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Dispersion of traffic platoons

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DISPERSION OF TRAFFIC PLATOONS

by

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DEDICATION

To Mom and Dad, you made it all possible with your love and encouragement.

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ABSTRACT

The general objective of this research was to examine the space/time distribution of traffic platoons over a long stretch of roadway with conditions predominant for the southern Arizona urban area. Two sites were chosen for data collection. Both traffic links were one mile long between two successive traffic signals and both were typical of the local low-friction traffic flow conditions. All data were recorded by observers using 20-channel Esterline-Angus recorders. The specifics of the data collection method permitted studying only variables such as the lane of travel, traffic composition, platoon size, traffic volume and the influence of an uphill gradient on platoon behavior.

The investigated platoons remained clearly bunched as they progressed downstream along the researched traffic links. The research indicates it would take much more than a mile (available distance) for the vehicles in the platoon to reach free-flow conditions.

CHAPTER I

INTRODUCTION

Background Information

Coordinating traffic control signals along arterial streets to produce a traffic progression has been a subject of considerable attention for years. The basic approach to traffic progression is that vehicles, once stopped and released from the first traffic signal or other control device of the system, travel along the arterial street grouped in the form of a platoon. This permits the traffic engineer to adjust traffic signals at subsequent intersections so the main stream of traffic, grouped into a platoon, can travel along the arterial street continuously. That continuous movement of the platoon helps to obtain maximum efficiency of the system in terms of minimum delay, maximum capacity, minimum stops and, therefore, reduction of rear-end accident frequency at the approach of arterial intersections.

A popular rule of thumb, found in the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) [1], is that traffic control signals within 1/2 mile of one another should be operated in coordination. However, the MUTCD does not address whether traffic signals spread more than 1/2 mile apart along an arterial street should be coordinated. Before the 1/2 mile rule of thumb was published in the MUTCD, most research on platoon behavior was conducted along distances of 2,000 feet or less. Therefore, the 1/2 mile rule of thumb can be attributed to the lack of comprehensive research done on a platoon's behavior along a longer distance. The question arises how far a traffic platoon traveling along an arterial road remains bunched together enough to still accommodate a downstream signal's green phase. The traffic platoon possesses a certain integrity expressed in its time length. Also, it is not known exactly what road geometry and site conditions influence traveling traffic platoons and to what extent.

The answers to these questions are especially sought in the local area of greater Tucson. With ample desert space it is very common to have major intersections with one mile spacing and little side interference. The nature of the concern was whether the platoon could be maintained under these conditions. Therefore, the 1/2 mile limitation for the coordination of traffic control signals may not be applicable to these conditions and needs to be verified or revised. It is found that on a well designed multi-lane roadway, without many driveways and mid-block disturbances, traffic can maintain its cohesion and benefit from progression up to 0.65 mile in terms of less delay. [2] Also, Graham and Chenu [3] concluded in their work that traffic remained in well defined platoons for a distance of one mile beyond the traffic signals. All of the guidelines which may be perfectly applicable to average conditions, however, may not have much value for a particular traffic link, or for a particular local area. As the platoon moves downstream away from the traffic signals where it was released, first differences in rate of acceleration, later, differences in speeds of individual vehicles, cause the platoon to extend its length. The rate of platoon's length increase or platoon's dispersion is believed to also be affected by a variety of other factors. A detailed list of factors having a possible influence on the platoon dispersion is included in the Literature Review chapter of this thesis.

The amount which a platoon disperses as it moves downstream from upstream's traffic signals has a major importance in traffic flow analysis and in traffic engineering design. Traffic moving in urban areas along arterial roads does not have much opportunity to reach a random flow condition. The arrival distribution pattern of traffic at a downstream traffic control will be more of a platoon, even a very dispersed one, than a random arrival. It is because of closely spaced traffic controls, other traffic interruptions or permanent site conditions which interrupt the flow of traffic even before it reaches a condition of random flow. The knowledge of the arrival patterns can help properly design traffic engineering systems and facilities, thus reducing the number of vehicles stopped and the total delay.

The newly published 1985 Highway Capacity Manual (HCM) [4] points to a close relationship between signal progression and a stopped delay which is used as a measure of level of service for signalized intersections. Progression adjustment factors included in the Manual vary greatly with volume/capacity ratio; lane group types, type of signal, and especially on traffic "arrival type." The "arrival type" characterizes approaching traffic in regards to its compactness and in which part of the traffic signal cycle (for example: beginning of red phase, middle of green phase, etc.) the platoon arrives at the intersection. The HCM suggests that the arrival type is best observed and determined in the field, however, the approximation of the type is also possible from time-space diagrams. The Manual indicates a very critical role of the arrival type on delay estimates and level of service determination.

A review of current practice and previous work suggests the following needs for the study of platoon dispersion:

1. The current rule of thumb found in MUTCD [1], that only traffic control signals within 1/2 mile of one another should be operated in coordination, has to be validated.
2. There is a need to refine the relationship between the platoon dispersion rate and actual road conditions to provide some general guidelines as to what values may be used for the wide range of different road conditions.
3. More work is needed in describing and defining the importance of factors influencing platoon dispersion.

Research Objective

The general objective of this study is to examine the space/time distribution of traffic platoons on selected traffic links over a stretch of roadway up to one mile. In particular, this research will attempt:

1. To identify and select traffic parameters which would not only describe platoon dispersion in a simple and adequate way, but also be comparable with traffic parameters used in other traffic engineering studies on platoon dispersion.
2. To determine compactness of the platoons

expressed in its time/length at selected locations along researched traffic links.

3. To determine if the traffic flow at downstream locations represents random flow or still exhibits some degree of grouping.
4. To determine the influence of factors such as traffic volume, traffic composition, lane distribution, mid-block disturbances and roadway gradient on platoon behavior.

The conclusion from this research would result in better traffic signal timing, which would lead to maximum traffic network efficiency by reducing vehicle delay, increasing system capacity, and minimizing number of stops; therefore obtaining maximum safety. Conclusions from platoon dispersion behavior can also be applied in estimation of intersection capacity and traffic flow performance for a variety of other applications.

Limitations

The number of researched traffic links were limited because of manpower constraints; therefore, it was not possible to obtain a full range of signal spacing and roadway environments. The method of data collection chosen excluded the possibility of recording data such as behavior of vehicles between sampling stations. In addition, the drivers' behavior was not examined since it was not within the scope of this current study.

CHAPTER II

REVIEW OF LITERATURE

There has been a sizeable number of studies conducted on the behavior of traffic platoons departing from a signalized intersection. The majority of the studies fall into two categories. The first has been experimental in which the data such as the vehicle's speed, platoon's size, traffic volumes, car headway, etc., have been collected and evaluated. The second category has been theoretical studies in which several mathematical theories of diffusion have been derived to describe platoon movement. Some of the studies combined both experimental and theoretical methods together.

The initial part of the literature review presents the studies in a chronological order. In addition, the last part of this chapter includes several subsections detailing with particular aspects of the platoon dispersion solicited from the review.

One of the early experimental studies on platoon behavior was done in 1953 by Lewis. [2] A traffic link 0.81 mile long on a four-lane semi-expressway was chosen. The study covered only distance up to 0.65 mile and Lewis did not study platoon movement beyond this point. The research objective was to determine whether the vehicles in a platoon once released from the first traffic signal would arrive at a second traffic signal in any relatively constant pattern.

The collection of data was conducted with a 20 channel Esterline-Angus recorder. Data such as beginning and end of green, vehicle passing times, line position of a particular vehicle and distinction between cars and trucks were recorded. Very little traffic interruption from minor residential streets was found; therefore, it was assumed that main traffic flow was uninterrupted. Frequency distribution of n-vehicle arrival time at each of the five points along the researched link was determined and plotted. Progression timing bands in which 50%, 70%, and 85% of platoon vehicles would pass a point at a given distance were also plotted.

Lewis did not define platoon dispersion in terms of any exact parameter. He only concluded that the dispersion linearly relates to distance from the signal and the line's slope presented on a time/distance chart and containing the first 50% of vehicles in a platoon, could be taken as a measure of dispersion. Lewis concluded also, that under similar traffic conditions and site characteristics, the traffic signals could be coordinated up to 0.65 mile.

Another experimental study was conducted by Graham and Chenu [3] on U.S. 40 in Fairfield, California, in 1962. The study objective was to determine the platoon dispersion at five points downstream from isolated traffic signals. Observations were taken during one afternoon, and seventy platoons containing 1,434 vehicles were studied. Data were collected using road tubes and an Esterline-Angus graphic recorder. Data such as the time of arrival of each vehicle at each station, speeds and vehicle type were recorded. During data analysis and evaluation, histograms showing the frequency distribution of vehicle arrivals at each station were plotted.

Graham and Chenu concluded that the traffic remained in well defined platoons for distances of one mile beyond the signal. With the width of the band representing 100% of the time of one cycle, 91% of the vehicles remained in the platoon up to 0.75 mile and 77% of the vehicles remained up to 1 mile. Very little traffic interruption from minor streets, service stations, and restaurants were found on this rural highway; therefore, it was assumed that main traffic flow was uninterrupted.

Just as Lewis failed to do in his research, Graham and Chenu neither defined dispersion in terms of any exact parameter, nor tried to identify factors causing platoon dispersion. The conclusions reached in both studies may be perfectly applicable to the researched traffic links or sites with similar characteristics, but they can be of little value for sites in general. It is because the behavior of a platoon can be affected by a variety of factors. Given the limitations of these two studies, it is understandable the results would contradict the rule of thumb found in the MUTCD [1]; that only traffic control signals within one-half mile of one another should be coordinated.

Some experimental studies were done based upon theoretical models. It is not the intent of this work to review in detail all the theoretical models, however it will be beneficial to point out some of their main characteristics.

The kinematic wave theory developed by Lighthill and Whitham [7] in 1955 compares the flow of traffic downstream from a set of signals to a kinematic wave based on a functional relationship between the flow, the concentration of vehicles per unit length of road and the distance along the road. No experimental studies based on this model were found in the course of the review.

The diffusion theory of platoon dispersion was proposed by Pacey [6] in 1956, with the basic assumption being that the cars in a platoon move with constant speeds distributed normally about a mean speed. Changes in the shape of the platoon in Pacey's theory are only related to differences in vehicle speeds within the platoon, with no interference by the overtaking vehicle. The model was tested on two expressways in England. In a theoretical and practical results comparison, Pacey concluded that especially for moderate to low traffic volumes, uninterrupted traffic flow and a relatively short distance (up to 0.4 of a mile), his diffusion model was reasonably accurate and could be applied in the field.

In 1962, Pacey's diffusion model was investigated in-depth and expanded by J. Grace and R. Potts. [8] An experimental study designed to test J. Grace's and R. Potts' model was conducted by R. Herman, R. Potts, and R. Rothery [9] on a four-lane divided highway. At two locations, 757 feet and 2,142 feet from the stop bar, pressure switches were used to record 88 platoons. There were no side interferences or intersections along the researched traffic link. By placing pressure tape switches 35 feet apart in each lane, speed "traps" were formed; it was possible to record not only vehicle arrival time but also the vehicle's current speed.

The results of the study indicated that the diffusion model describes traffic platoon dispersion quite accurately, especially for the front of the platoon, and when there is no side interference. In reality, however, the majority of platoons disperse when not subjected to such ideal conditions. There is always some type of interference such as left and right turning vehicles, heavy trucks, side traffic, frequent lane changes or rapid changes in traffic volumes.

A study in which the effects of different signal spacing and different traffic volumes on platoon dispersion characteristics were examined, was done by K. Bang [10] in 1967. In order to obtain comprehensive data about platoon behavior, the platoon's movement was filmed with a movie camera as the vehicles proceeded along the street. The movie camera was placed on top of a 44-story building in order to cover five intersections with a total traffic link length of 1,875 feet. The selected street was a two-way, six lane arterial in the downtown area in the city of Columbus, Ohio. Data represented 30 platoons containing 630 vehicles. All platoons including trucks were rejected. No parking or uncontrolled access existed along the street. The arrival time of every vehicle with respect to lane position and vehicle type was recorded at identifiable painted road markings. It was found that larger size platoons tend to be more compact which can be explained by more restrictions in passing maneuvers associated with high traffic volumes. Also, the diffusion model described in Pacey's research [6] was tested and results indicated the model agreed well the with studied traffic flow. The rejection of all platoons containing trucks, however, does not give an opportunity to study their influence on the platoon behavior.

Two years later, Z. Nemeth and R. Vecellio [11] conducted an experimental study where the same camera was used (like with Bang's research), to collect data along the same traffic link. The objective of the study was to investigate dispersing characteristics of platoons in regard to a difference in signal spacing and different traffic volumes on a city arterial street. Time intervals of 5 seconds were used to identify platoon dispersion characteristics. From data analysis it was found that for both the size of a platoon (5 different groups of cars) and the time of day (off-peak and peak hours), the difference in mean headway was not statistically significant. In other words, the authors suggest that other factors might describe dispersion of platoon better than a mean headway. Platoons with trucks were again excluded from consideration. Data collection for the research was conducted in a central business district (CBD) where traffic signals were so closely spaced that they permitted drivers to see one or more traffic signals ahead. The behavior of drivers and hence platoon dispersion could therefore vary from a case where drivers cannot see upcoming traffic signals.

In a report prepared by J. Treiterer, Z. Nemeth and R. Vecellio [12], a helicopter with a camera mounted on board was employed to achieve greater flexibility in data gathering. The two streets covered in data collection were one-way, 10,238 feet long, 5-lane arterials having nine signalized intersections. The helicopter followed a slow moving platoon of vehicles at an altitude of 1,000 to 1,500 feet. Pictures of the platoon were taken from the helicopter every 1 to 3 seconds. Data reduction consisted of measuring every car's X and Y coordinates and converting them, based upon ground control points, to headway and velocity data. A total of 28 platoons were covered. Characteristics of the platoons which were recorded included: platoon size, lane distribution, frequency of lane change maneuvers, and visually evaluated traffic disturbances. It was found that vehicle stoppages and slowdowns were the main cause of traffic disturbances. Therefore, the conclusion was that inefficiency of a progressive traffic signal system can be attributed to some of the following factors:

1. High frequency of lane change (highest recorded frequency was four changes per 1,000 foot section of roadway).
2. Traffic signal offset which is too short to too

long to efficiently accommodate the progression of traffic.

3. The pressure of initial queues of cars waiting at an intersection.
4. Bottlenecks such as lane dropouts or entering side street traffic.

Some other factors affecting platoon behavior such as signal spacing, roadway gradient, or traffic composition were not studied in this report. [12] Tabulated and plotted vehicle trajectories in time and distance relationship helped in arriving at many important conclusions. It was observed that platoon velocity, mean spacing, and mean headway decrease with the platoon's increase in size. Also, lane of travel had no effect on the platoon's behavior. Finally, there were four factors which described the platoon movement in a satisfactory way: coefficient of variation of velocity which was also considered as a good indication of traffic conditions, mean velocity, mean spacing, and traffic density. Two mathematical models were developed and after testing using data from the aerial film it was found that the results obtained from the models were very close to the results obtained in the field.

This research, which was more comprehensive than all previous studies of platoon movement, also employed two unique approaches. These were the use of heavily travelled urban arterials as study sites and the use of a helicopter-mounted camera to collect very comprehensive data on the platoon's behavior. However, out of the three factors the authors claimed would describe platoon movement in a satisfactory way, only the mean spacing value can be obtained using a ground based traffic data recorders. Also, the observation of a total of 28 platoons does not give a broad statistical base for data analysis.

Many studies reviewed thus far have dealt with characteristics of an average platoon. Ferguson [13] in his study analyzed platoons of particular time lengths and volumes. His approach gave less of a skewed distribution of vehicle arrivals. Data on platoon behavior was collected on two contrasting sites in Glasgow, Scotland. The first site was a downtown city street; one lane of a two-lane, two-way street, where overtaking was extremely unlikely. The second site was two-lanes of a four-lane divided highway. In the analysis of data, the platoons were grouped based upon their time lengths and their volume levels. Platoon splitting due to lane changing was very satisfactorily explained by the two-platoon theory.

From the review of the article, not much can be determined about site disturbances and other single factors influencing platoon behavior. Ferguson monitored platoon movement only up to 1,200 feet from the intersection. Data bunching from both contrasting sites does not allow for a future comparison of the different research data from the similar sites. Ignoring the 2½ percent of the very fast and the 2½ percent of the very slow vehicles enabled him to devise a method for calculating a smoothing factor and enabled him to derive a delay-offset relationship establishing an optional signal setting.

A very interesting approach was presented in the description of the basis for platooning model development, based upon Robertson's model. [14] His TRANSYT model incorporated a technique of allowing for the dispersion of platoons using exponential smoothing techniques in predicting platoon behavior. Traffic data sets covered four sites in the western part of London and Leslie Street in Toronto, and they were matched against predicted platoon patterns with a good fit and an average error of 13.8% observed. These experimental studies helped in calibration of the constant K which assumes values between 0 and 1.0 depending on roadway characteristics and flow conditions.

$$F = \frac{1}{1 - Kt}$$

where

F = smoothing factor controlling platoon dispersion rate;

t = average travel time (in seconds); and

K = constant describing roadway characteristics and flow conditions.

Robertson suggested that the smoothing factor should be calibrated for particular local conditions based upon site characteristics such as traffic volume and its composition, roadway width, gradient, side traffic, etc.

Robertson's TRANSYT model is recognized as one of the most realistic for many of macroscopic computerized traffic simulation models. Unlike some other models, it assumed the platoons disperse as they travel between traffic signals. However, a proper choice of dispersion factor or smoothing factor for a particular condition is critical for the model to accurately predict traffic flow pattern. There were studies [15, 16] done to calibrate TRANSYT and other signal optimization programs such as SIGRID and MAXBAND for a wide range of conditions. SIGRID is a simplified version of the SIGOP program which also proved to be a valuable tool in signal timing optimization of traffic networks.

El-Reedy and Ashworth [17] conducted a study of platoon dispersion along a single arterial street in Sheffield, England. The average side interference was mainly created by city buses and by vehicles turning into the researched road from minor roads downstream. However, all turning vehicles and stopped buses were excluded from the data collection. The data were collected on three different days at three different stations: 1,082 feet, 1,378 feet, and 1,837 feet downstream from the traffic signal. There were 229 platoons recorded on two cameras using time-lapse photography. Vehicles were considered to be traveling in a platoon if headway times between consecutive vehicles were less or equal to 4 seconds. The goodness of fit of the observed traffic flow patterns with predicted traffic flow patterns, using both Pacey's formula and Robertson's recurrence relationship were evaluated for each station. The predicted platoon arrival patterns differed substantially from the actual recorded patterns. However, by choosing the custom constant values of the travel time factor and platoon dispersion factor in a recurrence relationship, a much closer fit between observed and predicted arrival times was achieved. In general, the results of the research indicate that the correlation factors used in Robertson's model should be chosen individually for particular conditions.

Robertson's model was checked for its accuracy in conditions found in the U.S. [5] Data were collected along Route 7 in Fairfax County, Virginia. Three stations at 100, 400, and 800 feet were set and the total number of vehicles in all lanes passing each location was recorded with synchronized watches in four-second time intervals. After careful selection of the K factor, data obtained at the first 100 foot station were applied to the model and platoon dispersions were estimated for the 400 and 800 foot stations. Again, a very good agreement between predicted and estimated platoon dispersion rates was obtained. Effects of mid-block driveways and vehicles turning right on red from a side street were also studied. After field data collection on Road 29 in Fairfax County, Virginia, it was found that even high driveway traffic volume (200 vph entering and 300 vph leaving) and right-on-red traffic volumes had a negligible effect on the platoon dispersion pattern.

Parsonson and Tarnoff [5] concluded that the results obtained in their work could provide a basis for future research to separate and quantify the effects of various factors influencing the platoon behavior. Applying an average platoon dispersion rate factor to most of the conditions did not necessarily produce satisfactory results. And even if the outcome obtained was within the desired accuracy of the method, the results would be dramatically improved if the dispersion rate factor reflected actual road conditions. But, because the calibration of any of the platoon dispersion models using actual site conditions can be very expensive, a great need exists for general guidelines; for some sort of a cookbook containing quantified and singling-out of all platoon dispersion factors with a recipe on how to combine them together to obtain the best agreement between actual and computed platoon dispersions.

Another calibration of the TRANSYT platoon dispersion model was conducted by McCoy, Balderson, Hsueh and Mohaddes [16] during the summer of 1981. The objective of that research was to study the passenger car platoons on urban arterial streets under low-friction traffic flow conditions and to calibrate the TRANSYT model for the observed conditions. Six study sites, typical of low-friction traffic flow conditions were selected in Lincoln, Nebraska. They had no off-street parking while only two of the sections had driveway volumes which were considered negligible and did not interfere with the studied platoons. Two test sites were two-way, two-lane streets while the other four were two-way, four-lane divided arterials. The platoons containing vehicles other than passenger cars were excluded from the analysis. A total of 1,700 platoons were recorded using a 20-pen recorder. The platoons were monitored at four stations along each test site. The last station was located 1,000 feet downstream from the traffic signals.

The constant values for the travel time factor and platoon dispersion factor that provided the best agreement between observed values and those predicted by the TRANSYT model were derived. The Kolmogorov-Smirov (K-S) test was used to evaluate the goodness of fit between expected and observed platoon flow patterns.

McCoy et al. [16] concluded that the dispersion of passenger-car platoons on a four-lane divided street is less than on a two-way, two-lane arterial street; and smaller platoons experience less dispersion than larger platoons. Also, the correlation factors chosen were different from those recommended in the past. McCoy et al. as well as the research of El-Reedy and Ashworth [17] agree on the need for custom chosen platoon dispersion constants based upon individual site and traffic characteristics.

An efficient technique of estimating optimum offsets for traffic signals and for measuring platoon profiles was described by Whitehead, Rose and Millar. [18] The comprehensive data were collected manually from 263 approaches to signalized intersections. The observers recorded on tally sheets the number of passing vehicles within five second intervals. For each intersection the average time required for free-flowing vehicles to travel from the observation point to the downstream intersection's stop line was also recorded. The exact location for observation posts was determined by proceeding upstream from the downstream intersection until the illumination of brake-lights of vehicles slowing down to join the queue could be observed throughout the cycle. The observers were instructed to collect the data only during conditions of a permanent nature. If the conditions were temporary or the traffic congestion was too great, the collection of data was rescheduled for another time. The data were compared and analyzed by a computer program created for the project. It was found that the least squares approximation technique of the simulated delay curve used in the program makes consistent and accurate estimates of the desired offset and importance factor. The desired offset was found to be independent of platoon coherence, volume and day of the week.

Whitehead et al. [18] concluded that the platoon arrival patterns are influenced by the current signal timing elements such as cycle length, offset and split. The practicality of this research comes from the fact that its simulated results, expressed in delay, can be compared to the data output from SIGRID. The optimum offsets were found to be stable over time when values for the importance factor derived from the research were used.

One of the most comprehensive research projects on platoon dispersion was the work of J. M. Smelt. [19]. The study was experimental in nature, involving data on 47 platoons collected along a divided, six-lane, two-way arterial road in suburbs of Melbourne, Australia. Stations with detectors were placed 200; 400; 600; 800; 1,200; and 1,600 meters downstream from the starting intersection. Unfortunately, due to faulty equipment at the station 1,600 meters downstream, only three platoons were recorded at that station. All the values for parameters describing the dispersion of platoons were compared. The comparison was between sites, at the same site for different platoon sizes, and between similar size platoons with and without multi-axle vehicles.

An important conclusion of this work was that the traffic flow is still highly platooned at the 1,200 meter station. With an observed gap size increase between successive vehicles, a long distance was required for the traffic to reach random flow. The increase in the platoon's time length was found to be 22% between stations 200 and 1,200 meters.

Several suggestions were made by J. Smelt for further work and future improvements in data collection and data analysis, such as:

1. A larger number of platoons needed to be recorded to have enough in each group to successfully perform tests determining significant differences.
2. There is a need to express platoon behavior in parameters that other researchers have used or

to develop a universal and widely accepted platoon dispersion parameter, so the results between different research projects could be compared.

3. Data collected from several locations could have a real benefit in determining and clarifying the influence of site specific characteristics on platoon behavior.

Tan, Gipps and Young's objective of their research [20] was to create a model of platoon dispersion and validate it against computer simulated vehicle movements. A computer simulation method called Multi-Lane Traffic Simulation (MULTISIM) was chosen as an inexpensive and less time consuming alternative to field data collection. Tan, Gipps and Young's investigation had shown that the following factors will produce significant differences in the results of that dispersion model:

Volume of traffic;

Composition of traffic; and

Mean desired speed of drivers.

The varying sets of data were input into the model which provided predictions of the mean vehicle travel time and their position within the initial platoon. By fitting a multiple linear regression equation to MULTISIM's data, the coefficients of the model were determined, but only for one particular set of traffic conditions. Tan, Gipps and Young concluded that for another set of traffic conditions the model may not work and a different set of coefficients needs to be determined.

A paper describing traffic composition in passenger-car equivalents (pce's) was published in 1984 by Aerde and Yagar. [21] Pce's were derived for the purpose of platooning analyses, among other ones. Using the radar-platoon data collection techniques, comprehensive data were gathered from 37 different two-lane rural highway locations. The research by Aerde and Yagar is significant because it is one of the first studies which presents comprehensive and quantitative estimates of vehicle-type impact on platoon behavior.

The most recent research on platoon dispersion was published in 1985 and conducted by Castle and Bonniville [22] in the City of Kuwait. The data were collected along a number of arterial roads at distances up to 2.2 kilometers (1.36 miles). The roads were six-lane divided urban arterials with negligible site traffic interference. With no pedestrian activity and a very low volume of heavy trucks and buses, the traffic was able to travel between signalized intersections smoothly and rapidly. Platoons recorded were compared with platoons predicted by the TRANSYT model. It was found that despite the long distances involved, (up to

2,200 meters), the platoons remained coherent enough to warrant traffic signal coordination between successive intersections. It was conservatively estimated that the delay of traffic could be reduced by more than 10% by implementing traffic progression. Castle and Bonniville also concluded that the default values of the TRANSYT program are adequate for a large range of traffic and site conditions.

Other research on traffic flow and operation was also reviewed. Despite the fact that in some of them, platoon behavior was not the main subject, it was still possible to obtain valuable insights and thoughts regarding same to the advantage of this research. From Spitz's work, [23] it was possible to obtain some practical information about data collection with Esterline-Angus multiple recorders. Wright [24] presented a bunching model in which overtaking is not allowed. The work of Wright compliments the existing platoon diffusion theory which permits vehicles to freely overtake one another.

A summary of the studies reviewed pertinent to platoon dispersion is included in Table 1 in chronological order.

Table 1. Summary of studies reviewed.

Authors & Publishing Year	Pacey, M.G. 1956 (6)	Lewis, B.J. 1958 (2)	Graham, E.F. Chenu, D.C. 1962 (3)
Type of Facility, Location	2 similar sites, expressway type, London, England	semi-urban 4-lane highway, Richmond,Calif.	4-lane rural expressway, Fairfield,Calif.
Distance Between Traffic Signals	isolated traffic signals	0.81 mile	isolated traffic signal
Recording Method	N/A	20 channel Esterline - Angus pen recorder (manual actuations)	electromechanical traffic analyzer & Esterline - Angus graphic recorder
Stations' Distance Downstream from Upstream Signalized Intersection	1. Immediately Downstream of the traffic signals. 2. 550 m.	0.03 mile 0.21 mile 0.34 mile 0.50 mile 0.65 mile	150 feet 0.25 mile 0.50 mile 0.75 mile 1.00 mile
Number of Platoons Studied	20 signal cycles studied	104-175	70
Brief Site Discription, Other Comments	For moderated to low volumes along short distances up to 0.4 mile, Pacey's kinematic model was found to be accurate	Several minor residential streets with uninterrupted traffic flow, highway rises slightly with the crest at 0.55 mile.	ADT-20,000 vehicles no side interruptions, highway on a level tangent.

Table 1. Summary of studies reviewed (Continued).

Authors & Publishing Year	Underwood, R.T. 1963 (27)	Herman, R. Potts ,R.B. Rothery, R.W. 1964 (9)	Ferguson, J.A. 1967 (13)
Type of Facility, Location	2 sites, 2-lane 2-way & 4-lane divided carriageway, Melbourne,Australia	4-lane divided highway, Warren,Michigan	2 contrasting sites: 4-lane 2-way highway 2-lane 2-way city street, Glasgow,Scotland
Distance Between Traffic Signals	no traffic signal	isolated traffic signal	isolated traffic signal
Recording Method	20-pen recorder	Computer Traffic Data Acquisition System (pressure switches)	Site #1: Portable tape recorders synchronized with stop-watches Site #2: Time-lapse
Stations' Distance Downstream from Upstream Signalized Intersection	One random location at each site	757 feet 2142 feet	Site #1 Site#2 102 feet 100 feet 344 feet 300 feet 700 feet 600 feet 1200 feet
Number of Platoons Studied	several hundred platoons studied at each site	88	750 vehicles (2 sites)
Brief Site Discription, Other Comments	**Did not study platoon dispersion. Studied headways of platoons for various volumes of traffic and speed of leading cars.**	40 mile/hour speed limit, no interstections and no interference from side activity.	Site #1: No junction within 2000 feet, Site #2: Center of city street- overtaking extremely unlikely.

Table 1. Summary of studies reviewed (Continued).

Authors & Publishing Year	Bang, K.L. 1967 (10)	Robertson, D.I. 1969 (14)	Nemeth, Z.A. Vecellio, R.L. 1970 (11)
Type of Facility, Location	2-way,6-lane city street, Columbus,Ohio	city streets (4 sites), London,England	one-way, 5-lane urban arterials, Columbus,Ohio
Distance Between Traffic Signals	3 traffic signals, total distance 1,875 feet	isolated traffic signal	9 signalized intersections, total distance 10,238 feet
Recording Method	stationary movie camera	Manual	helicopter-mounted aerial camera
Stations' Distance Downstream from Upstream Signalized Intersection	five sections, with an average lenght of 350 feet	91 meters 183 meters 305 meters	38 ground points (spacing between points approximately 300 feet)
Number of Platoons Studied	30	700 (4 sites)	28 (2 sites)
Brief Site Discription, Other Comments	No off street parking or uncontrolled access.	Parking permitted on portions of the street.	Parking permitted on portions of the street. Cross traffic is considered significant only at the signalized intersections.

Table 1. Summary of studies reviewed (Continued).

Authors & Publishing Year	Treiterer, J. Nemeth, Z. Vecellio, R. 1973 (12)	Whitehead, D.W. Rose, K. Millar, B.D. 1976 (15)	Lam, J.K. 1977 (17)
Type of Facility, Location	2 study sites, both one-way, 5-lane urban arterials, Columbus,Ohio	260 signalized intersections, Ottawa,Canada	high type suburb. arterial with multiple lanes, Toronto,Canada
Distance Between Traffic Signals	9 signalized intersections, distances between intersections 350 feet to 2450 feet	no information provided	not available
Recording Method	helicopter-mounted aeial camera	Manual (tape recorders, stop watches and tally sheets)	camera
Stations' Distance Downstream from Upstream Signalized Intersection	Continous method of recording platoon movement	100 ft. plus-upstream from downstream signalized intersection, (1 control station at each approach)	152 feet 341 feet 457 feet
Number of Platoons Studied	28	usually 15 signal cycles for one signalized approach	30
Brief Site Discription, Other Comments	The most compre-hensive evaluation of vehicles' movements in the platoons.	Due to a great variety of approaches studied and method of data collection, no information was given abourt particular site characteristics.	6 roadway segments, left turn bays, no driveways.

Table 1. Summary of studies reviewed (Continued).

Authors & Publishing Year	El-Reedy, T.Y. Ashworth, R. 1978 (17)	Tarnoff, P.J. Parsonson, P.S. 1981 (5)	McCoy, P.T. Balderson, E.A. Hsueh, R.T. Mohaddes, A.K. 1983 (16)
Type of Facility, Location	single carriageway 2-lanes 2-way, Sheffield,England	4-lane divided high-type suburb. arterial, Virginia	6 arterial street segments, Lincoln,Nebraska
Distance Between Traffic Signals	isolated traffic signal	1000 feet	not given
Recording Method	time-lapse photography, 2 cameras	Manual with synchronized watches in 4 sec. intervals	20 pen recorder
Stations' Distance Downstream from Upstream Signalized Intersection	3 different stations during 3 different days 330 m. 420 m. 560 m.	100 feet 400 feet 800 feet	0 feet, (at intersection), 300 feet, 600 feet, 1000 feet,
Number of Platoons Studied	229	N/A	1700 (6 sites)
Brief Site Discription, Other Comments	downhill gradient of 5%, Poor correlation with Pacey's formula and Robertson's formula using standard K values, need for custom coefficient values.	Authors concluded that flow patterns can be estimated from a knowledge of the upstream intersection, platoon dispersion factors need to be refined.	Two sites two-way two-lane and four sites four-lane divided highways. All sites had very little or no site interference.

Table 1. Summary of studies reviewed (Continued).

Authors & Publishing Year	Smelt, J. 1983 (19)	Tan, Y.W. Gipps, P.G. Young, B.E. 1984 (20)	Aerde, M.V. Yagar, S. 1984 (21)
Type of Facility, Location	suburban arterial 6-lane, 2-way divided highway, Melbourne, Australia	N/A	rural highway sites, Ontario, Canada
Distance Between Traffic Signals	isolated traffic signal	isolated traffic signal	no traffic signals
Recording Method	Manual (data logger)	All data were generated using a micro-simulation computer model	Radar-platoon data collection technique
Stations' Distance Downstream from Upstream Signalized Intersection	200 m. 400 m. 600 m. 800 m. 1200 m. 1600 m.	0, 50, 100, 150, 200, 300, 400, 500, 600, 700, 800 meters	non applicable
Number of Platoons Studied	47	not given	Number of vehicles recorded: 267,536 - pass. cars 14,021 - trucks 10,804 - RVs
Brief Site Discription, Other Comments	No off street parking permitted, negligible side traffic, speed limit 75 km/hr.	Buses and turning vehicles were excluded from the analysis, variable input of volume of traffic from 1000 to 3000 veh/hours.	37 different sites, All two-lane, two-way highways.

Table 1. Summary of studies reviewed (Continued).

Authors & Publishing Year	Castle, D.E. Bonniville, J.W. 1985 (22)
Type of Facility, Location	8 arterial road segments, Kuwait,Kuwait
Distance Between Traffic Signals	from 350 meters to over 2200 meters
Recording Method	Manual method, (tally sheets and synchronized clocks)
Stations' Distance Downstream from Upstream Signalized Intersection	at intersections, plus 3 stations at varying distances up to 2200 meters
Number of Platoons Studied	not given
Brief Site Discription, Other Comments	negligible site interference, very low volume of heavy trucks and buses.

Factors Affecting Platoon Dispersion

Based upon the literature review, the rate of platoon length increase or platoon dispersion is believed to be affected by a variety of factors, such as:

1. Varying signal spacing and its offset
2. Signal visibility by approaching drivers
3. Traffic volume
4. Traffic composition
5. Street width, number of lanes and speed regulations
6. Roadway gradient
7. Off-street parking
8. Local driver behavior
9. Mid-block impedance to the traffic flow created by vehicles entering and exiting side streets, shopping centers or apartment driveways
10. Pedestrian traffic

There has been a number of practical and theoretical studies which have attempted to determine the influence of different factors in relation to how a platoon disperses. It has been found that the existence of different road conditions has a great effect on platoon characteristics and before implementation of a traffic progression system, every possible factor influencing platoon dispersion should be determined and its importance ascertained. [5] However, because of variety, sensitivity and correlativity of the factors, it is difficult to describe them all, assign each a separate value and apply them later to a variety of different traffic situations. Treiterer, Nemeth and Vecellio [12] concluded in their research that the principal variables affecting platoon movement were signal spacing, signal offset and platoon size. It was acknowledged that there are also additional factors influencing platoon behavior to a lesser degree such as signal visibility, roadway gradient and number of commercial trucks.

A collection of the platoon dispersion factors found during a review of the literature is presented in Table 2. Some of the factors have been evaluated in-depth and some are only suspected to have a possible effect on platoon behavior. The same variables have been found to affect the platoon movement not only to a different degree, but sometimes they have quite the opposite influence on platoon behavior. Nemeth and Vecellio [11] found that for the volume effect, the influence on mean headway as a measure of platoon dispersion is not statistically significant. Bang [10] concluded that the platoon size has an influence on a dispersion rate (defined as change in mean headway per foot) and larger platoons were found to be less dispersed. On the other hand, the results of a study done by McCoy, Balderson Hsueh and Mohaddes [16] indicate that smaller platoon sizes

Table 2. Platoon dispersion factors from literature review

PLATOON DISPERSION FACTORS	Nemeth, Vecello(11)	Lewis(2)	Graham Chenu(3)	Tarnoff, Parsonson(5)	Underwood(29)	Treiterer Nemeth Vecello(12)	Bang(10)	Smelt(19)	Robertson(14)	McCoy Balderson Hsueh Mohaddes(16)
Traffic Signal Spacing & Offset	1(Low Vol) 2(High Vol)					2	2	3		
Traffic Volume (Platoon Size)	2			3		1	1	1	3	1
Traffic Composition (Commercial Trucks & Cars)	3	2		3		3		2	3	
Roadway Gradient				2		3		3	3	
Mid-Block Impendances (Vehicles Entering & Exiting Side Streets)		4(Low Vol)	4(Low Vol)				3	3		
Traffic Signal Visibility	3					3				
Mid-Block Impendances, Off-Street Parking, Roadway Characteristics (Low/Heavy Friction)	3						3		3	
Street Width, Number of Lanes, Speed Regulated				1*	1	2**			3	1
Time of the Day (Peak/Off-Peak Hours)	2					2				

* Includes split between suburb and CBD conditions.
** Lane of travel.

1-Factor studied, has effect on platoon dispersion.
2-Factor studied, does not have effect on platoon dispersion.
3-Factor mentioned for possible influence but not studied.
4-Factor believed to have no influence therefore disregarded.

experience slightly less dispersion than larger platoon sizes. However, a careful research comparison reveals many, sometimes major, differences in characteristics of the test sites and in choice of traffic parameters describing the behavior of a group of vehicles.

Some of the data collection was done in CBD areas where signal spacing was short enough to permit drivers to see traffic signals at one or more intersections ahead. In these cases, the driver's behavior would obviously be different than in a situation where they had a clear run with no traffic signals being seen ahead. In a recent study conducted by Bleyl [25] changes in velocities for traffic approaching a signalized intersection were found to be significant within 500 feet of the intersection for drivers who observed a red traffic light. This especially makes studies involving the driver behavior variable [10, 11, 12, 13] less applicable because the study of driver behavior is not within the scope of this current research.

The most common factors influencing platoon dispersion researched were: platoon size, amount of trucks, side traffic, and lane of travel. Where traffic composition was concerned, only information concerning truck percentages was provided in some of the studies.

Study Methods

The review of previous studies revealed two different approaches to evaluating platoon dispersion. The first is to create a theoretical model and fit it into practice by adjusting a constant value, sensitive to conditions, on a particular street. However, this constant calibration procedure has been found to be not only expensive and time consuming, but for a wide range of conditions, quite unnecessary. [22] The second approach is to collect actual data from a street and compare different values of the same factor influencing platoon dispersion; usually platoons with a contrasting number of cars or different signal spacing. Only Ferguson [13] and Robertson [14] carried out a comparison of moving platoons on two contrasting sites. Of course, the two approaches described can be combined and the results obtained from the experimental part can be used to validate the accuracy of a theoretical model. However, constant values derived from the model would reflect traffic conditions found only along a particular traffic link.

A platoon dispersion model created by Robertson [14] has been used in work of Tarnoff and Parsonson [5] as one of the steps to estimate the benefits of coordinated traffic signals over independent traffic signals. The model worked well, but was limited to express particular traffic conditions by a constant value.

In all the experimental studies, two ways of platoon dispersion measurements were applied. The first method, applied in a number of studies [10,11,12,17,21,26] relies on measuring the platoon characteristics at a given instant over a length of road which leads to a distribution of platoons in space. The second method is to measure the platoon characteristics as they pass a given point on a roadway which gives a distribution of platoons in time. That second method is much easier and more convenient. It does not require either expensive equipment, such as a helicopter, nor tall buildings from which a film camera can cover movement of a platoon along researched traffic links.

Length of Researched Traffic Links

The lengths of researched traffic links varied from 600 feet to 10,240 feet. In the 10,240 foot stretch, there were nine traffic signals with the largest distance between two signalized intersections of 2,460 feet. Two recent studies done by Smelt [19] and Castle and Bonniville, [22] significantly increased the length of studied traffic links. In Smelt's research the study section between two traffic signals was 1900 meters long. The last data collection station site was located 1600 meters downstream from the platoon starting point. The length of the longest traffic link without signals studied by Castle and Bonniville was not available; however, the furtherest data collection station was located 2200 meters downstream from the platoon starting point. Castle and Bonniville noted that sufficient distance to avoid interference by queuing vehicles was provided between the last data collection station and the downstream traffic signal.

Along the longest researched traffic link (over 2200 meters), the moving traffic consisted mostly of vehicles with the same characteristics (passenger cars) and site interference to the rapidly moving traffic platoons was almost non-existent.

Data Size for Statistical Analysis

A basis for adequate statistical analysis was not expressed as sufficient data size was not provided in some of the reviewed studies, while none of them provided any desirable data size information. An especially small number of platoons was collected in studies [10,11,12,18] where the research dealt with distribution of platoons in space.

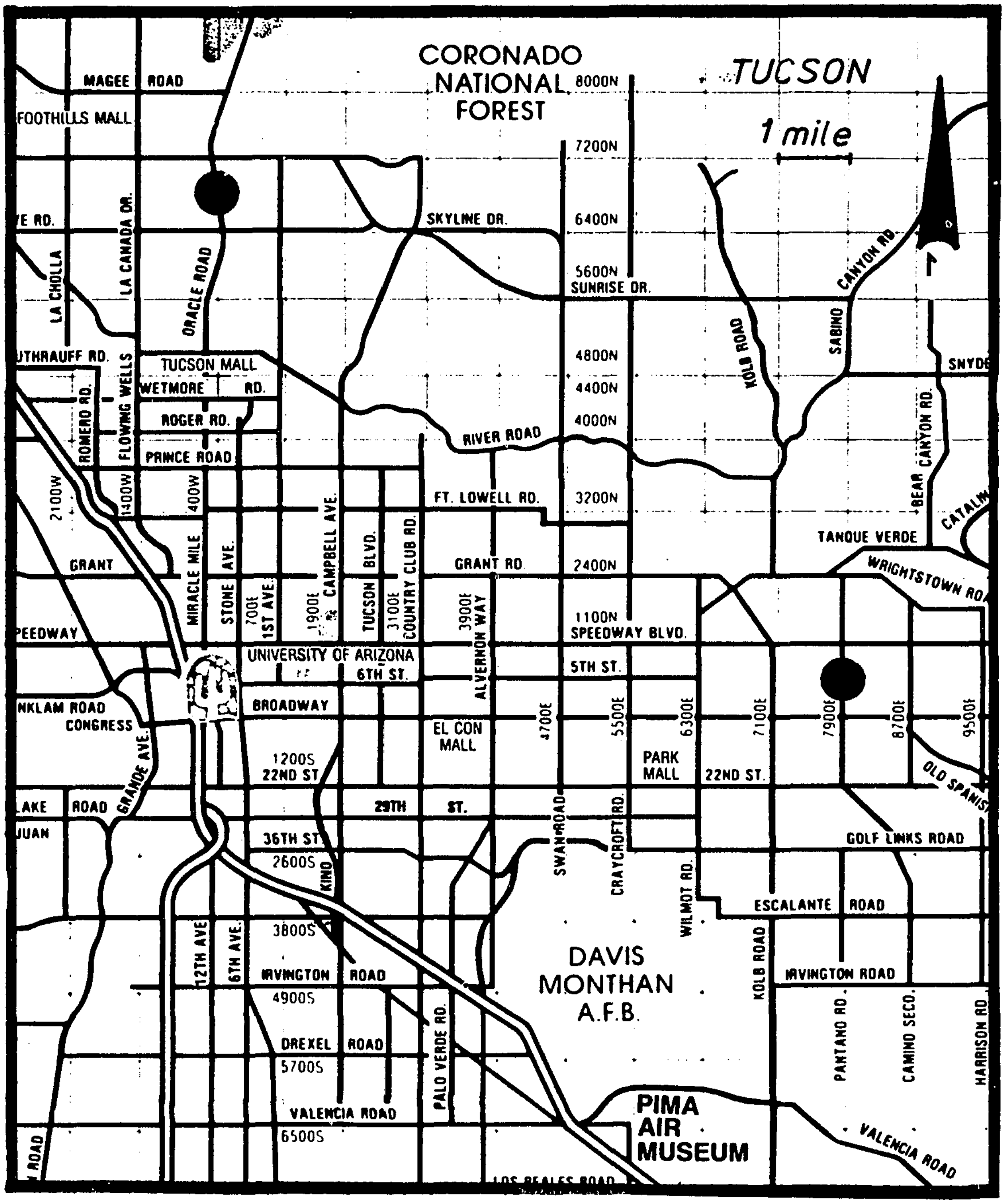
CHAPTER III

DATA ACQUISITION

Test Site Selection

Several traffic links in the Tucson, Arizona area were considered and examined for data collection, all one mile long between two successive traffic signals. An effort was made to find arterial streets that were typical of local low-friction traffic flow conditions. Characteristics of the sites influencing traffic platoons such as traffic volumes, signal visibility, number of lanes, side traffic disturbances, and off-street parking were taken into account during the selection. Figure 1 indicates the general locations of the following two study sites that were chosen.

1. A northbound section of North Oracle Road between Orange Grove Road and Ina Road with moderate traffic disturbances created by shopping complexes near the intersections at both ends of the study section. A locality plan for North Oracle Road can be found in Figure 2. Two residential streets, one serving townhouses and the other, Casa Adobes Drive, serving



● -indicates study site

Figure 1. General locations of the study site

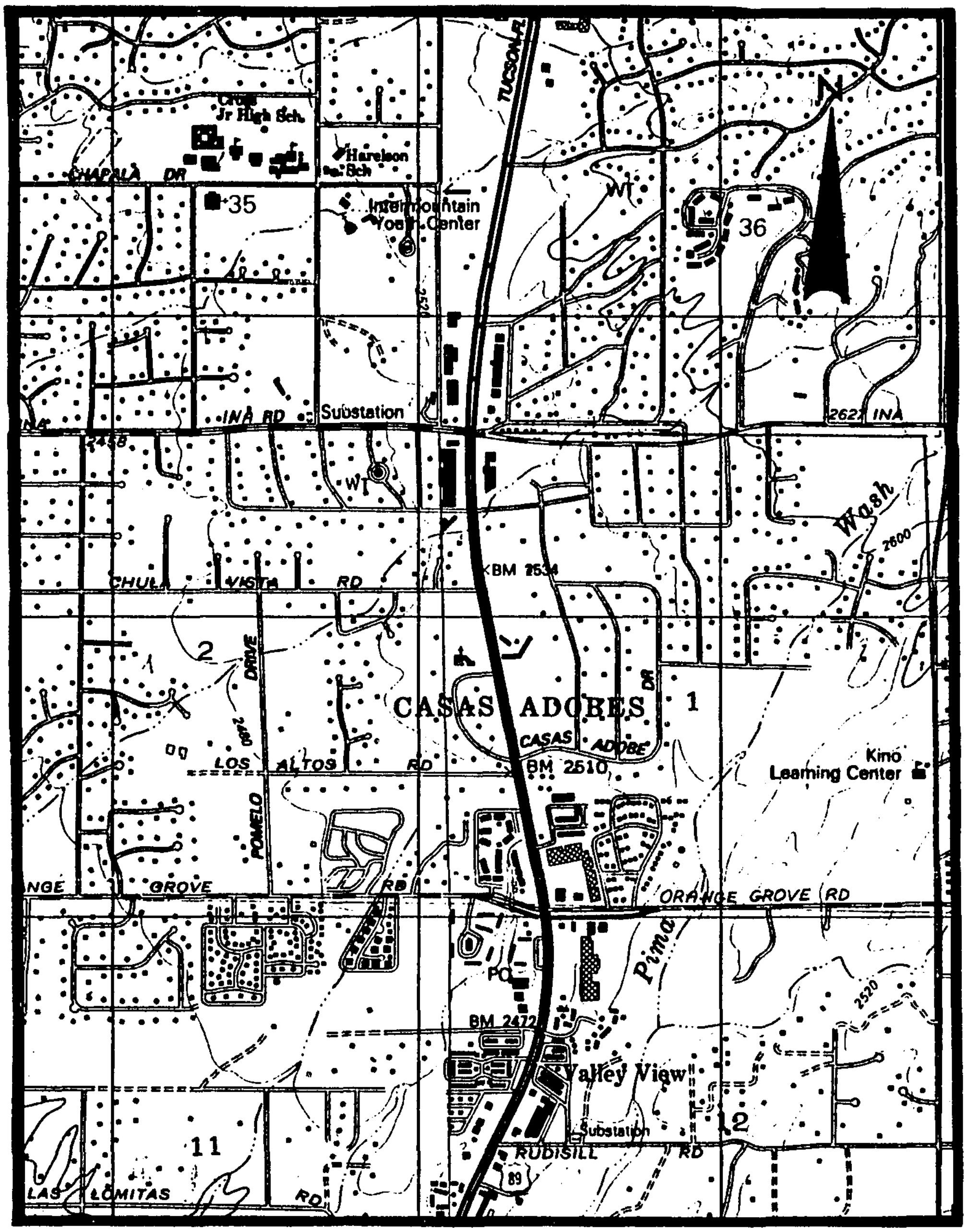


Figure 2. A locality plan for North Oracle Road study site.

a guest lodge, have very light, almost negligible traffic flow. Oracle Road is a major arterial with three twelve-foot lanes in each direction divided by a raised median. The selected section carried traffic of about 15,000 A.D.T. at the time of the data collection. Left turning vehicles had protected turn bays. The Ina Road traffic signals could not be seen before ¼ of a mile of the intersection. The test area is illustrated in Figure 3.

2. A northbound section of Pantano Road between Broadway Boulevard and Speedway Boulevard with two residential streets, one leading to an apartment complex under construction and the other to a subdivision which had very little traffic at the time of the study. A locality plan for Pantano Road can be found in Figure 4. These streets caused very little disturbance to through traffic. The selected street, which carried 9,300 A.D.T. northbound at the time of the study, had two lanes in each direction, each twelve-foot wide, and a middle lane for left turning vehicles. There was a five inch high curb along the street. Figure 5 shows a diagrammatic sketch of the study site, together

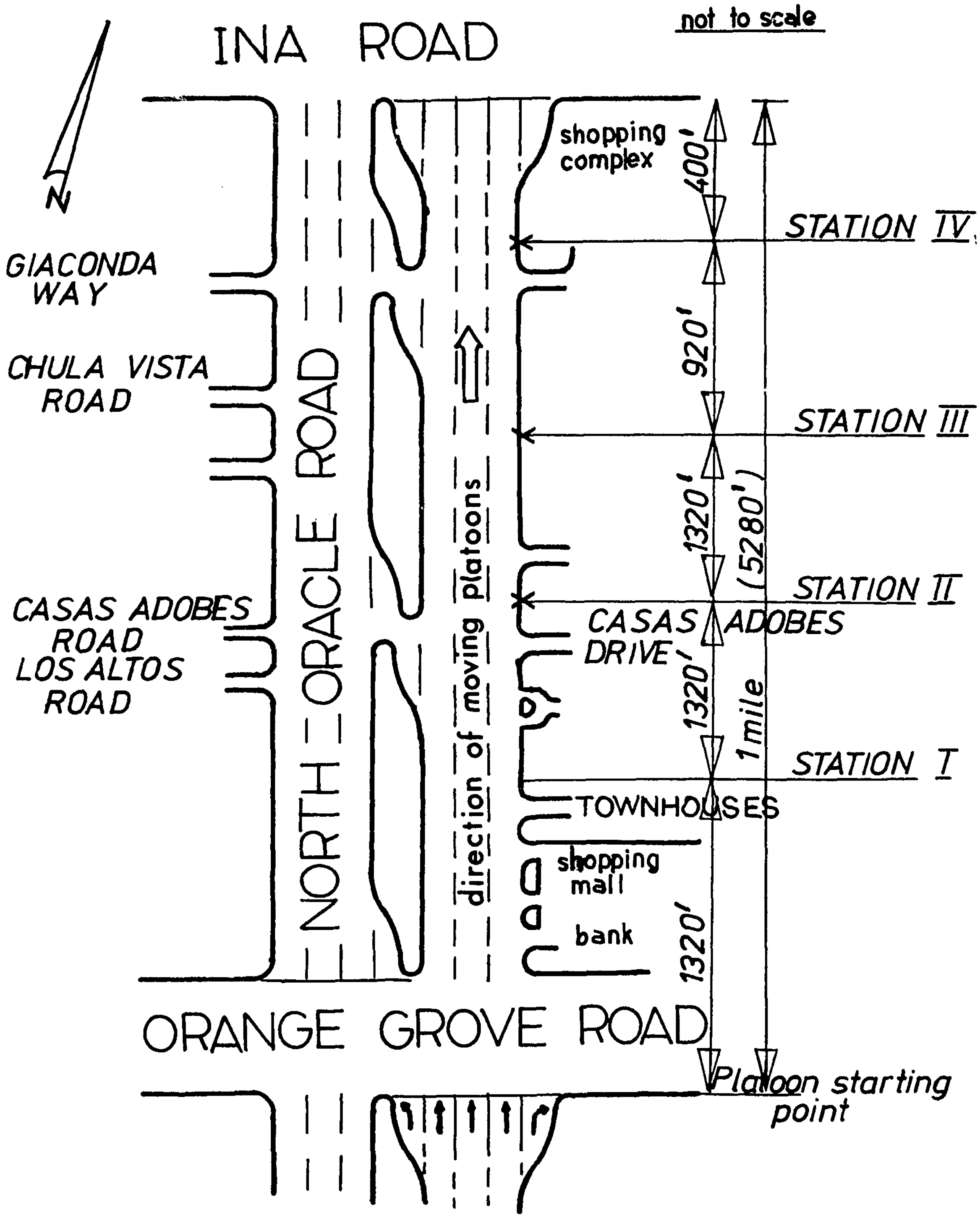


Figure 3. Test area for North Oracle Road

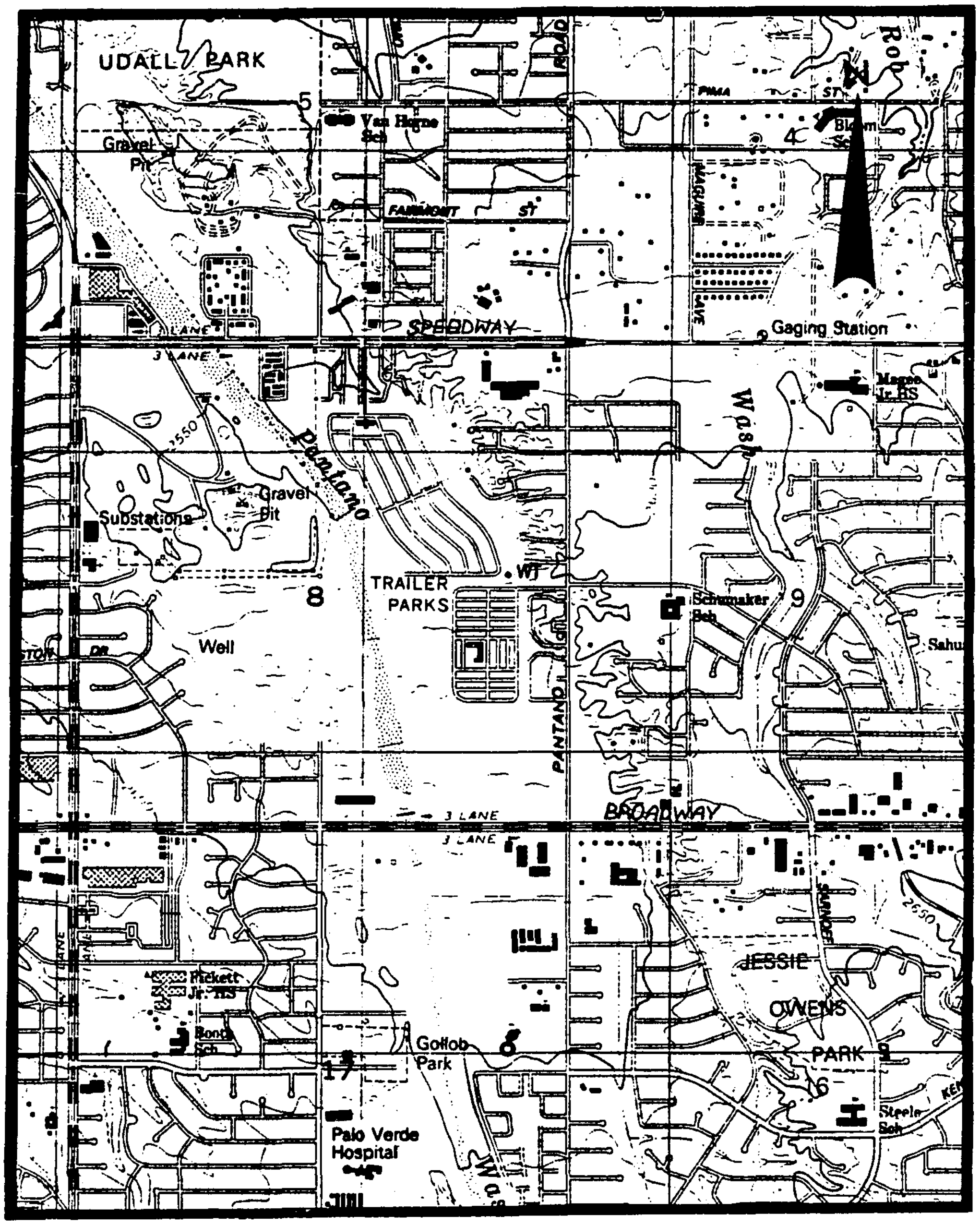


Figure 4. A locality plan for Pantano Road study site

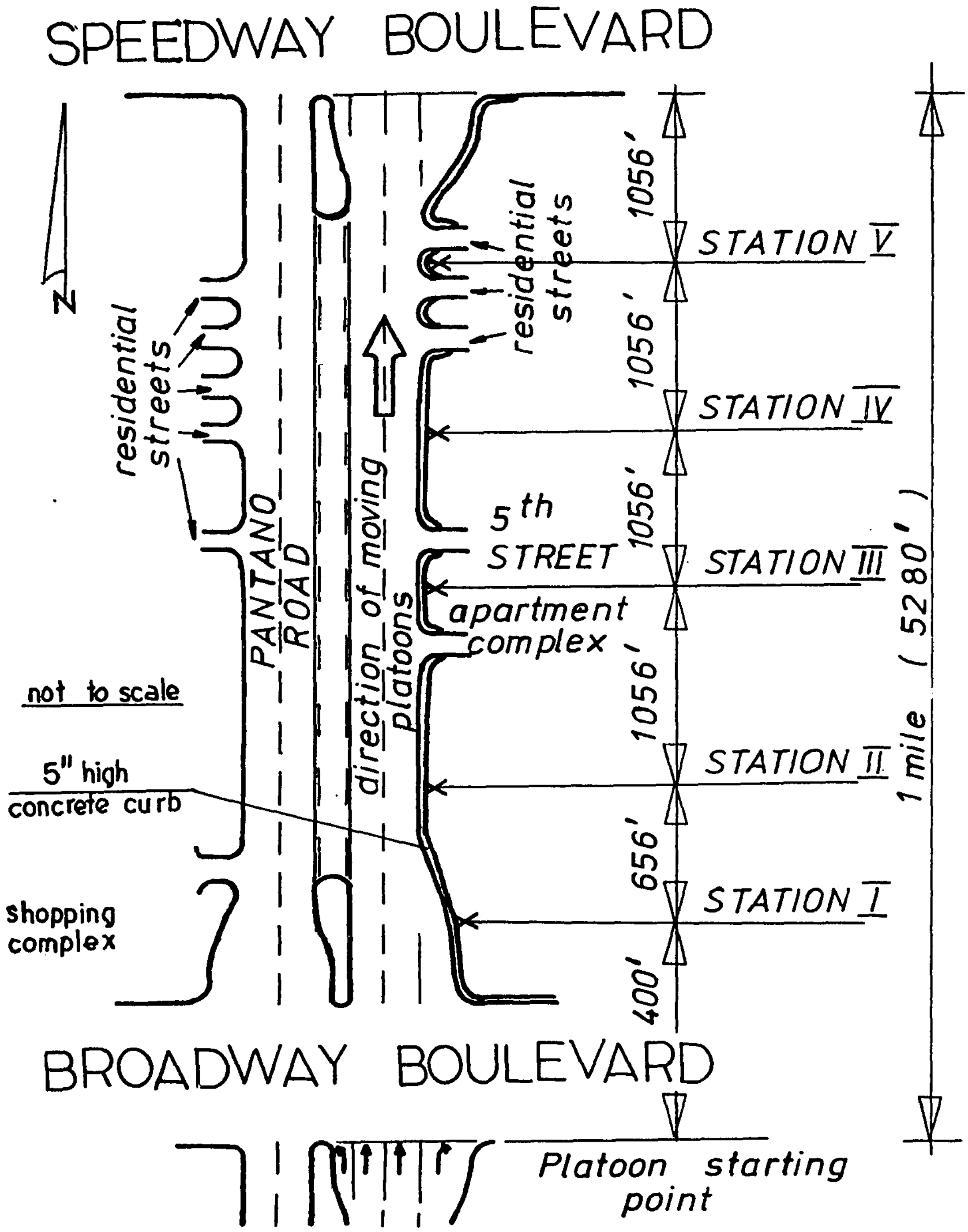


Figure 5. Test Area for Pantano Road

with the location of five data collection stations. A portion of the researched traffic link along Pantano Road had an uphill gradient of over 2.5 percent. A longitudinal profile of the researched part of Pantano Road between Broadway Boulevard and Speedway Boulevard is presented in Figure 6. Due to the terrain configuration, traffic signals at Speedway Boulevard could be seen only from about 1,400 feet before the intersection.

Both selected traffic links were one mile long between successive traffic signals. Side traffic interference was very small, almost negligible. Due to the terrain configuration in both cases, traffic signals could not be seen clearly by an approaching driver before the last 1,400 feet.

North Oracle Road at the study section had roughly three times as much traffic as Pantano Road between Speedway Boulevard and Broadway Boulevard.

Data Collection

The reviewed experimental studies measured traffic platoons in two ways. One was to observe platoons as they proceeded along a researched road link by using a film camera. This method, which gives distribution of passing

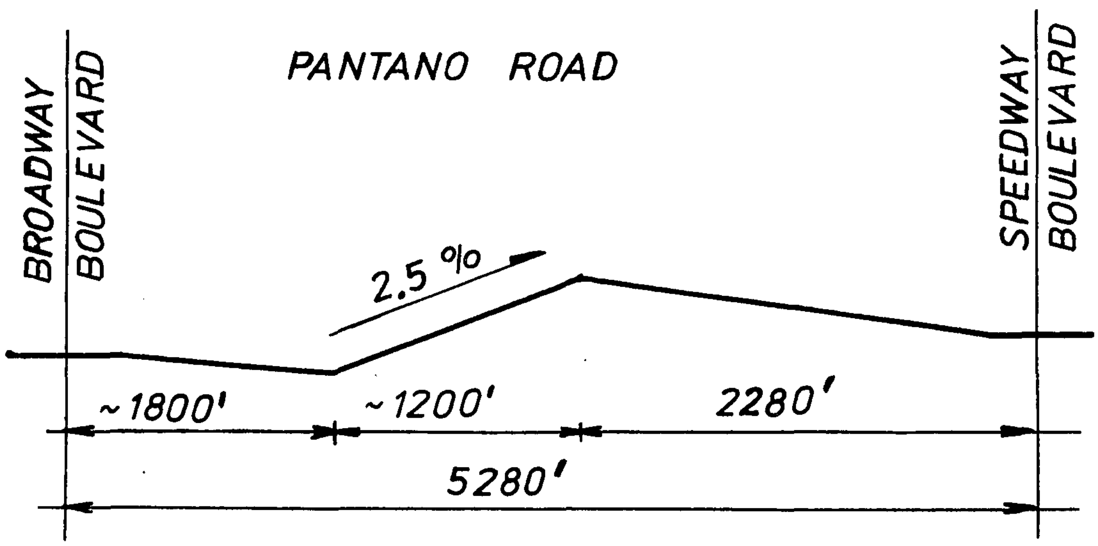


Figure 6. Longitudinal profile of Pantano Road between Broadway Boulevard and Speedway Boulevard

vehicles in space and permits measurement of any traffic variables. However, a high camera placement was needed to cover platoon movement throughout the entire road length. Because of the high cost, the use of a helicopter was ruled out and a test site with a high-rise building could not be found. The second method of measuring traffic platoon movement is to record passing vehicles at a given point on a street giving distribution of passing vehicles in time. Using only a road detector, data such as traffic composition and behavior of vehicles between sampling stations cannot be found. Manual observation of traffic instead of road detectors at a given point permits recording of traffic composition; however, vehicle speeds and lane changes due to side or other interference are still very hard to record. This method, in spite of a few limitations is much simpler and less expensive than the first one. Weighing all pros and cons of the two methods, the one which gives a distribution of passing vehicles in time at a given point was selected. The data were recorded using a 20-channel Esterline-Angus recorder shown in Figure 7.

From the review of the literature it was found that there are several variables affecting platoon movement on urban arterials. The compilation of the variables can be found in Table 2 in the Literature Review chapter. The specifics of data collection method permitted studying only

Figure 7. Esterline-Angus 20-channel recorder used in platoon data collection

four major variables. They are as follows:

1. Lane of travel.
2. Traffic composition.
3. Platoon size.
4. Traffic volume.

In addition to the above four variables, a longitudinal alignment of the Pantano study area created an opportunity to evaluate the influence of an uphill gradient on platoon behavior.

The following data were recorded:

1. The beginning of a green phase at the upstream intersection for the through movement - the movement when a platoon of vehicles waiting under a red signal is released and starts traveling downstream along the researched road.
2. Actual time position of every vehicle in a platoon on each lane, passing a particular station with its front axle, at a known distance from the intersection. The actual time positions were related to the beginning of the green phase.
3. Each vehicle with more than four wheels was recorded separately and during further analysis called a "truck". The trucks category consists of a broad range of vehicles including RVs,

semi-trucks, pick-up trucks with rear dual tires and buses.

All data were collected at one station at a time. After a sufficient size of the data were obtained at one station the observer then moved to the next station and collected data there. The data were not collected at all stations at the same time.

The pens on the Esterline-Angus recorder were activated by the observer every time when a vehicle which was a part of a platoon, on any of the lanes, passed with its front axle the particular station at the known distance from the intersection. A sample copy of graph paper is shown in Appendix A. The data were recorded based on lane of travel. Also, a vehicle which belongs in the truck category was recorded separately to distinguish it from passenger cars and motorcycles category. Because the platoon movement data were collected at each station at a different time, the first (or lead) vehicle at each location was not the same vehicle.

A minimum size of the platoon sample for each station was determined for 95 percent confidence limits. A number of platoons collected exceeded the planning values and for each station were large enough to satisfy planning values with 99 percent confidence.

There is almost universal agreement between researchers as to what constitutes a platoon. It can be defined as a group of vehicles in which headway between two successive vehicles is smaller or equal to some critical headway. However, the critical headway is a very complex variable and depends on a number of sites, driver and vehicle characteristics. Not surprisingly, several different values of critical headway were found in the literature review, ranging from 4 seconds in El-Reedy and Ashworth's paper [17] to 9 seconds in the 1950 Highway Capacity Manual. [33] Aerde and Yagar [21] concluded in their research, that the error due to subjective selection of platoons using the human observer method was smaller than the one due to difference between critical headways adopted by other researchers. Therefore, it was decided that for the purpose of this research a human observer method, rather than any mathematical model or arbitrarily chosen value would provide better and more site-specific results. All the vehicles which were a part of the starting platoon at the upstream intersections were considered in the data collection to be a part of the moving platoon even if the initial headway exceeded 8 seconds. The largest value for the critical headway found during the literature review was 9 seconds. The 1950 Highway Capacity Manual [33] stated 9 seconds to be the value of the critical headway, the maximum time spacing of the lead vehicle's speed clearly affects the speed of the following vehicle. The 1965 Highway Capacity Manual [34] quotes the same 9 second value. Due to complexity of the term "critical headway," a headway of 9 seconds was chosen for the critical headway along North Oracle Road where it was not known whether the vehicles in the moving platoon were a part of the starting platoon at the upstream intersection.

In the present research, it was possible to simultaneously obtain the vehicle arrival times and the headways between every consecutive vehicle on each lane.

The observer could see all starting platoons at the North Oracle Road and Orange Grove Road intersection only from station 1 at the North Oracle Road study site. Therefore, at that station all vehicles which were not a part of the starting platoon were rejected from the data collection. At stations 2, 3 and 4 along North Oracle Road, the observer collecting data did not have visual contact with the starting platoons. The starting time of the green phase for the through movement was transmitted by another observer stationed at the upstream intersection through a two-way radio. However, due to the large size of the platoons, it was impossible to transmit a description of every vehicle from the initial platoon to the second observer located at one of the stations in order to reject other vehicles which joined the platoon somewhere between the station and the upstream intersection. Therefore, the platoon data collected at stations 2, 3 and 4 contain some vehicles which exited from side streets or driveways and joined the platoon between the starting and the sampling point. During the data reduction, the platoon time limits for these stations were determined by eliminating all vehicles which were positioned over 9 seconds behind the last vehicle of the platoon without regard for individual lane. The "9 second value" for the critical headway was the largest found during the literature review.

From each of the five stations along the Pantano Road study site, the observer saw the entire traffic link. Therefore, it was possible to recognize and reject from the data collection all vehicles which were not a part of the starting platoon at the Broadway Boulevard and Pantano Road intersection.

If the traffic conditions along the researched traffic links during the data collection were unusual and temporary in nature, such as a lane closure due to construction or an accident, the data collection was postponed to a later date.

Oracle Road Data Collection

The field data along the researched part of Oracle Road were collected in October of 1983 and during the first two weeks of November 1983. Daily hours of data collection were between 10 AM and 2 PM and only on mid-weekdays. On North Oracle Road four stations were set at distances of 1,320 feet (¼ mile), 2,640 feet (½ mile), 3,960 feet (3/4 mile), and 4,880 (1 mile minus 400 feet) beyond the North Oracle-Orange Grove intersection. The location of station #4 (one mile minus 400 feet) was determined by moving upstream from the downstream intersection of North Oracle Road and Ina Road until it was visually observed that:

-the vehicles in the platoon did not have their brake lights illuminated, and

-there was no noticeable speed change.

Along North Oracle Road a crew of two observers was needed to record the data. One was stationed at the intersection of North Oracle Road and Orange Grove Road to transmit the starting time of the green phase for the through movement through a two-way radio to the other observer who was stationed at one of the stations along North Oracle Road. Traffic signals at this intersection had eight phases. Several photographs of North Oracle Road study site are shown in Figures 8 through 17. During the data

Figure 8. A platoon of traffic forming on North Oracle Road, south of Orange Grove Road, prior to entering test section.

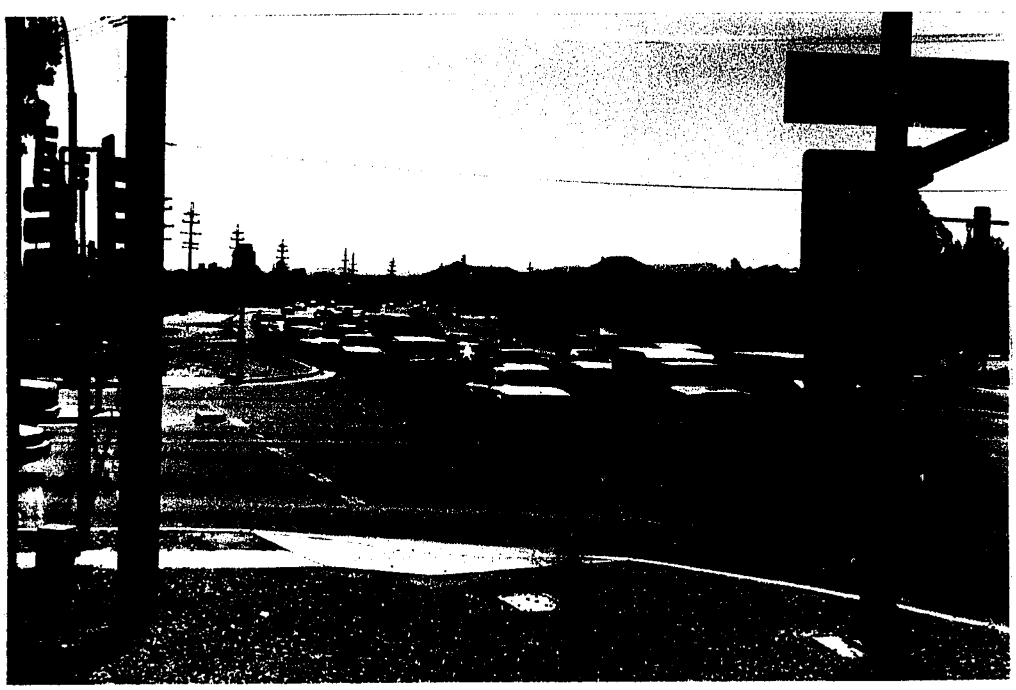


Figure 9. The platoon moving from starting line upstream on North Oracle Road.

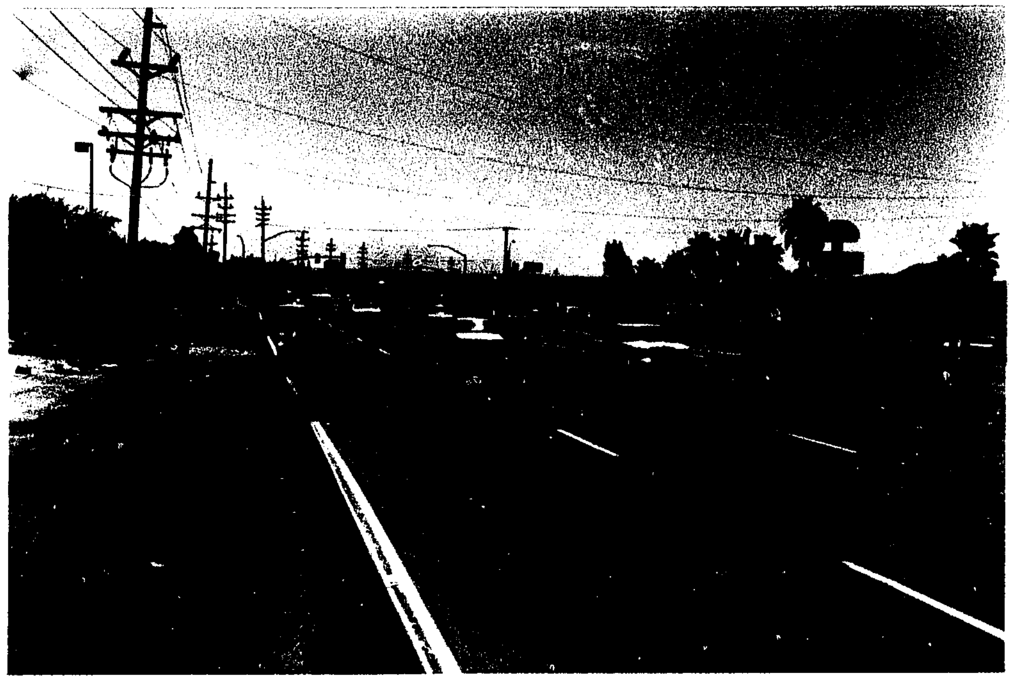


Figure 10. A platoon approaching Station I on North Oracle Road.

Figure 11. Downstream view from Station I on North Oracle Road.

Figure 12. Densely packed platoon approaching Station II at North Oracle Road.

Figure 13. A platoon approaching the 3960 feet site (Station III) at North Oracle Road.

Figure 14. An end of a platoon which just passed Station III at North Oracle Road.

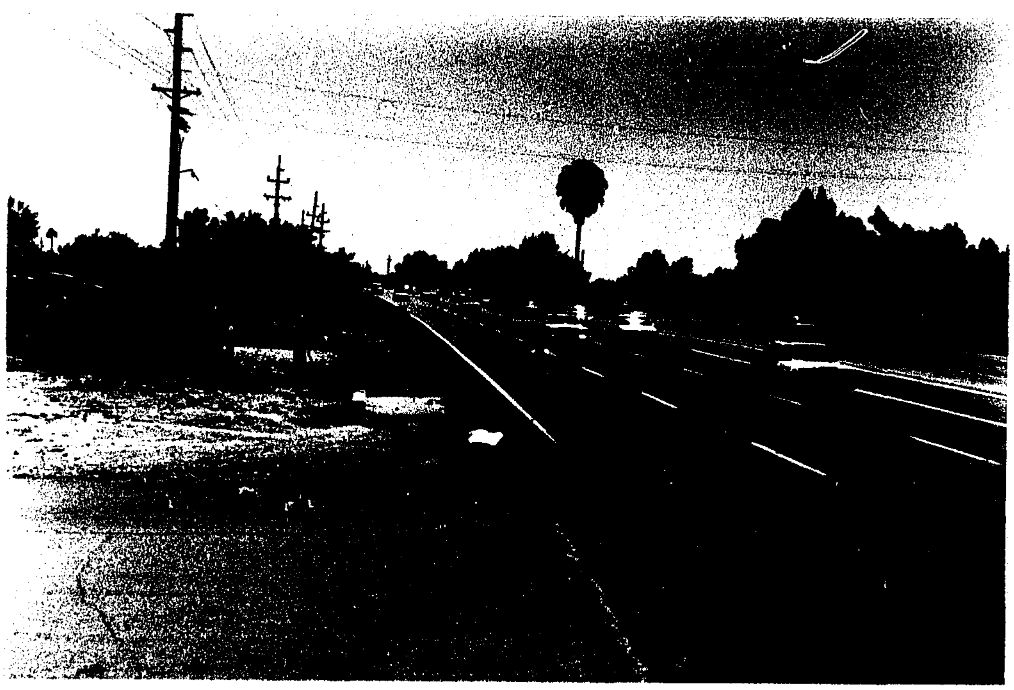


Figure 15. A platoon approaching Station IV (1 mile-400 feet) at North Oracle Road.

Figure 16. Vehicles in a platoon stopping at the downstream's traffic signals on North Oracle Road.

Figure 17. Low traffic flow between platoons on North Oracle Road.

collection, the weather was clear with good visibility and dry pavement.

Pantano Road Data Collection

The field data on Pantano Road were collected between August 18, 1983 and September 20, 1983. The data collection was conducted only on mid-weekdays and between 10 AM and 2 PM. Observations were made at five locations beyond the traffic signal. Stations were located at 400 feet, 1,056 feet (1/5 mile), 2,112 feet (2/5 mile), 3,168 feet (3/5 mile), and 4,224 feet (4/5 mile) beyond the Broadway Boulevard-Pantano Road intersection. The locations of the stations on Pantano Road were selected in a different fashion from those on North Oracle Road for two reasons. The first criterion was to determine platoon behavior pattern on an upgrade; therefore, a station was set approximately at the bottom of the hill and one at the top of the hill. The second reason was that the majority of the vehicles traveling downstream were turning left from Pantano Road onto Speedway Boulevard. From visual observations, it was estimated that at least 1,000 feet between the downstream intersection and the station location would yield accurate collection data, which were not distorted or seriously influenced by drivers anticipating left turns or just simply watching traffic signals turning red or green. Along Pantano Road it was possible to collect all the data with only one observer. Traffic signals at the intersection of Pantano Road and Broadway Boulevard had only two phases at the time of the study. Therefore, from each of the five stations the observer could see the starting of the green phase for the through movement. At stations #4 and #5, the starting of the green phase needed to be observed through binoculars due to the large distance between these stations and the Pantano-Broadway traffic signals. Several photographs of Pantano Road study site are shown in Figures 18 through 25. During the data collection, the weather was again clear with good visibility and dry pavement.

Traffic Disturbances

The nature of the data collection technique precluded obtaining simultaneous data as to what effect side traffic exiting from midblock streets and driveways had on passing platoons. Side traffic along Pantano Road was negligible and did not create any disturbances to the traveling platoons. The highest side traffic recorded along the researched part of North Oracle Road was 240 v.p.h. entering into, and 260 v.p.h. exiting from a shopping complex on the northeast corner of the intersection of North Oracle Road and Orange Grove Road. These values were obtained by an observer who counted the number of entering and exiting vehicles during two consecutive days, Tuesday and Wednesday of the last week of September 1983. There were

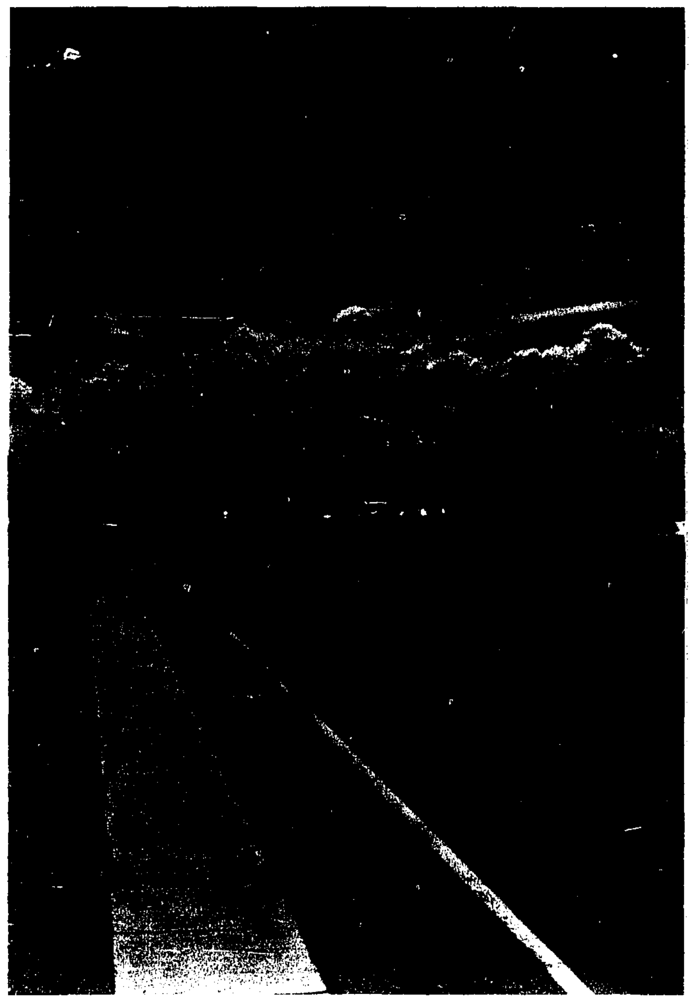


Figure 18. A platoon of traffic forming on Pantano Road, south of Broadway Boulevard, prior to entering the test section. The picture was taken at Station I at 400 feet.

Figure 19. A very dense platoon crossing Broadway Boulevard and approaching Station I on Pantano Road.

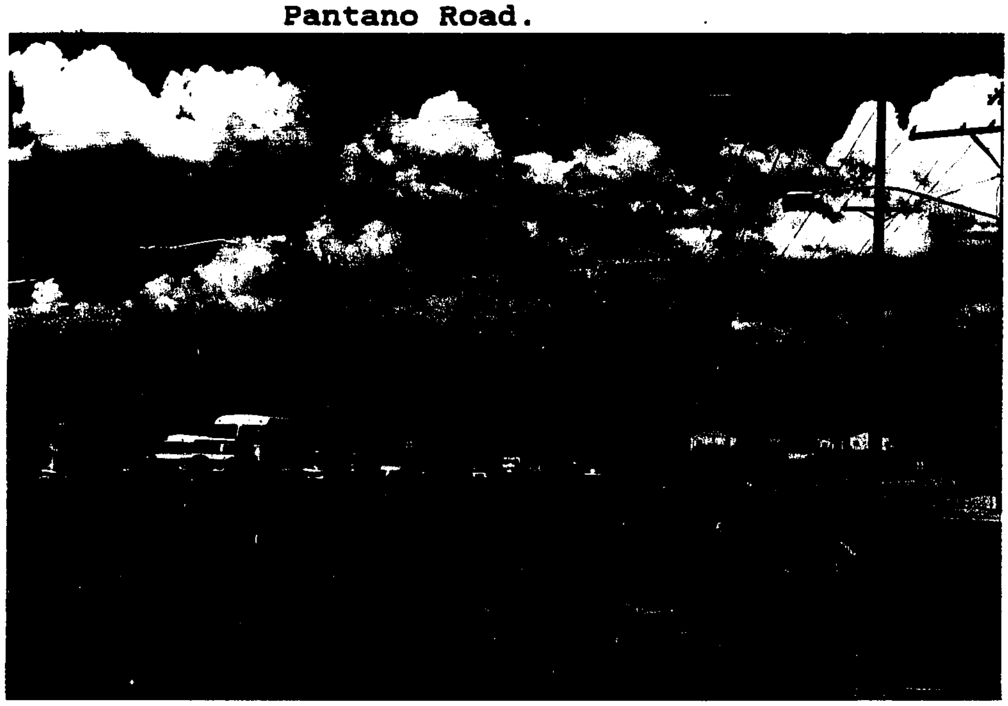


Figure 20. Downstream view at the Pantano Road test section from the stopline (platoon starting point).

Figure 21.
Uphill section of Pantano Road - A view from Station II.

Figure 22. An unusually large number of the vehicles in a platoon approaching Station III on Pantano Road.

Figure 23. A platoon of traffic approaching Station IV on Pantano Road.

Figure 24. A downstream view at the intersection of Pantano Road and Speedway Boulevard from Station V.

Figure 25. A platoon of cars approaching Station V on Pantano Road.

two traffic counts performed each day from 10:00 A,M, to 11:00 A.M. and from 1:00 P.M. to 2:00 P.M. It was observed that vehicles exiting from side streets and driveways did not create any major disturbances to moving platoons. Generally, the vehicles waiting to enter the main street did not enter it, unless a suitable gap in moving traffic was available. However, the vehicles which were part of the recorded platoons and turned into that shopping complex, did create disturbances to the flow of traffic in the right lane of travel.

Traffic Composition

It was not known what effect and if any, the presence of trucks and other non-passenger vehicles would have on the platoon behavior. Therefore, during the data collection, each truck was recorded separately. As previously indicated, a variety of light trucks with twin tires on rear axles, buses, semi-trucks and RVs were included in the "truck" category.

CHAPTER IV

ANALYSES AND RESULTS

The following general steps were used to examine the data:

1. The data (vehicles) were recorded based on lane of travel; therefore it was possible to compare mean vehicles arrival times between adjacent lanes. Where significant differences were not found during the comparison, the platoons from the station's adjacent lanes were combined together for the analysis of the platoon dispersion.
2. The effect of platoon size on platoon dispersion at each study site was evaluated. Also, a comparison was made between both sites to determine what effect, if any, traffic volume had on platoon characteristics.
3. The platoons containing trucks were compared to all collected platoon populations to determine effects of heavy vehicles on platoon dispersion.
4. The platoon's movement on the uphill part of the Pantano link was compared to the platoon movement along the level sections of the road.

A total of 417 platoons containing 5,178 cars and trucks were recorded. A summary of vehicles recorded during the data collection at both sites is presented in Table 3.

It was found during the literature review that a great variety of statistical tests were used to investigate a goodness-of-fit between variables. The most popular comparison test used in four of the reviewed research studies was a chi-squared test. A least-squared regression routine was applied in two comparisons, while a "t" test, Kolmogorov-Smirov test and analysis of variance, "F" test, were used in separate projects. Because the chi-squared, "t" and "F" distributions are all related to normal distribution, and the random variables "t" and chi-squared are only special cases of the random variable "F", it was decided that for goodness-of-fit comparisons the "F" distribution would be used.

Lane Distribution

All the data were recorded based on lane of travel. A vehicle lane distribution in percent per site/station is presented in Table 4. As shown, there is a higher tendency for the vehicles to travel in the left lane "the fast lane," than in the right lane "the slow lane." A slight difference in the lane distribution at station 5 can be attributed to a high number of vehicles turning left from Pantano Road onto Speedway Boulevard.

Table 3. Summary of vehicles recorded.

Study Site	Pantano Road	Oracle Road
Total Vehicles	1,277	3,901
Number of Trucks	42	110
Number of Platoons	214	203
Number of Platoons per Station:		
Station I	31	32
Station II	19	51
Station III	42	65
Station IV	50	55
Station V	72	NA

Table 4. Vehicle lane distribution in percent per site/station.

Site	Pantano Road		Oracle Road		
Lane Sta.	Right	Left	Left	Middle	Right
#1	40%	60%	41%	39%	20%
#2	38%	62%	43%	31%	26%
#3	41%	59%	47%	28%	25%
#4	38%	62%	43%	32%	25%
#5	36%	64%	-	-	-

Travel data for any lane of traffic for North Oracle Road study site are presented in Tables 5 through 8 and for Pantano Road in Table 9. The tables contain mean vehicle arrival times and the number of vehicles recorded at each lane and station. Variance values were used in the latter part of this chapter for statistical comparison. Due to the large size of platoons recorded along North Oracle Road study site, the data presented in Table 5 through 8 are for every second platoon vehicle only, starting with the first vehicle of the platoon. An average platoon size recorded along the Pantano Road study site was much smaller. Therefore, the data presented in Table 9 is limited to four platoon vehicles only. In general, the comparison of the mean vehicle arrival times in Tables 5 through 9 shows that the vehicles traveling in the right lane are slower than the vehicles traveling in the left lane. For North Oracle, it can also be observed that the vehicles traveling on the middle lane are slightly slower than the vehicles traveling on the left lane.

Effect of Lane of Travel

A statistical analysis was used to determine whether platoon behavior can be influenced by the travel lane. The test used was the comparison of the variances of two different samples to find out whether the samples represented the same or different populations. Variances are

Table 5. Lane of travel data - North Oracle Road, Station #1.

STATION #1									
VEHICLE NUMBER IN PLATOON	MEAN TRAVEL TIME (SECONDS)			VARIANCE (SECONDS)			SAMPLE SIZE		
	RIGHT LANE	MIDDLE LANE	LEFT LANE	RIGHT LANE	MIDDLE LANE	LEFT LANE	RIGHT LANE	MIDDLE LANE	LEFT LANE
#1	30.2	27.7	27.4	13.2	3.6	3.9	32	32	32
#3	38.9	32.0	33.4	15.2	3.4	3.9	25	30	32
#5	47.6	36.4	37.2	44.9	7.5	6.1	4	24	28
#7	52.3	42.1	41.8	3.4	17.6	8.5	2	20	20
#9	-	44.9	45.5	-	12.6	9.6	-	7	8
#11	-	50.5	48.5	-	15.9	2.8	-	5	3

Table 6. Lane of travel data - North Oracle Road, Station #2.

STATION #2									
VEHICLE NUMBER IN PLATOON	MEAN TRAVEL TIME (SECONDS)			VARIANCE (SECONDS)			SAMPLE SIZE		
	RIGHT LANE	MIDDLE LANE	LEFT LANE	RIGHT LANE	MIDDLE LANE	LEFT LANE	RIGHT LANE	MIDDLE LANE	LEFT LANE
#1	46.2	45.1	45.0	13.0	9.9	9.7	32	32	32
#3	57.5	53.1	52.2	37.6	24.5	15.5	47	50	51
#5	67.3	60.8	57.4	43.1	28.3	22.0	29	35	47
#7	71.4	66.1	63.2	42.6	39.3	29.6	10	22	40
#9	77.0	71.0	68.3	109.4	39.8	23.5	4	9	26
#11	76.5	77.7	74.1	-	0.9	21.4	1	2	11

Table 7. Lane of travel data - North Oracle Road, Station #3.

STATION #3									
VEHICLE NUMBER IN PLATOON	MEAN TRAVEL TIME (SECONDS)			VARIANCE (SECONDS)			SAMPLE SIZE		
	RIGHT LANE	MIDDLE LANE	LEFT LANE	RIGHT LANE	MIDDLE LANE	LEFT LANE	RIGHT LANE	MIDDLE LANE	LEFT LANE
#1	65.9	64.8	64.3	22.7	15.0	13.3	65	65	65
#3	75.4	75.2	69.8	26.2	27.0	18.2	54	62	64
#5	83.7	81.8	76.6	20.9	41.1	31.2	36	45	62
#7	90.3	87.9	82.2	33.1	41.6	35.7	18	18	55
#9	97.2	90.4	86.2	49.1	8.0	21.0	5	6	39
#11	-	-	-	-	-	-	-	-	-

Table 8. Lane of travel data - North Oracle Road, Station #4.

STATION #4									
VEHICLE NUMBER IN PLATOON	MEAN TRAVEL TIME (SECONDS)			VARIANCE (SECONDS)			SAMPLE SIZE		
	RIGHT LANE	MIDDLE LANE	LEFT LANE	RIGHT LANE	MIDDLE LANE	LEFT LANE	RIGHT LANE	MIDDLE LANE	LEFT LANE
#1	78.2	76.4	76.4	27.9	26.8	23.3	55	55	55
#3	91.4	86.7	84.3	48.3	41.9	31.9	50	51	53
#5	99.5	94.8	90.5	72.4	53.1	32.1	23	36	46
#7	107.7	100.3	96.7	44.0	24.5	45.5	11	21	37
#9	-	108.4	102.5	-	44.8	42.1	-	8	26
#11	-	109.4	104.4	-	38.5	27.4	-	3	11

Table 9. Lane of travel data - Pantano Road study site.

Vehicle number in platoon	Sta. #	Mean Travel Time (seconds)		Variance (seconds)		Sample Size	
		Right Lane	Left Lane	Right Lane	Left Lane	Right Lane	Left Lane
First vehicle in the platoon	I	13.5	13.4	2.5	1.9	31	31
	II	22.8	22.5	5.7	4.8	19	19
	III	38.8	38.3	13.0	15.7	42	42
	IV	57.2	56.4	28.8	20.6	48	49
	V	70.9	69.2	40.2	35.8	71	72
Second vehicle in the platoon	I	16.0	15.7	3.3	2.1	29	30
	II	26.6	24.8	6.5	5.9	19	19
	III	42.0	41.2	15.9	15.5	36	40
	IV	60.9	59.7	19.6	21.3	37	49
	V	76.4	72.7	46.6	34.7	52	72
Third vehicle in the platoon	I	17.6	17.5	2.6	2.3	11	26
	II	28.2	26.9	10.8	11.8	8	17
	III	42.4	43.5	19.9	19.1	11	29
	IV	61.9	61.4	15.7	17.9	14	43
	V	78.7	76.6	80.6	46.7	16	59
Fourth vehicle in the platoon	I	19.4	19.1	1.5	1.1	4	15
	II	25.7	28.0	0.0	5.1	1	13
	III	43.1	44.4	20.3	1.3	2	13
	IV	69.7	64.5	0.0	13.2	1	17
	V	80.7	78.5	20.2	41.6	5	29

said to be homogenous when they may be considered to have come from the same or from equally normal populations. The homogeneity of variances was tested by computing the "F" Ratio as follows:

$$F = \frac{S_1^2}{S_2^2}$$

where:

S_1^2 - larger variance of random sample 1 of size n_1

S_2^2 - smaller variance of random sample 2 of size n_2

The computed value of "F" ratio was then compared with the critical "Fcr" value. If the computed "F" value is less than the critical "Fcr" value, the variances are accepted as homogeneous. The variances used in statistical comparison were derived from the mean arrival times of the vehicles located in the platoons at each of the stations. Due to the large platoon sizes along North Oracle Road, only every second vehicle in a platoon was included in the statistical analysis. For Pantano Road study site, the statistical data on lane effect were large enough to evaluate first, second and third vehicle in the platoon only.

To illustrate the procedure employed, a specific example will be presented. In Table 9, the first vehicle in the observed combined platoons at Station 4 for example, had a mean arrival time of 57.2 seconds for the right lane and 56.4 seconds for the left lane. To determine whether the difference between two means could be considered significant in the statistical sense, the "F" ratio was calculated using both populations variations and was found to be less than "Fcr" of 1.53, at the 95% confidence level.

$$F = \frac{S_1^2}{S_2^2} = \frac{28.8}{20.6} = 1.40$$

$$F < Fcr \implies 1.40 < 1.53$$

The interpretation was that the variances are accepted as homogeneous and the difference is not significant. The conclusion can be drawn that the lane of travel had no significant effect on the mean arrival time of the first vehicle in the platoons at Station 4 at the Pantano Road study site.

The same procedure was applied to the other nine pairs of mean vehicle travel times along Pantano Road and to 49 pairs of mean vehicle travel times on North Oracle Road. On North Oracle Road, where three lanes of data had to be compared, three possible lane pairs were checked separately. A summary of the lane effect test results for North Oracle Road study site is presented in Table 10 and for the Pantano Road study site in Table 11.

Based upon the statistical comparison for North Oracle Road, there is no significant difference in mean vehicle arrival times between the left and middle lanes. However, the comparison of the right lane against the middle

Table 10. Statistical comparison test results of the effect of lane of travel for North Oracle Road study site.

Vehicle Position in Platoon	STA # 1			STA # 2			STA # 3			STA # 4		
	RL-ML	RL-LL	LL-ML	RL-ML	RL-LL	LL-ML	RL-ML	RL-LL	LL-ML	RL-ML	RL-LL	LL-ML
1 st	R	R	A	A	A	A	A	R	A	A	A	A
3 rd	R	R	A	A	R	A	A	A	A	A	A	A
5 th	R	R	A	A	R	A	R	A	A	A	R	A
7 th	A	A	A	A	A	A	A	A	A	A	A	A
9 th	*	*	A	A	R	A	A	R	A	*	*	A
11 th	*	*	A	*	*	A	*	*	*	*	*	A

RL - Right Lane
ML - Middle Lane
LL - Left Lane
R - statistically rejected at the 95% confidence level
A - statistically approved at the 95% confidence level
* - sample size too small for statistical comparision

Table 11. Statistical comparison test results of the effect of lane of travel for Pantano Road study site.

Station #	Vehicle position in platoon		
	First	Second	Third
	LL - RR	LL - RL	LL - RL
1	A	A	A
2	A	A	A
3	A	A	A
4	A	A	A
5	A	A	A

RL - Right Lane
LL - Left Lane
R - Statistically rejected at the 95% confidence level
A - Statistically accepted at the 95% confidence level
* - Sample size too small for statistical comparision

lane and the right lane against the left lane exhibits a statistical significance in the first third of the mile at a 95% confidence level. As the platoons move further away from the starting point, the statistical differences dissipate. At Station 3 only three out of fifteen comparisons were rejected , and at Station 4 only one comparison was rejected. Also, based upon the statistical comparison, it can be concluded that for the Pantano Road, a lane of travel has no significant effect on mean vehicle arrival times and, therefore, platoon behavior. The analysis of variance, "F" test, was also used to evaluate possible differences in lane utilization at the various stations. Vehicle lane distribution values, compiled in Table 4, were compared between stations on the same lane of travel. On Oracle Road a total of 18 possible pairs, 6 per lane, of vehicle lane distribution values were analyzed. All comparisons exhibited no statistical differences. For Pantano Road all possible 20 pairs, 10 per each lane, were checked and it was determined that there were no statistical differences observed. It can be concluded that there is an evident lack of changes in lane distribution at the various stations at 95 percent confidence level.

The obtained data opened the possibility for comparing "Lane Utilization Factors" used in Highway Capacity Manual (H.C.M.). [4] The lane utilization factors reflect the fact that where two or more lanes of traffic exist in the same direction, the flow will not divide equally over all available lanes. There is always going to be a lane with a higher volume of traffic and a lane with a lower volume of traffic. For average conditions HCM recommends using a value of one for the lane utilization factor. The value of one for the factor can be translated into the assumption of a 52.5-47.5 percent split of the traffic volume between two lanes. In a group of three lanes the value of one for the factor assumes that one lane with the heaviest traffic carries 36.7 percent of the total flow for the direction. Table 12 presents a comparison between results obtained in this research and Highway Capacity Manual values.

Distribution of Vehicle Arrivals

The true interest in the distribution of vehicle arrivals is in the platoon arrival patterns at the downstream intersection. For this analysis, the lane of travel is not very important. Therefore, for the analysis of the platoon dispersion, the platoon data from each lane were combined together at each station for each study location. For all the vehicles recorded in the combined data base, the frequency histograms of the distribution of vehicle arrivals were produced for each site and each

Table 12. Comparison of traffic volume distribution per lane in percent.

	Three lanes in a lane group			Two lanes in a lane group	
	Left Lane	Middle Lane	Right Lane	Left Lane	Right Lane
HCM [28]	36.7%	31.6%	31.7%	52.5%	47.5%
Research Findings					
Station I	41%	39%	20%	60%	40%
Station II	43%	31%	26%	62%	38%
Station III	47%	28%	25%	59%	41%
Station IV	48%	32%	25%	62%	38%
Station V	-	-	-	69%	36%

station. They are presented in Figure 26 through 34.

Also, based upon the statistical comparison, it can be concluded that for the Pantano Road, a lane of travel has no significant effect on mean vehicle arrival times and, therefore, platoon behavior.

The figures were developed using "SYSTAT"[32] computer program. The characteristic bell shape of each platoon progressing downstream from site to site was broadening and flattening at the successive downstream locations. A maximum time length of each combined platoon at every station was expressed in seconds and also in percent increase over Station 1 at each of the study site locations. For comparison purposes, the time lengths of the combined platoons at Station 1 were assumed to be 100%. The platoon dispersion data were tabulated and shown in Tables 13 and 14. The maximum recorded time length of a platoon for the last station was 57.5 seconds at Oracle Road and 38 seconds at Pantano Road. Both values include extremely fast and extremely slow vehicles. The platoon data for North Oracle Road study site may include vehicles which were not a part of the original starting platoon. These vehicles were most likely positioned at the very front or at the very end of the recorded platoons. The greatest increase in platoons length occurs between Station 1 and 2 for North Oracle Road and between Station 2 and 3 for Pantano Road. In both cases

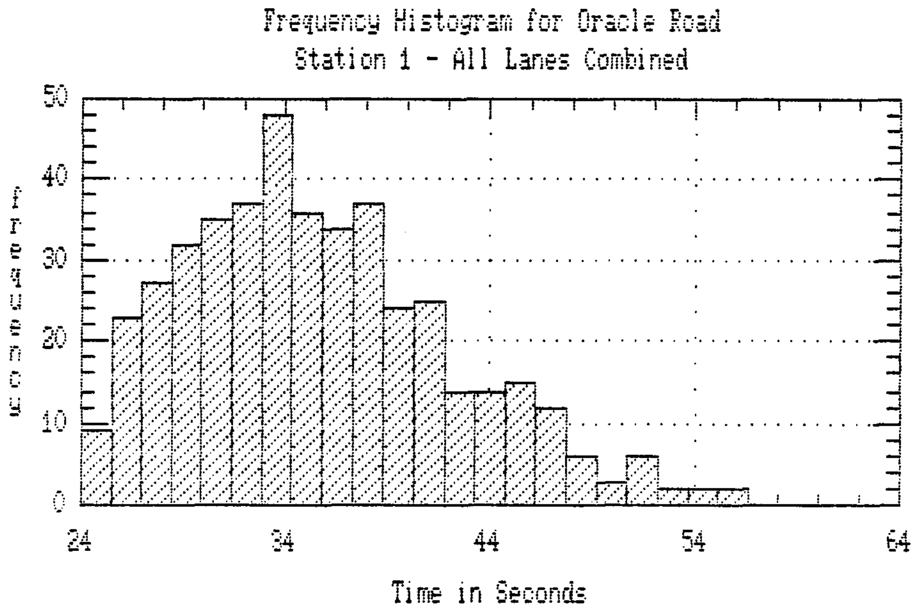


Figure 26. Frequency histogram of vehicle arrivals, Station I on North Oracle Road

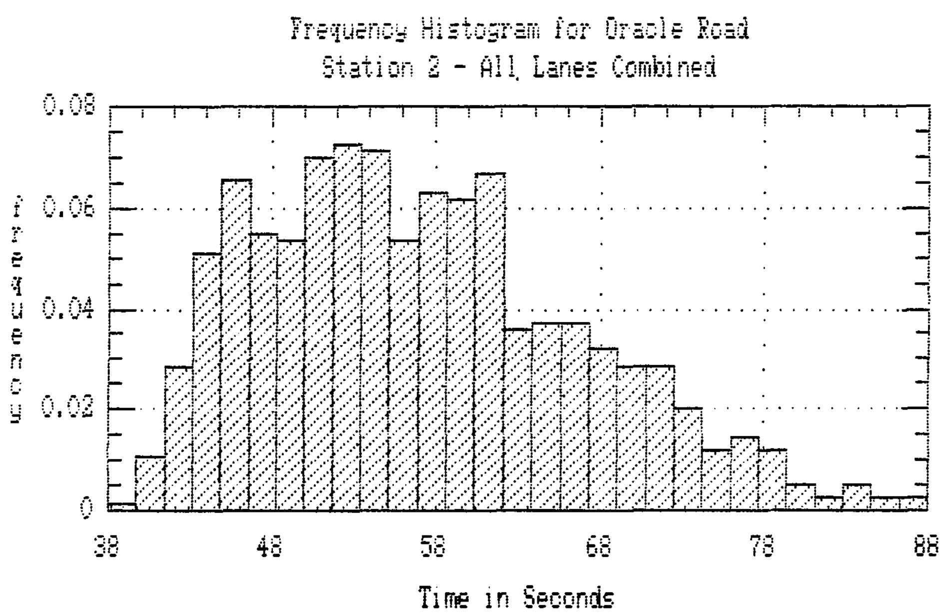


Figure 27. Frequency histogram of vehicle arrivals, Station II on North Oracle Road

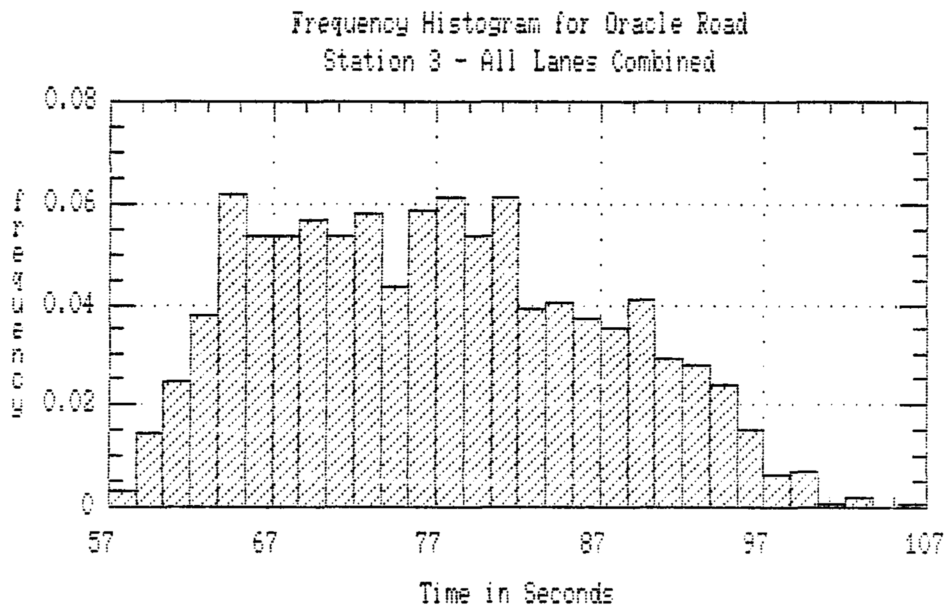


Figure 28. Frequency histogram of vehicle arrivals, Station III on North Oracle Road

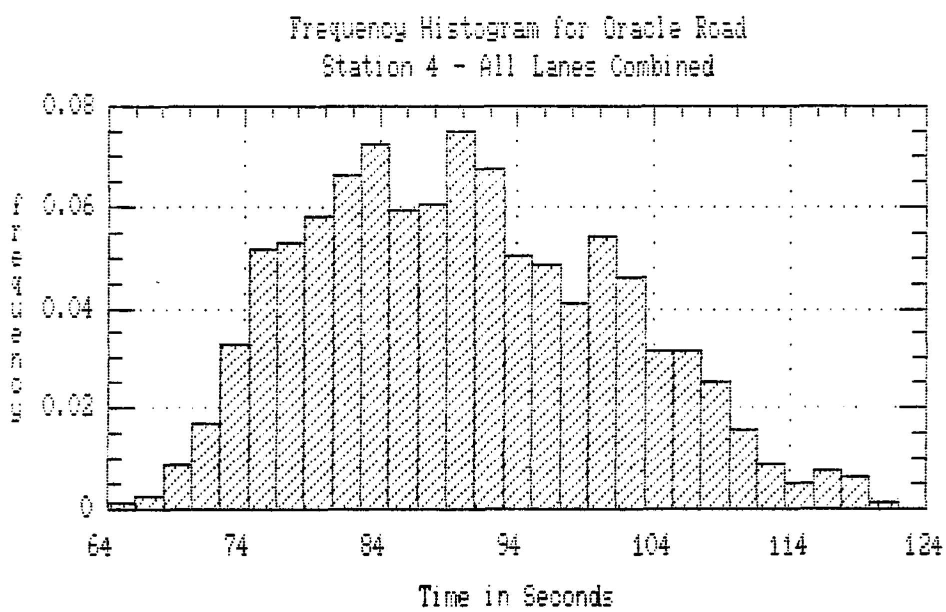


Figure 29. Frequency histogram of vehicle arrivals, Station IV on North Oracle Road

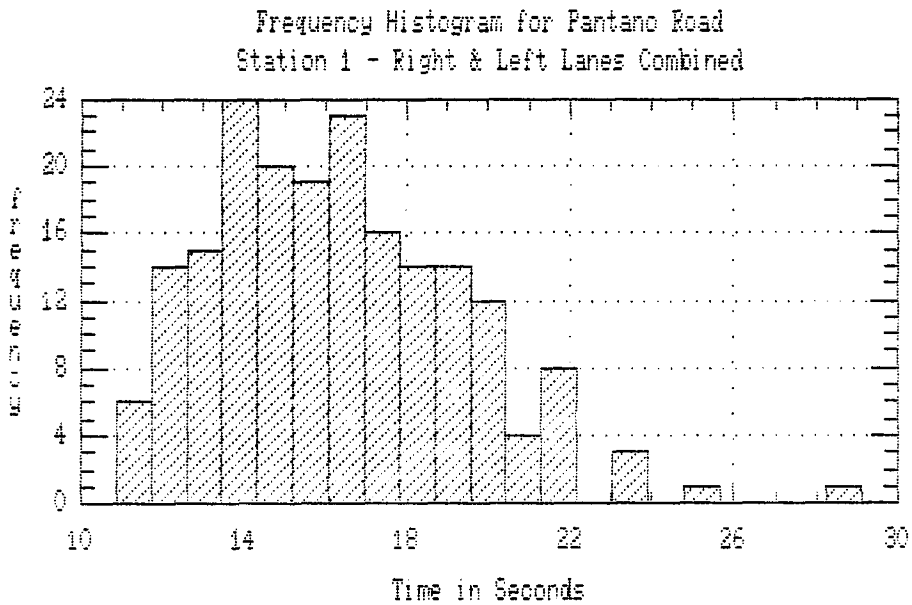


Figure 30. **Frequency histogram of vehicle arrivals, Station I on Pantano Road**

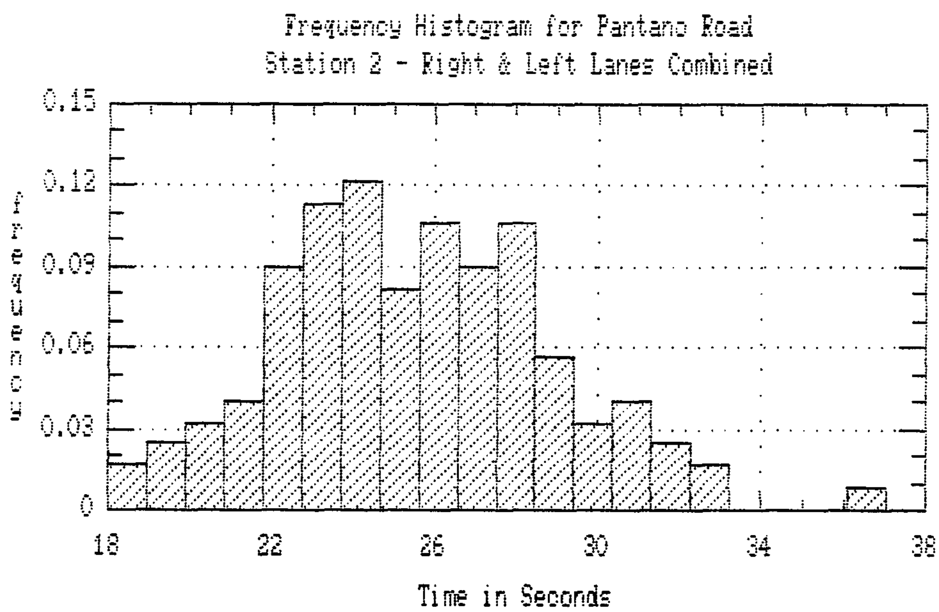


Figure 31. **Frequency histogram of vehicle arrivals, Station II on Pantano Road**

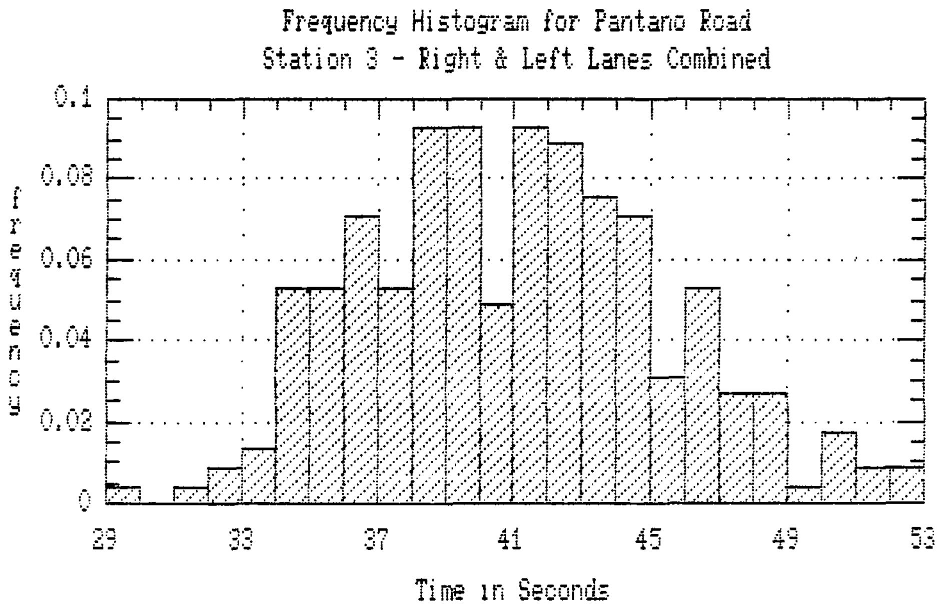


Figure 32. Frequency histogram of vehicle arrivals, Station III on Pantano Road

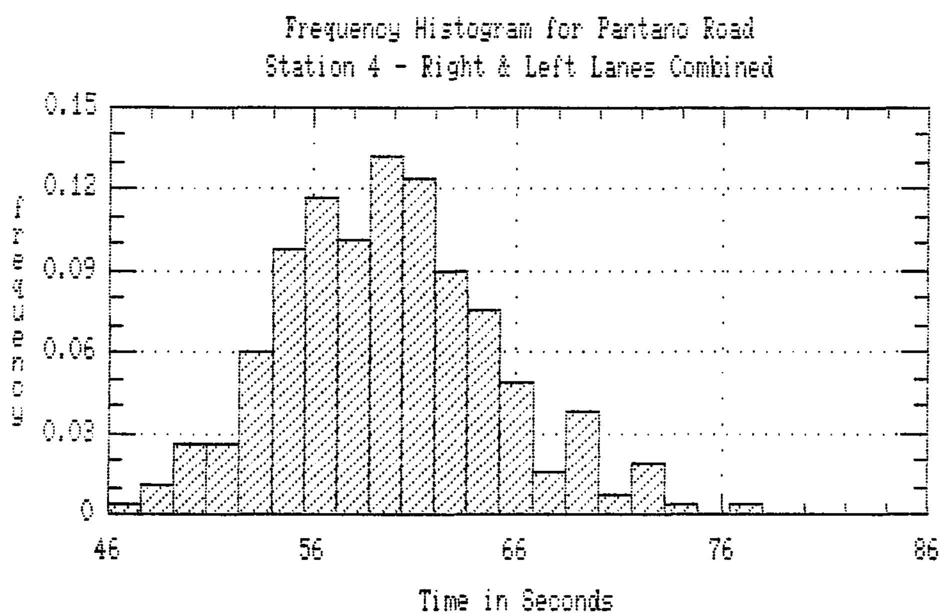


Figure 33. Frequency histogram of vehicle arrivals, Station IV on Pantano Road

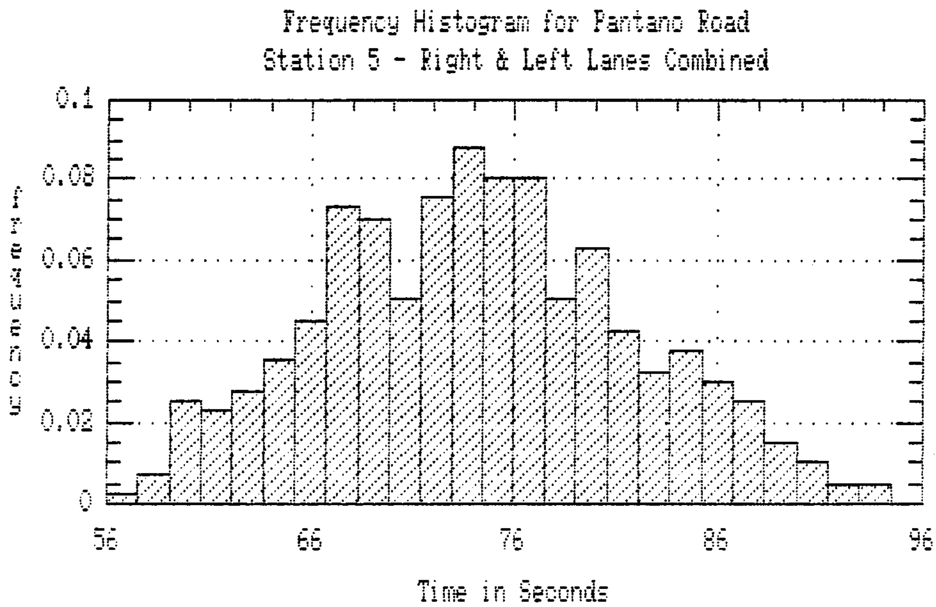


Figure 34. Frequency histogram of vehicle arrivals, Station V on Pantano Road

Table 13. Dispersion of platoons at Oracle Road study site.

Station	Maximum recorded time length of a platoon in seconds	Increase in platoon length in percent in relation to :		Mean time of first vehicle in a platoon in second
		next upstream station	Station #I	
STA I (1320')	32.2	0	0	28.4
STA II (2640')	48.5	51%	51%	45.4
STA III (3960')	49.5	2%	54%	65.0
STA IV (4880')	57.5	16%	79%	77.0

Table 14. Dispersion of platoons at Pantano Road study site.

Station	Maximum recorded time lenght of a platoon in seconds	Mean time of first vehicle in a platoon in seconds	Increase in platoon length in percent in relation to:	
			Closest upstream Station	Station #I
STA I (400')	17.5	13.4	0	0
STA II (1050')	18.5	22.7	6	6
STA III (2112')	23.6	38.6	28	35
STA IV (3168')	29.9	56.8	27	71
STA V (4224')	37.7	70.1	26	115

the distance from the platoon starting point is approximately the same, somewhere between 1,000 and 2,500 feet. For Pantano Road, platoon time length increase becomes very uniform past Station 2. However, at Oracle Road the platoon time length increase is almost negligible between Stations 2 and 3. Between Stations 3 and 4, the increase is smaller than for a comparable distance at Pantano Road.

The dispersion of a platoon is simply an increase in the platoon's length as it moves away from the upstream traffic signals. Along North Oracle study site, that increase was from an initial time length of 32.2 seconds at Station 1 to 57.5 seconds at Station 4. This is an increase of 79% over the distance of about 3/4 of a mile. For Pantano Road the increase was 115%. However, due to much smaller platoon sizes, the maximum observed time length of a platoon recorded at Station 5 was 37.7 seconds. That time length can still be accommodated at the downstream traffic signal's green phase. The moving vehicles did reach a free flowing conditions at neither of the study sites. The vehicles stayed in clearly visible platoons throughout the entire length of the researched traffic links.

Effect of Traffic Volume on Platoon Dispersion

The dispersion characteristics of platoons with a high number of vehicles will be compared to platoons with a low number of vehicles. The number of the recorded vehicles in a platoon on one lane was between 1 to 18 for North Oracle Road and 1 to 7 for Pantano Road.

By definition, a platoon is a group with two or more vehicles. One vehicle cannot be a platoon because one vehicle cannot disperse. However, one vehicle category for addition to platoons was included in this subsection. During the data collection, several single vehicles were recorded on one lane of travel while on the adjacent lane or lanes, there was a platoon consisting of two or more vehicles. Therefore, the single vehicles were not part of the platoon as per definition, but they were physically part of a larger platoon consisting of vehicles on two or three lanes combined. The arrival patterns of a single vehicle at stations along the studied traffic links and at the downstream traffic signals are just as important as the arrival patterns of the first vehicle in a platoon on the adjacent lane.

Due to the insignificant statistical differences in mean vehicle arrival times between the lane of travel, all vehicle lane data from each station were combined together, except for North Oracle's right lane at Station 1 and 2.

The accuracy of the comparison results for the effect of traffic volume on platoon dispersion could be lost if the statistically different mean vehicle arrival times were combined together just for the sake of increasing data sizes. Tables 15, 16 and 17 present how the particular platoon sizes and single vehicles were distributed between stations at both of the study locations.

A Comparison of distribution of majority of traffic at North Oracle Road is presented in Table 18. The table shows that the proportion of the same size platoons remain fairly constant through the traffic links.

However, some trends can be observed:

1. North Oracle Road
   - Number of smaller size platoons, up to 4 vehicles is significantly higher on the right lane than on the left lane, especially at Stations I and II.
   - The majority of traffic is carried by platoons with sizes ranging between 4 and 9 vehicles per platoon.
2. Pantano Road
   - The number of single vehicles significantly increases as the traffic moves downstream.
   - The number of the largest size platoons (from 4 vehicles up) decreases some as the traffic moves

Table 15. Number of platoons recorded at North Oracle Road, all lanes combined (except for right lane at stations I and II).

Platoon size or number of vehicles	Station			
	I	II	III	IV
1	0	0	6	1
2	2	1	10	11
3	5	5	14	11
4	5	14	24	36
5	4	12	24	15
6	8	9	24	19
7	15	11	24	20
8	10	16	16	16
9	5	16	17	12
10	2	5	13	8
11	5	5	2	6
12	2	5	7	3
13	0	1	2	3
14	1	0	2	0
15	0	2	4	2
16	0	0	2	0
17	0	0	0	0
18	0	0	1	0

Table 16. Number of platoons recorded at North Oracle Road, Station I and II - right lane.

Platoon size or number of vehicles	Station	
	I	II
1	3	0
2	5	4
3	8	3
4	11	14
5	1	11
6	2	8
7	2	5
8	0	1
9	0	0
10 - 13	0	0
14	0	1

Table 17. Number of platoons recorded at Pantano Road study site (both lanes combined).

Platoon size or number of vehicles	Stations				
	STA I	STA II	STA III	STA IV	STA V
1	1	0	8	12	19
2	23	13	36	29	49
3	16	11	25	36	41
4	10	8	8	14	19
5	7	4	4	4	10
6	2	2	2	0	3
7	1	0	1	1	2

Table 18. Distribution of majority of traffic at North Oracle Road in percent.

Platoon size or number of vehicles	Stations					
	Lanes combined except right lane at sta. I and II				Right lane	
	I	II	III	IV	I	II
1 - 3 (incl.)	11%	6%	17%	14%	51%	42%
4 - 9 (incl.)	75%	76%	65%	72%	49%	50%
9 - 18	14%	18%	18%	14%	0%	8%

downstream. A sudden increase of a large size platoons at Station V can be attributed to a high number of vehicles changing lane position from right to left in anticipation of the left turn at Pantano Road - Broadway Boulevard intersection.

- A majority of traffic is carried by medium size platoons, between 2 and 4 vehicles per platoon. The comparison of distribution of majority of traffic at Pantano Road is presented in Table 19.

Platoons with the same number of vehicles were compared between two study sites. Generally, as shown in Figures 35 to 40, it is evident that all the platoons disperse. However, the least dispersion was experienced by smallest size platoons. The slope of a line in Figures 37 to 41 can be used as an indicator of the rate of platoon dispersion. The steeper the slope the bigger the dispersion. Also, platoons traveling along North Oracle Road spread out faster than their counterparts from Pantano Road with one exception. One explanation for this behavior is that initially much higher traffic volume and larger platoons on North Oracle do not permit drivers to choose an acceleration rate they would like nor to travel with individually desirable speeds. It just takes longer with higher traffic volumes to create enough space on the road to travel at

Table 19. Distribution of majority of traffic at Pantano Road in percent.

Platoon size or number of vehicles	Stations				
	I	II	III	IV	V
1 - 4 (incl.)	84%	85%	93%	95%	90%
2 - 4 (incl.)	82%	85%	83%	83%	77%
5 - 7 (incl.)	16%	15%	7%	5%	10%

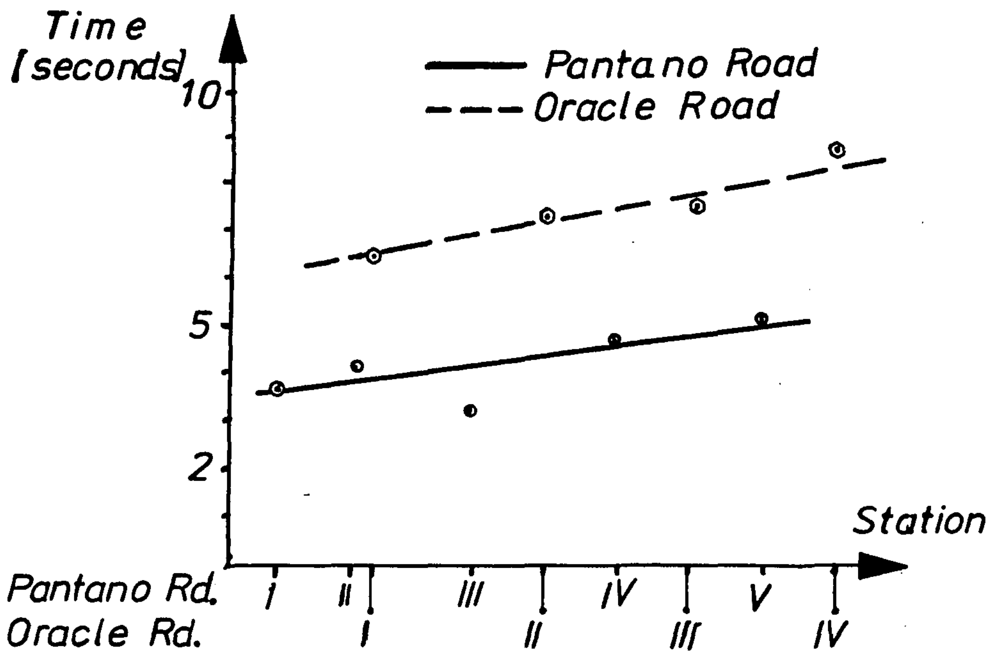


Figure 35. Time length of 2 vehicle platoon

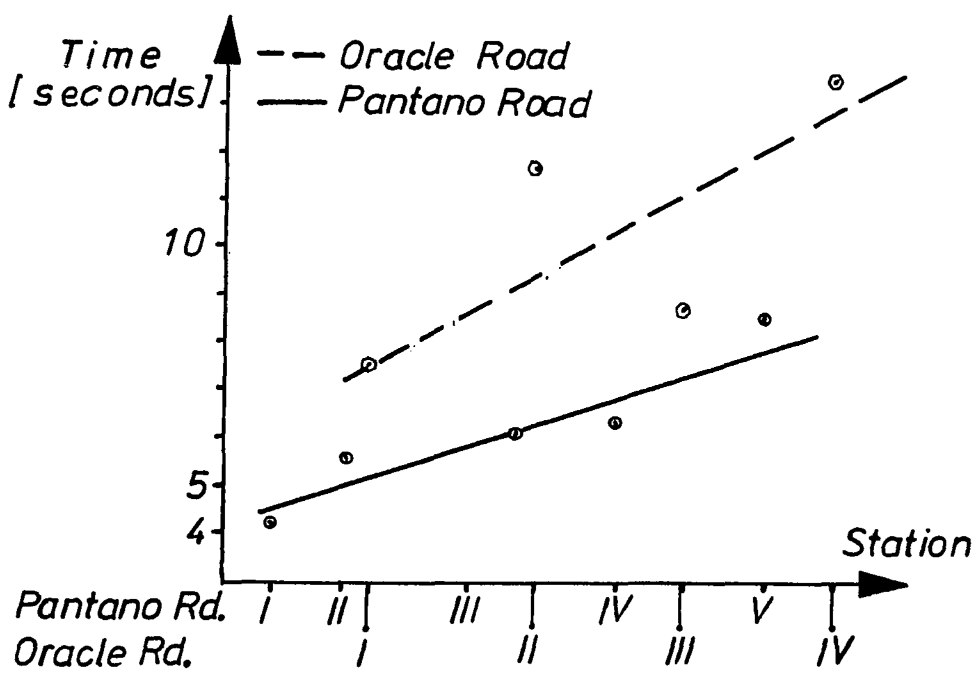


Figure 36. Time length of 3 vehicle platoon

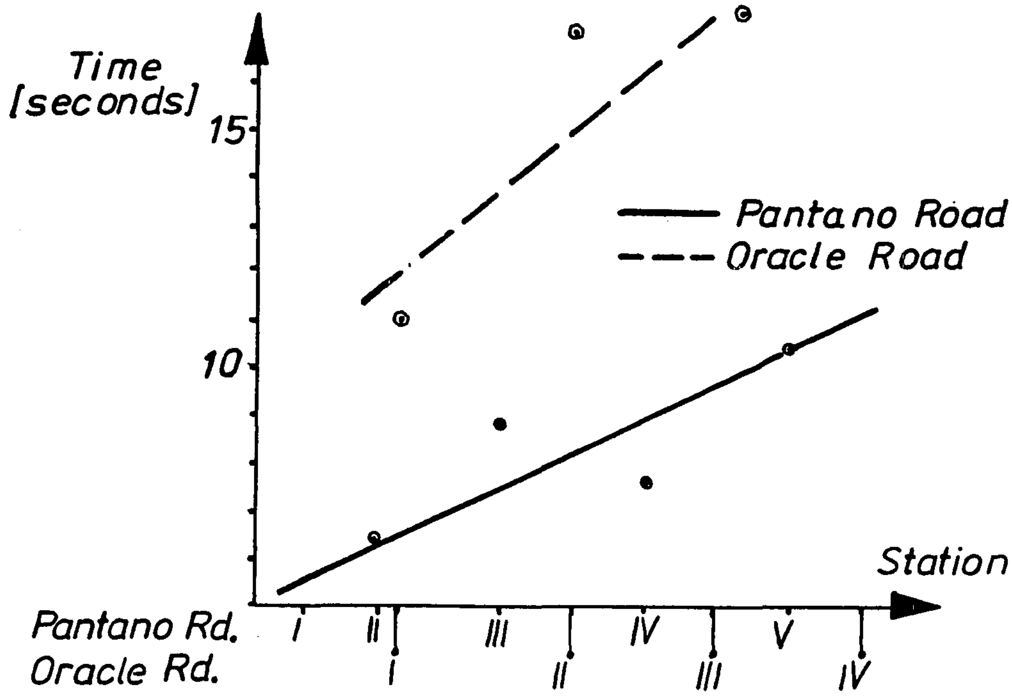


Figure 37. Time length of 4 vehicle platoon

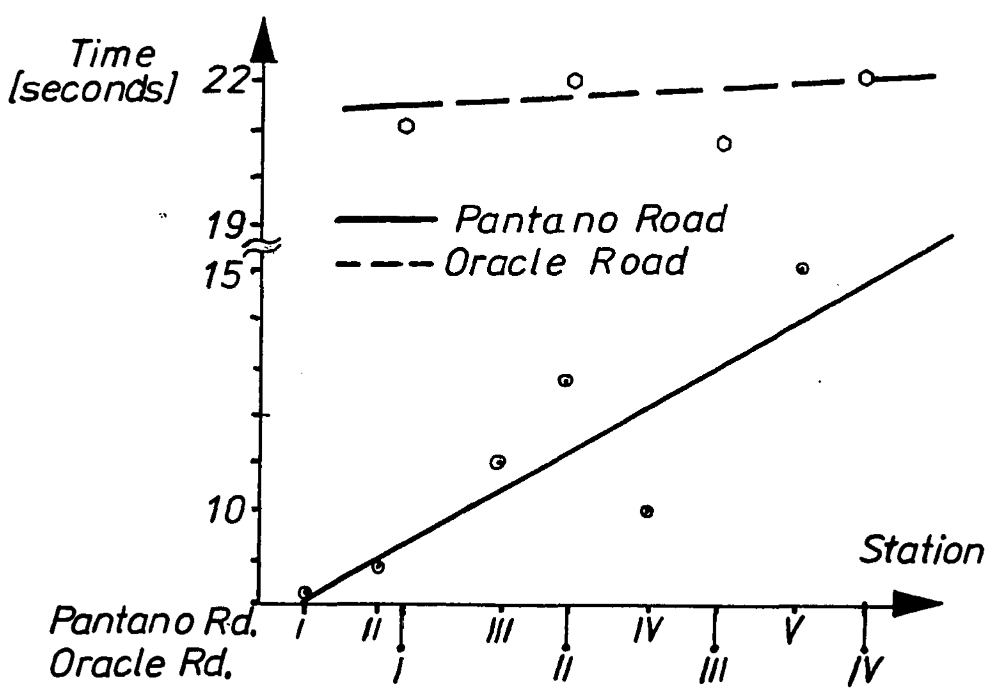


Figure 38. Time length of 5 vehicle platoon

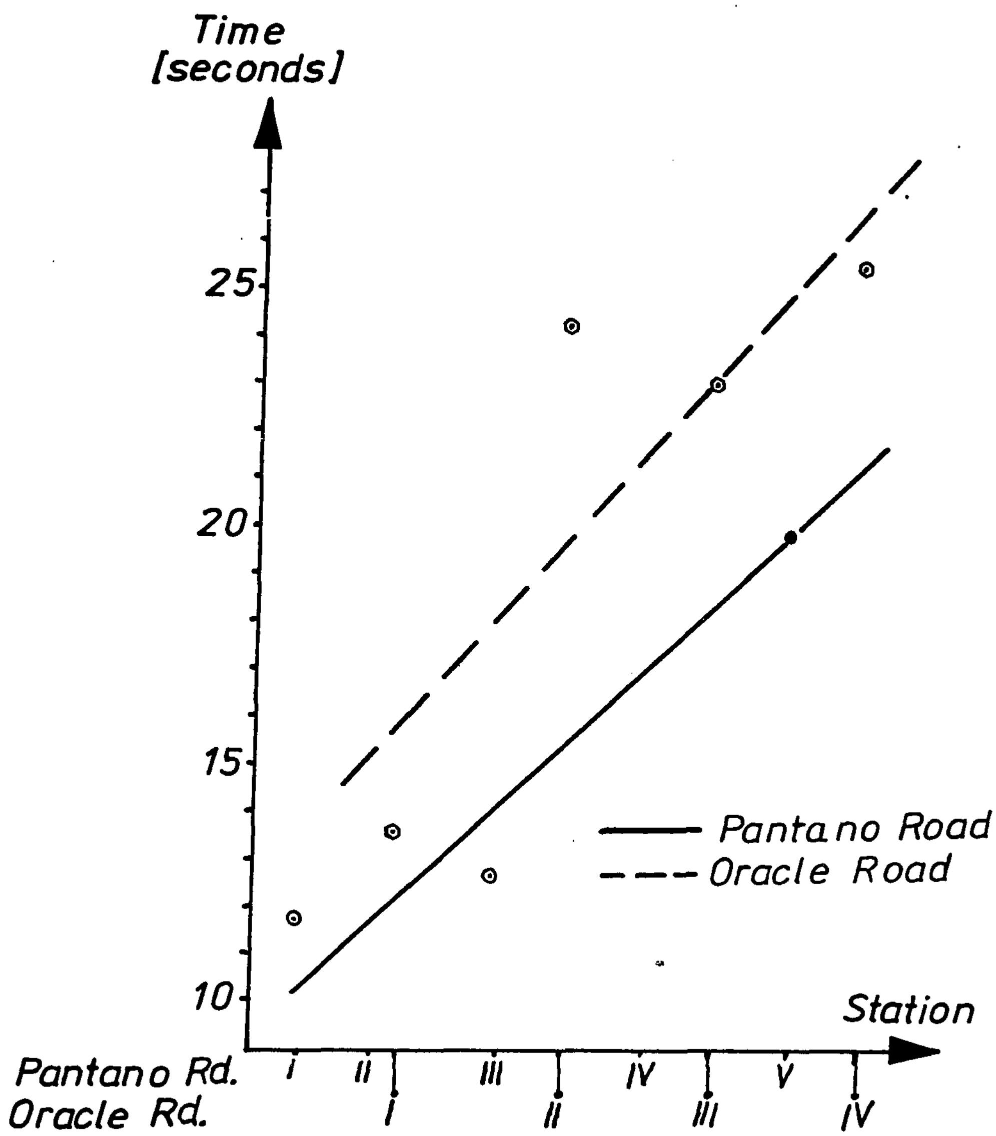


Figure 39. **Time length of 6 vehicle platoon**

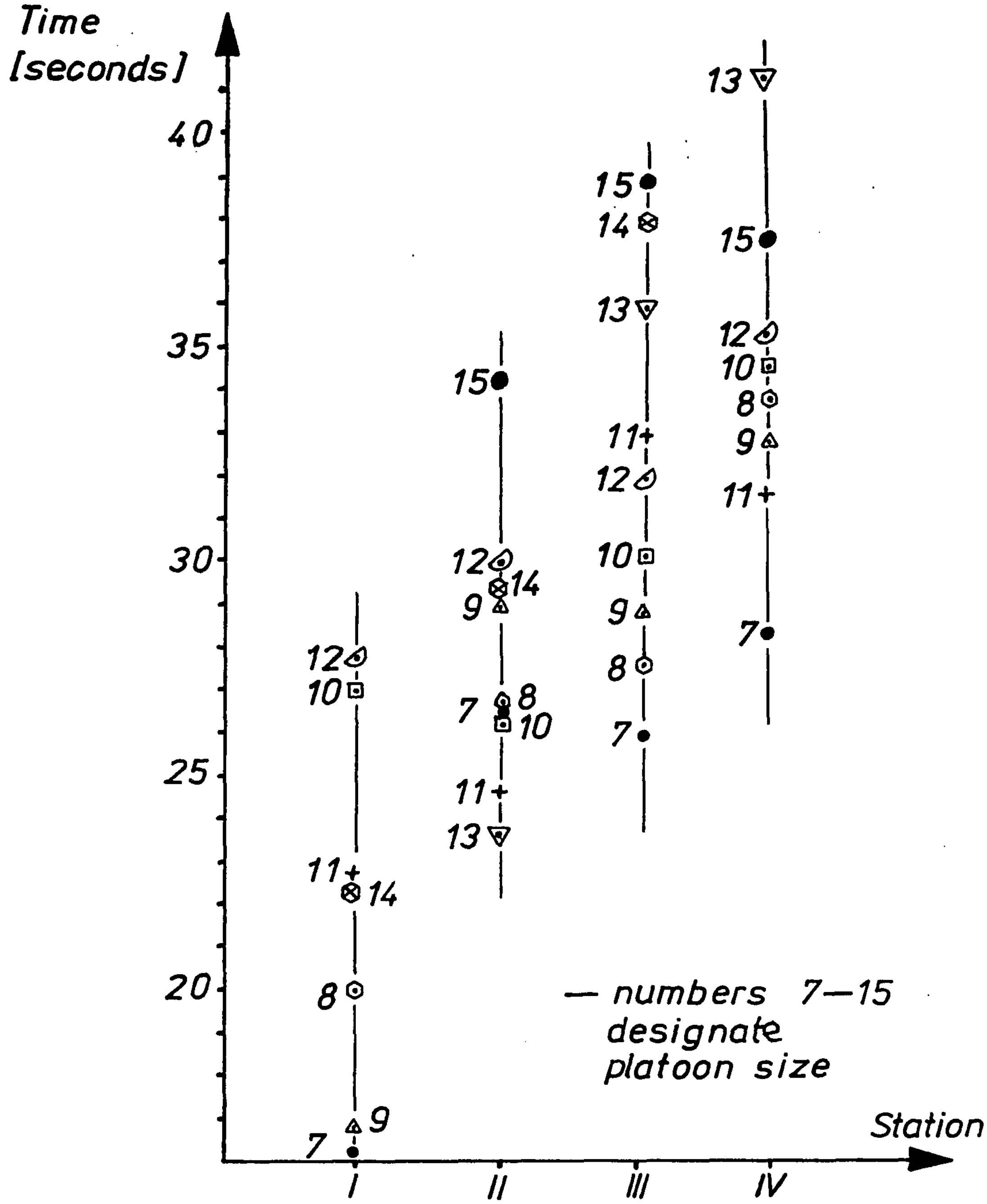


Figure 40. Time length of n-size platoon along North Oracle Road

approximately unrestrained flow conditions, but still within the platoon boundaries.

The mean arrival time of the n:th vehicle in a platoon for both locations was plotted in Figure 41. To assure the clarity of the chart, only trajectories for odd position of vehicles in the platoons were shown. It has to be noted that the trajectories shown in Figure 41 are not the trajectories of the same vehicle. These are the average values of the nth vehicle at the various stations. The data collection method precluded from tracing vehicles through the study section.

Along North Oracle Road, the platoon clearly spreads as it moves downstream. However, most of the dispersion occurs at the front and at the rear of the platoon. There is little spread between vehicles 5 and 11. Figure 41 shows a very interesting platoon behavior along Pantano Road. The very front of the platoon disperses constantly throughout the entire length of traffic link. However, the center of the platoon gets very compacted around 2000 feet away from the platoon starting point and later it disperses at a fast rate with more or less rear of the platoon slowing down. The initial bunching and later slowdown of the rear of the platoon can be attributed to the 2.5 percent upgrade between Stations III and IV. As shown in Figure 41 the first and to

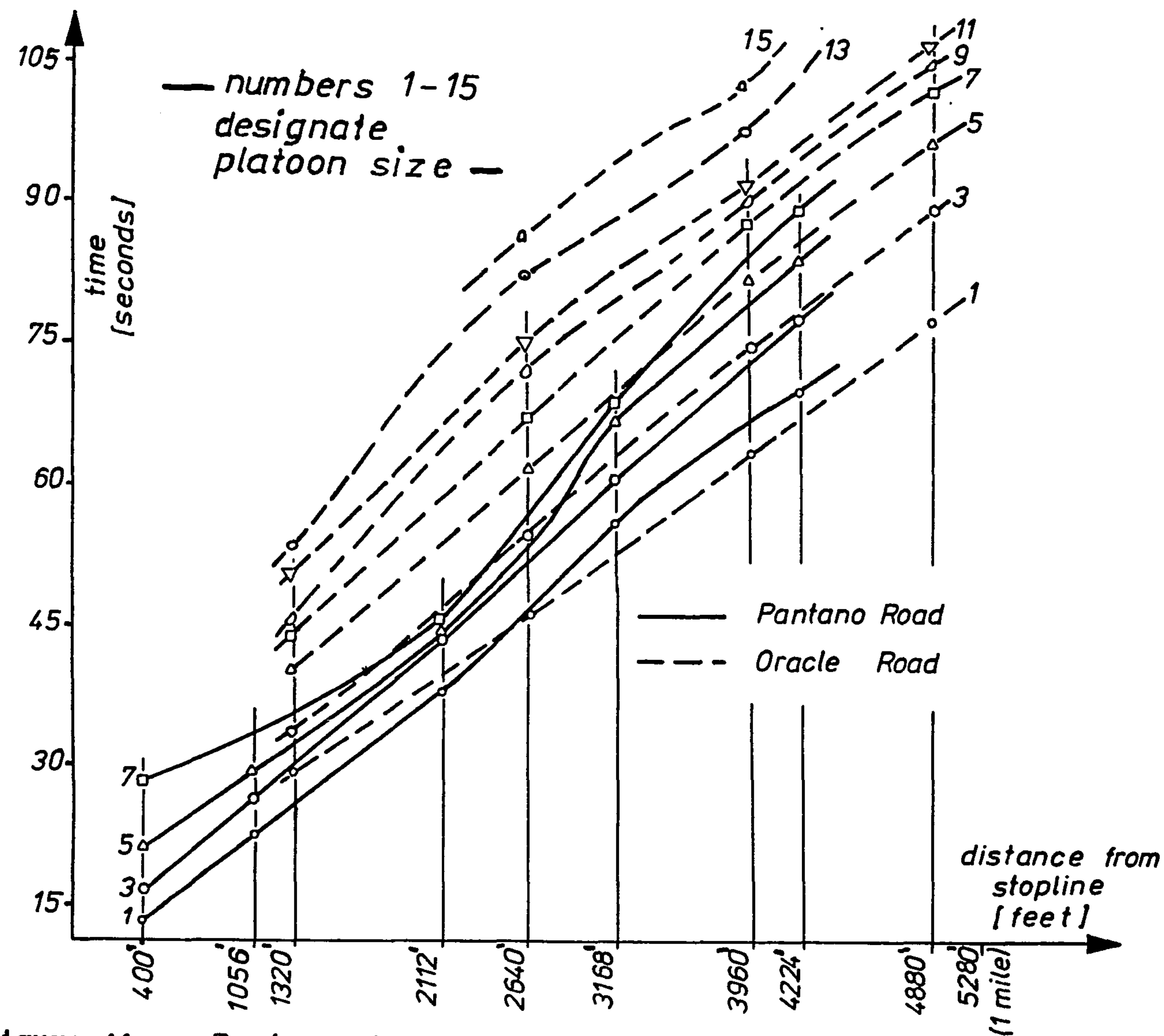


Figure 41. Trajectories of n:th vehicle at both study locations

some extent the second vehicle in the platoon is not affected by the size of the platoon.

Traffic Composition and Effect of Trucks on Platoon Dispersion

The recorded truck data were very limited. On Pantano Road out of 1,209 vehicles recorded at 5 stations, 41 were trucks or 3.4 percent. Along North Oracle Road the average proportion of trucks was even lower, 110 out of a total of 3,901 vehicles were recorded at the location or 2.8 percent.

It was not known what effect, if any, the presence of trucks and other non-passenger vehicles would have on the platoon behavior. Therefore, mean arrival times for trucks at each of the stations and study locations were compared to mean arrival of cars and motorcycles at the respective stations and study locations. The statistical analysis used here was the comparison of the variances of two different samples to find whether the samples represent the same or different populations. The "F" test was used for statistical comparison. The variances used in the comparison were derived from the mean arrival times of the trucks and of the cars and motorcycles at each of the stations and study locations. The data sample size to test the effect of trucks on platoon dispersion was found to be too small to test every possible variation. On North Oracle Road, it was possible to test several pairs of data but only at Stations

2, 3, and 4. Station 1 did not have enough truck data collected. As a platoon moves downstream, the number of significant differences decrease rapidly before the 1/2 mile station as shown in Table 20 At Stations 3 and 4, only two tests were rejected for vehicles in the fifth and eighth place. The interpretation is that the trucks on North Oracle Road have practically no significant effect on platoon dispersion after 1/2 mile.

Along Pantano Road the truck sample size was too small to perform any meaningful statistical evaluation of the effect of trucks on platoon behavior.

For further analysis the trucks were left in the sample.

Headways

One of the useful traffic flow characteristics is a headway distribution between successive vehicles in a platoon. For a known number of vehicles in the platoon, a mean headway can give an indication of a platoon dispersion at several downstream locations. Due to the characteristics of the data collection method, the presentation of this analysis is based upon headways obtained from a single lane platoon.

The mean headways were calculated from the differences in the average arrival time of successive vehicles in platoons at each station and study location. Figures 42 and 43 present plotted headways for Oracle Road and Pantano

Table 20. Statistical comparison test results for truck effect along North Oracle Road study site.

Vehicle position in platoon	STA I	STA II	STA III	STA IV
first	*	A	A	*
second	*	*	*	A
third	*	R	A	A
fourth	*	*	A	*
fifth	*	R	R	A
sixth	*	*	*	A
seventh	*	*	A	*
eighth	*	R	A	R
ninth	*	R	A	*

* - sample size too small for statistical comparision
R - statistically rejected at 95% confidence level
A - statistically accepted at 95% confidence level

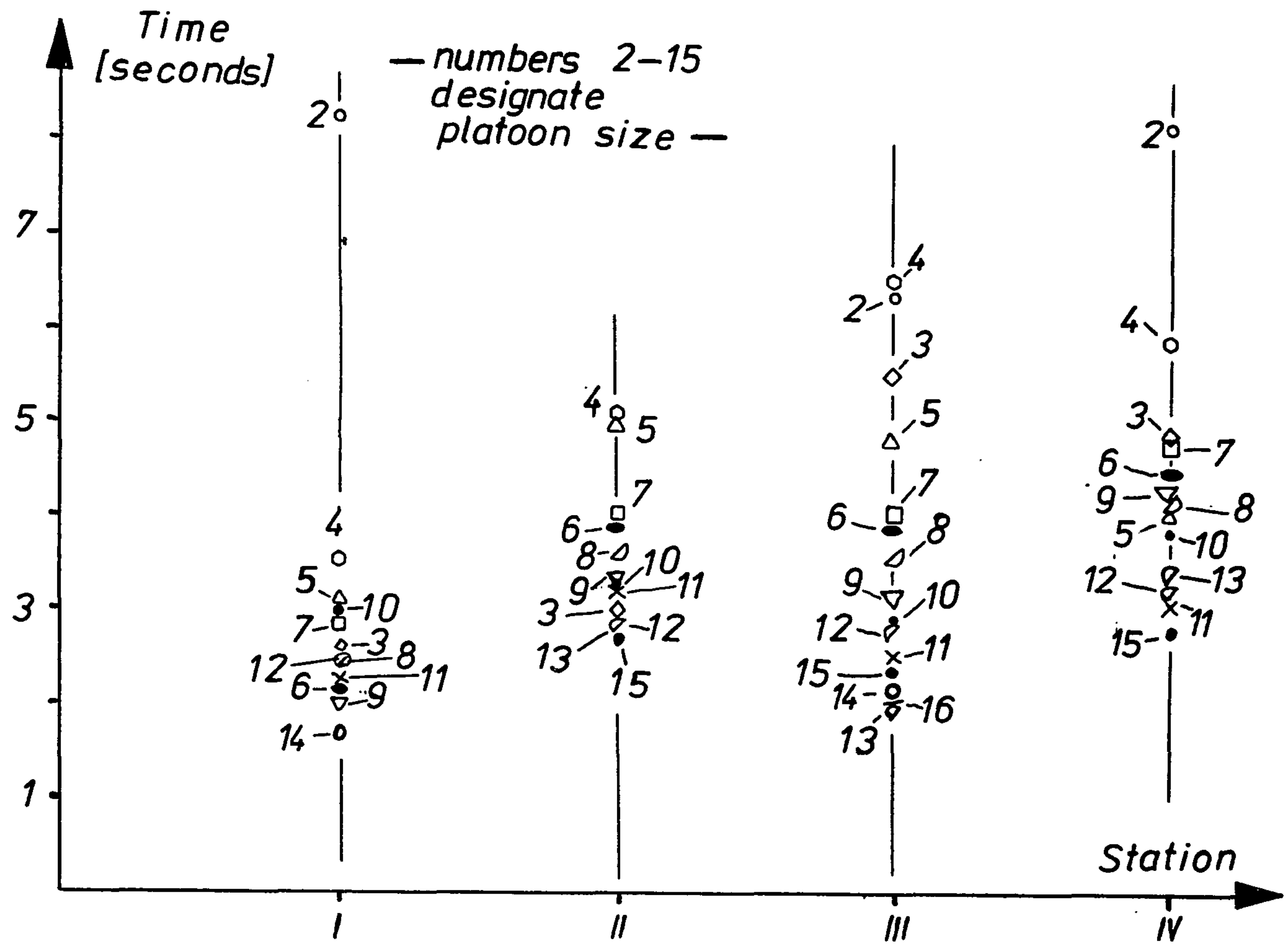


Figure 42. Mean vehicle headways for n-size platoons, North Oracle Road.

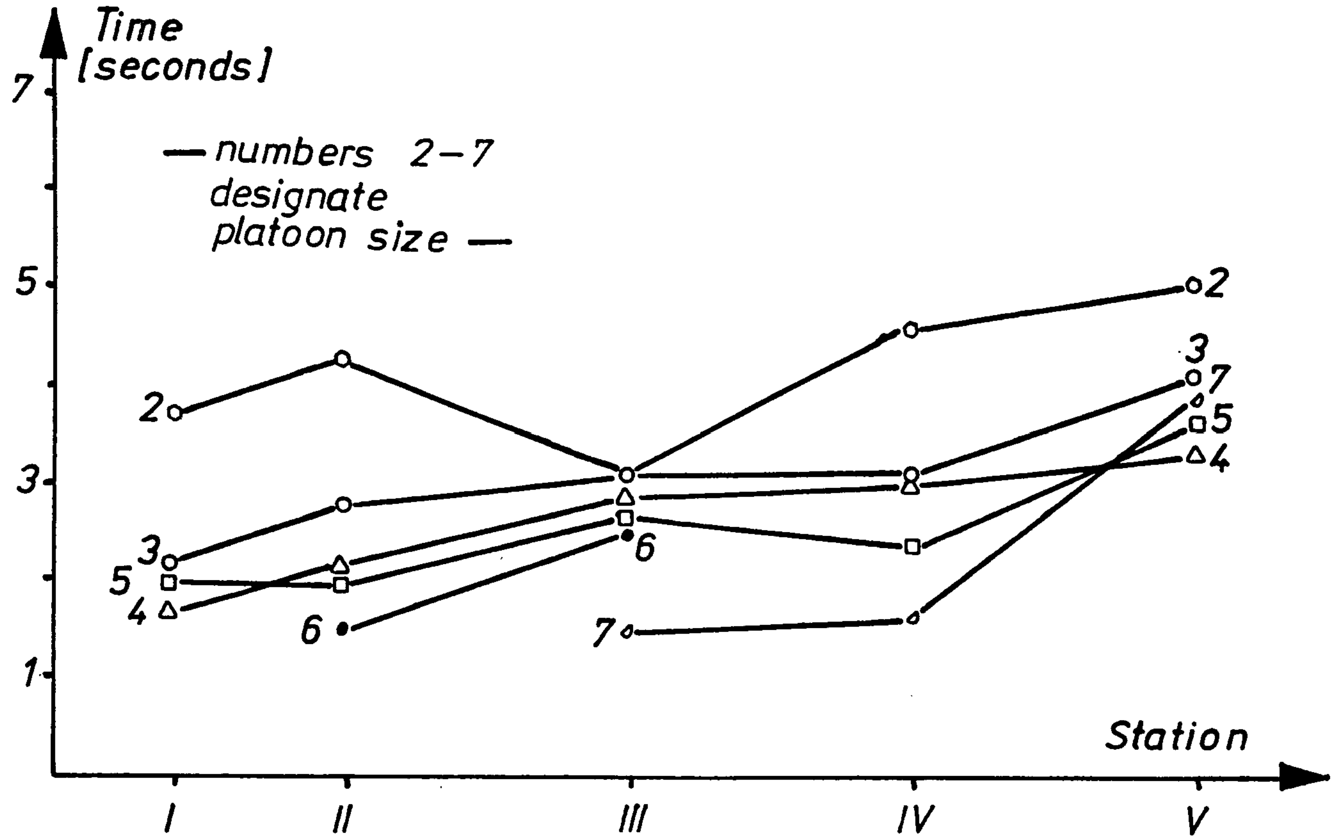


Figure 43. Mean vehicle headways for n-size platoons. Pantano Road/both lanes combined

Road, all lane combined. It is apparent that the mean headway exhibits stable general pattern of a slight increase over the studied distance. The headways between vehicles in the larger size platoons are much smaller than in a small size platoon.

For North Oracle Road the mean time headway varied in a rather small range of about 2.5 seconds. Only the mean headways for 3 vehicle platoon varied in a range up to 3 second value. Ninety-two percent of all headways between observed vehicles were between 2 and 5 seconds. Mean vehicle headways for each n-size platoon and station were compared against the mean vehicle headways for the same size platoon at the other stations. The "F" test was used for statistical comparison. Seventy-three pairs of mean headways were evaluated. At 95 percent confidence level, there was no significant difference between 59 pairs or 81 percent.

For Pantano Road 49 pairs of mean headways of n-size platoons were evaluated. At 95 percent confidence level, there was no significant differences in 31 comparisons or 70.5 percent.

CHAPTER V

CONCLUSIONS

The general objective of this research was to examine the space/time distribution of the traffic platoons over a longer stretch of roadway with conditions predominant for the southern Arizona urban area. Several important conclusions about platoon behavior can be drawn from this research.

-The lane of travel has no significant effect on the platoon's behavior between signalized intersections separated by more than 1/2 mile. The longer vehicle arrival times in the right lane, recorded at Stations 1 and 2 along North Oracle Road are the result of the propagation of disturbances caused earlier by vehicles slowing and turning into driveways. The vehicle arrival time comparison between lanes of travel on North Oracle Road shows that the propagation of disturbances to traveling platoons in the right lane dissipates after about 1/2 mile and does not show any statistical significance after that distance.

-The observed differences in changes in lane distribution at various stations were not statistically significant. The volume of traffic traveling on a left lane was higher than on the middle or right lane. For North

Oracle Road study site, the average distribution of traffic volume was 26%, 33% and 41% per right, middle and left lane respectively. For Pantano Road, it was 38% per right lane and 62% per left lane.

-The vehicles stayed in clearly visible platoons throughout the entire length of the researched traffic links. The moving vehicles did not reach free flowing conditions at either of the study sites. With the observed rate of platoon spreading, it would take much more than a mile (available distance) for the vehicles in the platoon to reach free-flow conditions. The platoon as it moves away from the upstream traffic signals was found to increase in length. Along North Oracle Road that increase was from an initial time length of 32.2 seconds at the first station to 57.5 seconds, or 79 percent, at the last station. For Pantano Road that increase was 115%. However, due to much smaller platoon sizes than at North Oracle Road, the maximum observed time length of a platoon recorded at the last station was 38 seconds. The average time length of the platoons recorded close to the downstream traffic signals could easily be compensated in the downstream signal's green phase.

-The relationship between platoon dispersion and platoon size was investigated. The results indicate that larger platoon sizes experience more dispersion than smaller platoon sizes. Along North Oracle Road, (higher volume of traffic than on Pantano Road) there is little spread between the 5th and 11th mean vehicle in a platoon, while the majority of traffic volume is carried by platoons with sizes ranging between 4 and 9 vehicles per platoon. Most of the dispersion occurs in the front and in the rear of the platoon. Along Pantano Road, the majority of traffic is carried by platoons of sizes between 2 and 4 vehicles. Also, the platoons travel ing along North Oracle Road spread out faster than their counterparts from Pantano Road. One explanation for this behavior is that Oracle Road's three lanes in one direction instead of two, create more opportunity for lane change and passing maneuvers. It permits drivers to choose an acceleration rate and to travel with individually desirable speeds.

-The 2.5 percent upgrade along parts of Pantano Road had a great influence on platoon behavior. Some platoons even experienced "a reverse dispersion," bunching instead of dispersing, while traveling up the hill.

-The mean headways of the successive vehicles in platoons at each station and study location were compared. It is apparent that the mean headway exhibits stable general pattern of a slight increase over the studied distance. The headways between vehicles in the larger size platoons are much smaller than in the small size platoons.

However, the results from the statistical comparison proved inconclusive.

-The trucks which were a part of the collected data along North Oracle Road had no significant effect on platoon dispersion after one half mile. However, in the first one third mile the trucks had some influence on platoon behavior. The data size were too small to be investigated for the truck effect along Pantano Road.

The thesis contributed several important elements to the platoon behavior research. The most comprehensive literature review ever accomplished on the subject can be found in chapter II. The literature review findings paved the way to the particular site selection and the method of data collection. Although the data collection method was used in the past by other researchers, the site selection was what differed from previous research. Overall, the traffic links compared had a few similar and a few different characteristics. The differences were in number of lanes, the traffic volumes, and the different average size of platoons. The similarities were the drivers behavior (within the same city), site interference, width of traffic lanes, percentage of trucks, and speed regulations.

Recommendations

The research not only answered several questions but also uncovered a variety of aspects of platoon behavior which should be investigated further. These aspects include:

-Data should be collected from a large variety of sites. A comparison between different sites can reveal the specific influence of platoon dispersion factors which are characteristic to a specific site. For example, the influence of side interference for each traffic link could be determined and possibly quantified.

-An appropriately large data base needs to be collected in order to thoroughly investigate truck influence on platoon behavior for a variety of traffic volumes.

-The one grade condition at Pantano Road does not address the full scope of the influence of grades. More research will be necessary to cover this point.

-The study did not cover the relationship between platoon dispersion and the timing offset of the traffic signals along the arterial. The offset influences the behavior of the front of the platoons because the drivers approaching a green traffic signal will drive differently than drivers approaching a red traffic signal.

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APPENDIX A

Sample Copy of Graph Paper