Clearance Interval at Traffic Signals

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This research was a pilot study to identify promising modifications of amber period duration, transverse pavement markings, and supplemental advanced signing that gave evidence of improvements of safe operations at signalized intersections. The dilemma zone problem for minimum amber periods was extensively researched. It was found that increasing the amber phase at an urban location from 3 to 5 seconds increased the percentage of motorists operating in an unsafe or unexpected manner. Increasing the amber phase at the rural location from 5 to 7 seconds decreased the percentage of motorists operating in an unsafe or unexpected manner. However, it was found that the installation of experimental transverse pavement markings at the urban location slightly decreased the percentages of motorists operating in an unsafe or unexpected manner. Also, the installation of experimental transverse pavement markings at the rural location increased the percentage of motorists operating in an unsafe or unexpected manner.

•THE purpose of this study was to conduct a pilot investigation of traffic behavior as related to the amber period at traffic signals, and of possible modifications in amber period duration, advance signing, and additional pavement markings. The first part reviews current practice and discusses theoretical analysis. The second part is concerned with experimental field studies and includes the design of experiment and field work, film analysis, data processing and data reduction, and experimental field study results.[1]

CURRENT PRACTICE

Amber Law

To determine the prevalent practice regarding the amber clearance interval, a questionnaire (Fig. 1) was sent to 50 state highway departments, 32 major cities outside California, and 17 California cities. Of the 49 other states responding, 14 have laws similar to California's law that permits vehicles to legally enter the intersection during the amber period. On the other hand, 27 states have adopted laws requiring vehicular traffic to have completely cleared the intersection before the end of the amber phase. The remaining 8 states follow a law that falls in between the two extremes. A typical wording is: "Traffic facing the yellow signal shall stop before entering the nearest crosswalk at the intersection, but if such stop cannot be made in safety, a vehicle may be driven cautiously through the intersection." Table 1 outlines the three groups.

The applicable section of the Uniform Vehicle Code of the National Committee on Uniform Traffic Laws and Ordinances has been changed recently to allow vehicles to enter an intersection at any time prior to the termination of the amber phase. To compare, the 1956 edition states in Sec. 11-202-b-1: "Vehicular traffic facing the (yellow)

[1]The original manuscript contains a literature search, a list of references and an annotated bibliography which are not reproduced herein. This information is available from the Highway Research Board at cost of handling and reproduction. Refer to XS-12, Highway Research Record 221, 33 pp.

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CLEARANCE INTERVAL

CURRENT PRACTICE QUESTIONNAIRE

Please complete both sides, using space on other side for explanations, and return to: University of California, Institute of Transportation and Traffic Engineering, 1301 South 46th Street, Richmond, California 94804.

I. WHAT IS THE INTERPRETATION OF YOUR APPLICABLE LAW REGARDING THE AMBER PHASE?

A vehicle must either stop before entering the intersection or must clear the intersection before the end of the amber phase.

A vehicle must either stop before entering the intersection or must have entered the intersection before the end of the amber phase.

Other. (please specify on other side)

II. DO YOU BELIEVE THE CLEARANCE INTERVAL (LENGTH OF AMBER) TO BE A PROBLEM?

No.

Yes. If so, why?
- Safety
- Capacity
- Other. (please specify)

III. WHAT IS THE PREVALENT PRACTICE, REGARDING THE AMBER PHASE, IN YOUR CITY OR STATE?

Fixed amber time as a function of traffic conditions and/or location. e.g., 5 seconds for rural conditions and 3 seconds for urban conditions. Please specify.

secs. (urban)

secs. (rural)

Amber time based on approach speed. Please include graphs, equations, or explanation.

Additional phasing such as:
- Green-amber phase
- All-red phase.
- Flashing green phase.
- Other. (please specify)

Other. (please explain)

IV. AT PRESENT DO YOU HAVE ANY SIGNALIZED INTERSECTIONS WITH SPECIAL PHASING SUCH AS: (PLEASE INDICATE APPROXIMATE NUMBER AFTER DESCRIPTION)

Flashing green phase preceding amber phase. ______(approx. number)

Green-amber phase preceding amber phase. ______(approx. number)

All-red phase. ______(approx. number)

Numerical countdown or other display device. ______(number) (please explain)

Other. (please explain)

V. HAVE YOU MADE ANY STUDIES OF THE CLEARANCE INTERVAL PROBLEM?

Yes.

Study now in progress.

No.

VI. IF THE ANSWER TO V IS YES, IS INFORMATION FROM THE STUDY AVAILABLE?

Information enclosed.

Information will be forwarded by separate mail.

Information may be found in ______(name of article and date of publication).

No.

VII. WOULD YOU BE INTERESTED IN OBTAINING A COPY OF THE FINAL REPORT OF THIS PILOT STUDY?

Yes. No.

Please use the space below for explanations or further comments. Please attach an extra sheet if necessary. Thank you for your cooperation.

Figure 1. Current practice questionnaire.

TABLE 1

CURRENT PRACTICE CRITERIA

City-County	Law	Problems	Prevalent Practice	Special Phasing—No. of Intersections	Studies Made
			(a) Cities and Counties		
Outside California					
Albuquerque	—[a]	Safety	$T = 3$ to 4.1 sec, $T = f(V_0, W)$; all-red phase used infrequently	All-red phase, 4 to 5 intersections	No
Amarillo	—[a]	None	Urban $T = 2.7$ to 3.6 sec, Rural $T = 3.2$ to 4.0 sec; $T = f(V_0$, W, traffic type, turbulence). Some all-red	All-red phase, 4 intersections	Individual studies
Atlanta	—[a]	"Confusion"	Urban $T = 3$ sec, Rural $T = 5$ sec	All-red phase, 15-20 intersections	No
Baltimore	—[a]	Safety	Urban $T = 3$ sec, Rural $T = 5$ sec	All-red phase, 250 out of 1,038	No
Dallas	—[a]	Safety	$T = 0.8 + 0.04\,V + \frac{0.7\,W}{V}$; Urban $T = 3.5$ to 4 sec; Rural $T = 4$ to 5 sec. A few all-red	All-red phase; 15 intersections	No
Fort Worth	—[a]	None	$T = f(V_0 + W)$, all-red phase	All-red phase, 5 intersections	No
Minneapolis	—[a]	Safety and capacity	Urban $T = 3$ sec, Rural $T = f(V_0, W)$; all-red phase	All-red phase, 6 intersections	Yes
New Orleans	—[a]	Other	$T = f(V_0$, W, sight distance)	All-red phase, 6 intersections	Yes
New York	—[a]	None	$T = \Delta T + f(V_0) + 1.5$ to 2 sec of all-red "period." $T = 4$ to 5 sec	All-red "phase" (for pedestrians) 20 intersections	No
Phoenix	—[a]	None	$T = f(t, V, W)$; $T \leq 5$ sec	All-red phase, 249 out of 360 (being removed)	Yes
Pittsburgh	—[a]	Safety and capacity	$T = 3$ sec (minimum) of green-amber + 2 sec of amber	Green-amber, 575 intersections	In progress
San Antonio	—[a]	None	$T = 3$ sec for $V_0 \leq 35$ to 5 sec for $V_0 > 50$ mph	All-red phase, 10 intersections	No
In California					
Berkeley	—[a]	Safety and capacity	$T = 3$ sec min + $f(V_0, W)$	All-red phase, 3 intersections—pedestrain signals	Yes
Redding	—[a]	Safety and capacity	$T = 3$ to 5 sec	None	No
Outside California					
Akron	—[b]	Safety	Urban $T = 3$ sec; Suburban $T = 4$ sec for $V = 35$ mph; all-red for problem intersections	All-red phase, 15 intersections	No
Chicago	—[b]	None	Urban $T = 3.25$ sec, Suburban T up to 5 sec; all-red phase	All-red 80, a few green-yellow and red-yellow	No
Cincinnati	—[b]	None	$T = 3$ seconds generally	All-red phase, 290 intersections	No
Cleveland	—[b]	None	Urban $T = 3$ sec, Rural $T = 5$ sec if speed limit ≥ 50 mph	All-red phase at wide intersection; 35 intersections	No
Denver	—[b]	None	$T = 3 + \frac{V - 30}{10} + \frac{W - 50}{10}$; $V = 30, 40, 50\ldots$ mph; $W = 50, 60, 70\ldots$ ft; all red	All-red phase, 24 out of 937 intersections	In progress
Kansas City, Mo.	—[b]	Safety if T is short	$T = f(V_0, W, t)$; $T = 3.5$ to 5 sec	All-red phase, 10 intersections	No
Norfolk	—[b]	Safety and capacity	$T = 3$ to 5 sec, $T = f(V_0, W)$	All-red phase, 6 intersections	—
Rochester, N.Y.	—[b]	None	$T = 3$ to 4 sec	All-red phase, 10 intersections	No
St. Louis	—[b]	Safety	$T = f(V_0, W)$; $T = 2.5$ to 5.3 sec	All-red phase, 5 intersections	—
St. Paul	—[b]	Other	$T = 3.5$ to 4 sec	All-red phase, 6 intersections	No
Tempe, Ariz.	—[b]	Safety	Urban $T = 4$ sec, Rural $T = 6$ sec; $T = f(V_0)$	All-red phase, 7 intersections	Yes
In California					
Anaheim	—[b]	Safety and capacity	$T = 3$ to 4.5 sec for $V = 20$ to 60 mph	None	Yes
Burbank	—[b]	Safety and capacity	$T = 3$ sec (longer T for two locations); all-red phase	All-red phase, 10 intersections	Yes
Hayward	—[b]	Safety	Urban $T = 3$ sec, Suburban $T = 4$ sec	All-red phase, 1 intersection	No
Long Beach	—[b]	Safety and capacity	$T = 3$ to 4 sec; flashing green phase	All-red phase, 1 intersection	No
Los Angeles	—[b]	None	$T = f(V_0, W)$; $T = 3$ to 4.2 sec	All-red 20; "slot clearance" 100	No
Modesto	—[b]	None	$T = 4$ to 4.5 sec	None	No
Oakland	—[b]	None	Urban $T = 3$ sec; all-red and delayed red	All-red phase, 55 intersections	No
Riverside	—[b]	Safety	$T = 3$ to 4.5 sec (1 sec/10 mph); all-red phase	All-red phase, 6 intersections	No
Sacramento	—[b]	Safety and capacity	$T = 3$ sec min, $T = f(V_0)$	All-red period for wide intersections	No
San Diego	—[b]	Safety—citations	$T = f(V_0, W)$; few all-red for wide intersections	All-red phase, 3 intersections	Yes
San Francisco	—[b]	Safety	Usually $T = 3$ sec; $T > 3$ for wide intersections	None	No
San Jose	—[b]	Safety	Urban $T = 5$ sec, Rural $T = 3$ sec, $T = f(V_0$, W, accidents); all-red	All-red phase, 6 intersections	Yes—signal observance studies
Outside California					
Boston	—[c]	Safety and capacity	Urban $T = 3$ sec, Rural $T = 3$ sec; all-red	All-red phase, 70 intersections	No
Detroit	—[c]	Safety	All-red phase	All-red phase, 70 intersections	No
Milwaukee	—[c]	Safety—other	$T = 3.5$ sec min + all-red period	All-red phase, 575 intersections	In progress
Omaha	—[c]	Safety	$T = f(V_0)$; $T = 3.0$ sec for $V_0 = 25$ mph to 4.8 sec for $V_0 \geq 40$ mph	All-red phase, 2 intersections	No
Philadelphia	—[c]	Safety	$T = 3$ to 5 sec, $T = f(V_0, W)$	All-red phase, 50 intersections	No
Portland, Ore.	—[c]	Safety and capacity	Downtown: $T = 2.25$ sec + 1.35 sec all-red. Other: $T = 3 + 1.2$ sec all-red. $V > 40$ mph; $T = 4$ to 5 sec + 1 to 2 sec all-red	All-red, 550 intersections	Yes
Washington, D.C.	—[b]	Safety	Urban $T = 3.6$ to 4.2 sec; all-red phase	All-red phase, 120 intersections	In progress
Cook County, Ill.	—[c]	Safety and capacity	$T = 3$ sec both Urban and Rural		No
Louisville-Jefferson Co., Ky.	—[b]	Safety and capacity	Urban $T = 3$ to 4 sec, Rural $T = 4$ to 5 sec; all-red	All-red phase	
Alameda County, Calif.	—[b]	None	Urban $T = 3$ sec; Rural $T = 5$ sec	Right arrow during protected portion of other phase	No
Fresno County, Calif.	—[b]	Safety and capacity	Urban $T = 3 \pm$ sec, Rural $T = 5 \pm$ sec	None	No
Los Angelo County, Calif.	—[b]	None	Urban $T = 3$ sec, Rural $T = 3$ to 4.5 sec	All-red phase, 6 intersections	No

TABLE 1 (Continued)

State	Law	Problems	Prevalent Practice	Special Phasing— No. of Intersections	Studies Made
			(b) States		
Alabama	—[a]	None	Urban T = 3 sec, Rural T = 4 to 6 sec; all-red phase	All-red phase, 150 intersections	No
Alaska	—[a]	Safety	$T = f(V_0)$, T = 3 sec minimum up to 35 mph, to 5 sec for 50 mph	Green-amber phase, 1 intersection in Ketchikan	No
Arizona	—[a]	Safety	$T = t + \frac{V}{2d} + \frac{W + L}{V}$; all-red phase	All-red phase, 15 intersections	No
Arkansas	—[a]	Capacity	Urban T = 3 to 3 sec		No
Florida	—[a]	Safety and capacity	T = 2 sec after green arrow for left turns	All-red phase (N/A), numerical countdown, 1	No
Georgia	—[a]	Safety	Urban T = 3 sec, Rural T = 4 to 5 sec	All-red phase in 3 cities for high V_0 streets	No
Hawaii	—[a]	None	Urban T = 4 sec, Rural T = 4 sec		No
Idaho	—[a]	None	T = 3 to 5 sec; $T = f(V_0$, W, judgment)		No
Indiana	—[a]	None	Urban T = 3 sec, Rural T = 5 sec; all-red phase	All-red phase, 100 intersections	No
Iowa	—[a]	None	Urban T = 3 to 4 sec, Rural T = 5 to 7 sec	All-red phase used temporarily only at e.g., worksites	No
Louisiana	—[a]	Safety	T = 3 to 4.5 sec; all-red phase	All-red phase, 10 intersections	No
Michigan	—[a]	Safety	$T = f(V_0$, W, reaction time); all-red phase	All-red phase, 50 intersections out of 1,600	In progress
Mississippi	—[a]	None	Urban T = 3 sec, Rural T = 5 sec; all-red phase	All-red phase, 8 intersections	No
Missouri	—[a]	Safety and capacity	$T = 0.8 + 0.04\,V + \frac{0.7\,W}{V}$; all-red phase	All-red phase, 10 intersections	No
Montana	—[a]	Safety	$T = 0.8 + 0.04 + \frac{0.7\,W}{V}$; T = 3 to 5 sec; all-red phase	All-red phase, 1 intersection	No
Nebraska	—[a]	Safety	T = 3 to 5 sec; all-red phase	All-red phase, 15 intersections	No
Nevada	—[a]	None	$T = \frac{0.682}{V}$ (W, reaction and stopping distance), $3 < T < 5$ sec		No
New Hampshire	—[a]	Safety and capacity	Urban T = 4 sec, Rural T = 6 sec		No
New Mexico	—[a]	None	T = 3 to 4 sec for both Urban and Rural; all-red phase	All-red phase, 1 intersection	No
North Dakota	—[a]	None	$T = 0.8 + \frac{V}{22} + \frac{0.7\,W}{V}$; $3 \le T \le 6$ sec	All-red phase, 1 intersection	No
Rhode Island	—[a]	None	Urban T = 3 sec, Rural T = 5 sec	None	No
South Carolina	—[a]	Safety	$T = f(V_0)$	All-red phase, 20 intersections	Limited on safety
Texas	—[a]	None	$T = f(V, W) \le 5$ sec; all-red phase if $T > 5$ sec	All-red phase, number unknown	No
Utah	—[a]	None	T = 4 sec for both Urban and Rural	All-red phase, 50 intersections	No
Vermont	—[a]	Other	T = 3 to 5 sec; all-red phase, limited	All-red phase, 3 intersections (Under state jurisdiction)	No
Washington	—[a]	None	T = 3.5 sec for V_0 = 25 mph up to 5 sec for V_0 = 60 mph	All-red phase, 2 intersections	No
West Virginia	—[a]	Safety	$T = \frac{V}{10} \le 5$ sec; all-red phase	All-red phase; number not avaliable	No
Wyoming	—[a]	None	T = 3 + 1 sec for each 10 mph above 30. T = 3 to 5 sec		No
California	—[b]	Other	$T = f(V_0$, judgment)	All-red phase, 20 on very wide streets	In progress
Colorado	—[b]	Safety	T = 3 sec + 1 sec for each 10 mph above 30, $3 \le T \le 5$ sec; all-red phase	All-red, 6 intersections, yellow arrow being tried	Yellow arrow
Delaware	—[b]	Safety and capacity	Urban T = 5 sec, Rural T = 3.5 sec	All-red phase, 75 intersections	No
Illinois	—[b]	None	T = f(V, W, stopping distance)	All-red phase, 15 intersections	Limited on safety
Kansas	—[b]	Safety	$T = f(V_0$, W, traffic conditions); all-red phase (few)	All-red phase, 5 intersections	No
Kentucky	—[b]	None	$T = f(V_0)$; T = 3 sec up to 35 mph, to 5 sec at 50 mph	All-red phase, 10 intersections	No
Maine	—[b]	None	$T = f(V_0, W)$, $3 \le T \le 4$ sec; all-red phase if $T > 4$ sec	All-red phase, 10 intersections	No
Minnesota	—[b]	Safety and capacity	$T = f(V_0)$, $3 \le T \le 5$ sec; all-red phase	All-red phase, 20 intersections (rural)	No
New Jersey	—[b]	Other	$T = f(V_0)$; T = 3 sec + 1 sec for each 10 mph above 30; all-red phase	All-red phase, 800 intersections	No
North Carolina	—[b]	Safety	Urban T = 3 to 4 sec, Rural T = 3 to 5 sec; all-red phase	All-red phase, 100 intersections	No
Ohio	—[b]	None	$T = f(V_0)$; $T \le 4$ sec + all-red (1 to 3 sec); all-red phase	All-red phase, No. not available	No
Oklahoma	—[b]	None	$T = f(V_0)$; T = 3 sec for $V_0 \le 35$ mph, up to 5 sec for $V_0 \ge 45$ mph. All-red phase	All-red phase, 50 intersections	No
South Dakota	—[b]	Safety	Urban T = 3 normally	None	No
Tennessee	—[b]	Safety	Urban T = 3 sec, Rural T = 3 sec; all-red phase	All-red phase	No
Wisconsin	—[b]	Safety	T = 3 sec minimum to 6 sec maximum; all-red phase	All-red phase, 5 intersections	No
Connecticut	—[c]	Safety	$T = f(V_0$, W, accidents); $3 \le T \le 5$ sec	All-red phase, 150 intersections	No
Maryland	—[c]	None	Urban T = 3 to 4 sec, Rural T = 5 to 6 sec; all-red phase	All-red phase, 40 intersections	No
New York	—[c]	Safety	T = f(observed V_0), $3 \le T \le 5$ sec; all-red phase	All-red phase, 100 intersections	Under consideration
Oregon	—[c]	Safety	T = 4 to 8 sec, $T = f(V_0$, W, judgment)	All-red phase, 200 in Portland only	No
Pennsylvania	—[c]	Safety	T = 3 to 5 sec, $T = f(V_0, W)$; all-red phase	All-red 250, green-yellow 575 in Pittsburgh city	No
Virginia	—[c]	None	Urban T = 3 to 4 sec, Rural T = 4 to 5 sec; all-red phase	All-red phase, 10 intersections	No

Note: T = amber phase duration; t = reaction time; V_0 = approach speed; W = width of intersection.

[a]A vehicle must either stop before entering the intersection or must clear the intersection before the end of the amber phase.

[b]A vehicle must either stop before entering the intersection or must have entered the intersection before the end of the amber phase.

[c]Other.

TABLE 2

SUMMARY OF CURRENT VIEWS OF THE CLEARANCE INTERVAL PROBLEM

Responses	Law	Clearance Interval Problem						Total Responses
		No	Safety	Capacity	Safety and Capacity	Other	Subtotal	
Cities in Calif.	Permissive	5	4	0	7	1	17	17
Cities outside Calif.	Restrictive	5	3	0	2	2	12	
	Permissive	6	4	0	2	1	13	32
	Other	0	3	0	3	1	7	
States	Restrictive	14	9	1	3	1	28	
	Permissive	6	6	0	2	2	16	49
	Other	1	4	0	0	0	5	

signal is thereby warned that the red or 'stop' signal will be exhibited immediately thereafter and such vehicular traffic shall not enter or be crossing the intersection when the red or 'stop' signal is exhibited." The 1962 edition states in the same section: "Vehicular traffic facing a steady yellow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection." This change effected by the Uniform Vehicle Code has stimulated a few states to revise their law toward conformity with the recent code.

View of Clearance Interval Problem

Twelve of the 17 California city and county agencies viewed the clearance interval at traffic signals as a problem because of safety implications or the combination of safety and capacity considerations. Twenty-one out of 32 cities and counties outside California had similar views. The prevalent law regarding the amber phase, whether restrictive or permissive, does not seem to have a significant bearing on their view of the problem—61.5 percent and 54 percent respectively (Table 2). This is somewhat diff- different for the states responding. Forty-eight percent of those following a restrictive law viewed the clearance interval as a problem, compared to 62.5 percent of the states adopting a permissive law. This is somewhat contradictory to the fact that an intersection is hazardous from a safety point of view if the law adopted is restrictive and requires the traffic to clear the intersection when operating under a theoretically inadequate clearance interval. The cities appeared to consider the clearance interval more of a problem than did the states.

Prevalent Practice

The prevalent practice in California city and county agencies (as reported by 12 of the 17 agencies) was the fixed amber time (Table 3). The other 5 agencies modified the

TABLE 3

SUMMARY OF CURRENT PRACTICES CRITERIA

Responses	Law	Prevalent Practice					Special Phasing				Studies Made			Sub-total	Total Responding
		T Fixed	T = $f(V_0)$	T = $f(V_0, W)$	T = $f(V_0, W, Other)$	All-Red	All-Red	Green-Amber	Other	None	Yes	In Progress	No		
Cities in Calif.	P	12	1	4	0	3	10	0	1	6	4	0	13	17	17
Cities outside Calif.	R	3	2	4	3	5	11	1	0	0	3	1	8	12	
	P	7	2	3	1	4	13	0	0	0	1	2	10	18	32
	O	3	2	1	0	5	7	0	0	0	1	1	5	7	
States	R	14	5	6	3	13	21	1	(1)	6	1	1	26	28	
	P	5	6	2	2	10	14	0	(1)	1	1	1	13	15	49
	O	2	1	1	2	4	6	(1)	0	0	0	0	6	6	

Note: P stands for permissive law, R for restrictive law, and O for other type of law. Numbers in parentheses indicate states listed under more than one criterion. (Also see Highway Research In Progress, HRB, 1967.)

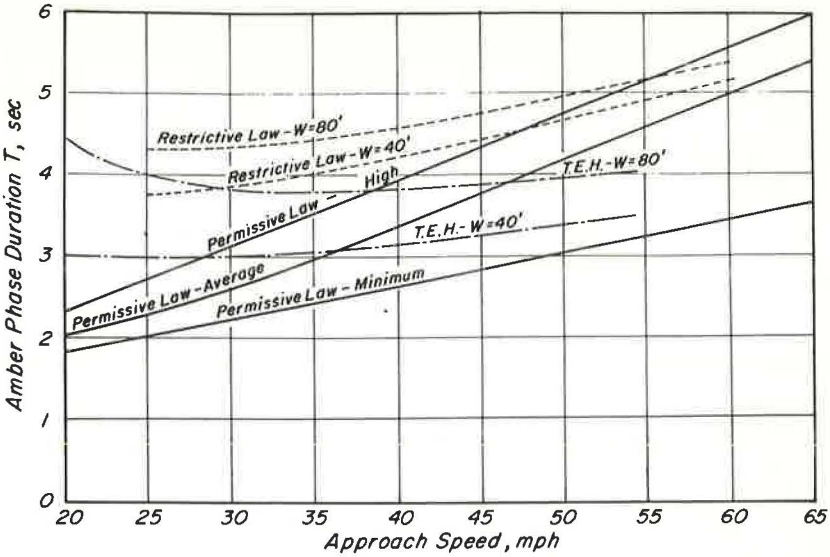

Figure 2. Comparison of amber phase duration for different practices.

amber time by considering approach speed and/or geometry. Three agencies reported the practice of using an all-red phase. Cities outside California having restrictive laws reported to have practices in conformity with that law (9 out of 12 used amber time modified according to speed, geometry and other parameters compared to 6 out of 13 agencies having permissive laws).

Of the 28 state highway departments following restrictive laws, 14 had fixed amber time. Thirteen had the all-red phase as prevalent practice, used mostly in situations where the amber time needed was excessive. The 15 states having permissive laws had a smaller percentage adopting fixed amber time and a considerably larger percentage using approach speed for modification (Table 3). Ten states employed the all-red phase at their intersections.

Most highway departments and city and county agencies limit the amber phase between 3 and 5 sec, which is in conformity with the Manual of Uniform Control Devices recommendations. Very few went below 3 sec or exceeded 6 sec where an all-red overlap was used if warranted by extraordinary geometric conditions, high approach speeds, high accident rate, or heavy turning movements. Authorities requiring vehicles to have cleared the intersection generally require longer clearance intervals and are probably unable to use the amber phase as a partial extension of the green interval and thereby increase intersection capacity. To show this, three types of practice are compared (Fig. 2). The first is the 1950 edition of the Traffic Engineers Handbook based on

$$Y = 0.8 + 0.04V + \frac{0.7D}{V}$$

where Y is the amber phase duration in sec; V, the speed in mph; and D, the intersection width. The second is Michigan's, obtained from a graph and adopted here as an example for the restrictive law practice. The third is that obtained by using

$$V_0 t_2 + \frac{V_0^2}{2d} = V_0 T + \frac{a}{2} (T - t_1)^2$$

with the following parameters (note that this equation deletes the width of intersection and thereby represents the permissive law):

Parameter	Minimum	Average	High
t_1, sec	0.40	0.85	1.20
t_2, sec	0.75	1.00	1.47
a, ft/sec^2	3.00	$13.50-0.145\ V_0$	$16-0.145\ V_0$
d, ft/sec^2	8.00	13.00	16.00

where T is the amber phase duration; V_0, the approach speed; t_1 and t_2 are the reaction times to clearing and stopping; and a, d are the acceleration and deceleration limits, respectively. The expressions (T is in sec and V_0 is in mph) resulting from these parameters are

Minimum, $T = 1.01 + 0.0397\ V_0$
Average, $T = 0.747 + 0.0585\ V_0 + 0.000166\ V_0^2$
High, $T = 0.366 + 0.0928\ V_0 - 0.000121\ V_0^2$

Special Signal Phasing

Among the special signal phasing, the all-red was predominant and is being used in varying degrees by almost all the agencies (Table 3). This phasing—a red overlap after the yellow interval—is favored mostly at accident-prone intersections where accidents of the right-angle collision type are frequent. It is also used by states that limit the length of the amber phase short of the clearance period required. This usually occurs at very wide intersections or at those exhibiting high approach speeds. The all-red interval is also favored for special traffic conditions where heavy turning movements occur, or at intersections with heavy commercial traffic. Some agencies, however, are proposing to discontinue the use of the all-red phase or have already discontinued it. The reasons include the danger of confusion when both a "pure amber" and an amber followed by all-red are being used in the same city. Also, the practice of turning left on red is in violation of certain traffic laws.

On the other hand, from a red overlap study in Portland, it was concluded that the removal of the all-red phase increased the accident rate and was unfavorable, even though intersections in the CBD showed increase in the highest average vehicles per cycle, and averaged less accidents for the test period. The study concludes justifying the red overlap.

Pittsburgh utilizes a green-amber phase of 3 to 5-sec duration before a standard amber interval of 2 sec at its 575 intersections, and has had favorable experience with it. The same phasing is used in Ketchikan, Alaska, for the only signal in the city. Florida and Abilene, Texas, are currently experimenting with numerical countdown devices.

THEORETICAL ANALYSIS

This section has two specific objectives. The first is to determine the required amber duration for a variety of conditions and as influenced by type of law. The second is to determine under what set of conditions dilemma zones would exist.

General Kinematics

A vehicle approaching a signalized intersection, when faced with the amber indication, will either have to stop or proceed to clear the intersection. In the latter case, a motorist can only accelerate when approaching the intersection at lower than the approach speed limit.

Certain relations of kinematics are important in conjunction with stopping and clearing. Curves should be smooth and with limited peaks. Speed profiles (Fig. 3) are good indications for patterns of drivers' reactions to the amber phase. Deceleration curves should have a limited peak, depending on comfort and convenience. A. D. May outlines

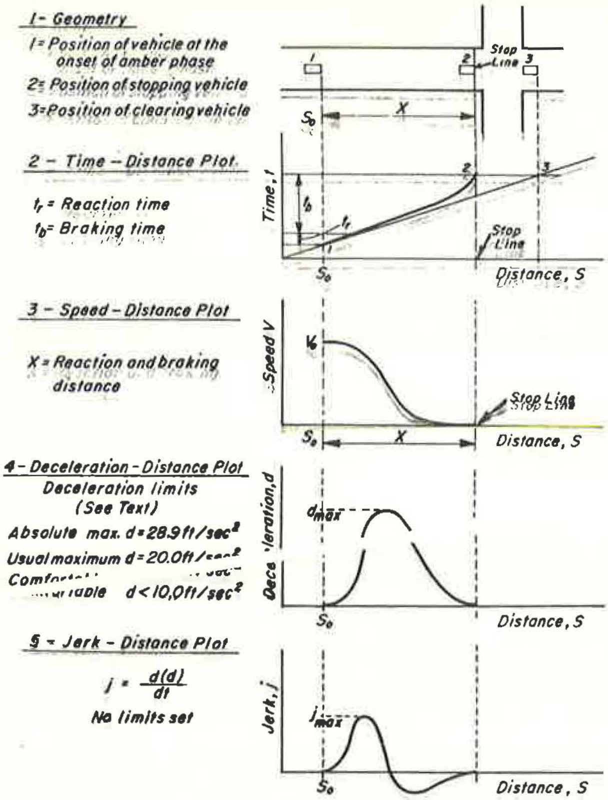

Figure 3. Intersection kinematics.

in the "Traffic Engineering Handbook" various values for acceleration and deceleration characteristics. Up to 1963, the absolute maximum deceleration under ideal conditions was 28.9 ft/sec^2 and the maximum under usual conditions was about 20 ft/sec^2. Practical values for deceleration used in everyday traffic conditions rarely exceed 8 to 9 ft/sec^2. Acceleration on the other hand has a more variant characteristic because it depends on the vehicle's power plant and the speed of travel. D. Gazis used a value of 16 - 0.145 V_0 for Detroit models, V_0 being the speed in ft/sec. No limits or values have yet been ascertained relative to the effect of time change of acceleration or deceleration (jerk in ft/sec^3).

Influence of Type of Law on Required Amber Duration

The portions of the two extreme laws pertinent to this analysis are (a) a vehicle must either stop before entering the intersection or must clear the intersection before the end of the amber phase; and (b) a vehicle must either stop before entering the intersection or must have entered the intersection before the end of the amber phase. Figure 4 shows the geometry of intersections for cases (a) and (b). Note that for the first case, both the effective width of intersection and the length of the vehicle are considered in W, whereas in the second case only the latter dimension L (or part of it) is included.

From the geometry of intersections, the following equations can be deduced as outlined by Gazis, relating stopping and clearing distances, reaction times, and approach speeds:

Case (a)

Stopping distance,

$$X_S \geq \frac{V_0^2}{2d} + V_0 t_2 \qquad \text{(a-1)}$$

Clearing distance,

$$X_C \leq V_0 T + \frac{a}{2}(T - t_1)^2 - W \qquad \text{(a-2)}$$

Case (b)

Stopping distance,

$$X_S \geq \frac{V_0^2}{2d} + V_0 t_2 \qquad \text{(b-1)}$$

Clearing distance,

$$X_C \leq V_0 T + \frac{a}{2}(T - t_1)^2 - L \qquad \text{(b-2)}$$

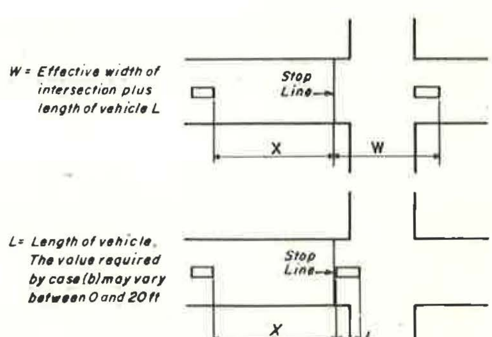

Figure 4. Geometric layouts of intersections for cases (a) and (b).

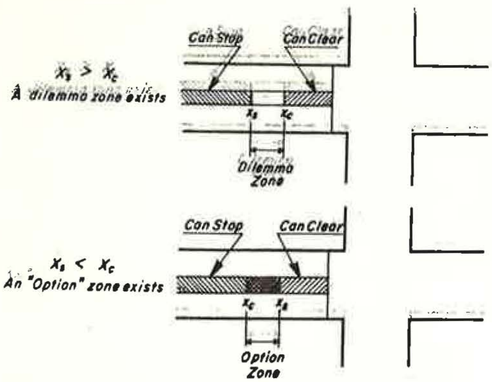

Figure 5. Schematic drawing for dilemma and option zones.

where

X_s, X_c = distance from stop line when the amber phase commences, ft;
V_0 = approach speed, ft/sec;
T = amber phase duration, sec;
L = length of vehicle, ft;
W = gross width of intersection (effective width plus length of vehicle), ft;
a = acceleration rate, ft/sec^2;
d = deceleration rate, ft/sec^2; and
t_1, t_2 = reaction times to accelerate and decelerate respectively, sec.

Three conditions can, however, exist relative to the dimensions of the stopping distance X_S and the clearing distance X_C:

Condition I

$X_S > X_C$: A dilemma zone exists within which the driver could neither stop safely nor clear the intersection (Fig. 5). This condition is more pertinent to case (a).

Condition II

$X_S = X_C$: The dilemma zone in this case is deleted.

Condition III

$X_S < X_C$: An option zone exists within which a driver can choose between stopping and clearing the intersection (Fig. 5).

In order to have a dilemma zone-free situation, the length of the amber phase can be obtained for two basic conditions.

Condition I—A vehicle is approaching the intersection at the approach speed limit. Clearance of the intersection is not accompanied by acceleration. Thus, assuming a = 0, and equating the expressions for stopping and clearing distances, the following equations result:

$$T_a = t_2 + \frac{V_0}{2d} + \frac{W}{V_0} \qquad \text{(a-3)}$$

$$T_b = t_2 + \frac{V_0}{2d} + \frac{L}{V_0} \qquad \text{(b-3)}$$

Since L can be expressed as a function of W, Eq. b-3 may be considered as a special case of Eq. a-3. Figure 6 shows a plot of T_{min} - t_2 (amber phase duration less the reaction time to stopping) vs approach speed V_0 for various intersection widths, W.

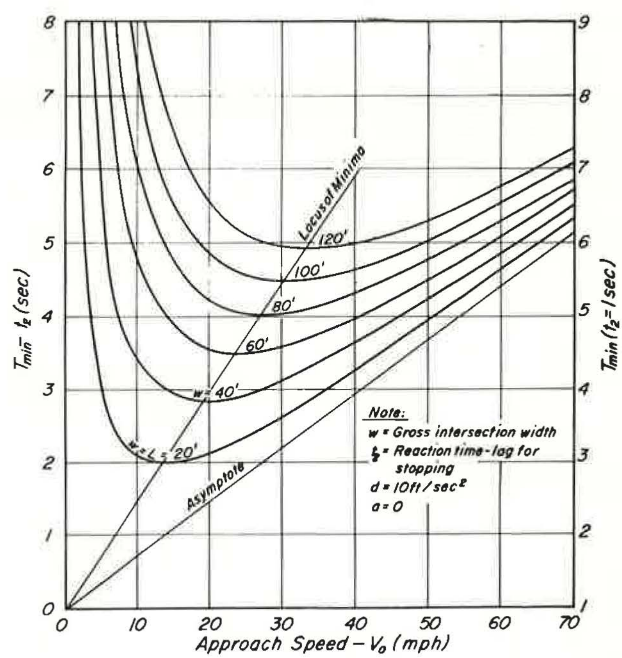

Figure 6. Variation of the minimum amber period T_{min} vs constant approach speed for dilemma zone-proof operation.

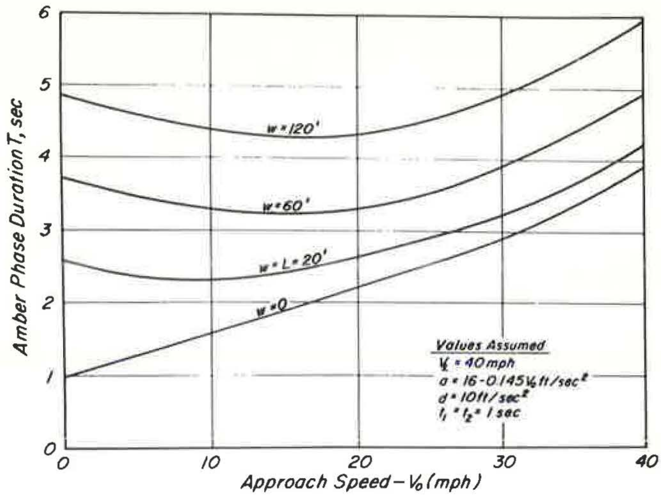

Figure 7. Length of amber phase vs approach speed for Condition II (a driver can accelerate when clearing the intersection).

The amber period T is subscripted as minimum because the value of deceleration is taken to be a "maximum practical" value of 10 ft/sec^2. Case (b) is represented by the lowest curve of the series having L = 20 ft (could be less), whereas case (a) is represented by curves W = 40 ft through 120 ft.

Condition II—A vehicle is approaching the intersection at less than the approach speed limit, and can accelerate to clear the intersection. In this case the approach speed limit must be specified. Acceleration is dependent on the approach speed, and a value a = 16 - 0.145 V_0 of Gazis is adopted here. The stopping distance remains the same:

$$X_S \geq V_0 t_2 + \frac{V_0^2}{2d} \tag{4}$$

The clearing distance is dependent on whether the speed limit V_ℓ is attained within or outside the intersection.

In the first case

$$T \geq t_1 + \frac{V_\ell - V_0}{a}$$

and

$$X_C \leq V_0 t_1 - W + \frac{V_\ell^2 - V_0^2}{2a} + V_\ell\left(T - t_1 - \frac{V_\ell - V_0}{a}\right) \tag{5}$$

In the second case

$$T \leq t_1 + \frac{V_\ell - V_0}{a}$$

and

$$X_C \leq V_0 T - W + \frac{a}{2}(T - t_1)^2 \tag{6}$$

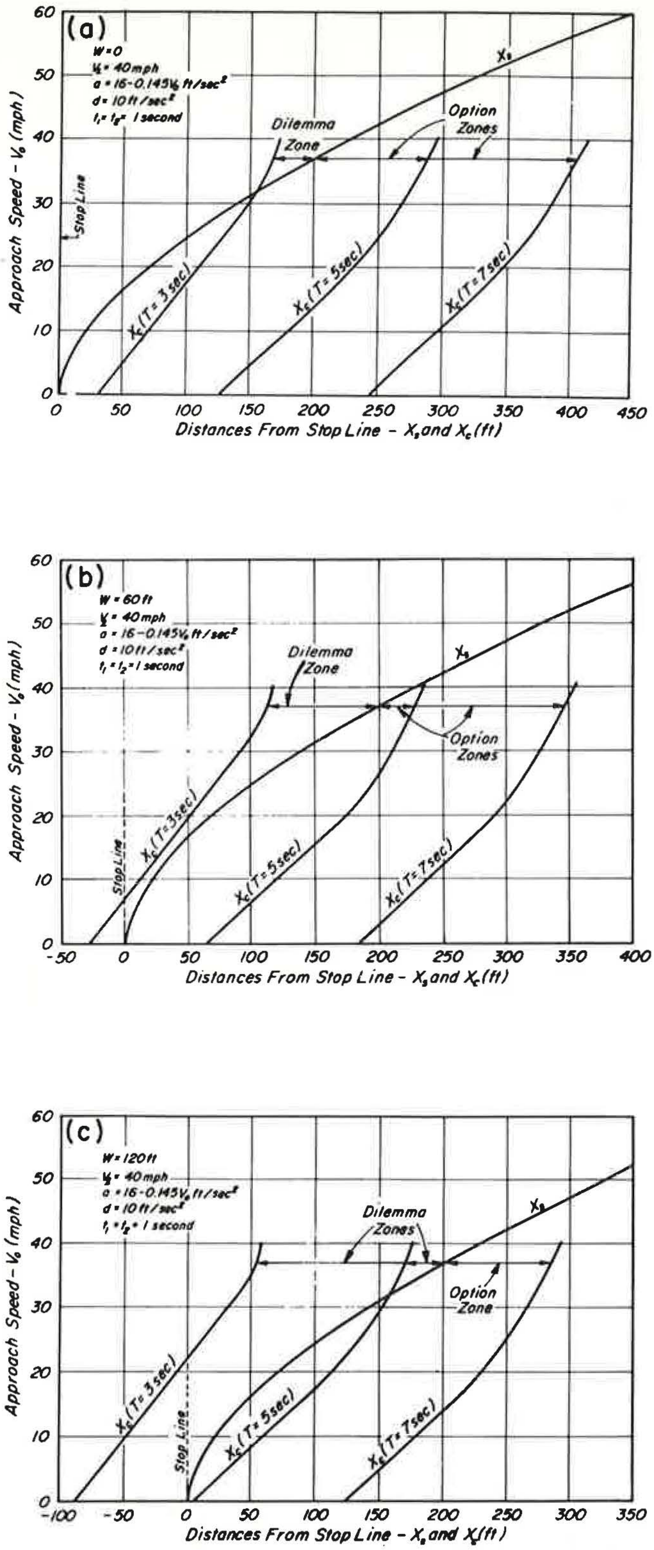

Figure 8. Stopping and clearing distances vs approach speed: (a) W = 0 ft; (b) W = 60 ft; (c) W = 120 ft.

The same relations for case (b), which requires a vehicle to just enter the intersection, can be arrived at with W either equal to zero or having a small value L. Variation of T vs V_0 is shown in Figure 7 for the values V_{ℓ} = 40 mph, a = 16 - 0.145 V_0 ft/sec^2, d = 10 ft/sec^2, and $t_1 = t_2$ = 1 sec. W is given values between zero, and L = 20 ft for case (b) and up to 120 ft for case (a). In this condition where a motorist can accelerate in order to clear the intersection, the curves of T vs V_0 become no longer asymptotic to the line V_0 = 0 as in the first condition where V_0 is assumed constant. Instead, a finite value for T at V = 0 results.

Dilemma and Option Zones

A direct way of showing the existence of a dilemma zone is to plot the stopping and clearing distances vs the approach speed. Such plots are shown in Figure 8 for various values of amber phase duration T, and gross intersection width W. Eqs. 4, 5, and 6 are used with a = 16 - 0.145 V_0 (V_0 in ft/sec), d = 10 ft/sec^2, $t_1 = t_2$ = 1 sec. It is assumed here that the speed limit V_{ℓ} is 40 mph, and that vehicles approaching the intersection at lower than the speed limit can only accelerate up to that limit.

DESIGN OF EXPERIMENT AND FIELD WORK

Controlled Conditions

Single approaches to a typical urban and rural signalized intersection were to be studied under four controlled conditions:

1. Clearance interval set according to existing state practice;
2. Clearance interval of longer duration to eliminate any possible dilemma zone;
3. Signalization supplemented by advance signing; and
4. Signalization supplemented by additional pavement markings.

Site Characteristics

To make the study as general as possible and to facilitate photographic work, a number of site characteristics were desired. They included:

1. Approach with two through lanes,
2. No left-turn lane,
3. No left-turn phasing,
4. Four-approach intersection,
5. Level slope of approach,
6. On state highway,
7. Good photo approach and camera location,
8. No advanced pavement sensors,
9. Urban approach speed 20 to 35 mph,
10. Rural approach speed 40 to 60 mph, and
11. Electric power available.

Modified Design of Experiment

The original design of experiment was a 2 × 4 matrix for studying two locations under four controlled conditions. To take advantage of an already scheduled installation of a "prepare to stop" sign and in order to use "controlled devices" in the field tests involving pavement markings, the design of experiment was modified to include five pairs of controlled conditions. This modified design is shown in Figure 9.

LOCATION / CONTROLLED CONDITIONS	URBAN-SAN PABLO AT VALE: NORMAL CONDITIONS	URBAN-SAN PABLO AT VALE: CONTROLLED CONDITIONS	RURAL-RT. 4 AT SUMMERVILLE: NORMAL CONDITIONS	RURAL-RT. 4 AT SUMMERVILLE: CONTROLLED CONDITIONS	JUNIPERO SERRA BLVD AT CLAY AVENUE: NORMAL CONDITIONS
Clearance Interval Existing State Practice	1 29 Mar. 1967 T=3 sec	3 27 May 1967 T=3 sec	5 22 Mar. 1967 T=5 sec	7 27 May 1967 T=5 sec	9 23 May 1967 T=4 sec
Clearance Interval Increased Duration	2 3 and 16 May 1967 T=5 sec		6 4 May 1967 T=7 sec		
Supplemental Advanced Signing					10 19 July 1967 T=4 sec
Supplemental Pavement Markings		4 3 June 1967 T=3 sec		8 3 June 1967 T=5 sec	

Figure 9. Modified design of experiment (shown in various cells are dates of filming and amber periods involved).

Site Selections

All state highway intersections under district 04 jurisdiction were studied. After careful investigation, two

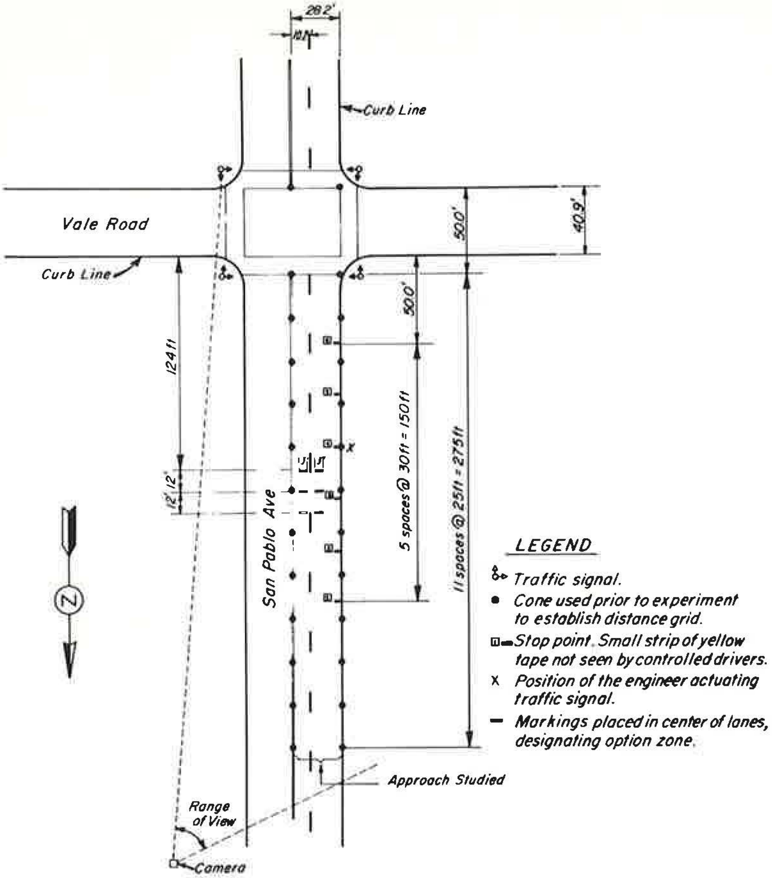

Figure 10. Urban intersection: San Pablo Ave. at Vale Rd., experiment layout for lanes studied.

intersections were selected. The urban site was located at the intersection of San Pablo Avenue (US 40) and Vale Road in San Pablo (Fig. 10), and the rural site was located at the intersection of Route 4 and Summerville in Antioch (Fig. 11). The urban location met all of the site characteristics fairly adequately, whereas the rural location had both left-turn lane and left-turn signal phasing, but it was the best location observed. It was decided that these locations were to be used for normal amber, lengthened amber, and advanced pavement marking phases of the study. A third location was afterwards selected to be used for advanced display phase under normal conditions. This site was located at Junipero Serra Blvd. and Clay Ave. in South San Francisco (Fig. 12).

Camera Setup

A 16-mm pulse camera (MK 100 ES) was used at a speed of two frames per second. The film was 7241-EF Ektachrome high-speed 100 color-type film. There were 400 ft per roll, which at 2 frames per second lasted approximately 2 hours. For the normal conditions, the standard amber and the lengthened amber phases, filming was done either Tuesday, Wednesday, or Thursday; Monday and Friday being thought of as rather extraordinary traffic days for all locations. For each phase of the study, it was decided to take two reels of film. The filming was carried out between 1:00 p.m. and 6:00 p.m. It was assumed and also noted from preliminary observations that the first reel taken from 1:00 p.m. to 3:30 p.m. was light traffic, and from 3:30 p.m. to 6:00 p.m. was heavy traffic.

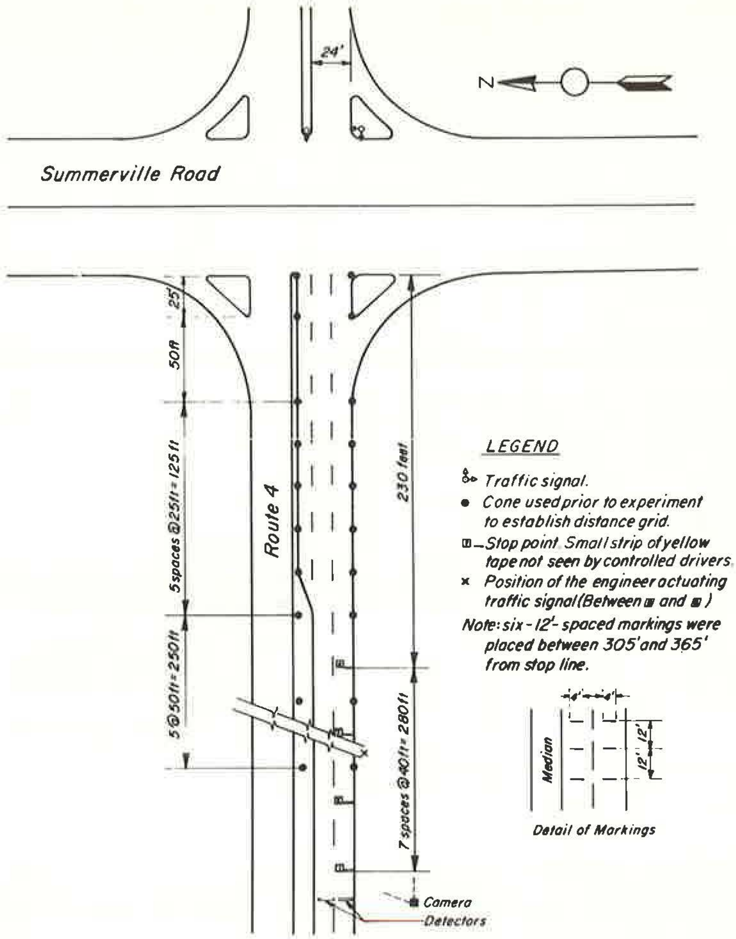

Figure 11. Rural intersection: Route 4 at Summerville Rd., experiment layout.

Two consecutive Saturdays were chosen for filming the advanced pavement marking phase. Since the only vehicles of interest were the control-driver vehicles, Saturday was a convenient time, the traffic conditions being fairly light. Filming was done only when the control vehicles were in range of the camera (the camera was fixed in all cases). Eight controlled drivers were required, and each driver made approximately 15 runs for each location and controlled condition (see Fig. 9 for date of each filming).

The camera at San Pablo and Vale was positioned on top of a ladder placed on top of a panel truck in an adjacent vacant lot where electricity was available. The camera at Route 4 and Summerville was on the roof of an adjacent building. The camera at Junipero Serra Blvd. and Clay Ave. was on a hillside adjacent to Junipero Serra Blvd. At San Pablo and Clay Ave. locations, the signal could be seen well enough for analysis purposes. However, at Summerville, the signal was not easily definable. Therefore, a light bulb was connected in the camera range to the signal so that it would be on only when the signal was in the amber phase.

Photographic Processes and Controlled Conditions

Traffic cones were placed at intervals on the sides of the lanes to use as a reference. These cones were temporarily placed at the beginning of each setup, photographed for 3 min, and then taken up so they would not influence traffic (see Figures 10, 11, and 12 for cone layouts).

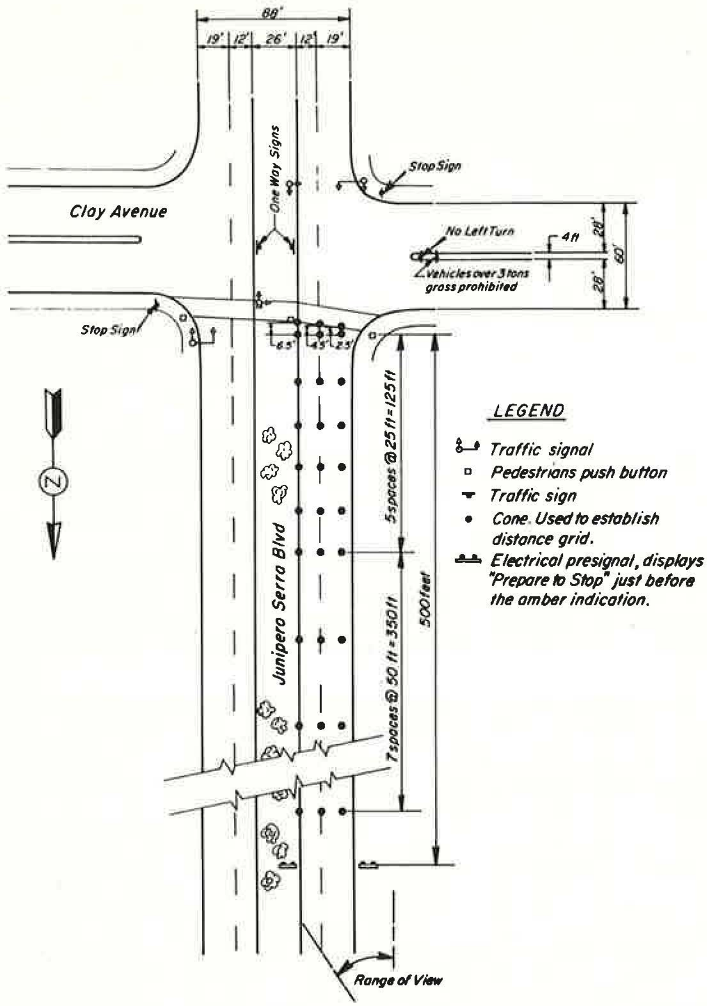

Figure 12. Junipero Serra Blvd. at Clay Ave., experiment layout.

To establish the feasibility of the different sites and camera locations, several preliminary films were made. Cone layouts were included to determine the accuracy of our measurements and reasonable cone positions. The cones could be more easily seen if painted bright orange instead of the standard yellow. All three sites were photographed with existing conditions with the state standard length of amber: at San Pablo and Vale Road, amber = 3.0 sec; at Route 4 and Summerville Road, amber = 5.0 sec; and at Junipero Serra Blvd. and Clay Ave., amber = 4.0 sec.

The intersection at South San Francisco was peculiar in that it is actuated only by pedestrians. During slack pedestrian periods, it was necessary to push the actuator to obtain a fairly standard cycle.

Later, San Pablo and Route 4 were photographed with the lengthened amber period: 5.0-sec amber at San Pablo, Vale; and 7.0-sec amber at Route 4, Summerville. Special precautions were taken at Summerville Road in lengthening the amber. It was stepped up in two stages before being photographed: one week at 6.0 sec and one week at 7.0 sec.

San Pablo and Route 4 were next photographed under the existing conditions without and with pavement markings using controlled drivers. For both with and without pavement marking phases, the drivers were instructed to drive at the approach

TABLE 4

MATRIX OF VEHICLES CAUGHT IN VARIOUS APPROACH SPEED-STOP POINT COMBINATIONS

Condition	Speed	Stop Point							
		1	2	3	4	5	6	7	8
(a) San Pablo at Vale (urban)									
Before markings	25	10	9	7	6	6	6		
	30	9	6	6	6	6	11		
	35	6	9	9	8	9	6		
With markings	25	7	6	6	6	6	6		
	30	6	6	6	7	6	6		
	35	6	7	6	6	7	6		
(b) Route 4 at Summerville (rural)									
Before markings	40	13	6	6	7	6	7	6	6
	50	6	6	6	8	10	6	6	-
	60	6	13	10	6	6	6	-	-
With markings	40	-	-	6	6	6	6	6	6
	50	4	6	6	6	6	6	6	6
	60	6	6	6	6	6	6	6	-

speed specified in their log; at Route 4 these speeds were 40, 50, and 60 mph, and at San Pablo, were 25, 30, and 35 mph. In the without-markings phase, the drivers were told to react as normally as possible to the signal. In the with-markings phase, the drivers were told that the markings were designed for 50 mph. The drivers were told if they did not reach the markings when the light turned amber they were advised to stop. If they were in the zone, the drivers had the option to stop or go through. However, they were told to still rely on their own judgment, and the markings were to be only an aid. These markings were made of strips of special epoxy bonded tape, 8 in. wide (Figs. 10 and 11).

To get a spread of stopping distances, a number of stop points were created and the signals were wired for semimanual operation. The points were uniformly spaced on the pavement (unseen by the drivers) and randomly selected so that for each point there would be a minimum of 6 control vehicles for each approach speed-stop point combination (see Table 4).

The signals were operated by a traffic engineer stationed some distance back from the intersections. When the control vehicles passed a specified stop point, the engineer started the cycle. At San Pablo when the cycle was started, the signal would turn instantaneously yellow if at least 10 sec of green had elapsed; the average cycle was approximately 65 sec. Six stop points were required and laid out (Fig. 10). They were placed so the cars at higher speeds would almost always stop for the points farthest from the intersection, and cars at lower speeds for points nearest the intersection would almost always pass through. At Route 4 eight stop points were required. When the cycle was started, there was a 1.8-sec delay before the light would turn amber if at least 20 sec of green had elapsed; the average cycle was approximately 85 sec. This was due to the behavior of the signal mechanism. For this reason, the stop points were placed approximately 100 ft farther back than if the signal mechanism had been instantaneous.

The last filming operation was carried out for Junipero Serra Blvd. at Clay Ave., under the controlled condition of an advanced sign placed 500 ft from the intersection with Clay Ave. The sign displays a "prepare to stop" message just prior to the beginning of the amber phase and returns to a "blank-out" state just before the end of the red phase.

FILM ANALYSIS, DATA PROCESSING AND DATA REDUCTION

Film Analysis

The purpose of the film analysis was to determine the time-distance trace of vehicles passing through the intersections. Specifically, this time-distance function was needed to determine driver reaction to the amber phase of the signal.

To obtain the time-distance trace, two requirements had to be fulfilled: a time relationship had to exist between different pictures taken of one particular car, and a distance grid had to be established on the road. The first requirement was satisfied by using time-lapse photography. Pictures were taken of the intersection at ½-sec intervals, establishing a time relationship between frames. Also, continuous movies could be made of the intersection because of the relatively small film requirements: 100 ft of film could record more than 30 min of events.

The second requirement was satisfied by establishing a grid system on the road. Before filming began, highly visible traffic markers were placed at equal distance intervals on both sides of the road. Next, the first few frames of film were used to record their location. Later, these frames were used to reestablish the grid. Specifically, what was done was to project a frame on which the cones were recorded on a sheet of paper. Then the position of the cones was recorded on the paper, together with a number of reference marks (for example, the centerline of the road, road signs, or telephone poles). Using the positions of the cones, a grid could be drawn. The distances between the cones were known, and thus a calibrated "master" could be made from which time-distance traces of individual vehicles could be obtained. Since in this study the needed results were driver reaction to the amber phase of the signal, screening had to be done in choosing the cars which were to be traced through the intersection. Several criteria were used in the screening procedure.

Driver' reaction should be almost exclusively due to the amber phase of the signal. This type of reaction is opposed to the reaction due to heavy traffic, an intended left or right turn, or police interference. Furthermore, the vehicle had to be sufficiently close to the intersection when the light turned amber so that the driver had to make a real decision regarding whether he should go through.

To determine the trace of the vehicle, the consecutive frames of a particular car were projected on a sheet of paper. A distinctive feature on the car was then plotted on the paper for each frame. At the rural location the front tire was plotted, in the urban location the left-front tire was plotted, while at the Clay Ave. location the left-rear bumper was plotted. In addition to these points, a number of reference marks were recorded so that later the trace of the vehicle could be superimposed on the master.

Once the vehicle trace and reference marks were plotted, the trace was superimposed on the master, overlaying the identical reference marks. The position of the car in the distance grid could then be read off the master. To determine the position of the car relative to the stop line of the intersection, linear interpolation was used for those distances that fell between the grid lines determined by the traffic cones. The distances were then recorded on the specially designed data sheets.

Data Sheets and Data Cards

The format of the data sheets (Fig. 13) was designed primarily so that later the data could be easily transferred to IBM cards for computer reduction. For each trace, a set of data was made: the first card contained certain parameters; the second card, identification and data of 12 position points of the car; and, if more position points were

CARD I

Identif. No. 1 2 3 4	5	No. /Frames 6 7	
9052		1 4	

CARD II

Ident. No. 1 2 3 4	Location & Control 5	Catch No. 6 7 8	Vehicle No. 9 10	Veh. Type 11	Movement 12	Extraordinary Movement 13	Frame No. of 1st Amber frame 14 15 16 17 18	No. frames when intersection is clear 19 20
9052	6	005	0 2	5	6	4	11627	0 4

Location & Control Code:
1 = Rural-Existing
2 = Rural-Increased Amber
3 = Rural-Marking
4 = Rural-Controlled
5 = Urban-Existing
6 = Urban-Increased Amber
7 = Urban-Markings
8 = Clay Ave. -Existing
9 = Clay Ave. Signs
0 = Urban-Controlled

Vehicle Type Code:
1 = Passenger Car
2 = Bus
3 = Motorcycle
4 = Truck
5 = Pick-up truck

Movement Code:
1 = Straight thru
2 = Left turn
3 = right turn
4 = changes lane
5 = U-Turn
6 = Stops, will go straight
7 = Stops, will make left turn
8 = Stops, will make right turn
9 = Queueing

Extraordinary Movement Code:
1 = Accident
2 = Pedestrian interference
3 = Skid
4 = Nothing
5 = Ambulance, police, fire
6 = Violations

1 (21–25)	2 (26–30)	3 (31–35)	4 (36–40)	5 (41–45)	6 (46–50)	7 (51–55)	8 (56–60)	9 (61–65)	10 (66–70)	11 (71–75)	12 (76–80)
12229	22204	22888	22156	22888	22115	22099	22083	22070	22888	32050	32040

CARD III

Ident. No. 1 2 3 4	13 (5–9)	14 (10–14)	15 (15–19)	16 (20–24)	17 (25–29)	18 (30–34)	19 (35–39)	20 (40–44)	21 (45–49)	22 (50)
9052	32034	32028								

Where in each frame:

Column 1 - Signal Code:
1 = green
2 = amber
3 = red

Column 2 - Lane Code:
1 = lane nearest curb
2 = lane second nearest curb
3 = lane third nearest curb

Columns 3 - 5 — Location:
Distance from intersection in feet

Figure 13. Format of film analysis—sample.

available on the car, a third card would contain up to a maximum of 24 points. The exact data contained on the data sheets and data cards are as follows:

First Card

Columns 1-4: Identification number. The first digit of this number is composed of the right digit of the reel number on which the car movement is recorded. The middle two digits contain the last two digits of the catch number. The last digit consists of the vehicle number.

Second Card

Columns 1-4: Identification number. Same as for the first card.

Column 5: Location and control number. The coding for this number is as follows:

1 Rural location, existing condition
2 Rural location, with increased amber phase length
3 Rural location, with markings
4 Rural location, controlled experiment
5 Urban location, existing condition
6 Urban location, with increased amber phase length
7 Urban location, with markings
8 Clay Avenue location, existing condition
9 Clay Avenue location, with markings
0 Urban location, controlled experiment

Columns 6-8: Catch number. The catch number is assigned consecutively, starting with 001 for the first catch at the beginning of a reel of film. A catch exists when, at the time the light turns amber, a vehicle is located within the grid as determined by the traffic cones.

Columns 9-10: Vehicle number. Vehicle numbers are assigned consecutively within a catch, starting with 01 for the vehicle located closest to the intersection.

Column 11: The vehicle type code. This code was assigned as follows:

1 Passenger car
2 Bus
3 Motorcycle
4 Truck
5 Pickup truck

Column 12: Movement code. Code assignment:

1 Straight
2 Left turn
3 Right turn
4 Changes lane
5 U-Turn
6 Stops, will go straight
7 Stops, will make left turn
8 Stops, will make right turn
9 Queueing

Column 13: This column contains the extraordinary movement code. The following extraordinary movements were considered and coded:

1 Accident
2 Pedestrian interference
3 Skid
4 Nothing
5 Ambulance interference
6 Violation

Columns 14-18: The frame number of the first amber frame for this particular vehicle. In all cases the projector frame counter was set to the number 11,111 at the first amber frame of the first catch of vehicles.

Columns 19-20: Contain the number of frames, starting with the first red frame, during which the intersection was clear of cars interfering with the direction of traffic under study. In case no traffic crossed, the number 99 was recorded.

Columns 21-80: These 60 columns were filled with 12 five-digit numbers. Within the five-digit number the coding was as follows:

Column 1: Signal code. This code was assigned:
- 1 Green
- 2 Amber
- 3 Red

Column 2: Lane code. Coding was assigned as follows:
- 1 Lane nearest the curb
- 2 Lane second nearest curb
- 3 Lane third nearest curb

Columns 3-5: The distance that the car was located from the stop line, as determined from the trace and the master. The distance is given in feet. In case this distance could not be determined due to an obstruction, the number 888 was recorded instead.

On this second card a maximum of 12 frames could be recorded. In case this was not sufficient, a third card was used.

Third Card

Columns 1-4: Identification number. Same as for first card.

Columns 5-80: These columns contained five digit numbers coded in the same manner as was done for the second card in the last 60 columns.

Data Reduction

The data contained on the coding sheets were punched on IBM cards. The processing of the data cards was accomplished in the following steps:

1. Preliminary checking of punched cards: a computer program was prepared to check distances and signal codes. This procedure eliminated most of the punching errors.
2. Polynomial curve fit: curve fits of different degrees were applied to the raw data, the best of which was found to be the fourth degree polynomial. This step was necessary to infer unknown data points as well as to smooth the time-distance trace of vehicles.
3. Summary of results: the output of the fourth degree polynomial curve fit was used as an input for the summary program. The output of this program included: (i) identification number defining a vehicle in one of the 10 cells studied; (ii) number of frames used to trace the vehicle's position; (iii) movement code, acceptance or rejection; (iv) distance and speed at the beginning of the amber phase; (v) distance and speed at the last recorded frame of amber phase; (vi) maximum speed; (vii) maximum acceleration; (viii) maximum deceleration; (ix) extraordinary movement code; and (x) lane change and entry. Speed (in ft/sec) is obtained by doubling the distance traveled during each ½ sec, divided by 1.467. Speed change (in ft/sec^2) is found by doubling the difference between speeds of two consecutive half seconds.
4. Final proofing: this step was necessary to correct any errors not screened by the first two steps. Indications for such errors were obtained mostly from excessive or unrealistic acceleration or deceleration rates displayed by the summary program. The previous steps were repeated for such errors.

Among the inaccuracies involved were those due to equipment limitations, human difficulties in reading a vehicle's position from the film and the texture of the films used.

PILOT STUDY RESULTS

The results from the pilot study are presented in five parts. The number of vehicles observed in each cell is shown on the design of experiment (Fig. 14).

Effect of Increased Amber Phase at Urban Location

The measurements obtained for the urban location using the standard length of amber phase of 3 sec (cell one) were compared with the measurements obtained for the

CONTROLLED CONDITIONS \ LOCATION	URBAN-SAN PABLO AT VALE		RURAL-RT.4 AT SUMMERVILLE		JUNIPERO SERRA BLVD AT CLAY AVENUE
	NORMAL CONDITIONS	CONTROLLED CONDITIONS	NORMAL CONDITIONS	CONTROLLED CONDITIONS	NORMAL CONDITIONS
Clearance Interval Existing State Practice	1 108/112/220	3 63/51/114	5 25/19/44	7 52/78/130	9 45/46/91
Clearance Interval Increased Duration	2 71/103/174		6 32/19/51		
Supplemental Advanced Signing					10 20/78/98
Supplemental Pavement Markings		4 33/44/77		8 64/56/120	

Figure 14. Number of observations for cells studied (108/112/220 = accepting vehicles/rejecting vehicles/total vehicles).

same urban location using a longer amber period of 5 sec (cell two) in order to ascertain the effect of increased amber phase duration. Two sets of analyses were undertaken: (a) acceptance-rejection characteristics, and (b) risk measurements.

The acceptance-rejection characteristics are shown in Figure 15 for cell one (existing amber duration) and in Figure 16 for cell two (increased amber duration). A solid dot symbol is used to denote vehicles passing through the intersection on the amber (accepting) and an X symbol is used to denote vehicles stopping (rejecting). The solid curves denote the minimum distances for the different approach speeds that vehicles may safely stop before entering the intersection, assuming a maximum deceleration rate of 10 ft/sec^2. Therefore, any X symbol to the left of the solid curve indicates a vehicle that will exceed an average deceleration rate of 10 ft/sec^2 if the vehicle is to halt at the stop line. The dashed curves denote the maximum distance for the different approach speeds that vehicles may enter the intersection before the end of the amber phase. These dashed curves are based on indicated amber phase durations and for an acceleration rate of 5 ft/sec^2, which was

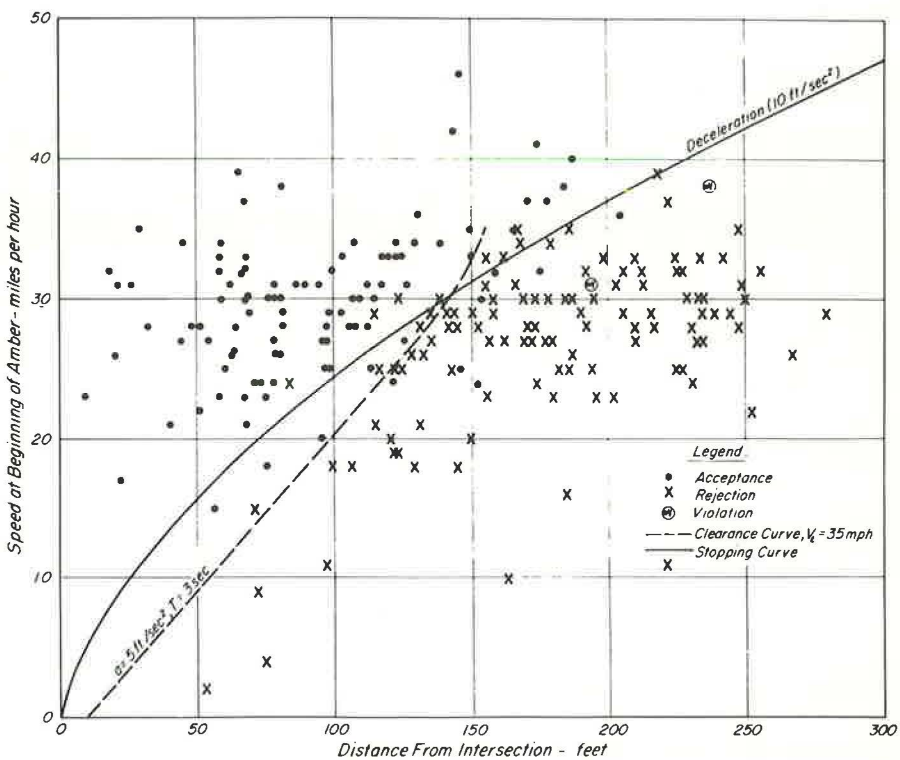

Figure 15. Cell one acceptance-rejection characteristics.

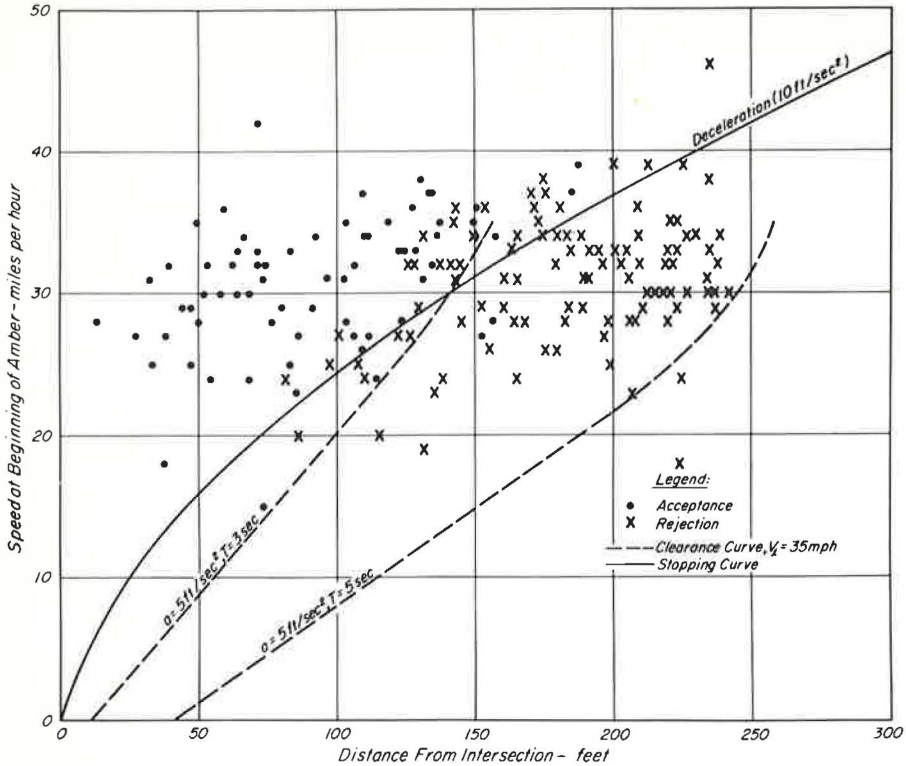

Figure 16. Cell two acceptance-rejection characteristics.

assumed to be safe and reasonable for the conditions studied. Therefore, any dot symbol to the right of the dashed curves indicates a vehicle that will exceed the allowable acceleration rate or legal speed limit or both if the vehicle is to enter the intersection before the end of the amber phase. The solid and dashed curves partition the graph into four regions: acceptance (left of solid and dashed curves); rejection (right of solid and dashed curves); option (right of solid curve and left of dashed curve); and dilemma zone (left of solid curve and right of dashed curve).

A summary of measures of safe and unsafe operations for cells one and two is given in Table 5. Generally, there was only a slight detrimental effect on safe operations due to increasing amber duration; in individual measures there were significant changes. A high percentage of rejecting vehicles was transferred from the rejection region to the option region with increased amber duration. There was a rather high percentage of rejecting vehicles in the acceptance region, but increasing amber duration eliminated the dilemma region and also the vehicles accepting in the rejection region. The most significant observation is that although increasing the amber duration changed the boundary locations between regions, and therefore the percent of vehicles observed in each region, the behavior of traffic in accepting and rejecting the amber phase at various distances from the intersection remained

TABLE 5

CELLS ONE AND TWO MEASURES OF SAFE AND UNSAFE OPERATIONS

Measures of Safe and Unsafe Operations	Cell One Existing Amber Duration (%)	Cell Two Increased Amber Duration (%)
(a) Safe or Expected Operations		
Accepting in acceptance region	39	39
Rejecting in rejection region	45	1
Option region	4	45
Total	88	85
(b) Unsafe or Unexpected Operations		
Rejecting in acceptance region	2	15
Accepting in rejection region	5	0
Dilemma region	5	0
Total	12	15

TABLE 6

RISK MEASUREMENTS OF CELLS ONE AND TWO

Risk Measurements	Cell One Existing Amber Duration (%)	Cell Two Increased Amber Duration (%)
(a) Accepting Vehicles		
Exceeded speed limit after beginning of amber	8	20
Exceeded deceleration rate of 15 ft/sec²	1	1
Exceeded acceleration rate of 8 ft/sec²	3	10
Exceeded deceleration rate of 15/sec² and acceleration rate of 8 ft/sec²	0	0
Entered intersection on red phase	2	0
Changed lanes during amber phase	0	0
Percent of accepting vehicles involved in one or more risks	13	28
(b) Rejecting Vehicles		
Exceeding speed limit after beginning of amber	0	1
Exceeded deceleration rate of 15 ft/sec²	5	12
Exceeded acceleration rate of 8 ft/sec²	3	5
Exceeded deceleration rate of 15 ft/sec² and acceleration rate of 8 ft/sec²	0	0
Changed lanes during amber phase	0	0
Percent of rejecting vehicles involved in one or more risks	8	20
Percent of all vehicles involved in one or more risks	11	24

essentially unchanged. It appears that traffic is unaffected by increasing amber duration either because the drivers are unaware of the increase or the drivers are aware but not affected by it. One-fourth of the vehicles classified as performing in an unsafe or unexpected manner in cell one were exceeding the speed limit when the signal changed to amber. One-third of the vehicles classified as performing in an unsafe or unexpected manner in cell two were exceeding the speed limit when the signal changed to amber.

The solid curves denoting the deceleration rate limit for stopping divided the sets of data points in such a manner that the number of rejecting vehicles to the left of the curve is approximately equal to the number of accepting vehicles to the right. Eighty-seven percent of all observed vehicles in cells one and two were on the expected side of the deceleration curve. Fifteen percent of the rejecting vehicles were unexpectedly on the left of the deceleration curve and 11 percent of the accepting vehicles were unexpectedly on the right of the deceleration curve. The drivers observed during the shorter amber period appeared to be slightly more aggressive than drivers observed during the longer amber period.

The second set of analyses was directed toward evaluating measures of risk for the two cells in question. A summary comparing the risk measurements for cells one and two is given in Table 6. There was a higher percentage of vehicles in the various risk measurements with the increased amber duration, with the single exception of vehicles entering the intersection on the red phase. Two out of 108 accepting vehicles in cell one entered the intersection on the red phases; there were no such events with the increased amber duration. There were 2 vehicles (3%) in cell two that would have been classified as entering the intersection on the red phase if a 3-second amber had been in operation. All other risk measurements, while perhaps not as critical, gave no indication that safer operations resulted from increased amber duration. In fact, if any change was noted, the increased amber phase gave a higher percentage of risk measurements.

Effect of Increased Amber Phase at Rural Location

The measurements obtained for the rural location using the 5-sec standard length of amber phase (cell five) were compared with the measurements obtained for the same rural location using a 7-sec period (cell six) to ascertain the effect of the increase. The same two sets of analyses were undertaken.

The acceptance-rejection characteristics are shown in Figure 17 for cell five and in Figure 18 for cell six. These figures were constructed in a manner similar to Figures 15 and 16.

A summary of measures of safe and unsafe operations for cells five and six are given in Table 7. There was a higher percentage of vehicles that operated in a safe or expected manner with the increased duration. There appeared to be two specific changes: (a) by increasing the amber duration, 8 percent of the vehicles which would have been in the group marked "rejecting in rejection region" were transferred to "option region" group; (b) percentage of vehicles in the group, "rejecting in acceptance" was reduced. This specific change is attributable to the increased amber phase, but the relatively small sample size should be noted.

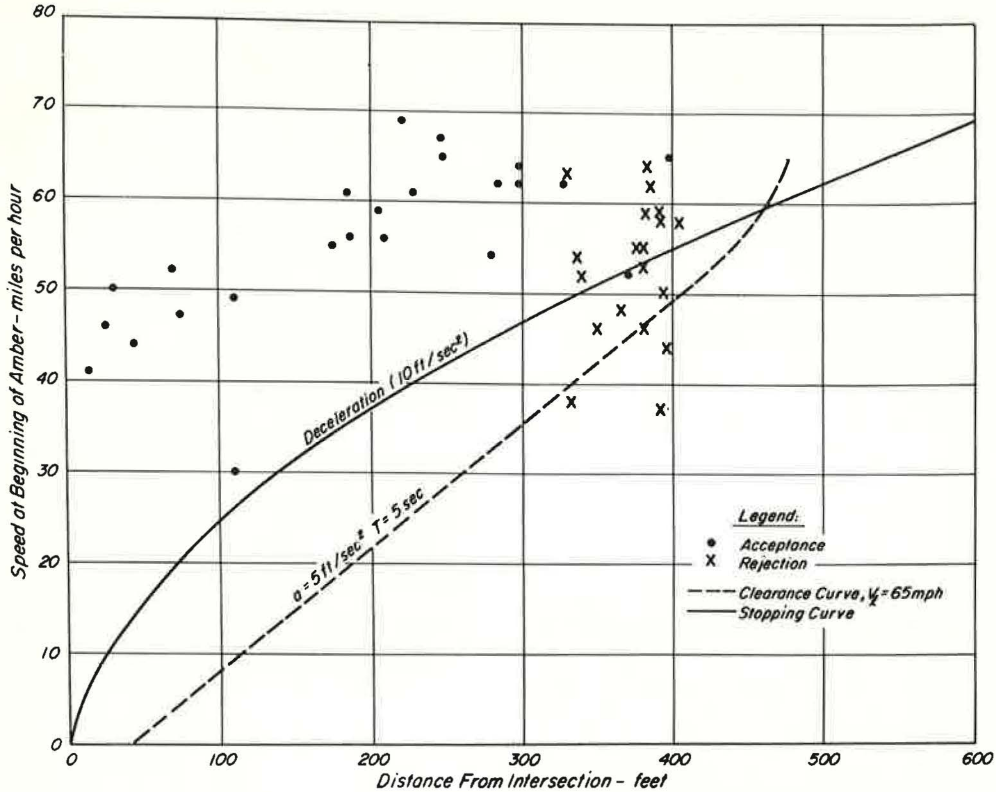

Figure 17. Cell five acceptance-rejection characteristics.

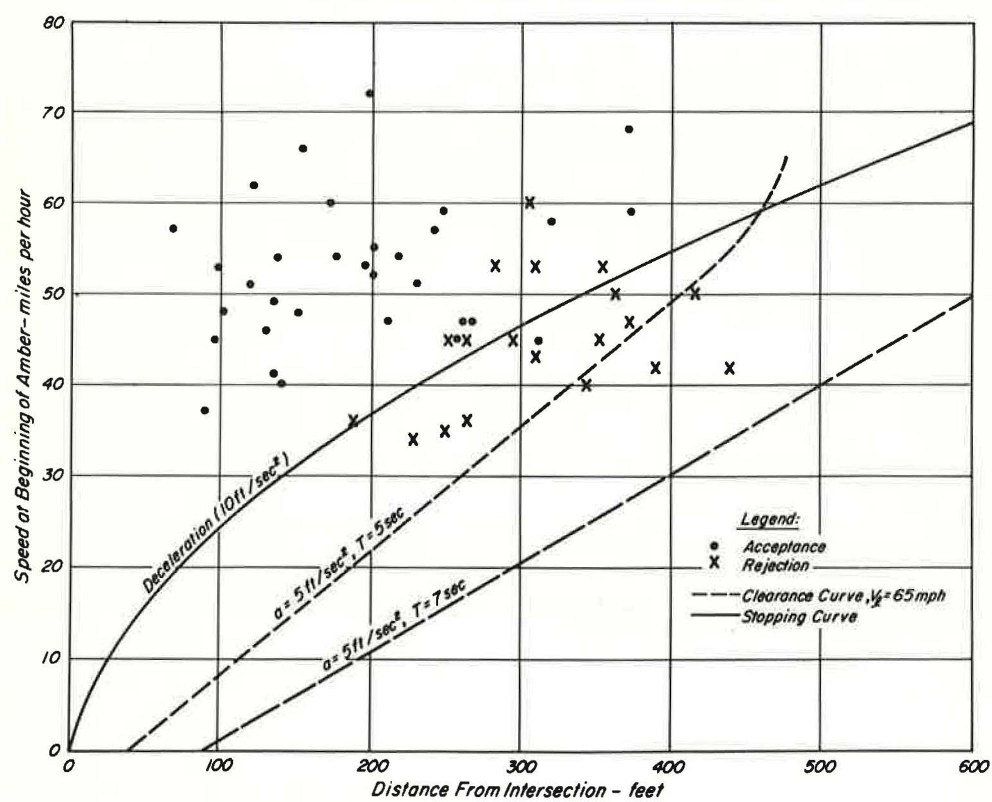

Figure 18. Cell six acceptance-rejection characteristics.

TABLE 7

CELLS FIVE AND SIX MEASURES OF SAFE AND UNSAFE OPERATIONS

Measures of Safe and Unsafe Operations	Cell Five Existing Amber Duration (%)	Cell Six Increased Amber Duration (%)
(a) Safe or Expected Operations		
Accepting in acceptance region	55	61
Rejecting in rejection region	9	0
Option region	11	25
Total	75	86
(b) Unsafe or Unexpected Operations		
Rejecting in acceptance region	25	14
Accepting in rejection region	0	0
Dilemma region	0	0
Total	25	14

TABLE 8

RISK MEASUREMENTS OF CELLS FIVE AND SIX

Risk Measurements	Cell Five Existing Amber Duration (%)	Cell Six Increased Amber Duration (%)
(a) Accepting Vehicles		
Exceeded speed limit after beginning of amber	12	0
Exceeded deceleration rate of 15 ft/sec²	0	0
Exceeded acceleration rate of 8 ft/sec²	52	25
Exceeded deceleration rate of 15 ft/sec² and acceleration rate of 8 ft/sec²	0	0
Entered intersection on red phase	4	0
Changed lanes during amber phase	4	0
Percent of accepting vehicles involved in one or more risks	60	25
(b) Rejecting Vehicles		
Exceeded speed limit after beginning of amber	0	0
Exceeded deceleration rate of 15 ft/sec²	5	26
Exceeded acceleration rate of 8 ft/sec²	5	0
Exceeded deceleration rate of 15 ft/sec² and acceleration rate of 8 ft/sec²	0	0
Changed lanes during amber phase	0	0
Percent of rejecting vehicles involved in one or more risks	10	26
Percent of all vehicles involved in one or more risks	39	26

The second set of analyses was directed toward evaluating measures of risk for the two cells in question. A summary comparing the risk measurements for cells five and six is given in Table 8. The percentage of accepting vehicles in cell six involved in risk was less than those in cell five. On the other hand, the percentage of rejecting vehicles in cell six involved in risk was greater than those in cell five. There was an overall decrease in the percentage of all vehicles involved in risk when the amber duration was increased.

Effect of Pavement Markings at Urban Location

The measurements obtained for the urban location using the standard length of amber phase of 3 sec without pavement markings and with controlled drivers (cell three) were compared with the measurements obtained for the same urban location, the same duration with pavement markings and with the same controlled drivers (cell four). This permitted the evaluation of the effect of transverse pavement markings on improving safe operations. Again, acceptance-rejection characteristics and risk measurements were analyzed.

The acceptance-rejection characteristics are shown in Figure 19 for cell three and in Figure 20 for cell four. These figures were constructed in a manner similar to that used previously.

Table 9 summarizes measures of safe and unsafe operations for cells three and four. There was a higher percentage of vehicles which operated in a safe or expected manner with the pavement markings than under similar conditions without the pavement markings. The major improvement was the reduced percentage of vehicles in the "rejecting in the acceptance region" group.

Table 10 summarizes the risk measurements for cells three and four. The difference in risk between the two conditions was inconsistent. Generally, the percentage of accepting vehicles involved in a risk was greater in cell four, whereas the percentage of rejecting vehicles involved in a risk was less. Overall, there was little change in risks with pavement markings present.

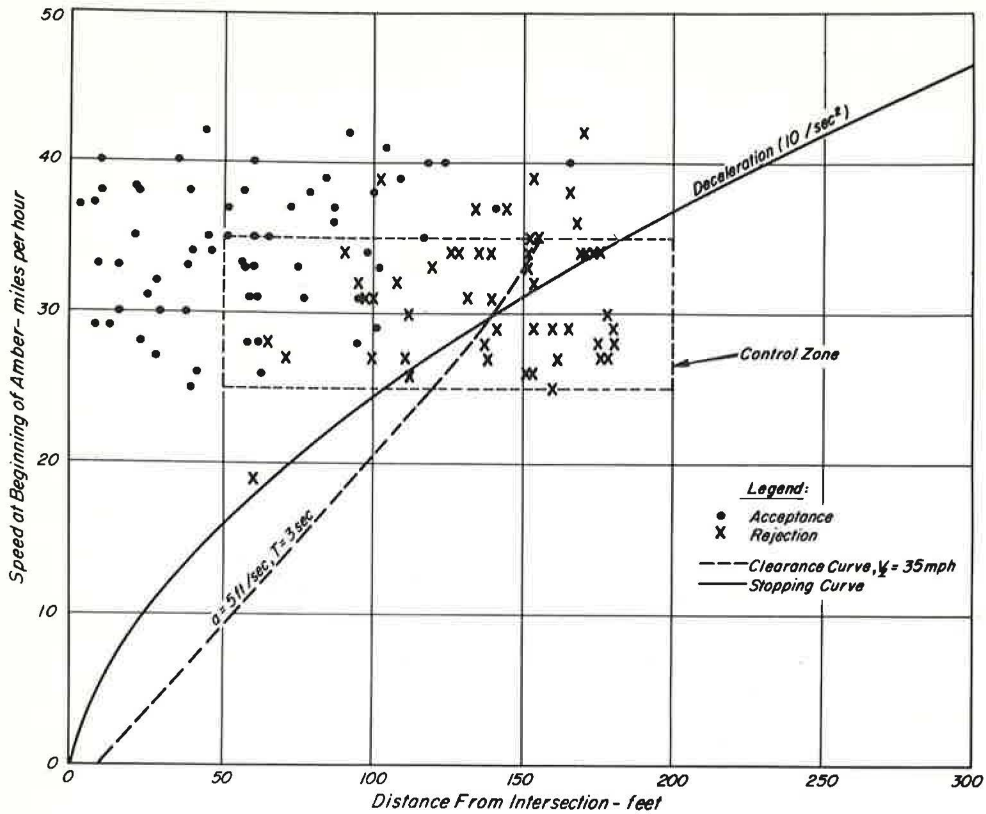

Figure 19. Cell three acceptance-rejection characteristics.

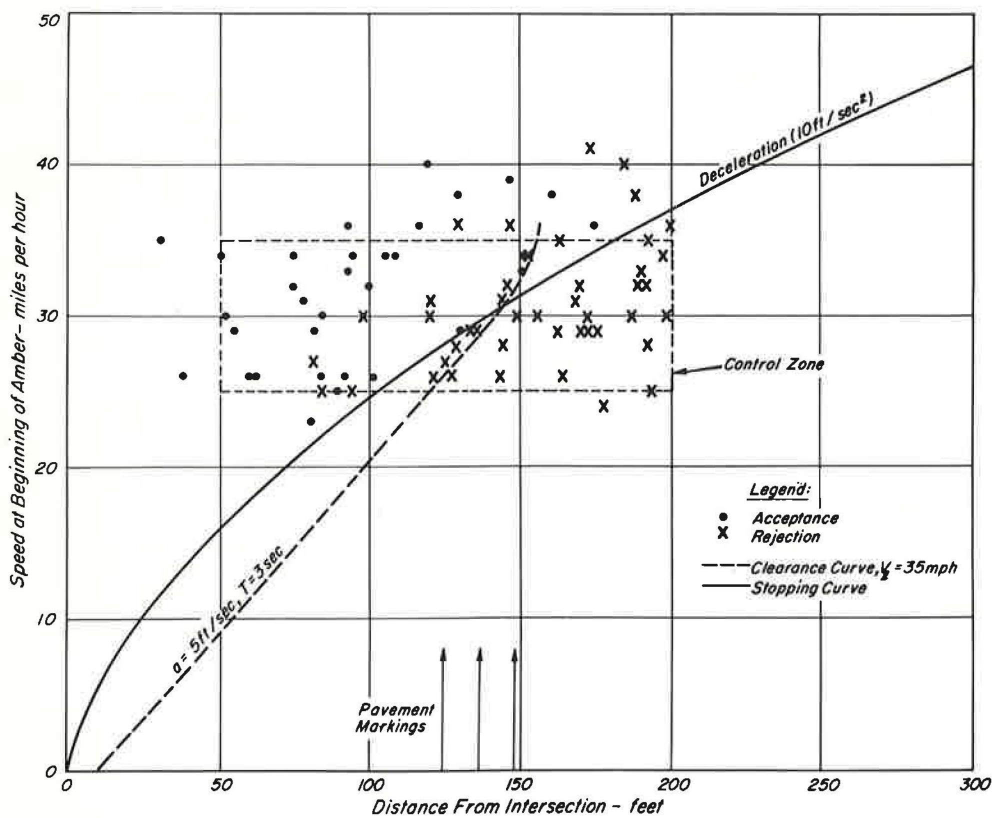

Figure 20. Cell four acceptance-rejection characteristics.

TABLE 9

CELLS THREE AND FOUR MEASURES OF SAFE AND UNSAFE OPERATIONS

Measures of Safe and Unsafe Operations	Cell Three Without Pavement Markings (%)	Cell Four With Pavement Markings (%)
(a) Safe or Expected Operations		
Accepting in acceptance region	54	40
Rejecting in rejection region	14	31
Option region	1	7
Total	69	78
(b) Unsafe or Unexpected Operations		
Rejecting in acceptance region	22	14
Accepting in rejection region	0	0
Dilemma region	9	8
Total	31	22

TABLE 10

RISK MEASUREMENTS OF CELLS THREE AND FOUR

Risk Measurements	Cell Three Without Pavement Markings (%)	Cell Four With Pavement Markings (%)
(a) Accepting Vehicles		
Exceeded speed limit after beginning of amber	5	15
Exceeded deceleration rate of 15 ft/sec²	6	0
Exceeded acceleration rate of 8 ft/sec²	21	33
Exceeded deceleration rate of 15 ft/sec² and acceleration rate of 8 ft/sec²	2	0
Entered intersection on red phase	0	3
Changed lanes during amber phase	0	0
Percent of accepting vehicles involved in one or more risks	29	42
(b) Rejecting Vehicles		
Exceeded speed limit after beginning of amber	4	0
Exceeded deceleration rate of 15 ft/sec²	16	11
Exceeded acceleration rate of 8 ft/sec²	8	4
Exceeded deceleration rate of 15 ft/sec² and acceleration rate of 8 ft/sec²	2	0
Changed lanes during amber phase	0	0
Percent of rejecting vehicles involved in one or more risks	24	15
Percent of all vehicles involved in one or more risks	26	27

Effect of Pavement Markings at Rural Location

The measurements obtained for the rural location using the standard length of amber phase of 5 sec without pavement markings and with controlled drivers (cell seven) were compared with the measurements obtained for the same rural location using the same standard length with pavement markings and with the same controlled drivers (cell eight). This permitted the evaluation of the effect of transverse pavement markings on improving safe operations.

The acceptance-rejection characteristics are shown in Figure 21 for cell seven and in Figure 22 for cell eight.

Table 11 summarizes measures of safe and unsafe operations for cells seven and eight. There was a slightly lower percentage of vehicles that operated in a safe or expected manner with the pavement markings than under similar conditions without pavement markings. The major individual change was the increase of the percentage of vehicles in the group "rejecting in acceptance region" and the decrease of the percentage of vehicles in the group "option region." Overall, there was a slight detrimental effect of pavement markings on safe operations.

Table 12 summarizes the risk measurements for cells seven and eight. The pavement markings had an adverse effect on rejecting vehicles and a slight adverse effect on accepting vehicles. Generally, the experiments evaluating the effect of pavement markings on safe operations indicated that safe operations did not improve with pavement markings at the rural location.

TABLE 11

CELLS SEVEN AND EIGHT MEASURES OF SAFE AND UNSAFE OPERATIONS

Measures of Safe and Unsafe Operations	Cell Seven Without Pavement Markings (%)	Cell Eight With Pavement Markings (%)
(a) Safe or Expected Operations		
Accepting in acceptance region	40	54
Rejecting in rejection region	14	3
Option region	25	15
Total	79	72
(b) Unsafe or Unexpected Operations		
Rejecting in acceptance region	21	27
Accepting in rejection region	0	0
Dilemma region	0	0
Total	21	28

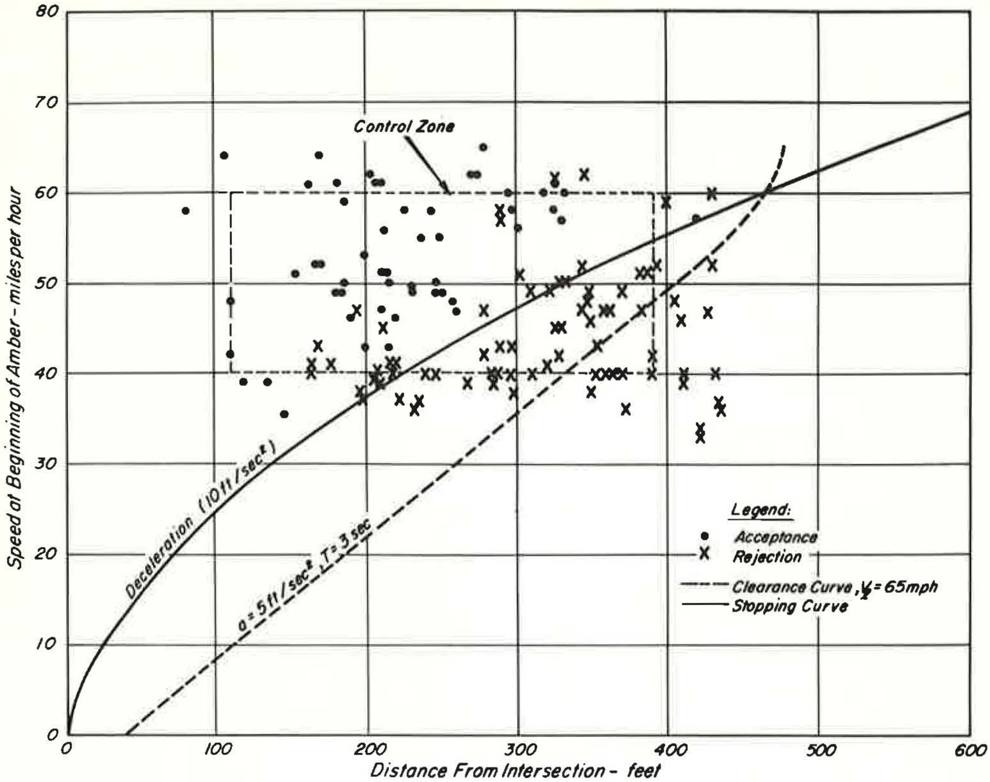

Figure 21. Cell seven acceptance-rejection characteristics.

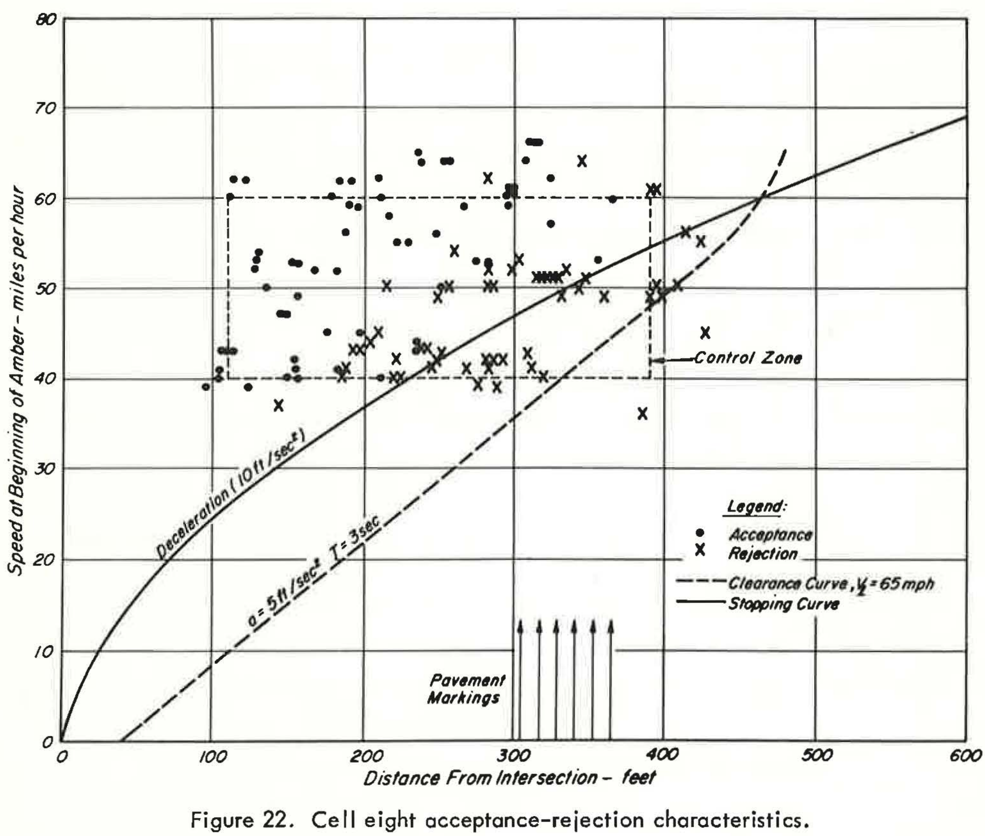

Figure 22. Cell eight acceptance-rejection characteristics.

TABLE 12

RISK MEASUREMENTS OF CELLS SEVEN AND EIGHT

Risk Measurements	Cell Seven Without Pavement Markings (%)	Cell Eight With Pavement Markings (%)
(a) Accepting Vehicles		
Exceeded speed limit after beginning of amber	2	5
Exceeded deceleration rate of 15 ft/sec^2	0	2
Exceeded acceleration rate of 8 ft/sec^2	38	36
Exceeded deceleration rate of 15 ft/sec^2 and acceleration rate of 8 ft/sec^2	0	2
Entered intersection on red phase	0	2
Changed lanes during amber phase	0	2
Percent of accepting vehicles involved in one or more risks	38	41
(b) Rejecting Vehicles		
Exceeded speed limit after beginning of amber	0	0
Exceeded deceleration rate of 15 ft/sec^2	10	20
Exceeded acceleration rate of 8 ft/sec^2	13	18
Exceeded deceleration rate of 15 ft/sec^2 and acceleration rate of 8 ft/sec^2	1	2
Changed lanes during amber phase	0	0
Percent of rejecting vehicles involved in one or more risks	22	36
Percent of all vehicles involved in one or more risks	28	38

Effect of Supplemental Advanced Signing

The measurements obtained at the Junipero Serra Boulevard location without the "prepare to stop" supplemental advanced signing (cell nine) were compared with the measurements obtained for the same location with the "prepare to stop" supplemental advanced signing (cell ten). This permitted the evaluation of the effect of supplemental advanced signing on improving safe operations.

The acceptance-rejection characteristics are shown in Figure 23 for cell nine and in Figure 24 for cell ten.

Table 13 summarizes measures of safe and unsafe operations for cells nine and ten. There was a higher percentage of vehicles operating in a safe or expected manner with the supplemental advanced signing than without signing. The most significant change that the "prepare to stop" signal seemed to have affected was a reduction in the percentage of vehicles

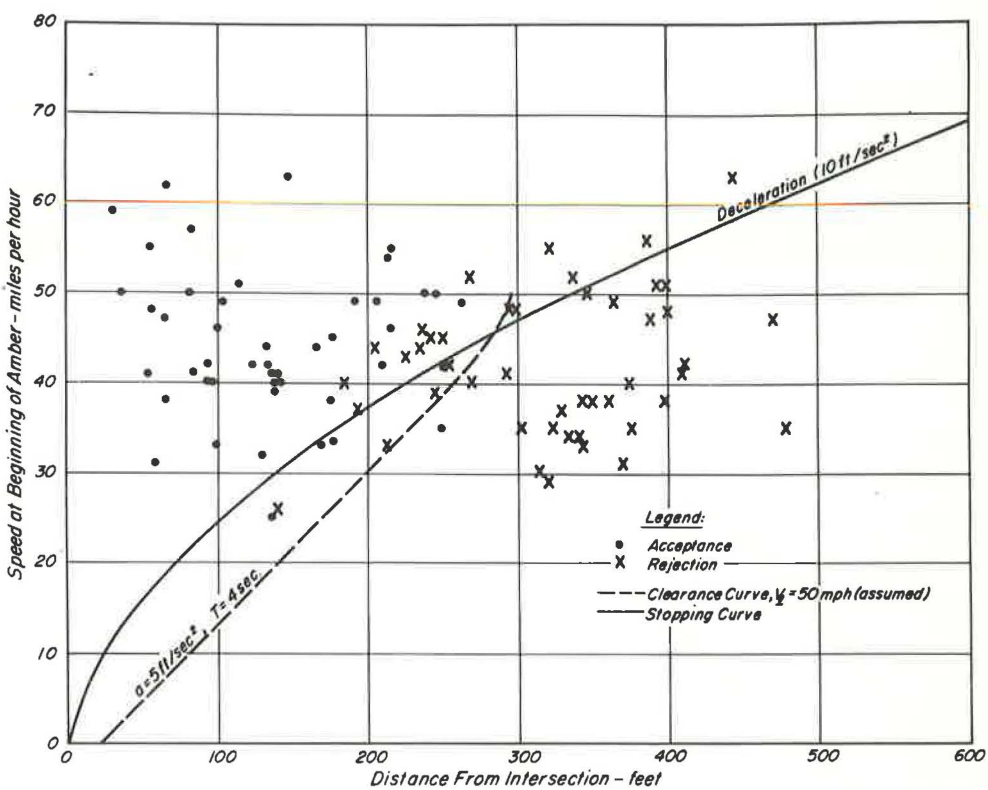

Figure 23. Cell nine acceptance-rejection characteristics.

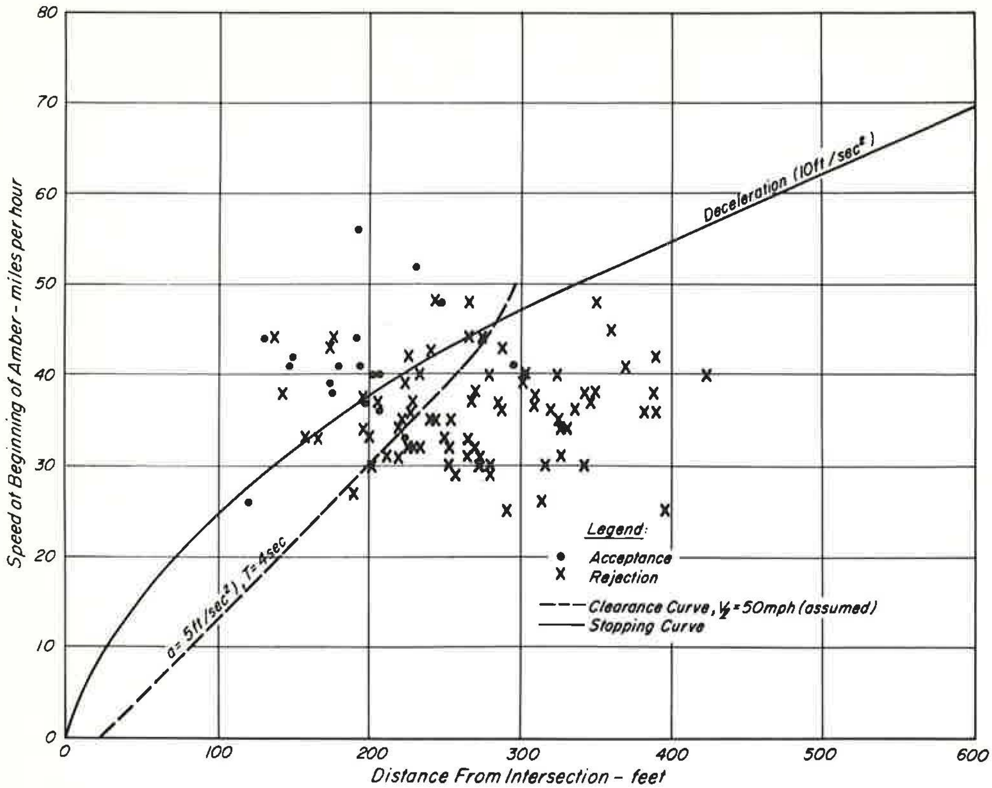

Figure 24. Cell ten acceptance-rejection characteristics.

caught in the dilemma zone from 7 percent (cell nine) to 0 percent (cell ten). This was accomplished by a marked reduction in the approach speed ceiling of the speed-distance plots (Figs. 23 and 24), which in effect had transferred to the option zone the percentage of vehicles that otherwise would have been caught in the dilemma zone (Table 13). Overall, the supplemental advanced signing resulted in the improvement of safe operations.

Table 14 summarizes the risk measurements for cells nine and ten. The values of risk measurements for the accepting and rejecting vehicles were augmented by high percentages of vehicles exceeding the indicated acceleration and deceleration rates. This was due primarily to the difficulty encountered in reading the exact positions of vehicles from the film because of the inherent peculiarities of the site in question. These values, however, were obtained under the same site conditions and same procedural method of analysis, and thus were consistent in relation to each other.

The results of cells nine and ten were then compared to determine the effect of supplemental advanced signing on safe operations. With such signing the percentages of risk measurements were less, for both accepting and rejecting vehicles, than those without signing. Overall, the

TABLE 13

CELLS NINE AND TEN MEASURES OF SAFE AND UNSAFE OPERATIONS

Measures of Safe and Unsafe Operations	Cell Nine Without Advanced Signing (%)	Cell Ten With Advanced Signing (%)
(a) Safe or Expected Operations		
Accepting in acceptance region	43	14
Rejecting in rejection region	30	57
Option region	9	18
Total	82	89
(b) Unsafe or Unexpected Operations		
Rejecting in acceptance region	10	9
Accepting in rejection region	1	2
Dilemma region	7	0
Total	18	11

TABLE 14

RISK MEASUREMENTS OF CELLS NINE AND TEN

Risk Measurements	Cell Nine Without Advanced Signing (%)	Cell Ten With Advanced Signing (%)
(a) Accepting Vehicles		
Exceeded speed limit after beginning of amber	35	10
Exceeded deceleration rate of 15 ft/sec²	49	20
Exceeded acceleration rate of 8 ft/sec²	58	45
Exceeded deceleration rate of 15 ft/sec² and acceleration rate of 8 ft/sec²	29	15
Entered intersection on red phase	4	10
Changed lanes during amber phase	2	0
Percent of accepting vehicles involved in one or more risks	89	55
(b) Rejecting Vehicles		
Exceeded speed limit after beginning of amber	0	1
Exceeded deceleration rate of 15 ft/sec²	35	26
Exceeded acceleration rate of 8 ft/sec²	28	34
Exceeded deceleration rate of 15 ft/sec² and acceleration rate of 8 ft/sec²	9	6
Changed lanes during amber phase	0	0
Percent of rejecting vehicles involved in one or more risks	60	54
Percent of all vehicles involved in one or more risks	74	54

effect of supplemental advanced signing was to improve safe operations at the location studied. This inference was consistent with that obtained from the acceptance-rejection plots.

SUMMARY

It should be emphasized that the purpose of this pilot investigation was to identify promising modifications of amber period duration, transverse pavement markings, and supplemental advanced signing which gave evidence of improvements of safe operations at signalized intersections. The purpose was not to provide conclusive evidence for the modifications studied. A comprehensive summary tabulation of the two sets of risk measurements for each of the ten cells of data is shown in Figure 25.

1. An extensive search of the literature was undertaken and some 76 references were studied in detail. Although much has been written on this subject, specific means for further improving safe operations at signalized intersections have not been thoroughly tested and validated.

2. Fifteen states have laws similar to California pertaining to the behavior of motorists with regard to the amber phase. The California law is in agreement with the recently revised Manual on Uniform Traffic Control Devices. The current practice in California with regard to amber duration is similar to other states with similar laws. Although many states recognize this aspect of signal operations as a safety and/or capacity problem, only a few states have research studies under way.

3. The theoretical analyses have shown that the type of law pertaining to the behavior of motorists with regard to the amber phase has a significant influence on traffic engineering practices that provide safe operations. The current California practice is in keeping with the current California law and either eliminates or greatly minimizes the possibility of a dilemma zone. Equations have been developed to calculate the minimum amber time in order to eliminate the dilemma zone and provide safe operations.

4. Increasing the amber phase at the urban location from 3 to 5 sec increased the percentage of motorists operating in an unsafe or unexpected manner.

5. Increasing the amber phase at the rural location from 5 to 7 sec decreased the percentage of motorists operating in an unsafe or unexpected manner.

6. The installation of experimental transverse pavement markings at the urban location slightly

CONTROLLED CONDITIONS \ LOCATION	URBAN-SAN PABLO AT VALE		RURAL-RT. 4 AT SUMMERVILLE		JUNIPERO SERRA BLVD AT CLAY AVENUE
	NORMAL CONDITIONS	CONTROLLED CONDITIONS	NORMAL CONDITIONS	CONTROLLED CONDITIONS	NORMAL CONDITIONS
Clearance Interval Existing State Practice	1 12/11	3 31/26	5 25/39	7 21/28	9 18/74
Clearance Interval Increased Duration	2 15/24		6 14/26		
Supplemental Advanced Signing					10 11/54
Supplemental Pavement Markings		4 22/27		8 28/38	

Figure 25. Summary of two sets of risk measurements (12/11 = % unsafe operations, acceptance-rejection/% risk measurements).

decreased the percentages of motorists operating in an unsafe or unexpected manner.

7. The installation of experimental transverse pavement markings at the rural location increased the percentage of motorists operating in an unsafe or unexpected manner.

8. The installation of supplemental advance signing location decreased the percentage of motorists operating in an unsafe or unexpected manner.

9. Future studies extending this work and directed toward providing conclusive evidence for modification improvements will require more accurate measurements than were obtained in this pilot study. Greater photographic detail, perhaps from the air, coupled with more frequent exposures per unit of time will be necessary.

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