Investigation of the Dynamics of Platoon Dispersion

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An investigation is being conducted to relate dispersion characteristics of platoons on signalized arterials to signal spacing and platoon size. A 16-mm time-lapse camera was used to collect data on platoon dispersion characteristics. By switching one traffic signal to flashing amber, the spacing between the platoon formation point and the first regular traffic signal was increased by 597 ft. The change caused the platoons to spread more although the behavior of the lead vehicle did not change. The difference was statistically significant for smaller sized platoons only. Vehicles were found to be more closely packed in larger platoons than in smaller platoons. The dimensionless diffusion constant, defined as the ratio of the standard deviation of the speed distribution and its mean speed, was used to predict arrival frequencies at one point downstream from the traffic signal. The difference between the theoretical arrival frequency distribution and the observed frequency distribution was not statistically significant. The mean headways of off-peak-hour and peak-hour platoons for identical platoon sizes were compared. The difference was not statistically significant. The preliminary results of this study justify further investigation on a more comprehensive scale. A helicopter-mounted metric aerial camera is currently being used to collect data on one-way signalized arterials. A semiautomatic monocomparator is being used for data analysis. The data are being incorporated into a mathematical model for describing the behavior of a platoon of vehicles as it passes through a series of signalized intersections.

•THE DISTRIBUTION of traffic on an open section of a multilane highway is nearly random as long as overtaking opportunities are not restricted. If a traffic signal is introduced at one point on this highway, then queues of vehicles will be formed periodically during the red phases of the signal. The distribution of traffic, observed a short distance downstream from this signal, is not random any more. Vehicles arrive at this point in platoons. If a second traffic signal is placed on the roadway at this point, then it is possible to coordinate the 2 signals so that a platoon released by the first signal will arrive at the second signal on green. Based on the dispersing characteristics of platoons, the offset as well as the cycle split of the second signal could be designed to minimize interference with the flow of traffic.

A considerable amount of experimenting is involved in the coordination of traffic signals because not enough is known about the behavior of platoons under various conditions. Although dispersion of platoons at isolated intersections has been studied extensively (1, 2), much less is known of the extent to which different factors influence the behavior of platoons on urban arterials (3).

For example, the signal spacing on arterials is often small enough to permit the drivers to observe the display of traffic lights at one or more intersections ahead. The

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behavior of drivers under these circumstances probably deviates from that observed on open roadways.

The objective of this study is to investigate platoon movements on arterials and to attempt to relate dispersing characteristics of platoons to signal spacing and to traffic volumes. Research was started in April 1968 under the sponsorship of the Ohio Department of Highways in cooperation with the Federal Highway Administration. This paper is based on the work performed to date (4).

The research efforts can be divided into 3 principal phases. Phases 1 and 2 represent the completed portions of the project, whereas Phase 3 represents current research efforts. In Phase 1, platoon data along a 4-block signalized arterial were collected with a 16-mm camera operating at 12 frames per second. Emphasis in the data analysis portion is concentrated on the analysis of the arrival times for the platoon vehicles at selected points along the signalized arterial. Arrival characteristics are related to signal spacing and platoon size. In Phase 2, the 16-mm camera was operated at 1 frame per second. The test site for this phase consisted of a 2-block segment of the site studied in Phase 1. The data are analyzed in Phase 2 for purposes of relating the effects of traffic volume and time of day (peak and off-peak hours) to platoon dispersion characteristics. In Phase 3, aerial photography is used for collecting platoon data along extensive sections of one-way urban arterials. The aim of the data analysis is to develop a macroscopic model for describing the behavior of a platoon as it progresses along a signalized urban arterial.

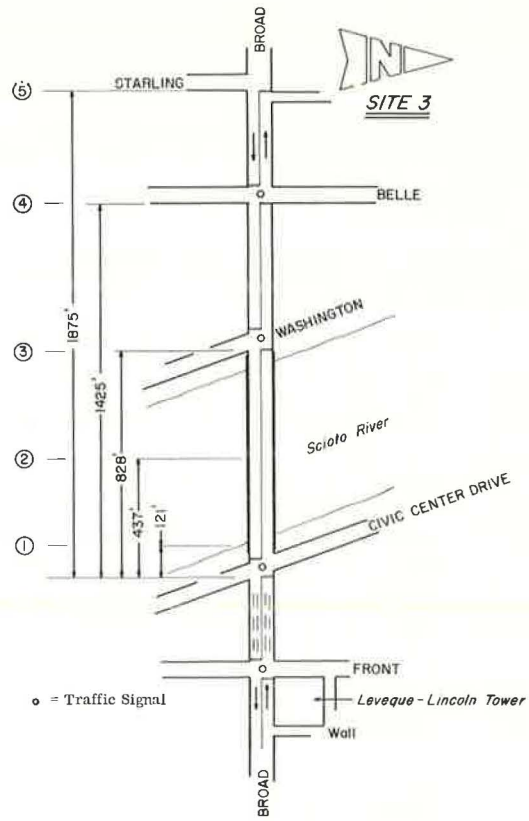

Figure 1. Study site.

PHASE 1

Data Collection

In Phase 1, data were collected by means of a 16-mm Bolex camera. The speed of operation is 12 frames per second. A section of West Broad Street in the downtown area of the city of Columbus, Ohio, was selected as a test site (Fig. 1). This section of West Broad Street is a two-way, six-lane arterial with an average lane width of 10 ft. No parking is permitted and left-turning volumes are low. Every intersection in the study area is signal-controlled. Care was taken to exclude platoons with trucks from consideration.

The LeVeque-Lincoln Tower, a 44-floor office building, provided an excellent observation point for this study site. The platoons were formed by the traffic signal at Civic Center Drive and were filmed from the moment the line of vehicles started at this point until the time the platoon had crossed the intersection at Starling Street. The data collection took place between 3:00 and 6:00 p.m. to obtain both off-peak-hour and peak-hour traffic. On all days the weather conditions were favorable with dry pavement and good visibility. A total of six 100-ft, 16-mm color films were taken; three of these were exposed with the traffic signals at Washington Boulevard put on flashing amber.

The films were analyzed with the aid of a Kodak analyst projector that has provision for frame-by-frame operation and is equipped with a frame counter. For analysis purposes the study site was divided into 5 sections. The arrival time of the first vehicle at location 1 was used as a time reference point for each platoon, marking zero time. The cumulative frame number of the passage of each platoon member at each of the 5 locations was recorded and converted into arrival times.

Data Analysis

For analysis purposes the platoon data were divided into the following 4 conditions according to platoon size and signal operation at Washington Boulevard:

Condition	Signal Operation	Platoon Size
A_h	Regular	Long
A_1	Regular	Short
B_h	Flashing	Long
B_1	Flashing	Short

Long platoons contained an average of 20 vehicles, and short platoons contained an average of 10 vehicles. A sample of 30 platoons was investigated. The sample sizes for the different conditions were thus quite small. Some conclusions, however, can be drawn regarding platoon dispersion characteristics.

For each condition the mean arrival time of the n th vehicle at each of the 5 locations was calculated. From these data average vehicle trajectories were constructed, as shown for condition A_h in Figure 2. For clarity only the path of every second platoon vehicle is shown. Figure 2 shows that the platoon becomes more and more dispersed as it proceeds from location 1 to location 5. The spreading of the platoon seems to occur mostly at the front and at the rear, while vehicles in the middle move along the road with more or less constant time headways.

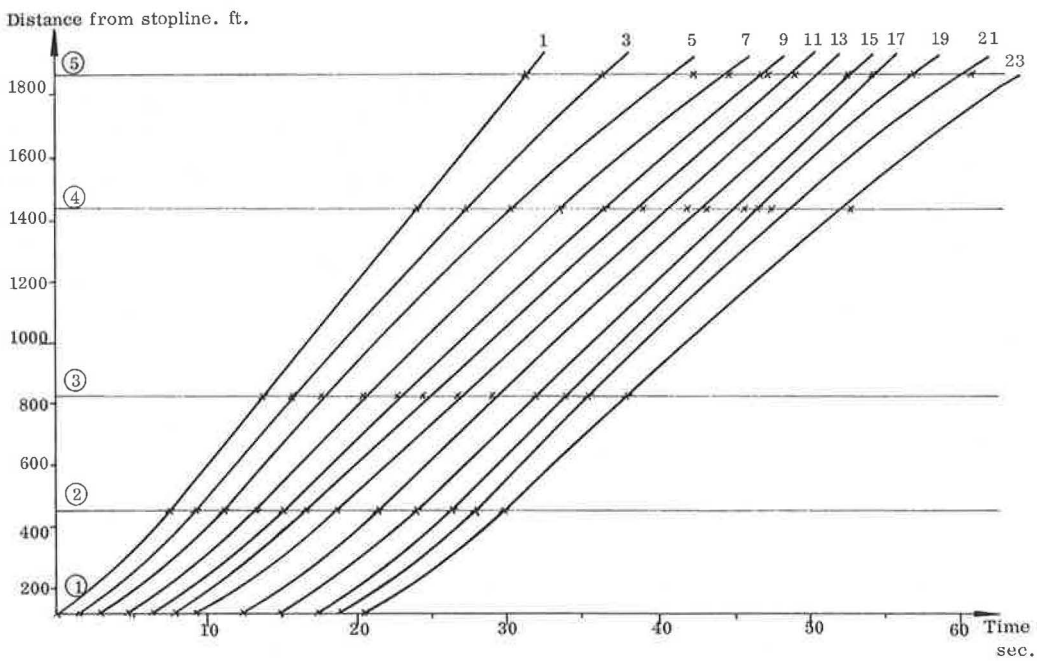

Figure 2. Mean arrival times of n th vehicle at locations 1 through 5 for condition A_h.

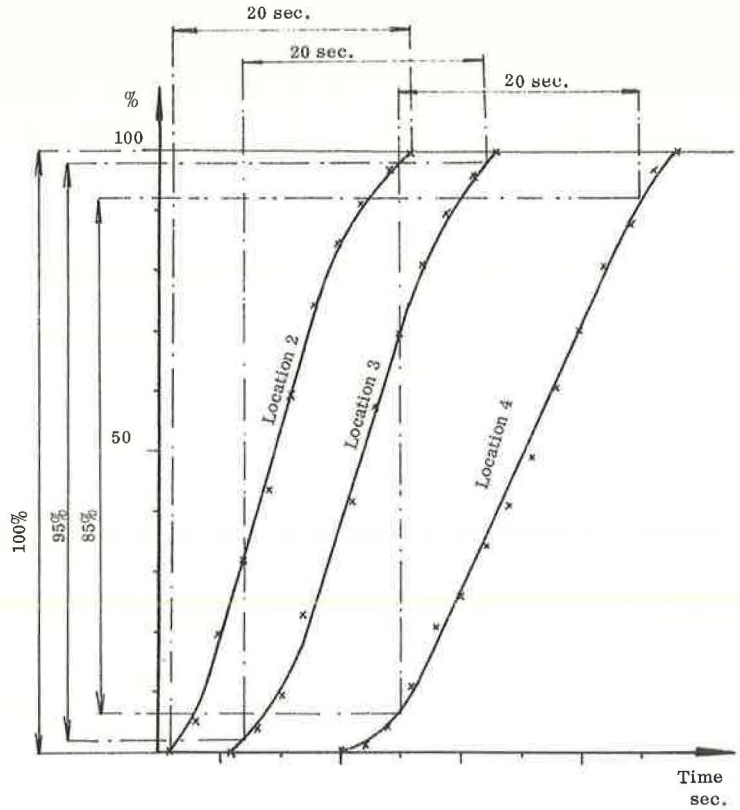

Figure 3. Cumulative distribution of arrival times at locations 2, 3, and 4 for condition A_h.

Figure 3 shows the cumulative distribution of arrival times at locations 2, 3, and 4. From this diagram the percentile of platoon vehicles remaining within different bandwidths can be estimated. A 20-second bandwidth, for example, would include 100 percent of the platoon vehicles at location 2, 95 percent at location 3, and only 85 percent at location 4.

In order to study the influence of different signal spacing on the behavior of platoons, the traffic signal at location 3 was turned on flashing amber operation during the second phase of field data collection. The spacing between the platoon starting point and the first regular traffic signal along the test road was in this way increased from 828 to 1,425 ft.

Figure 4 shows the mean arrival times of vehicles for conditions A_h and B_h and average vehicle trajectories constructed between stations 2 and 4. With the exception of lead vehicles, for which trajectories for conditions A_h and B_h are almost identical, vehicles of the B_h platoons arrive later at each station than vehicles of the A_h platoons. This delay is increased from vehicle 3 to vehicles farther back in the platoon. Even at low volumes, the average B_1 platoon seems to be somewhat slower than the average A_1 platoon.

The difference in arrival frequencies at station 3 under the 2 different conditions was tested for statistical significance. The chi-square test was used to determine whether the 2 distributions of arrival frequencies came from the same unspecified population. A significant difference was observed at the 5 percent level of significance for low-volume conditions. The test, however, was not significant for high-volume conditions.

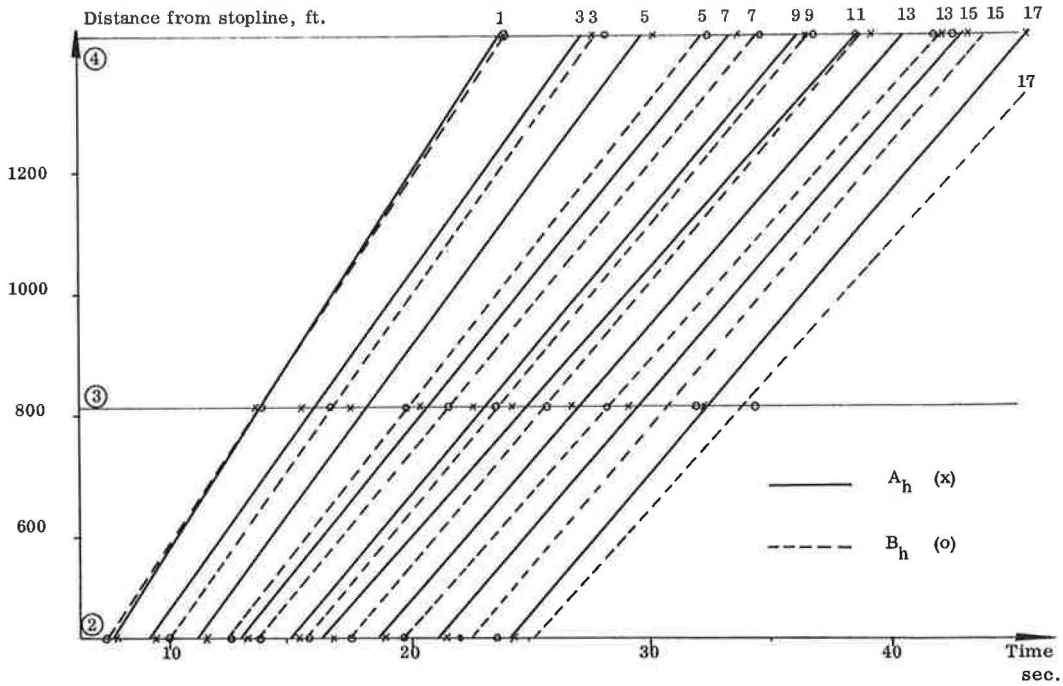

Figure 4. Mean arrival times of n th vehicle at locations 2, 3, and 4 for conditions A_h and B_h.

The platoon data obtained from the study were also divided into groups according to the number of vehicles in each platoon. The average vehicle trajectories of 1 high-volume group comprising platoons with an average of 20 vehicles was compared with those of a low-volume group comprising platoons with an average of 10 vehicles. It was found that the first vehicle in a platoon is not affected by the size of the platoon, but vehicles farther back in the low-volume platoons are more and more delayed compared with corresponding high-volume vehicle paths.

Smaller platoons are thus less compact. One explanation for this observation is that vehicles tend to distribute less evenly over the available traffic lanes at low traffic volumes. It must be mentioned here that all vehicles stopped by the red phase at Civic Center Drive were considered to be members of a platoon, regardless of the lane of travel.

A kinematic model of platoon dispersion, proposed by Pacey (5) and tested by the General Motors Research Laboratories (6), assumes that each car in a platoon moves with constant speed. The distribution of the speeds is considered normal, with a mean speed m and standard deviation σ. The rate at which a platoon spreads as it passes down the highway is determined by the dimensionless diffusion constant

$$\alpha = \frac{\sigma}{m}$$

A large α indicates rapid spreading of the platoon, because it is a measurement of the relative difference in speed between members of the platoon. Arrival rate and speed distributions were observed on an open roadway at 2 stations 1,385 ft apart. Results of the experiment indicated that the kinematic model can be used to predict the behavior of the front of freely moving platoons in moderate flow. The behavior of the rear of the platoon varied from platoon to platoon.

As the kinematic model proved to be of value for platoons leaving a single intersection, it seemed to be of interest to evaluate its applicability to platoons proceeding along a signalized arterial. For this purpose, the arrival frequencies of the 150 vehicles of 10 platoons at locations 2 and 4 were plotted (Fig. 5).

The average speed of each vehicle between locations 2 and 3 was calculated, and the mean and standard deviation of the speed distribution of the whole sample were evaluated. The resulting speed distribution had the following characteristics:

$$\bar{x} = \frac{\Sigma x_i}{n} = 55.5 \text{ ft/sec}$$

$$s = \sqrt{\frac{\Sigma(x - \bar{x})^2}{n - 1}} = 8.26 \text{ ft/sec}$$

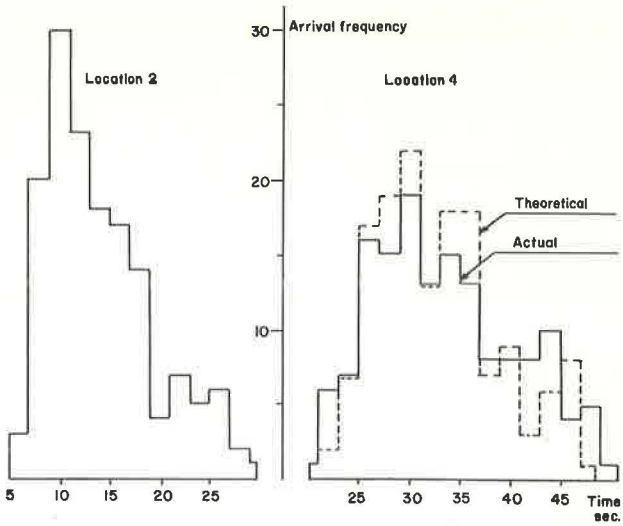

Figure 5. Arrival frequencies at locations 2 and 4. (The dashed histogram at right gives the arrival frequency at location 4 extrapolated from the arrival times at location 2 by using the kinematic model of traffic flow.)

The following value of α was obtained:

$$\alpha = \frac{8.26}{55.5} = 0.149 \approx 0.15$$

The theoretical arrival frequency at location 4 was then obtained by adding a travel time to the observed arrival time at location 2 for each vehicle. This travel time was derived from samples of the speed distribution by using a table of random normal deviates. The theoretical arrival frequency at location 4 thus obtained is shown to the right in Figure 5 together with the observed arrival frequency at the same location.

In order to determine the statistical goodness of fit, the chi-square statistic was used. The computed value of the statistic for the 5 percent risk level is 22.36. Because the computed statistic is less than the critical value, the hypothesis that the observed and theoretical arrival time frequencies belong to the same distribution is therefore accepted.

Although the scope of the preceding study is admittedly limited, it appears that the kinematic model may be applicable to a wider range of situations than just traffic leaving an isolated intersection.

PHASE 2

Data Collection

In Phase 2 of the study, the time-lapse camera is operated at 1 frame per second. A 5-ft grid system was superimposed over a projected image of the site, and the position of the vehicles was estimated to the nearest foot. Two of the 16-mm films were analyzed to investigate (a) the effect of platoon size on platoon dispersion and (b) the effect of time of day (peak or off-peak hours) on platoon dispersion. For this phase of the study, the study area consisted of 1,000 ft on West Broad Street extending from Civic Center Drive to a point past Washington Boulevard (Fig. 1). Platoon characteristics of westbound traffic were analyzed. Data reduction time was reduced by recording from every fifth frame. It was felt that time intervals of 5 seconds would permit the accuracy required for identification of platoon dispersion characteristics.

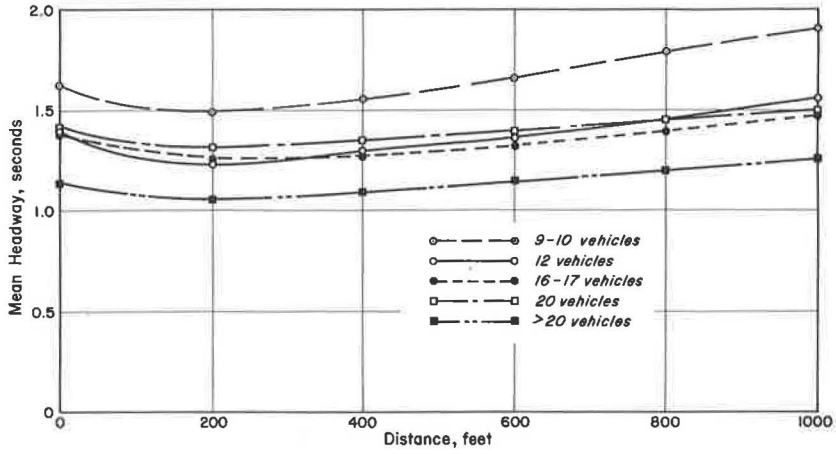

Figure 6. Effect of volume (platoon size) on vehicle headways.

Data Analysis

The effect of volume on platoon dispersion was determined by calculating mean time headways for platoons of various sizes at a number of downstream locations from Civic Center Drive. Five groups of vehicles were selected according to size and combined to yield a set of mean headways per group at intervals of 200 ft. The grouping was as follows:

Number of Vehicles	Number of Platoons
9 and 10	8
12	5
16 and 17	6
20	4
>20	6

The results of the data analysis are shown in Figure 6. It can be noted that, except for the slightly anomalous behavior of the 20-vehicle platoons, mean headways show a tendency to decrease with increasing traffic volumes. This effect can be related to the observation that vehicles are more evenly distributed over the available lanes of travel during periods of high volumes than during periods of low volumes.

The statistical significance of the results was determined by an analysis of variance as follows:

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Volume	4	19.28	4.28	
Error	425	632.14	1.49	3.24

For the headway differences to be significant at the 90 percent level, the critical value of F is 3.76. Therefore, the hypothesis that mean headways are affected by platoon size is rejected.

The effect of time of day on platoon dispersion was determined by computing mean time headways for peak-hour and off-peak-hour traffic. Platoons of the following sizes were selected for analysis:

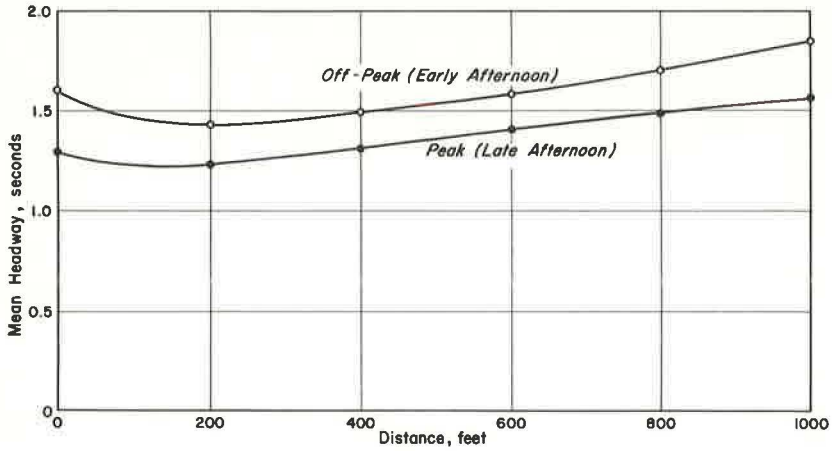

Figure 7. Effect of time of day on vehicle headways.

Number of Vehicles in Platoon	Number of Off-Peak Platoons	Number of Peak Platoons
6	1	1
7	3	1
11	2	1
12	2	3
13	1	1
17	1	2

There were 103 vehicles with 93 headways in the off-peak platoons and 107 vehicles with 98 headways in the peak platoons. Note that platoons of the same size were selected from either film to eliminate any bias due to platoon size. In cases where more than 1 platoon of a given size in the same film are indicated, data were averaged and considered as a single platoon. Mean time headways for each of the 2 groups of vehicles were then computed. The results are shown in Figure 7. It is evident that peak-period platoons appear somewhat "tighter," having shorter headways than those from the off-peak period.

In order to investigate the statistical validity of the results, confidence intervals for the difference between the 2 mean headways at 2 different locations, 400 ft and 1,000 ft, were calculated. The results for the 90 percent level of confidence indicate rejection of the hypothesis that the sample means are not the same; that is, the differences are not statistically significant.

Thus both for the volume effect and for the time-of-day effect the influence on mean headways is not statistically significant. The suggestion is that a better measure of platoon dispersion than mean headway may be of value. More specifically, the distribution of headways at locations downstream from the signal is deemed worthy of future investigation.

PHASE 3

Data Collection

The use of a ground-based camera system for purposes of data collection has limited the scope of the present project. Study sites had to be chosen adjacent to tall buildings and consequently the distance over which the behavior of a platoon could be observed was limited. In order to fulfill the project objective of investigating platoon movements

on urban arterials in a comprehensive manner, it was felt necessary that the restrictions attendent with the use of the 16-mm camera had to be removed.

To achieve a greater degree of freedom for data collection purposes, aerial photography is being employed in the remaining phases of the project. An aerial camera mounted on a helicopter possesses the important advantages of permitting flexibility in choosing study sites and permitting extensive coverage of a signalized arterial.

The camera being used for data collection is the KA-62A aerial camera. This metric camera has a focal length of 3 in. with a 4.5- by 4.5-in. film format. Figure 8 shows the camera mounted in the helicopter.

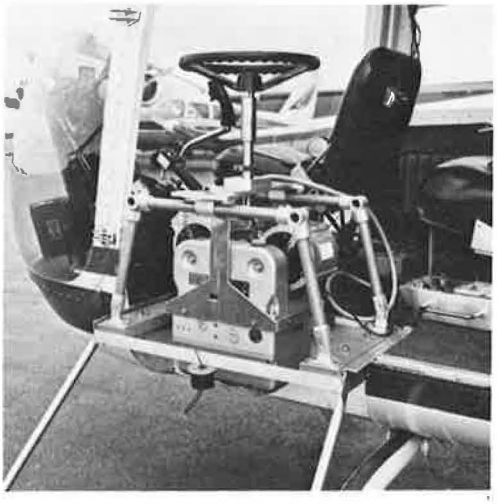

Figure 8. KA-62A aerial camera mounted in Bell helicopter.

It is intended that one-way signalized urban arterials will serve as study sites for the aerial phase of this project. Several flights have been made over major arterials in Columbus, Ohio. Initial study sites are the one-way urban arterials of Summit Avenue and North Fourth Street from First Avenue to Hudson Street. Both streets are 5-lane arterials having 10 signalized intersections with distances between signals ranging from approximately 350 to 2,175 ft.

A preliminary test flight over the selected study sites was flown at altitudes of 1,000, 1,500, and 2,000 ft above ground level for the purposes of investigating different flight altitudes as to film coverage and ease of vehicle identification, determining the extent of problems associated with overhanging trees adjacent to the curb lanes, determining the extent of problems associated with shade during peak traffic conditions, and determining the ability of the helicopter to follow a slow-moving platoon of vehicles on an urban street.

As a result of viewing the film taken during the test flight, it was decided that photographs taken from a 1,000 altitude above ground level would provide adequate coverage of the study site for determining platoon dispersion characteristics. A typical photograph of a study section taken from the 1,000-ft altitude is shown in Figure 9.

Overhanging trees are present only sporadically throughout the study sections and consequently pose no major problem. It would be rare indeed for a vehicle to be completely obscured by tree cover. The problem of losing vehicles in the shade is nonexistent for the altitude at which the photographs were taken. Film analysis revealed that the vehicles could easily be identified throughout the study sections regardless of the presence of shadows.

The helicopter used for the aerial surveys is a Bell Ranger helicopter owned by the Ohio Department of Highways. Although the helicopter is not considered a hovering aircraft, only minor difficulties were experienced in following a slow-moving platoon of vehicles. The ability of the camera to be swung in a horizontal plane tends to offset the fact that the helicopter's velocity may not match the speed of the platoon.

In order to relate dispersion characteristics to signal timing, it is necessary to indicate on the film the particular signal indication at one of the signalized intersections. Because a progression system is in operation at the time of data collection flights, knowledge of the offset pattern and the time interval between photographs will then permit determination of the signal phase at each of the remaining signalized intersections.

The phase changes at one of the photographed intersections was indicated by an electronically operated signal indicator that was constructed. This device consists of 12 two-inch square aluminum rods mounted on a 4 ft by 3 ft 10 in. wooden base. Rotation of the shafts by means of a synchronous motor permits a total of 4 different and distinct

Figure 9. Typical photograph of a study site taken with KA-62A aerial camera.

designs to be displayed. In operation, the device is connected directly to the traffic control box at the intersection at which the phasing is desired. For the initial data collection flights, photographs have been taken at 3-second time intervals. Different designs are displayed at the following times: during the red phase of the signal, at 1 second after the beginning of green, at 2 seconds after the beginning of green, and from 3 seconds after the beginning of green until the end of the amber phase. The developed film has revealed the device to be quite successful.

Considerable experience in the reduction of data from aerial photographs has been accumulated by the staff of the Transportation Research Center. Reduction equipment consists of a Mann monocomparator, Type 829D, connected by means of a data transfer device to an IBM keypunch. Computer programs are available for translating the photo coordinates to velocity and headway measurements.

Data Analysis

A mathematical model for describing the behavior of a platoon of vehicles as it passes through a series of signalized intersections is being developed. Independent variables of traffic volume, spacing between signals, and lane of travel have been identified.

The approach taken is to develop a macroscopic model of a probabilistic nature. Empirical data will be analyzed to identify platoon dispersion characteristics and thus serve as input to the model. In the data analysis phase, principal measures of platoon dispersion that will be used consist of time headway distributions and velocity distributions at selected points downstream from a given traffic signal. Determination of headway distributions will permit the auxiliary measures of mean, variance, and coefficient of variation, often termed the diffusion constant. Other measures of dispersion of interest include platoon length (both in time and space) and the number of stopped vehicles per signalized intersection.

The basis of the model is the following. An arrival distribution of traffic is considered an input to a series of signalized intersections. The initial arrival distribution is considered a function of volume. During the red phase, a queue of vehicles

builds up at the first intersection. The queue is then released during the green phase. Dispersion of the queue takes place as a function of block length (defined as the distance between signals), traffic volume, and lane of travel. Because of the dispersion of the traffic, a distribution of vehicle arrivals occurs at the adjacent signal, and this distribution is different, but related, to the former arrival distribution. The process of dispersion and definition of new arrival distributions then occurs in a repetitive fashion as the platoon progresses along the arterial.

The technique used for relating the different components of the model will be a special simulation language termed GPSS. This computer language is ideally suited for describing the properties of a macroscopic system.

A battery of computer programs has been developed to aid in the statistical analysis of the data. The aim of the statistical design is to determine the statistical significance of the measures of platoon dispersion for the different conditions of the independent variables. Nonparametric tests being used consist of the Kolmogorov-Smirnov two-sample test, Mann-Whitney U-test, and the chi-square test. In addition, an attempt is being made to identify the time headway and velocity distributions at selected points between signals.

CONCLUSIONS

Platoon dispersion characteristics were investigated on a number of signalized arterials in Columbus, Ohio. A 16-mm time-lapse camera was used to collect data on platoon dispersion characteristics.

A before-and-after analysis was conducted to determine the effect of increasing the physical spacing between traffic signals on a given urban arterial. Changing a 3-phase traffic signal to flashing operation caused traffic platoons to exhibit greater dispersion although the behavior of the lead vehicle did not change. The difference in dispersion characteristics was statistically significant for low-volume platoons only. Vehicles were found to be more closely packed in the larger platoons than in the smaller platoons.

The kinematic model of platoon dispersion as formulated by Pacey was found to be a valid method for predicting vehicle arrivals at a point downstream from the traffic signal.

The effect of mean time headway on platoon size and time of day was established. The results were not statistically significant, indicating the need for a more sensitive measure of platoon dispersion.

Current research efforts are concentrated on developing a mathematical model for describing the dispersion of a platoon as it progresses along a signalized arterial. Data for the model are being collected by means of aerial photography.

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