Effect of Signal Timing on Traffic Flow and Crashes at Signalized Intersections

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ABSTRACT

The relationship of the timing of traffic signal clearance intervals (yellow phase plus red light in all directions) to traffic flow and crash rates at signalized intersections was examined. Specially designed traffic data-logging devices provided information on the presence and speed of vehicles and the signal timing for 91 signalized intersections throughout the United States. Results showed that intersections with more adequate clearance intervals had substantially fewer rear-end and right-angle crashes than those with less adequate clearance intervals. The observed flow of traffic through the intersections after the onset of yellow was largely unaffected by variation in the lengths of clearance intervals; thus the proportion of drivers exposed to cross-street traffic decreased as the clearance interval lengths increased. Ideally, clearance intervals should be long enough to allow slower traffic approaching the intersection to cross before the cross-street traffic starts. However, for the intersections examined in this study, the group with the highest average crash rate also had the slowest average crossing speed, the widest cross streets, and the shortest and least adequate clearance intervals. Crash increases associated with deficient clearance intervals may be caused by abrupt stops by drivers who are reluctant to traverse wide cross streets with traffic waiting to start up or by vehicles unable to clear the intersection under cross-street red-light protection.

The timing of traffic signal clearance intervals can affect crash rates at signalized intersections. The clearance interval is the period that covers both the yellow signal phase and any subsequent time during which signals for all approaches are red. When clearance intervals are not properly timed, some drivers may be forced to choose between abruptly stopping or loosing the cross-street red-light protection while crossing the intersection. Abrupt stopping can cause rear-end crashes and the loss of cross-street red-light protection can cause right-angle crashes. Loss of cross-street red-light protection occurs because some drivers who do not stop after the onset of the yellow light will clear the intersection only after the cross-street red light ends and the cross-street traffic begins to move into the intersection. These drivers are at increased risk of a collision with cross-street traffic. The proportion of drivers exposed to this risk depends on the proportion of drivers who do not stop and the proportion among them who do not clear the intersection before the cross-street light turns green.

A method for setting the clearance interval to minimize the number of drivers who can neither stop safely nor clear the intersection before the onset of the red light was published by Gazis et al. in 1960 (1). Their work suggests that the proportion of drivers at risk of a crash can be reduced to zero for drivers traveling at similar speeds, with similar perception and reaction times and similar deceleration rates.

The 1982 edition of the Transportation and Traffic Engineering Handbook (2) recommends the use of 10 ft/sec^2 as the threshold value for the deceleration rate in Gazis' timing formula. The higher value of 15 ft/sec^2 contained in the previous edition of the Handbook was reduced because research had shown the higher value to be incompatible with observed driver behavior; that is, drivers typically would not brake hard to stop after the onset of yellow (3-7). Repeated observations of driver response to the onset of yellow demonstrated that less than 10 to 20 percent of all drivers are either able or willing to decelerate at rates in excess of 15 ft/sec^2. The 10 ft/sec^2 threshold allows cars to brake more slowly and results in a longer clearance interval. Studies have also shown that only about 10 to 20 percent of all drivers will disregard the yellow signal and continue through the intersection when deceleration rates less than 10 ft/sec^2 would have been sufficient for stopping. Moreover, lengthening the clearance intervals was not found to increase the percentage of drivers who disregard the yellow light (7).

A 1980 survey of intersections in the southeast reported that about one-half had clearance intervals shorter than those calculated by using the too-high 15-ft/sec^2 deceleration rate recommended by the Handbook at the time of the survey (5). The survey also found that almost none of the intersections were adequately timed compared with intersections in which clearance intervals were based on the more recently recommended lower deceleration rate of 10 ft/sec^2.

Although driver response to the onset of yellow has been extensively researched, the effect on the rate of intersection crashes caused by departures from the recommended signal timing practice has not been systematically assessed. The measurement of this effect was the principal goal of the present study. The other goal was to model driver response to yellow signal light changes at intersections. The results of an investigation of crashes at 91 intersections from eight metropolitan areas throughout the United States are reported herein.

STUDY APPROACH

Data were obtained on police-reported crashes during 1979 and 1980 and on the average daily traffic (ADT) volumes through the intersecting streets for the 91 intersections studied. The physical layouts of the intersections were recorded, and specially designed devices for logging traffic data were used to monitor signal changes, vehicle speeds, and the times vehicles passed a point on the far side of the intersections.

Preliminary data analysis identified six variables related to traffic flow and crash rates at intersections: cross-street width, estimated average crossing time, indirect measures of yellow signal timing, indirect measures of the yellow and all-red phases of signal timing, the ADT for the monitored street, and its ratio to the cross-street ADT. These variables were used jointly to sort the intersections into eight relatively homogeneous clusters through the standard statistical procedure of cluster analysis. The variation in crash rates between the intersection clusters proved to be statistically significant at the conventional 0.05 level. The eight intersection clusters were then ranked on crash rates in an ascending sequence, and neighboring clusters with nonsignificant crash rate differences were merged into five overlapping intersection cluster groups to smooth out the variations in the other variables.

The average values of more than 30 intersection variables were determined for each of the five intersection cluster groups. These variables included nine crash rates based on alternative definitions, descriptions of the physical layout, and signal timing as well as traffic flow measures both just before and just after the onset of yellow. These measures were analyzed, and factors associated with variations in clearance interval lengths, driver responses to the onset of yellow, and crash rates were identified.

DATA COLLECTION

Traffic Data Logging System

Traffic data were collected at the far side of intersections by using the traffic data logging system developed by PRC Voorhees (8). This system includes an arrangement of Leupold-Stevens steel-jacketed coaxial cables and cable transducers for the detection of vehicles and the traffic data logger (TDL) unit for the processing and storing of the signals received from both the cable transducers and the traffic signal power lines.

A typical cable arrangement is shown in Figure 1. Cables C1 and C2 are approximately 3 ft apart and span the width of the street for one direction of traffic. The other two cables, CR and CC, are laid directly adjacent to C2 and only halfway into lanes 1 and 2, respectively. When a wheel crosses a cable, the cable transducer produces a pulse that is recorded by the TDL.

The TDL consists of an internal clock, a microprocessor, and a cassette tape recorder. The TDL was designed to encode and record the time and the source cable for every cable actuation by the number of vehicle axles. For example, a two-axle vehicle traveling in lane 2 would produce six actuations: Both wheels on the first and on the second axle would actuate C1, C2, and CC (but not CR). Thus the record for this vehicle would contain six events (e.g., two actuations for each of the three cables).

The TDL also monitored the power lines to the traffic signal through four separate input channels. The status of the traffic signal was recorded at each cable actuation. Signal phase changes and their times of occurrence were also encoded as independent events.

The actuation data were processed first to represent axles and then to simulate vehicles. Axles were accounted for by matching corresponding actuations of cables C1 and C2. Axle speeds were calculated by dividing the known C1 to C2 distance by the elapsed crossing time, and axle lane position was determined from the actuation pattern of the cables.

Axles were then combined to represent vehicles by an algorithm on the basis of matching lane position and speed criteria and the relative distances between the axles. Subroutines were developed to sort out the records for special cases such as those that were caused by the axle configurations of large trucks or by a vehicle occupying two lanes. Unmatched, isolated axles were retained as single-axle vehicles. Experience with the TDL system indicated that single-axle records resulted when one of the axles of a two-axle vehicle was incorrectly identified from its actuations. Traffic signal timing was also decoded.

The TDL system and the associated software were tested at two sites, one in Richmond, Virginia, and one in Miami, Florida (see Table 1). About 95 percent of all vehicles noted by human observers were detected by the system, and more than three-quarters of those detected were correctly identified. The mean speed, as measured by hand-held radar guns, was 7 percent greater than the mean speed obtained by the TDL system at the Richmond site and 1 percent less than that obtained by the TDL system at the Miami site.

Intersections

The traffic flow and crash results reported in this paper were based on data collected at 91 intersections during 1980 and 1981. Data were collected both during the day and at night, but only the daytime (6:00 a.m. to 8:00 p.m.) traffic observations and crashes were used in this report. An observation period ranged from 1.5 hr to almost a complete day.

Intersections were selected from eight jurisdictions located in different regions of the United States: Chicago, Illinois; Denver, Colorado; Miami, Florida; Montgomery County, Maryland; Richmond, Virginia; San Diego, California; San Jose, California; and White Plains, New York. A summary of the test locations and the applicable yellow signal traffic laws is given in Table 2. The jurisdictions were chosen on the basis of their willingness to cooperate in the study, availability of crash data, and availability of PRC Voorhees personnel. The intersections chosen represent a wide range of intersection parameters, including

1. Average approach speed (35 to 55 mph),
2. Cross-street width (20 to 124 ft),
3. Yellow phase (2.8 to 5.7 sec), and
4. All-red phase (0 to 3.0 sec).

Intersections located within some of the jurisdictions often were similar in one or more design and signal timing characteristics. For example, almost all of the Denver intersections had a 3-sec yellow phase followed by a 2-sec red phase and did not have any left-turn signal phases. All-red phases

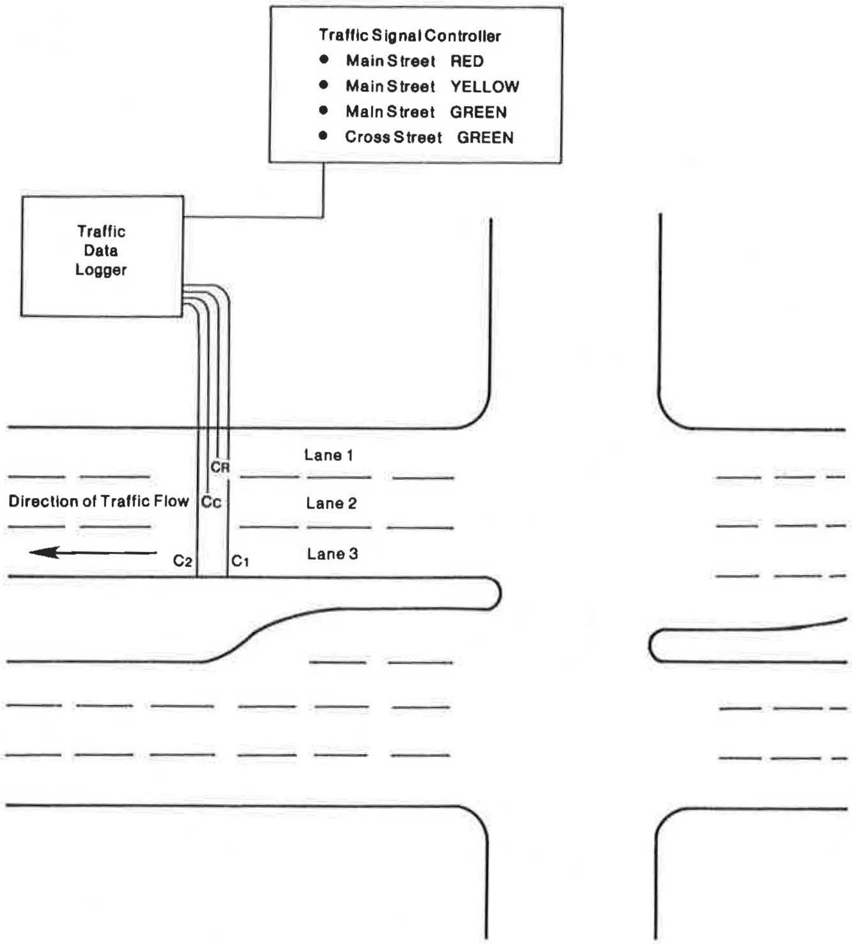


FIGURE 1 Schematic illustration of TDL installation.

were not present or were very short (less than 0.5 sec) at the San Jose sites. Intersections in Richmond, San Diego, and San Jose were typically complex with many independent activated phases. In Miami many of the intersections had permissive left-turn phasing.

Crash Data

Police-reported data were used to identify the intersection crashes during 1979 and 1980 that involved two vehicles. Crashes in which both of the vehicles traveled on the monitored street were grouped together; crashes in which one of the two vehicles traveled on the monitored street and the other on the cross street were placed in a second group. Crashes not fitting either group were not analyzed in the present paper. The shared-approach street crashes of the first group were mostly rear-end crashes. The cross-street crashes of the second group were mostly right-angle crashes.

TABLE 1 Traffic Data Logging System Validation Tests

Test Conditions	Richmond, Virginia	Miami, Florida
No. of lanes	2	3
ADT	23,108	20,000
Speed limit (mph)	45	55
Intersection width (ft)	33	40
Timing (sec)		
Yellow	3.5	5.0
All-red	1.5	1.0
Mean radar speed (mph)	39.6	43.6
Mean TDL speed (mph)	37.2	43.9
TDL performance		
Vehicle detected		
Percent	94	96
No.	312	200
Correctly identified		
Percent	73	81
No.	293	192

DATA ANALYSIS

Six variables, chosen after extensive preliminary analyses of the data, were used for grouping the intersections on the basis of their similarities and

TABLE 2 Intersection Locations and Yellow Signal Laws

Jurisdiction	No. of Intersections	Yellow Signal Law[a]
Chicago, Illinois	2	Stop on yellow
Denver, Colorado	16	Enter on yellow
Miami, Florida	13	Enter on yellow
Montgomery County, Maryland	10	Enter on yellow
Richmond, Virginia	15	Stop on yellow
San Diego, California	11	Enter on yellow
San Jose, California	21	Enter on yellow
White Plains, New York	3	Enter on yellow

[a]The laws were categorized as either allowing an approaching motorist to enter the intersections during yellow or requiring that motorists stop before the intersection if they can safely do so.

differences. The variables were cross-street width (ft), average crossing time (sec), the reciprocal of the braking deceleration rate implied by the yellow phase [DECEL(Y)] (sec^2/ft), the reciprocal of the braking deceleration rate implied by the yellow plus the all-red phase [DECEL(Y+AR)] (sec^2/ft), the ADT on the monitored street (MADT), and its ratio to the cross-street ADT (ADT Ratio).

DECEL(Y) was computed by algebraically solving the Gazis timing formula (1) for the deceleration rate with the observed yellow phase as the clearance interval, and DECEL(Y+AR) was computed the same way from a combination of the yellow and all-red phases. That is, DECEL(Y+AR) = V/{(Y+AR) - t - [(W+L)/V]} in terms of the notation used in the Handbook (2). For some intersections, the yellow phase was so short that it was not sufficient for a vehicle to clear the intersection even if it entered at the beginning of the phase. Thus the estimated value for the deceleration rate based on yellow alone became negative. The resulting numerical instability in the estimate for the deceleration rate would have rendered averages based on it also unstable. The use of the reciprocal deceleration rate circumvented this problem.

A standard cluster analysis package [Ward's algorithm with the STD option (9)] was used to sort intersection data on the six variables into eight disjoint intersection clusters. It was found that cluster membership accounted for about 75 percent of the total intersection variance (R^2 = 0.75) for the six variables.

The rate of crashes per ADT on the monitored street (MADT in 10,000s) was adjusted in proportion to the inverse of the cycle length to allow for the resulting variation in the proportion of vehicles that encountered the onset of a yellow light. The formula used included the average cycle length (about 72 sec) as a scale factor:

ACR = 10,000 x (72/Cycle length)
x (Frequency of shared-approach and cross-street crashes/MADT).

Statistical variability in the adjusted crash rate (ACR) was stabilized by taking square roots, and the variation in $(ACR)^{1/2}$ among the intersection clusters was tested by means of analysis of variance. The relationship between cluster membership and the crash-rate measure [$(ACR)^{1/2}$] was statistically significant ($F_{7,83}$ = 4.36, $p < 0.001$).

The eight disjoint intersection clusters were then ranked according to crash rate estimates in ascending order. Neighboring clusters with crash rates that were similar except for statistical fluctuations were identified by using the Waller-Duncan multiple range test (SAS Institute, 1982), and the intersections in clusters with similar average crash rates were pooled. This procedure yielded five partially overlapping groups of intersections. The first and second groups, for example, included intersection clusters 1 to 4 and 2 to 5, respectively, and overlapped in clusters 2 to 4, but the fifth group included clusters 6 to 8 and overlapped with neither the first nor the second group.

Intersections that were included in cluster groups that did not have significantly different mean adjusted crash rates were pooled. The descriptive statistics for these five groups--labeled A thorough E--are given in Table 3.

As the data in Table 3 indicate, the averages of many of the variables increased or decreased steadily across the five intersection cluster groups. This pattern of variation was further investigated by linearly regressing the variable averages on an index called the relative rank of the intersection cluster group. (By definition, the value of the relative rank increased steadily from cluster group A to cluster group E approximately in proportion to

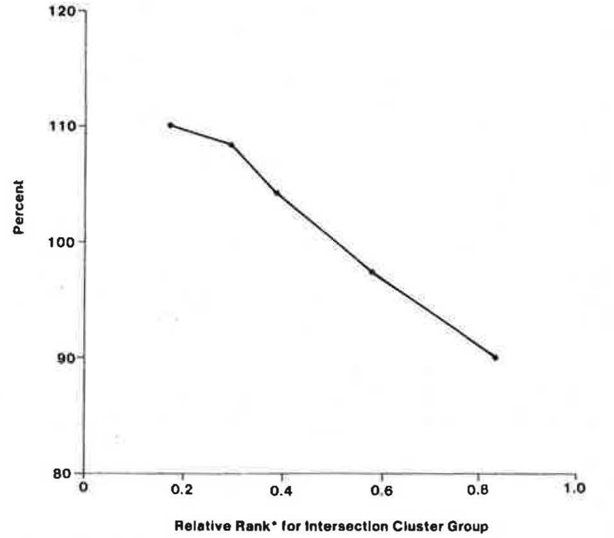
TABLE 3 Intersection Averages for Characteristics by Cluster Group

	Cluster Group Average					Regression on Relative Rank		
Variable[a]	A	B	C	D	E	R^2	Constant	Slope
$(ACR)^{1/2}$	0.92	1.11	1.26	1.53	1.84	1.00	0.70	1.40
$(SACR)^{1/2}$	0.54	0.68	0.78	0.96	1.21	1.00	0.38	1.00
$(CACR)^{1/2}$	0.59	0.71	0.81	1.01	1.18	0.99	0.45	0.91
$(ACR1)^{1/2}$	1.25	1.23	1.23	1.47	1.52	0.84	1.11	0.51
$(SACR1)^{1/2}$	0.79	0.78	0.76	0.89	0.92	0.77	0.71	0.24
$(CACR1)^{1/2}$	0.73	0.76	0.79	0.99	1.03	0.91	0.63	0.51
SCR	1.50	2.18	2.29	2.34	2.73	0.80	1.50	1.55
CCR	1.31	1.84	1.90	2.24	2.24	0.78	1.32	1.30
$(SCR+CCR)^{1/2}$	1.34	1.71	1.80	1.94	2.05	0.83	1.33	0.95
R clearance (sec)	4.76	4.73	4.91	4.96	5.23	0.91	4.58	0.74
Yellow (sec)	4.07	3.73	3.72	3.70	3.88	0.07	3.89	-0.16
All-red (sec)	1.16	1.39	1.37	1.11	0.81	0.60	1.49	-0.70
Clearance ratio	1.10	1.08	1.04	0.97	0.90	0.99	1.16	-0.32
Yellow ratio	0.85	0.79	0.76	0.75	0.74	0.67	0.84	-0.14
All-red ratio	0.24	0.29	0.28	0.22	0.16	0.66	0.32	-0.17
Green phase (sec)	43.3	46.7	45.0	39.7	31.3	0.79	50.8	-21.0
Red phase (sec)	24.5	26.2	36.4	37.0	51.2	0.92	16.9	39.8
Cycle length (sec)	73.0	78.0	86.5	81.6	87.2	0.61	73.1	17.9
DECEL(Y) (sec^2/ft)	0.074	0.062	0.052	0.050	0.042	0.86	0.077	-0.044
DECEL(Y+AR) (sec^2/ft)	0.117	0.115	0.105	0.094	0.076	0.98	0.13	-0.064
F(Y)	1.99	1.53	1.28	1.30	1.18	0.67	1.92	-1.02
F(Y+AR)	2.96	2.72	2.36	2.30	1.89	0.94	3.15	-1.54
RF(Y+AR)	2.74	2.50	2.30	2.47	2.35	0.43	2.67	-0.43
FDIFF	-0.22	-0.22	-0.07	0.17	0.46	0.97	-0.48	1.11
Approach speed (ft/sec)	55.2	53.8	52.4	51.7	48.8	0.97	56.6	-9.2
ADT ratio	4.7	3.1	2.7	2.4	1.3	0.88	4.8	-4.4
Cross street ADT (000s)	8.1	11.7	15.5	14.9	19.4	0.86	6.9	15.3
Monitored street ADT (000s)	21.1	25.3	25.0	21.2	16.6	0.50	26.3	-9.7
Cross-street width (ft)	38.1	39.4	48.7	52.3	67.7	0.95	28.7	45.0
Crossing time (sec)	0.70	0.74	0.98	1.05	1.45	0.95	0.46	1.14
Presence of left-turn lane (%)	12	22	20	19	10	0.16	0.20	-0.08
Relative rank	0.17	0.30	0.39	0.58	0.83	1.00	0.00	1.00

[a] Variable names are explained in text.

the number of intersections included in clusters with lower crash rates.) The relative ranks of the five intersection cluster groups were calculated as follows. First, the intersection clusters were ranked in ascending order from 1 to 8 according to average crash rate. Second, the intersections in the first cluster group were numbered from 1 to 5, those in the second from 6 to 10, those in the third from 11 to 18, and so on until all 91 intersections were numbered. Finally, these numbers were averaged for the intersections in the cluster group and divided by 91 to obtain the relative rank of each.

Because cluster membership accounted for 75 percent of the total intersection variance, and because the cluster groups were formed by pooling clusters with similar crash rates so that crash rate variation within cluster groups was reduced by construction, these linear regressions are likely to give a fairly complete account of all crash-rate-related variation among the intersections. However, because there was considerable overlap among adjacent cluster groups, the R^2 values may overstate the extent to which the relative ranks are linearly related to the other variables. The last three columns in Table 3 present the intercept, slope, and R^2 values for these regressions.



* The relative rank of an intersection cluster group was set to the weighted average of the ranks of the clusters in that group. The individual clusters were initially ranked in ascending order by their crash rates.

FIGURE 2 Average clearance interval as a percentage of recommended value by intersection cluster group.

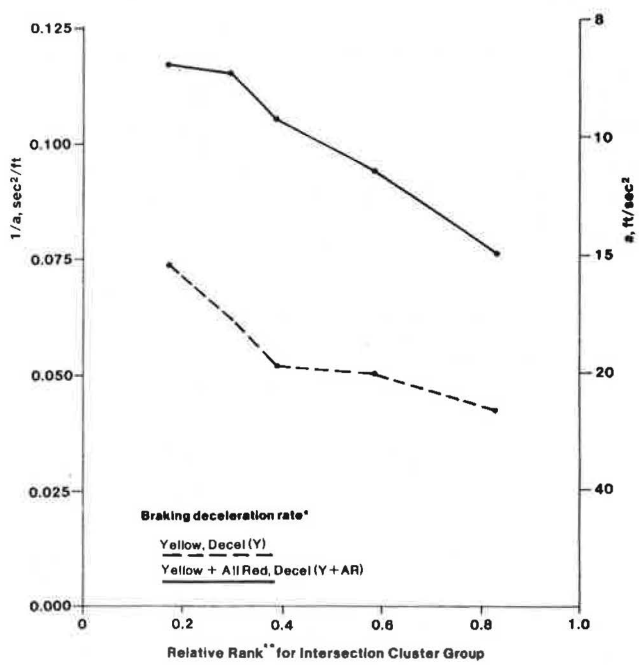
Clearance Interval Averages by Intersection Cluster Groups

Recommended clearance intervals (R clearance in Table 3) were computed for all intersections by using the timing formula with the recommended value of 10 ft/sec^2 for the deceleration rate. In Figure 2 the combined lengths of the observed yellow plus all-red phases were converted to percentages of the recommended clearance intervals (the clearance ratio), averaged within intersection cluster groups, and plotted against the relative ranks for the intersection cluster groups. As Figure 2 shows, these clearance ratios declined steadily across the cluster groups (R^2 = 0.99) from 110 to 90 percent, which indicates that cluster groups with higher relative ranks had less adequate clearance intervals than those with lower relative ranks. The clearance ratios based on the average duration of the yellow phase also declined steadily, from 85 to 74 percent of the total recommended clearance interval, across the intersection cluster groups (R^2 = 0.67).

The relative importance of the monitored streets was measured as the average of the ratio of the ADT on the monitored streets divided by the ADT on the cross streets. The ADT ratio steadily decreased with increasing relative ranks from about 4.2 to about 1.3 (R^2 = 0.88). The data also indicate that relatively more important streets have larger clearance ratios and conversely, relatively less important streets had smaller clearance ratios. Interestingly, the crossing time (vehicle approach speed divided by cross-street width) increased as the clearance interval became shorter. At the opposite extreme, the average monitored street ADT exceeded the average cross-street ADT by the largest amount for the intersection cluster group with clearance intervals closest to the recommended intervals.

Braking Deceleration Rates by Intersection Cluster Groups

The braking deceleration rates implied by the observed lengths of the yellow and combined yellow plus all-red phases were calculated by solving the timing formula algebraically (see Data Analysis section). This solution provides the rate of deceleration that allows a driver traveling at the average intersection speed to either clear the intersection during the yellow phase or stop without entering the intersection. The reciprocals of these rates were averaged within cluster groups; these averages [DECEL(Y) and DECEL(Y+AR)] were plotted against the intersection cluster group relative ranks in Figure 3. As the figure shows, DECEL(Y+AR)



* Recommended clearance interval timing formula was solved in terms of its braking deceleration factor (see text).

** The relative rank of an intersection cluster group was set to the weighted average of the ranks of the clusters in that group. The individual clusters were initially ranked in ascending order by their crash rates.

FIGURE 3 Averages of one over the braking deceleration rates (1/a) implied by the yellow phase and the clearance interval by intersection cluster group.

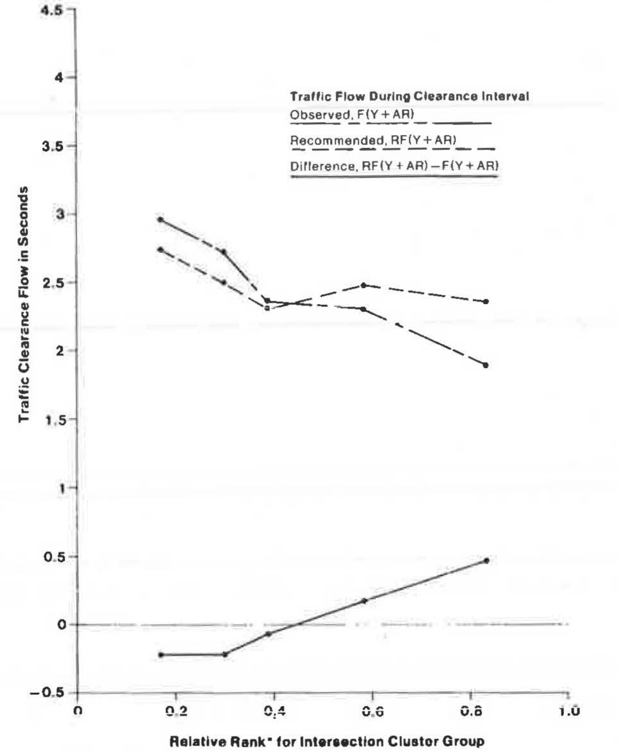
declined steadily between the intersection cluster groups with the lowest and highest relative ranks (R^2 = 0.98). This change in DECEL(Y+AR) corresponds to an increase in the implied braking deceleration rate [1/DECEL(Y+AR)] from 8.5 to 13.2 ft/sec². When only the yellow phase is considered, the comparable increase in the braking deceleration rates [1/DECEL(Y)] was from 13.5 to 23.8 ft/sec²--all higher than the currently recommended rate of 10 ft/sec². These results show that at the intersections in cluster groups with high relative ranks, drivers were expected to decelerate at higher rates than at the intersections in cluster groups with low relative ranks.

Average Traffic Flow After Onset of Yellow by Intersection Cluster Group

For each intersection, a base flow rate of vehicles was defined as the average number of vehicles per second that cleared the intersection during 4-sec periods just before the onset of yellow. To assess the response of traffic to the onset of yellow, the average number of vehicles that entered the intersection after the onset of yellow and cleared it during the yellow plus all-red phases was divided by the base flow rate. This ratio, called the total clearance flow [F(Y+AR)], would be proportional to the length of the clearance interval if no vehicles responded to the onset of yellow by stopping. More realistically, the total clearance flow was expected to increase with the length of the clearance interval and to decrease with the proportion of vehicles that stop in response to the onset of yellow.

As the plot of F(Y+AR) against relative ranks of intersection cluster groups in Figure 4 shows, the total clearance flow steadily decreases from about 3 sec for the intersection cluster group with the lowest relative rank to about 1.9 sec for the group with the highest relative rank (R^2 = 0.94). For intersections in the lowest relative rank cluster group, the average number of vehicles that entered the intersection after the onset of yellow and cleared during the clearance interval was about the same as the average number of vehicles that cleared it during the 3 sec just before the onset of yellow. The comparable figure for the highest relative rank cluster group was 1.9 sec. This result shows that as the clearance ratio decreased (see Figure 2), the clearance flow also decreased. If this clearance flow decrease was caused by increased stopping, then the volume of traffic that could have stopped, but did not, at the recommended deceleration rate would also have had to decrease by comparable amounts.

The recommended clearance interval (R clearance) was calculated for each intersection by using the timing formula with a = 10 ft/sec². The total clearance flow that corresponds to these standard clearance intervals [RF(Y+AR)] was determined from R clearance in the same way as F(Y+AR) was from the observed clearance intervals. As the plot of RF(Y+AR) in Figure 4 shows, the decrease from 2.7 to 2.4 sec was only about one-third of the comparable decrease in the total clearance flow [F(Y+AR)]. The difference between these quantities [FDIFF = RF(Y+AR) - F(Y+AR)] measures the volume of the flow (in seconds) that failed to clear the intersection during the clearance interval but could have stopped at the recommended 10 ft/sec² deceleration. This difference increased steadily with increasing intersection cluster group relative ranks (R^2 = 0.97), which indicates that as the relative lengths of the clearance intervals decreased (see Figure 2), the volume of traffic that failed to clear the intersections during the clearance intervals increased.



* The relative rank of an intersection cluster group was set to the weighted average of the ranks of the clusters in that group. The individual clusters were initially ranked in ascending order by their crash rates.

FIGURE 4 Average traffic clearance flow after the onset of yellow during observed and recommended clearance intervals in multiples of flow rate at time of the onset of yellow by intersection cluster group.

These results suggest that despite variation in the lengths of clearance intervals, driver response to the yellow signal was largely unaffected; consequently, the proportion of drivers who crossed the intersections without protection from cross-street traffic increased when clearance intervals were too short. The slight increase in the flow of traffic traveling during the time period that corresponds to the recommended interval at intersections with deficient or too short clearance intervals may reflect, in part, increased stopping by drivers faced with short clearance intervals and, in part, the enhanced likelihood of drivers responding to a yellow signal of any duration when approaching a cross street with heavy traffic.

Average Crash Rates by Intersection Cluster Groups

The number of police-reported daytime crashes involving two or more vehicles during 1979 and 1980 was divided by the ADT on the monitored street (MADT in 10,000s) and adjusted for cycle frequency per unit of time (see Data Analysis section). The square root of the resulting crash rate [$(ACR)^{1/2}$] was averaged within each intersection cluster group and plotted against the average of the intersection clearance ratios in Figure 5. As the figure shows, $(ACR)^{1/2}$ increased linearly with the clearance ratios, and the highest value of $(ACR)^{1/2}$ was about twice as large as its lowest value. Thus a difference of approximately 20 percent in the ratio of observed to recommended clearance intervals coincided with a difference of a factor of 4 in the ACR.

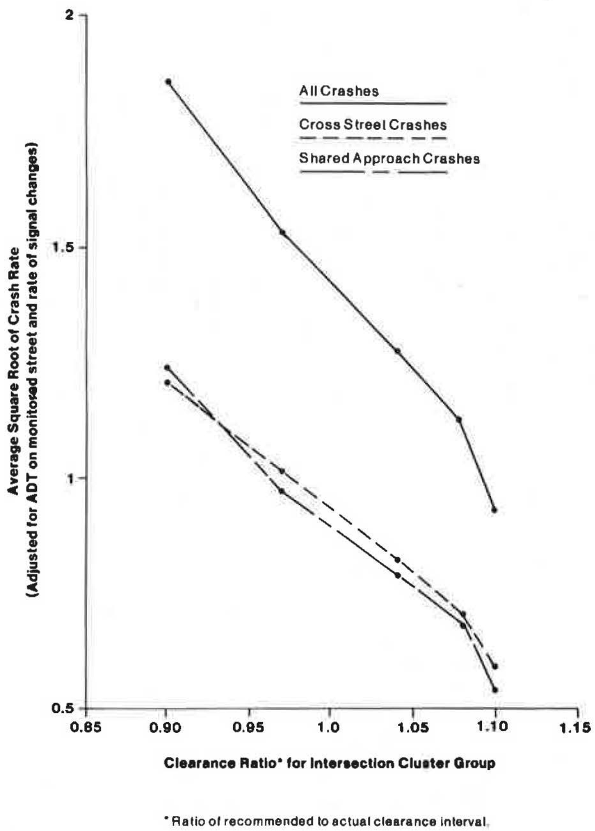


FIGURE 5 Average square root of crash rates by crash type and intersection cluster group.

Similar calculations based on shared-approach crashes alone produced nearly identical results for the adjusted rate of shared-approach crashes (SACR). For cross-street crashes (CACR) that involved one vehicle from the monitored approach and one from the cross street, the results were also nearly identical to those already described.

The sensitivity of these results to the manner of crash rate definition was also explored. Regardless of the manner in which the crash rate was calculated, intersection cluster groups with the least adequate clearance intervals had higher crash rates than those with longer clearance intervals. Even without adjusting for cycle frequencies, intersections with the least adequate clearance intervals had on average 71 percent higher cross-street crashes (CCR) and 82 percent higher shared-approach crashes (SCR) than those with the most adequate clearance intervals. The comparable difference based on the square root of their sum $[(SCR + CCR)^{1/2}]$ was 134 percent.

To allow for the effect of variation in cross-street traffic, the ACR was divided by the cross-street ADT (in 10,000s): ACR1 = 10,000 ACR/ADT. In terms of ACR1, the crash rate of intersection cluster groups with the least adequate clearance intervals exceeded those with the most adequate clearance intervals by about 48 percent. The comparable difference based on cross-street crashes (CACR1) was 99 percent. For shared-approach crashes (SACR1) it was 36 percent.

Miscellaneous Results

The results given in Table 3 show that the five cluster groups differ from one another in almost all respects. Specifically, the average approach speed, the ADT ratio, and the average green phase for the monitored street decreased, whereas the cross-street width, the average crossing time, the cross-street ADT, the red phase, and the complete cycle time increased with increasing relative ranks. The ADT on the monitored street first increased and then decreased.

DISCUSSION OF RESULTS

The relationships between crashes, clearance interval signal timing, and the movement of vehicles reported in this study are based on the analysis of data from 91 signalized intersections in eight metropolitan areas of the United States. Cluster analysis was used to group intersections in terms of their characteristics, the groups were ranked in order of increasing crash rates, and intersections from groups with similar crash rates were combined to form larger groups. Regardless of the manner in which the crash rate was calculated, the intersection groups with the less adequate average clearance intervals had higher average crash rates than those with more adequate average clearance intervals. The combined crash rates for shared approach (e.g., rear-end) and cross-street (e.g., right-angle) crashes differed by 130 percent across the five intersection cluster groups. When these rates were adjusted for signal cycle frequency and ADT on the monitored street, the difference from the lowest to highest crash rates rose to 300 percent. If adjustments for cross-street ADT were also made, the crash rates were still 50 percent greater for the intersections with the least adequate intervals than for those with longer intervals. The variations in crash rates among the cluster groups were associated with specific clearance interval timing, traffic flow, and intersection characteristics.

Crash rates increased as the adequacy of the clearance intervals, based on currently recommended procedures, decreased. The clearance interval durations for the five cluster groups ranged from 10 percent shorter than recommended to 10 percent longer. The crash rate for the group with the least adequate clearance intervals was higher than for the group with the most adequate intervals.

Although the duration of clearance intervals varied across cluster groups, the traffic flow during the clearance interval was largely unaffected. However, clearance interval duration did affect the proportion of drivers who cleared the intersection. The number of drivers who did not clear the intersection during the clearance interval, although they could have stopped at the recommended maximum deceleration rate of 10 ft/sec^2, sharply increased for the intersection groups with the least adequate clearance intervals. Thus, although the traffic flow was similar, the proportion of drivers exposed to cross-street traffic increased and crash rates also increased as the adequacy of the clearance interval decreased.

The ADT on the monitored approach street declined in comparison to the ADT on the cross street as crash rates increased among the cluster groups. As the importance of the monitored street declined, the cross streets were also wider and the monitored traffic slower. These differences resulted in the monitored vehicles requiring increased crossing time to traverse the intersection. If the clearance intervals for these intersections had been calculated on the basis of current recommendations, they would have had longer clearance intervals. These intersections should have had the longest clearance intervals of the intersections studied, whereas they actually had the shortest.

The interpretation of these data by the authors of the overall pattern of association between intersection characteristics, clearance intervals, traffic flow, and crash rates is that the increasing deficiency of clearance interval timing increased the proportion of drivers who would have to stop more quickly than they were accustomed to stopping to avoid entering the intersection without cross-street red protection. However, most drivers cannot or do not stop at high deceleration rates, so that the proportion of drivers who enter intersections and do not clear them during the clearance interval increases sharply. The reduced separation of the two traffic streams and the forced increases in braking lead to substantial increases in crashes.

The most important implication of these results for the practicing traffic engineer is that because drivers cannot be effectively stopped by law from entering intersections after the onset of yellow, it is necessary to time intersections so as to allow a driver who is already in the intersection to clear it before the start-up of the cross-street traffic. Use of the long formula given in the Transportation and Traffic Engineering Handbook (2), with necessary adjustments for the actual path of clearing vehicles, stopline placement, frequency of trucks, and presence of grades, will normally achieve this goal. However, the present analysis was not designed to determine either the optimal signal timing rules or the optimal split between the yellow and all-red phases.

In a recent paper Parsonson and Santiago (5) reviewed a liability suit in which the city of Flint, Michigan, was held responsible for the wrongful death of a driver who died in a crash when his car was hit by a truck at an intersection with an inadequate yellow phase and no all-red phase. The authors of that paper warned the traffic engineering profession that "the traditional design standards for the timing of the clearance period (yellow plus all-red) for traffic signals are inappropriate and unreasonable in some important aspects. They can yield values that are too short for safety...." The authors then recommended improved design procedures "which the engineer would feel more comfortable defending in court."

It has been shown in this paper that even the currently accepted standards are commonly ignored and that clearance intervals that are too short are statistically associated with larger-than-average crash rates. These results and the Flint case should serve to further underline the need to adopt improved clearance interval timing procedures throughout the United States.

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