Driver Characteristics at Intersections

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Headways and gap acceptance characteristics of drivers at signalized intersections in the Phoenix metropolitan area were analyzed using time-lapse photographic techniques. Simultaneous operation of two cameras allowed for the recording of the particular movement involved and for the recording of license plates.

Out-of-state vehicles have headways significantly longer than in-state vehicles when the vehicles in question are at the beginning or near the end of the queue. When the out-of-state vehicles are located in the center of the queue, their headways approach those of the in-state registrants. For left turning vehicles, there is no significant difference between the gap acceptance characteristics of in-state or out-of-state vehicles. Vehicles registered in the states which do not have the "right turn on red" law make little use thereof. All categories of drivers had similar gap acceptance characteristics when they did make use of the law. A sign indicating the legality of the movement increased its usage by all categories of drivers.

•THERE is a widespread agreement among traffic engineers working in Arizona concerning the fact that out-of-state drivers display different driving characteristics from in-state drivers. If the driving characteristics of the two groups are different, then signs and signals along streets carrying high concentrations of tourist traffic should be designed to compensate for the unusual characteristics of this group. Because of the importance of tourism to the economy of Arizona and the influence of out-of-state tourist traffic on the capacity and safety of Arizona streets and highways, if was felt that this problem should be investigated.

STATEMENT OF THE PROBLEM

The number of waiting vehicles that can cross a signalized intersection in a given period of time depends basically on how soon the vehicles begin to move after the signal changes to green and how fast each individual vehicle in the queue reacts to the acceleration of the vehicle immediately ahead. This process continues until all cars in the queue are progressing or have progressed through the intersection. The dissipation of a queue of vehicles after the signal changes to green depends on the reaction time and acceleration characteristics of each individual driver and vehicle. Thus, the total time for a group of vehicles to pass through a signalized intersection can vary considerably depending on the alertness and aggressiveness of the individual drivers, their familiarity with the intersection in question, and the acceleration characteristics of the vehicles which the drivers control.

The fact is accepted that all drivers, when exposed to the same situation, have different reaction times. That different drivers when placed behind the wheel of identical cars will accelerate from a standing start at different rates is also accepted. These characteristics inject a certain expected variability into any field data collected concerning vehicle performance at intersections.

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Following similar reasoning, it could be possible that drivers unfamiliar with an area might display different reaction and acceleration characteristics from local drivers. One specific group of drivers who would be unfamiliar with an area and would probably display different driving characteristics are tourists. Also, the fact that they are on vacation may well influence their aggressiveness.

From November to April each year, Arizona experiences a major influx of tourists. Although many tourists arrive in Phoenix by plane or train, predominantly they arrive by car or have use of a car while in the area.

In addition to the problems which out-of-state drivers encounter due to their unfamiliarity with the local street and highway system, Arizona has a law concerning the right turn on a red light which is not in conformance with the standards as set forth in the "Manual on Uniform Traffic Control Devices" (1). The Manual states: "Permitting vehicle operators to make right or left turns during the showing of the red signal without a modifying arrow or sign is not recommended." The Motor Vehicle Laws of Arizona (2) state the following: "The driver of a vehicle which is stopped as close as practicable at the entrance to the crosswalk on the near side of the intersection, or, if there is no crosswalk, then at the entrance to the intersection, in obedience to a red or "stop" signal, may make a right turn, but shall yield the right-of-way to pedestrians and other traffic proceeding as directed by the signal."

The purposes of this investigation were threefold: (a) to determine and compare headway characteristics of in-state and out-of-state vehicles at signalized intersections; (b) to determine the "right turn on red" characteristics of in-state and out-of-state drivers; and (c) to determine the gap acceptance characteristics of in-state and out-of-state drivers turning left.

PREVIOUS RESEARCH

A thorough analysis of literature related to the problem was accomplished. Reports concerning vehicle headways and gaps and turning characteristics were analyzed, and pertinent information is summarized in this section.

Acceleration Characteristics

The simplest method of determining intersection characteristics involves a determination of vehicle headways. The Highway Capacity Manual (3) defines headway as "The interval of time between individual vehicles moving in the same lane measured from head to head as they pass a given point." This definition was adhered to in this report.

Considerable research has been conducted concerning the characteristics of vehicular flow at signalized intersections. Apparently Greenshields (4) in 1947 was the first to investigate comprehensively all aspects of traffic performance at urban street intersections. Since 1947, many others (5, 6, 7) have performed similar investigations.

In order to determine acceleration characteristics of vehicles at signalized intersections, Greenshields studied the following factors of individual behavior: (a) the time required for vehicles to commence motion; (b) distances reached by vehicles in given time intervals after starting, which are dependent on average accelerations between points; and (c) spacing between vehicles. The time required for a vehicle to commence motion is determined by the reaction time of the driver. Greenshields considered two types of reaction times: first, reaction time of the first vehicle related to the signal change, and second, the reaction time between the movements of successive vehicles. Starting reaction time is defined as the interval between the signal change to green and the movement of the first waiting vehicle. It was found that this time varied from 0.6 to 2.9 sec. Reaction time between successive vehicles is defined as the time elapsed between starting movements of two successive vehicles in line. This time seems to vary from 1.0 to 1.75 sec (4).

The three primary factors which affect vehicle performance in a queue are position of stop, reaction time, and time-distance performance. Reaction time, as discussed previously, depends on the characteristics of individual drivers. The exact position of

stop depends on pavement markings. The time-distance performance of each individual vehicle is not as easily analyzed. However, the distances reached in given times are of great significance to the traffic engineer because they form the basis for timing signals and for determining street capacities.

Generally, most investigators have found that headways between successive vehicles decrease at a lessening rate as one progresses through the queue. As speeds increase, time-spacing between vehicles decreases until the fifth-in-line vehicle has entered the intersection. After the fifth vehicle, headways tend to level out at approximately 2.0 sec (4, 8).

The results of a study conducted by Wildermuth (7) indicate that the length of the green phase does have a substantial effect on average headways; with a 10-sec green phase, the average headway was 2.35 sec, and with a 35- to 45-sec green phase, 2.00-sec headways were obtained. Large vehicles and turning traffic both tend to reduce the capacity of signalized intersections because they have greater headways. This conforms to the results of other investigators. As the green phase of an intersection increases, the effect of the initial starting characteristic of the queue is decreased and the vehicles far back in the queue have a greater effect on the average headway. Therefore, for long phases, average headway will be less than for shorter phases.

The preceding information formed a foundation upon which the analysis in this report is based. However, after a thorough search of the literature, no information was found which analyzed headway characteristics of different groups of drivers. Information abounds concerning all vehicles as a single group and the average headway characteristics of the individual vehicles within this group. It is unfortunate that so little has been determined concerning headway characteristics of specific groups of drivers and the relationships of these characteristics of overall headway characteristics.

Acceptable Right Turn Gaps

Because of the limited use of the "right turn on red" law, apparently no research has been accomplished concerning the gap acceptance of vehicles turning right on red. Considerable research has been conducted concerning gap acceptance at stop-signed intersections.

The term gap as used in this report is defined as the time interval between the arrival at a point by one vehicle and the arrival at the same point by the next succeeding vehicle traveling in the same direction. Gaps were measured from the rear of the first vehicle to the front of the succeeding vehicle. The vehicles' lengths were not included in the measurements.

The definition of gap as used in this report differs from the definition used by Solberg and Oppenlander (9), Bissell (10), and Greenshields (4). Their gap measurement conformed to the definition of headway as given previously in this report. Solberg found in his research that the median acceptance time for right turns was 7.30 sec. In his field investigation Bissell obtained median lag and gap acceptance times of 5.25 sec.

Greenshields defines the average minimum acceptable gap as that value which is accepted by 50 percent of the drivers. At a stop-sign intersection, the minimum acceptable time gap for right turning movements was found to be about 6.1 sec. It should be noted that Solberg did his research in Indiana, Bissell in California and Virginia, and Greenshields in Connecticut. Perhaps different areas of the country contain drivers who will take more chances (by accepting a smaller gap) than drivers from other parts of the country.

"Right Turn on Red"

Published data concerning right turn on red as related to successful use of the law were reviewed. Rankin (11) sent a questionnaire regarding the use of the right turn law to 20 cities with populations from 100,000 to 500,000. Of the 18 cities which replied, 11 allowed right turns on red with an arrow, 2 allowed right turns on red if signed, 3 allowed right turns on red with no sign, and 2 did not allow right turns on red. Both cities which did not allow right turns on red indicated that they had in the past but had eliminated the law because of numerous accidents. Of the 11 cities which allowed right turns

on red with an arrow, six indicated that they restricted the practice to special locations at outlying intersections which had low pedestrian volumes and ample lanes to allow merging movements. Unfortunately the responding cities were not grouped into geographical classification as to states allowing or not allowing the right turn on red.

A paper concerning the right turn on red problem where answering cities were segregated as to geographical location was written by Ray (12). A questionnaire regarding accidents and delays as related to right turning movements at signalized intersections was sent to 57 cities; 45 cities in 25 states replied. In responding to the question, "Have accidents resulting from right turns on red been a significant part of total accidents at intersections?" 4 cities indicated that they had experienced an accident problem. Three of these permitted such a turn only when a green-arrow indication appeared.

None of the 13 California cities contacted reported any problem. This is significant because the right turn on red law prevails in California as it does in Arizona. In connection with the California analysis, Ray attributed the apparent success of the turn law to the following factors: (a) traffic in California must stop on a red light before turning right; (b) traffic does not need to stop on a red light before turning right with a green-arrow indication; and (c) motorists in California must observe pedestrian right-of-way at all times. These factors apply equally well to Arizona traffic.

As a continuation of the analysis, Ray studied travel time and delay at specific intersections in California. The study was controlled so that the only factor affecting travel time was the manner in which right turns were made. It was determined that during off-peak periods travel time was reduced 7 percent by making use of the right turn on red law. During off-peak periods delay at each right turn signal was reduced 68 percent. During peak periods delay was reduced 38 percent.

Ray found that the right turn on red law does not add any hazard at signalized intersections. He concluded that the use of the law presents an opportunity to decrease delay and increase capacity at all signalized intersections.

Acceptable Left Turn Gaps

The subject of delay of left turning vehicles and left turn channelization has been studied at length. However, reference was found in the literature to only one study concerning left turn gap acceptability. This report by Kaiser (13) investigated opposed left turn crossings at an urban intersection. He found that delayed left turning drivers refused all gaps less than 3.75 sec and accepted all gaps of 4.75 or greater. The median value was 4.25 sec.

SURVEY ON RIGHT TURN ON RED LAW

A wide diversity of opinion exists concerning the use of a right turn on a red signal indication. Traffic engineers in many parts of the country feel that a turning movement of this type will decrease the capacity of an intersection and endanger the lives of pedestrians in the crosswalks. However, other traffic engineers feel that intersection capacity is increased and pedestrian lives are not jeopardized through the judicious use of the right turn on red law.

Classification of Drivers

In order to analyze the use of the right turn on red law in Arizona, three groups of drivers were established. Group 1 contained all drivers of vehicles registered in Arizona. Group 2 contained all drivers of vehicles registered in other states which have a similar law concerning right turn on red. Group 3 contained drivers of all vehicles registered in states which do not have a similar turn law. Presumably drivers in Group 1 would be aware of the law and act accordingly at all times. Since in the "before" section of the study none of the intersections studied were signed to explain the legality of the movement, considerable uncertainty existed concerning the turning characteristics of drivers in Group 2 and Group 3.

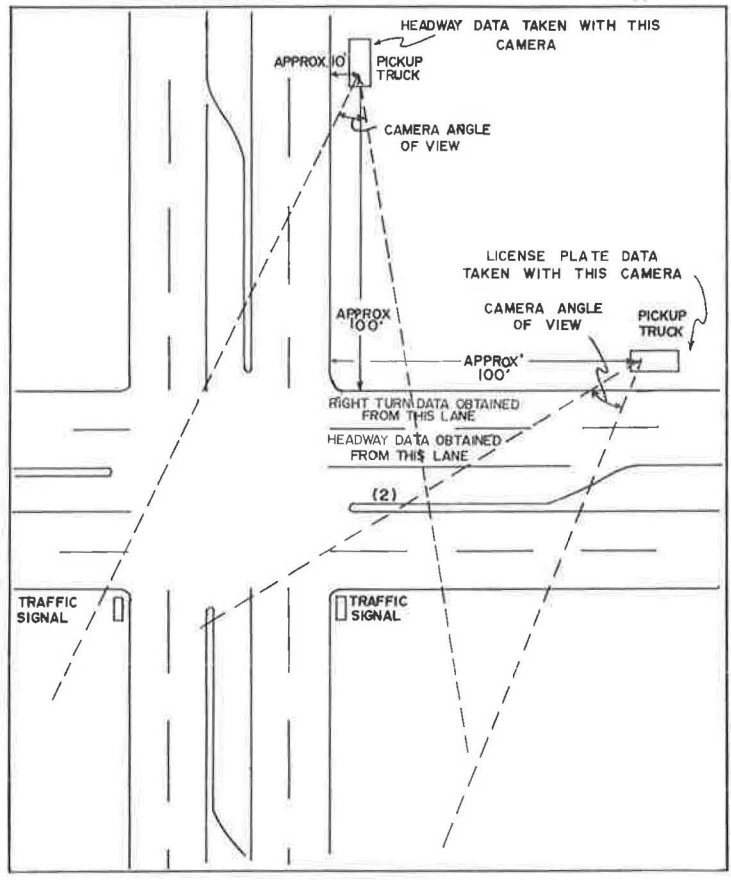

Figure 1. Typical camera location, headways and right turn gaps.

Questionnaire

To determine the legality of the right turn on red law in other states, a questionnaire was sent to the traffic engineer of each highway department in each of the 48 contiguous states. Prevailing opinions concerning the use of the law and the existing legality of the law were received from engineers in 44 states. Connecticut, New York, Tennessee, and West Virginia did not respond to the questionnaire. Of the states which answered the letter, 6 indicated that the right turn on red was allowable by state law. The states where the turn is legal are Arizona, California, Nevada, Oregon, Utah, and Washington. Alabama and South Dakota indicated that the law could be legally adopted by any municipality desiring to do so.

Figure 2. Driver's view of equipment installation.

There is general disagreement concerning the use of the right turn on red law. Basically, areas of the country where the law had never been used were strongly opposed to the concept, while states in which the turn law was legal were strongly in favor of the practice. Also, it was observed that engineers in all states where the turning movement in question was a legal

Figure 3. Location of equipment in truck.

maneuver felt that intersection capacity was improved and no specific hazards to pedestrians were caused by the use of the law. No record was found of a state which had legalized the right turn on red and then revoked the law.

Gap Acceptance

The fact that intersection capacity is either increased or decreased through the use of the law is obviously in question. One method of determining the actual effect of right turns at an intersection involves a study of gap acceptance. If the mean gap accepted is only 2 or 3 sec and through traffic is moving through the intersection at more than 25 mph, turning cars will force through traffic to slow down and thus the capacity of the intersection will be decreased and the accident potential will be increased. However, if the mean gap accepted is 6 sec or more, turning cars will not force through traffic to slow down and the capacity of the intersection will be increased with no increase in the vehicle accident potential.

EQUIPMENT AND PROCEDURES

To provide a permanent study record, and to facilitate desired exactness of measurement, time-lapse photography was selected as the most appropriate means of recording gaps and headways.

Equipment

Two 16-mm Bell & Howell movie cameras, Model 70-Dr, driven by electric motors, were used to film the traffic. The drive unit connected to the camera mounted on a tripod was geared for speeds of either 60 or 100 frames per min. For this analysis the 100-frames/min speed was used throughout. A 12-volt battery working through an inverter powered the electric motorized drive unit which operated the camera; thus the entire assembly was portable and self-contained.

The camera which was used to collect headway and gap data was equipped with a 10-mm wide-angle lens. This camera operated at a shutter speed of $^1/_{50}$ sec. The camera used to collect license-plate data was equipped with a 50-mm telephoto lens. This camera operated at a shutter speed of $^1/_{100}$ sec.

Upon receipt of all components, a test location was filmed and drive speed was checked. Variation was found to range from -1.7 to +3.0 percent. The drive speed was checked periodically during filming and was found to be consistently within this range.

Figure 4. Camera view of intersection.

Camera Location for Collection of Headway and Right Turn Data

At each intersection, the camera tripod was mounted in the bed of a pickup truck which was parked from 80 to 125 ft from the corner. The camera in the truck was positioned 10 ft above the ground and offset 8 to 12 ft from the oncoming (outside) traffic lane. The focal axis was perpendicular to the traffic lanes in which headway

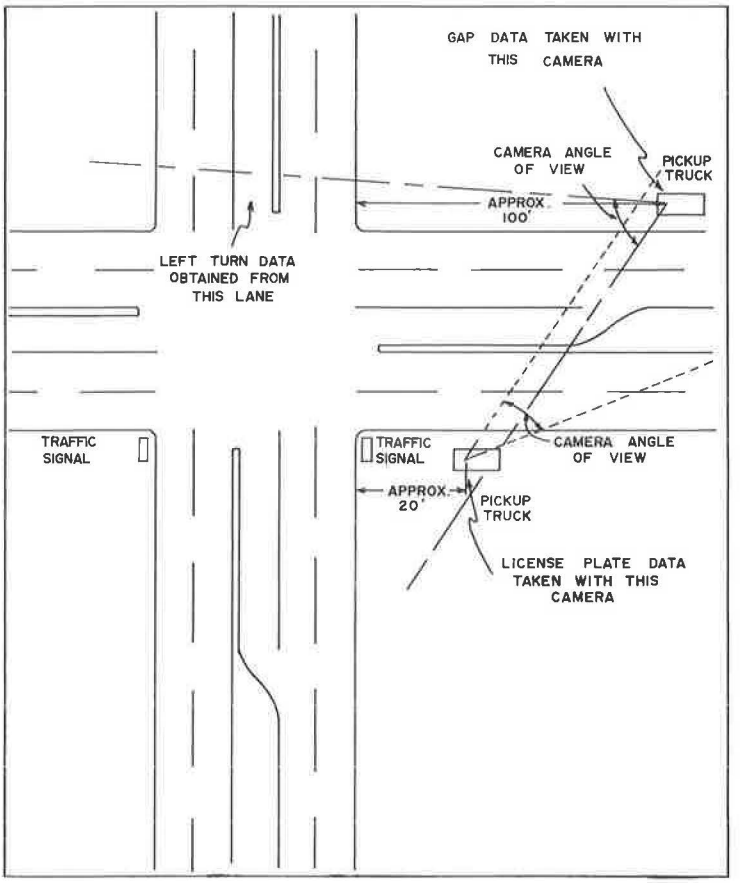

Figure 5. Typical camera location, left turn gaps.

and right turn gap data were being collected. The field of vision necessarily encompassed at least one traffic signal head to establish the initiation of the green phase. In all cases, the initiation of green on the street under analysis coincided with the initiation of red on the cross street.

The camera used to obtain license-plate data was placed approximately 100 ft in advance of the approach. The focal axis was oriented nearly parallel to the approach lanes and toward the intersection. Thus, rear license plates were photographed as vehicles entered the queue. This system was adopted after several other possibilities were tried.

Figure 1 is a sketch of an intersection and the locations of the pickup trucks containing the cameras. Camera orientation with respect to the lanes of traffic under analysis may be observed. Figure 2 shows a driver's view of part of the equipment installation. This photo was taken from the point marked (2) on the intersection sketch (Fig. 1). The unobtrusive nature of the equipment in the background of the photo should be noted. Figure 3 shows the location of the camera equipment in the bed of the truck. Use of the stepladder shown in the photo was necessary when determining the field of view prior to filming. Figure 4 shows the view of the intersection as seen through the camera with which the headway data were collected.

Camera Location for Collection of Left Turn Data

The camera used to collect the gap data was located in a manner similar to the location used to obtain headway data. However, the camera used to obtain license-plate

TABLE 1

SUMMARY OF INTERSECTION CHARACTERISTICS

City	Major Street	Posted Speed Limit (mph)	ADT	Minor Street	Posted Speed Limit (mph)	ADT
Scottsdale	Scottsdale Rd.	35	20, 280	McDowell Rd.	35	20, 560
Tempe	Apache Blvd.	35	23, 531	Rural Rd.	35	6, 670
Phoenix	Van Buren St.	35	18, 900	32nd St.	35	10, 350
Scottsdale	Scottsdale Rd.	25	19, 700	2nd St.	25	1, 830
Phoenix	McDowell Rd.	35	20, 730	Central Ave.	35	25, 750
Phoenix	Indian School Rd.	40	16, 125	44th St.	35	14, 460

Note: Major street = street on which headways were measured.
Minor street = street on which gaps were measured.
Grades at all intersections were level or nearly level.
Adequate sight distance existed at all intersections.
Commercial development at all intersections was extensive.

information was positioned so that the left turning vehicle passed through the field of view of the camera immediately after the turning maneuver was completed. This was done to obtain photographs of the rear license plate of each vehicle.

Figure 5 shows the locations of the pickup trucks containing the cameras. It is important to position the camera which photographs the rear license plates of the turning vehicles close to the intersection corner. Once the vehicles accelerate to 25 mph or more, it becomes extremely difficult to read the plate from the film.

Analysis Procedure

Data were collected on weekdays. All data were collected on color film. Two observers, upon commencement of filming, noted the color of the leading car in each queue and the length of the queue.

A daylight rear projection screen with an acetate cover was used to view the developed film containing the headway and gap information. Headways were measured with reference to an extension of the curb line which was nearest and parallel to the stop line. Gaps were measured at the merge point of turning traffic on the cross street. All reference lines and measurement points were drawn on the acetate cover.

The film containing the license-plate information was viewed on a screen adjacent to the rear projection screen. Both films were viewed concurrently. One technician read the license plate of the vehicle and thus classified the origin of the vehicle while at the same time the other technician measured the headway or gap of the same vehicle.

A frame counter on the projector was used to obtain the time increment of each measurement. Occurrences were estimated to the nearest quarter frame (0. 15 sec).

Intersections Studied

A total of seven intersections were studied. In all but one case, one approach was filmed for analysis at each site. At Scottsdale Road and McDowell Road two approaches (north and west) were analyzed. All intersections were normal at-grade designs with right-angle crossings. All locations were signal-controlled. Some used fixed time and others had actuated equipment. The general characteristics of the intersections are contained in Table 1.

Statistical Procedures

Statistical tests were utilized to determine whether there were significant differences between vehicle time headways at different intersections and also to determine relationships between headways of in-state and out-of-state vehicles. It was determined that in order to detect a headway time difference of 0. 3 sec with 95 percent confidence, a sample size of at least 37 was required.

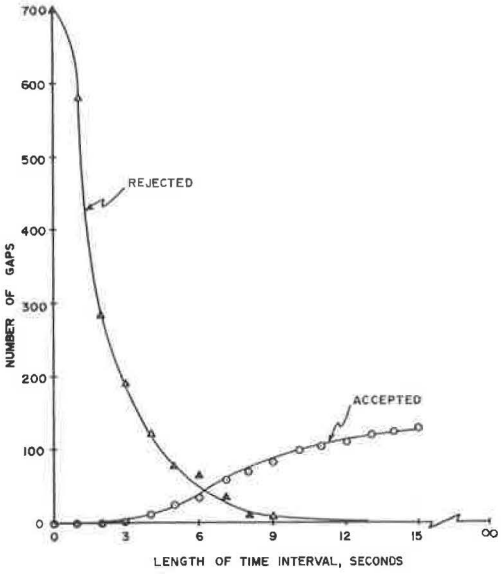

Figure 6. Distribution of accepted and rejected gaps for left turning movements, Arizona vehicles, total number.

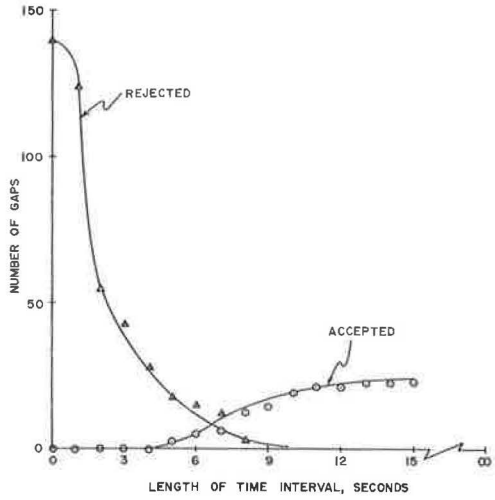

Figure 7. Distribution of accepted and rejected gaps for left turning movements, out-of-state vehicles, total number.

When testing whether there was a difference between in-state and out-of-state headways, it was assumed that the data had a normal distribution. This assumption was made only after several plots of the data were drawn and found to reasonably approximate the normal curve.

Various statistical tests were then utilized to study the difference in the headway data. The Student's "t" distribution was used to determine the existence of significant differences between in-state and out-of-state headway data at a particular intersection. Cochran's test was used to study the homogeneity of variances of data from several intersections. A test devised by Hicks (14) was used to determine if there was a significant difference in the data collected from several intersections.

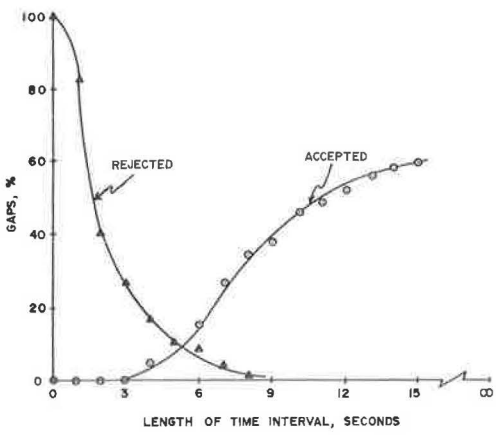

Figure 8. Distribution of accepted and rejected gaps for left turning movements, Arizona vehicles, percent.

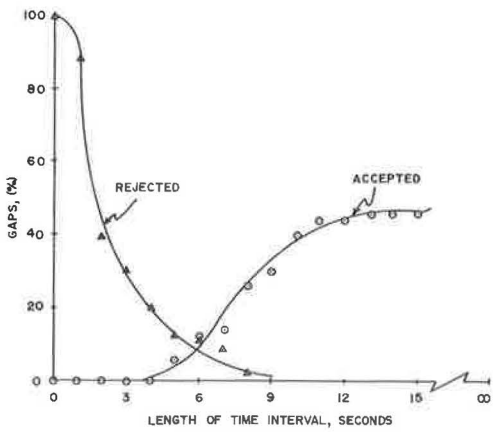

Figure 9. Distribution of accepted and rejected gaps for left turning movements, out-of-state vehicles, percent.

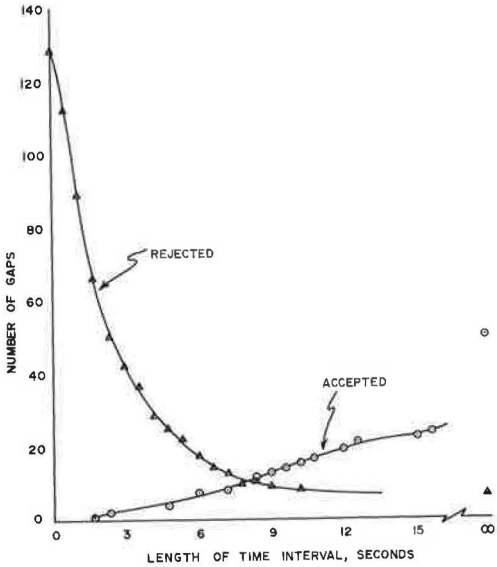

Figure 10. Distribution of accepted and rejected gaps at all intersections, total number of right turns.

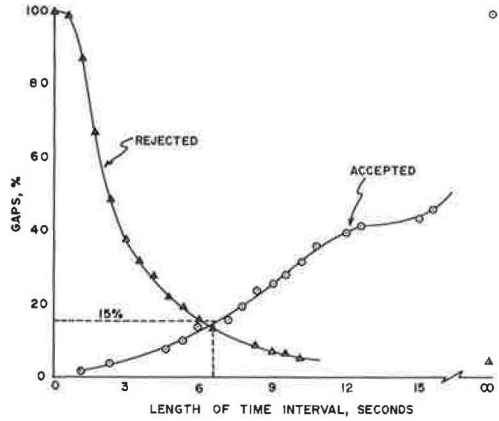

Figure 11. Distribution of accepted and rejected gaps at all intersections, percent of right turns.

TURNING CHARACTERISTIC RESULTS

The results of the field measurements concerning left and right turn gap acceptance and acceptance of the right turn on red law follow. All data pertain only to passenger vehicles and light pickup trucks.

Gap Acceptance of Vehicles Turning Left

Left turn gap data from the westbound approach on McDowell turning south on Scottsdale Road and from the southbound approach on Scottsdale Road turning east on McDowell were collected and combined. The left turning movements of 260 passenger vehicles and light trucks were obtained. Twenty-one percent of the vehicles were from out of state.

A complete description of the actual number of in-state vehicles turning left and the gap acceptance characteristics of the vehicles are shown in Figure 6. Figure 7 presents the same data for out-of-state vehicles. Figures 8 and 9 show the data with the number of vehicles expressed as a percentage.

It can be seen that the point of intersection of the acceptance and rejection curves in Figures 8 and 9 is approximately 5.5 sec. This point indicates a gap time which has an equal chance of acceptance or rejection by the average driver. Tests indicate that there is no significant difference between the gap acceptance characteristics of in-state and out-of-state drivers.

It may be possible to adopt a corollary to the 85th percentile rule as applied to speed limit determination for gap acceptance analysis. It appears that from 10 to 15 percent of the drivers will accept a gap which is so small that through traffic is impeded. Field observations indicate that for speed limits of 35 to 40 mph a 6-sec gap is the minimum gap which can be safely accepted without impeding through traffic or requiring excessive acceleration on the part of the turning vehicle. Figure 9 indicates that the gap which 15 percent of the drivers will accept is 6 sec.

Gap Acceptance of Vehicles Turning Right

It was determined that the gap data from different intersections could be combined. Consequently, all gap data presented represent a combination of data obtained from the

TABLE 2

RIGHT TURN GAP ACCEPTANCE AND REJECTION CHARACTERISTICS BY STATE REGISTRATION GROUP

Characteristic	Registration of Vehicle		
	Arizona	Other States With RTOR	Other States
(a) Number of Vehicles			
Accepted a gap	50	2	6
Rejected all gaps	24	4	10
Rejected all gaps but had at least one gap >6 sec	11	2	9
Total vehicles	74	6	16
(b) Percent of Vehicles			
Accepted a gap	67	33	37
Rejected all gaps	33	67	62
Rejected all gaps but had at least one gap >6 sec (% in terms of total rejections)	46	50	90

following intersections: Scottsdale Road and McDowell Road westbound; Apache Boulevard and Rural Road westbound; 32nd Street and Van Buren Street westbound; and Indian School Road and 44th Street eastbound.

The sample population in the film analysis contained 3,606 vehicles, 403 of which turned right. Of these 403 turning vehicles, 58 accepted a gap and turned right on red. Approximately 28 percent of the turning vehicles showed out-of-state registration. All data represent a combination of both in-state and out-of-state gap acceptance. Since it was proved in the left turn study that vehicle origin had no effect on gap acceptance, it was assumed that if a driver was aware of the law, the actual gap accepted would not depend on the driver's home state. Figure 10 shows the data in terms of total number of accepted and rejected gaps and Figure 11 shows percent of accepted and rejected gaps.

The fact that the time gap acceptable by an individual driver depends to a certain extent on the lane position of the cars in the through lanes is acknowledged. For example, when the gap occurs between a car in the right lane and a car in the left lane, a driver will accept a slightly smaller gap than when the gap occurs between a car in the left lane and a car in the right lane. However, there is no way to predict the distribution of cars in the through lanes. Therefore, determining different acceptable gaps for different positions of cars in the through lanes would introduce unnecessary complexity into the analysis.

Figure 11 shows that the point of intersection of the acceptance and rejection curves is 6.6 sec. This point of intersection indicates a time, in this case 6.6 sec, which represents a gap that would have an equal chance of acceptance or rejection by the average driver. Because of the compatibility of the left turn and right turn gap analysis, a 6-sec gap will be considered to be the minimum acceptable time gap. The results are given in Table 2 where turning characteristics in terms of total numbers observed and in terms of percent observed are listed. One section of the table notes the number and percent of vehicles that rejected all gaps but had at least one gap greater than 6 sec. Although the sample size is small, the data indicate that drivers from states without right turn on red laws react differently. This difference is obvious since 90 percent of those out-of-state drivers rejecting all gaps had a gap of greater than 6 sec, whereas only 50 percent of other drivers rejected these longer gaps. This may indicate that a significant proportion of drivers are unaware of the law. The fact that data on only 96 vehicles were obtained where the population size (vehicles in right lane) was over 3,600 indicates the data collection problem involved with obtaining this type of information.

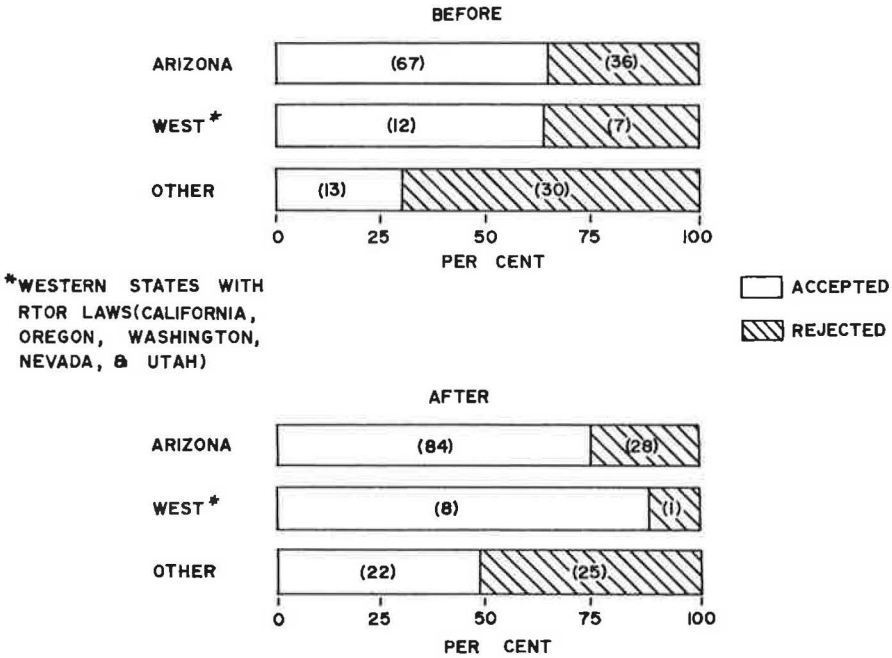

Figure 12. Right turn on red opportunities.

TABLE 3

RIGHT TURN CHARACTERISTICS AT SCOTTSDALE ROAD AND 5TH AVENUE

Characteristic	Registration of Vehicle		
	Arizona	Other States With RTOR	Other States
Before			
Total traffic			
Number	5218	1572	
Percent	76.8	23.2	
Total right turns			
Number	725	71	211
Percent	72.0	7.0	21.0
Right turns on red			
Number	67	12	13
Percent of right turns	9.2	16.9	6.2
After			
Total traffic			
Number	5011	1684	
Percent	74.9	25.1	
Total right turns			
Number	685	51	267
Percent	68.3	5.1	26.6
Right turns on red			
Number	84	8	22
Percent of right turns	12.3	15.7	8.2

TABLE 4

VEHICLE CLASSIFICATION BY REGISTRATION FOR THROUGH-LANE HEADWAY MEASUREMENTS, INITIAL PERIOD

Location	Total In-State Vehicles	Total Out-of-State Vehicles	In-State %	Out-of-State %
Scottsdale Rd. and McDowell Rd. southbound	310	90	77.5	22.5
Scottsdale Rd. and McDowell Rd. westbound	345	45	88.5	11.5
Apache Blvd. and Rural Rd. westbound	225	80	73.8	26.2
Van Buren St. and 32nd St. westbound	324	107	75.2	24.8
Scottsdale Rd. and 2nd St. northbound	321	95	77.2	22.8

Acceptance of the Right Turn on Red Law

In order to further study gap acceptance characteristics, a T intersection in Scottsdale was observed. At this intersection there was no cross traffic; therefore, motorists desiring to turn right were not faced with the choice of accepting a suitable gap in order to accomplish the right turn.

Because the right turn gap acceptance characteristics study indicated poor utilization of the right turn on red law, it was decided to perform a "before-and-after" study at this intersection. The "before" part of the study consisted of manual observation of driver acceptance of the law. The "after" part consisted of manual observation of driver acceptance of the law when the drivers were reminded that the right turn on red movement was a legal maneuver at that intersection. This was accomplished by the installation of a standard 24 by 18-in. sign on which was printed "RIGHT TURN ON RED AFTER STOP."

In the "before" study a total of 6,890 vehicles traveling in the outside lane were observed. Of these, 1,007 vehicles turned right. Twenty-eight percent of the turning vehicles were from out of state.

In the "after" study a total of 6,695 vehicles traveling in the outside lane were observed. Of these, 1,003 vehicles turned right. Thirty-two percent of the turning vehicles were from out of state.

More complete information concerning turning characteristics of vehicles at this intersection is given in Table 3 and Figure 12. Table 3 gives a numerical breakdown and Figure 12 shows a graphical comparison of the data. The "before" test indicates that 65 percent of the Arizona drivers, 63 percent of drivers from other states with the right turn law, and 30 percent of drivers from other states accepted the law. The "after" test indicates that 75 percent of the Arizona drivers, 89 percent of drivers from other states with the right turn law, and 47 percent of drivers from other states accepted the law. Use of the information sign significantly improved acceptance of the right turn on red law.

TABLE 5

VEHICLE CLASSIFICATION BY REGISTRATION FOR THROUGH-LANE HEADWAY MEASUREMENTS, FINAL PERIOD

Location	Total In-State Vehicles	Total Out-of-State Vehicles	In-State %	Out-of-State %
Scottsdale Rd. and McDowell Rd. southbound	483	95	83.5	16.5
Scottsdale Rd. and McDowell Rd. westbound	509	67	88.4	11.6

HEADWAY RESULTS

The investigation of headway characteristics can be separated into three distinct phases: the initial study, the final study, and the seasonal study. All data presented pertain only to passenger vehicles and light pickup trucks.

The Initial Study

The initial headway measurement period began in September 1964, and continued until June 1965. During this period, measurement techniques were developed and a variety of intersections were studied. Since the purpose of the investigation was to study phenomena caused by changes in driver population, it was desired to find an intersection through which large numbers of out-of-state vehicles passed. In order to determine the effect of out-of-state drivers on all positions in the queue, an intersection where large queues developed also was required.

It was soon determined that very few intersections met the out-of-state vehicle and queue requirements. It seems that because of the progressive signalization which exists on most streets in the area, the only period of the day when queue lengths greater than six cars consistently occur is during the morning and evening peak periods. Unfortunately, out-of-state vehicles, whose drivers are usually tourists, tend to stay off the streets during peak periods. Thus, analysis during peak periods proved to be generally unsuitable.

Consequently, the first problem encountered was to find an intersection which suited the project requirements. Next, it had to be determined whether or not headway data from a particular intersection would be representative of headway characteristics of the entire area.

The first step in the investigation involved data accumulation at several intersections in the area where volume counts indicated both high volumes and a large proportion of out-of-state vehicles. Table 4 summarizes the registration of vehicles whose headways were measured during the initial portion of the study. The data shown are only for vehicles in the inside lane (the through lane nearest the centerline) and all measurements were made during off-peak periods. In general, headways in the outside lane are not comparable with headways in the inside lane because of the right turning and parking movements which occur in or near the outside lane and do not occur in the inside lane. At all intersections but one (Scottsdale Road and 2nd Street), a separate left turn lane allowed traffic in the inside lane to proceed without obstruction. Thus, the headways are based on lanes with uninterrupted through movements.

In all cases concerning vehicle headways, the time required for the first vehicle in the queue to respond to the light change and advance to the reference line is not included in this section of the report. The figures show the headway between the first and second vehicles and all succeeding vehicles. The time required for the first vehicle in the queue to cross the reference line is not reported because the distance to the reference line varies from intersection to intersection.

The total population size for the headway data was 5,347 vehicles, approximately 23 percent of which were out-of-state vehicles. In spite of the sample size, some intersections produced meager data concerning the headway characteristics of vehicles within the queue.

In this initial portion of the study, data sufficient to form definite conclusions concerning headway characteristics were not obtained. However, it was determined that there was no significant difference between headway characteristics at four of the approaches tested. Because of the data collection problems, it was decided to collect headway data intensively at one specific intersection in order to obtain information in large enough quentities to form conclusions which were statistically correct. After examining the data collected during the initial study and considering the queue lengths which occurred at each intersection, the intersection of Scottsdale Road and McDowell Road was selected for more intensive study.

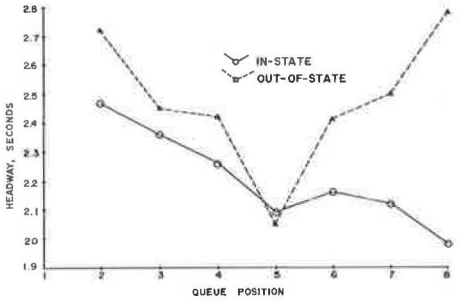

Figure 13. Headways of in-state and out-of-state vehicles.

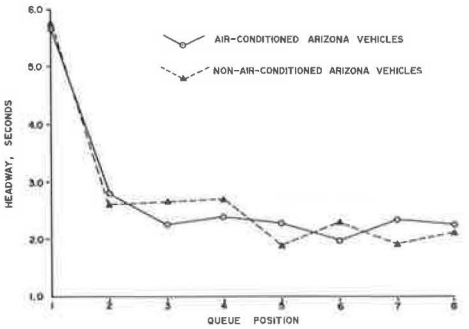

Figure 14. In-state headways for air-conditioned and non-air-conditioned vehicles.

The Final Study

The final headway measurement period began in January 1966, and continued until April 1966. This time period was selected because of its higher proportion of out-of-state traffic. Table 5 summarizes the registration of vehicles whose headways were measured during the final portion of the study. As in the initial study, the data shown are only for vehicles in the inside lane traveling during off-peak periods.

The headway relationships of in-state and out-of-state vehicles are shown in Figure 13. The points shown on the curves represent a compilation of data obtained during both the initial and final study. Analysis indicated that data for all the locations in question could be combined without impairing the significance of the results.

It can be determined by examining the curves in Figure 13 that the headway between the first and second cars for in-state vehicles is significantly different from the headway for out-of-state vehicles. The difference between in-state and out-of-state vehicle headways of the third, fourth, and fifth cars is not significant. After the fifth car, the divergence between in-state and out-of-state vehicles begins to increase until for the eighth car in a queue, the mean headway of in-state vehicles is 1.98 sec while the mean headway of out-of-state vehicles is 2.78 sec, an 0.80-sec difference. In all cases but that of the fifth car, the mean headway of out-of-state vehicles is greater than the mean headway of in-state vehicles.

The Seasonal Study

Because of the extremely high temperatures which occur in Phoenix during the summer months, a large proportion of cars in the area are air-conditioned. One objective was to determine if there is a difference in headways when comparing air-conditioned and non-air-conditioned vehicles. The second objective was to determine if there is a difference in headways when comparing in-state vehicles operating during the summer months and in-state vehicles operating during the winter months.

An intersection in downtown Phoenix (Central and McDowell) was selected for the study. Data were collected during the afternoon peak hours in March and August, 1965. During the afternoon peak hours, the lanes in question were flowing at about practical capacity.

The average maximum daily temperature in Phoenix during the month of August is 102 F. In the sample taken for this analysis, 46 percent of the vehicles were found to be air-conditioned. Because of the high temperature during the summer data collection period, if the windows of the vehicle were up, it was assumed that the vehicle was air-conditioned.

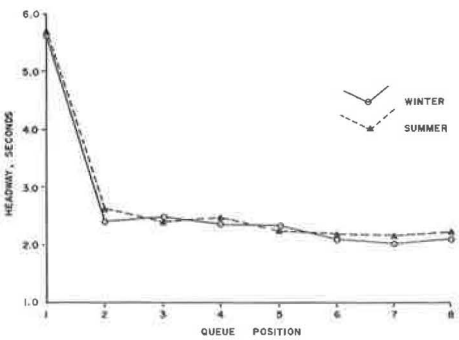

Figure 15. In-state headways for summer and winter.

No data relating to the driver characteristics of persons in air-conditioned and non-air-conditioned vehicles were found during the literature search. Consequently, at the beginning of the test, various theories were proposed concerning the driver characteristics of the two groups. For instance, it was thought that drivers in non-air-conditioned vehicles would be more erratic and aggressive than drivers in air-conditioned vehicles.

Headway measurements were taken in the two through lanes of eastbound traffic. It was determined that there was no difference between the vehicle headways of air-conditioned vehicles and non-air-conditioned vehicles. The data are shown in Figure 14.

There is approximately a 40-degree seasonal difference in the average maximum daily temperature in Phoenix. After it had been determined that there was no difference between headway characteristics of air-conditioned and non-air-conditioned vehicles, the next step in the procedure was to determine if there was a seasonal difference in headway characteristics of vehicles operating during August and March.

No data relating to seasonal variations in headway data were found during the literature search. It was thought that the out-of-state traffic, which forms a large percentage of the total traffic in winter, might influence the vehicle headways of Arizona drivers. Out-of-state traffic during the summer months was less than 1 percent on the street in question during the observation period; therefore, during the summer, headway characteristics of Arizona drivers are independent of out-of-state drivers. The sample taken during March contained 305 Arizona vehicles and the sample taken during August contained 568 Arizona vehicles. It was determined that there is no seasonal variation for in-state vehicle headways. The data are shown in Figure 15.

CONCLUSIONS

The three main purposes of this investigation were to (a) determine and compare headway characteristics of in-state and out-of-state vehicles at signalized intersections; (b) determine the right turn on red characteristics of in-state and out-of-state drivers; and (c) determine the gap acceptance characteristics of in-state and out-of-state drivers turning left. The conclusions which have been reached from this research are discussed in the following.

Headway Characteristics

In general, during off-peak periods, the headway for the first and second vehicle in a queue is longer in the case of an out-of-state vehicle than in the case of an in-state vehicle; the headway of the third, fourth, and fifth vehicles is basically the same for in-state and out-of-state vehicles; and the headway of the sixth, seventh, and eighth vehicles (and probably subsequent vehicles in the queue) is significantly longer in the case of an out-of-state vehicle than in the case of an in-state vehicle. For example, the headway of the second out-of-state vehicle in the queue is 0.3 sec longer than the headway of the second in-state vehicle, and the headway of the eighth out-of-state vehicle in the queue is 0.80 sec longer than the headway of the eighth in-state vehicle.

Probably drivers of out-of-state vehicles located in the first or second position in the queue take longer to accelerate than local drivers because of unfamiliarity with the intersections, thus causing the observed increase in headway. Drivers of vehicles in the third, fourth, and fifth position in the queue began to accelerate at similar rates regardless of driver origin because of two factors: (a) the drivers merely have to follow the car ahead of them, so familiarity or lack of familiarity with an intersection has little effect on headway; and (b) because the vehicles are situated in the midst of the queue, the drivers are under pressure from following vehicles to accelerate as quickly as possible. However, when an out-of-state vehicle is near or at the end of a queue and under little pressure from following vehicles, the driver does not accelerate as rapidly as a local driver.

The result of this phenomenon presents an interesting effect on capacity analysis. Where possible capacity is being considered (with the corresponding formation of long queues which do not clear with each signal cycle), there is little significant difference between headways of in-state and out-of-state drivers. But, if practical capacity is to be attained, then the value of the capacity would be decreased as the proportion of out-of-state traffic increases. This would be necessary since each queue should clear

within a green phase and, as indicated above, this would produce longer headways for the out-of-state vehicles near the end of the queue.

Development of specific adjustment factors to be used in capacity analysis has not been accomplished. The new Highway Capacity Manual (15) was not available until the last month of this project. This manual includes fundamental changes in definitions and concepts from the old manual (3). The preceding paragraph describes how the observed phenomena could be interpreted in terms of the older concept of practical and possible capacity.

Gap Acceptance Characteristics

Both in-state and out-of-state drivers exhibit similar gap acceptance characteristics for both left and right turning movements. It has been determined that a 6-sec gap is the minimum acceptable time gap for a section of roadway which has a maximum speed limit of 35 mph. At least 85 percent of all turning vehicles will reject all gaps of less than 6 sec. Thus, the gap accepted is nearly always large enough so that through-traffic is not forced to slow down because of turning movements. Therefore, the capacity of an intersection where 6-sec gaps are available will be increased.

Right Turn on Red Characteristics

As a result of this research, it has been shown that informing the public of the legality of the right turn on red maneuver improves the acceptance of the law. At the intersection of Scottsdale Road and 5th Avenue, installation of an information sign increased acceptance from 65 to 75 percent for Arizona drivers; from 63 to 89 percent for drivers from other states where the law exists; and from 30 to 47 percent for drivers from states where the turn is illegal. More effective communication concerning the law would probably further increase the above percentages.

In Arizona, use of the right turn on red law reduces delay and travel time and increases the capacity of signalized intersections. However, this turning movement can only be used successfully in states where pedestrian rights are observed by the driving public.

REFERENCES

1. Manual on Uniform Traffic Control Devices. U. S. Bureau of Public Roads, Washington, p. 162, 1961.
2. The Motor Vehicle Laws of Arizona. Motor Vehicle Division, Arizona Highway Department. Phoenix, Paragraph 28-645, Sec. 3-b, 1962.
3. Highway Capacity Manual. U. S. Bureau of Public Roads, Washington, p. 17, 19
4. Greenshields, B. D., Schapiro, D., and Ericksen, E. L. Traffic Performance at Urban Street Intersections. Bureau of Highway Traffic, Technical Report No. 1. Yale University, New Haven, Chapter 2, 1947.
5. Bartle, R. M., Skoro, V., and Gerlough, D. L. Starting Delay Time and Time Spacing of Vehicles Entering Signalized Intersections. HRB Bull. 112, pp. 33-41, 1956.
6. May, A. D., and Wagner, F. A. Headway Characteristics and Interrelationship of Fundamental Characteristics of Traffic Flow. HRB Proc., Vol. 39, pp. 524-547, 1960.
7. Wildermuth, B. R. Average Vehicle Headways of Signalized Intersections. Traffic Engineering, Vol. 33, No. 2, pp. 14-16, Nov. 1962.
8. Drew, D. R. Design and Signalization of High Type Facilities. Traffic Engineering, Vol. 33, No. 10, p. 24, July 1963.
9. Solberg, P., and Oppenlander, J. C. Lag and Gap Acceptances at Stop-Controll Intersections. Unpublished Highway Research Project Report, Purdue University, Lafayette, 1964.
10. Bissell, H. H. Traffic Gap Acceptance From a Stop Sign. Unpublished Graduat Research Report, Institute of Transportation and Traffic Engineering, University of California, Berkeley, 1960.

11. Rankin, W. W. Report on Results From Right Turn on Red Light Questionnaire Survey. Traffic Engineering, Vol. 26, No. 1, p. 30, March 1955.
12. Ray, J. C. Experience With Right Turn on Red. Proc. Inst. of Traffic Engineers, p. 11, 1956.
13. Kaiser, F. J., Jr. Left Turn Gap Acceptance. Bureau of Highway Traffic, Student Thesis Manuscript. Yale University, 1951.
14. Hicks, C. R. Fundamental Concepts in the Design of Experiments. Holt, Rinehart and Winston, New York, pp. 17, 27, 1964.
15. Highway Capacity Manual, 1965. HRB Spec. Rept. 87, 1965.