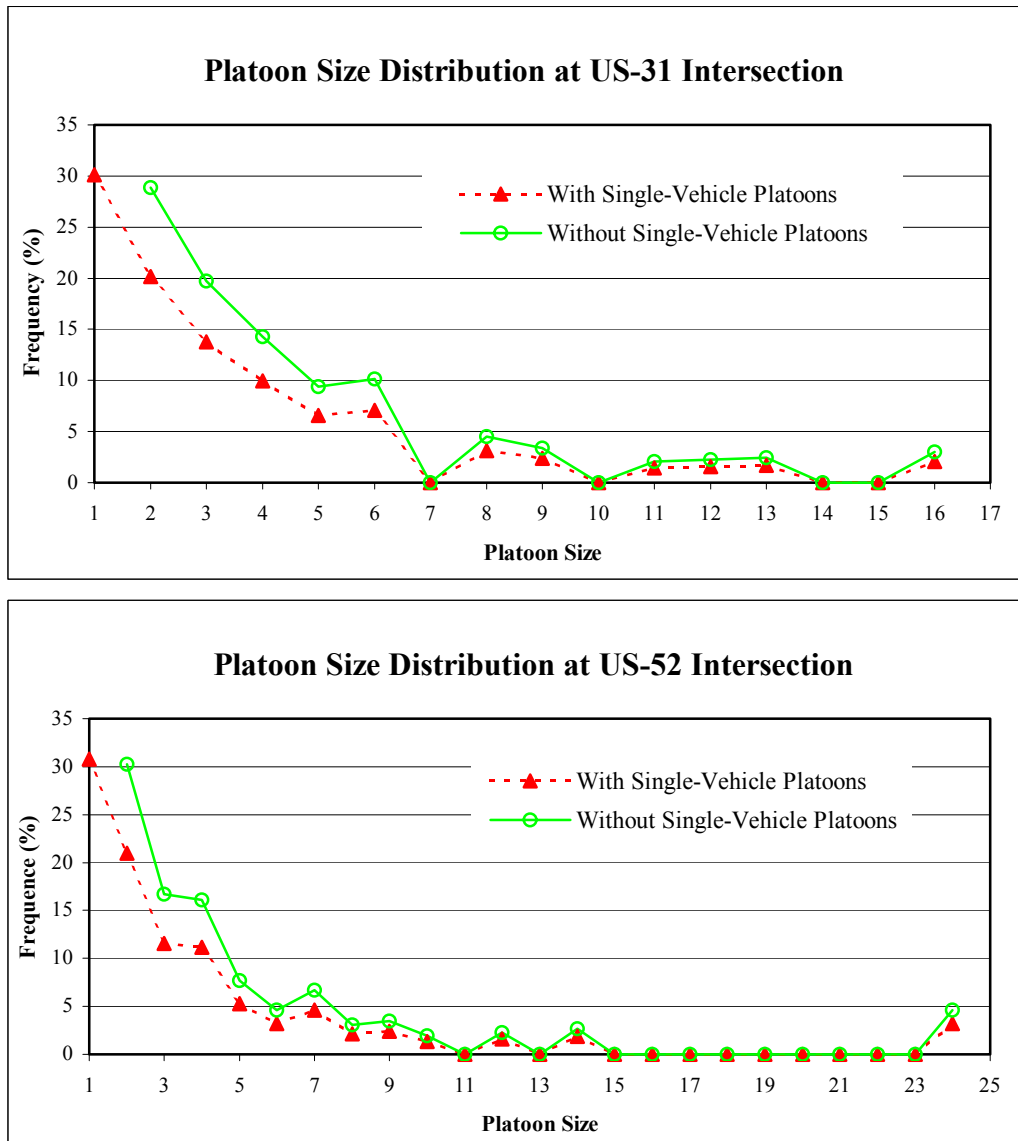
Traffic measurements at three intersections were utilized for fitting the mathematical distributions. The expected platoon size frequencies for each distribution model were calculated to compare with the observed frequencies.  $\chi^2$  goodness-of-fit tests (Walpole and Myers 1972) were conducted to determine which of the distributions could best represent the actual platoon size distribution. The observed and expected platoon size distributions along with the goodness-of-fit test results are presented in Table 3.1.

At a significance level of  $\alpha=0.05$ , the critical value of the goodness-of-fit test is  $\chi^2_{0.95}(9)=19.02$ . A goodness-of-fit test between observed frequency  $O_i$  and expected

frequency  $E_i$  is based on the quantity  $\chi^2 = \sum_{i=1}^k \frac{(O_i - E_i)^2}{E_i}$ . If  $\chi^2 \leq \chi^2_{0.95}(9)=19.02$ , the fit

is good; otherwise, the fit is poor. The test results show that the negative exponential distribution fits the platoon size distributions at the US-30 and US-52 intersections at  $\alpha=0.05$ . However, both distributions were rejected by the goodness-of-fit tests for the given  $\alpha$  value for the platoon size distribution at the US-31 intersection. Under this situation that not all of the distribution models fit a common distribution, selection of an appropriate distribution involves some practical considerations and judgments. Underwood (1964) and Gerlough and Huber (1975) demonstrated that as in many engineering selection processes, selection of a suitable distribution represents a compromise economic considerations and faithfulness of the model. Generally, the selected distribution should represent the shape of the natural spread of the actual data

measurements. In addition, a distribution should not be too sophisticated for practical applications. Therefore, based on the goodness-of-fit test results and the fact that the general shape of the distribution curve at US-31 follows the same trend as those at the other two locations, the negative exponential distribution was selected to represent platoon size distribution.



**Figure 3.1. Platoon Size Distributions at Two Intersections**

**Table 3.1. Goodness-of-Fit Tests for Platoon Size Distributions**

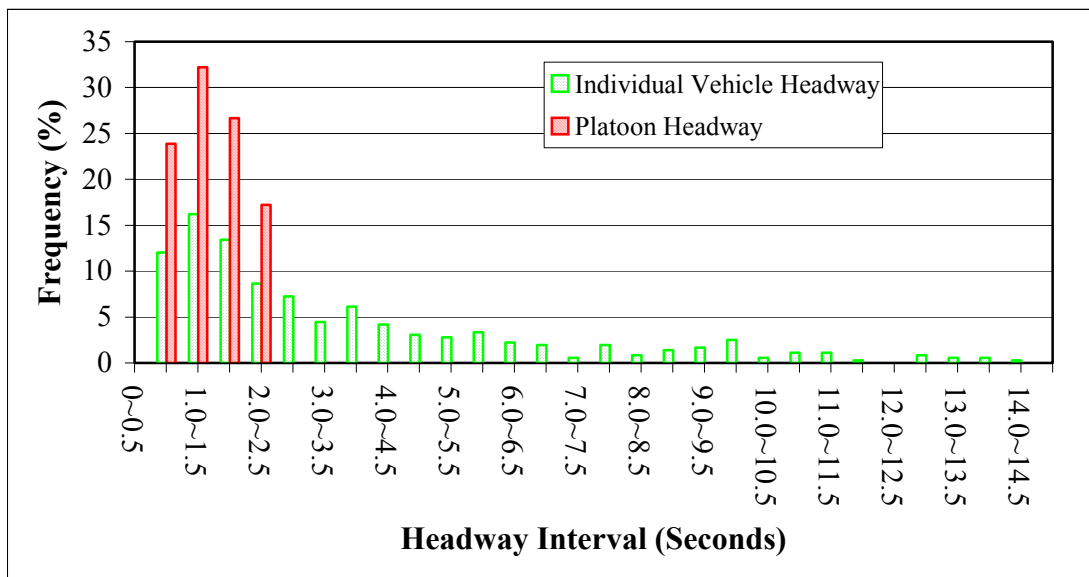
Platoon Size	Negative Exponential		Lognormal	
	Observed Frequencies	Expected Frequencies	Observed Frequencies	Expected Frequencies
<b>Intersection at US-30 one mile east of I-65 (Valparaiso)</b>				
1	93	93.43	39	15.56
2	54	68.74	15	25.40
3	39	50.57	12	17.57
4	27	37.20	7	10.95
5	20	27.37	3	7.14
6	17	20.14	4	4.57
7	13	14.81	3	3.20
8	10	10.90	3	2.18
9	7	8.02	2	1.55
>10	3	5.90	5	4.89
	$\chi^2=11.65 < \chi^2_{0.95}=19.02$		$\chi^2=45.69 > \chi^2_{0.95}=19.02$	
<b>Intersection at US-31 and Apperson Way (Kokomo)</b>				
1	101	62.1	52	32.6
2	49	38.2	24	37.0
3	25	23.5	12	19.0
4	13	14.5	6	9.0
5	7	8.9	2	4.5
6	5	6.5	3	2.3
7	2	3.4	0	1.3
8	2	2.1	0	0.7
9	2	1.3	1	0.4
>10	1	0.8	1	0.8
	$\chi^2=29.6 > \chi^2_{0.95}=19.02$		$\chi^2=24.1 > \chi^2_{0.95}=19.02$	
<b>Intersection at US-52 and Duncan Road (Lafayette)</b>				
1	59.15	77	35	14.09
2	45.44	42	9	22.87
3	34.91	33	4	16.54
4	26.81	29	8	11.13
5	20.60	21	5	4.69
6	15.82	16	3	8.01
7	12.16	13	1	3.65
8	9.34	12	3	2.69
9	7.17	9	1	1.95
>10	5.51	8	8	7.37
	$\chi^2=8.35 < \chi^2_{0.95}=19.02$		$\chi^2=55.4 > \chi^2_{0.95}=19.02$	

### **3.2 Platoon Headway Distribution**

A platoon headway is defined as the average of individual headways within a vehicle platoon. This definition is a simplification of the actual headways within a platoon because the individual headways within a platoon are unequal in reality. Since this definition does not change the relative temporal and spatial positions of the vehicle platoons in the traffic stream, the simplification will not affect the characteristics of the platoon-based traffic flows. When analyzing headway distributions of individual vehicles, lognormal distributions were often utilized to fit headway data (Daou 1964 and May 1965). However, individual vehicle headways and platoon headways differ in statistical characteristics. Figure 3.2 shows the distributions of the individual and platoon headways measured at the US-31 intersection. As can be seen, the platoon headway distribution exhibits a symmetrical pattern while the individual vehicle headway distribution skews to the left and spreads over a wide range. The difference in distributions is attributed to the fact that the maximum platoon headway is limited to 2.5 seconds, but the individual vehicle headway has no upper limit. The symmetrical pattern suggests that the platoon headways more likely follow a normal distribution rather than a lognormal distribution.

Platoon headway frequencies at two intersections are plotted in Figure 3.3. The platoon headways at both intersections distribute symmetrically around the mode of approximately 1.5 seconds. The goodness-of-fit tests were conducted to determine which of the distribution model, the normal distribution or the lognormal distribution, should be used for platoon headway distribution. As presented in Table 3.2, the platoon

measurements were divided into 6 cells with a headway interval of 0.4 seconds for  $\chi^2$  tests. At a significance level of 0.05, the critical value is  $\chi^2_{0.95}(5)=11.07$ . For the US-52 intersection, the normal distribution is accepted and the lognormal distribution is rejected. However, for the US-31 intersection, both normal and lognormal distributions are accepted. This leads the conclusion that the normal distribution model should be used to represent the platoon headway distributions. Moreover, the test results also indicate that in some cases, such as at the US-31 intersection, the platoon headways could be represented by more than one mathematical distribution. Generally, when more than one mathematical distributions can be utilized, it is advisable to choose a model that can simplify the analysis procedure without sacrificing the accuracy. Since the normal distribution is simpler to use than the lognormal distribution, the normal distribution should be selected.



**Figure 3.2. Distributions of Individual Headways and Platoon Headways**

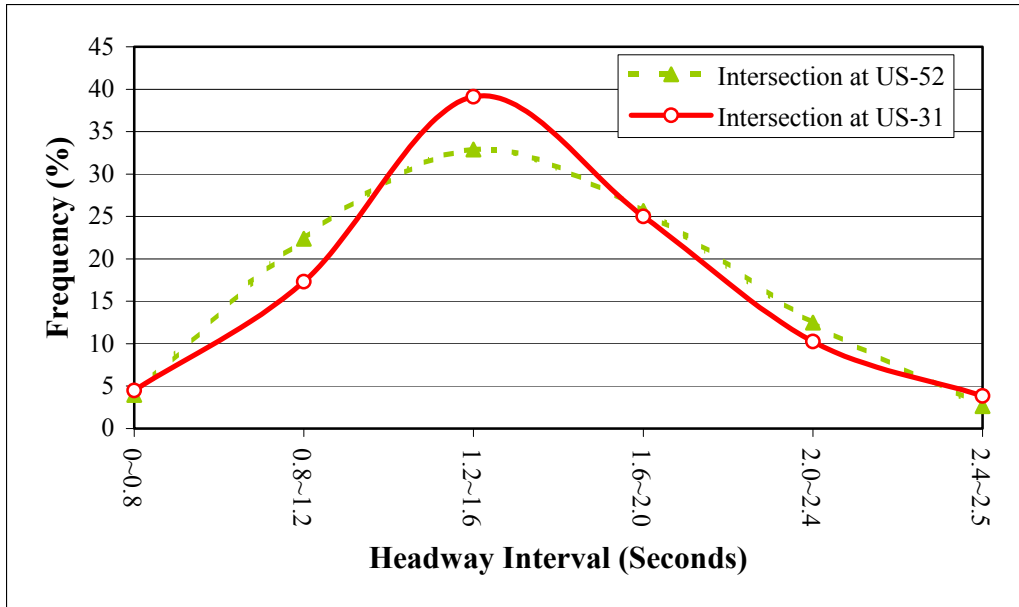


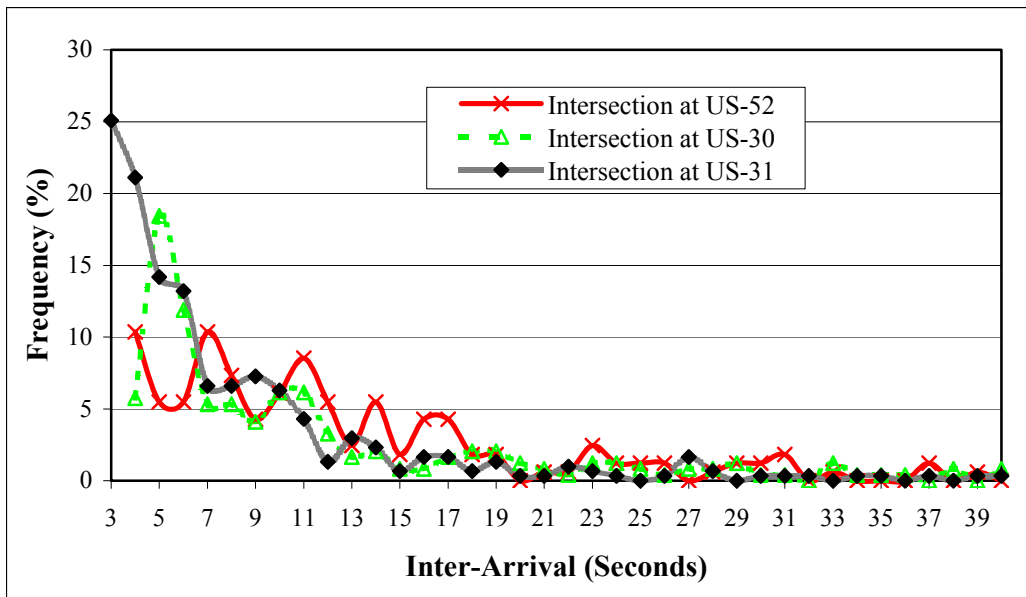
Figure 3.3. Measured Platoon Headway Distributions

Table 3.2. Goodness-of-Fit Tests for Platoon Headway Distributions

Normal Distribution			Lognormal Distribution		
Platoon Headway (sec)	Observed Frequencies	Expected Frequencies	Platoon Headway (sec)	Observed Frequencies	Expected Frequencies
<b>Intersection at US-52 and Duncan Road (Lafayette)</b>					
< 0.80	6	6.68	< 0.80	6	1.92
0.80 ~ 1.20	34	25.75	0.80 ~ 1.20	34	31.39
1.20 ~ 1.60	50	50.78	1.20 ~ 1.60	50	58.29
1.60 ~ 2.00	39	46.25	1.60 ~ 2.00	39	38.92
2.00 ~ 2.40	19	19.45	2.00 ~ 2.40	19	15.80
>2.40	4	4.10	>2.40	4	6.68
$\chi^2=3.824 < \chi^2_{0.95}=11.07$			$\chi^2=16.56 > \chi^2_{0.95}=11.07$		
<b>Intersection at US-31 and Apperson Way (Kokomo)</b>					
< 0.80	7	9.5	< 0.80	7	3.8
0.80 ~ 1.20	27	31.2	0.80 ~ 1.20	27	39.9
1.20 ~ 1.60	61	53.0	1.20 ~ 1.60	61	58.6
1.60 ~ 2.00	39	42.9	1.60 ~ 2.00	39	34.6
2.00 ~ 2.40	16	16.2	2.00 ~ 2.40	16	13.4
>2.40	6	3.12	>2.40	6	5.8
$\chi^2=5.46 < \chi^2_{0.95}=11.07$			$\chi^2=8.02 < \chi^2_{0.95}=11.07$		

### 3.3 Platoon Inter-Arrival Time Distribution

A platoon inter-arrival time is defined as the time interval between two successive platoons. That is, a platoon inter-arrival time is the headway between the last vehicle of a vehicle platoon and the first vehicle of the following vehicle platoon. Figure 3.4 illustrates the distributions of platoon inter-arrival times measured at three intersections. It is observed that all three distribution curves skew to the left with a similar trend. The platoon inter-arrival times range from 3 seconds to 40 seconds. The minimum observed platoon inter-arrival time is restricted by the critical headway of 2.5 seconds. Table 4 summarizes the goodness-of-fit test results for normal and lognormal distributions.



**Figure 3.4. Distributions of Inter-Arrival Time Measurements**

To examine the effect of time intervals on data distribution,  $\chi^2$  tests were performed with respect to different number of time intervals. The distributions of the observed platoon inter-arrival times were arranged according to time intervals of 1, 2 and

3 seconds, with 28, 14 and 10 test cells, respectively. Table 3.3 contains the critical  $\chi^2_{0.95}$  values and the computed  $\chi^2$  values for the respective number of test cells. These values indicate that all the computed  $\chi^2$  values exceed the corresponding critical  $\chi^2_{0.95}$  for the normal distribution and all the computed  $\chi^2$  values are below the corresponding critical  $\chi^2_{0.95}$  for the lognormal distribution. That is, with a significant level of 0.05, the lognormal distribution model is accepted and the normal distribution model is rejected for the platoon inter-arrival time distribution. The values in the table also show that as the time interval increases (or the number of test cells decreases), both the critical  $\chi^2_{0.95}$  and the computed  $\chi^2$  values decreases.

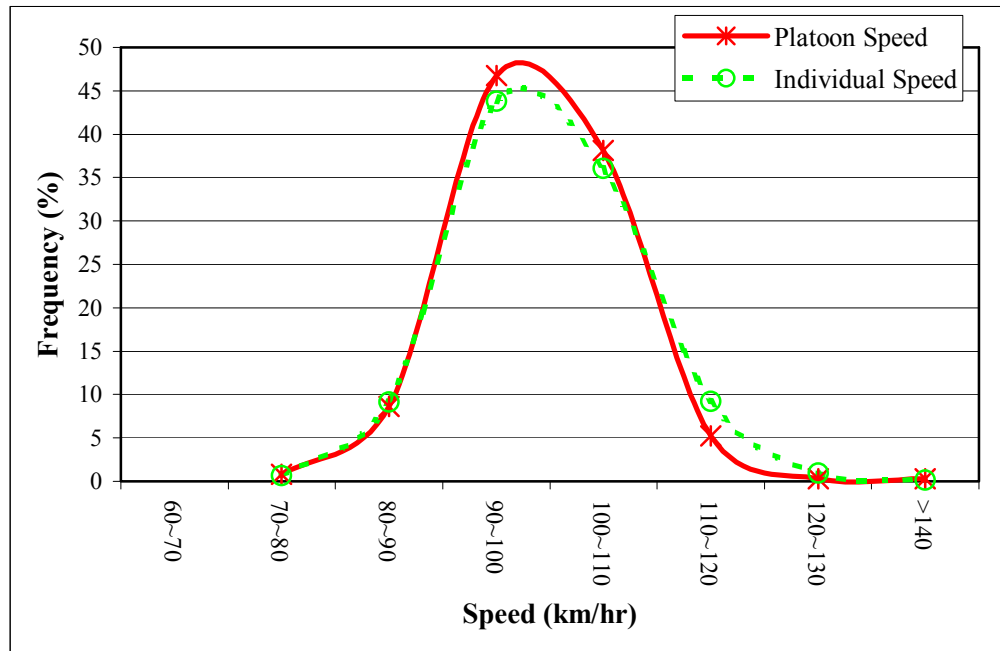
**Table 3.3. Goodness-of Fit Tests for Platoon Inter-Arrival Times**

Intersection	Interval	Number of Test Cells	$\chi^2_{0.95}$	Computed $\chi^2$	
				Normal	Lognormal
US-30	1 second	28	40.11	115.82	24.52
	2 seconds	14	22.36	86.17	11.74
	3 seconds	10	16.92	74.24	9.27
US-52	1 second	28	40.11	126.00	28.33
	2 seconds	14	22.36	88.95	18.75
	3 seconds	10	16.92	79.83	14.62

### 3.4 Platoon Speed Distribution

Platoon speed is defined as the average speed of all vehicles in a platoon. Although the individual vehicle speeds within a platoon may not be exactly the same, the differences in vehicle speeds are expected to be minimal because of the constraint of the pre-determined critical headway. Plotted in Figure 3.5 are the distributions of the individual speed measurements and the platoon speed measurements at the US-31

intersection. The similarities of the two speed distributions are clearly illustrated by the two curves. Both the normal (Leong 1968) and lognormal (Haight and Mosher 1962) distribution models have been utilized for individual vehicle speeds. It appears in Figure 3.5 that the normal distribution may better represent the natural shape of the speed distribution.



**Figure 3.5. Individual Speed and Platoon Speed Distributions**

Table 3.4 presents results of the  $\chi^2$  goodness-of-fit tests conducted to fit the normal and lognormal distributions to the platoon speeds measured at the US-31 intersection. The critical  $\chi^2_{0.95}$  value at a significant level of 0.05 is 11.07. Compared to the computed  $\chi^2$  values, the normal distribution is accepted and the lognormal distribution is rejected. Therefore, the normal distribution model is recommended for the platoon speed distributions.

**Table 3.4. Goodness-of Fit Tests for Platoon Speeds**

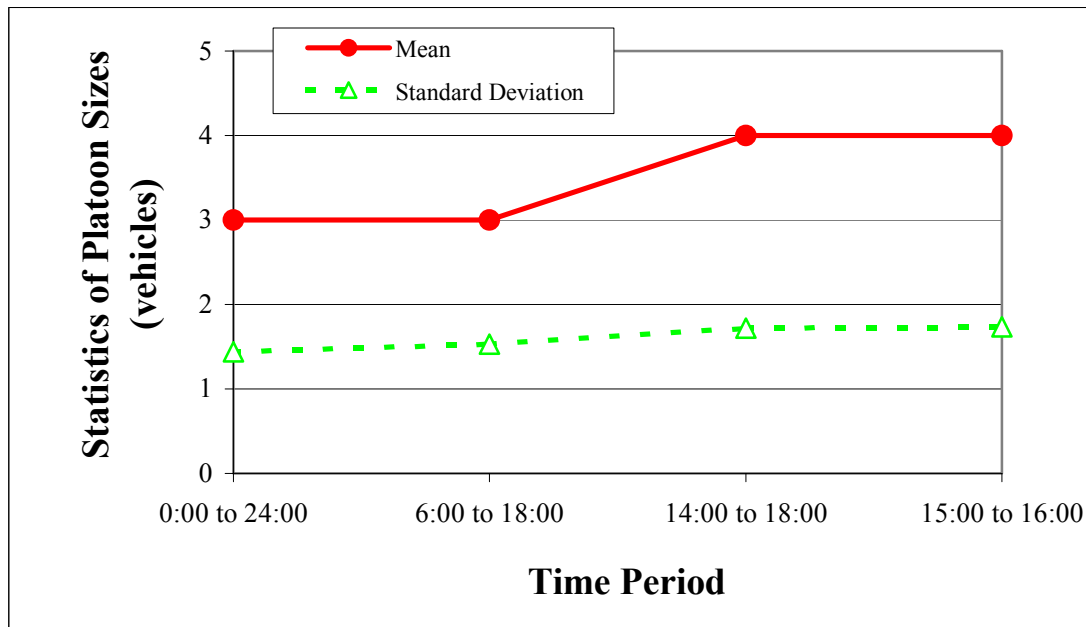
Normal Distribution			Lognormal Distribution		
Platoon Speed (km/hr)	Observed Frequencies	Expected Frequencies	Platoon Speed (km/hr)	Observed Frequencies	Expected Frequencies
<b>Intersection at US-31 and Apperson Way (Kokomo)</b>					
0~80	3	1.23	0~80	3	0.50
80~90	33	35.85	80~90	33	34.66
90~100	179	173.58	90~100	179	181.43
100~110	146	149.14	100~110	146	141.56
110~120	20	22.67	110~120	20	23.71
>120	2	0.54	>120	2	1.15
$\chi^2=7.34 < \chi^2_{0.95}=11.07$			$\chi^2=14.03 > \chi^2_{0.95}=11.07$		

### 3.5 Basic Characteristics of Platoon Variables

Basic statistics of platoon variables, such as mean and standard deviation, are the basis of the platoon variable characteristics. As traffic flow rates change continuously, the platoon characteristics vary during different time periods. To reveal the statistics of platoon variables, the platoon traffic data was collected and analyzed with respect to four time durations. They include a 24-hour period, a 12-hour day time period, a 4-hour period covering before, during, and after a peak hour, and a one peak hour period. Since this study deals with only isolated intersections in rural or semi-urban areas, traffic flows are almost always non-congested at the selected intersections. The calculated statistics of platoon sizes, platoon headways, platoon speeds, and platoon inter-arrival times are presented in Figures 3.6, 3.7, 3.8, and 3.9, respectively. It should be noted that the non-platoon vehicles are not included in the platoon size statistics. This is different from

the platoon size distribution analysis that treated these vehicles as single-vehicle platoons in order to simplify the distribution model.

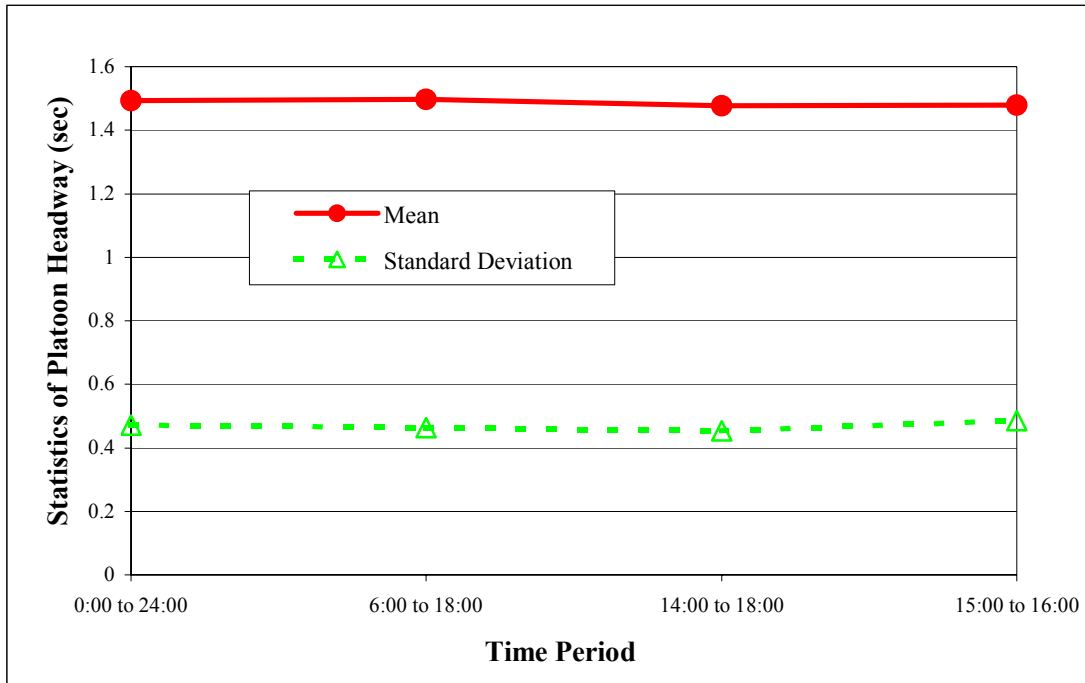
As demonstrated in Figure 3.6, the mean platoon size is 3 vehicles for the 24-hour and the 12-hour periods, and 4 vehicles for 4-hour and 1-hour periods. The standard deviation also increases slightly as the time period shortens. This implies that as traffic volume increases, the mean platoon size decreases with slight greater standard deviation. The fact that the mean platoon size increased only by one vehicle indicates that the majority of platooned vehicles travel in groups of 3 to 4 vehicles.



**Figure 3.6. Statistics of Platoon Sizes during Different Time Periods**

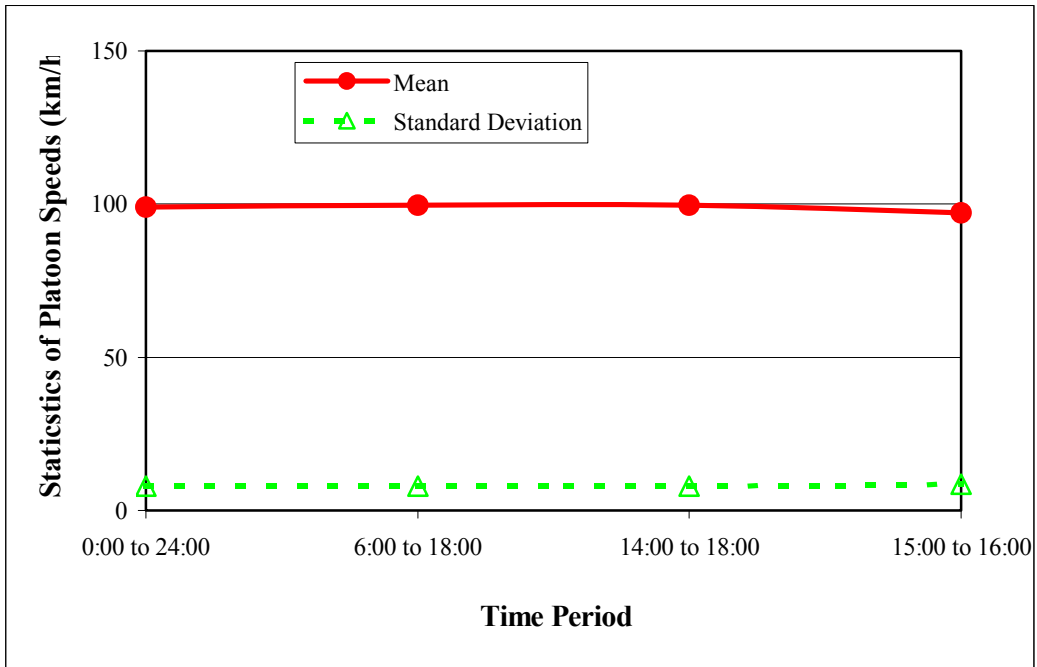
Figure 3.7 clearly reveals the stability of platoon headways under different traffic conditions. The means of platoon headways range from 1.47 to 1.50 seconds and the standard deviations are between 0.45 and 0.49 seconds for the four time periods. As defined early, a platoon headway is the average value of headways of all vehicles within

a platoon. The statistics of platoon headways also indicate that the perceived safe headway by motorists is about 1.5 seconds in average. The stability of platoon headway is attributed to the constraints of the perceived safe headway and the pre-determined critical headway value (2.5 seconds).

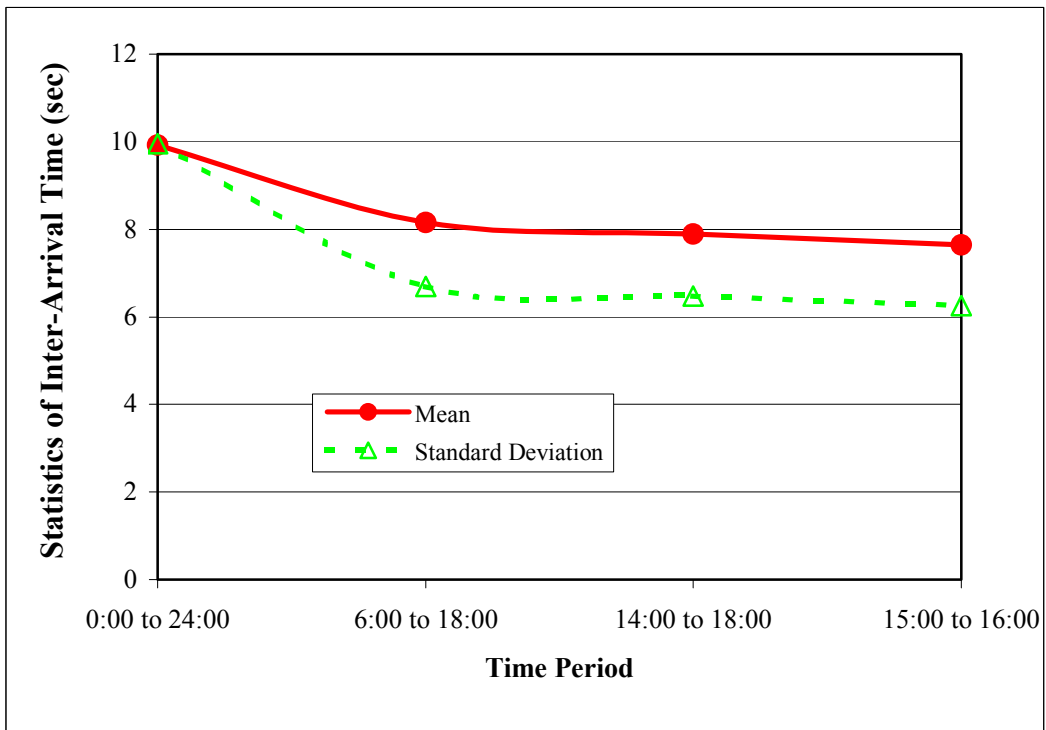


**Figure 3.7. Statistics of Platoon Headways during Different Time Periods**

Figure 3.8 shows that the statistics of platoon speeds are also stable during the four time periods. This was expected because of the fact that the traffic flows were non-congested at the selected intersections. Figure 3.9 exhibits that the values of mean and standard deviation of the inter-arrival time measurements decrease and stabilize as the time period shortens. This means that when traffic volume increases, the headways between vehicle platoons decreases and stabilizes at a certain level.



**Figure 3.8. Statistics of Platoon Speeds during Different Time Periods**

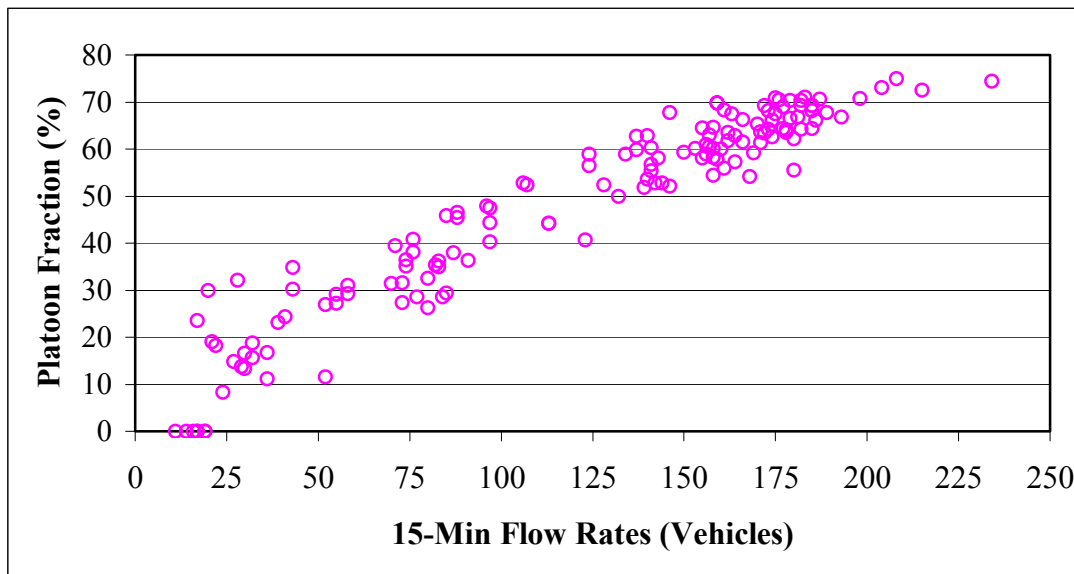


**Figure 3.9. Statistics of Inter-Arrival Times during Different Time Periods**

Based on traffic flow theory, as the traffic flow rate increases, the average headway decreases. When the flow rates increase to a certain level, the average headway will eventually decrease to below the specified critical headway of 2.5 seconds for identifying vehicle platoons. That is, all vehicles will be classified into a very long vehicle platoon at the saturated traffic flow rate. Therefore, the percentage of vehicles belonging to platoons can reach 100% as traffic flow rate increases. This percentage, named platoon fraction, is apparently a function of traffic flow rate. Figure 3.10 illustrates the relationship between the measured platoon fraction and the traffic flow rate. A regression equation between platoon fraction and traffic flow rate was obtained with the measured platoon-based traffic data. The coefficient of determination of the regression is  $r^2 = 0.9213$ .

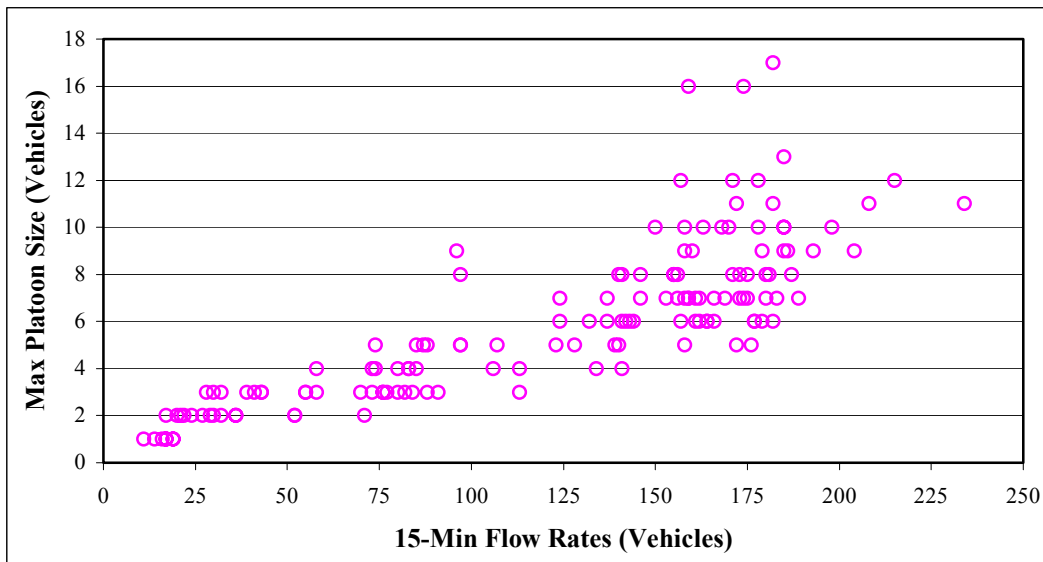
$$P_{\%} = 1.6739q^{0.70822} \quad (3.7)$$

where  $P_{\%}$  = platoon fraction (%), and  $q$  = 15-minutes flow rate (vehicles).



**Figure 3.10. Platoon Fraction and Traffic Flow Rate Relationship**

Similarly, the maximum platoon size is also affected by traffic flow rate and their relationship can also be established through regression. Figure 3.11 shows the relationship between the measured maximum platoon size and the traffic flow rate and Equation 3.8 is the corresponding regression equation (with  $r^2 = 0.905$ ).



**Figure 3.11. Maximum Platoon Size and Traffic Flow Rate Relationship**

$$S_{\max} = 0.1313q^{0.7821} \quad (3.8)$$

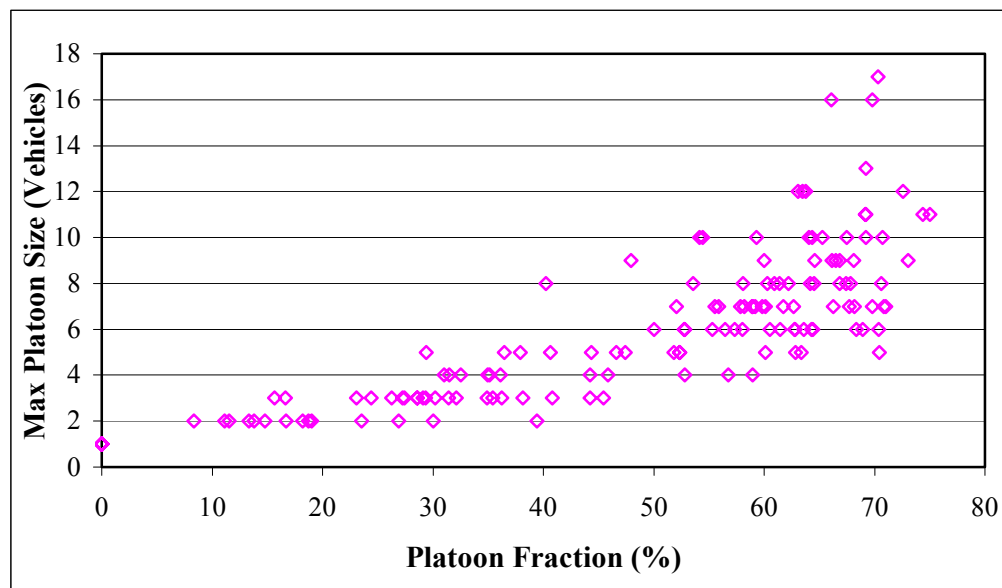
where  $S_{\max}$  = maximum platoon size (vehicles); and  $q$  = 15-minute flow rate (vehicles)

As both the platoon fraction and maximum platoon size increase with traffic flow rate, an effort was also made to establish the relationship between the platoon fraction and maximum platoon size. It can be imaged that when the flow rate becomes saturated, the average headway will be below the selected critical headway, so that the platoon fraction will approach 100% and the maximum platoon size will include all the vehicles

in the traffic stream. Figure 3.12 depicts the relationship between the measured maximum platoon size and the platoon fraction. The regression equation between the two quantities is given below (with  $r^2 = 0.846$ ):

$$S_{\max} = 0.1054q^{0.9624} \quad (3.9)$$

where  $S_{\max}$  = maximum platoon size, and  $P_{\%}$  = platoon fraction (%).



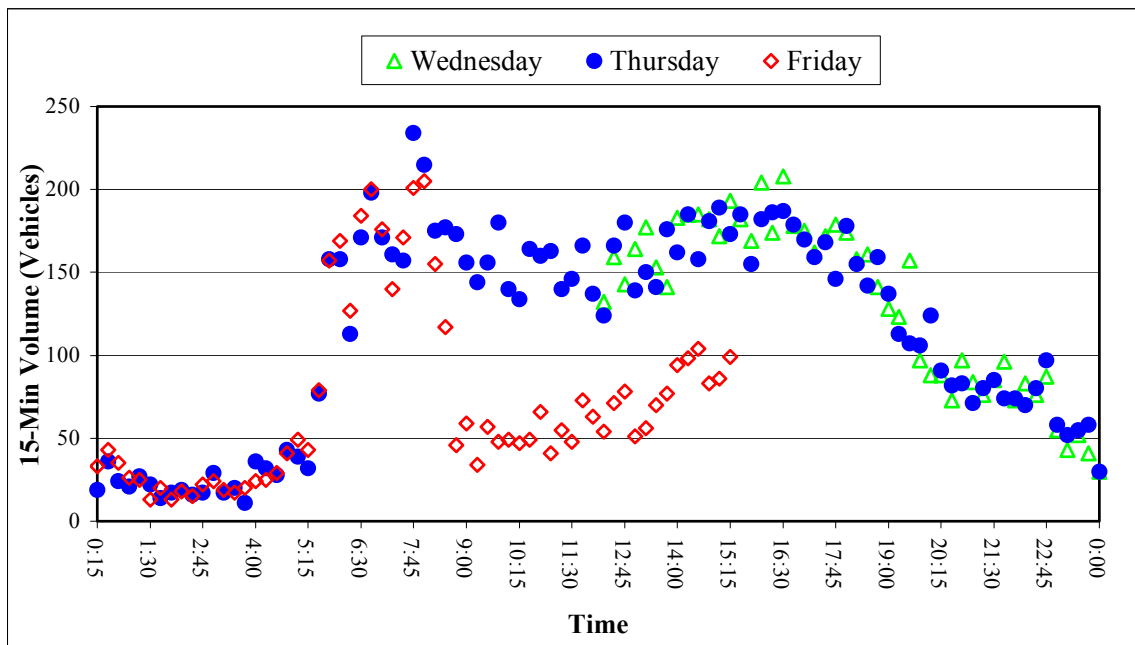
**Figure 3.12. Maximum Platoon Size and Platoon Fraction Relationship**

### 3.6 Variations of Platoon Characteristics

As reported in the Highway Capacity Manual, traffic flows vary by month of the year, day of the week, hour of the day, and sub-hourly intervals within the hour. Because vehicle platoon characteristics depend to a great extent on flow rates, they also vary from time to time accordingly. During peak periods, more vehicles will travel together in groups, and vehicle platoons may become denser and larger. Also, vehicle platoon characteristics exhibit directional variations. A highway corridor serving a city may

experience tremendous vehicle platoons into the city in the morning and out of the city in the afternoon. This section is to present the temporal variations of vehicle characteristics based on the data measured in this study.

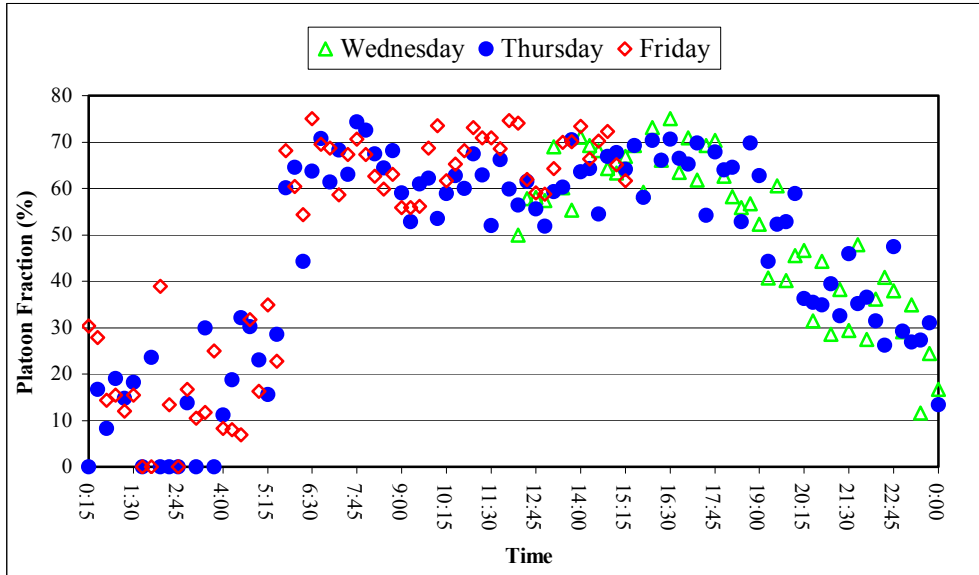
In general, the platoon fraction and the maximum platoon size are the two principal factors we may consider to determine the demand of platoons. In order to examine the daily variations of these two factors, this study measured traffic data at the US-31 intersection in Kokomo continuously for about 50 hours. The data covered three days' measurements, from 12:00 on June 13, 2001 (Wednesday) to 15:30 on June 15, 2001 (Friday). The results are plotted in Figures 3.13 through 3.15.



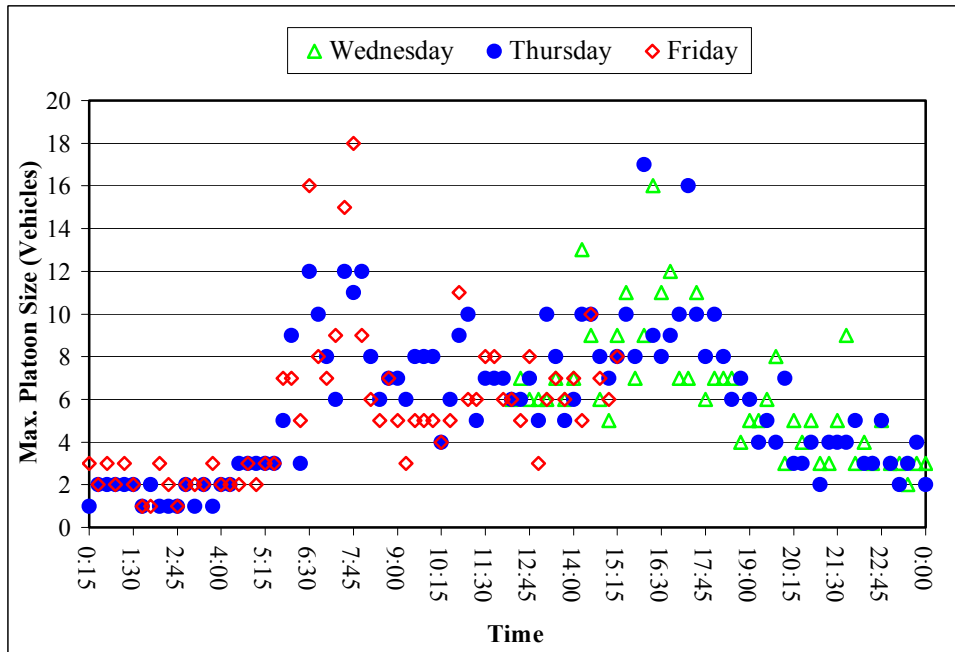
**Figure 3.13. Daily Variations of 15-Min Flow Rates**

As illustrated in Figure 3.13, two evident peak periods were observed over a day, one in the morning, and the other in the afternoon. The variations of 15-min flow rates on Wednesday and Thursday exhibited a similar pattern. On Friday, the variations of 15-

minute flow rates followed the same trend as those on Thursday before 8:00. However, the 15-minute flow rates dropped significantly. Notice that the data were collected on US-31 southbound and the measured vehicles were those traveling into the city.



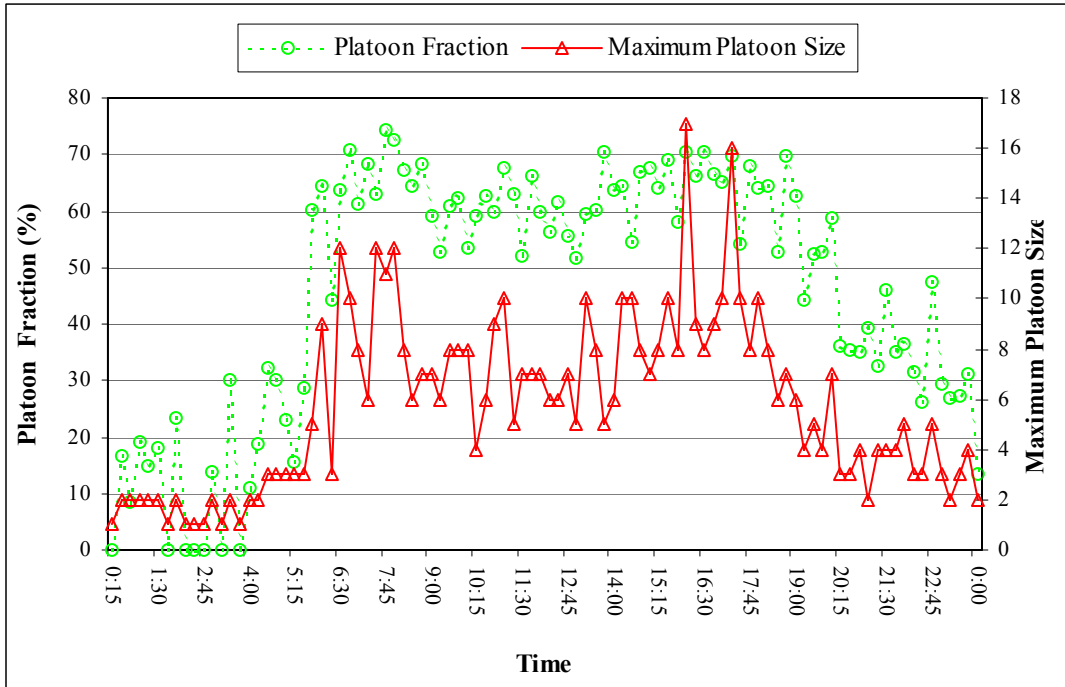
**Figure 3.14. Daily Variations of Platoon Fractions**



**Figure 3.15. Daily Variations of Platoon Sizes**

The daily variations of platoon flows did not exhibit the same pattern as the daily variations of 15-minute flow rates. However, the vehicle platoon flows measured on these three days followed a similar trend as shown in Figures 3.14 and 3.15. The variations of platoon fraction and the maximum platoon size were similar on these three days. This implies that the platoon flows may not experience significant daily variations as the traffic flows. To further investigate the hourly variations of platoon flows, the platoon flows over a 24-hour period (Thursday) are plotted in Figure 3.16.

It is evident that the hourly variations of platoon flows follow the same pattern as the hourly variations of 15-minute flow rates (see Figure 3.13). The platoon fraction and the maximum platoon size increase as the 15-minute flow rate increases. The peak platoon fraction and platoon sizes occur when the 15-minute flow rate reaches its peak value. This is because the platoons are defined using a critical headway. For a specific critical headway such as 2.5-second used in this study, the individual vehicle headways decrease as traffic flow rate increases. As a result, vehicle platoons may become longer and denser. Based on the above observations, it can be concluded that while traffic flow rates may vary daily and hourly, the variations of platoon flows may not exhibit a daily pattern. The platoon flows vary mainly with respect to the traffic flow rates.



**Figure 3.16. Hourly Variations of Platoon Fractions and Platoon Sizes**

## **CHAPTER 4. SIMULATION OF PLATOON-BASED SIGNAL SYSTEM**

As discussed in the preceding chapters, the concept of the platoon-based signal system is proposed only for isolated intersections. In Indiana, such intersections are usually located on highway corridors in the suburban areas. A typical example is US-31 in Kokomo. Kokomo is an essential and integral part of the automotive business of many world class automotive manufacturing corporations. US-31 in Kokomo runs through the industry park with many automotive electronics and transmission plants. During peak hours, the percentage of vehicles in platoon may reach 75%. Therefore, it will result in a great benefit in terms of time saving if the signal system can be designed by taking into account the presentation of vehicle platoons. This chapter presents the logics used to consider platoon characteristics in signal timing. Also presented in this chapter are the algorithms used in development of a computer simulation program for evaluating the resulting delay.

### **4.1 Platoon-Based Signal Timing**

At an isolated intersection of a major road with a minor road, the possible delay depends to a great extent on the traffic conditions on the major road; given the traffic volume on the major road is much higher than that on the minor road. If the traffic volume on the minor road is very low and no traffic signal is needed, delay only occurs on the minor road, and theoretically, no delay will occur on the major road. Oliver (1962) formulated this problem and presented procedures to solve this problem. Once the need of traffic signals is justified, the signal system is usually designed to operate in one of the

following modes: pre-timed operation, semi-actuated operation or full-actuated operation. Because of the constraints involved in these operations, vehicle platoons in main traffic flow may be interrupted again and again. To minimize possible interruption to vehicle platoons on the major road, this study presents a platoon-based operation mode below.

### **Considerations of Platoon-Based Signal Timing**

There are three principal considerations in developing an algorithm for platoon-based signal timing. First, the possible interruption to platoon movements on the major road should be minimized. Therefore, the detector for detecting vehicle platoons on the major road should be installed at an optimal location as discussed in Chapter 2. With an optimal location, the detector should detect more than 85% vehicle platoons so that the controller can respond accordingly. Once the platoon detector location is selected, the passage time for a vehicle to travel from the detector to the stop line is computed below:

$$\Delta g = P_1 = \frac{d_2}{1.468S_1} \quad (4.1)$$

where  $P_1$  = passage time on the major road, seconds

$d_2$  = distance from the detector to stop line on the major road, feet

$S_1$  = approach speed on the major road, mph

A second consideration is the maximum waiting time on the minor road. In order to minimize possible interruption to vehicle platoons, it may require large green time on the major road. As a result, vehicles on the minor road may be required to wait for a relatively large time. To avoid unreasonable waiting time or possible large vehicle queues

on the minor road, a maximum waiting time should be established. However, it should be pointed out that the maximum time varies from person to person. Determination of the maximum waiting is not pure science and requires great experience and expertise. In this study, simulation is employed to verify the maximum waiting time. The third consideration is the minimum green time on the minor road to assure safety. The minimum green time depends on the detector location and can be estimated by assuming a full queue between the stop line and the detector below (McShane et al. 1998):

$$G_{\min} = 4 + 2 \times \left( \frac{d_3}{20} \right) \quad (4.2)$$

where  $G_{\min}$  = minimum green time, sec.  $G_{\min}$  is rounded to an integer.

$d_2$  = distance between detector and stop line on the minor road, ft

4, 2, and 20 = assumed start-up time (sec), saturation headway (sec), and distance between consecutive vehicles in queue (ft), respectively.

The placement of the detector on the minor road depends on the approach speed, the desired minimum green time, and the driveway surrounding conditions. Optimal detector locations can be found elsewhere (JHK 1991) and the passage time on the minor road can be computed accordingly:

$$P_2 = \frac{d_3}{1.468S_2} \quad (4.3)$$

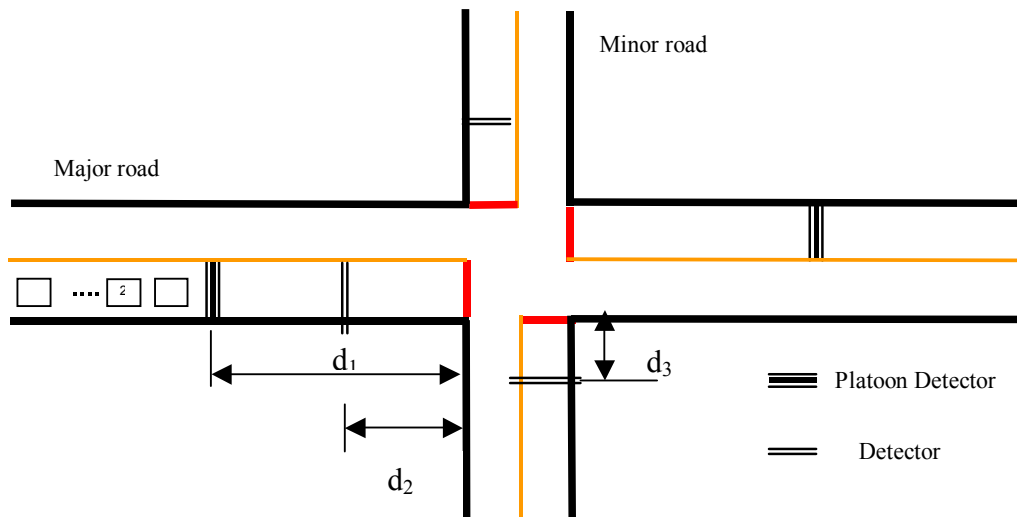
where  $P_2$  = passage time on the minor road, sec

$d_3$  = distance from the detector to stop line on the minor road, ft

$S_2$  = approach speed on the minor road, mph

### **Logics Used in Platoon-Based Signal Timing**

The logics for considering platoon characteristics in signal system timing rely on those factors discussed above, i.e. detection of the platoon arrivals on the major road, maximum waiting time on the minor road, and minimum green time on the minor road. Given an isolated intersection as shown in Figure 4.1, where vehicle platoon is the principal characteristic.



**Figure 4.1. Illustration of an Isolated Intersection**

Assume that the current green phase is on the major road. Once the arrival of vehicles on the major road is detected, the green time is extended by an amount of time below

$$\Delta g_p = P_1 + (n - 1) \times h_1 \quad (4.4)$$

where  $\Delta g_p$  = green time extension for vehicle platoon (seconds)

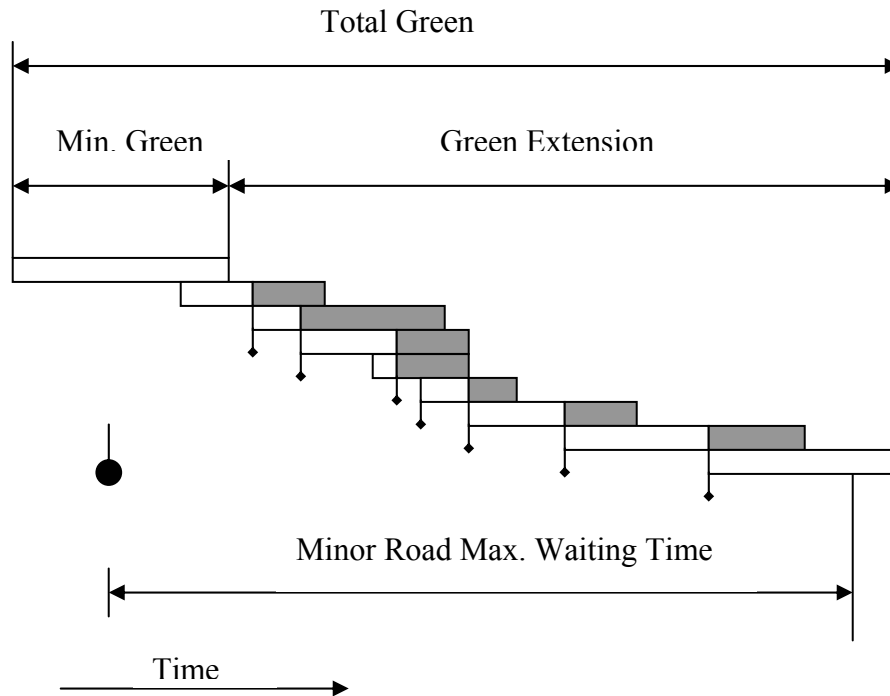
$P_1$  = platoon passage time computed using Equation 4.1 (seconds)

$n$  = platoon size (number of vehicles in the platoon)

$h_1$  = average platoon headway of the vehicle platoon (seconds)

As can be seen in Equations 4.1 and 4.4, the green time extension for an individual vehicle ( $\Delta g$ ) is a constant and the green time extension for a platoon ( $\Delta g_p$ ) changes with platoon size and headway. In addition, when platoon size  $n$  is 1,  $\Delta g_p$  is equal to  $\Delta g = P_1$ . That is, non-platoon vehicles are also included in Equation 4.4 as a special platoon, or a platoon with size 1. The operation of a platoon-based actuated phase on the major road is illustrated in Figure 4.2.

When a green indication is initiated on the major road, it will be retained for at least the specified minimum green time. When a vehicle platoon is detected during this minimum green period, if the unused portion of the minimum green time is larger than  $\Delta g_p$  calculated using Equation 4.4, then no green time extension is needed. Otherwise, an amount of green time equal to  $\Delta g_p$  is added from the time of the actuation. If a subsequent actuation occurs within this green time extension, a new value of  $\Delta g_p$  is calculated and is added to the green from the time of the actuation. It should be noted that  $\Delta g_p$  is not a constant value and it must be calculated for each vehicle platoon detected. This process continues until the green is terminated under one of two conditions: 1) a green extension time elapses without additional actuation, or 2) an actuation occurs after the maximum waiting time for the minor road has been reached.



- Legend
- Detector actuation on minor road
  - ↓ Platoon detector actuation on maior road
  - Unexpired portions of extended green

**Figure 4.2 Operation of Platoon-Based Actuated Major Road Green Phase**

Compared to the conventional actuated signal timing (JHK & Associates 1991), this platoon-based actuated signal control is similar to the individual-vehicle-based actuated signal control in many aspects. However, the platoon-based actuated signal control algorithm possesses the following distinctive properties:

1. A platoon detector must be installed on the major road at an appropriate distance from the stop line. The distance between the platoon detector and the stop line can be determined as described in Chapter 2.

2. A green time extension for the platoon-based control,  $\Delta g_p$ , varies with platoon size and headway, while that for the conventional control is a constant value.
3. The maximum waiting time for the minor road may be exceeded to allow the approaching platoon to pass the intersection under the condition that the platoon is detected before the maximum waiting time is reached. That is, as long as an actuation occurs before the maximum green time is reached, a green time will be added for the approaching platoon even if this added green time will extend beyond the maximum waiting time. The last green time extension in Figure 4.2 illustrates a situation that the maximum waiting time is exceeded to allow a vehicle platoon to pass the intersection. This is different from the conventional control in which the current green phase is terminated as soon as the maximum waiting time on the conflicting phase is reached.

The purpose of this platoon-based actuated control algorithm is to minimize possible interruptions to the vehicle platoons and thus to reduce traffic delays at isolated intersections. A platoon detector must be installed at a sufficient distance from the stop line so that pertinent information on vehicle platoons, such as platoon size and average headway, can be obtained. A green time extension is calculated for each approaching vehicle platoon subject to specified minimum green time for the major road and maximum waiting time for the minor road. It is unique that, in the platoon-based signal control, different vehicle platoons generally require different green time extensions because of their platoon characteristics. In order to avoid a vehicle queue being stopped when switching the green phase to the minor road, the last green time extension of a

major road green phase might extend beyond the specified maximum waiting time as necessary.

The platoon-based signal timing modifies the normal green time to better accommodate vehicle platoons so that the traffic delays associated with stopped vehicle platoons as well as the total delays at the intersection can be minimized. The platoon-based signal timing will inevitably result in negative impacts to the traffic on the minor road. However, the negative impacts will be constrained by the maximum waiting time on the minor road. Furthermore, the negative impacts will also be limited by the fact that the proposed method will only be applied at the intersections with low traffic volumes on the minor road. The detection of vehicle platoons and modification of signal timing can be realized in a similar manner as in Transit Signal Priority (TSP) or Signal Preemption. A recently published report (Baker et al. 2002) provides detailed information on TSP applications. Baker et al. indicated in the report that although signal priority and signal preemption are often used synonymously, they are different processes. Signal priority modifies the normal signal operation process to facilitate the movement of in-service transit vehicles (buses or streetcars) through intersections, while preemption interrupts the normal process for special events such as an approaching train or responding fire engine. The proposed platoon-based traffic signal can therefore be controlled by the mechanism similar to TSP. When a vehicle platoon is detected, the platoon can be treated as an approaching bus and the signal controller can then be activated to accommodate this “bus” according to the proposed green time extension algorithms.

## **4.2 Development of Computer Simulation Program**

There exist many traffic simulation software packages, such as TRANSYT-7F and CORSIM. The existing simulation programs can be employed to analyze traffic signals for both urban streets and rural highways. However, they simulate vehicle flows based on the distributions of individual arriving vehicle at the intersections. No studies or documents were found to address platoon-based signal control simulations. In order to efficiently evaluate the proposed platoon-based signal control algorithm, a computer simulation program was developed based on the characteristics of traffic flows at the selected isolated intersections in Indiana in terms of vehicle platoons. This simulation program, named TraSin, can be used to evaluate traffic delays under platoon-based signal control at given isolated intersections. The simulation program, written with Microsoft Visual Basic 6.0, consists of three major sub-programs, including traffic flow generation, platoon detector location selection, and traffic delay evaluation.

As discussed above, the four key platoon variables, i.e. platoon size, platoon headway, platoon inter-arrival time, and platoon speed, follow the negative exponential distribution, the normal distribution, the lognormal distribution, and the normal distribution, respectively. To simulate platoon-based traffic conditions, random vehicle flows must be generated in terms of the four platoon variables with their corresponding mathematical distributions. This can be achieved by using computer generated random numbers with desired mathematical distributions. Similar to many other computer languages, Visual Basic contains built-in subroutines for generating uniformly distributed

random numbers between 0 and 1. In order to realistically and accurately simulate a platoon variable, a uniformly distributed random number must be converted to a number following a desired distribution. In TraSin, generation of platoon-based traffic flows is achieved by generating uniform random numbers and then converting these random numbers to the numbers following appropriate distributions. Pooch and Wall (1993) present the procedures for conversions of random numbers from uniform distribution to other distributions. The methods for generating random numbers that follow the three types of desired mathematical distributions are given below:

1. If  $r$  is a uniform random number, the  $r$  can be converted to a negative exponentially distributed number  $X$  using the following equation:

$$X = -\bar{X} \ln(r) \quad (4.5)$$

where  $\bar{X}$  is the expected mean of observed  $X$  values.

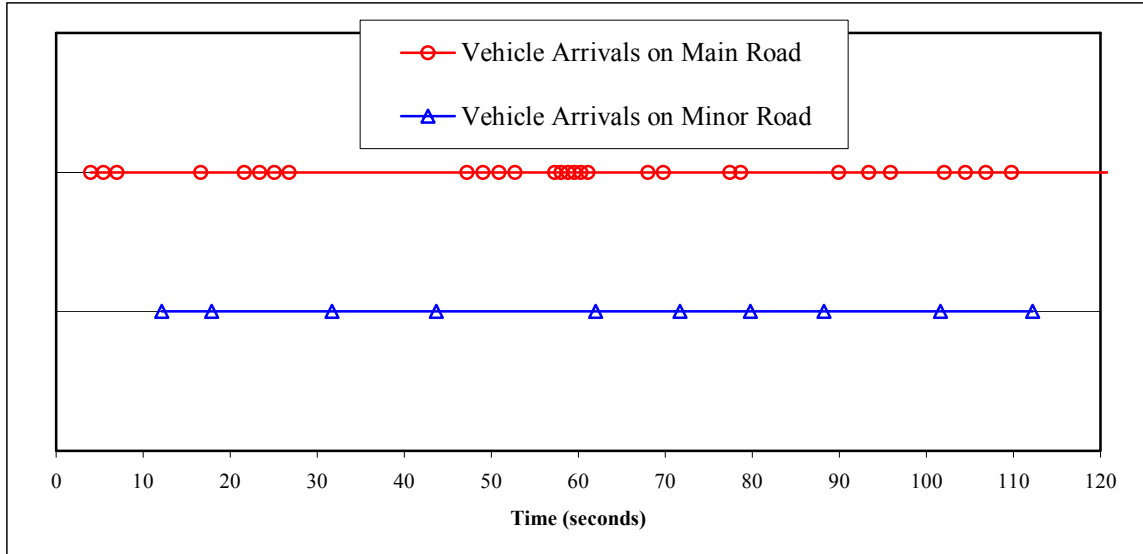
2. To generate one normal distribution random number  $X$ , twelve uniform random numbers should first be generated as  $r_1, r_2, r_3, \dots, r_{12}$ . Summing the 12 uniform random numbers gives  $R = \sum_{i=1}^{12} r_i$ , then  $R$  is a random number from an approximate normal distribution with a mean of 6 and a variance of 1. The corresponding standard normal distribution is  $Z = R - 6$ . This number can be transformed to a normal distribution number  $X$  with a mean  $\mu$  and a variance  $\sigma^2$ :

$$X = \mu + \sigma Z \quad (4.6)$$

3. To obtain a random number with a lognormal distribution, the normal distribution number  $X$  from Equation 4.6 can be assumed to be the logarithm of a measured variable  $Y$ , i.e.  $X = \ln(Y)$ . Therefore, to generate a lognormal distribution number  $Y$ , a normal distribution random number  $X$  should first be generated using Equation 4.6 with twelve uniform random numbers. Then  $Y$  can be calculated using the following equation:

$$Y = e^X \quad (4.7)$$

By generating random numbers with desired distributions, traffic flow on the major road can be simulated in terms of vehicle platoons characterized by platoon size, platoon headway, platoon speed, and inter-arrival time. Traffic flow on the minor road can also be generated according to a series of randomly generated vehicle headways. As illustrated in Figure 4.3, vehicles arriving at a specific intersection can be presented in a unique time sequence.



**Figure 4.3. Simulated Vehicle Arrivals at Intersection**

The simulation program, TraSin, consists of three sub-programs. The first sub-program is designed to generate random traffic characteristics to simulate traffic flow. The second sub-program is used to evaluate detector locations and other design parameters. The third sub-program is to simulate the operation of the signal system and compute average vehicle delays for a given traffic condition at the intersection. Figures 4.4, 4.5, and 4.6 show the three windows of the simulation program, **Start** window, **Input** window, and **Simulation** window, respectively. The **Start** window shows general information about this program. A user can choose to quit the program or to continue executing the program. The **Input** window is for users to input required information such as traffic information and road conditions. The first category of the required information is the statistic results of the platoon characteristics on the major road, including average platoon size, average platoon headway, average platoon inter-arrival, average platoon speed, and the corresponding standard deviations. This information is used to generate the traffic flow on the major road. The second category of the required

information is used to generate traffic flow on the minor road, including average headway, average speed, and the corresponding standard deviations. The third category of the information includes road conditions and other information used to evaluate detector location, passage time and minimum green time. The **Simulation** window is used to perform simulation. Users can set simulation constraints such as maximum waiting time, platoon detector location, and running time.



Figure 4.4. Start Window of TraSin

Traffic Platoon Simulation - Form 2/3: Input

## Basic Information

**I. Platoon Parameters on Main Road**

Size		Headway(s)		Speed(mph)		Inter-Arrival (s)	
Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

**II. Vehicles on Side Road**

Headway(s)		Speed(mph)	
Mean	Stdev	Mean	Stdev
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

**III. Others**

Lane No. on Main Rd (1-Direction):  Approach Speed on Main (mph):

Lane No. on Side Rd (1-Direction):  Approach Speed on Side (mph):

PHF:  v/c Ratio:

Figure 4.5. Input Window of TraSin

Traffic Platoon Simulation - Form 3/3: Simulation

## Simulation

**I. Running Information**

Length of Run (min.)	Max Waiting Time on Side Rd (s)	Pla. Detector Position
<input type="text"/>	<input type="text"/>	<input type="radio"/> Min <input type="radio"/> Max <input type="radio"/> Ave

**II. Simulation Results**

(a) Detector Locations (ft)

Side Road (ft)	Main Road (ft)	
<input type="text"/>	<input type="text"/>	<input type="text"/>

(b) Timing Parameters

	Min Green Time (s)	Passage Time (s)	Yellow and All Red (s)	Max Green Time (s)
Main Road:	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Side Road:	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

(c) Estimated Delays

Main Road (s/veh):  Side Road (s/veh):

Figure 4.6. Simulation Window of TraSin

## **CHAPTER 5. SENSITIVITY STUDIES**

The computer simulation program, TraSin, was developed to address the specific issues associated with use of the platoon-based signal timing at isolated intersections. With this simulation program, users can evaluate potential system performance under user specified traffic conditions. Sensitivity analysis can be conducted to examine the impact of design parameters on the performance of platoon-based signal control in terms of vehicle delays. As application examples, TraSin was utilized to simulate the performance of platoon-based traffic control with specified traffic volumes at an intersection. The effects of traffic flow rate and maximum waiting time on the traffic delays are discussed in the following based on the simulation results.

### **5.1 Effect of Minor Road Traffic Flow Rate**

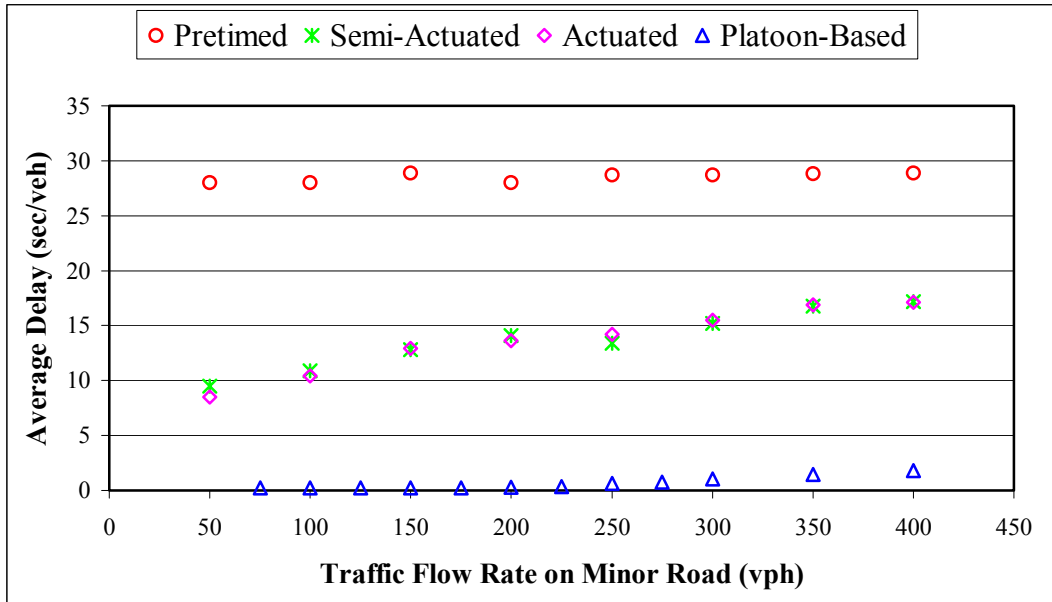
It is emphasized that the platoon-based signal timing algorithm was developed for isolated intersections with relatively high traffic volume on the major road and low traffic volume on the minor road. The purpose of the platoon-based signal timing is to reduced the total traffic delay at an intersection by minimizing potential interruptions to the vehicle platoons on the major road at the expense of increased traffic delays on the minor road. Therefore, the traffic flow rate on the minor road must be sufficiently low in order for the platoon-based signal control to be effective.

To examine the effect of minor road traffic flow rates on traffic delays, computer simulations were conducted using TraSin and CORSIM with assumed intersection traffic conditions. In the simulation analysis, it was specified that the traffic flow rate on the

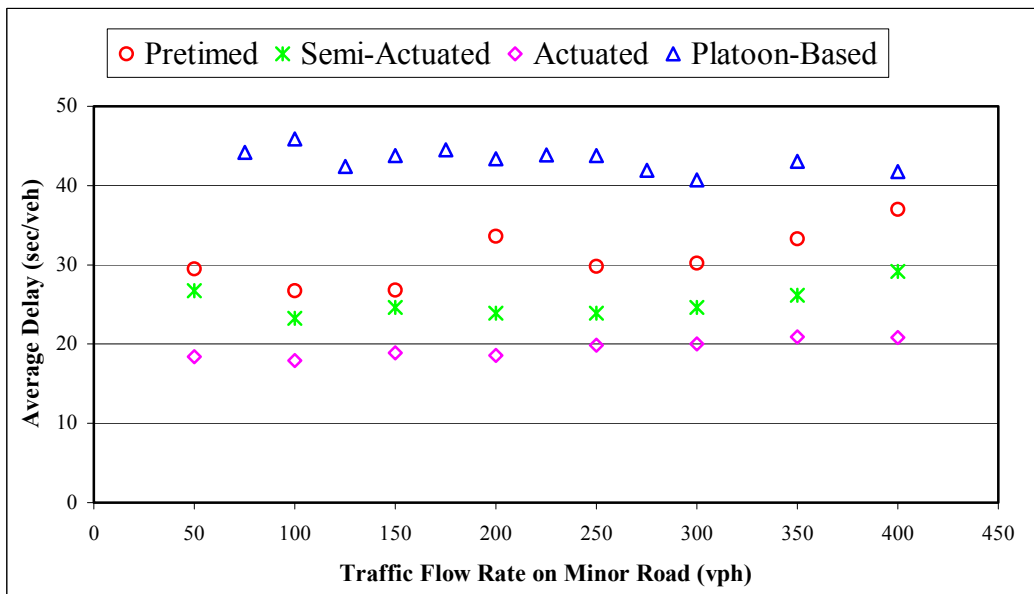
major road was 1000 vehicles per hour (vph) and that the maximum waiting time for the minor road was 90 seconds. The traffic delays were calculated at different levels of minor road traffic flow rates with both platoon-based (TraSin) and individual-vehicle-based (CORSIM) simulations. Three types of individual-vehicle-based signal controls, i.e. pre-timed, semi-actuated, and actuated controls, were simulated with CORSIM. The simulation results of TraSin are compared to those of CORSIM to evaluate the effectiveness of the platoon-based signal control method.

Figures 5.1 and 5.2 show the traffic delays on the major road and minor road at different levels of minor road traffic flow rates. Figure 5.1 indicates that on the major road the pre-timed control would result in the highest delay and the platoon-based control would produce the lowest delay. As the minor road traffic flow rate increases, the simulated delay for pre-timed control remains stable, and the simulated delays for the other types of signal controls increase. Compared to the conventional signal control methods, the platoon-based signal control produced much lower traffic delay on the major road (Figure 5.1) at the expense of higher traffic delay on the minor road (Figure 5.2). Since the purpose of the platoon-based signal control is to reduce the total delay at an intersection, the performance of the signal control should be evaluated in terms of the total delay at the intersection. Figure 5.3 displays the simulated total delays at the intersection for all signal control modes in terms of vehicle-seconds per hour. The figure shows that the total delay increases as the minor road traffic volume increases and that the platoon-based signal control yields the lowest total delay among the four control methods. The simulation results indicate that the proposed platoon-based signal control

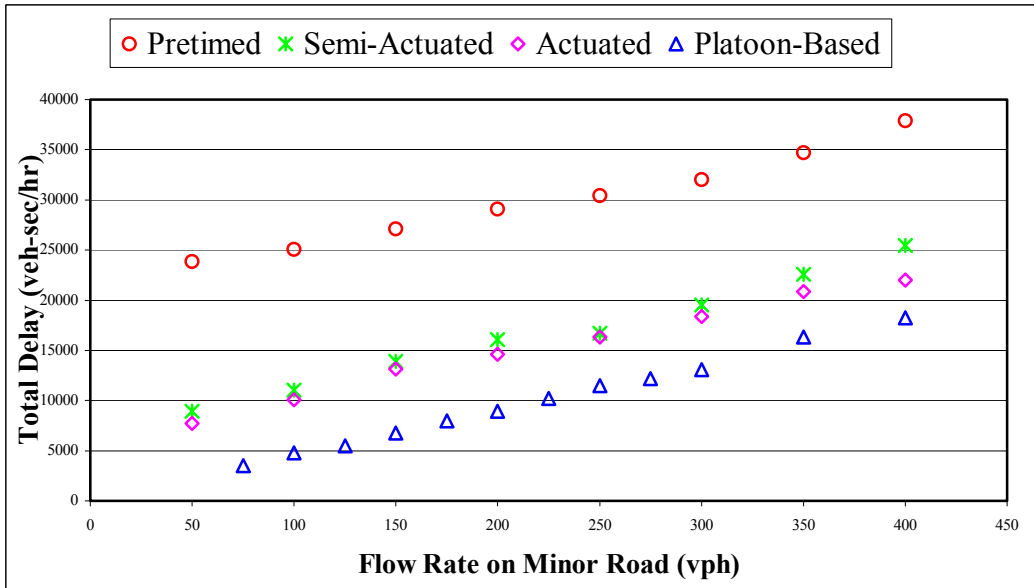
mode can indeed outperform the conventional signal control methods at isolated intersections.



**Figure 5.1. Simulated Average Traffic Delays on Major road**



**Figure 5.2. Simulated Average Traffic Delays on Minor Road**



**Figure 5.3. Total Delays at the Intersection**

## 5.2 Effect of Minor Road Maximum Waiting Time

The maximum waiting time for the minor road is the allowed minor road red time between the first vehicle detector actuation on the minor road and the termination of the red phase on the minor road. This portion of the minor road red time is specified to avoid unreasonable long waiting time on the minor road. The simulation program can be used to analyze the effect of maximum waiting time on traffic delays.

To examine the effect of maximum waiting time, simulations were conducted with TraSin to estimate traffic delays for different maximum waiting times. Two levels of minor road traffic volumes, 30 vph and 100 vph, were utilized for the simulations while a major road traffic volume of 1000 vph was assumed. The simulated traffic delay values are plotted in Figures 5.4, 5.5, and 5.6 for minor road traffic volumes of 30 vph and 100 vph with maximum waiting time values between 30 to 180 seconds. For

comparison purpose, the simulated delays are expressed as average delays in terms of seconds per vehicle (sec/veh). Figure 5.4 shows that the average delay on the major road decreases as the maximum waiting time increases for both minor road volumes. Figure 5.5 indicates that the average delay on the minor road increases as the maximum waiting time increases. The two figures also show that the average delays for the two levels of minor road traffic volume are not significantly different and follow very similar patterns. The patterns of delay changes in Figures 5.4 and 5.5 are as expected because more vehicle platoons on the major road are allowed to pass the intersection without stopping while the vehicles on the minor road would have to endure a longer waiting time.

Figure 5.6 illustrates the total average delay at the intersection, which was obtained by multiplying each average delay with its respective traffic volume and dividing the sum of the two products by the total traffic volume. For the minor road traffic volume of 100 vph, as the maximum waiting time increases, the total average delay increases. Therefore, for the given traffic volumes (1000 vph for the major road and 100 vph for the minor road), longer maximum waiting time will produce higher traffic delays at the intersection. However, for the minor road traffic volume of 30 vph, the total average delay decreases first and then increases when the maximum waiting time is greater than 45 seconds. This implies that 45-second maximum waiting time will result in a minimum total average delay for the minor road traffic volume of 30 vph. In addition, it can be seen in Figure 5.6 that the curve for 100 vph has a greater slope than that for 30 vph. This means that the effect of maximum waiting time on traffic delay increases as traffic volume on the minor road increases.

It should be pointed out that choosing a maximum waiting time involves a great deal of engineering judgment and experience. Many factors, such as intersection location, traffic flow rates, and drivers' endurance of waiting time, must be considered and often compromised in determining an appropriate maximum waiting time. Currently, there is no agreeable procedure for selecting an optimal value of waiting time. Nonetheless, as shown by the simulation results, simulation analysis should provide a basis for traffic engineers to make better engineering decisions on maximum waiting time.

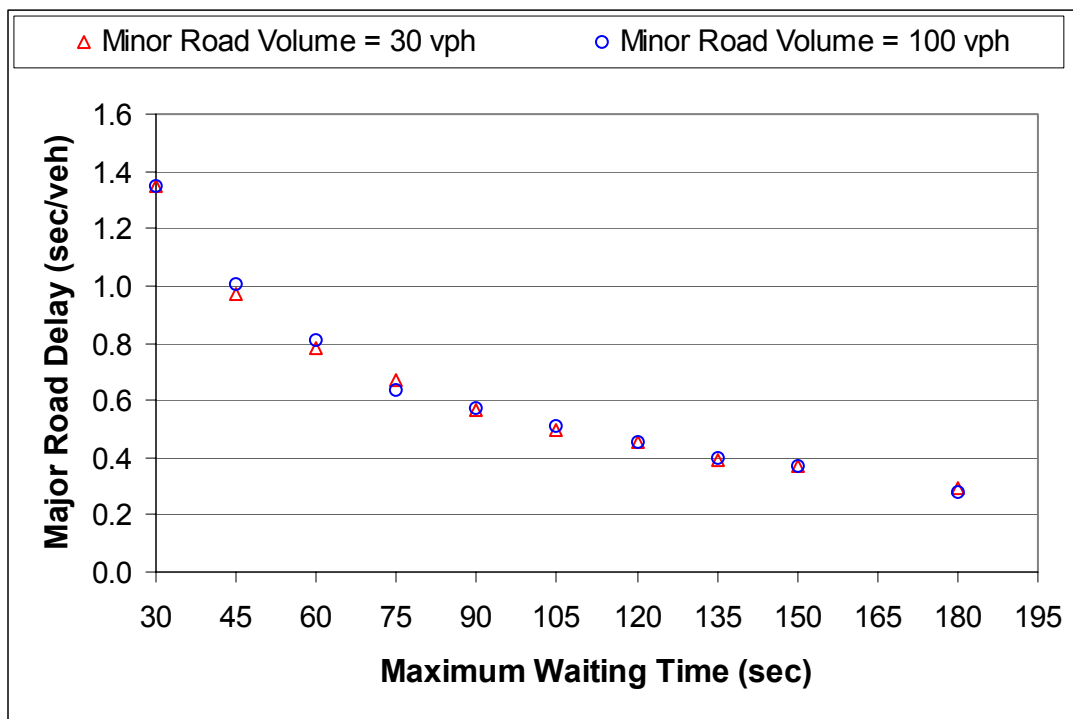


Figure 5.4. Simulated Average Delay on Major Road

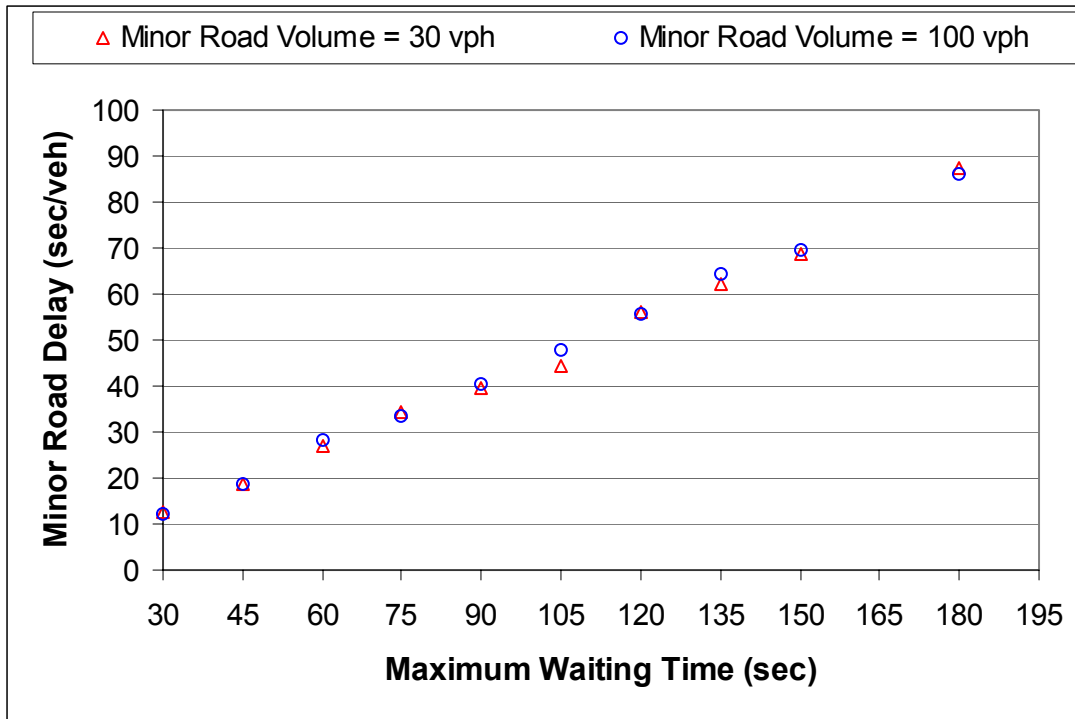


Figure 5.5. Simulated Average Delay on Minor Road

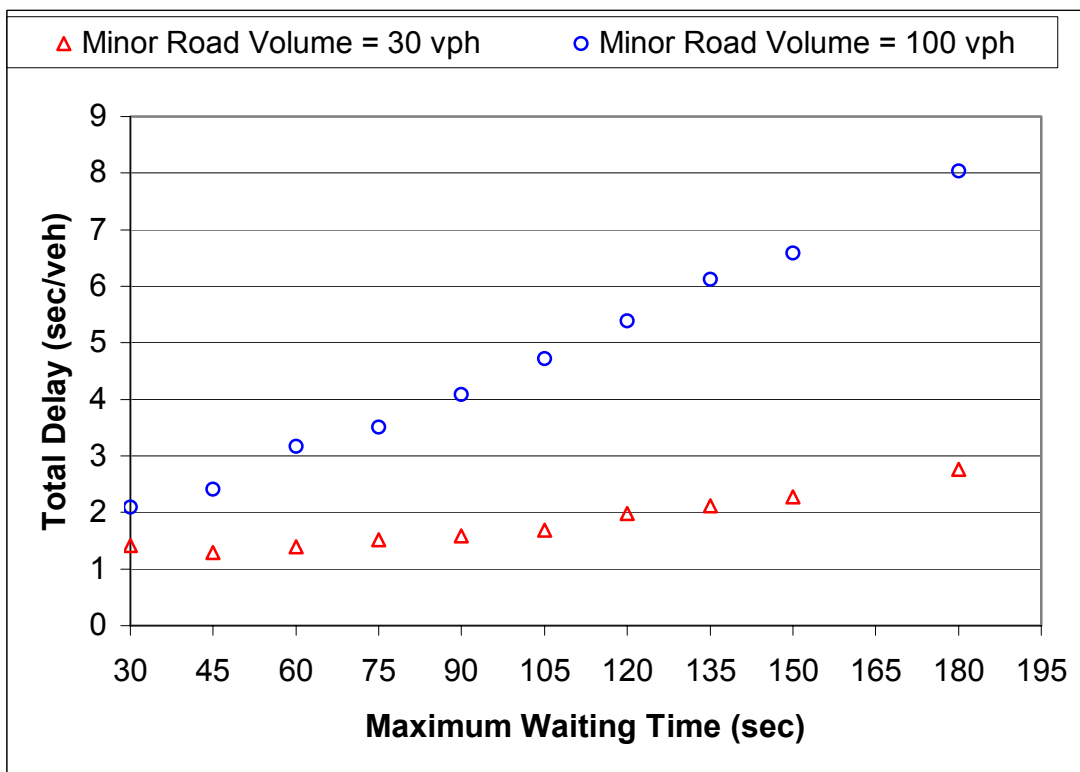
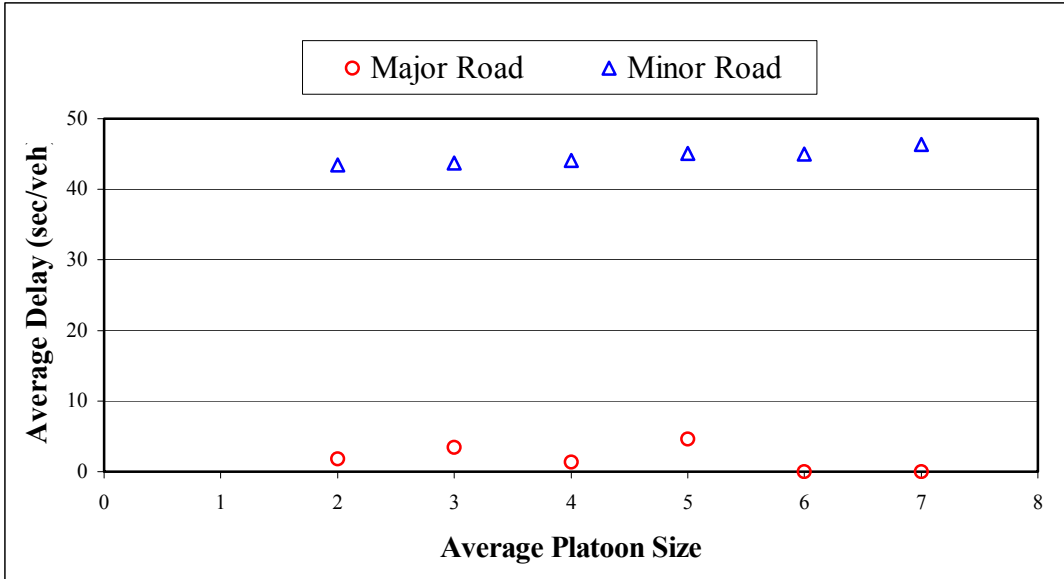


Figure 5.6. Simulated Total Average Delay

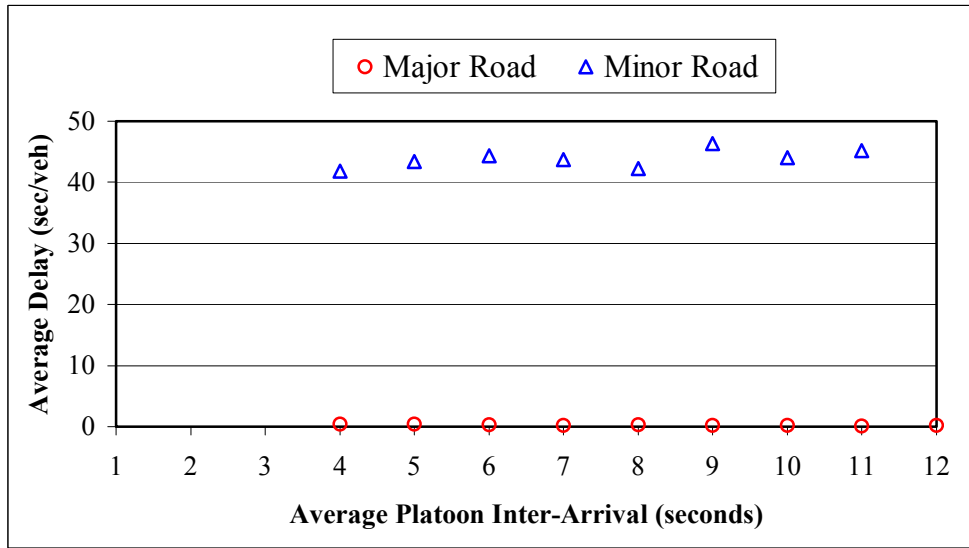
### 5.3 Effect of Platoon Characteristics

In Chapter 2, vehicle platoon is defined in terms of platoon size, platoon headway, platoon inter-arrival, and platoon speed. Also, as shown in Chapter 2, the vehicle platoon characteristics vary from time to time over a specific road because of the fluctuation of the flow rate. As the flow rate increases, more vehicles will travel in platoon. Consequently, the platoon size increases and the inter-arrival time decreases. Therefore, the effect of platoon characteristics on the system performance fundamentally reflects the effect of the flow rate on major road.

Figure 5.7 shows the variations of the estimated delay with the average platoon size. The platoon characteristics were the results of a field survey conducted on US31 in Kokomo, Indiana. This figure was created by only changing the average platoon size. All other values such as platoon headway and platoon inter-arrival were not changed. It is illustrated that as the average platoon size increases, the delay increases slightly on the minor road. However, the delay on the major road fluctuates and no typical relationship exists between the delay and the average platoon size. Figure 5.8 shows the variations of the estimated delay with platoon inter-arrivals. It is illustrated that the effect of platoon inter-arrival on the delay is insignificant, especially on the major road.



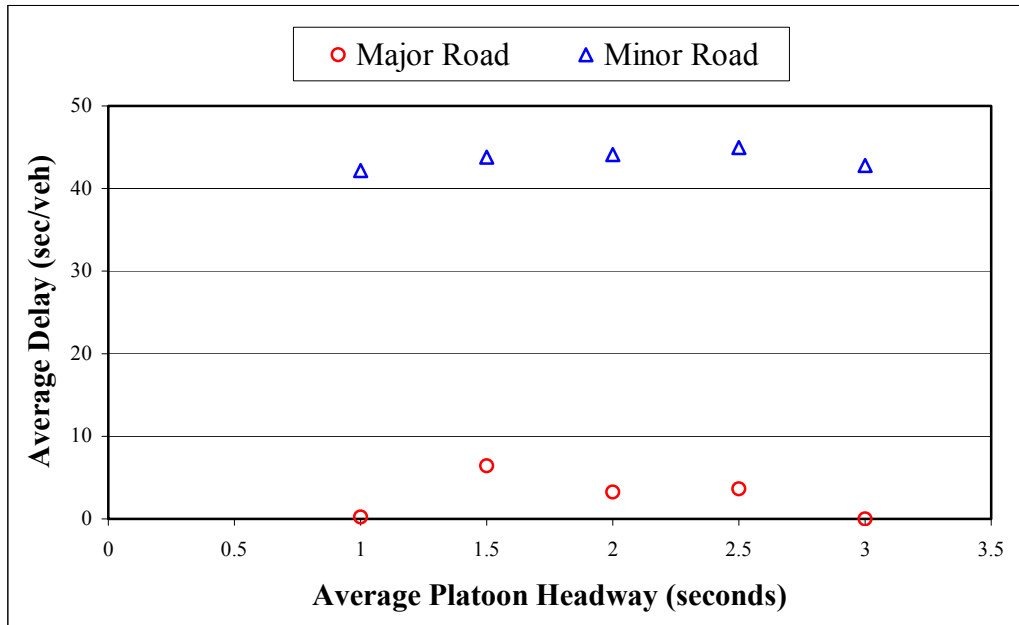
**Figure 5.7. Variations of Average Delay with Average Platoon Size**



**Figure 5.8. Variations of Average Delay with Average Platoon Inter-Arrival**

Small platoon headways indicate dense platoons. If other platoon characteristics remain unchanged, small average platoon headways indicate large flow rates. Figure 5.9 gives the variations of the estimated delay with the average platoon headway. As the average platoon headway increases, the estimated delays on both main and minor roads

increases, and then decreases. The largest delay on the major road occurs when the average platoon headway is 1.5 sec. It should be noted that when the platoon detector location changes, the results may change.

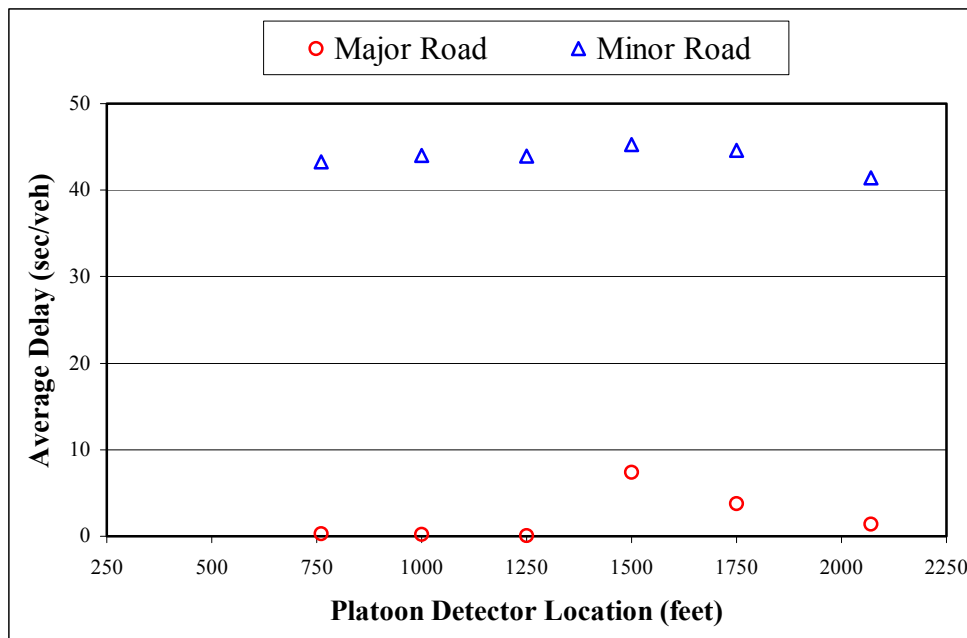


**Figure 5.9. Variations of Average Delay with Average Platoon Headway**

#### 5.4 Effect of Platoon Detector Location

As mentioned in the preceding chapters, the location of platoon detector on major road is one of the most important parameters for platoon-based signal timing. Chapter 2 presents two equations for estimating the minimum and the maximum locations on the basis of the platoon characteristics measured over a specific road. An optimal platoon detector location also depends on other factors as discussed in Chapter 2. With the **TraSin** simulation program, we can estimate the resultant delays due to different platoon detector locations. Those estimated delays are the essential information for quantifying costs or benefits in economic analysis.

Figure 5.10 shows the variations of the estimated delay with platoon detector location. The estimated minimum and maximum platoon detector location are 760 ft and 2070 ft, respectively. As demonstrated in Figure 5.10, the platoon detector location has greater effect on the major road delay than on the minor road delay. The largest delays occur when the platoon detector location is placed at a distance of 1500 ft upstream of the intersection. When the detector is placed at other locations, the delay, especially on the major road, drops significantly. It appears that with the **TraSin** simulation program, we can identify the platoon detector location that may result in large delay.



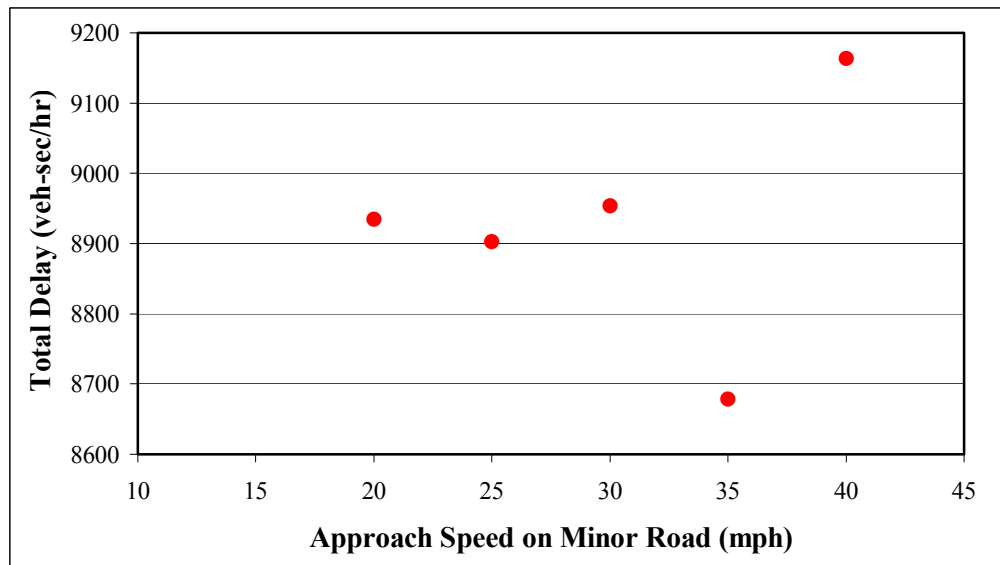
**Figure 5.10. Variations of Average Delay with Platoon Detector Location**

### 5.5 Effect of Approach Speed of Minor Road

While the approach speed of the minor road is another important parameter for platoon-based signal timing, there is no special requirement for the approach speed on the

minor road. Like the approach speed in other operation modes, the approach speed affects the selection of detector location on the minor road, and therefore affects the minimum green time and passage time. Therefore, the minor road approach speed affects the delay, especially on the minor road.

Figure 5.11 shows the variations of the estimated total delay with the minor road approach speed. It is demonstrated that when the approach speed is relatively low, (less than 30 mph in this case), the effect of approach speed is negligible. After the approach speed exceeds 30 mph, the estimated total delay fluctuates significantly. This is because as the minor road approach speed increases, the detector location increases and the minimum green time also increases. It is natural that the possibility to satisfy a larger minimum green time is always less than a smaller minimum green time. Consequently, the delay on the minor road increases. On the other hand, the delay on the major road may also increase so as to give a larger green time to the minor road.



**Figure 5.11. Variations of Total Delay with Approach Speed on Minor Road**

## **5.6 Combined Effect of Design Parameters**

As pointed out above, the above sensitivity studies were conducted by changing one design parameter and maintaining other parameters' values. In reality, the system performance is the result of the combined effect of all design parameters. In order to get a full picture of the system performance, it is advisable for us to combine the effects of a group of individual design parameters that may have close interaction. Graphical summary is useful in displaying these combined effects.

For example, Figures 5.12 and 5.13 show the effect of average platoon headway on the estimated delay when the platoon detector is placed at three different locations, i.e. the minimum, mean, and maximum calculated distances. On the minor road, the greatest delay occurs to the average platoon headway of 2.5 sec when the platoon detector is placed at the maximum distance and the smallest delay to the average platoon headway of 2.0 sec when the platoon detector is placed at the minimum distance. On the major road, however, the largest delay is observed at 2.0-sec average platoon headway when the detector is placed at the minimum distance.

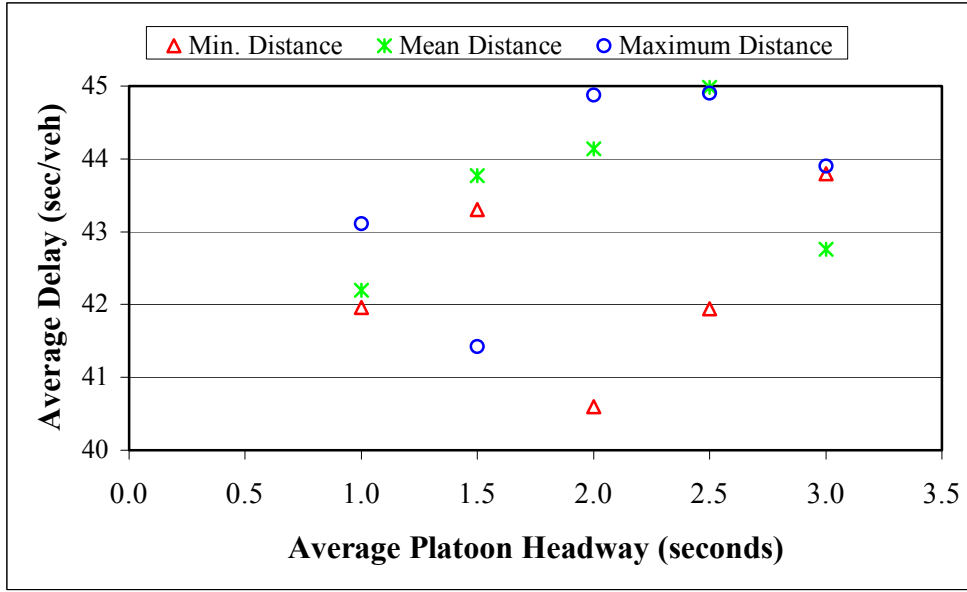


Figure 5.12. Effect of Platoon Headway on Average Delay on Minor Road

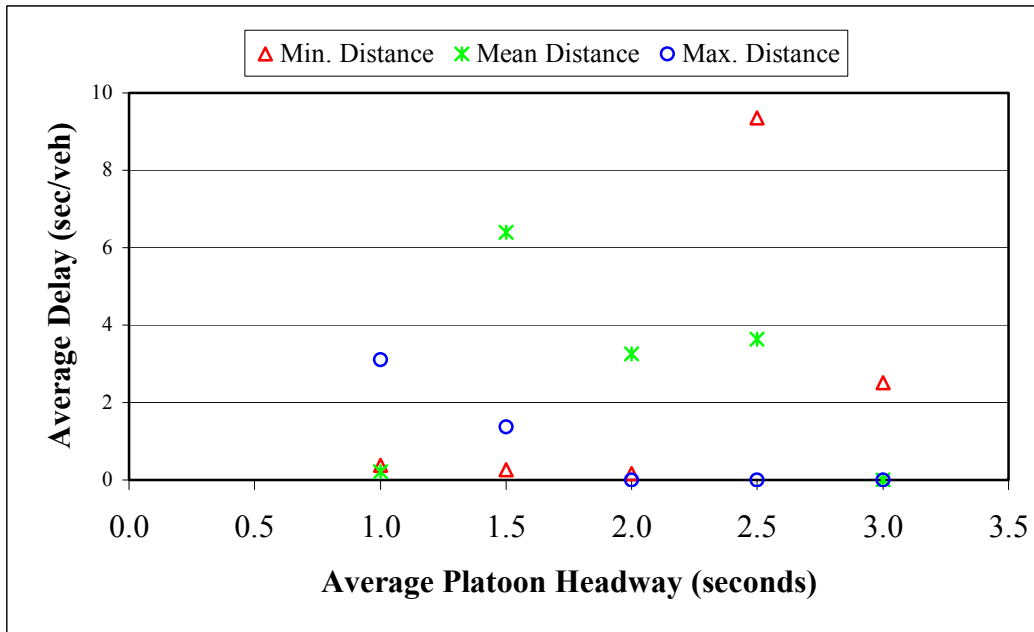


Figure 5.13. Effect of Platoon Headway on Average Delay on Major Road

## CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

Through this study, traffic flow on Indiana rural corridors was analyzed in terms of vehicle platoon movements. Traffic data was collected at selected locations to capture the characteristics of vehicle platoon movements. With the platoon data, the distributions of the vehicle platoon variables were determined. These distribution models were then utilized to formulate platoon generating patterns and to derive a platoon-based control algorithm. In addition, a platoon simulation program was developed as a tool to analyze platoon-based signal controls under different highway layouts and traffic conditions. Generally, the results and findings of this study are as follows.

- To effectively represent the characteristics of a traffic flow in terms of vehicle platoons, the following vital variables must be measured – the platoon size, the average headway of vehicles within the platoon, the platoon speed, and the inter-arrival time between consecutive platoons. These four variables were utilized as a basis for the development of the platoon distribution and simulation models.
- The analysis of the Indiana traffic data indicates that the critical headway is 2.5 seconds, which is the vehicle headway value used to judge whether a vehicle belongs to the same platoon as the vehicle immediately preceding it. This is because the platoon characteristics are relatively stable when the vehicle headway is less than 2.5 seconds. Traffic control in terms of vehicle platoons with this critical value would therefore be effective.
- The equations were derived to determine the optimal locations for platoon detectors. The optimal distance of a platoon detector from the stop line at an

intersection can be computed using the typical values of platoon speed, size, and headway. The equations assure that the produced platoon detector location would enable the detectors to obtain sufficient platoon information without significant variations and also at limited installation and maintenance cost. These equations were verified with collected traffic flow data at several intersections. The verification indicated that the optimal distance of the platoon detector from the intersection stop line ranges from a third of a mile to one mile.

- The distributions of different vehicle platoon measurements were determined through statistical analysis and tests. It was found that the platoons sizes follow the negative exponential distribution, the average headways of vehicles within vehicle platoons have normal distributions, the inter-arrival times between consecutive platoons fit the lognormal distributions, and the platoon speeds suit the normal distributions. The distributions of these platoon measurements are essential for modeling traffic flow with platoons and for developing platoon simulation program. More importantly, they provide a foundation with a new point of view to analyze traffic flows in terms of vehicle platoons.
- The platoon-based signal timing logic was established to allow detected vehicle platoons to go through an intersection before the green light for the major road approach is terminated. This logic would minimize traffic delays under the condition that the maximum waiting time for vehicles on the minor road should not be exceeded.
- The computer simulation program, **TraSin**, was developed based on the developed signal timing logic and the distributions of platoon measurements.

With this simulation program, the optimal detector locations can be determined and the potential system performance can be evaluated in terms of traffic delay. It provides an analytical tool to study various effects of platoon characteristics under different traffic conditions.

Based on the findings listed above, the following implementation items are recommended:

1. INDOT should work with a manufacturer of traffic control devices to design and make vehicle platoon detectors in accordance with the traffic control algorithm developed in this study. Only a few of the detectors will be needed for experimental uses in selected pilot intersection(s). The new detectors will not be drastically different from the conventional vehicle detectors. It is believed that only some minor modifications are needed to convert the conventional detectors to the vehicle queue detectors.
2. Some intersections should be selected to evaluate the platoon-based traffic control system. A “before and after” performance evaluation should be conducted in each of the pilot intersections to examine the magnitude of reductions in traffic delays. Calibration and modification of the platoon-based traffic control mechanism will be made according to the field evaluation.
3. The simulation program will be used in the field evaluation to determine the appropriate values of various parameters of the traffic control system. The actual and simulated performances will be compared so that the platoon-based traffic control model and the simulation program can be further modified and improved.

4. Based on the successfulness of the field trial, the application of platoon-based control method would be gradually expanded in the state.

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