TRAFFIC DELAY AND WARRANTS FOR CONTROL DEVICES

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Delay to vehicular and pedestrian traffic is one of several criteria frequently used in the selection and evaluation of traffic control devices. In the past, there has been no practical technique for measuring, recording, and analyzing delay data in sufficient quantities to provide a sound basis either for developing delay-based warrants or for determining the relative effectiveness of various control devices in limiting delay to tolerable values. A unique digital delay data recorder that was developed and used successfully for collecting over 240 hours of field data at 19 different intersections is described. This device records up to 12 channels of information from human observers or traffic signal controllers in a form directly suitable for computer processing. Complete summary statistics, which can involve processing as many as 360,000 data items, can be obtained on an overnight basis for 6 hours of field observation. These statistics include 19 delay-related traffic parameters and may be summarized for any selected time intervals. Analysis of delay data from field studies conducted over a 3-year period facilitated the development of a new set of minimum volume warrants for the installation of four-way stop-sign control and the validation of a proposed set of traffic volume warrants for the installation of actuated signal control. These warrants are presented in a tabular and graphic form that is suitable for ready application by practicing traffic engineers.

•TRAFFIC control devices ranging in complexity from signs and pavement markings to sophisticated signal systems are used to assign the right-of-way alternately to traffic on the several approaches to street and highway intersections. The relative effectiveness of these devices can be measured in terms of delay to motorists and number of accidents. The objective is to move the maximum volume of traffic safely through the intersection with minimum delay.

Even though delay to vehicular and pedestrian traffic is a frequently used criterion for selecting and evaluating traffic control devices, no practical technique for measuring, recording, and analyzing delay data in sufficient quantities to serve as the basis for delay-based warrants has been available. A unique digital delay data recorder that was used successfully over a 3-year period for collecting some 240 hours of field data at 19 different intersections is described in this paper. Analysis of these data facilitated the development of a set of minimum volume warrants for installing four-way stops and provided a basis for validating a set of proposed traffic volume warrants for actuated signals.

Several potential applications for the delay recording equipment and the associated analysis techniques are suggested. These include collecting quantitative information for before-and-after studies of traffic control efficiency.

D3 RECORDER

In order to record the large amounts of data needed for studying vehicular delay characteristics at intersections in a form directly suitable for computer processing, the dig-

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ital delay data recorder (D3 Recorder) was developed. This electromechanical instrument is capable of recording automatically coded switch closures that indicate the number of stopped vehicles, the cumulative traffic volume, and the signal indication for each approach lane (up to 12) on a moment-by-moment basis for extended periods of several hours.

Although bulky in its present form, the equipment is easily transported and can be set up at a field site in about 30 min. From 6 to 18 observers are required to provide instantaneous input information regarding the number of stopped vehicles and the number of vehicles that enter the intersection. The observer accomplishes this simply by actuating a push-button switch. The signal indication on each approach is sensed by a direct wire connection to the appropriate power contact at the signal controller.

Data are converted to a digital format and punched directly onto paper tape at the study site. The punched paper tape serves as an inexpensive intermediate storage location inasmuch as the data must be transferred finally to magnetic tape for computer processing. Most computation centers, however, have facilities for reading punched paper tape on a routine basis. Other advantages of the punched-paper-tape recording are that an experienced operator can spot-check the data by visual inspection in the field and that the record is permanent.

Field experience with the recorder over a 3-year period proved it to be quite simple and efficient to operate. A full-time crew of eight men, mostly high-school students, were trained for studies that were made during the summer months of 1966 and 1967. Less than 30 min of instruction was required for each new observer. A review of data that were input by duplicate observers in a special study indicated that reliable information could be obtained even with this minimal observer training.

Each observer was equipped with a data input module containing two push-button switches (add and subtract) and a remote indicating counter. This module was connected to the recorder by a small multiconductor electrical cable 200 ft long so that the observer could be as inconspicuous as possible while watching the traffic. All that was required of the delay observers was to keep an instantaneous count of the number of stopped vehicles showing on the indicating counter. The traffic volume observers simply added a count for each vehicle that entered and cleared the intersection.

The recorder was programmed to scan sequentially all input channels and record channel identification, signal indication, number of stopped vehicles, and number of vehicles that had entered the intersection. When 12 channels were being used, each channel was scanned every 3 sec; when only six channels were used, the scan rate was once each 1.44 sec. These rates were selected as a suitable compromise when considering equipment complexity, quantity of data to be processed, driver and observer reaction time, and statistical sampling.

From the data recorded in the field, several pertinent values related to delay were calculated. Delay relationships for each individual approach and for the intersection as a whole were summarized for several selected time periods. After data from several studies were evaluated, a 15-min analysis period was chosen for continued use. The values that were calculated for each approach for 15-min periods were

1. Traffic volume;
2. Total vehicle-seconds of delay;
3. Total number of vehicles stopped;
4. Average delay per vehicle;
5. Average delay per vehicle stopped;
6. Percent of vehicles stopped;
7. Total green time;
8. Number of complete cycles;
9. Average green time per cycle; and
10. Average cycle length.

The first six items were calculated for the sum of all approaches as well. The seventh and ninth items were characteristic of a given direction, and the eighth and tenth were characteristic of the intersection control. Attempts were made to calculate other relationships such as the vehicle-seconds of delay due to left turns, the total number of

TYPICAL CALCULATIONS FOR A 15-MINUTE PERIOD

WOODROW AND KOENIG JULY 25, 1967 0715 TO 0915 FULL ACTUATED

TIME PERIOD 800 - 815

COMPUTED INFORMATION	APPROACH A	APPROACH B	APPROACH C	APPROACH D
TRAFFIC VOLUME	97.00	77.00	28.00	84.00
TOTAL VEH-SECS OF DELAY	578.88	544.32	220.32	612.00
VEH-SECS OF DELAY DUE TO LEFT TURNS	4.32	7.20	18.72	8.64
TOTAL NO OF VEHS STOPPED	40.00	49.00	14.00	44.00
TOTAL NO OF STOPS	43.00	51.00	18.00	47.00
AVERAGE DELAY PER VEHICLE STOPPED	14.47	11.11	15.74	13.91
AVERAGE DELAY PER VEHICLE	5.97	7.07	7.87	7.29
AVERAGE DELAY TO THE FIRST VEHICLE	15.16	14.47	14.94	14.23
PERCENTAGE OF VEHICLES STOPPED	41.24	63.64	50.00	52.38
TOTAL GREEN TIME	406.08	485.28	410.40	485.28
AVERAGE GREEN TIME PER CYCLE	17.10	19.56	17.16	19.56
NUMBER OF CYCLES	24.00	24.00	24.00	24.00
AVERAGE LENGTH OF CYCLE	36.96	36.84	36.90	36.84
TOTAL X TIME	0.	0.	0.	0.

TOTAL TRAFFIC VOLUME	286.00
TOTAL VEH-SECS OF DELAY ALL APP.	1955.52
TOTAL NUMBER OF VEHS STOPPED ALL APP.	147.00
TOTAL NUMBER OF STOPS ALL APP.	159.00
AVERAGE DELAY PER VEH STOPPED ALL APP.	13.30
AVERAGE DELAY PER VEHICLE ALL APP.	6.84
PERCENTAGE OF VEHICLES STOPPED ALL APP.	51.40
AVERAGE DELAY TO FIRST VEH ALL APP.	14.65

APPROACH A IS SOUTHBOUND
APPROACH B IS WESTBOUND
APPROACH C IS NORTHBOUND
APPROACH D IS EASTBOUND

Figure 1. Example of calculations.

stops, and the average delay to the first vehicle. There were, however, difficulties in calculating these values, which limited their usefulness in the analysis of intersection delay characteristics.

An example of the calculations made for a 15-min period at a typical intersection is shown in Figure 1. The 10 values previously listed are given along with one additional value, "Total X Time." This value refers to the total time in the time period during which data were missing or otherwise unusable.

The traffic volume was determined as the difference between the recorded volumes at the beginning and end of the time period under study.

Vehicle-seconds of delay were computed as the product of the sum of the indicated number of stopped vehicles for each recording interval in the time period and the length of the interval, which was either 1.44 or 3.00 sec.

When the indicated number of stopped vehicles is plotted as the ordinate versus the midpoint of each recording interval on a continuous time scale, the area under the curve is equivalent to this calculation.

The total number of vehicles stopped was determined for each approach by counting the increases in the indicated number of stopped vehicles during each red signal indication and in the first few seconds of green signal time. Here, the assumption was that an arriving vehicle was forced to stop at the rear of the queue. When an increase in the indicated number of stopped vehicles occurred during the green signal indication, it was observed in the field that this was most often due to a previously stopped vehicle waiting to make a left turn.

By addding both types of increases we get a quantity called the total number of stops. If an increase in the indicated number of stopped vehicles occurred during a green signal, the number of stopped vehicles was accumulated for each interval until a decrease was observed. The vehicle-seconds of delay due to left turns were then calculated by multiplying this accumulated number by the recording interval length.

Of course, this method of determining the number of vehicles stopped and the left-turn delay is not foolproof. A vehicle could arrive at the rear of a queue just as a vehicle departs from the front, and the indicated number of stopped vehicles would remain unchanged.

The average delay per vehicle and per vehicle stopped was calculated by dividing the total vehicle-seconds of delay by the volume and the total number of vehicles stopped respectively.

Total green time was measured by counting the number of intervals in which the green signal was displayed and multiplying by the interval length. The determination of the number of complete signal cycles was slightly more complicated. The interval at which the red signal indication first changed to green was noted. The next time that red changed to green marked the end of the first cycle. Thus, the total number of times that red changed to green during the time period under study was one more than the number of complete cycles. The average green time per complete cycle and the average length of a complete cycle were then easily computed.

The average delay to the first vehicle was calculated as the total delay to all first vehicles observed in the time period divided by the number of first vehicles observed. A first vehicle was considered observed at the first recording interval that indicated at least one stopped vehicle after the preceding recording interval had indicated no stopped vehicles, subject to the limitation that only those events taking place during a red signal indication would be counted. For each first vehicle observed, the number of recording intervals was counted, up to but not including the interval when the indicated number of stopped vehicles decreased. The total of these intervals multiplied by the interval length yielded the total delay to first vehicles. A precaution was taken so that once a first vehicle was observed, the associated decrease had to occur in the same time period. Otherwise, the observation was counted for the next time period. Those values that were applicable to the intersection as a whole were obtained by appropriate summation and subsequent calculation.

There are obvious advantages to having detailed quantitative information concerning traffic performance at an intersection. The D3 Recorder represents a first-generation attempt at providing a practical tool for obtaining such information. Even though the feasibility of developing workable equipment and analysis techniques has been demonstrated, there are some disadvantages to be considered. The principal disadvantage associated with the use of the recorder is the large number of observers required. Drivers are curious about the presence of the equipment, the people, and the wires connected to the signal controller, and this curiosity tends to result in a gaper's block in the traffic stream. A sign reading "Traffic Survey" placed on the recorder was quite effective in minimizing this phenomenon. The other major disadvantage in the recorder was the result of its being constructed before sophisticated electronic switching components were readily available. The recorder can now be designed to fit into a small suitcase and weigh less than 50 lb by using solid-state devices that are commercially available.

STUDY SITES

All of the sites selected for study were located in Austin, Texas, except for one intersection in San Antonio and a special before-and-after study of a diamond interchange on the Gulf Freeway in Houston. A total of 19 intersections were selected at which 124 individual studies, consisting of approximately 240 hours of observed data, were performed.

Except for the diamond interchange, all the intersections had four approaches and were essentially right-angle crossings. The sites were generally situated in suburban areas that were classified as either outlying business districts or residential fringe areas. Parking was prohibited on all approaches in virtually all instances, and sight distances were generally adequate. The volume of pedestrian and truck traffic at each intersection location was negligible.

Every effort was made to select intersections that had similar geometric proportions and that included several in each control type category. It was also desired that each intersection be isolated so that the delay characteristics of the type of control were measured without being greatly influenced by nearby similarly controlled intersections; however, this was virtually impossible to do.

The number of two-way and four-way stop-sign controlled intersections in the vicinity of Austin that had appreciable traffic volumes was limited. Thus, the stop-controlled intersections included in this study cover a range of geometrical proportions and cannot be classified by a simple set of characteristics.

Only one pretimed intersection that was deemed suitable for inclusion in this research effort was found in Austin. Not one semi-actuated controlled intersection was found suitable.

However, several similar full-actuated intersections were studied. These intersections were first studied in their existing condition and then the controller settings were changed. The initial, maximum, and vehicle intervals were varied for separate studies. The controller was then made to operate as a pretimed and a semi-actuated controller, and more delay data were recorded. This made it possible to investigate the delay characteristics at an intersection operating under several different control modes.

STOP-SIGN CONTROLLED INTERSECTIONS

Three intersections in Austin (29th and Jefferson, 19th and Chicon, and 38th and Speedway) were studied under two-way stop control at various times during the day, including the morning and evening peak periods as well as a midday period. Preliminary work showed no discernible evidence that delay characteristics were affected by the time of day for the data recorded in this study.

In Figure 2, the sum of vehicle delay on the two stop-sign controlled approaches is plotted as a function of the total volume on all four approaches for 15-min intervals. It may be observed in this figure that delay increases rather gradually to a volume of about 200 to 250 vehicles per 15-min interval. At this volume, a break in the curve occurs and delay increases quite sharply with further volume increases.

Five intersections in Austin (Woodrow and Justin, North Loop and Woodrow, 19th and Chicon, 15th and Congress, and Balcones and Hancock) were studied under four-way stop-sign control, each at various times during the day.

The relationship between total delay and total volume for four-way stop control is shown in Figure 3. A direct comparison of Figures 2 and 3 illustrates the larger total delay experienced at four-way stop controlled intersections.

For a given volume on an approach, the total delay and the average delay were greatly reduced for a stop-sign controlled approach when intersection control was changed from two-way to four-way stop control. However, the total delay experienced on all intersection approaches is greater for four-way than for two-way stop control for equal intersection volumes. This, of course, is because all vehicles must stop and suffer delay under four-way stop control. Thus, a reduction in average delay experience (for the stopped vehicles) must be traded off with an increase in total delay when converting from two-way to four-way stop control.

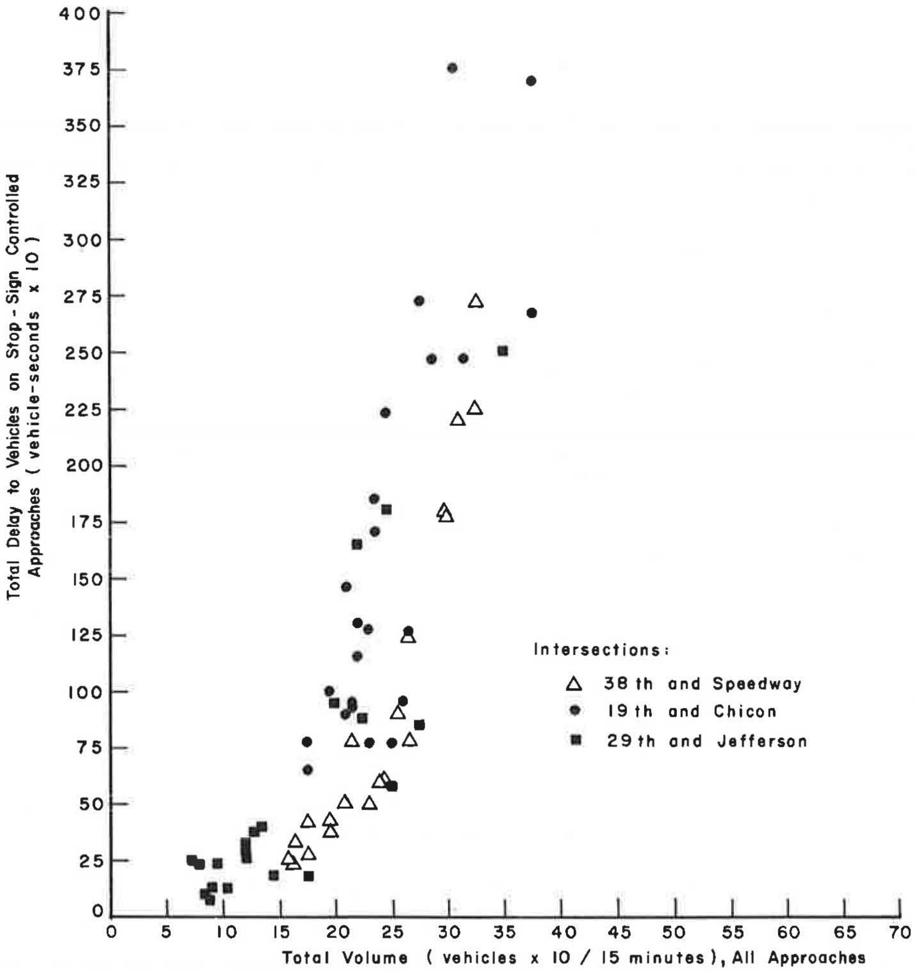

Figure 2. Total delay to vehicles on stop-sign controlled approaches versus total volume (two-way stop control, 15-min intervals).

It is important to note that in Figure 3 the plotted data were observed at five different intersections. The consistency of these data is rather marked and indicates that a strong relationship exists. A square-root transformation was made on the delay variable. A regression yielded a relationship having an R^2 of 0.984 with the following functional form:

$$y = (18.95 + 0.00044\, x^2)^2$$

where

y = the total vehicle-seconds of delay per 15-min interval and
x = the total vehicular volume per 15-min interval.

This relationship is plotted in Figure 3. A square-root transformation is often of value in working with data that are Poisson-distributed. The hypothesis of Poisson-distributed data, however, could not easily be tested.

In comparing two-way and four-way stop operation, reference to Figures 1 and 2 shows that total delay began to increase very rapidly at total volumes of from 200 to 250 vehicles per 15-min interval for two-way stops and from 250 to 300 vehicles per 15-min

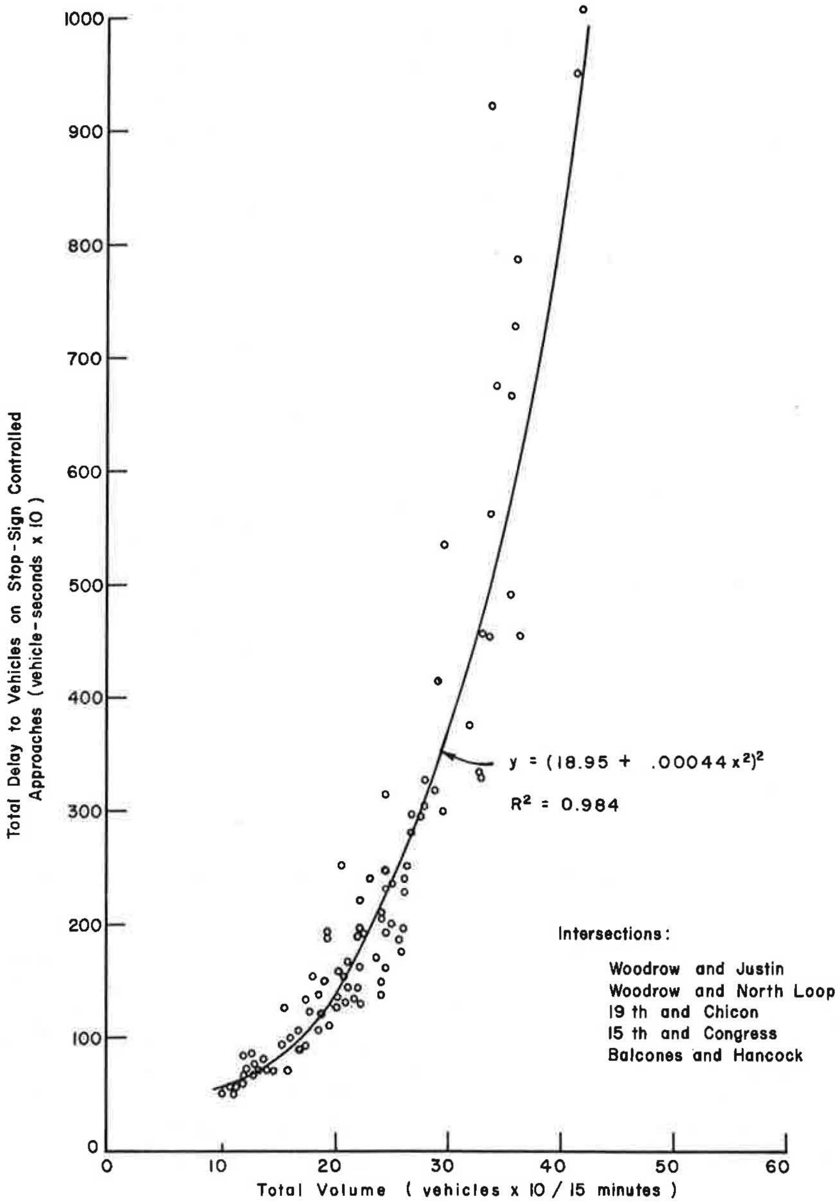

Figure 3. Total delay versus total volume (five intersections, four-way stop control, 15-min intervals).

interval for four-way stops. These 15-min volumes of 250 and 300 vehicles may be termed the critical volumes for two-way and four-way stops respectively. The corresponding critical hourly volumes are 750 and 900 as determined from analysis of the same field data on an hourly basis.

In studying the characteristics of intersections, many variables deserve consideration, including directional volumes, turning movements, approach speeds, width and number of lanes, truck and pedestrian traffic, intersection geometry, and distance to adjacent intersections, among others. In almost all cases in this study, such factors as directional volumes, lane widths, intersection geometry, and the location of adjacent intersections were measured or could be determined. Truck and pedestrian traffic was very minor and was considered to have negligible effects in most instances.

Few data on turning movements and approach speeds were available. Some manual counts of left-turn movements were kept, but these did not appear to have much influence on the delay characteristics of the intersections studied. In general, for almost all variables other than delay and volume, the range of the recorded variable was so limited that its significance, if any, was masked. The geometric layout of each intersection studied under stop-sign control will show differences in geometry, but these seemingly did not influence delay characteristics.

It is of particular importance to recognize that no conclusion is drawn regarding the irrelevance of these variables to delay characteristics other than in the limited range to which the variables were confined in the studies reported. Additional studies designed especially to measure the influence of these variables must be carried out if the variables are to be understood thoroughly.

WARRANTS FOR FOUR-WAY STOP

The generally accepted warrants pertaining to the installation of stop signs, yield signs, and the various types of signals are published in the Manual on Uniform Traffic Control Devices (1). The purpose of these signs and signals is to assign right-of-way to traffic on the approaches to an intersection where conditions of hazard exist such that uncontrolled intersection operation is not feasible and the normal rule, "the vehicle on the right has the right-of-way," cannot be applied safely or efficiently.

The normal hierarchy of control devices, with respect to both cost and effectiveness, is probably the following: yield sign; two-way stop sign; four-way stop sign; and the several signal configurations, including pretimed, semi-actuated, full-actuated, and volume-density devices.

In general, a yield sign is employed for special intersection configurations such as channelized right-turn lanes, intersections with a divided highway, or ramp entrances with inadequate or no acceleration lanes. Yield signs should also be considered applicable at intersections where stop signs are warranted but visibility and speed conditions are such that a full stop is not necessary for safety.

Stop signs may be warranted at almost any intersection of a minor road with a main road or an intersection of two main roads, at an unsignalized intersection in a signalized area, and at railroad crossings. However, stop signs are warranted at any intersection where hazard or accident history indicates a need for stop-sign control. Generally, the two opposing minor-stream flows are stopped while the larger, major-stream flows are not stopped. Under certain conditions, all four approach flows must stop. This necessitates four-way stop control, for which the Manual (1) lists more specific warrants, as opposed to the general policy outlined for yield and two-way stop control.

A four-way stop may be used as a temporary measure at an intersection to be signalized and at an intersection with turning and right-angle accidents accumulating to at least five within a 12-month period. In addition, certain minimum traffic volumes are established:

1. The total, all-approach vehicular volume must average at least 500 vehicles per hour for any 8 hours of an average day.
2. The combined vehicular and pedestrian volume from the minor approaches must average at least 200 units per hour for the same 8 hours with an average delay of 30 sec per vehicle or more for the minor-street traffic during the maximum hour.
3. The volume warrants are reduced to 70 percent of those previously given when the 85th percentile approach speed of major-street traffic exceeds 40 mph.

The Manual suggests, among several qualifications regarding the installation of stop signs, that a four-way stop not be used where the traffic volumes on the intersecting streets are very unequal. If the volumes are heavy enough to warrant additional controls in this instance, a signal installation might be preferable.

The results of the study reported here show that the total delay experienced at four-way stop intersections is virtually unaffected by traffic splits ranging from 50/50 to about

80/20 (Fig. 3) at total intersection volumes up to about 1,400 vehicles per hour for 4 by 4 intersections and up to about 1,100 vehicles per hour for 2 by 2 intersections. Furthermore, the data give no indication of any influence on delay due to the traffic split when analyzed on an approach basis. These were the greatest hourly volumes observed at these intersection types in this study. Of course, this does not imply that the delay experience at these volumes is satisfactory.

Therefore, it is suggested that when the installation of a four-way stop sign is under consideration, the traffic split should not be a factor in making the decision. At larger volumes at which the traffic split might be a factor, a signal installation, rather than a four-way stop installation, should be given consideration.

The results of this study show that the total delay is greater at four-way stops than at two-way stops for a given total volume throughout the range of total volumes observed. Thus, a warrant for four-way stops should be designed to limit the average delay experience rather than the total delay experience.

The warrants given in the Manual set two main conditions: first, to impose a minimum average volume over an 8-hour period and, second, to impose a minimum deviation from the maximum-hour volume such that an average delay to stopped vehicles of at least 30 sec is experienced during the maximum hour. This means that at least 4, and possibly 5 or 6, of the 8 hours will have volumes under 500 vehicles per hour, but the highest hour must have between 900 and 1,000 vehicles per hour.

It would seem more realistic to set a limit on average delay and to work backwards to establish a set of volume warrants. The numbers of hours to be used in computing an average volume must be selected first. As stated previously, 4 to 6 of the 8 hours would have volumes under 500 vehicles per hour, which is below the critical volume of 750 vehicles per hour as mentioned previously in this paper for two-way stops. In establishing a new warrant, it was decided to use 4 hours. Both of the 2-hour periods would probably center around each of the morning and afternoon peak periods.

The following procedure was used in establishing the warrants:

1. A range for tolerable average delay was selected. Analysis of the data shown in Figure 2 yields average delays to stopped vehicles of 20, 30, and 35 sec per vehicle for 15-min total intersection volumes of 220, 285, and 320 respectively. These average delays are characteristic of through-to-stopped-vehicle ratios of about 80/20 to 60/40. Average delays are lower for ratios outside this range.

2. A range for peak-hour factor was selected. A peak-hour factor was necessary to convert the 15-min volume of step 1 to a maximum-hour volume. Three ranges of peak-hour factors were used—0.75 to 0.80, 0.80 to 0.85, and 0.85 to 0.90:

$$\text{PHF} = \frac{\text{Peak-Hour Volume}}{4\ (\text{Peak 15-Min Volume})}$$

3. A peak-period factor was selected. This factor was used to convert the maximum-hour volume of step 2 to the average hourly volume observed during the 2-hour peak period. The peak-period factor is similar to the well-known peak-hour factor and is calculated in the following manner:

$$\text{PPF} = \frac{\text{Sum of Volumes for Four Peak Hours}}{\text{4 times Maximum-Hour Volume}}$$

or

$$\text{PPF} = \frac{\text{Average Hourly Volume}}{\text{Maximum-Hour Volume}}$$

Thus, the average hourly volume for the 4-hour period is the product of the maximum-hour volume and the peak-period factor. Four peak-period factors that were representative of the observed data from this study were used in this analysis: 0.60, 0.70, 0.80, and 0.90.

The application of this procedure resulted in the establishment of the minimum volume warrants for four-way stop signs (Table 1). It is the province of the engineer in charge to decide on the average delay and peaking factors to be used in each specific case. However, it is recommended that (a) the peaking factors be based on field observations (or local experience), (b) an average delay of 30 sec per stopped vehicle be used, and (c) the maximum average intersection volume permitted for two-way stop operation be set within the range of 750 to 800 vehicles per hour. It is also recommended that, when the 85th percentile speed on the major street exceeds 40 mph, the warrants should be reduced to 70 percent of the values in Table 1.

TABLE 1

VOLUME WARRANTS FOR FOUR-WAY STOP-SIGN INSTALLATION

Peak-Period Factor	Minimum 4-Hour Average Intersection Volumes for Average Delays of		
	20 sec	30 sec	35 sec
Peak-Hour Factor = 0.75-0.80			
0.60	400	525	600
0.70	475	625	700
0.80	550	700	800
0.90	625	800	900
Peak-Hour Factor = 0.80-0.85			
0.60	425	550	625
0.70	500	650	750
0.80	575	750	850
0.90	650	850	950
Peak-Hour Factor = 0.85-0.90			
0.60	450	600	675
0.70	550	700	800
0.80	625	800	900
0.90	700	900	1,000

Notes: 1. An average delay of 30 sec per stopped vehicle is recommended for general use.
2. Intersection volumes are all-approach totals.
3. Major-minor flow ratios from 80/20 to 60/40 are included.
4. Maximum hourly volume for two-way operation is 800 vehicles per hour (4-hour average).
5. Peak-period factor equals the average hourly volume for 4 hours divided by the maximum hourly volume.

SIGNALIZED INTERSECTIONS

Traffic signals are used to assign the right-of-way alternately to vehicles or queues of vehicles passing through an intersection. For maximum efficiency, the signals should be timed so that (a) the total delay to all traffic using the intersection is minimized, (b) no individual vehicle experiences excessive delay, and (c) the average delay per vehicle is tolerable for the circumstances.

Studies of stopped-time delay at eight isolated signalized intersections, which were operated under pretimed, semi-actuated, and full-actuated control, indicated that traffic-actuated control generally resulted in less delay than pretimed control for the range of conditions observed. Apportioning of the green time was found to have a pronounced effect on delay for pretimed control. Semi-actuated control was most effective at locations where less than about 40 percent of the total traffic was consistently carried on the street equipped for detection of vehicles. Full-actuated control resulted in less delay than the two other types when the total traffic was split approximately 50/50 on the two streets or where short-time demands fluctuated on various approaches during the day.

Warrants for actuated traffic signals, which are described in the following section of this paper, were evaluated and found to provide good guidelines for selecting actuated equipment for locations where traffic volumes do not warrant pretimed signals. Delay studies at three locations that met the suggested warrants for actuated control, but not for pretimed control, showed that actuated control consistently resulted in less delay than pretimed equipment up to total volumes of about 450 vehicles per 15 min.

Studies of the effect of dial settings of actuated signal controllers on delay indicated that these settings were not extremely critical over the rather limited ranges considered to be practicable. If long loop-type detectors (40 to 80 ft long) or other suitable vehicle presence detectors that have become available since these studies were conducted are used, problems associated with detector placement, initial intervals, and vehicle intervals are virtually eliminated. Very precise controller response can be achieved by setting initial and vehicle intervals to minimum values.

An economic analysis of a representative intersection showed that the higher equipment, maintenance, and operating costs of actuated control could be easily compensated for in less than 2 years by the lower stopping, idling, and time costs that would accrue to road users from the more efficient traffic control.

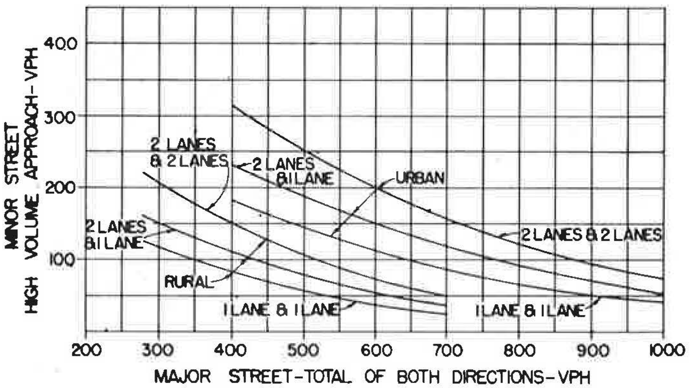

Figure 4. Warrant volumes for traffic-actuated signals, 8 high hours.

ACTUATED SIGNAL WARRANTS

A set of vehicular volume curves has been developed and used by the Texas Highway Department as a guideline in determining whether the installation of a traffic-actuated signal is justified. Volume warrants for each of (a) any 8 high hours, (b) any 4 high hours, (c) any 2 high hours, and (d) any high hour, which are shown in Figures 4 through 7 respectively, were developed as a means of analyzing the vehicular volumes, cross traffic, and peak-hour volume warrant factors for traffic-actuated signals given in the 1961 edition of the Manual on Uniform Traffic Control Devices (1). Whenever the major-street (total of both approaches) and minor-street high-approach (one direction only) volumes for each of the hours being tested rise above the applicable curve for the warrant condition, the possible installation of a traffic-actuated signal may be considered further. Although the high-volume approach on the minor street may change from hour to hour, the major-street and minor-street volumes for the same hours must be applied. The rural curves are applicable when the 85th percentile speed along the major street exceeds 40 mph or when the intersection lies within an isolated community of less than 10,000 population. The urban curves are applicable for all other conditions.

The traffic signal warrant curves for each of any 8 high hours shown in Figure 4 are based on a combined application of the volumes of pretimed traffic signal warrants 1, 2, and 6 in the Manual (1) together with a capacity curve developed by D. E. Dyas (2) for uncontrolled intersections. It may be noted that when the traffic volumes given in the

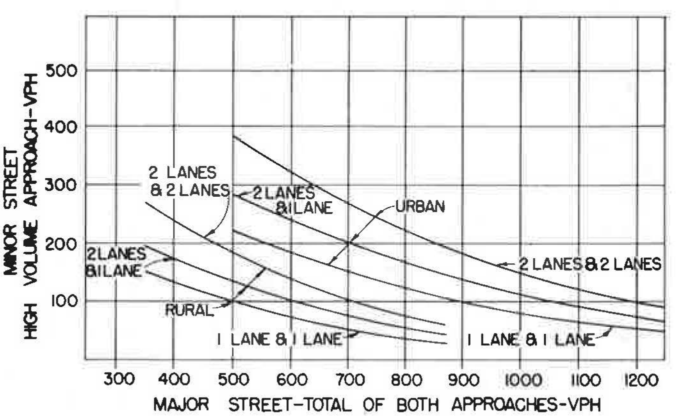

Figure 5. Warrant volumes for traffic-actuated signals, 4 high hours.

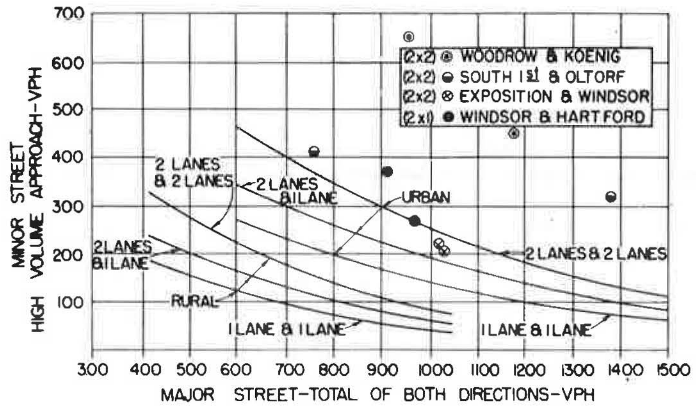

Figure 6. Warrant volumes for traffic-actuated signals, 2 high hours.

referenced warrants 1, 2, and 6 are plotted in Figure 4, the volumes fall very close to the applicable curve.

The curves shown in Figures 5, 6, and 7 represent 1.25, 1.50, and 1.75 times the volumes that comprise the curves given in Figure 4. The 1.25 and 1.50 factors are based on a traffic study conducted by the Texas Highway Department in which it was found from the vehicular volumes at 20 permanent traffic counting stations that the average hourly volume of the 8 high hours and the highest hourly volume of an average weekday were respectively 25 percent and 50 percent more than that of the 8th high hour. It was concluded that, if an intersection has traffic volumes during each of 4 high hours falling on or above a curve representing 1.25 times the volumes (Fig. 5) of those of the applicable 8 high hours curve (Fig. 4), a traffic signal could be considered further. If the traffic volumes are high during only 2 hours of a day, however, the volumes for both hours should be sufficient to fall on or above a curve having 1.50 times the volumes (Fig. 6) of the applicable 8 high hours curve. It was also concluded that if the traffic volumes are unusually high during only 1 hour of the day, these volumes should fall on or above a curve representing 1.75 times the volumes (Fig. 7) of the applicable 8 high hours curve.

The hourly traffic volumes for four study intersections having traffic-actuated signals were used in an evaluation of the curves shown in Figures 4 through 7. The results of the study show that, although none of the four intersections had sufficient traffic to meet the pretimed signal warrants set forth in the Manual, the volumes at all four intersections satisfy at least one of the urban warrants, and one intersection—South First at

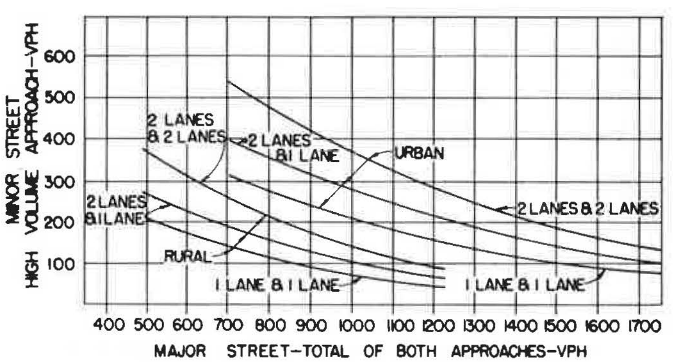

Figure 7. Warrant volumes for traffic-actuated signals, 1 high hour.

Oltorf—satisfies all four. As an example, the traffic volumes for the 2 high hours of the traffic counts for each of the four study intersections are plotted in Figure 6. As shown, three of the four intersections have sufficient volumes during 2 hours of the day to exceed the applicable warrant curve. The intersection of Exposition Boulevard and Windsor Road did not meet the warrant requirements for 4 hours. The traffic volumes at this intersection were sufficient, however, to meet the applicable warrant curve requirements for 4 high hours (Fig. 5).

SPECIAL STUDIES

The practical feasilibity of using multichannel digital recording equipment in the field for comparative delay studies was demonstrated. The recording and data analysis techniques that were developed are useful for many types of before-and-after evaluation studies. Minor modifications to the observation and analysis techniques will make it possible to use equipment similar to the D3 Recorder for studying traffic phenomena such as headways, gaps, arrival patterns, and intersection capacity.

MODERNIZED EQUIPMENT

Recent spectacular advancements in electronic instrumentation have rendered the electromechanical hardware, but not the concept, of the digital data delay recorder obsolete. Development of a new instrument system with the same basic capabilities as the D3 Recorder is recommended. It is now possible to have a portable unit the size of a small suitcase with all the features needed to conduct field traffic studies at the most complex intersections. This unit would overcome most of the limitations such as bulk, scanning rate, and complex operation associated with the D3 Recorder.

TRAFFIC SIMULATION

Computer simulation of traffic flow at intersections is potentially a powerful tool for studying intersection efficiency, but up to now very little adequate field data have been available for validating simulation models. Data collected in the traffic studies described in this report include extensive amounts of several types of information needed for verifying such models. Some of the recorded or computer information is directly applicable; other relationships can be deduced.

It is recommended that serious consideration be given to developing computer simulation models that can be used to evaluate traffic flow at isolated intersections and on street networks. Once properly verified models are available, wide ranges of traffic patterns, intersection configurations, and control techniques can be evaluated rapidly and conveniently without resorting to cut-and-try field techniques. Delay recording equipment can be used to establish quantitative information concerning realistic ranges of parameters to be evaluated by simulation.

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REFERENCES

1. Manual on Uniform Traffic Control Devices for Streets and Highways. U. S. Bureau of Public Roads, June 1961.
2. Dyas, D. E. Traffic Engineering and the Highway Engineer. Traffic Engineering and Control. Vol. 5, No. 3, July 1963, pp. 171-175.