Platoon Movement of Traffic From an Isolated Signalized Intersection

BRIAN J. LEWIS, Civil Engineer, Skidmore, Owings and Merrill
San Francisco, California

The paper discusses an investigation of the extent to which motor vehicles remain bunched together when traveling freely down a semi-expressway type of facility after having been formed into platoons by an isolated signalized intersection. Observations of space-time data were made at five different locations downstream from a signalized intersection at distances up to 0.65 mi. The subsequent analysis shows that a definite pattern of vehicle performance prevails, and a method is suggested for coordinating the timing of a second traffic signal, placed at any distance up to 0.65 mi, to afford less delay to the traffic stream than if the signal were allowed to operate in some entirely random manner.

THE TIMING of traffic signals to produce a coordinated progressive system on an urban street has been the subject of considerable attention by traffic engineers (1, 2), but there appears to be a dearth of literature on the subject of the maintenance of vehicle platooning on urban streets (3), and none on the extent to which vehicles remain together on an open road after leaving a signalized intersection. The Manual on Uniform Traffic Control Devices (4), section 211, infers that it is impractical to coordinate two signals if the distance between them is more than 1,200 ft, and the Traffic Engineering Handbook mentions that sometimes signals as far apart as 2,500 ft may be coordinated. However, it should be remembered this is for an urban street where a speed limit is in force, and the vehicles are not free flowing in the fullest sense.

The platooning of vehicles (the extent to which vehicles remain in a compact group) has not been defined in terms of any exact parameter, and the attempts that have been made by some workers (5) led to the conclusion that examination of space-time data in the laboratory, to decide when a platoon ceased to be a platoon, by different workers led to different conclusions. The personal equation had not been satisfactorily resolved.

It is not the purpose of this paper to define a measure of platooning but to examine the space-time distribution of free-flowing vehicles on a semi-urban street after they had been effectively formed into platoons by a signalized intersection. Thereby it is hoped to show that a definite pattern of vehicle performance prevails, and a traffic signal placed some distance down the highway from the issuing intersection could afford less delay to the traffic stream if coordinated in some way with the first signal than if allowed to operate in an entirely random maner.

This investigation was prompted by an existing traffic situation in Richmond, California. Free flowing traffic on a major 4-lane highway passed through a signalized intersection, and, 0.81 mi farther along, the highway passed through another signalized intersection which had only a very small volume of side street traffic. Casual observation made it appear that far too often the second signal, which was vehicle actuated, turned to main street red just before a platoon of vehicles arived thus delaying the main body of the platoon. The signal had been "held" on main street green by the "tail-enders" of the previous platoon and "had no way of knowing" the main body of the platoon was about to approach. Had the signal been coordinated with the previous intersection, the main street red could have been injected to delay only one or two tail-enders, rather than waiting for a predetermined gap in the traffic stream before switching to side street green. The investigation was, therefore, to determine whether the platooned vehicles arrived at a point some 0.81 mi distant from the issuing signal in any relatively constant pattern.

LOCATION OF TEST SITE

The site chosen for the investigation was the intersection of East Shore Highway and

Carlson Boulevard at Richmond. The signal at this intersection is 3-phase traffic-actuated.

Traffic moving southwards on East Shore out of this intersection has a virtually clear run for 0.81 mi to the next signal at Central Avenue. Several minor residential streets intersect the highway in this section, however, the volume of turn-on and turn-off traffic is very small and for all practical purposes the flow may be considered to be uninterrupted. There are two lanes in each direction, designated the curb lane and the center lane, with a 4 ft wide painted center dividing strip. The road is posted with a 45 mph speed limit.

The highway rises slightly to the south with the crest of the rise at 0.55 mi south of the signal. The signal at Central Avenue is 2-phase traffic-actuated, and is first seen by the driver of a southbound vehicle when about 0.60 mi south of Carlson Boulevard. The traffic on Central Avenue does not usually exceed 150 vehicles per hour, and at peak periods the traffic on East Shore is about 2,000 vehicles per hour.

COLLECTION OF DATA

The following data were recorded with a 20 channel Esterline-Angus recorder, the pens being actuated by the observers: (a) the time at the beginning and end of the green and red signals southbound on East Shore Highway at Carlson Boulevard, (b) the time when vehicles passed a station at a known distance south of the intersection, (c) a distinction was made between cars and trucks and whether vehicles were in the curb or center lane, (d) a separate record was made of the first vehicle in each platoon.

Records were taken at 5 different stations south of the signal, at 0.03, 0.21, 0.34, 0.50, and 0.65 mi. These stations were designated 1, 2, 3, 4, and 5, respectively. Care was taken to ensure that similar climatic conditions prevailed on each afternoon that data was collected. Data were taken only between 1 p.m. and 5:30 p.m. on middle weekdays in an effort to reduce possible variations.

ANALYSIS OF THE DATA

Data were transcribed from the recorder charts by single signal cycles. Although

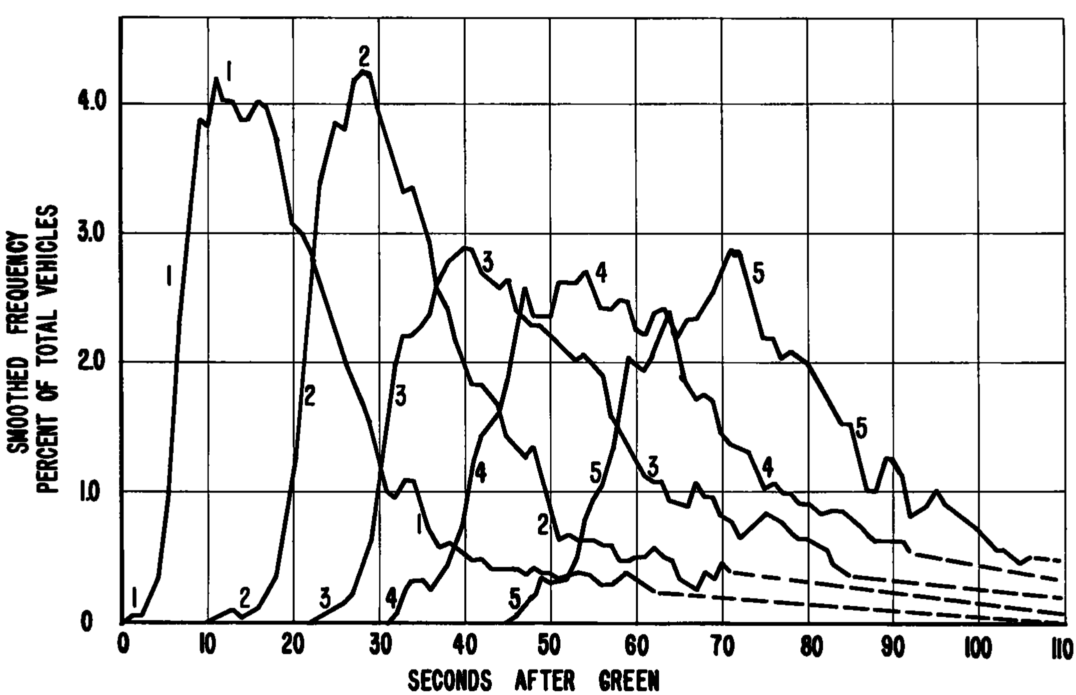

Figure 1. Frequency distributions of vehicle arrival times at 5 stations.

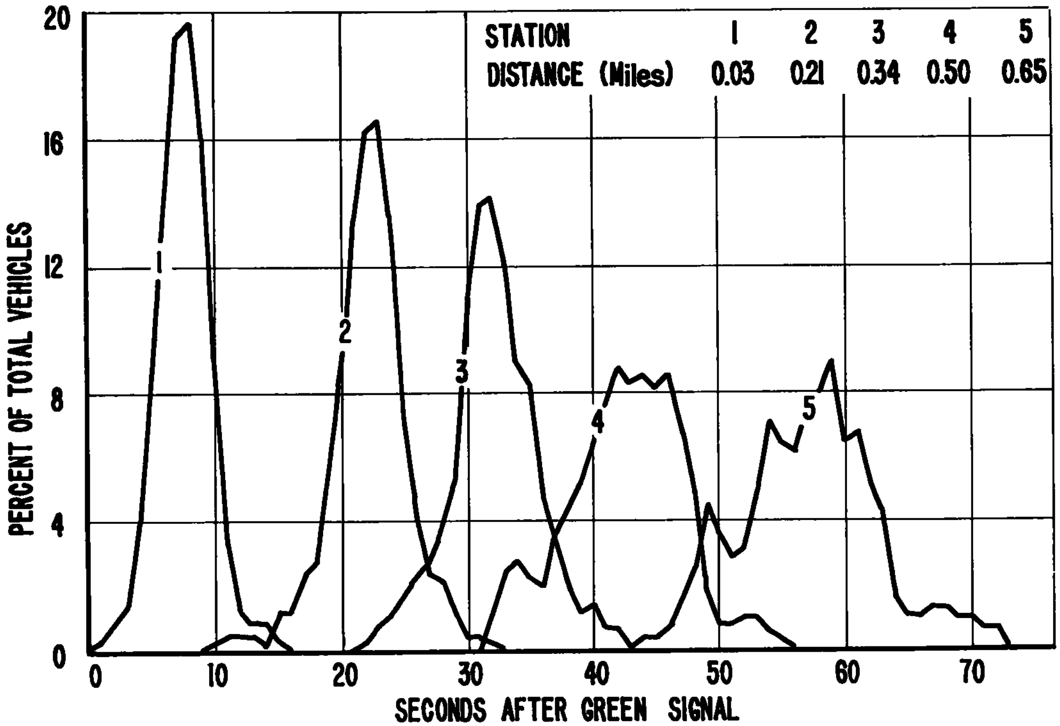

Figure 2. Frequency distributions of arrival times of first vehicle in a platoon at 5 stations distant from the signal.

the number of vehicles in each station sample was approximately the same, the number of cycles showed slightly greater variation (Table 1).

TABLE 1

SAMPLE SIZES

Station	No. in Sample	No. of Cycles	Veh. per Cycle
1	2,082	120	17.35
2	2,334	175	13.32
3	2,113	120	17.61
4	2,390	136	17.57
5	1,951	104	18.75

Although not a rigorous measure of replication of conditions, the number of vehicles per cycle is fairly constant. The low figure for station 2 is explained by the fact that a larger number of the cycles investigated were in the off-peak period.

It was not known what effect the presence of trucks would have on the behavior of the general traffic stream; therefore, a distinction was made, in recording, between trucks and automobiles. A Chi-squared test was conducted on the ratio of trucks to cars for each afternoon to see if there was any significant difference between days in the nature of the traffic. The calculation revealed a probability of 4.93 percent, which satisfies a 2.5 percent level of significance. There was not a difference, as the probability falls just short of the 5 percent level. In the light of later analysis it was felt that the level of 4.93 percent was high enough for it to be assumed that the variation of car-truck ratio for different afternoons would not have any significant effect on the phenomenon under investigation. The average proportion of trucks was 12.6 percent of the total number of vehicles.

It was noticed that there was a tendency for vehicles to change lane with increasing distance from the signal. A Chi-squared test showed that the movement of cars from the curb lane to the center lane with increasing distance was significant for automobiles, but that the distribution of trucks between the two lanes was constant regardless of the distance from the signal. A Chi-squared test on the distribution of all vehicles by lanes showed the movement from curb to center lane with increasing distance to be significant (the proportion of cars to trucks was sufficiently great for the effect of the cars to completely outweigh the effect of the trucks). It was concluded that slight variations of the car-truck ratio would not have any effect on the over-all traffic performance, and hence the 4.93 percent level of probability was acceptable.

Reduction of the data gave traffic distribution by 1-sec intervals, and it was felt that as the data were already available in this form accuracy would be lost if the vehicles were grouped into say 2-, 3-, or 5-sec intervals. However, 1-sec intervals led to "uneven" frequency diagrams—accordingly all frequency diagrams were plotted as smoothed frequency polygons. This method employs moving averages and is acceptable for obtaining an approximation to the probable frequency curve or theoretical law being measured (6).

In all tables and graphs frequencies quoted are the smoothed values obtained by summing the frequencies in the particular interval and the two adjacent intervals and dividing by three. The area under the curve remains unaltered by this adjustment.

The frequency curves of arrival times of all vehicles at each of the five stations are shown in Figure 1 as a percent of total vehicles in 1-sec frequency intervals. Near the signal the distribution is sharply peaked with little or no tail, but at greater distances the curve is less peaked with a long tail. This is because the fastest and slowest vehicles do not have an opportunity to become appreciably detached from the main body of the platoon until about a quarter of a mile has been traversed. In every case the complete range of arrival times at a particular station is about 100 sec, which is

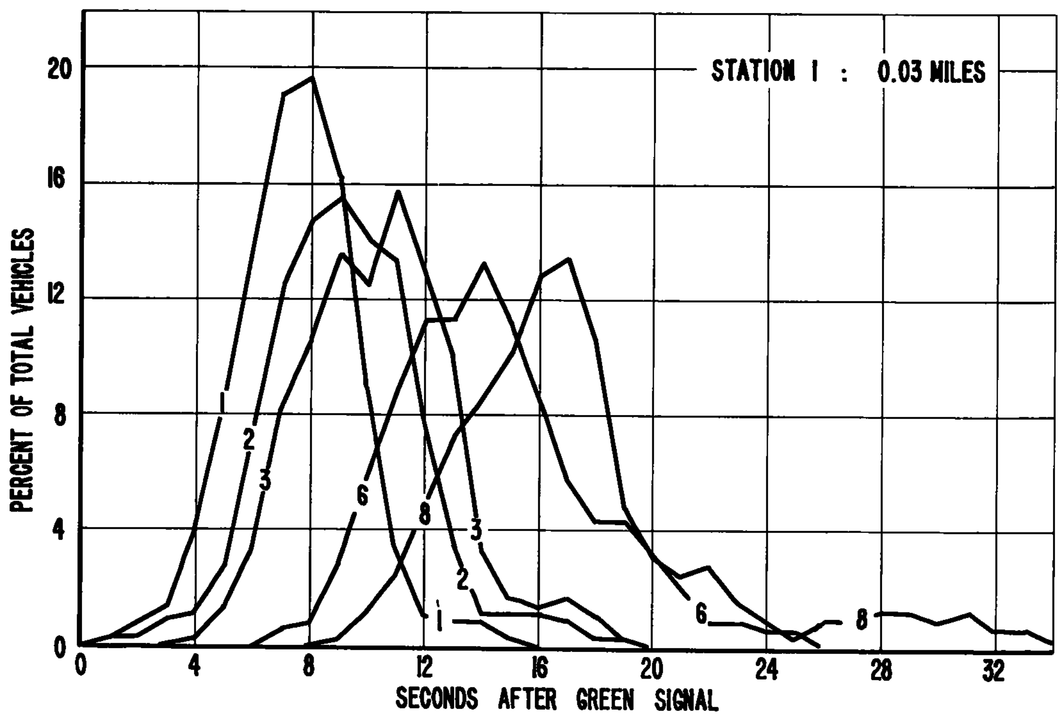

Figure 3. Frequency distributions of arrival times of nth vehicle in a platoon.

the average length of the signal cycle during the peak period. However, the majority of these "end" vehicles in the distribution are either turn-on vehicles or "free right turns" at Carlson Boulevard, neither of which were accounted for separately on the record.

Single vehicles are, in effect, very short platoons; therefore, the frequency distributions of the arrival times of the nth vehicle in a platoon were evaluated. Bartle (3) has reported that for higher values of n the frequency polygon is adversely affected by light volumes (small platoons). However, as the average number of vehicles per cycle southbound on East Shore was approximately 17, a study of the arrival times of the nth vehicle at the five stations for values of n of 1, 2, 3, 6 and 8 would yield useful information that would not be biased by any small cycles or small platoon parameter. The smoothed frequency polygons are reproduced in Figures 3, 4, 5, 6 and 7.

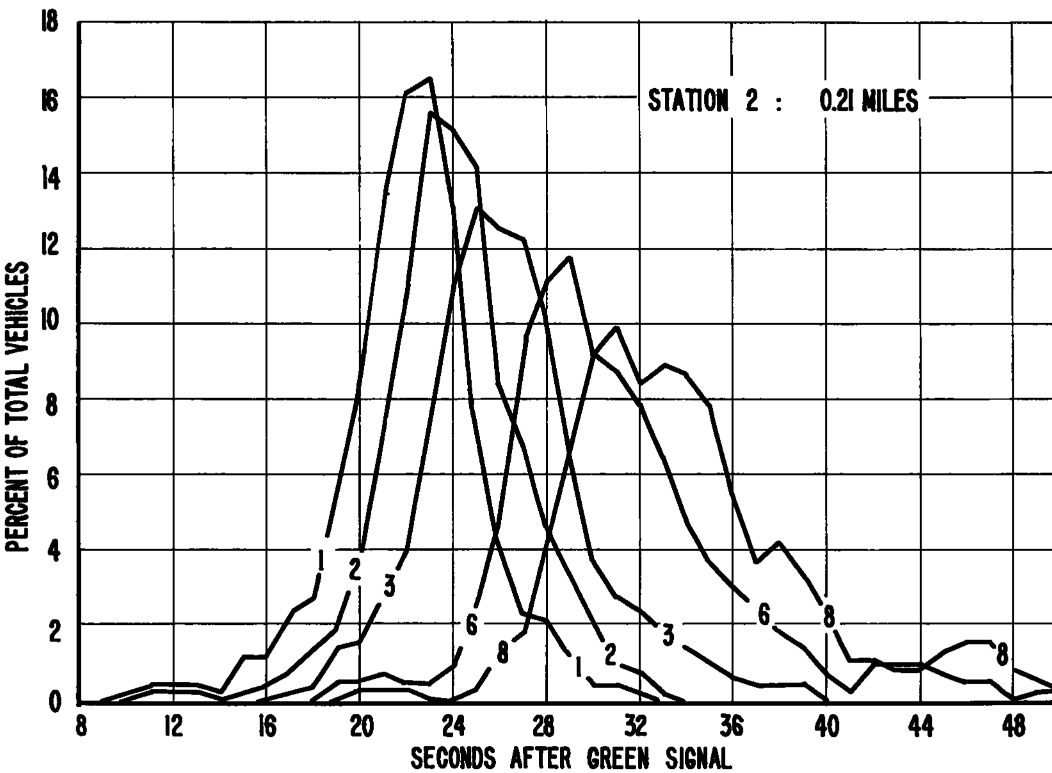

Figure 4. Frequency distributions of arrival times of nth vehicle in a platoon.

By comparing the frequency polygon for the arrival time of the first vehicle at each of the five stations (Figure 2) with the frequency polygons for all the vehicles (Figure 1), the single car diagram exhibits the same decay tendency with increasing distance, and this effect is also found to be present if a comparison is made between frequency diagrams for the 2nd, 3rd, 6th and 8th vehicles.

The mean arrival time of the nth vehicle at each of the five stations was also calculated and plotted with respect to distance (Figure 8). A linear relationship existed between mean arrival time of the nth vehicle and distance. Statistical analysis showed the degree of correlation to be very significant for each of these lines.

Bartle has discussed the study of the percentile ranges in the arrival time distribution for traffic proceeding along an urban street with a coordinated signal system. He thought that the standard semi-inter-quartile range, the difference between the 25th and the 75th percentiles, was not entirely satisfactory because the distribution of the first 25 percent of all vehicles is important. He decided more or less arbitrarily that

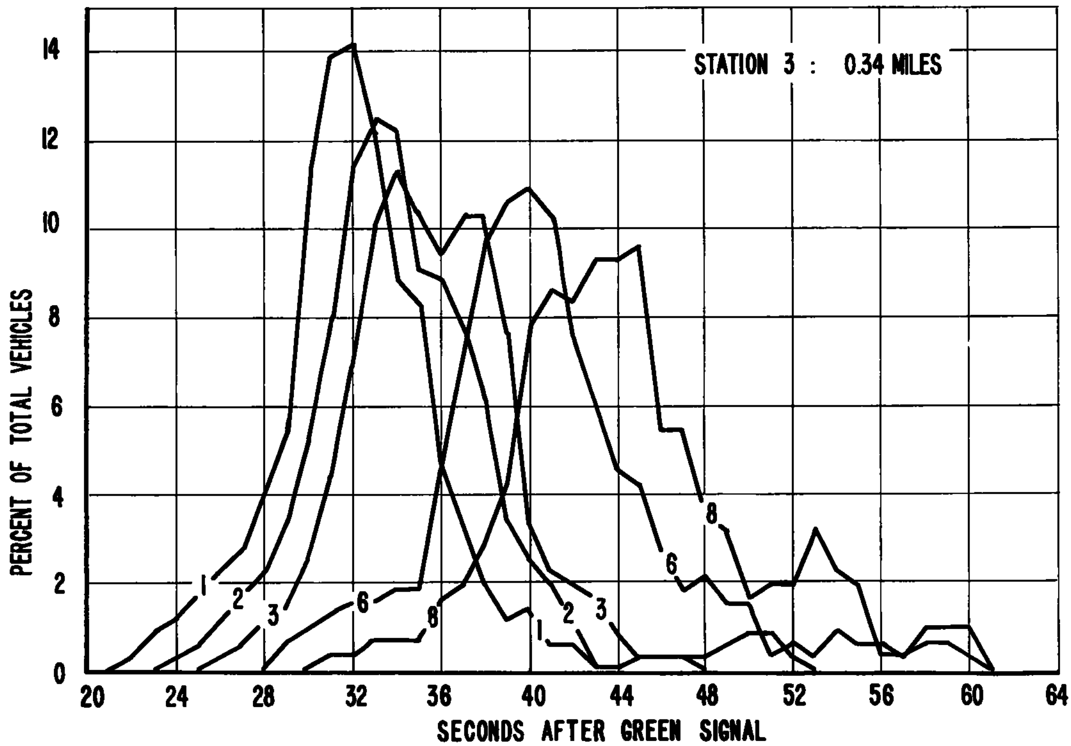

Figure 5. Frequency distributions of arrival times of nth vehicle in a platoon.

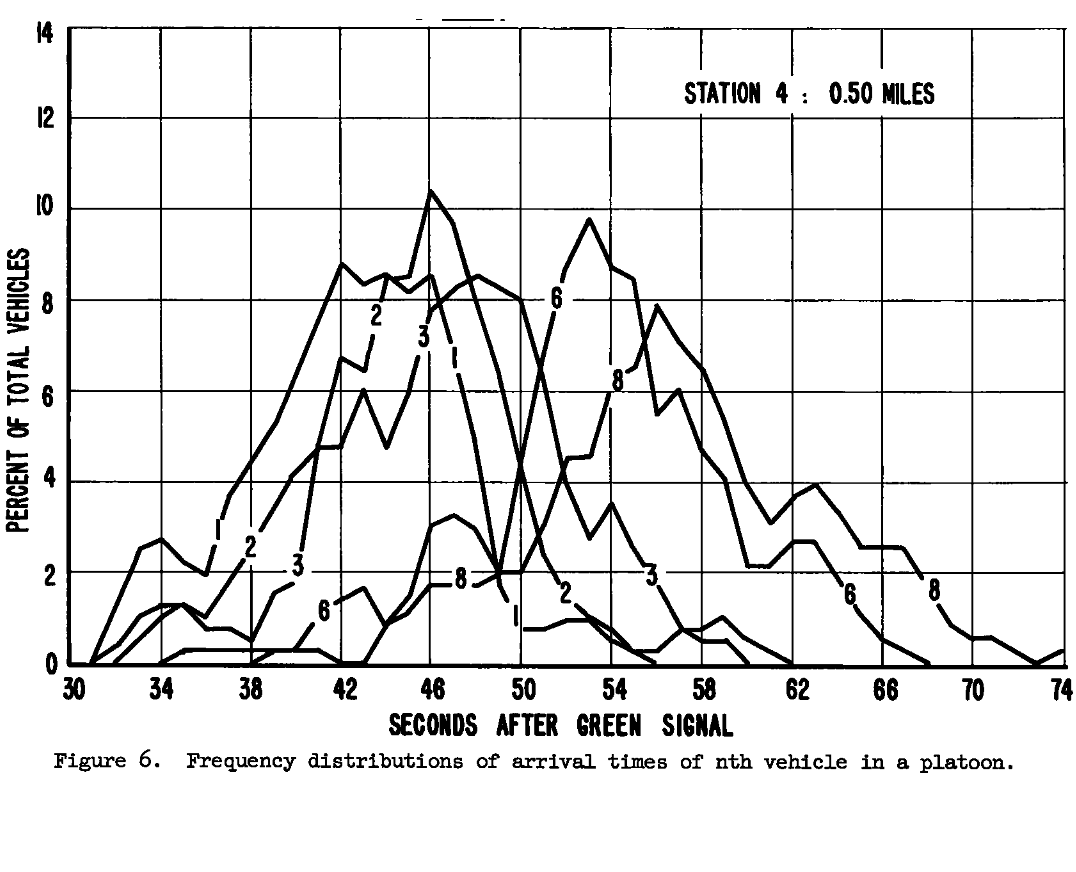

Figure 6. Frequency distributions of arrival times of nth vehicle in a platoon.

the difference between the 5th and 55th percentiles was a representative range, although it was not capable of rigorous statistical use. The first 5 percent are likely to be exceptional drivers, probably driving well in excess of the speed limit, and, if considered, are likely to prejudice any judgment made on the average driver in the main body of the platoon. Therefore, this range , which has an added advantage of containing half of the arrival times, was investigated.

The 55th, 50th, 5th and 0 (the latest time after the green signal up to which no vehicles have arrived) percentiles were calculated from the vehicle arrival time frequency distributions for each of the five stations. These times were plotted with respect to station and a linear relationship was found to obtain for time for each percentile with respect to distance (Figure 9). The time increment between the 0 and 5 percent lines is much greater than that between the 50 and 55 percent lines, supporting the theory that the first 5 percent should probably not be catered to in timing a signal progression. From Figure 9 the time for the P_x percent of vehicles in a platoon to pass a given point was abstracted, where x is the value of the range either 0 to 50 percent or 5 to 55 percent (Figure 10). Though both lines include 50 percent of the vehicles passing a given station, the time increment for the 0 to 50 range is as much as 8.38 sec greater at 0.65 mi from the signal. The slope of either of these lines, but preferably the 5 to 55 percent range, could be taken as a measure of rate of decay of platooning. If the slope of the line were zero the vehicles would be platooned to the same extent at 0.50 mi as they were at 0.10 mi, however the line shows nothing about the extent of platooning at any one point. Definition of this latter phenomenon was not within the scope of the examination. The linearity of the relationship between time for the range (P_5 to P_{55}) to pass a given point versus distance was examined, the correlation coefficient gave a probability level of 1.12 percent, which is significant.

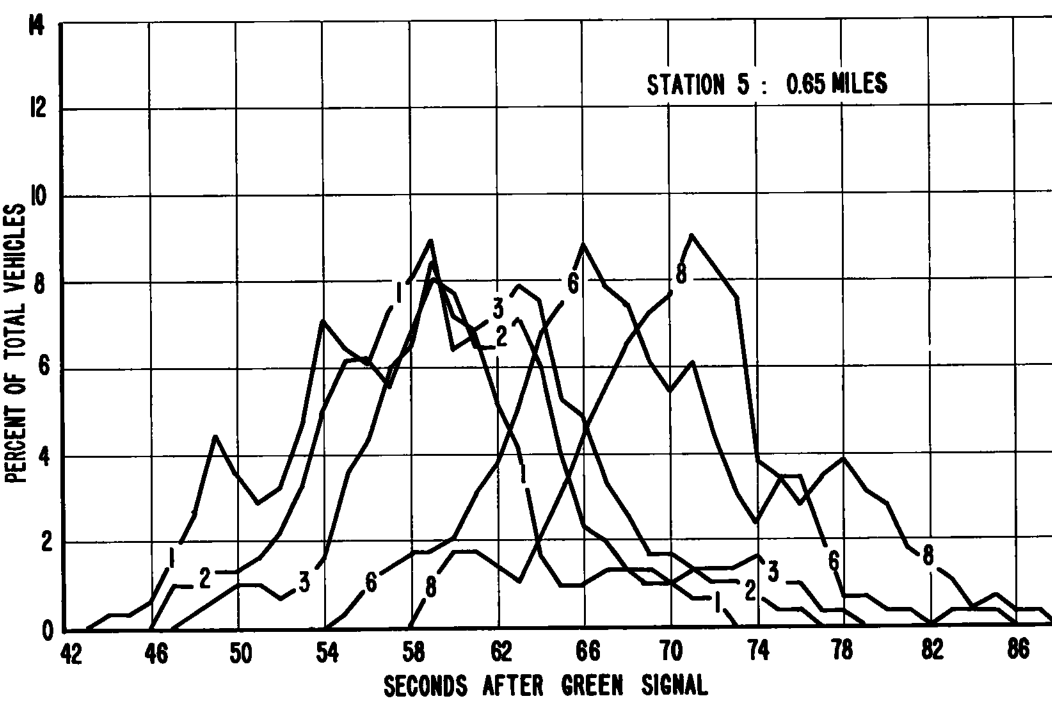

Figure 7. Frequency distributions of arrival times of nth vehicle in a platoon.

Examination of the frequency diagrams of the arrival times of the nth vehicle at each of the stations does not reveal any reason why these distributions should be other than normal. If the equivalent normal distributions are fitted to the data for each of these points perhaps a relationship between them can be determined (7, 8).

For a given distribution, say for the nth vehicle at the mth station, with mean μ and standard deviation σ, the equation of the equivalent normal curve is given by

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

The maximum value of y at the mode is given when $x = \mu$ hence

$$y = \frac{1}{\sigma\sqrt{2\pi}} \qquad (2a)$$

or

$$y = \frac{0.399}{\sigma} \qquad (2b)$$

that is,

$$y = \frac{\text{constant}}{\sigma} \qquad (2c)$$

For each distribution σ is known, hence a curve of $\frac{\text{constant}}{\sigma}$ can be plotted against distance for each station for a given value of n. For ease of computation and graphical presentation the value of the constant was arbitrarily taken as 10 and

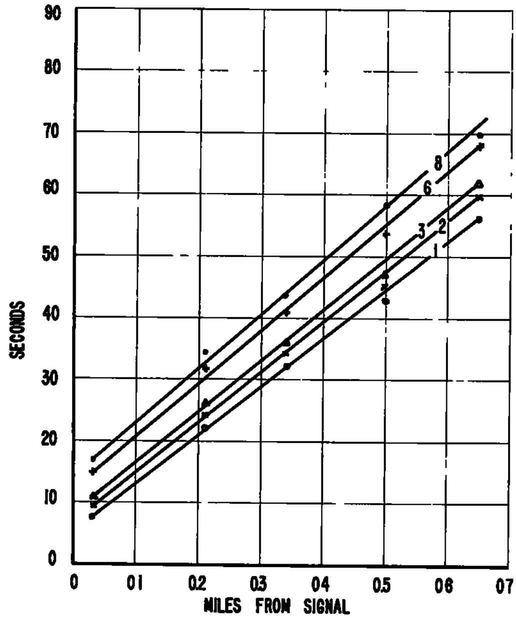

Figure 8. Mean arrival time of nth car versus distance.

curves were plotted of ($y = \frac{10}{\sigma}$) versus distance (d) for each value of n.

It was found that a linear relationship obtained between y and d. Analysis of the correlation coefficient for each line showed a high degree of significance for each line except for n = 6, where the level of probability was 10.01 percent which is not significant. Inspection of the data shows that this rejection is probably due to the value of the standard deviation for station 2. The correlation of the line for n = 8 is good, with a probability level of 1.30 percent, which is significant. There does not appear to be any particular reason why the correlation for n = 6 should not be as good as for other values of n.

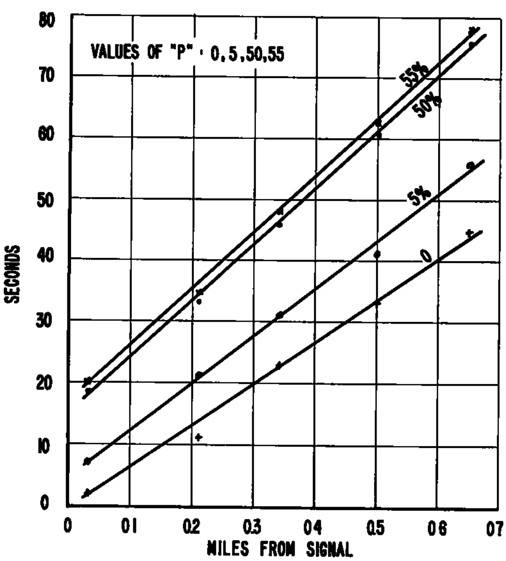

Figure 9. Time for the Pth percentile of vehicles in a platoon to pass a point at a given distance.

ESTABLISHMENT OF A SIGNAL TIMING DIAGRAM

The analysis shows that it would be possible to construct a signal timing diagram for the highway similar to the type used for signal progressions on urban streets (1). Although it would not be possible to cater to a smooth progression of all vehicles at the greater distances, it is possible to arrange the timing of main street green to coincide with the time of greatest vehicle flow density. From the distributions of arrival times of all the vehicles at the five stations, the shortest intervals were calculated in which 50, 70, and 85 percent of the vehicles in a platoon could pass a given station. The lower and upper limits of this interval were designated t_1 and t_2 respectively. For a given percent interval, say the 50 percent interval, the values of t_1 and t_2

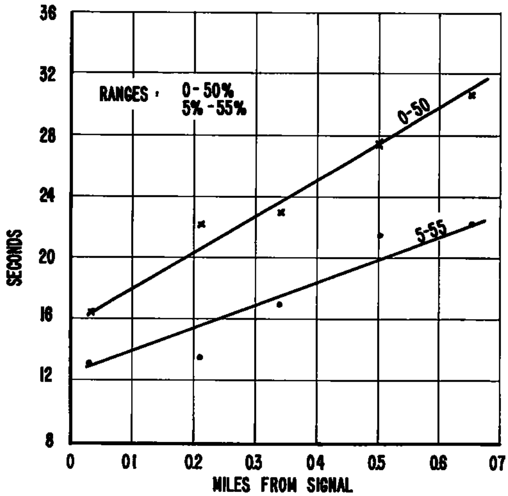

Figure 10. Time for P_x percent of vehicles in a platoon to pass a point at a given distance.

at each of the five stations were linearly related with respect to distance, that is, the shortest interval in which 50 percent of the vehicles in a platoon would pass a given point was a "band" which widened out as the distance away from the issuing

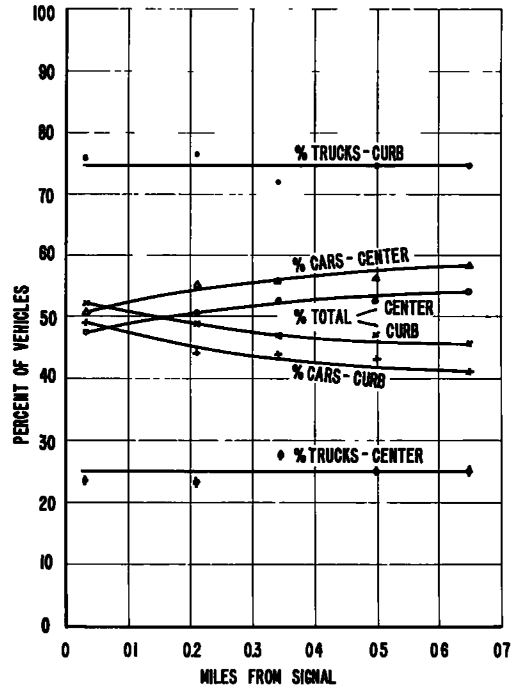

Figure 11. Distribution of traffic by lanes.

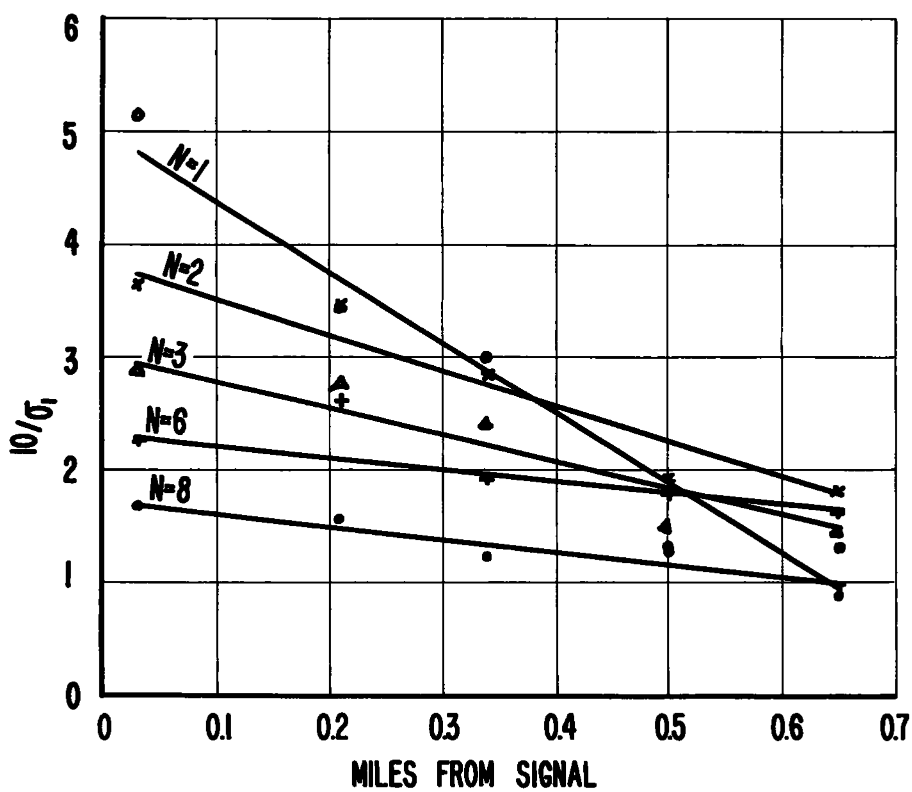

Figure 12. $10/\sigma_1$ versus distance for nth vehicle.

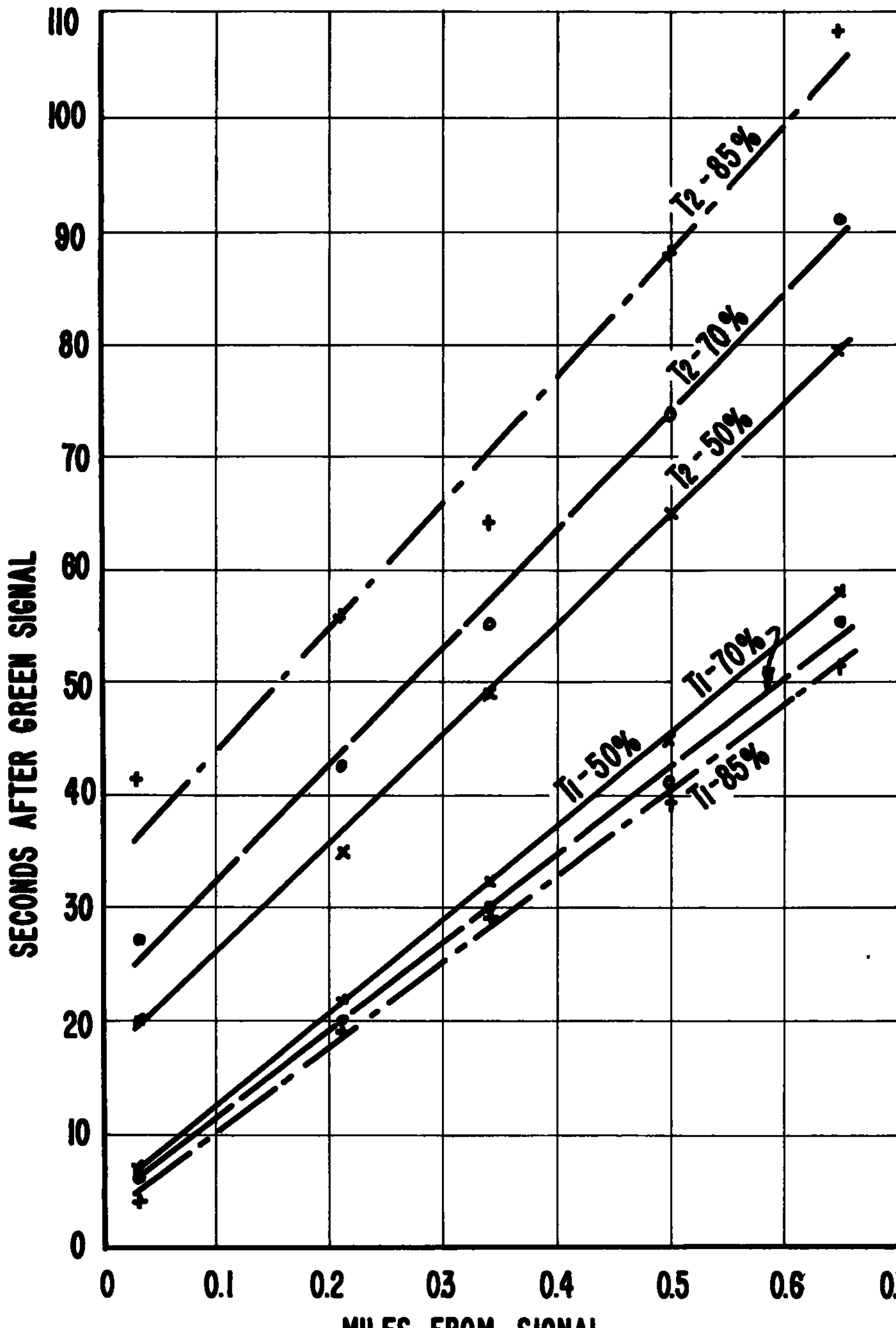

Figure 13. Progression timing bands. Lower and upper limits of smallest period in which 50%, 70% and 85% of platoon vehicles will pass a point at a given distance.

signal was increased. Correlation coefficients for each of the lines for t_1 and t_2 for the 50, 70, and 85 percent intervals were determined, the levels of probability were all significant. These bands, when reproduced graphically (Figure 13) are in effect a progression diagram. If, at some future date, a signal were required 0.50 mi south of Carlson Boulevard, the timing could be so coordinated that the main street green went on 43 sec after green at Carlson and went off 74 sec after beginning of green at

Carlson. This would ensure free passage of 70 percent of the vehicles on East Shore Highway. For example, a 60-sec fixed-time cycle at Carlson Boulevard could have 30 sec green on East Shore and 30 sec for left turn and green on Carlson Boulevard, at the same time a signal 0. 50 mi south of Carlson, also fixed time, could have 31 sec main street green and 29 sec main street red and would not delay 70 percent of the main street vehicles.

SUMMARY AND CONCLUSIONS

Frequency diagrams of the arrival times of all vehicles at given points distant from an issuing signalized intersection were determined. Frequency diagrams of the arrival times of the nth vehicle were also calculated and plotted. Analysis showed : (a) the maximum ordinates of the equivalent normal distributions of the arrival times of the nth vehicles were linearly related to the distance from the signal, (b) the mean arrival time of the nth vehicle was linearly related to distance from the signal, (c) the time for the Pth percentile of vehicles in a platoon, and the time for the (P_{55} to P_5) interval were linearly related to distance from the signal, (d) that a progression diagram for distances up to 0. 65 mi could be plotted for all vehicles which would allow greater success in timing the main street green of a signal downstream from the intersection than might be anticipated from random selection.

Under similar traffic conditions, with vehicle speeds up to 45 mph on high speed urban expressways, it appears that at least the same and probably less delay can be achieved with two coordinated fixed-time signals than with two independent traffic actuated signals, the latter being considerably more expensive to purchase and install.

ACKNOWLEDGMENT

The author would like to express his appreciation to L. M. K. Boelter, Dean of the College of Engineering, and J. H. Mathewson, Assistant Director of the Institute of Transportation and Traffic Engineering, University of California at Los Angeles, for authorizing this work on the Berkeley campus, and to D. S. Berry, formerly Assistant Director of the Institute of Transportation and Traffic Engineering, University of California, Berkeley, for advice given during the investigation.

REFERENCES

1. Institute of Traffic Engineers, "Traffic Engineering Handbook," Institute of Traffic Engineers, New Haven, Connecticut, 1950.

2. Herwald, N., "Further Aspects of Traffic Control with Particular Reference to the 'Autoflex' Progressive System," Journal of Scientific Instruments, Vol. 15, No. 8, Aug. 1938.

3. Bartel, R. M., "Platoon Formation on Signalized Streets, "Institute of Transportation and Traffic Engineering, Los Angeles, unpub.

4. Public Roads Administration, "Manual on Uniform Traffic Control Devices for Streets and Highways," P. R. A., Washington, D. C., 1948.

5. Forbes, T. W., "Speed, Headway and Volume Relationships on a Freeway," Proceedings. Institute of Traffic Engineers, 1951.

6. Greenshields, B. D., and Weida, F. M., "Statistics with Applications to Highway Traffic Analyses," Eno Foundation, Saugatuck, Connecticut.

7. Davis, O. L., "Statistical Methods in Research and Production," Oliver and Boyd, London, 1949.

8. Dixon, W. J., and Massey, F. J., "Introduction to Statistical Analysis," McGraw-Hill Book Company, Incorporated, New York, 1951.

9. Proc., Institute of Traffic Engineers, 1951. Greenshields, B. D., "Some Space-Time Relationships of Traffic in Urban Areas," Proc., Institute of Traffic Engineers, 1946.

10. Conley, R. A., "Effect of Grade on Starting Headway Time," Traffic Engineering, Vol. 22, No. 4, January 1952.

11. Herrey, E. M. J., and Herrey, H., "Principles of Physics Applied to Traffic Movements and Road Conditions," American Journal of Physics, Vol 13, No. 1, February, 1945.

12. Lewis, B. J., "Platoon Movement of Traffic From an Isolated Signalized Intersection," Thesis submitted in partial fulfillment of the requirements for the degree M. S. in Engineering, University of California, Los Angeles.