INDIANA DEPARTMENT OF TRANSPORTATION

Research Division

Development of a Platoon-Based Adaptive Traffic Signal Control System

FHWA/INDOT/SPR-2145

Final Report

Project No. SPR-2145

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INDIANA DEPARTMENT OF TRANSPORTATION

December 1999

DEVELOPMENT OF A PLATOON-BASED ADAPTIVE TRAFFIC SIGNAL CONTROL SYSTEM

INDOT Research

TECHNICAL *Summary*

Technology Transfer and Project Implementation Information

TRB Subject Code: 55-03 Traffic Flow Capacity and Measurements
Publication No.: FHWA/INDOT/SPR-2145

December 1999
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INTRODUCTION

Road traffic problems are usually created at intersections where vehicles are often interrupted due to traffic signs and signals. In Indiana, there exist many isolated intersections of major roads with minor roads. It was observed that on those major roads, such as multi-lane highways, the vehicle platoons were predominant traffic characteristics. However, the current traffic control systems could not account for the presence of vehicle platoons, and vehicle platoons were interrupted or stopped very often, leading to a rise in travel time, fuel consumption and pollutant emission. It was thought that if the vehicle platoons were predictable, a platoon-based signal control algorithm could be developed to take the platoon information into consideration so as to minimize interruptions to the movement of vehicle platoons on the major roads.

The objective of this study was to investigate the characteristics of vehicle platoons on Indiana highway corridors, and to develop a control algorithm for timing signals at isolated intersections accordingly. In addition, this study investigated deployment of detectors for acquiring real time platoon information and developed a simulation program for generating and visualizing platoons.

FINDINGS

In the course of performing this study, an extensive review of related literature was performed, and thousands of fundamental traffic measurements, such as arrival time, speed and vehicle classification were made on US52, US30 and other roads. Statistical analysis and site studies were conducted to examine those measurements. The main findings are summarized below.

Vehicle platoons should be characterized using four basic variables, platoon headway, platoon size, inter-platoon headway and platoon speed. With these four variables, the position of a specific vehicle platoon in a traffic flow can be easily determined. The platoon size was defined with a range of one to infinity so as to simplify the application problems and make it possible to use one distribution function to account for both platooned vehicles and single-vehicles.

It is of importance to define an appropriate critical headway in platoon studies. Larger critical headway provides more information, but requires larger detection area and higher installation and maintenance costs. It was found that a 2.5-sec critical headway was reasonable, accounting for about 70% of total traffic volume. Defined using such a critical headway, the platoon behaviors were quite stable.

Based on the χ^2 test results, it was found that the platoon headway and speed could be modeled using the normal distribution function. The inter-platoon headways and platoon sizes distributed with respect to the lognormal and negative exponential distribution functions, respectively. However, it was indicated that by the simulation results, many small values could be produced for the inter-platoon headway and platoon size functions. The coefficients of variations for platoon speed, platoon headway, Platoon size and inter-platoon headway were approximately 10%, 25%, 75% and 80%, respectively.

Deployment of vehicle detectors for acquiring platoon information was determined by assuming that the platoon detection area should account for a typical vehicle platoon. Positions of platoon detectors depend on the platoon size, headway and speed, and varies from several hundred feet to one thousand feet or more. Equations have been developed to establish the lower and upper bounds for determining platoon detector positions.

A platoon-based adaptive signal timing algorithm was derived by giving the priority to vehicle platoons on the major road. This algorithm consists of acquiring real time traffic information on all approaches and computing time saving on current green phase and vehicle delay on current red phase. The decision to maintain or change the current phase is made by comparing the computed saving and delay.

IMPLEMENTATIONS

The traffic measurements can be used by the INDOT Operations Support Division to identify vehicle acceleration and deceleration patterns and arrival sequence, so as to evaluate and upgrade the existing systems. One disadvantage was identified associated with use of current traffic counters during data collection. Suggestions for necessary improvements were made to suppliers. It is believed that future traffic counters should be able to measure vehicle arrival time up to 10ths of a second and provide required accuracy for platoon studies.

This research further investigated how to characterize vehicle platoons. The INDOT Roadway Management and Operations Support Divisions may use the results to study traffic congestion. The platoon simulation program, VPSim can be employed by traffic engineers to get a full picture of vehicle platoon movements. With some modifications, this program will be employed in another JTRP research to generate vehicle platoons at intersections.

This research presented a new dimension to take into account vehicle platoons in signal control systems. The proposed signal control algorithm can be employed by INDOT to re-time those intersections where vehicle platoons are predominant traffic characteristics.

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Joint Transportation Research Program
Project No. SPR-2145

In Cooperation with
U.S. Department of Transportation
Federal Highway Administration

December 1999

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient Catalog No.
FHWA/INDOT/SPR-2145		
4. Title and Subtitle Development of a Platoon-Based Adaptive Traffic Signal Control System		5. Report Date December 1999 6. Performing Organization Code
7. Author(s) Yi Jiang, Shuo Li and Dan Shamo		8. Performing Organization Report No. FHWA/INDOT/SPR-2145
9. Performing Organization Name and Address Indiana Department of Transportation Division of Research and ITS Office 1205 Montgomery Street West Lafayette, IN 47906		10. Work Unit No. 11. Contract or Grant No. SPR-2145
12. Sponsoring Agency Name and Address Indiana Department of Transportation Division of Research 1205 Montgomery Street West Lafayette, IN 47906		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Federal Highway Administration

16. Abstract

Road traffic problems are usually created at intersections where vehicles are often interrupted due to traffic signs and signals. In Indiana, there exist many isolated intersections of major roads with minor roads. It was observed that on those major roads, such as multi-lane highways, the vehicle platoons were predominant traffic characteristics. However, the current traffic control systems could not account for the presence of vehicle platoons, and vehicle platoons were interrupted or stopped very often, leading to a rise in travel time, fuel consumption and pollutant emission. It was thought that if the vehicle platoons were predictable, a platoon-based signal control algorithm could be developed to take the platoon information into consideration so as to minimize interruptions to the movement of vehicle platoons on the major roads. This study investigated the characteristics of vehicle platoons on Indiana highway corridors, and developed a control algorithm for timing signals at isolated intersections accordingly. This study also investigated deployment of detectors for acquiring real time platoon information and developed a simulation program for generating and visualizing platoons.

A large amount of traffic data, such as arrival time, speed and vehicle classification was collected on Indiana highway corridors. Statistical analysis and site studies were conducted to examine vehicle platoon behaviors. It was found that vehicle platoons should be characterized using four basic variables, platoon headway, platoon size, inter-platoon headway and platoon speed. With these four variables, the position of a specific vehicle platoon in a traffic flow can be easily determined. The platoon size was defined with a range of one to infinity so as to simplify the application problems and make it possible to use one distribution function to account for both platooned vehicles and single-vehicles. It is of importance to define an appropriate critical headway in platoon studies. Larger critical headway provides more information, but requires larger detection area and higher installation and maintenance costs. It was found that a 2.5-sec critical headway was reasonable, accounting for about 70% of total traffic volume. Defined using such a critical headway, the platoon behaviors were quite stable. Based on the χ^2 test results, it was found that the platoon headway and speed could be modeled using the normal distribution function. The inter-platoon headways and platoon sizes distributed with respect to the lognormal and negative exponential distribution functions, respectively. However, it was indicated that by the simulation results, many small values could be produced for the inter-platoon headway and platoon size functions. The coefficients of variations for platoon speed, platoon headway, Platoon size and inter-platoon headway were approximately 10%, 25%, 75% and 80%, respectively. Deployment of vehicle detectors for acquiring platoon information was determined by assuming that the platoon detection area should account for a typical vehicle platoon. Positions of platoon detectors depend on the platoon size, headway and speed, and varies from several hundred feet to one thousand feet or more. Equations have been developed to establish the lower and upper bounds for the positions of platoon detectors. A platoon-based adaptive signal timing algorithm was derived by giving the priority to vehicle platoons on the major road. This algorithm consists of acquiring real time traffic information on all approaches and computing time saving on current green phase and vehicle delay on current red phase. The decision to maintain or change the current phase is made by comparing the computed saving and delay.

The traffic data can be used by the INDOT Operations Support Division to identify vehicle acceleration and deceleration patterns and arrival sequence, so as to evaluate and upgrade the existing systems. One disadvantage was identified associated with use of current traffic counters during data collection. Suggestions for necessary improvements were made to suppliers. It is believed that future traffic counters should be able to measure vehicle arrival time in multi-lanes up to 10ths of a second and provide required accuracy for platoon studies. This research further investigated how to characterize vehicle platoons. The INDOT Roadway Management and Operations Support Divisions may use the results to study traffic congestion. The platoon simulation program, VPSim can be employed by traffic engineers to get a full picture of vehicle platoon movements. With some modifications, this program will be employed in another JTRP research to generate vehicle platoons at intersections. This research presented a new dimension to take into account vehicle platoons in signal control systems. The proposed signal control algorithm can be employed by INDOT to re-time those intersections where vehicle platoons are predominant traffic characteristics.

17. Key Words	18. Distribution Statement
Traffic control, isolated intersection, vehicle platoon, critical headway, platoon headway, platoon size, platoon speed, inter-platoon headway, platoon detector, saving and delay.	No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this Page)	21. No. of Pages	22. Price
Unclassified	Unclassified	56	

Form DOT 1700.7 (8-69)

ACKNOWLEDGMENTS

This research project was sponsored by the Indiana Department of Transportation in cooperation with the Federal Highway Administration through the Joint Transportation Research Program. The authors would like to thank the study advisory committee members, Wendal Meyer, Greg Walk and Mahammed Kuadeer, for their valuable assistance and technical guidance.

Appreciation is also expressed to Dr. Darcy Bullock, Associate Professor of the School of Civil Engineering, Purdue University, and Mr. Jay Wasson, ITS Engineer of the Indiana Department of Transportation, for their support during data collection and analysis for this research.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

INTRODUCTION

Many road traffic problems are usually created at intersections, such as traffic delay, traffic safety and traffic pollution. At an intersection, vehicle flows are periodically interrupted due to traffic signs or signals so as to give the right-of-way to the conflicting vehicle flows. As a result, vehicles are often slowed down or stopped within the area of intersection, leading to 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).

The theoretical principles proposed by TRANSYT-7F and CORSIM apply, in large measure, for traffic signal control at rural highway intersections. For example, 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 universal traffic simulation software does not work well. On Indiana highway corridors, many isolated intersections in rural areas consist of intersecting major and minor roads. It is observed that the major road usually has a high traffic volume and the minor road a low traffic volume. Vehicles on major roads usually travel in platoons, especially during peak hours. To utilize the green time and reduce delay further, the platoon characteristics, such as platoon size and headway within a platoon, should be considered in traffic signal timing at such highway intersections.

1.1 Problem Statement and Research Objective

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. It was observed that due to the intermittent interruption of traffic signals, vehicles on the major road usually travel in platoons. In Indiana, the traffic signal timing systems are designed in accordance to Indiana Design Manual (Indiana Dept of Transportation 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 will perhaps be stopped so as 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 further.

HCM (Highway Capacity Manual 1994) has adopted a platoon ratio lettered R_p, taking into account the presence of platoons. R_p is related to vehicle arrival type, and can be pre-calculated when P, the proportion of all vehicles in movement arriving during the green phase is known. The fundamental of R_p is not sound enough and issues may arise from how to determine it. As observed in the field, the number of platooned vehicles (platoon size) changes from time to time, and is not a constant. An arbitrary value of platoon ratio can not represent the real platoon characteristics. It is desirable to achieve the arrival of platoons on green by employing a platoon identification technique and allocating the green phase accordingly.

The objective of this project was to investigate vehicle platoon characteristics and to develop a 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. Although the primary emphasis was given to development of a platoon-based adaptive control logic, there were two secondary emphases: determination of an appropriate deployment of detectors which enables traffic signal systems to identify platoons, and development of simulation program for generating platoons.

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; (3) platoon simulation; and (4) derivation of a signal control logic taking into account platoon characteristics on major roads.

In order to achieve the research objective, the following research approach was adopted in the course of performing this project. First, 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 intersections on US52 and US30 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.

Next, 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. In addition, this simulation program was developed using Visual Basic 5®, which enables users to visualize platoon movements. Following the aforementioned work, a platoon based adaptive logic was recommended for traffic signal timing. Finally, issues associated with implementation of the proposed control logic were identified, and further studies were recommended.

CHAPTER TWO

CURRENT TRAFFIC SIGNAL CONTROL SYSTEMS

A traffic signal control system of high LOS (level-of-service), either a simple two-phase pretimed control system or a complex multi-phase actuated control system, arises from a proper traffic signal design. The design of traffic signals involves determination of signal phase plan and selection of strategy for allocating signal time. In addition, careful detector placements will enhance the performance of signal control system. To achieve a high performance traffic signal design, it requires accurate acquisition of traffic data, better understanding of the prevailing roadway conditions, reliable analytical models and engineering experience. This chapter reviews the research results pertaining to the proposed project, re-examines existing methods and models, and presents the major findings.

2.1 Description of Signal Control Systems

2.1.1 Types of Signal Control

Three main types of signal control are pretimed signal control, semi-actuated signal control and fully actuated signal control (HCM 1994, National Electrical Manufacturers Association 1983, and Kell and Fullerton 1991). One type of signal control may work well at certain intersections, but not necessarily well at others. The selection of signal type should be made on the basis of actual roadway characteristics, traffic characteristics, budget and engineering practice.

Pretimed signal control is operated with a predetermined cycle length, phase plan and phase times. In this form of control, signal rotates in each cycle, and repeats in a fixed sequence. The pretimed signal control is inexpensive in installation, operation and maintenance, since no other equipment is required but a controller assembly. However, it can not respond to changes in traffic conditions, and is less efficient. Therefore, the pretimed signal control is usually used at isolated intersections.

For semi-actuated signal control, vehicle detectors are normally placed on the minor road. The green indication is given to the major road at all times until the detectors on the minor road are actuated. After a preset change interval, the green is given to the minor road, and remains if an additional actuation is received within a predetermined interval. When the maximum green time is reached on the minor road, the green is returned to the major road. In semi-actuated operation, cycle length and green times may vary from cycle to cycle in response to the actual need, and the traffic demand on the minor road is always identified and its green time is fully utilized. At isolated intersections, semi-actuated signal control is often operated in a two-phase plan and the vehicles on the minor road will benefit from the vehicle-actuated features, especially when the gaps in the major traffic stream is not sufficient. However, the vehicle-actuated features can not enhance the effectiveness at most coordinated intersections.

In fully actuated signal control, vehicle detectors are provided for all approaches to the intersection. All signal phases are controlled by detector actuation, and each phase is subject to a minimum and a maximum green time. Cycle length and signal phases can be adjusted from cycle to cycle according to the actual traffic conditions. At isolated fully actuated intersections, there are three controlling parameters: maximum green time, vehicle interval and initial green. In fully actuated operation, the green times are fully utilized. However, as the saturation degrees on all approaches increase, its efficiency worsens. In such situations, the fully actuated operation may function like a pretimed signal control, as allocation of green times is limited among signal phases. This control system is the most often used system at isolated intersections, whereas it is the most complex and expensive control system.

2.1.2 Basic Signal Phase Plan

Phase plan has a significant impact on the effectiveness of signal control system at a signalized intersection. Phase plan is set to determine the number of signal phases and the corresponding sequence. HCM (1994) provides a general guideline for signal phase plan. Usually, two-phase plan is the first consideration in traffic signal design due to its simplicity. In a two-phase plan, a green phase is given to one of the two intersecting roads in turn, and turning vehicles are allowed to proceed based on a permitted mode. As turning volume increases, insufficient gaps in the opposing traffic stream will lead to greater delay.

When left-turn requires protected phase, i.e., left-turn volumes reaches a threshold volume of 100 to 200 vph or the speed of opposing traffic stream is over 40 mph (HCM 1994), a multiphase plan has to be employed. Selection of phases relies on the number of turns requiring protected phasing. However, too many phases will complicate the design and lead to additional delay due to the lost time of each phase. In Indiana, INDOT prefers to use two-phase and six-phase operations (Indiana Department of Transportation 1995).

2.1.3 Vehicle Detection

Vehicle detection is conducted using imbedded vehicle detectors such as inductive loop and magnetic detectors. Reliable vehicle detection requires high performance detectors and thoughtful deployment of detectors. In general, there are two detector configurations: small-area detection and large-area detection. Small-area detectors can be operated in either the presence mode or the pulse mode using short loop or magnetic detectors. Large-area detectors, however, are operated in the presence mode using long loop detectors. Because the selection of detectors is beyond the scope of this project, presented hereafter are only the findings pertaining to the deployment of detectors.

In small-area detection, detectors simply detect the passage of a vehicle at a spot location. Although magnetic detectors can be used, short loop detectors are the most widely used detectors for small-area detection. Small-area detectors are set to have locking detection memory. This locking feature allows a vehicle demand to be held even after the vehicle leaves the detection area, until that demand has been satisfied by the display of green to that phase. Small-area detection is relatively inexpensive, but gives no information between the detector and downstream stop line. Large-area detection operated in the presence mode in conjunction with non-locking detection memory is often referred to as loop-occupancy control. In this detection, a vehicle arriving at the intersection can demand green, and its call is held for as long as the vehicle remains in the detection area. Large-area detection eliminates the blackout observed in the small-area detection, and can be operated very well when platoons are well formed. The disadvantages of large-area detection are higher installation costs and greater maintenance problems.

The SSITE committee (ITE South Section Technical Committee 1974 and 1976) pulled together the most pertinent publications and restated the relationship between detector location and control efficiencies. For a small-are detection, the SSITE summarized four principal and two additional criteria which have been used by different traffic agencies or investigators for determining detector lengths. It concluded that the location or set-back of small-area detectors should be three to four seconds of travel time, but not more than 120 feet.

For a large-area detection with low-speed approaches (less than 25~30 mph), the detector length is estimated using the following equation:

$$L = 1.47V(3 - UE) - 18 \quad \text{.......(2.1)}$$

where L = detector length, ft; V = vehicle speed, mph; UE = vehicle interval, sec; 18 = average vehicle length, ft; 3 = desired allowable gap, sec; and 1.47 = factor converting the vehicle speed from mph to ft/sec. For a large-area detection with high-speed approaches, SSITE recommended the detector length as shown 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)

2.2 Principals for Traffic Signal Timing

Traffic delay is the fundamental for designing traffic signal control systems and evaluating performance of signalized intersections. It is also the key variable in calculation of vehicle operation costs such as fuel consumption and pollutant emission. Furthermore, traffic delay is perceptible and measurable by both motorists and traffic engineers. In essence, traffic delay can be obtained from the so-called Time-Distance diagram (trajectory) for vehicles traveling within the area of an intersection. Following the estimation of traffic delay, a criterion must be determined to time traffic signal. This section presents those models and criteria currently employed for traffic signal design.

2.2.1 Models for Estimating Traffic Delay

Traffic delay is normally estimated in terms of uniform delay and random delay. The basic model for estimating uniform delay at a signalized intersection was derived using queuing theories (May 1965, Newell 1965, Gerlough and Huber 1975). In such theories, vehicles arriving at the intersection are considered as customers waiting for service, and the intersection is the server providing service. When vehicles arrive at a uniform rate q and the queue is dissipated at a uniform rate s, the delay can be calculated using the following equation

$$\bar{d} = \frac{C(1-\lambda)^2}{2(1-y)} \qquad (2.2)$$

where $\bar{d}$ = average uniform delay per vehicle; C = cycle length; λ = g/C (i.e., effective green ratio); y = q/s (flow ratio, i.e., the ratio of actual flow rate q to the saturation flow rate s).

As specified in estimating uniform delay, Equation 2.2 is developed under the assumption that vehicles arrive at a uniform rate q and is dissipated at a uniform rate s. In virtue, vehicles arrive and leave randomly. The assumption of constant q and s will lead to an under-estimate of delay, especially when the intersection becomes saturated. Webster (1958) laid the foundation for evaluating the effects of random arrivals and published a model as follows:

$$d = \frac{C(1-\lambda)^2}{2(1-y)} + \frac{x^2}{2q(1-x)} - 0.65\left(\frac{C}{q^2}\right)^{1/3} x^{(2+5\lambda)} \quad \text{.......(2.3)}$$

where d = random delay per vehicle; x = q/c (i.e., degree of saturation or volume-to-capacity ratio); and the other variables are as defined earlier.

Equation 2.3 consists of three terms. The first term on the right side is the uniform delay as expressed in Equation 2.2, the second term is the effect of random arrivals that can be derived theoretically (Allsop 1972), and the third item is a correction term obtained from simulation data. In general, the effects of the random and correction terms are not significant. While Equation 2.3 works well in most situations, it does not apply when x approaches 1.0. May and Keller (1967) investigated the movement of vehicles at over-saturated intersections (x >1.0) using a deterministic queue model. They estimated delay in terms of a normal delay and an over-saturated delay. Akcelik (1980) also investigated situations where x is close to 1.0 and developed delay a delay model under specific assumptions. HCM (1994) estimates delay in terms of uniform delay and incremental delay as follows:

$$d = d_1 DF + d_2 \quad \text{.......(2.4)}$$

where d = average stopped delay; DF = delay adjustment factor accounting for quality of progression and control type; d_1 and d_2 = uniform delay and incremental delay, respectively, and are expressed as

$$d_1 = \frac{0.38C(1-g/C)^2}{2\{1-(g/C)Min(X,1.0)\}} \qquad (2.5)$$

$$d_2 = 173X^2\left\{(X-1)+\left[(X-1)^2+mXc\right]^{0.5}\right\} \qquad (2.6)$$

where X = degree of saturation for lane group as defined in Equation 2.3; c = capacity for lane group, vph; and m = incremental delay calibration term accounting for the effect of arrival type and degree of platoon. Obviously, the principles underlying the HCM delay models are the same as those adopted by Webster and other investigators.

2.2.2 Criteria for Timing Traffic Signals

Traffic signal control involves determining a proper cycle length, C, and allocating green time to each signal phase under the constraints of traffic and road characteristics. It is natural and simple to develop an algorithm to control traffic signal by minimizing traffic delay. Following this criterion, cycle length and green times for all phases are selected so as to generate a minimum delay, according to actual flow rates, and saturation flows. Therefore, the traffic signal timing can be expressed a nonlinear programming problem, i.e., an optimization model as

$$\begin{aligned} \textbf{Min} \quad & d = f(g_1, g_2, \ldots\ldots g_n) \\ \textbf{s.t.} \quad & g_1 \geq g_1^{min} \\ & g_2 \geq g_2^{min} \\ & \ldots \\ & g_n \geq g_n^{min} \end{aligned} \qquad (2.7)$$

where $f(g_1, g_2, \ldots g_n)$ = objective function; g_i = effective green for the ith phase; and g_1^{min} = minimum green required for the ith phase.

The objective function is usually the sum of delays arising from all lane groups and can be written in form of Equation 2.3. The constraints vary from situation to situation, and usually include a minimum green for safe pedestrian crossing or a maximum cycle length for avoiding a malfunctioning signal, or both. Solving Equation 2.7 requires complex derivation and tedious calculation. For a problem of two signal phases, the solution can be reached by using numerical approaches such as a computer spreadsheet proposed by Winston (1993) and Daganzo (1997). For three or more phases, more sophisticated numerical algorithms are necessary to perform searching for optimal solutions. Webster (1958) did an excellent pioneer study, and derived an analytical expression for determining optimal cycle length by ignoring the third term in Equation 2.3 as follows:

$$C_0 = \frac{1.5L + 5}{1 - \sum y_i} \quad \text{.........(2.8)}$$

where C_0 = optimal cycle; L = lost time per cycle; and $y_i = (q_i/s_i)_c$ (i.e., critical flow ratio for phase i). After C_0 is obtained, it is weighted according to the value of critical flow ratio, and allocated to each phase

$$g_i = \frac{y_i}{\sum y_i}(C_0 - L) \quad \text{.........(2.9)}$$

Miller (1963) proposed an adaptive algorithm based on the criterion of minimizing the total vehicle delay. In an attempt to achieve real time optimal signal operation, his algorithm makes decision to extend a current green phase by examining a control function. This control function is constructed as the difference between the gain made by those vehicles that pass the intersection during the extension and the loss to the vehicles queuing on the intersecting approaches due to the extension. Some tests indicated that the optimizing algorithm could not guarantee better signal operation, whereas most studies demonstrated that adaptive algorithms have the potential to reduce traffic delay (Bang 1976, Lin 1988).

2.2.3 Summary

Traffic signal control design involves selecting control type, planning signal phase, deploying vehicle detectors and optimizing signal time. An efficient signal control system arises from engineering plan, quality data acquisition and reliable timing algorithms. Control type and signal phase plan depend on the real-life traffic and road conditions at intersections, and should be determined by taking into account these conditions in conjunction with local experience and policy. Careful selection of control type and phase plan can achieve efficient use of available time and space. Deployment of detectors should be determined on the basis of vehicle-detector interaction. A thoughtful detector deployment can provide more information on traffic flows in the vicinity of intersection, and therefore enhance the effectiveness of signal control system. Signal timing is perhaps one of the most creative and critical parts in traffic signal control. Due to the great efforts made by worldwide investigators since the late 1950s, tremendous advancement has been observed and traffic signal control systems are now more efficient, reliable, environmentally friendly and safer.

However, problems have been identified associated with the current traffic control systems in certain special situations. First, there is no scheme taking into account the presence of vehicle platoons soundly. This has affected the efficiency of control system and the use of green time, especially at isolated intersections consisting of a major road and a minor road. While those universal software packages, such as TRANSYT-7F and CORSIM, can provide solutions to most situations, they do not necessarily guarantee improved solution to every traffic control problem. Moreover, it appears impractical to employ the existing software such as the TRANSYT-7F in a real control system due to the non-uniqueness and divergence problems. This hassles the intention to use an optimization scheme in the real-world signal control system. A second problem is the fact of the existence of vehicle platoons on highways has been overlooked. In Indiana, the number of vehicles has increased by 37% since 1980; and it is very common that vehicles travel in platoons on Indiana highway corridors. More data are required to better understand the characteristics of vehicle platoons on Indiana highways.

Finally, issues may arise as to how the real time vehicle platoons can be detected for signal timing. It seems that detecting platoons requires much larger detection area. For the presence detectors, it is found by some studies (Cribbins and Meyer 1975) that efficiency of signal control system increases as the detector length was shortened. In contrast, Bang (1976) demonstrated that in the studies of traffic optimization logic (TOL), the efficiency of TOL depends on the accuracy of the detector information and the time interval; and the vehicle should preferably be detected far in advance of the intersection. Two causes leading to these different conclusions are probably the inherent differences among the traffic characteristics employed in different models, and the control strategies used by different investigators. It is needed to investigate appropriate control logic on the basis of real platoon characteristics and deployment of platoon detectors.

CHAPTER THREE

PLATOON DATA COLLECTION AND ANALYSIS

In most field traffic studies, data analysis was undertaken by recognizing that traffic flows were made up of individual vehicles. Measurements, such as vehicle headway and speed, are examined to fit certain known mathematical distributions, and the corresponding statistical parameters are then calculated. In this study, however, data analysis was performed based on the field observation that vehicle platoons, rather than individual vehicles, are the primary components of traffic flows. Four variables used in this study to describe platoon characteristics are platoon headway, platoon size, platoon speed and inter-platoon headway. The task of this chapter is to study field measurements so as to obtain a comprehensive understanding of platoon properties. It is believed that knowledge of these four variables is of essence in the design of traffic signal systems based on vehicle platoons.

3.1 Data Collection

Field traffic measurements, such as vehicle count, vehicle speed and arrival time, were made using traffic counters/classifiers in conjunction with pneumatic tubes at selected intersections on US30 in Lake county and US52 in West Lafayette. Pneumatic tubes were installed upstream of intersections. The distance between the tubes and stop line was determined so as to minimize effect of turning vehicles and provide more platoon information. It varied from about 150 m (490 ft.) to 1,600 m (1 mile) depending on the actual road and traffic conditions, such as presence of turning lanes and percentage of turning vehicles. Also utilized in this study are traffic data measured by fifteen weigh-in-motion stations operating on Indiana highways.

While data were collected in both driving and passing lanes on major road, data analysis was analyzed separately. The main reason is that vehicles usually use driving lanes, especially on roads in rural areas where traffic volumes are usually moderate or less. Based on the traffic records collected the weigh-in-motion stations, it is observed that the lane distribution of traffic varied with traffic volumes. Figure 3.1 gives the variation of distribution factors for the driving lane with AADT on Indiana highway corridors. As AADT increases, the number of vehicles using driving lane decreases. Theoretically speaking, the distribution factor for driving lane will approach 0.50 when traffic volume becomes heavy. It is also observed that in Indiana, AADT varied dramatically depending on the location of observation. As an example, SR2 has an AADT of 5,800 out of Laporte, and 25,000 in Laporte. Accordingly, vehicle lane distribution varies from site to site. For a specific road, the lane distribution is governed by both the number of lanes and the AADT value. In reality, most of Indiana highway corridors with four lanes have a distribution factor ranging from 0.85 to 0.92. If AADT is known, the driving lane distribution factor, DF, can be estimated using the following empirical equation developed by this study:

$$DF = 1.0 - 0.0011 AADT^{0.505} \qquad (r = 0.865) \ldots\ldots (3.1)$$

where r = correlation coefficient.

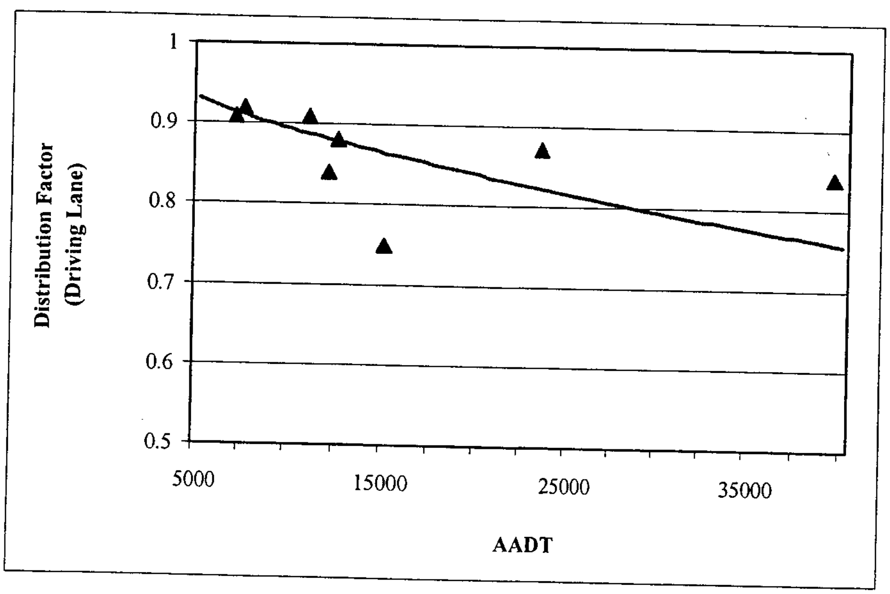

Figure 3.1 Variation of Driving Lane Distribution Factor with AADT

Analysis was performed to compare the data collected in both driving and passing lanes. As an illustration of the discrepancies between those two groups of data, Figure 3.2 presents the headway measurements in the form of relative frequency distribution. Those measurements were taken on US52 in West Lafayette from 15:30 p.m. to 16:40 p.m. In general, the variations of headway measurements taken in both the lanes follow a similar trend. However, it is obvious that the two distributions are centered at different positions on the horizontal axis. The headway distribution in the passing lane tends to spread out further than that in the driving lane, and the distribution of headway in the driving lane has most of its area close to the mean. This can be extended to conclude that the headway measurements taken in the passing lane has a more variable distribution, leading to more variable results. Similar observations can be made from vehicle speed measurements as shown in Figure 3.3. Both the distribution curves are skewed to the right, but the measurements made in the driving lane are grouped around the mean as expected and the distribution curve of passing lane has experienced larger variations. The above description establishes that mixing data in both lanes will result in greater variations and complicate data analysis and traffic measurements made in driving lanes may produce more stable platoon characteristics.

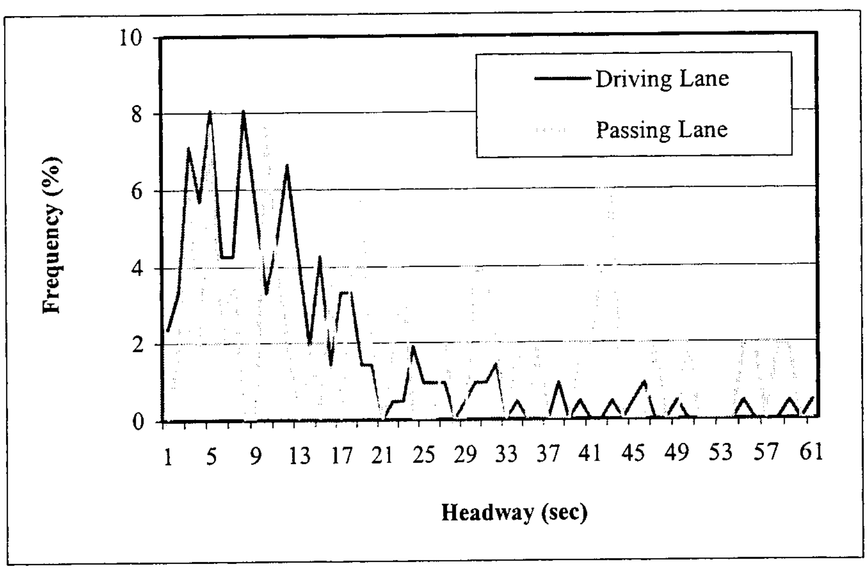

Figure 3.2 Headway Frequencies in Both Driving and Passing Lanes

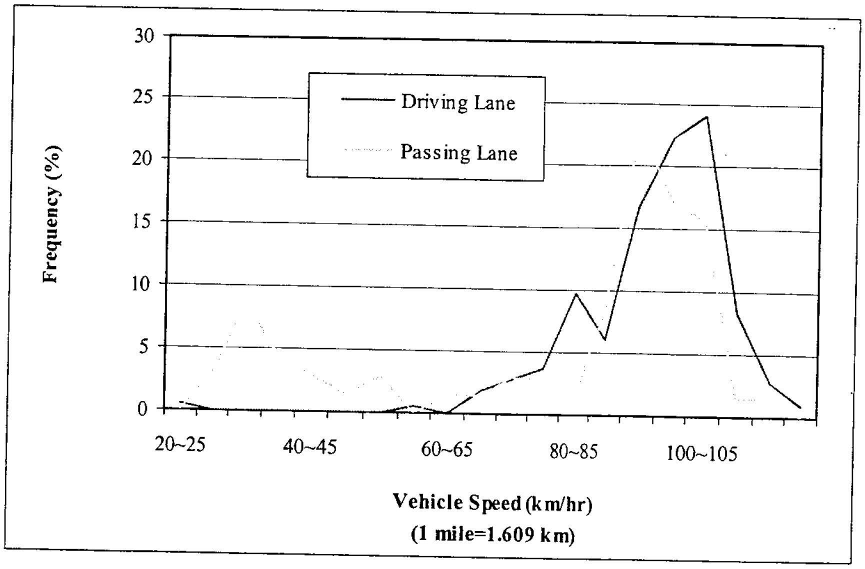

Figure 3.3 Speed Frequencies in Both Driving and Passing Lanes

3.2 Platoon Definition and Critical Headway

Vehicle platoon is defined as a group of vehicles with successive headways less than a pre-determined value of time that is called critical headway. Figure 3.4 shows the fundamental components of a vehicle platoon, in which, h_i is known as the individual vehicle headway, IPH the inter-platoon headway, n the platoon size and V_{k-1} the platoon speed. Once those variables are known, the platoon position and its movement can be determined. It is also assumed that a platoon should have stability under all traffic conditions and the vehicles in a platoon should be interdependent (Athol 1965).

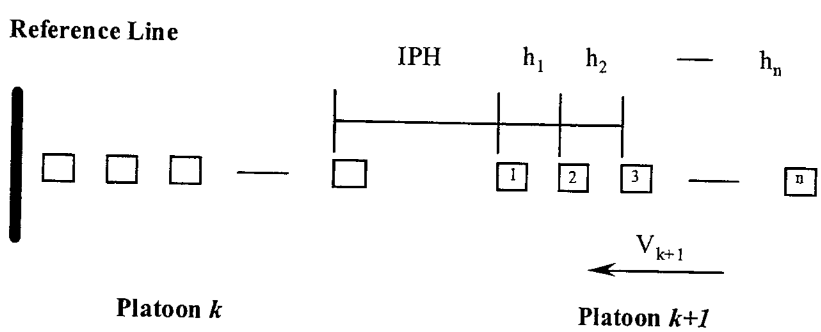

Figure 3.4 Illustration of Vehicle Platoons

The above platoon definition is very general since there is no an arbitrary critical headway. However, a small change of tenths of a second in the critical headway will generate tremendous changes in the resultant platoon behaviors. Therefore, it is of great importance to select a proper value of the critical headway based on the specified applications. There are two main factors that have effects on the selection of critical headways: the existing individual headways and the design of traffic signal. May (1965) investigated individual headway distributions and concluded that vehicle headways are rarely less than 0.5 sec, and rarely over 10 sec either when flow rate is greater than 15 vehicles per minute. Athol investigated the effects of critical headways of 1.2, 1.5, 2.1 and 2.7 sec on platoon behavior, such as platoon size and inter-platoon headway, and finally selected a critical headway of 2.1 sec corresponding to a volume of 1500 vphpl. Headway data were collected on US30 and US52 as shown in Figure 3.5. It is illustrated that headway data spread over a wide range, and up to 40% of headway data is over 10 sec on US52. This can be attributed mainly to the fact of relatively low traffic volume and large fraction of trucks (see Table 3.1). It should also be noted that the approach speed at rural highway intersections is usually greater than that at urban street intersections. High speeds and presence of trucks may lead to larger headways.

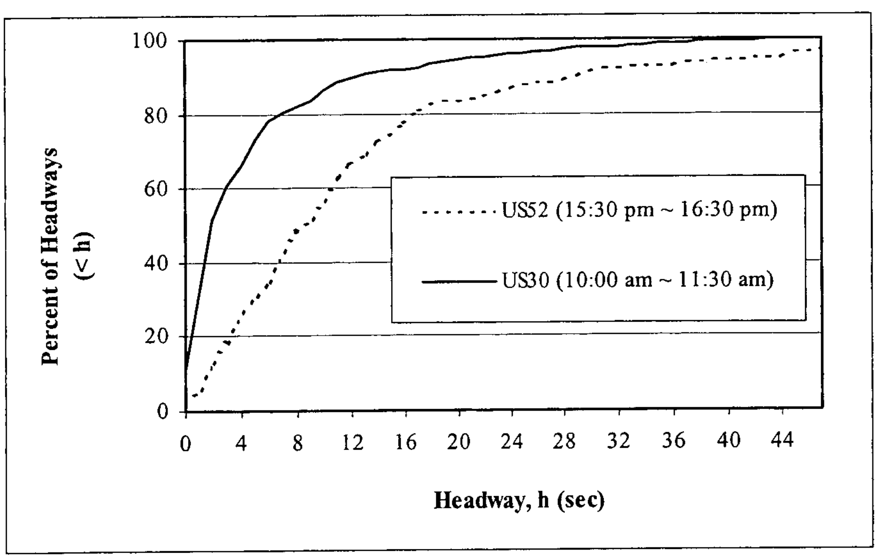

Figure 3.5 Cumulative Distributions of Headways

Table 3.1 Summary of Monthly Traffic Data (One Direction)

Road	Peak-Hour Volume (vph)	Speed* (km/h)	Percent of Trucks (%)
SR2	825	94	14.2
SR37	1620	93	12.1
SR66	730	92	12.7
SR332	1050	95	9.3
US31	1100	101	16.3
US27	905	96	17.8
US52	1586	88	16.2

Approximately 30,000 traffic measurements were examined with respect to a critical headway of 1.5, 2.0, 2.5, 3.0 and 3.5 sec, respectively, so as to identify the appropriate critical headway. The frequencies of platoon size are plotted in Figure 3.6. It is shown that vehicle platoon observations were dominated by the two-vehicle platoons. The proportion of two-vehicle platoons increases with decreasing the critical headway, accounting for about 45% of total traffic for the 3.5-sec critical headway and 74 % for the 1.5-sec critical headway. As the critical headway increased, however, more vehicles were grouped into platoons. The proportion of large size platoons increased and that of small size platoons decreased as the critical headway increased.

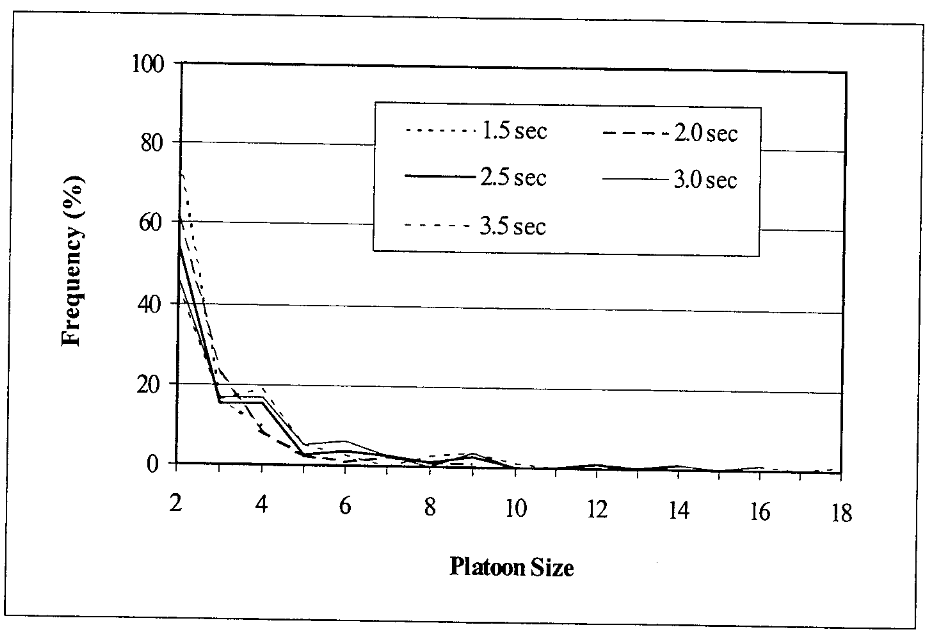

Figure 3.6 Distributions of Platoon Size by Critical Headway

As indicated in Figure 3.6, the platoon size grows with the critical headway employed. Detecting large vehicle platoons requires a large detection area with large area vehicle detectors, leading to a significant rise in installation and maintenance costs. In contrast, use of a small critical headway will result in a small value of the average platoon size, but may not provide sufficient vehicle platoon information. Therefore, determination of an appropriate critical headway should make a compromise between platoon detection and incurred costs. Figure 3.7 shows the variations of the proportion of platooned vehicles with critical headways. Also presented in Figure 3.7 is the relationship between the dispersion of platoon sizes with critical headways. The platooned vehicles were measured in terms of the percent of the total traffic volume, and the platoon size dispersion in terms of the coefficient of variation (the ratio of standard deviation to mean).

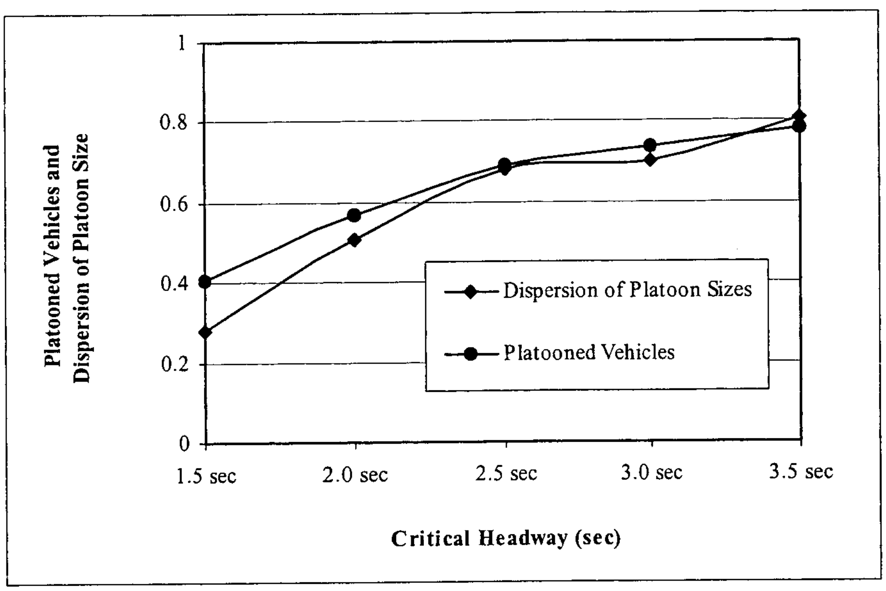

Figure 3.7 Proportions of Platooned Vehicles and Platoon Size Dispersion

Again, it is demonstrated that the proportion of platooned vehicles increased as the critical headway increased and the variations of platoon size became larger. However, it appears that the 2.5-sec critical headway is an inflection point for both curves. When the critical headway exceeds this point, both curves become level and the variations are smooth. This implies that for the 2.5-sec critical headway, the platoon characteristics may remain relatively stable. Following the above finding, this project based its data analysis on the 2.5-sec critical headway. It should be pointed out that again, selection of the critical headway depends on the real traffic and road conditions and must be determined according to the specific situations and applications

3.3 Platoon Characteristics

3.3.1 Platoon Headways

The platoon headway is known as the average value of individual headways within a platoon. In reality, the individual headways within a platoon are unequal. Due to the assumption of interdependency and stability, it is advisable to mirror the platoon headway using the average of individual headways. To determine platoon headways, it requires identifying vehicle platoons with respect to the critical headway. This can be easily done by use of the Excel worksheet. It should be stressed that individual headways and platoon headways differ in statistical characteristics. Figure 3.8 shows the distributions of the individual and platoon headways measured on US52. The distribution of individual headway measurements was skewed to the left and spread over the range of zero to infinity. Many investigators, such as Daou (1964) and May (1965), proposed to use the lognormal distribution for individual headway distributions. On the contrary, the platoon headway measurements tended to distribute symmetrically about the mean, ranging from zero to the critical headway. Therefore, the normal distribution might be more suitable for the platoon headway distribution.

To determine the distribution model for the platoon headways, thousands of headway measurements were examined. The mode of platoon headway measurements was around 1.5 sec, and the mean value fluctuated slightly, varying from 1.4 sec to 1.8 sec with a variation coefficient of approximately 40%. It was also supported by use of the χ^2 test that the normal distribution could be used for the platoon headway measurements. Table 3.2 presents one-hour original platoon headway measurements and the corresponding results of two χ^2 tests. The first test was to test the goodness of fitting the normal distribution to the platoon headway measurements, and the second test fitting the lognormal distribution to the platoon headway measurements. The original platoon measurements were divided into 6 groups by use of a time interval of 0.4 sec. At a significance level of 0.05, the expected χ^2 value is 7.815. The computed χ^2 value in the first test was 3.824 that was less than the expected χ^2 value, and in the second test, the computed χ^2 value was 16.56 that exceeded the expected χ^2 value. Therefore, the hypothesis of the normal distribution was accepted and the lognormal distribution was rejected.

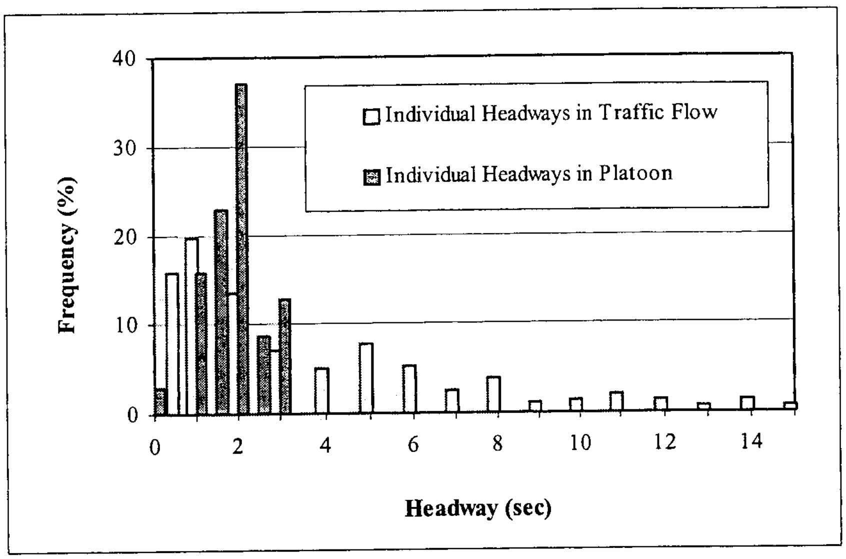

Figure 3.8 Comparison of Individual Headway Distribution and Platoon Headway Distribution

Notice that the results of χ^2 tests in Table 3.2 can not be used to establish that the lognormal distribution is unsuitable for the platoon headways. Changing division of groups and interval may result in the lognormal distribution being accepted. As illustrated in Table 3.2, the significant difference arose from the first group. If the original measurements are divided into seven groups by using a time interval of 0.30 and the first group is 0 sec to 0.70 sec and the seventh group is 2.20 sec to infinity, both the normal and lognormal distributions are accepted. However, the lognormal distribution is more-complicated in calculation than the normal distribution. It is always advisable to utilize models that can simplify the analysis procedure without scarifying the accuracy.

Table 3.2 One-Hour Platoon Headway Measurements and Results of χ^2 tests

Platoon Headway (sec)	Observed Frequency	Platoon Headway (sec)	Observed Frequency	Platoon Headway (sec)	Observed Frequency
0.40	1	1.33	1	1.73	1
0.70	1	1.35	1	1.77	1
0.75	1	1.36	1	1.78	2
0.80	4	1.38	1	1.79	1
0.90	2	1.39	1	1.80	4
0.98	1	1.40	5	1.82	1
1.00	8	1.45	4	1.83	2
1.05	2	1.47	1	1.85	5
1.06	1	1.48	1	1.88	1
1.10	8	1.50	9	1.90	5
1.13	1	1.52	1	2.00	6
1.15	1	1.53	1	2.10	8
1.16	1	1.55	4	2.15	1
1.17	1	1.57	2	2.20	3
1.18	1	1.60	6	2.27	1
1.20	7	1.63	2	2.40	6
1.23	2	1.65	1	2.50	4
1.27	1	1.67	1		
1.30	8	1.70	6		
Mean: 1.55 sec			**Standard Deviation: 0.44 sec**		

χ^2 Test 1: Normal Distribution			**χ^2 Test 2: Lognormal Distribution**		
Groups (sec)	**Observed Frequency**	**Expected Frequency**	**Groups (sec)**	**Observed Frequency**	**Expected Frequency**
< 0.80	6	6.68	< 0.80	7	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
χ^2	3.824	7.815	χ^2	16.56	7.815

3.3.2 Inter-Platoon Headways

Inter-platoon headway is referred to as the time interval between two successive platoons. Figure 3.9 illustrates the distributions of inter-platoon headways measured on US30 and US52. It is observed that both the distributions follow a similar trend, and are skewed to the left. The left tail of the curve was constricted by the critical headway, and the right tail spread up to 40 sec. The modes took place around 4 sec, and were smaller than the corresponding medians that were 9 sec for US52 and 7 sec for US30. The means were greater than the medians. It was also found that there existed effects of use of critical headways on the modes and medians, but are negligible.

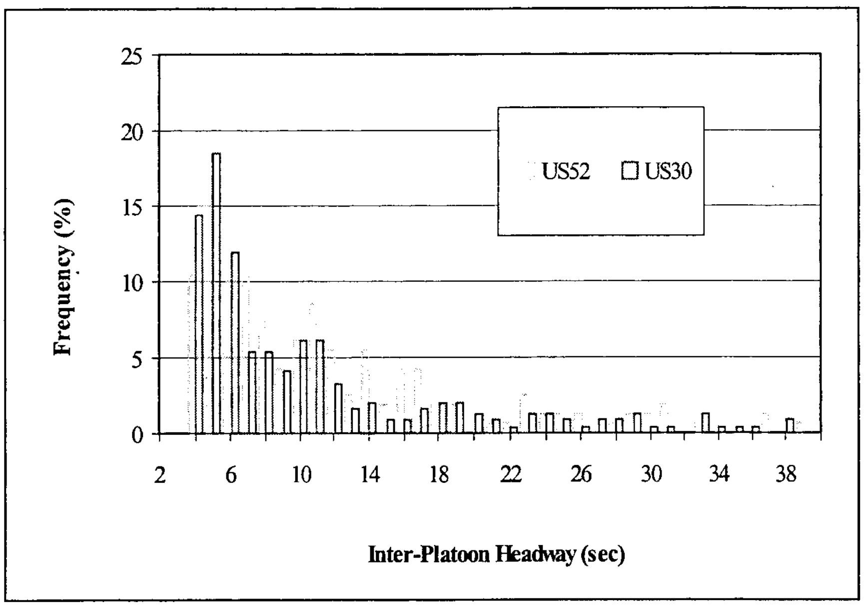

Figure 3.9 Distributions of Inter-Platoon Headways

χ^2 tests were performed to check the goodness of fit between the measured data distributions and the expected statistical distributions. Table 3.3 summarizes the computed and expected χ^2 values with respect to three time intervals, 1 sec, 2 sec and 3 sec. Calculations were carried out for both the normal and lognormal distributions at a significance level of 0.05. As the time interval increased, the computed χ^2 values decreased considerably. The largest computed χ^2 values were obtained when 1-sec interval was employed. For the hypothesis of normal distribution, the computed χ^2 values exceeded the expected χ^2 regardless of the time intervals employed. However, the computed χ^2 values were less than the expected values for the three time intervals except for US52 when 3-sec interval was used. This implies that there is no significant difference between the measured distributions and lognormal distribution.

Table 3.3 Results of χ^2 Tests for Inter-Platoon Headways

Location	Interval	No. of Groups	Expected $\chi^2_{0.95}$	Computed $\chi^2_{0.95}$	
				Normal	Lognormal
US30	1 sec	28	40.65	115.82	24.52
	2 sec	14	19.68	86.17	11.74
	3 sec	10	14.07	74.24	9.27
US52	1 sec	28	40.65	126.00	28.33
	2 sec	14	19.68	88.95	18.75
	3 sec	10	14.07	79.83	14.62

3.3.3 Platoon Sizes

Platoon size is known as the number of vehicles within a platoon. Traffic flow is composed of two components, vehicle platoons and remaining vehicles. This study defined a special platoon, i.e., single-vehicle platoon, so as to account for those remaining vehicles. Consequently, the two traffic components were combined into one component, vehicle platoons with sizes ranging from one to infinity. There exist two primary advantages associated with taking the single-vehicle platoons into consideration. First, the number of arriving vehicles can be estimated using one platoon size distribution model. This may simplify the procedures for simulating platoon behaviors. Secondly, extremely large platoons may be avoided, leading to savings in platoon detection. Figure 3.10 presents distributions of platoon sizes observed on US52 on the basis of the 2.5-sec critical headway. The solid line was developed by taking into account the single-vehicle platoons, and the broken line without considering the single-vehicle platoons. It is illustrated that the solid line is dominated by the single-vehicle platoons accounting for about 60% of total platoons (30% of total vehicles) and the broken line by the two-vehicle platoons accounting for approximately 50% of total platoons (10% of total vehicles). Therefore, the mean platoon size for solid line decreased by virtue of the single-vehicle platoons. It is expected that the estimated platoon size (see Chapter 5) using the solid line will be less than that using the broken line by about three vehicles or more. It is also estimated that about 97% of total platoons or 83% of total vehicles will be detected by utilizing the solid line, compared with 99% of total platoons or 92% of total vehicles by utilizing the broken line.

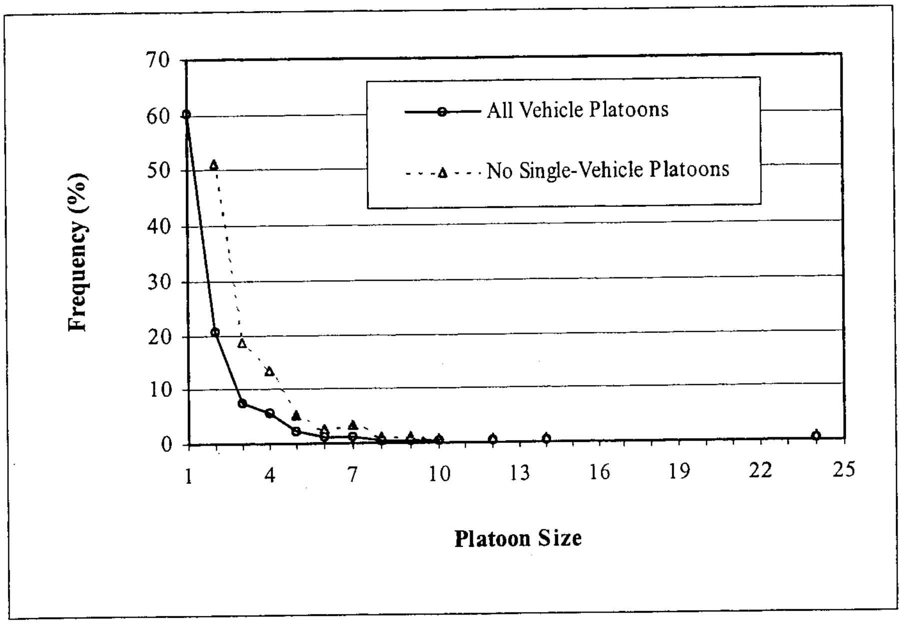

Figure 3.10 Distributions of Platoon Sizes

χ^2 tests were conducted to examine the goodness of fitting three distributions, negative binomial, negative exponential and lognormal distributions to the platoon size observations made on US30 and US52, respectively. The test results are presented in Table 3.4. Assuming a significance level of 0.05 gives that $\chi^2_{0.95}(7) = 14.07$. It is shown that the negative exponential distribution was accepted, i.e., $\chi^2 < \chi^2_{0.95}(7)$ in both cases. However, the negative binomial and lognormal distributions were rejected. Generally, the distributions of measured platoon sizes are skewed to the left with a ratio of standard deviation to mean greater than 1.0. Therefore, significant discrepancies will always arise between the expected and measured frequencies for the first group.

Table 3.4 Results of χ^2 Tests for Three Platoon Size Distributions

Platoon Size	Negative Binomial Measured f_m	Negative Binomial Expected f_e	Negative Exponential Measured Cumulative f_m	Negative Exponential Expected Cumulative f_e	Lognormal Measured f_m	Lognormal Expected f_e
	US30 (Mean: 3.258 Standard Deviation: 3.352)					
1	39	16.92	93	93.43	39	15.56
2	15	13.99	54	68.74	15	25.40
3	12	11.03	39	50.57	12	17.57
4	7	8.48	27	37.20	7	10.95
5	3	6.42	20	27.37	3	7.14
6	4	4.81	17	20.14	4	4.57
7	3	3.58	13	14.81	3	3.20
8	3	2.64	10	10.90	3	2.18
9	2	1.95	7	8.02	2	1.55
>10	5	1.43	3	5.90	5	4.89
χ^2	40.27		11.65		45.69	
	US52 (Mean: 3.792 Standard Deviation: 4.228)					
1	35	12.72	59.15	77	35	14.09
2	9	10.13	45.44	42	9	22.87
3	4	8.03	34.91	33	4	16.54
4	8	6.36	26.81	29	8	11.13
5	5	5.03	20.60	21	5	4.69
6	3	3.98	15.82	16	3	8.01
7	1	3.15	12.16	13	1	3.65
8	3	2.48	9.34	12	3	2.69
9	1	1.96	7.17	9	1	1.95
>10	8	1.26	5.51	8	8	7.37
χ^2	80.14		8.35		55.47	

Because vehicle platoons are defined by the critical headway, platoon sizes depend mainly on the critical headway accordingly. If the observation point is within a specific intersection area, say less than 300 m away from the stop line, the average platoon size for different critical headways can be estimated using the following equation developed by this study

$$n = 1.20 + 0.804\ CH \qquad (3.2)$$

where n = average platoon size and CH = critical headway (sec). Notice that the computed platoon size should be rounded up to an integer.

3.3.4 Platoon Speeds

Platoon speed is referred to as the average speed of all vehicles in a platoon. Because the individual vehicle behavior in a platoon relies on the other vehicles in the platoon, the vehicle speeds in the platoon are expected to show some stability. There exist several factors that will probably have an effect on platoon speeds. The most significant factor is perhaps the post speed. Based on speed data measured on US52 in West Lafayette, it was found that speed measurements were relatively uniform. Approximately 90 percent of vehicles traveled within a range from the post speed minus 16 km/hr (10 mph) to plus 16 km/hr (10 mph). 40 percent of the speed measurements exceeded the post speed, and 15 percent of the speed measurements exceeded the post speed by 8 km (5 miles) and 5 percent by 16 km (10 miles). Figure 3.11 illustrates the speed distribution curves on six highways. It is demonstrated that those curves followed a similar trend and were centered approximately at the same point on the horizontal speed axis. In addition, all of the six curves were symmetrical with respect to the center. This indicates that the variations of vehicle speeds are basically uniform on Indiana highways.

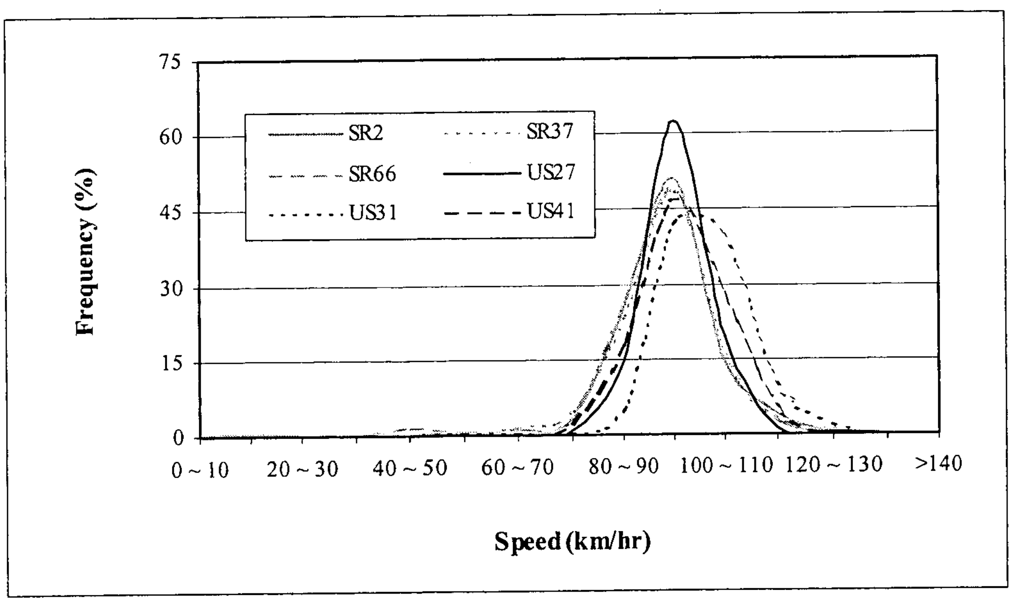

Figure 3.11 Distributions of Vehicle Speed Measurements

Because the platoon speed is the average of individual speeds, i.e., the arithmetic mean, there is no significant difference in distributions between the platoon speed observation and the individual speed observations. Therefore, those distribution models for individual vehicle speeds, such as the normal (Leong 1968) and lognormal (Haight and Mosher 1962) functions, may be used to characterize the platoon speed distributions. Table 3.5 presents daily speed distribution (over 9800 individual measurements) on US52. Also presented in Table 3.5 is hourly speed distribution abstracted from the above measurements.

Table 3.5 Speed Measurement s and χ^2 Test Results

Speed (km/hr)	Observed Distribution		Normal Distribution		Lognormal Distribution	
	Daily	Hourly	Daily	Hourly	Daily	Hourly
≤ 56	41	5	8.60	1.45	0.71	0.20
56 ~ 64	132	30	96.92	13.08	43.85	7.58
64 ~ 72	541	49	591.23	65.29	551.69	67.60
72 ~ 80	2036	176	1841.02	175.09	2070.49	193.90
80 ~ 88	3277	254	3087.08	240.56	3208.16	244.65
88 ~ 96	2484	178	2681.51	176.45	2454.11	163.02
96 ~ 104	1041	53	1213.77	68.43	1112.08	66.08
104 ~ 112	227	9	286.53	14.08	322.19	17.74
>112	65	2	37.34	1.55	80.72	4.23
χ^2				6.43		12.45

The χ^2 tests were undertaken to examine the goodness of fitting the normal and lognormal distributions to those speed measurements. The results were also tabulated in Table 3.5. No matter how to group the speed measurements, the lognormal distribution was rejected for the daily speed distribution. Recall that the speed measurements were very uniform and 90 percent of the measurements spread over a range of (Post speed-10 miles, Post speed+10 moles). The skewed lognormal distribution and the measured speed distribution differed mainly in both the lower and upper tails. The traffic flow, however, could undergo some hourly stability, leading the hourly speed distribution to a symmetrical one. For hourly speed measurements, the computed χ^2 value based on the normal distribution was 6.43 that less than 9.488, the expected χ^2 value when the first three groups were combined (as highlighted). Nevertheless, the lognormal distribution was rejected as the computed χ^2 value was less than the expected χ^2 value.

CHAPTER FOUR

DEVELOPMENT OF PLATOON SIMULATION PROGRAM

It is common practice to utilize simulation technologies to address traffic problems, as field experiments are expensive and time consuming. The fundamental of traffic simulation is to generate random traffic characteristics so as to simulate traffic flow by utilizing a computer. As discussed in the preceding chapter, vehicle platoons are characterized by use of four variables, platoon headway, inter-platoon headway, platoon size and platoon speed. This chapter is to describe the development of a computer program to simulate vehicle platoons, i.e., to generate platoon characteristics. Emphasis is given to derivation of mathematical models to generate random platoon variables with normal and lognormal distributions.

4.1 Generation of Random Platoon Variables

Generally, generation of random platoon variables consists of two steps, generation of a random numbers varying from 0 to 1 and generation of the desired variable based on the generated random number in conjunction with a specific distribution. Generation of random numbers is quite simple. Most of computer languages have a built-in function that returns a random real number between 0 and 1. Generation of the desired variable is actually a process of back-analysis of probability problems. First, a specific distribution function is assigned to the desired variable and the generated random number is treated as a probability, i.e., the value of the distribution function. Then, the desired variable can be determined by solving the distribution function with respect to the probability inversely. For exponential and Poisson functions, their inverse functions can be easily solved. Nevertheless, most of distribution functions, such as normal and lognormal distributions, have no explicit expressions and their inverse functions do not exist in closed form. Therefore, there exist many approximate methods for generating random variables without closed form distribution functions. The following presents a simple method for normal and lognormal variables.

For a normal random variable X, with mean μ_X and standard deviation σ_X, we can construct a standard normal random variable $Z = (X-\mu)/\sigma$. Then, the probability for $X \leq \xi$ can be determined using the equality of $P(X\leq\xi) = P\{Z\leq(\xi-\mu)/\sigma\}$. If the probability is given, say $P(X\leq\xi) = R$, the Z value is the root of the above equality and the desired X can be calculated using $X=Z\sigma_X+\mu_X$. To search for the value of Z, this study employed an approximate expression (Electronic Industry Press 1983)

$$Z = \begin{cases} \sqrt{y_0 \sum_1^{11} a_i y_0^{(i-1)}} & (R \geq 0.50) \\ -\sqrt{y_0 \sum_1^{11} a_i y_0^{(i-1)}} & (R < 0.50) \end{cases} \qquad \text{.....(4.1)}$$

where a_i is coefficient; and y_0 is constant depending on the random number R and

$$y_0 = -\mathrm{Ln}\{4R(1-R)\} \qquad \text{.....(4.2)}$$

For a lognormal random variable, Y with mean μ_Y and standard deviation σ_Y, we can construct a random variable $X=\mathrm{Ln}(Y)$. The variable X is normally distributed with mean μ_X and standard deviation σ_X given as follows:

$$\mu_X = \mathrm{Ln}\left(\frac{\mu_Y}{\sqrt{1+(\sigma_Y/\mu_Y)^2}}\right) \qquad \text{.....(4.3)}$$

$$\sigma_X = \sqrt{\mathrm{Ln}\left(1+(\sigma_Y/\mu_Y)^2\right)} \qquad \text{.....(4.4)}$$

where all variables are as defined earlier. After the value of normal random variable X is obtained, the lognormal random variable Y is given as Y = Exp(X).

4.2 Platoon Simulation Computer Program

Visual Basic® 5 was employed to develop a program, named VPSim (Vehicle Platoon Simulator) for simulating vehicle platoons. The generated platoons are those arriving at a specific intersection. VPSim not only produces those four platoon variables, but allows users to visualize platoon movements as well. The program consists of two main parts, input and display. Once the VPSim is started, an input window is produced as shown in Figure 4.1. User can input statistical values of platoon variables, like mean and standard deviation. Also, user can select the form of distribution function for a platoon variable. The platoon variables can be Poisson, exponential, normal or lognormal random variables. On the input window, two command buttons, Exit and Next, are provided. Clicking the Exit button (or pressing Alt+X) terminates the VPSim program, and clicking the Next button (or pressing Alt+N) continues the program. The input window will be hidden and the display window produced.

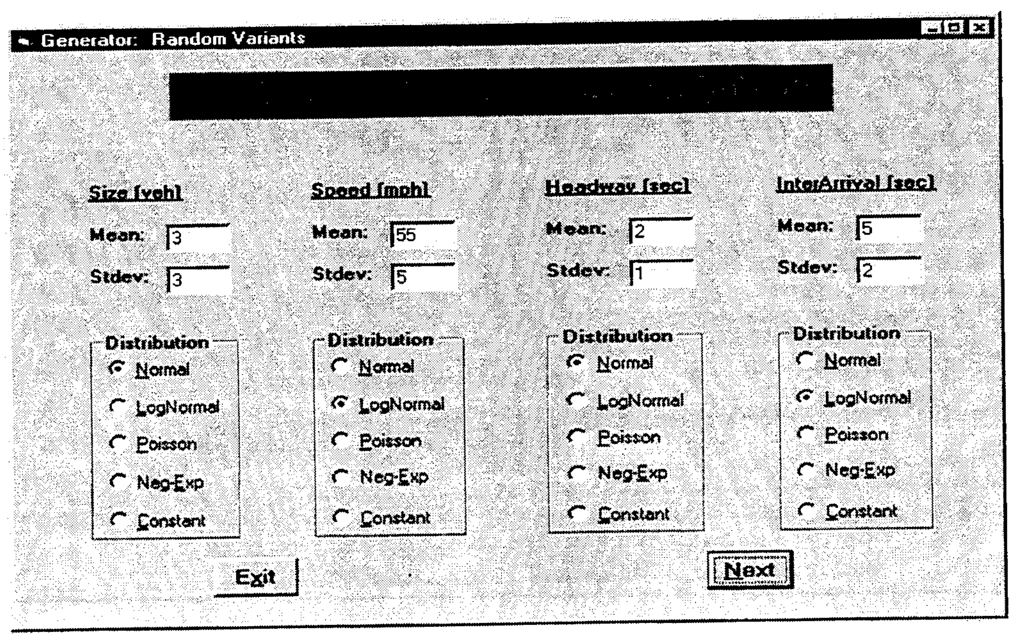

Figure 4.1 Illustration of Input Window

The display window is designed to provide simulation results and generate vehicle animation. In addition to platoon variables (platoon size, platoon headway, inter-platoon headway and platoon speed), the display window also presents the running time, number of total vehicles. There are four command buttons, Return, Pause, Print and Go. The Return button produces the input window again so as for the user to change input. The Go button starts simulation and vehicle animation. The remaining buttons are used to print results and stop the program. As illustrated in Figure 4.2, different vehicle colors represent different platoons. While VPSim is developed mainly to generate platoon variables, it can be modified to simulate traffic control problems arising from vehicle platoons. It was also thought that by use of the vehicle animation, the user could examine platoon movements and merging of platoons. In addition all generated platoon variables will be saved automatically into a text file that can be easily converted to an Excel file for reporting and plotting.

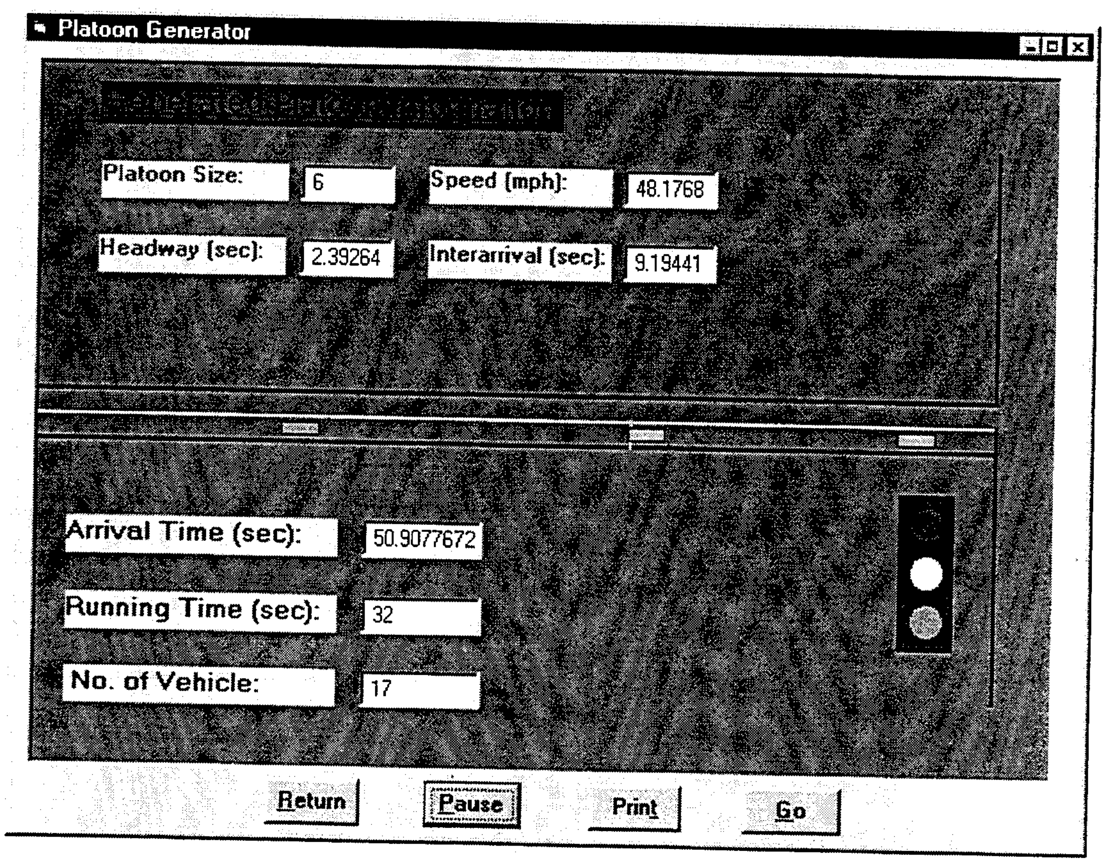

Figure 4.2 Illustration of Display Window

4.3 Comparison of Generated and Measured Platoon Variables

To examine the exactness of the algorithm employed in VPSim, comparisons were made between the observed and generated platoon variables. The observed data are those measured on US52 within one peak hour in the morning. Accordingly, the generated data were obtained by running VPSim for one hour based on the mean and standard deviation of the observed data. Figure 4.3 shows the platoon headway distributions. The platoon headways were assumed to distribute normally. It is demonstrated that the distribution of the generated data is close to that of the observed data and minor differences occurred around the central area.

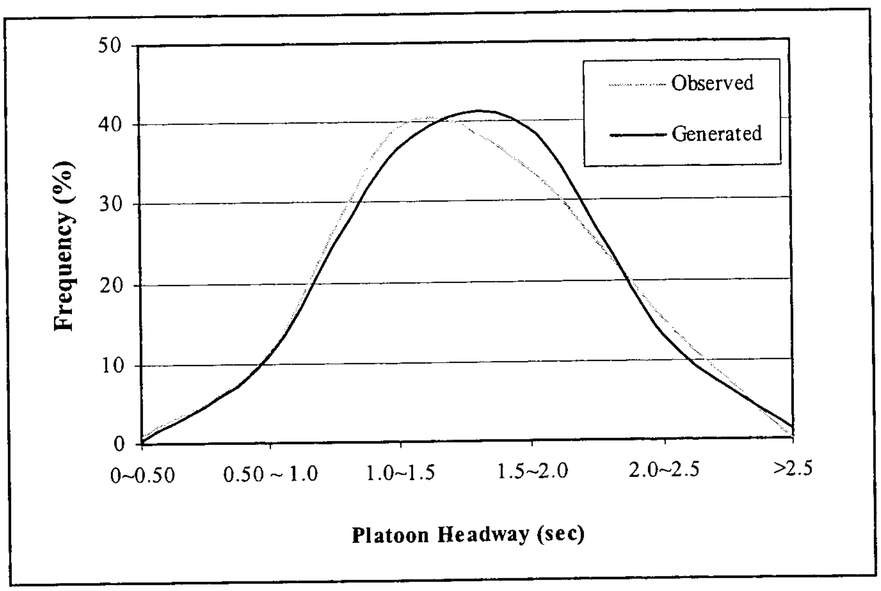

Figure 4.3 Comparison of Observed and Generated Platoon Headway Distributions

Figure 4.4 shows the distributions of the observed and generated platoon sizes. The generated platoon sizes were obtained based on the negative exponential distribution. Inspection of Figure 4.4 demonstrates that the observed and generated platoon sizes differed significantly when the platoon size equaled one. The generated platoon sizes distributed more flatly than the observed platoon sizes and the negative exponential distribution tended to produce many large platoons. This reveals that discrepancies may arise between the expected and observed data distributions, even though the expected distribution is confirmed by the results of χ^2 tests. Traffic conditions vary from time to time and location to location, and errors always exist in simulating the real world traffic conditions. However, the potential errors can be minimized by selecting an appropriate distribution model. To further investigate the distribution models for platoon sizes, more data will be collected in future studies.

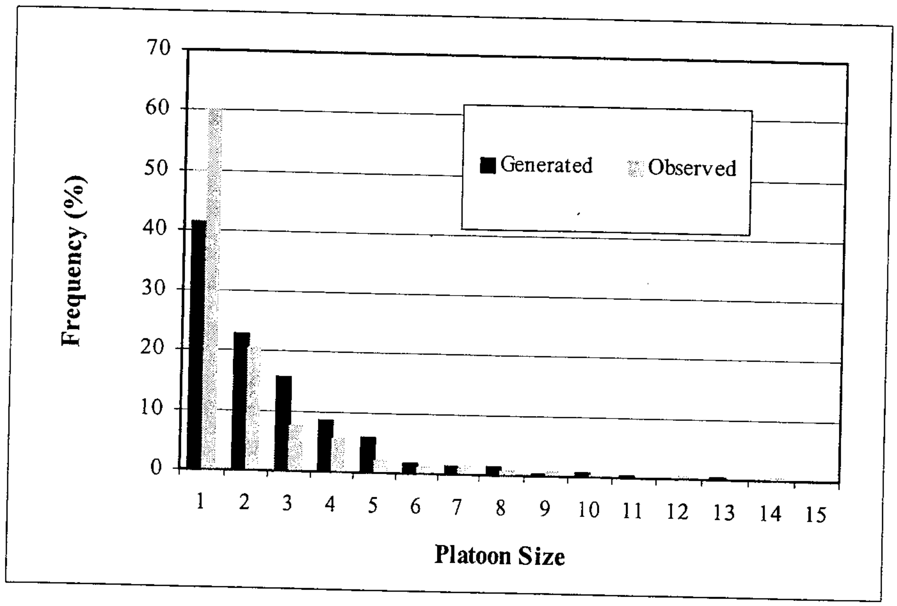

Figure 4.4 Comparison of Observed and Generated Platoon Size Distributions

Figure 4.5 shows the comparison of the inter-platoon headways observed on US52 and those generated with respect to the lognormal distribution. Recall that the inter-platoon headway is known as the time headway between two successive platoons. For that reason, the inter-platoon headway is always greater than the critical headway. However, the lognormal distribution may produce random values varying from zero to infinity. Therefore, the generated inter-platoon headways were not subject to the critical headway (2.5 sec), and many of them were less than the critical headway. This explains why both the observed and generated inter-platoon headways varied differently when inter-platoon headways were less than 4 sec. Figure 4.6 shows the distributions of the observed and generated platoon speeds. It is illustrated that the discrepancies are negligible.

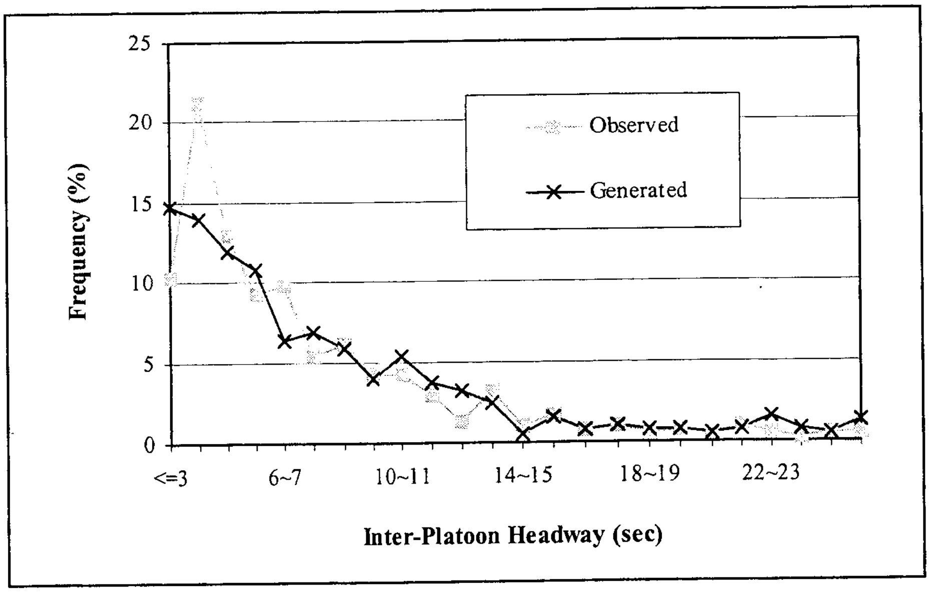

Figure 4.5 Comparison of Observed and Generated Inter-Platoon Headway Distributions

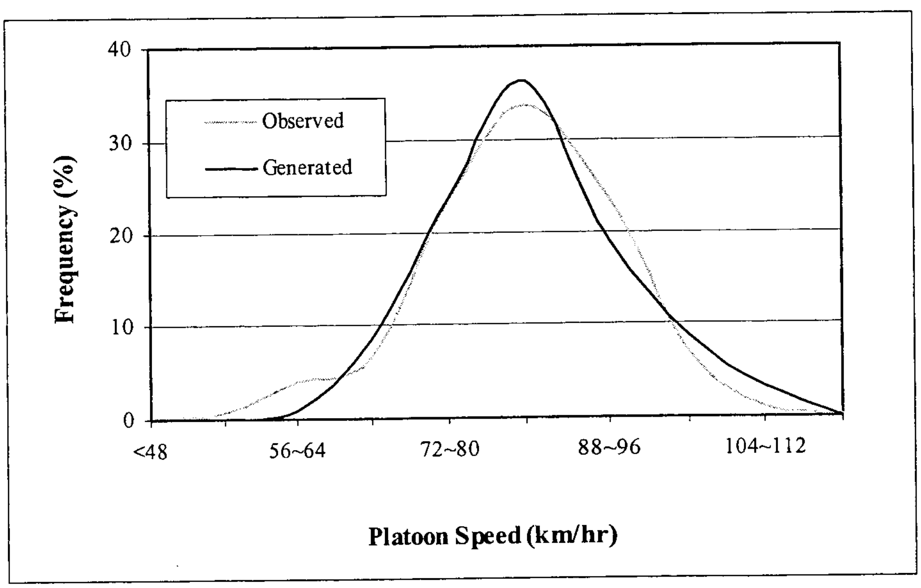

Figure 4.6 Comparison of Observed and Generated Platoon Speed Distributions

DEVELOPMENT OF PLATOON-BASED SIGNAL CONTROL SYSTEM

In conventional vehicle actuated signal control systems, either semi-actuated or fully actuated, the arrival of each vehicle is recorded by detectors within the area of intersection. Green time is extended to the vehicle registered, subject to a preset maximum green. This form of system is operated without knowledge of vehicle platoons arriving at the intersection. In such a system, detector setbacks are usually less than 120 ft for low-speed approaches and 450 ft for high-speed approaches. There is no spare time or space for acquiring and processing information on vehicle platoons. If additional detectors are placed on the major approach far enough upstream of the intersection, full information on vehicle platoons may be obtained so as to allow for adjusting signal time in response to demands of vehicle platoons rather than individual vehicles. It was thought that if the real time platoon information was obtainable, a platoon-based signal timing algorithm may be developed to minimize interruptions to vehicle platoons on the major road, and therefore to reduce traffic delay.

5.1 Deployment of Vehicle Detectors

To detect the presence of a vehicle platoon arriving upstream of the intersection, a detector should be placed on the major approach as shown in Figure 5-1. D_1 denotes the conventional detectors for signal timing, and D_2 is the additional detector for acquiring platoon information. D_2 is placed with a proper distance upstream from the conventional detector, ΔL. The larger the value of ΔL, the more information the detector can provide. It is obvious that ΔL is a function of platoon size, vehicle speed and vehicle interval within the platoon, and can be estimated using the following equation

$$\Delta L = 1.47V^*(N^*-1)H^*+18 \quad \text{(ft)} \qquad (5.1)$$

in which V* = typical platoon speed, mph, H* = typical platoon headway, sec, and N* = typical platoon size.

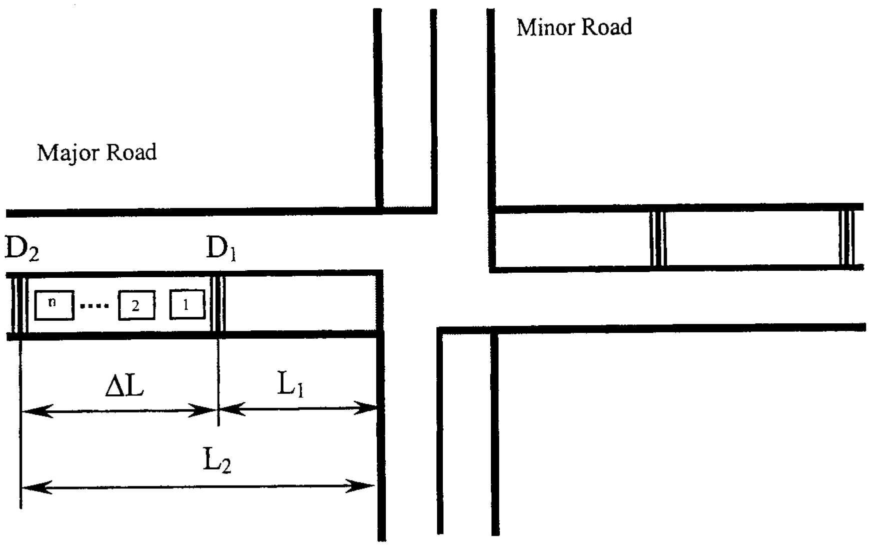

Figure 5.1 Deployment of Detectors

The above equation is derived by assuming that the space between D_1 and D_2 should at least be sufficient for the accumulation of one typical vehicle platoon. The additional platoon detector, D_2 is set to acquire platoon headway, size, speed, inter-platoon headway and time arriving at D_2. In this deployment, any abnormal happening in platoon can be identified in terms of the arrival times recorded by detectors D_2 and D_1. For high-speed approaches, adding a proper value of L_1 in Table 2.1 to ΔL gives the setback of D_2. If L_1 is determined for low-speed approaches by using Equation 2.1, L_2 can be simplified as follows:

$$L_2 = 1.47V * N * H * \qquad (5.2)$$

where all variables are as defined earlier.

As shown in Equations 5.1 and 5.2, determining the platoon detector setback requires determining the typical values of those platoon variables, like platoon speed, size and headway. The greater the typical platoon variables, the larger the platoon detection area. A large platoon detection area may generate more platoon information, but will lead to a rise in installation and maintenance costs. Therefore, determination of the typical platoon variables is a compromise between the desired values and incurred costs. There is no an arbitrary way for determining the typical platoon variables. However, the statistical values of the platoon variables should be used as a reference, and the lower bound for L_2 can estimated using the following equation

$$LL_2 = 1.47 m_v m_n m_h \left(1 + \lambda \sqrt{COV_v^{\,2} + COV_n^{\,2} + COV_h^{\,2}}\right) \qquad (5.3)$$

where LL_2 denotes the lower bound for L_2, m denotes the mean value, COV denotes the coefficient of variation and λ is a value depending on the confidence level. For a confidence level of 95%, λ equals 1.96.

It should be noted that in use of Equation 5.3, a very large or very small value of L_2 would probably be produced when the sample volume is small. Usually, platoon size has an effect on the value of L_2 most significantly. L_2 increases with increasing variations of platoon variables. To yield realistic typical platoon variables, it is necessary to employ at least one peak-hour platoon data to calculate the means and coefficients of variations used in Equation 5.3. Too large detection area can be avoided by substituting $N^* = m_n(1+\lambda COV_n)$, $V^* = m_V(1+\lambda COV_V)$ and $H^* = m_h(1+\lambda COV_h)$ into Equation 5.2. This yields an upper bound for L_2 as follows:

$$UL_2 = 1.47 m_V m_n m_h \left\{1 + \lambda \sum COV_i + \lambda^2 \sum COV_i COV_j\right\} \quad (i, j = V, h \text{ and } n,\ i \neq j) \qquad (5.4)$$

where UL_2 is the upper bound for L_2 and the other variables are as defined earlier.

It was thought that dissimilar values of L_2 within the two boundaries should provide platoon information without significant variations. A site study was conducted at the intersection of US52 and Ducane Road to investigate the variations in the platoon observations at two locations. The first location was about 100 m upstream of the intersection, which was equivalent to the lower bound of L_2, and the second location 300 m away from the intersection points, equivalent to the upper bound of L_2. The observations of platoon size and headway are presented in Figure 5.5. The platoon observations at first location experienced fewer variations than at the second location. The reason is that the first location was closer to the intersection, and vehicles normally slowed down and traveled smoothly because of the traffic light. In general, the platoon size and headway observations at two locations agreed to a certain degree.

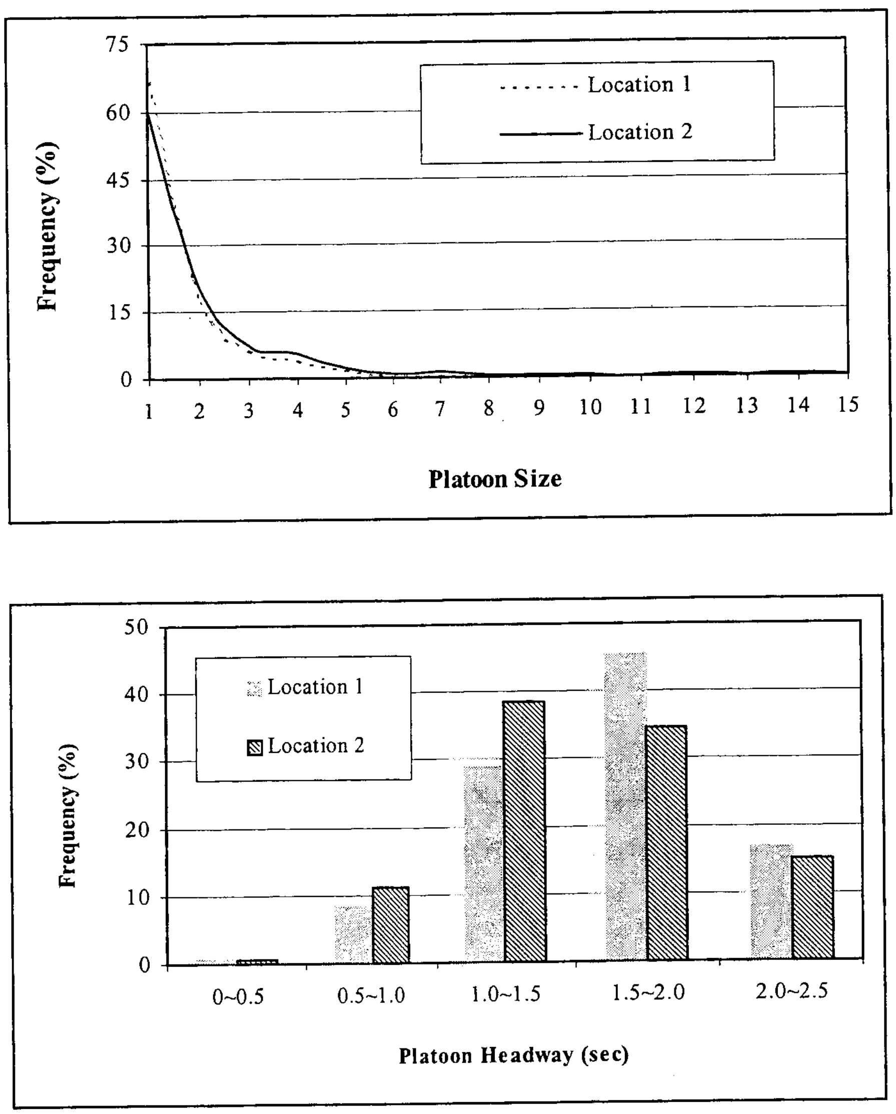

Figure 5.2 Comparison of Platoon Observations at Two Locations

5.2 Platoon-Based Adaptive Signal Control Algorithm

At an isolated intersection of a major road and a minor road, total vehicle delay usually depends on the traffic conditions on the major road. Therefore, it is natural to always give the priority to vehicles on the major roads, in particular those vehicle platoons, in development of the platoon-based adaptive signal control algorithm. The criterion for this form of control is to minimize the total vehicle delay by lessening disruptions to vehicle platoon movements on the major road. Accordingly, the control algorithm can be expressed in the form of so-called control or objective function (Bang 1976, Weinberg et al. 1966)

$$\Phi = (\text{Time Saving}) - (\text{Time Loss}) \qquad (5.5)$$

where Φ is the control function with respect to the current green phase, and both time saving and loss are total time saving and loss due to change of signal phases, respectively. If $\Phi<0$, the current green phase should be terminated immediately. Otherwise, the current green phase should remain until $\Phi<0$, subject to certain restrictions, such as maximum green time and tolerable waiting time.

5.2.1 Scenario I: Current Green Phase on Major Road

Evaluation of the value of control function requires computing the total time saving and loss based on the real time traffic data recorded using vehicle detectors. Figure 5.1 shows an intersection with vehicle detectors. Assume that the current green phase is on the major road. The time saving and loss due to extending the current green by Δt_1 can be estimated as follows:

The time saving on the major road by discharging vehicles during Δt_1 is

$$\text{Saving} = s_1 \Delta t_1 \left(g_{e2} + l_2\right) \qquad (5.6)$$

where s_l is the departure rate or saturation flow rate on the major road, and g_{e2} and l_2 are effective green time and lost time on the minor road, respectively. The extension of time, Δt_l, can be determined using the following equation

$$\Delta t_1 = \frac{18 + L_1}{V} + (n_1 - 1)h \quad \text{.......(5.7)}$$

in which L_l is the distance as shown in Figure 5.1, and V, n_l and h are platoon speed, size and headway on the major road, respectively.

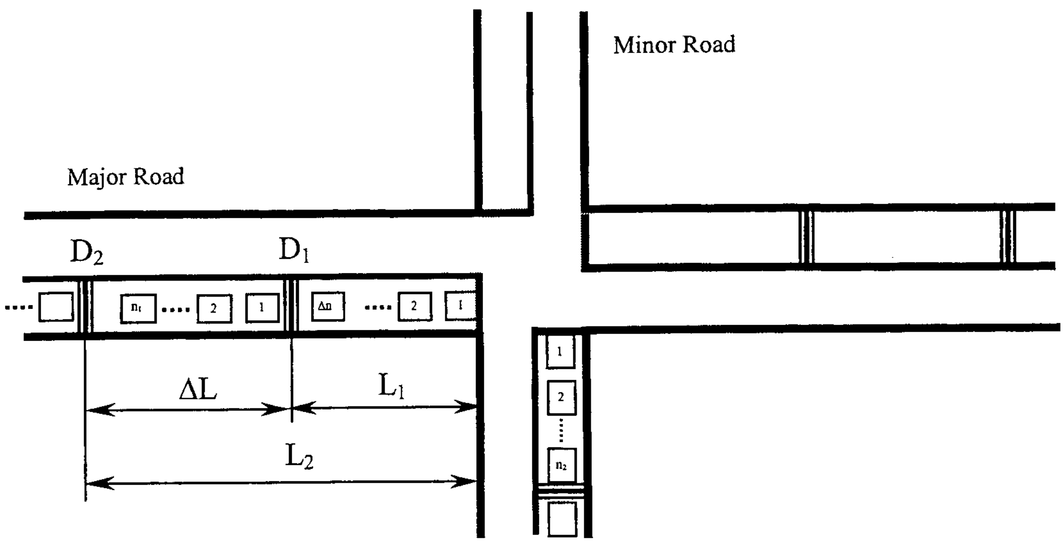

Figure 5.3 Illustration of Intersection with Vehicle Detectors

The time loss consists of two parts. The first part of time loss is the vehicle delay arisen from vehicles in queue on the minor during Δt_l and can be expressed as

$$D_2 = (G_1 + l_1)q_2\Delta t_1 \quad \text{.......(5.8)}$$

where D_2 is the vehicle delay as defined above, q_2 is the arrival rate on the minor road, and G_l and l_l are the elapsed green time and lost time on the major road, respectively.

The second part of time loss is the additional vehicle delay due to those vehicles that are arriving on the minor road and forced to stop during Δt_1. This delay can be written as the following equation

$$\Delta D_2 = \frac{1}{2} q_2 \Delta t_1^{\,2} \quad \text{......(5.9)}$$

where ΔD_2 is the additional vehicle delay, and the other variables are as defined earlier.

Adding ΔD_2 (Equation 5.5) to D_2 (Equation 5.4) results in the total time loss, Loss, on the minor road during Δt_1 as follows:

$$\text{Loss} = q_2 \Delta t_1 \left(G_1 + l_1 + \Delta t_1/2\right) \quad \text{......(5.10)}$$

The control function for this scenario where the current green phase is on the major road can be derived by substituting the time saving and loss into Equation 5.1

$$\Phi = \Delta t_1 \left[s_1\left(g_{e2} + l_2\right) - q_2\left(G_1 + l_1 + \Delta t_1/2\right)\right] \quad \text{......(5.11)}$$

5.2.2 Scenario II: Current Green Phase on Minor Road

In this scenario, the current green phase is on the minor road. Assume that the time extension is Δt_2. The time saving and loss can be evaluated following the analysis procedures described in the first scenario. The time saving on the minor road with respect to Δt_2 is defined by the following equation

$$\text{Saving} = s_2 \Delta t_2 \left(g_{e1} + l_1\right) \quad \text{......(5.12)}$$

where s_2 is the departure rate or saturation flow rate on the minor road, and g_{e1} and l_1 are the effective green time and lost time on the major, respectively.

Also, the time loss includes two parts, the vehicle delay, D_1, and the additional vehicle delay, ΔD_1. Those two forms of delays are expressed as follows, respectively

$$D_1 = (G_2 + l_2) q_1 \Delta t_2 \qquad (5.13)$$

$$\Delta D_1 = \frac{1}{2} q_1 \Delta t_2^{\ 2} \qquad (5.14)$$

where q_1 is the arrival rate on the major road, and G_2 and l_2 are the elapsed green time and lost time on the major, respectively.

Finally, the control function can be written in the form of the following equation

$$\Phi = \Delta t_2 [s_2 (g_{e1} + l_1) - q_1 (G_2 + l_2 + \Delta t_2/2)] \qquad (5.15)$$

5.3 Evaluation of Control Decision Variables

The platoon-based adaptive signal control algorithm developed in the preceding section can be illustrated using a flow chart in Figure 5.1. It is demonstrated that the proposed algorithm requires many types of traffic information. One type of traffic information is the real time traffic information on all approaches, including the platoon arrival sequence on the major road and vehicle arrival sequence on the minor road. Surveillance over the platoon movement on the major road is undertaken by installing an addition vehicle detector. Locations for the platoon detectors and other conventional vehicle detectors can be determined using those equations described in Chapter 2 and section 5.1. Also, the arrival and departure rates can also be determined on the basis of the measured traffic information.

A second type of traffic information is static information, such as maximum green and tolerable waiting time. These variables are control constraints and should be determined with respect to the pretimed signal control in conjunction with local experiences. Because the proposed signal control algorithm gives priority to vehicle platoons on the major road, the tolerable waiting time usually applies only on the major road.

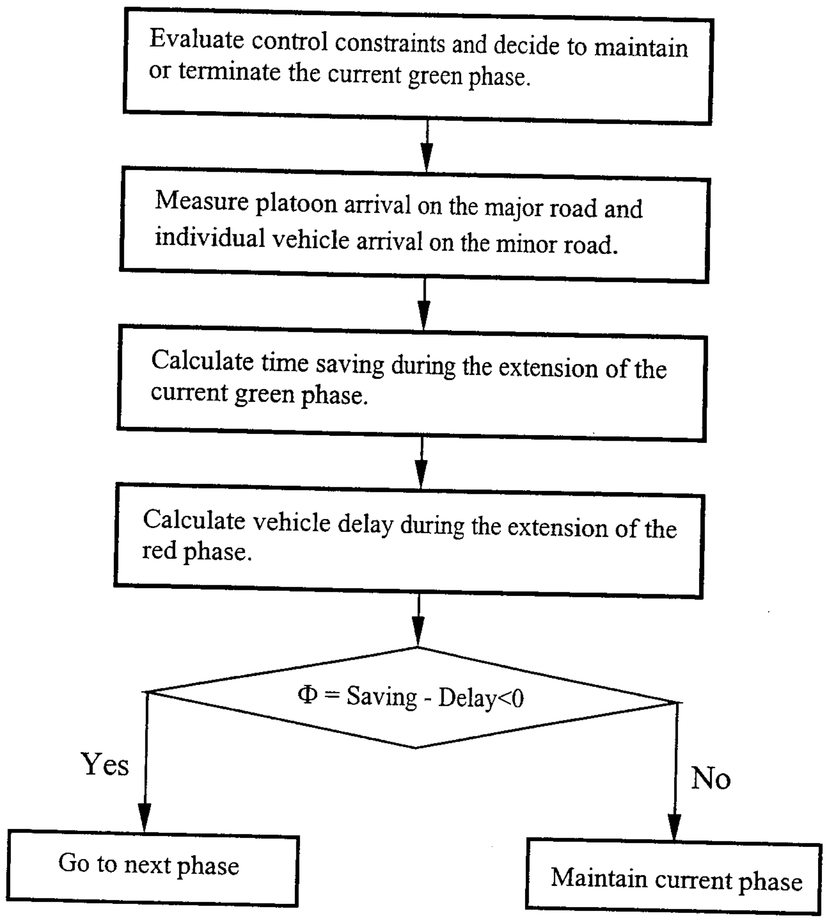

Figure 5.4 Flow Chart of Platoon-Based Adaptive Signal Control Algorithm

Notice that to utilize Equation 5.11 in the developed algorithm, the time extension, Δt_2, must be pre-set. Usually, Δt_2 should be sufficiently small so as not to distort vehicle arrival sequence. However, determination of Δt_2 should also account for time for data processing and computation. Based on the published literature (Bang 1976, Lin 1988), a value of Δt_2=1 to 2 sec is reasonable.

CHAPTER SIX

CONCLUSIONS AND IMPLEMENTATION RECOMMENDATIONS

In the course of undertaking this research project, vehicle platoon movement was recognized as the predominant characteristics of traffic flows on the major roads at isolated intersections. Based on the real world traffic data measured on Indiana highway corridors, this research examined vehicle platoon characteristics, investigated deployment of platoon detectors and developed a platoon-based signal control algorithm. A brief summary of main conclusions and implementation recommendations is presented below.

6.1 Conclusions

The following conclusions can be drawn from the results of this research:

To take into account the vehicle platoon movement in traffic signal control, the vehicle platoons should be characterized using four variables, platoon headway, platoon size, inter-platoon headway and platoon speed. These platoon variables can be measured using conventional vehicle detectors. Also, the position of a specific vehicle platoon in the traffic flow can be easily determined with these variables. It should be noted that the platoon size was defined with a range of one to infinity. This definition simplifies the application problems and makes it possible to use one distribution function to account for both platooned vehicles and single-vehicles in a traffic flow.

It is of importance to define an appropriate critical headway in platoon studies. On one hand, platoon headway, inter-platoon headway and platoon size increase with increasing the critical headway. Consequently, larger critical headway provides more information, but requires larger detection area and higher installation and maintenance costs. On the other hand, smaller critical headway creates greater savings in detector installation and maintenance but provide less information and larger variations. It was found that a critical headway of 2.5 sec was reasonable, accounting for about 70% of total traffic volume. With such a critical headway, the change of the fraction of the platooned vehicles was quite smooth and the detected platoon behaviors were quite stable. This may result in a signal control system with high performance.

Variations of platoon variables can be predicted using certain statistical distribution functions. Thousands of traffic measurements were employed to examine the forms of those distribution functions. Based on the results of χ^2 tests, it was found that the platoon headway and speed could be characterized using the normal distribution function. While it was supported that by the χ^2 tests, the inter-platoon headway distributed with respect to the lognormal distribution function and platoon size to the negative exponential distribution, it was indicated that by the simulation results, these two distribution functions tended to produce too many small values. Inter-platoon headway and platoon size experienced greater variations than platoon headway and speed. Platoon speed fluctuated around the post speed and underwent the lowest variations. The coefficients of variations for platoon speed, platoon headway, Platoon size and inter-platoon headway were approximately 10%, 25%, 75% and 80%, respectively.

To acquire real time platoon information, it is necessary to deploy additional vehicle detectors. Determination of those platoon detectors requires a compromise between costs and performance. Equations 5.1 to 5.4 were developed on the basis of traffic measurements made on US52 and US30 by assuming that the platoon detection area should account for a typical vehicle platoon. The proposed equations can be used to establish the lower and upper bounds for the position of platoon detectors. The estimated position of platoon detectors depends on the platoon size, headway and speed, and varies from several hundred feet to one thousand feet or more.

A platoon-based adaptive signal control algorithm was derived by giving the priority to vehicle platoons on the major road at a specific isolated intersection. This algorithm consists of acquiring real time traffic information on all approaches and computing time saving on current green phase and vehicle delay on current red phase.

The decision to maintain or change the current phase is made by comparing the computed saving and delay. It was thought that the proposed algorithm could minimize disruptions to vehicle platoons, and therefore result in delay reduction.

6.2 Implementation Recommendations

A large amount of traffic data, including arrival time, speed and vehicle classifications, was collected using traffic counters on Indiana highway corridors, including US52 and US30. The data not only served as the foundation for this research, but can also be used for other traffic studies. As an example, the data can be used by the INDOT Operations Support Division to identify the vehicle acceleration and deceleration patterns and arrival sequence, so as to evaluate and upgrade the existing systems. One crucial disadvantage was identified associated with use of current traffic counters during data collection and analysis. Suggestions for necessary improvements were made to the suppliers. With the proposed improvements, it is believed that future traffic counters should be able to measure vehicle arrival time up to 10ths of a second and provide required accuracy for platoon studies.

This research established an approach for investigating vehicle platoon movements. Although several research projects have been reported in investigation of vehicle platoons, this research further investigated how to characterize vehicle platoons. The INDOT Roadway Management and Operations Support Divisions may use the results to better study traffic congestion. The platoon simulation program, VPSim can be employed by traffic engineers to get a full picture of vehicle platoon movements at a specific point of highway. With some modifications, this program will be employed in another JTRP research project to generate vehicle platoons at intersections.

This research presented a new dimension to take into account vehicle platoons in signal control systems. The proposed signal control algorithm can be employed by INDOT to re-time those intersections where vehicle platoons are predominant traffic characteristics. It should be recognized that because there are many uncertainties with the real world traffic, it is needed to perform necessary experiments to examine how the proposed algorithm may be applied to the real signal control. However, it appears difficult to conduct field experiments on the existing signal systems. 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.

Simulation techniques are capable of providing estimates of the performance of the proposed algorithm prior to its actual implementation. With simulation techniques, it is possible for us to repeat identical situations and examine the algorithm under various predetermined traffic conditions. Currently, there are several traffic simulation software packages commercially available. However, those simulation packages cannot address every traffic problem. It is recommended to undertake future studies so as to utilize the results produced by this research project. The future studies should employ appropriate traffic counters to acquire more accurate traffic data to investigate platoon characteristics, especially platoon size and inter-platoon headway, and develop a special purpose simulation program to test the performance of the proposed platoon-based adaptive signal control algorithm.

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