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I am submitting herewith a dissertation written by Daniel Bruce Fambro entitled "An Evaluation of Three Active Warning Devices for Use at Railroad-Highway Grade Crossings." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Civil Engineering.

R. W. Heathington, Major Professor

We have read this dissertation
and recommend its acceptance:

Accepted for the Council:

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and Dean of The Graduate School

AN EVALUATION OF THREE ACTIVE WARNING DEVICES FOR USE AT RAILROAD-HIGHWAY GRADE CROSSINGS

A Dissertation

Presented for the

Doctor of Philosophy Degree

The University of Tennessee, Knoxville

Daniel Bruce Fambro

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DEDICATION

This dissertation is dedicated to my parents, Jack and Maxine Fambro, whose love, support, and sacrifices have made this and so much more possible, and to three special friends, Melinda and Chance Pollard and Ted Revis, whose memories will live with me forever.

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ABSTRACT

Research to improve safety at railroad-highway grade crossings has been ongoing for some fifty years; however, the methods used for warning motorists of impending danger at the crossing have changed little during this time. This research evaluated several innovative active warning devices in both the laboratory and the field, and documented their performance under normal conditions at existing crossings. The three basic systems being evaluated were four-quadrant gates, four-quadrant flashing light signals, and highway traffic signals.

In the laboratory study, 32 test subjects, two questionnaires, and an instrumented vehicle were used to evaluate the perceived and operational performance of two alternatives for each of the three basic systems in a near real-world environment. Each of the six innovative devices (two alternatives for each of three systems) tested were perceived as superior to existing active warning devices with the four-quadrant gates being the most effective and the four-quadrant flashing light signals the least effective of the three systems. In terms of driver behavior, the four-quadrant gates were the best performing for all measures of effectiveness with the ranking of the other two systems varying depending on the measure being evaluated. Based upon these results, one alternative of each basic system was chosen for a subsequent field evaluation.

In the field study, an automatically controlled video data collection system was used to collect driver behavior data at three grade crossings in Knoxville, both before and after the new devices were

installed. Each of the innovative devices performed acceptably, both from a technical and practical standpoint. Two of the devices, the four-quadrant gates and highway traffic signal, would improve safety at railroad-highway grade crossings. The third device evaluated in this research, four-quadrant flashing lights, resulted in no measurable differences in driver behavior. Based upon these results, it is recommended that four-quadrant gates and highway traffic signals be tested at additional crossings, and if these results are also favorable, that an effort be made to have them adopted by the Manual on Uniform Traffic Control Devices as standard active warning devices for use at railroad-highway grade crossings.

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I. INTRODUCTION

During the ten year period from 1977 to 1986, injuries and fatalities resulting from car-train accidents at railroad-highway grade crossings have decreased from 4,455 and 846 to 2,192 and 501, respectively (1). Much of this safety improvement can be attributed to the availability of federal funds for grade crossing improvement projects (2). The majority of this funding has been used to upgrade passive crossings to active ones and has resulted in 1986 in over one in four of the 192,454 public grade crossings having active warning devices. Presently, there are 22,066 crossings (11.5 percent) with automatic gates and 32,778 crossings (17.0 percent) with flashing light signals (3).

Even with these improvements, over 50 percent of all car-train accidents occurred at approximately 28 percent of the crossings with active warning devices (3). Although this apparently high number of accidents may be a result of higher vehicle and train volumes, and/or more complex railroad-highway geometrics at active crossings, it is likely that some of the accidents are caused by motorists either not seeing or not understanding the active warning devices presently used at railroad-highway grade crossings (4, 5). Therefore, it seems that the current devices could be improved.

Research to improve safety at railroad-highway grade crossings has been going on for some 50 years. However, the methods used for warning motorists of impending danger at a crossing have not changed significantly during this period of time even though many innovative warning

devices have been developed for use both at and in advance of crossings. In other words, field implementation of new concepts during the past 50 years has been minimal.

Background

Recognizing the need to fully address the issues and problems concerning active warning devices at railroad-highway grade crossings, the Federal Highway Administration sponsored a research project at the University of Tennessee to identify and evaluate innovative active warning devices with potential for improving safety at railroad-highway grade crossings. As part of this research, eight innovative active warning devices were identified as having potential for improving safety, and a subsequent analysis identified five of them for detailed laboratory evaluation (6). However, careful review of the five devices determined that they were in fact variations of three conceptually different "generic" or basic systems (e.g., automatic gates, flashing light signals, and highway traffic signals). For this reason, the laboratory testing evaluated six devices consisting of two variations of each of the three basic systems. These six devices included the five most promising of the eight candidate devices plus one additional device which appeared to have significant merit and was a logical variation of one of the three basic systems. The six devices chosen for laboratory testing were:

1. Four-quadrant flashing light signals and automatic gates with and without skirts;

2. Four-quadrant flashing light signals with and without overhead strobes; and
3. Highway traffic signals with white bar strobes in one or all red lenses.

Based upon the results of the laboratory evaluation, the three most desirable devices were chosen for subsequent field evaluation under normal traffic conditions at existing crossings.

Objectives

The overall objective of this research was to laboratory test the perceived and operational performance of each of the six candidate devices in a near real-world environment so as to identify the three most desirable devices for subsequent field testing, and then, to field test the operational performance of the three most desirable devices under normal traffic conditions at existing railroad-highway grade crossings. In order to accomplish this objective, the following tasks were conducted:

1. Evaluate the perceived and operational performance of the six candidate active warning devices in a laboratory environment;
2. Quantify driver performance measures in response to the existing traffic control devices at three railroad-highway grade crossings;
3. Install each of the three most desirable devices from the laboratory study at one of the three existing crossings; and
4. Compare the driver performance measures in response to the existing traffic control devices at the crossings to the

driver performance measures in response to the innovative traffic control devices at the same crossing.

Organization

This dissertation is divided into 11 Sections. Section I presents background information on the overall project and the objectives of this dissertation. Section II reviews the history and performance of warning devices used at railroad-highway grade crossings including previous driver performance studies at grade crossings. It also reviews previous driver performance studies at signalized highway intersections as highway traffic signals are one of the candidate devices. Section III describes the experimental plan for the laboratory evaluation of the six candidate devices and Section IV describes the results of this evaluation. The experimental plan and instrumentation, as well as data collection and reduction procedures, for field evaluation are described in Section V. Section VI summarizes the field site selection, and the design, construction, and installation of the prototype devices. Sections VII, VIII, and IX describe several driver performance measures at the three crossings selected as study sites, and compares these measures at the three crossings before and after the innovative devices were installed. Section X compares the relative effectiveness and costs of the three innovative warning devices and discusses crossing conditions where their installation has the greatest potential for improving safety at railroad-highway grade crossings. Conclusions and recommendations of this research are presented in Section XI.

II. REVIEW OF RELEVANT LITERATURE

At railroad-highway grade crossings, the warning system should provide appropriate, timely information in order to enable drivers to make simple decisions about whether or not it is safe to proceed over the crossing. If their informational needs are met, drivers should perform in an acceptable and safe manner. If their needs are not met, drivers may at times, perform in an erratic manner, and safety problems are likely to result. Driver needs at railroad-highway grade crossings can be broken down into three basic areas:

1. Approaching the crossing;
2. Within the critical stopping distance zone; and
3. Crossing the tracks.

When approaching the crossing, drivers need to be made aware of the crossing's presence. This can be accomplished by advance warning signs, pavement markings and sometimes by visual observation of either the crossing or the train itself. At some point when approaching the crossing, drivers reach a critical point where a decision must be made to stop if a train is approaching, or to proceed if one is not. Their need at this point is to be able to see either the train or an active warning device far enough away from the crossing to react and stop safely.

When actually crossing the tracks, driver needs are different depending upon whether passive or active warning devices are present. At passive crossings, drivers need to be able to see far enough down the tracks to determine whether or not it is safe to cross. At active

crossings, the active warning device conveys a message to the driver as to whether or not it is safe to cross. Therefore, it is imperative that the credibility of this message be maintained.

In summary, driver informational needs at railroad-highway grade crossings are that the warning system and/or train be highly visible and that conditions at the track itself be accurately represented. Driver performance measures are a means of assessing the adequacy of the warning system in meeting the driver's needs. The challenge of using driver performance measures for this purpose is the definition of what constitutes good driving behavior. This chapter reviews the development of the warning system itself as well as past research on driver performance at grade crossings and also at signalized highway intersections as highway traffic signals are one of the candidate devices for laboratory and field evaluation. The discussion will focus on active warning devices as they are the subject of this research.

Warning Devices for Use at Grade Crossings

There are two basic types of warning devices for use at railroad-highway grade crossings--passive devices and active devices. Passive devices, including signs and pavement markings, provide static warning of a grade crossing. Active devices warn drivers of the approach or presence of a train. Two types of active warning systems are in common use, i.e., flashing light signals and flashing light signals with automatic gates. Both of these systems combine passive signs and pavement markings with active warning devices to warn and regulate traffic at railroad-highway grade crossings.

Historical Development. One of the earliest active warning devices used in this country is that shown in Figure 1 -- a signalman on horseback preceding the train, waving a flag, and shouting "a train is coming" to warn people away from the tracks (7). From this, evolved the practice of a signalman standing at the crossing and waving a red flag or paddle during the day and a red-colored lantern at night to warn of approaching trains. The first steps toward replacing flagmen were taken around 1890 when an automatic switch was used to detect the presence of a train and activate a visual device known as a "wig-wag" which simulated the action of a signalman waving his flag or lantern (8). During the next few years, several types of flashing device signals were put into service. Most used a horizontal array of lights and simulated the signalman's swinging lantern by sequential lighting back and forth.

The forerunner of the modern-day flashing light signal was installed in 1913 by the Central Railroad of New Jersey at Woodbridge Avenue, Sewaren, New Jersey (9). Basically, the unit consisted of two alternately-flashing horizontal red lights each with 5 3/8-inch diameter lenses. The use of this device spread rapidly and operational experience soon revealed a need for much stronger lights, and as a result, the 8 3/8-inch diameter lens was introduced in 1923. By 1930, there were over 60 different warning devices being used on different railroads, and it was at this point in time that the American Association of Railroads (AAR) decided that the two most widely favored devices, the wig-wag and the flashing light signals, be adopted as standard.

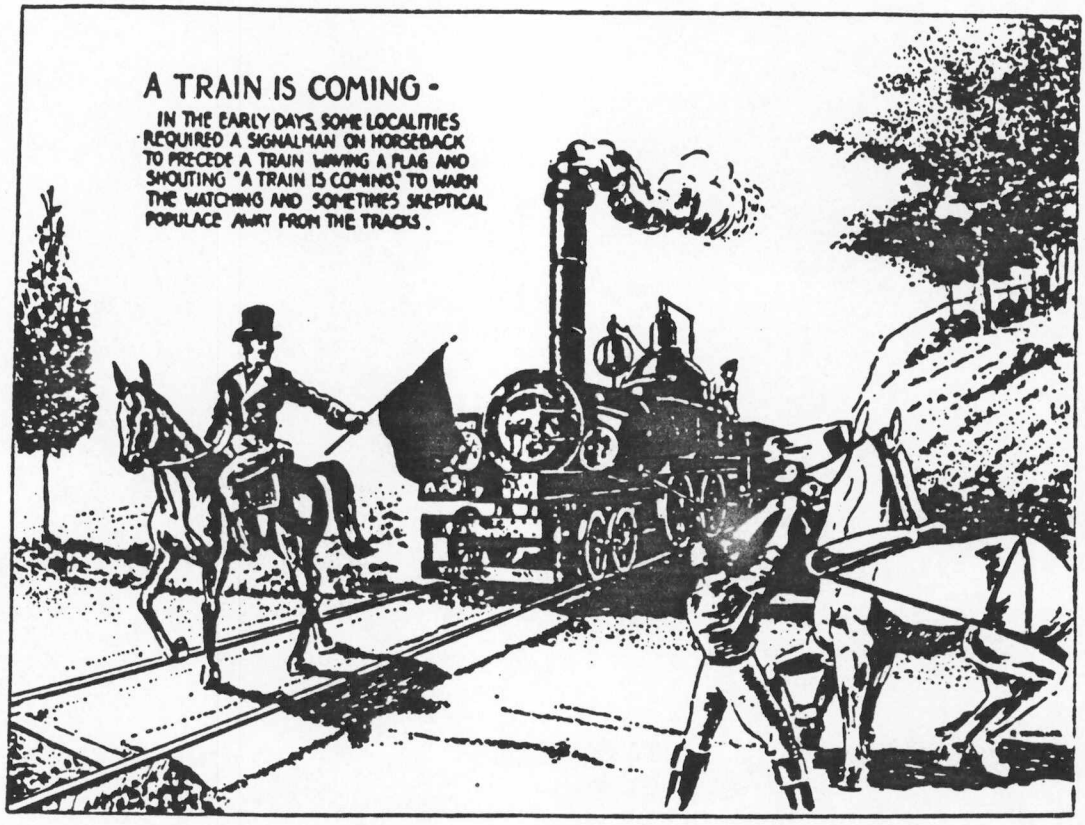
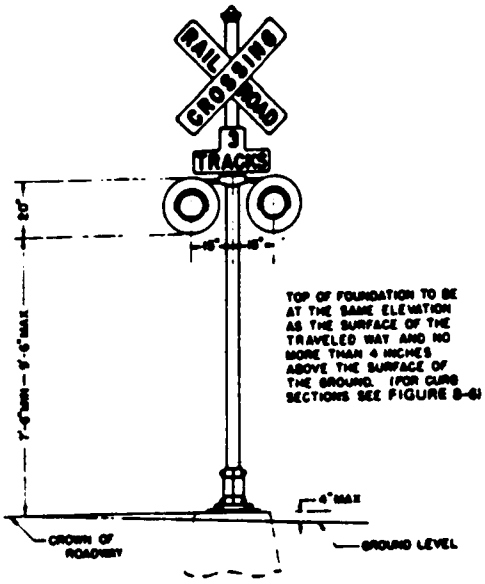


FIGURE 1. AN EARLY ACTIVE WARNING DEVICE FOR USE AT RAILROAD-HIGHWAY GRADE CROSSINGS

Since that time, use of the wig-wag for new construction has ceased and the two alternately-flashing horizontal lights have become the national standard.

The other type of active warning device in use today is the short-arm automatic gate. Originally, gates were designed for manual operation by a signalman. They would be lowered in advance of a train's arrival and raised after its departure. By 1935, there were about 4,700 manual gates at crossings in the United States (10). In the same year, 26 automatic gates were installed nationwide in an effort to provide more protection and reduce labor costs. Interestingly, both the manual and early automatic gates blocked the entire roadway as is currently done in much of Europe (11). It was not until July 1936 that the first short-arm automatic gate, today's standard, was installed. This concept was quickly accepted and within ten years short-arm gates were being installed at approximately 1,000 new crossings per year (10).

Flashing Light Signals. A standard flashing light signal assembly is illustrated in Figure 2 (12). It includes a standard crossbuck sign, an auxiliary "number of tracks" sign when there is more than one track, and the flashing light signals. The flashing lights can be either post- or cantilever-mounted. They are normally placed to the right of approaching highway traffic on all roadway approaches to the crossing. Additional pairs of lights can be mounted on the same support and directed toward highway traffic approaching from another or opposite direction. Signals on both sides of the street are used at one-way streets and certain divided highway locations. The signals, as well as



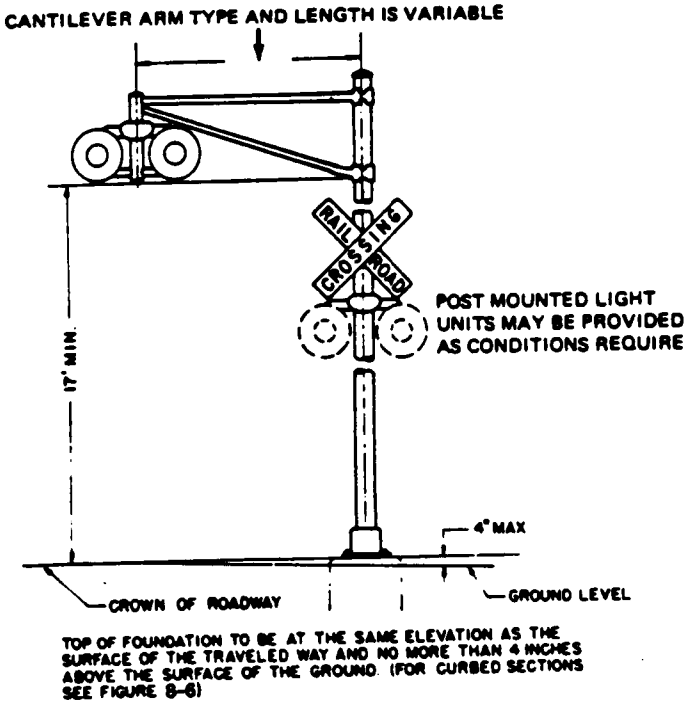
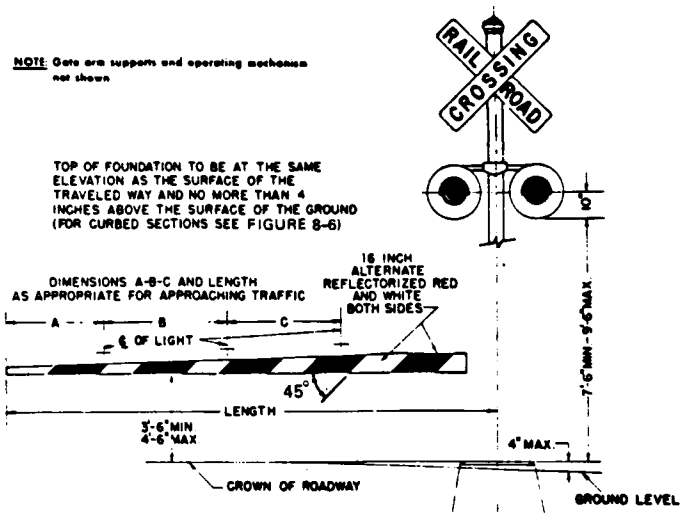


FIGURE 2. TYPICAL FLASHING LIGHT SIGNAL ASSEMBLIES

other active warning devices, are required to operate in a fail-safe manner, i.e., failures or loss of electrical power cause the warning system to be activated. A trickle-charged 12-volt battery system is used to provide backup power for, in most cases, more than 48 hours of normal operation.

Flashing light signals are activated a minimum of 20 seconds before the train's arrival whereupon the two lights begin to flash alternately at a rate of 35 to 55 times per minute (13). They continue to flash until after the train has cleared the crossing. The two lights are spaced 30 inches apart on a horizontal crossarm and consist of either two 8 3/8-inch or two 12-inch diameter red lenses, or roundels as they are more commonly called, each surrounded by 20-inch diameter black backgrounds. Inside the lamp housings are located a 10 to 36 watt bulb and a reflector. These low wattages are used because of the limitation of the backup power system. To compensate for this constraint, the reflector and roundel work in conjunction with one another to focus the hot spots of these lights along a relatively narrow-field or view. Therefore, focusing and aiming procedures are extremely critical.

Flashing Light Signals with Automatic Gates. An automatic short-arm gate is illustrated in Figure 3 (12). As shown, it is used in conjunction with a flashing light signal and consists of a drive mechanism and a fully reflectorized red and white striped gate arm with three lights. They may be located on the same post as the flashing light signals or separately mounted. When the gate is in the down position, it extends across the approaching lanes of traffic at a height



Typical minimum clearance is 2 feet from face of vertical curb to closest part of signal or gate arm in its upright position for a distance of 17 feet above the crown of the roadway.

Where there is no curb, a minimum horizontal clearance of 2 feet from edge of a paved or surfaced shoulder shall be provided with a minimum clearance of 6 feet from the edge of the traveled roadway where there is no curb or shoulder, the minimum horizontal clearance shall be 6 feet from the edge of the roadway.

Where gates are located in the median, additional width may be required to provide the minimum clearance for the counterweight supports.

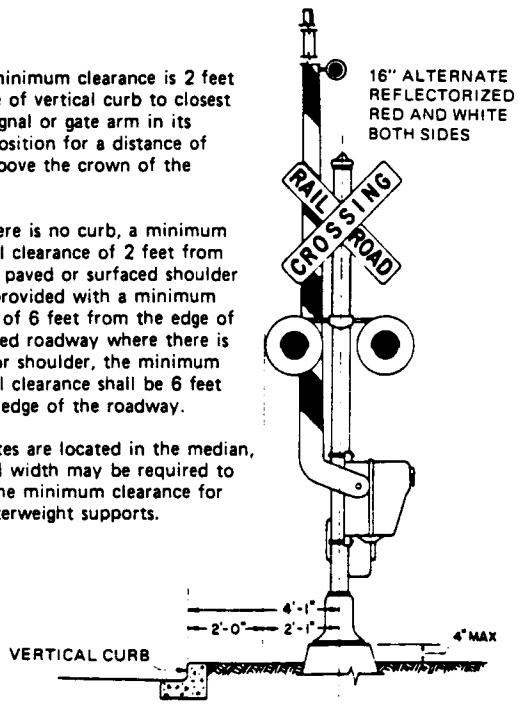


FIGURE 3. TYPICAL AUTOMATIC SHORT-ARM GATE INSTALLATION

of approximately four feet above the pavement's surface. The red and white stripes are 16 inches in length and are cut such that they slope down toward the center of the roadway at a 45 degree angle. The flash pattern of the gate arm lights is steady burn by the end or tip light and alternate flash by the two inside lights. They are activated at the same time as are the flashing light signals; however the downward motion of the gate arm generally lags the light activation by five to ten seconds. Gate arms can be made of aluminum, fiberglass, or wood. Their generally acceptable maximum practical length is 44 feet.

Guidelines for Use. Guidelines for the conditions under which different warning devices should be installed are contained in three documents--the Manual of Uniform Traffic Control Devices (MUTCD) (12), the Railroad-Highway Grade Crossing Handbook (14, 15), and the Traffic Control Devices Handbook (16). The first document has been adopted as a national standard and as such is a legal requirement whereas the other documents' contents provide guidelines and practical applications thereof. Basically, passive warning devices are required at all grade crossings, and active warning devices are recommended where increased levels of warning and/or control are needed. Factors used in determining the need for active warning devices are contained in the Railroad-Highway Grade Crossing Handbook (14, 15) and illustrated in Table 1.

The intent of these guidelines is to provide a consistent application of the warning devices so as not to violate a driver's expectancy; however, field installations do not always reflect this

TABLE 1. FACTORS USED IN DETERMINING THE NEED FOR ACTIVE TRAFFIC CONTROL DEVICES AT RAILROAD-HIGHWAY GRADE CROSSINGS

FACTORS CONSIDERED FOR FLASHING LIGHT SIGNALS	ADDITIONAL FACTORS CONSIDERED FOR AUTOMATIC GATES
• Vehicular traffic volume - an ADT of less than 1,000 would require other significant warrants;	• Multiple main line railroad tracks;
• Railroad traffic volume - less than 6 trains per day would normally represent light exposure except where passenger train operations exist;	• Multiple tracks where a train on or near the crossing can obscure the movement of another train approaching the crossing;
• Maximum train speeds - speeds greater than 50 miles per hour in rural areas or 35 miles per hour in urban areas deserve careful consideration;	• High speed train operations combined with limited sight distance;
• Maximum permissible vehicular speeds - speeds in excess of 35 miles per hour in rural areas or 25 miles per hour in urban areas deserve careful consideration;	• Combination of high speed and moderately high volume highway and railroad traffic;
• Pedestrian volumes - pedestrian volumes of 150 or more per hour may be a significant determinant;	• Presence of school buses, transit buses, or farm worker vehicles in the traffic flow;
• Accident record - occurrence of a train-involved accident within a three year period indicates a need for careful analysis;	• Presence of trucks carrying hazardous materials, particularly when the view down the track from a stopped vehicle is obstructed;
• Reduced sight distance - limited view of tracks should be checked for limited driver reaction; and	• Presence of passenger trains; and
• Elimination potential - closing lightly used crossings and installing active devices at more heavily used crossings should be considered.	• Continuance of accidents after installation of flashing lights.

fact. For example, in a study of 287 crossings in 44 states, 84 percent were judged not to be in conformance with MUTCD standards for one reason or another (17). However, only 11 percent of the crossings were not in compliance with the Railroad-Highway Grade Crossing Handbook guidelines (14, 15) in that the proper type of device was not installed, i.e., passive signs and markings alone or in combination with flashing light signals and/or automatic gates. Thus, it appears that the "Handbook" guidelines are being adhered to fairly well whereas strict compliance with the MUTCD standards are often not being met.

Driver's Responsibilities. Drivers are required to use reasonable and prudent behavior in operating their motor vehicles, whether it be at a railroad-highway grade crossing, a regular highway intersection, or any other place on the road. With regard to grade crossings, specific legal requirements are outlined in the Uniform Vehicle Code (UVC) (18) and in various state traffic regulations. Following is an excerpt from the UVC establishing driver duties at grade crossings.

> (a) Whenever any person driving a vehicle approaches a railroad grade crossing under any of the circumstances stated in this section, the driver of such vehicle shall stop within 50 feet, but not less than 15 feet, from the nearest rail of such railroad, and shall not proceed until he can do so safely. The foregoing requirements shall apply when:
> 1. A clearly visible electric or mechanical signal device gives warning of the immediate approach of a railroad train;
> 2. A crossing gate is lowered or when a human flagman gives or continues to give a signal of the approach or passage of a railroad train;
> 3. A railroad train approaching within approximately 1,500 feet of the highway crossing emits a signal audible from such distance and such railroad train, by reason of its speed or nearness to such crossing, is an immediate hazard;

4. An approaching railroad train is plainly visible and is in hazardous proximity to such crossing.

(b) No person shall drive any vehicle through, around or under any crossing gate or barrier at a railroad crossing while such gate or barrier is closed or is being opened or closed.

Unfortunately, not all states have traffic laws which are consistent with the UVC. This lack of consistency may be a source of confusion for some drivers. For example, there are at least 9 states that do not expressly prohibit driving under or around a lowered gate arm (19), and at least two of them, Louisiana and Missouri, actually permit a motorist to drive around a lowered gate arm when it is safe to do so.

Indeed, not all drivers understand their responsibilities at a grade crossing. In a study of 829 subjects (20), over 50 percent of the respondents thought they should stop at unsignalized crossings and 25 percent thought they should stop at all signalized crossings whether or not the signal was flashing. Approximately 30 percent of the respondents did not recognize the standard MUTCD (12) signs and markings associated with grade crossings and more than 50 percent thought that all crossings except those rarely used by trains were protected by active warning devices. Clearly, there is too large a percentage of motorists who do not fully understand and/or comprehend their legal responsibilities at railroad-highway grade crossings. The consequences of an improper decision at such a location can lead to death or serious injury.

Driver Performance at Grade Crossings

There is much published literature concerning safety at railroad-highway grade crossings. However, it is somewhat surprising that

only a limited number of studies have attempted to address and quantify driver behavior at grade crossings. The driver performance measures of effectiveness (MOE's) reported in these studies include looking behavior, speed profiles, speed changes, deceleration levels, and conflicts and violations. These MOE's are discussed individually in the following sections:

Looking Behavior. Looking behavior refers to whether and where the driver looks as he/she approaches a crossing. A general assumption regarding looking behavior is that a safe driver is one who looks for trains. However, this is not necessarily the case at active crossings where the warning device itself is an indication of an approaching train. At these locations, a safe driver has only to look for the warning device. However, a study of six crossings with flashing light signals in three different urban areas found that up to 50 percent of all drivers looked in at least one-direction during time periods when the signals were not activated (21). In addition, there appeared to be more looking during time periods of heavy train traffic.

In another study of three passive and six active crossings, behavioral data were collected on over 18,000 vehicles and from 1,200 driver questionnaires (22). Nearly 80 percent of the drivers interviewed said they detected a crossing by simply remembering that it was there, while approximately 20 percent relied on the warning system or visual observation. One percent of the drivers did not know they had just driven through a crossing. Looking behavior varied from site to site; however, no consistent differences in driver behavior were found

between active and passive crossings. The behavioral differences that did exist from site to site were a function of train volume and driver familiarity, i.e., familiar drivers tended to look more at crossings where train volumes were high and at the same crossing, they tended to look less than unfamiliar drivers. There was no difference in looking behavior at crossings with severe sight distance restrictions compared to those with minor or no restrictions. These collective findings seem to indicate that many drivers may be relying on past experience rather than on warning devices to determine whether or not a train is approaching.

Speed Profiles. Most driver behavior studies at grade crossings have considered approach speed profiles since speed data are easier to gather and interpret than looking behavior data. Figure 4 illustrates typical approach speed profiles for urban and rural crossings (23). Note in the figure that the speed data are expressed as percentages of the speeds at which the vehicles entered the crossing area. The data indicate that speed reductions at the passive crossings tended to be greater and occur sooner than at the active crossings. This was true in both urban and rural conditions; however, the differences were less at rural crossings. One shortcoming of comparing speed profiles at different crossings is the fact that speed reductions of familiar drivers are proportional to the roughness of the crossing surface, i.e., the rougher the crossing the greater the speed reduction. This relationship is illustrated in Figure 5 (23).

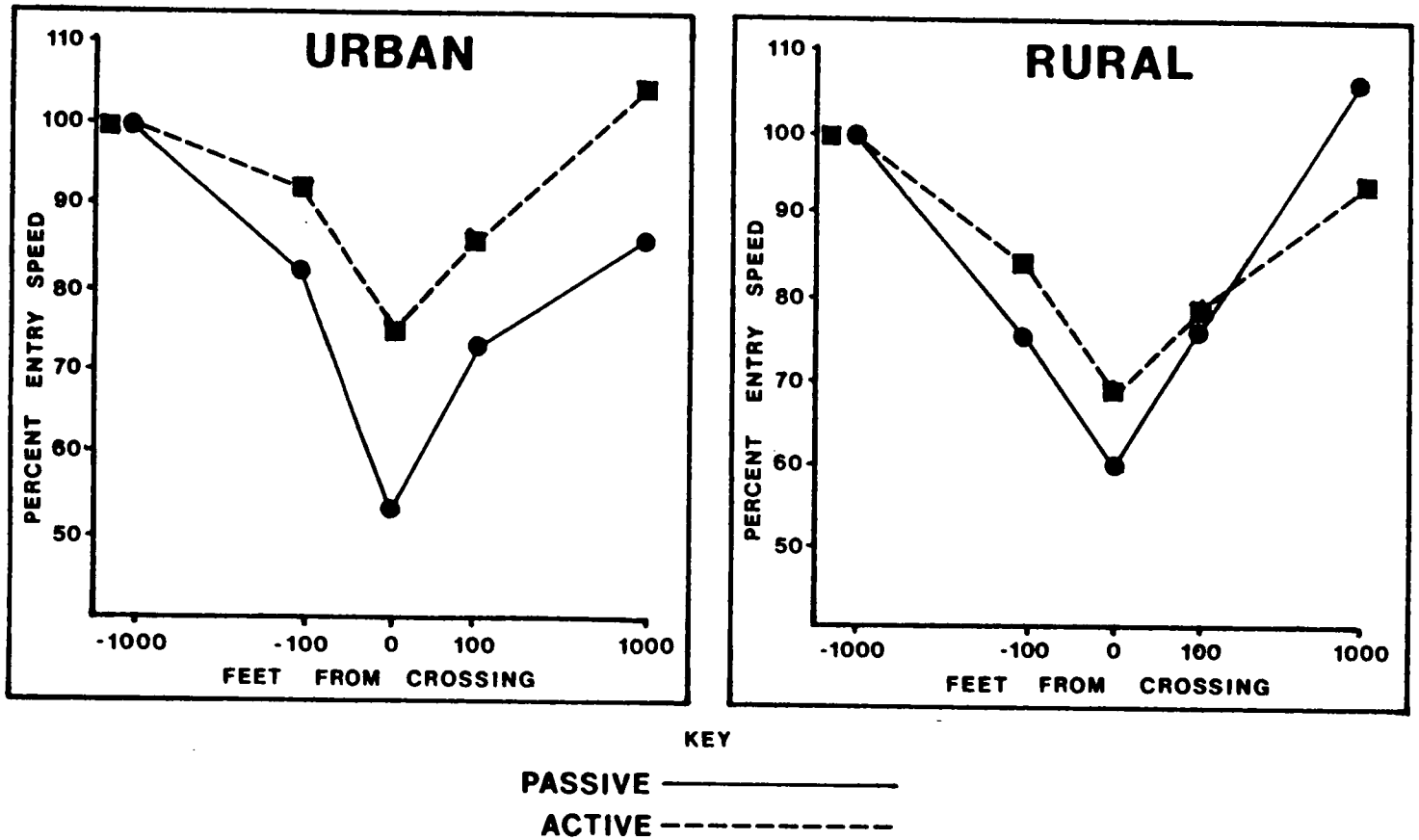


FIGURE 4. SPEED PROFILES BY PROTECTION TYPE FOR ALL VEHICLES AT TWO-LANE URBAN AND RURAL CROSSINGS

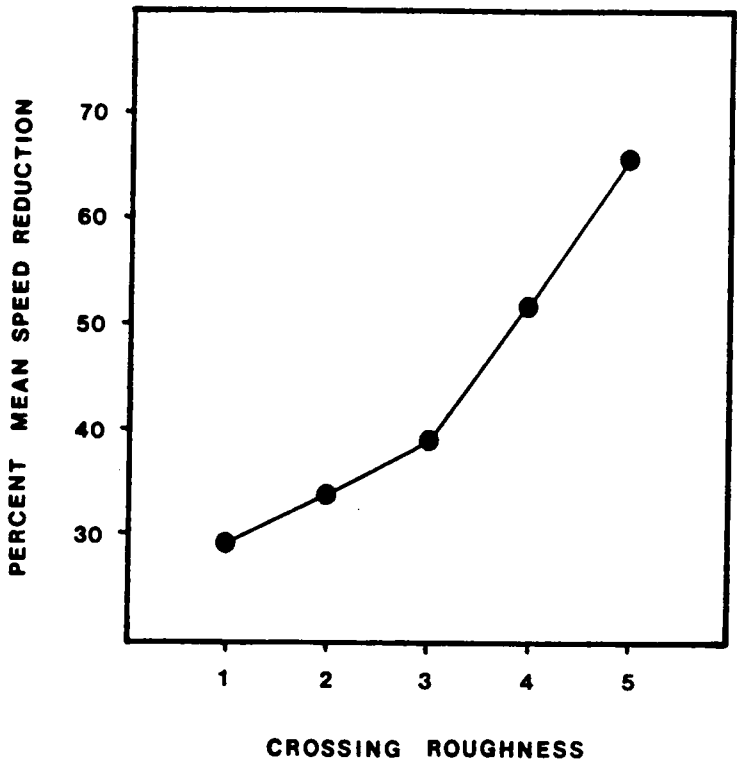


FIGURE 5. PERCENT SPEED REDUCTION AS RELATED TO CROSSING ROUGHNESS

When evaluating approach speed profiles in response to active warning devices, it should be recognized that the presence of the train and other vehicles will have an effect on approach speed. Therefore, speed profile data should be separated into categories of similar expected behavior. Past studies have in fact utilized four basic categories for approach speed profiles. In each successive category, drivers were presented with an additional visual stimulus at the crossing (24, 25). The first category, "free flow vehicles," included those vehicles traveling through the crossing with no stimulus other than the existence of the crossing and its nonactivated warning devices. The second category, "first unobstructed vehicles," included those vehicles that entered the crossing area while the warning devices were activated by the approach of a train, but chose to pass through the crossing. The added stimulus was that of the activated signals. The third category, "first obstructed vehicles," included those vehicles that entered the crossing area while the warning devices were activated and the train was already blocking the crossing or was in such close proximity as to present a hazard. These vehicles were obstructed by the added stimulus of train presence. The final category, "following vehicles," included those vehicles entering the crossing area under conditions of activated warning devices, a train blocking the crossing, and the added stimulus of one or more vehicles already stopped at the crossing.

Approach speed profiles for each of these vehicle categories are illustrated in Figure 6 (24). Note that free-flow vehicles entered the crossing area at about the same speed as the first unobstructed vehicle,

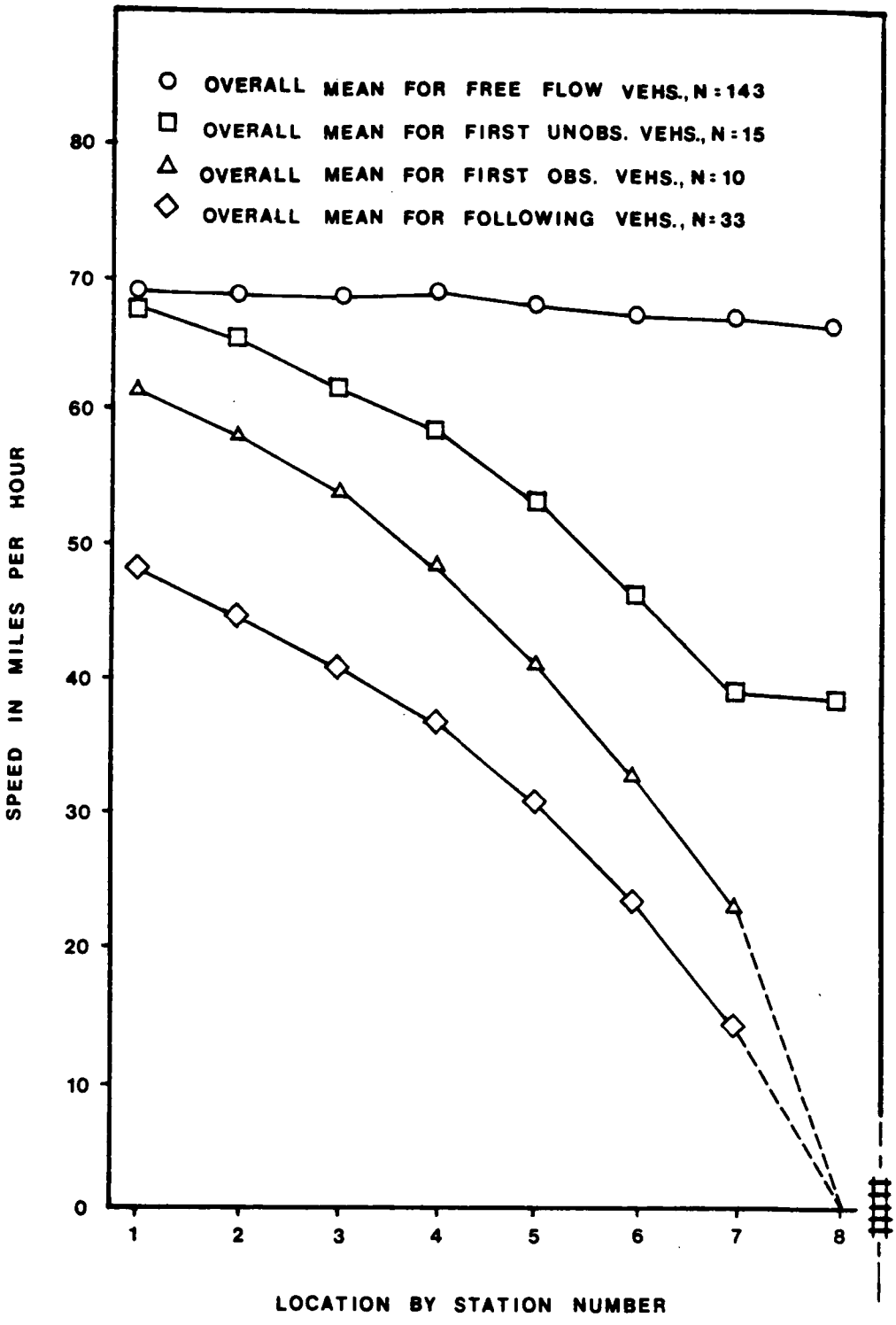


FIGURE 6. APPROACH SPEED PROFILES FOR DIFFERENT CATEGORIES OF ENTERING VEHICLES

but faster than the first obstructed and following vehicles; that entry speeds of first unobstructed vehicles may not be distinguishable from first obstructed vehicles, but are faster than those of following vehicles; and that entry speeds for first obstructed vehicles are faster than those of following vehicles. In each case the slower vehicles were in a category benefiting from an added stimulus at the crossing.

From these results, it might be inferred that flashing light signals, operating when a train is not in immediate presence, are not commanding enough to cause unobstructed drivers to decrease their speed until they are relatively close to the crossing. In other words, they either anticipate the possibility of crossing safely ahead of the train, or they do not see an indication of hazard as early as drivers in other categories. Drivers approaching the crossing when a hazard is indicated, first obstructed vehicles, slow down sooner and decelerate more gradually than those with only the activated flashing light signals in evidence. Finally, drivers faced with activated flashing light signals, a train blocking the crossing, and vehicles stopped in the roadway begin slowing down even further from the crossing. This final observation may point out some advantages of automatic gates in that they provide drivers with earlier visibility of a hazard in the roadway, while also eliminating the option of unobstructed motorists deciding to beat the train (24).

Perhaps the best use of approach speed profiles is in comparing different conditions at a particular grade crossing, since crossing roughness would not be a variable factor. At least two notable studies have used this approach. In the first, a comparison was made before and

after automatic gates were added to the existing flashing light signal system at the crossing (25). Figure 7 presents the speed profile results from this study. As shown in the figure, the first unobstructed drivers entered the crossing area at approximately free flow-speed and began to slow down to a speed of about 30 miles per hour. At this point in the before condition, the first unobstructed drivers decided it was safe to cross the tracks in front of the train whereas in the after condition, the automatic gates took this decision away from the driver. Thus, these drivers were reclassified as first obstructed. Taking the option to cross in front of the train away from the driver theoretically eliminates the possibility of a bad decision, provided the gates operate in a timely and reliable manner.

The other comparative study evaluated five warning device conditions at the same site (26):

1. Passive signs and markings;
2. Non-activated flashing light signals;
3. Activated flashing light signals;
4. Non-activated flashing light signals and raised automatic gates; and
5. Activated flashing light signals and lowered automatic gates.

Table 2 and Figure 8 summarize the results from this study. Basically, as drivers approached the study crossing, they reduced their speed significantly under all five conditions. Speed reductions in the presence of the passive signs were significantly greater than in the presence of the non-activated flashing light signal condition and automatic gates. However, 30 percent of the speed reductions were not

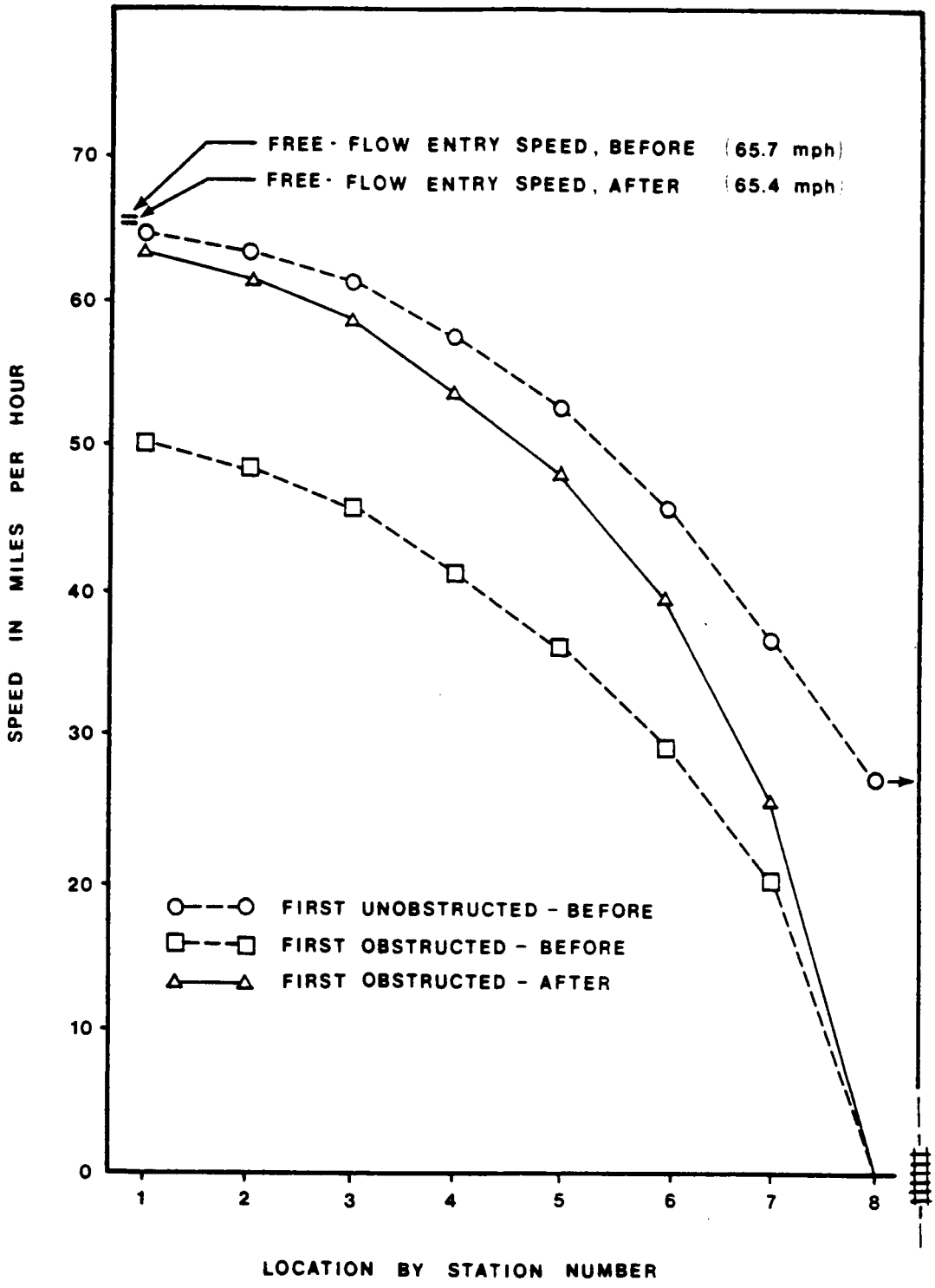


FIGURE 7. APPROACH SPEED PROFILES BEFORE AND AFTER FLASHING LIGHTS WERE REPLACED BY AUTOMATIC GATES

TABLE 2. DRIVER SPEEDS APPROACHING A RAILROAD-HIGHWAY GRADE CROSSING AS A FUNCTION OF DIFFERENT WARNING DEVICES

	Condition					
	Passive Signs (n=95)	Signal Off (n=130)	Signal Flashing (n=15)	Gate Raised (n=120)	Gate Lowered (n=7)	F-value (4,326)
Speed at 200 m						
Mean (km/hr)	56.1	59.3	54.5	59.1	45.0	7.64**
Standard Deviation	8.2	7.3	11.9	8.6	10.2	
Speed at 80 m						
Mean (km/hr)	47.7	54.1	43.8	54.2	38.7	13.26**
Standard Deviation	10.0	9.5	9.9	9.9	11.1	
Difference						
Mean (km/hr)	8.4	5.2	10.7	5.0	6.3	5.15**
Standard Deviation	8.9	7.2	7.0	5.7	6.0	
t_D	9.2**	8.3**	5.9**	9.6**	2.8*	

Note: 1 km/hr = 0.62 mi/hr; 1 meter = 3.28 feet; * = significant at 0.05 level; and ** = significant at 0.0001 level.

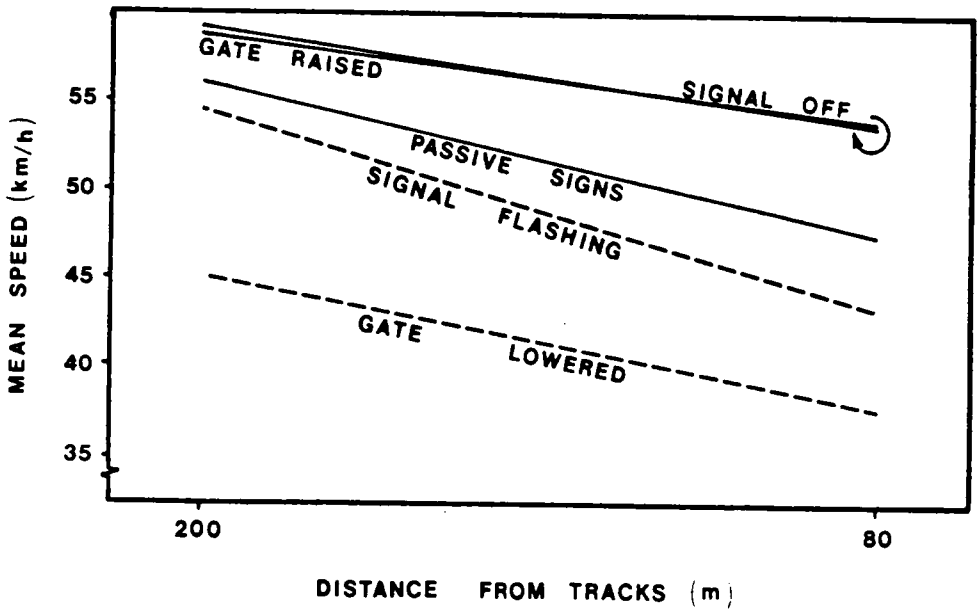


FIGURE 8. MEAN SPEED APPROACHING A RAILROAD-HIGHWAY GRADE CROSSING WITH DIFFERENT WARNING DEVICES

great enough to stop safely from the distance that a train could be seen. The lowered gate arm condition resulted in significantly lower speeds than did the activated flashing light signal condition indicating more of a resignation to stop in front of a lowered gate arm than in front of an activated flashing light signal. These observations support those from the other speed profile studies.

Speed Changes. Speed changes refer to differences in speed between successive points along the roadway. They can be either positive (acceleration) or negative (deceleration). Speed changes are important since there is some evidence accident rates are affected by speed and speed change variance (27). If this is true, railroad-highway grade crossings may be extremely dangerous locations because some drivers slow down to verify the way is clear, some drivers maintain their speed, and some drivers speed up to beat the train. Furthermore, the expected variance might be higher at an active grade crossing than at a signalized highway intersection because activated flashing light signals are an uncommon event whereas changing traffic signals are not.

Results from a study which specifically looked at speed changes on the approach to a grade crossing are summarized in Table 3 (21). From this table, it is seen that, individually, drivers varied their approach speeds and patterns of acceleration and deceleration from crossing to crossing as well as at each crossing. In other words, there were no discernible patterns either between or within crossings even though they all had active warning devices and all data were collected during non-activated conditions. Also, variance of the mean speed change

TABLE 3. PERCENTAGE OF VEHICLES WHICH DECELERATE (D), MAINTAIN A CONSTANT SPEED (C), OR ACCELERATE (A) BETWEEN ADJACENT OBSERVATION ZONES AT THE SIX RAILROAD CROSSINGS

Locations	Zone I-II			Zone II-III			Zone III-IV		
	D	C	A	D	C	A	D	C	A
Centre Street	33	20	48	90	5	4	89	3	8
Collins Bay Road	68	14	18	79	9	13	73	4	24
Gardiners Road	47	17	35	67	12	21	76	9	16
Sydenham Road	38	19	42	83	8	10	8	6	87
Elliot Avenue	87	2	11	34	10	56	58	16	26
McConnell Avenue	53	23	24	85	10	5	38	20	42

Note: Percentages may not total 100 because of rounding.

generally increased as the drivers got closer to the crossing at each of the sites. This infers that different drivers behave differently as they approach a grade crossing and these differences increase as they get closer to the crossing. Thus, the likelihood of between vehicle accidents increased.

Deceleration. Maximum deceleration is thought to be a good indicator of warning device effectiveness. Ideally, a driver slowing to a stop should do so gradually. If a driver exceeds some comfortable level of deceleration, it indicates severe braking due to a delayed or surprised reaction by the driver. The Traffic Engineering Handbook (28) defines several deceleration levels as follows:

1. Emergency - greater than 20 ft. per sec^2;
2. Very uncomfortable - 14 to 20 ft. per sec^2;
3. Uncomfortable - 11 to 14 ft. per sec^2;
4. Undesirable - 8 to 11 ft. per sec^2; and
5. Practical - less than 8 ft. per sec^2.

Two studies have analyzed deceleration levels at grade crossings and reached similar conclusions (24, 25). In the first study, 13 drivers out of 520 exceeded the practical deceleration level when approaching an activated flashing light signal (24). In the second study, eight drivers out of 261 exceeded the practical deceleration level when approaching an activated flashing light signal with lowered automatic gates (25). Thus, nearly all of the observed drivers in both studies decelerated at a practical level and no drivers were involved in an accident. This implies that large samples of deceleration levels

would be required to provide conclusive evidence of "unsafe" driver performance at railroad highway-grade crossings.

Conflicts and Violations. In the context of grade crossings, conflicts are undesirable driver actions which place the driver in a dangerous position relative to an approaching train. Violations are illegal driver behavior which may or may not also be a conflict. Both could be termed "risky behavior." One study found that only 46 percent of the drivers approaching crossings with activated flashing lights and 90 percent of the drivers approaching crossings with lowered automatic gates actually stopped at the crossing (29). It is not reported how many of those that did not stop, crossed unsafely; however, dependent upon state law (19), those who drove around the lowered gates probably did so illegally. Other studies have reported from 15 percent (23) to 60 percent (26) of approaching drivers crossing in front of a train while the flashing light signals were activated.

The most frequently cited causal factor for conflicts and violations is the large variability in warning times with train activated warning devices. Reportedly, warning times vary from as short as 17.5 seconds to as long as 2.5 minutes (21). Clearly, these longer warning times are excessive, giving drivers plenty of time to cross in front of the train and be in no real danger. The danger lies with those drivers expecting a long warning time and suddenly being faced with one that is minimum. It is in these situations that a driver may place his/her vehicle in an unsafe position. A related finding is that the longer the

warning time or the expected waiting time, the greater the probability and number of risky maneuvers (23).

Driver Performance at Signalized Highway Intersections

Driver behavior at signalized highway intersections is quite different from that at railroad-highway grade crossings. At a signalized intersection, the traffic signal is always illuminated communicating to drivers that either they should stop (red indication); they should proceed (green indication); or they should be prepared for a change in right-of-way (yellow indication). An unlit traffic signal indicates some type of hardware or power failure and this alone informs the drivers that they should proceed with caution. On the other hand, an unlit signal at a grade crossing indicates that no train is approaching and therefore it is safe to cross.

Most drivers encounter traffic signals on a daily basis and they expect a signal's indication to change frequently. For example, traffic signals commonly change intervals 500 or more times a day. In comparison, grade crossing signals rarely change more than 20 times per day, and in some instances change as few as once or twice per day. Because traffic signals are so common, drivers are aware of and confident in their operation. Driver awareness and confidence in grade crossing signals are probably low in comparison. Driver behavior studies at signalized highway intersections have focused on driver response and actions during the signal's change interval. The pertinent findings from those behavioral studies are discussed in the following sections.

Perception-Brake Reaction Time. At a traffic signal installation, perception time is the time for drivers to come to the realization that brakes must be applied, and brake reaction time is the time required to apply the brakes after perception. The two times cannot be separated during field measurements as it is impossible for an observer to differentiate when perception is accomplished and brake reaction starts. Therefore, the total of the two is generally reported, with the sum defined as the elapsed time from the onset of the yellow signal until the brakes are applied. Both of these points can be easily measured.

Several studies have measured perception-brake reaction time (PBRT) in response to a traffic signal change interval. One of the earliest studies used 87 observations from a single intersection to report a median PBRT of 1.1 seconds and an 85th percentile PBRT of 1.5 seconds (30). A more recent study relied on approximately 100 observations from each of six intersections to report a median PBRT of 1.3 seconds and 85th percentile times from 1.5 to 2.1 seconds (31). The Traffic Engineering Handbook assumes a PBRT in response to a yellow indication of one second (32); however, actual intersection stopping distance data (33, 34) revealed a much higher value of PBRT when stopping was made. When these data were analyzed using deceleration levels ranging from 8 to 15 feet per second per second, three categories of driver behavior (35) emerged as follows:

1. Forced stopping: when more than 85 percent of the drivers go through the intersection, those 15 percent or less of the drivers stopping take less than 1.0 seconds of PBRT;

2. Indecision stopping: when 50 percent of the drivers go through the intersection and 50 percent stop, PBRT is from 1.0 to 1.5 seconds; and
3. Comfortable stopping: when the majority of the drivers decide to stop, their PBRT is from 1.5 to 3.0 seconds.

One shortcoming of these studies is that none of them analyzed PBRT as a function of vehicle speed and distance from the intersection even though the data indicate relationships exist. Findings from one study which analyzed these relationships are presented in Figure 9 (36). As shown in the figure, PBRT decreases with an increase in speed; however, the mean PBRT tends to stabilize at about 0.9 seconds once speeds reach 45 miles per hour. In situations requiring immediate reaction, (e.g., approach speeds greater than 40 miles per hour), the mean PBRT did not increase with distance from the intersection. Instead, it appeared to be relatively constant at 0.9 seconds. Combining these results indicate that 1.2 seconds is a good estimate of an 85th percentile PBRT for both higher speeds and closer distances.

Time of day and weather conditions might also affect a driver's PBRT time. The only study which evaluated these effects reported no differences in driver behavior between day-night or wet-dry conditions (36). As a result of these findings, a mean PBRT of 0.9 seconds and an 85th percentile PBRT of 1.2 seconds were recommended as representative of driver behavior at signalized highway intersections for all lighting and weather conditions.

It should be noted that the PBRT's reported in the aforementioned studies are representative of operationally alert conditions in that

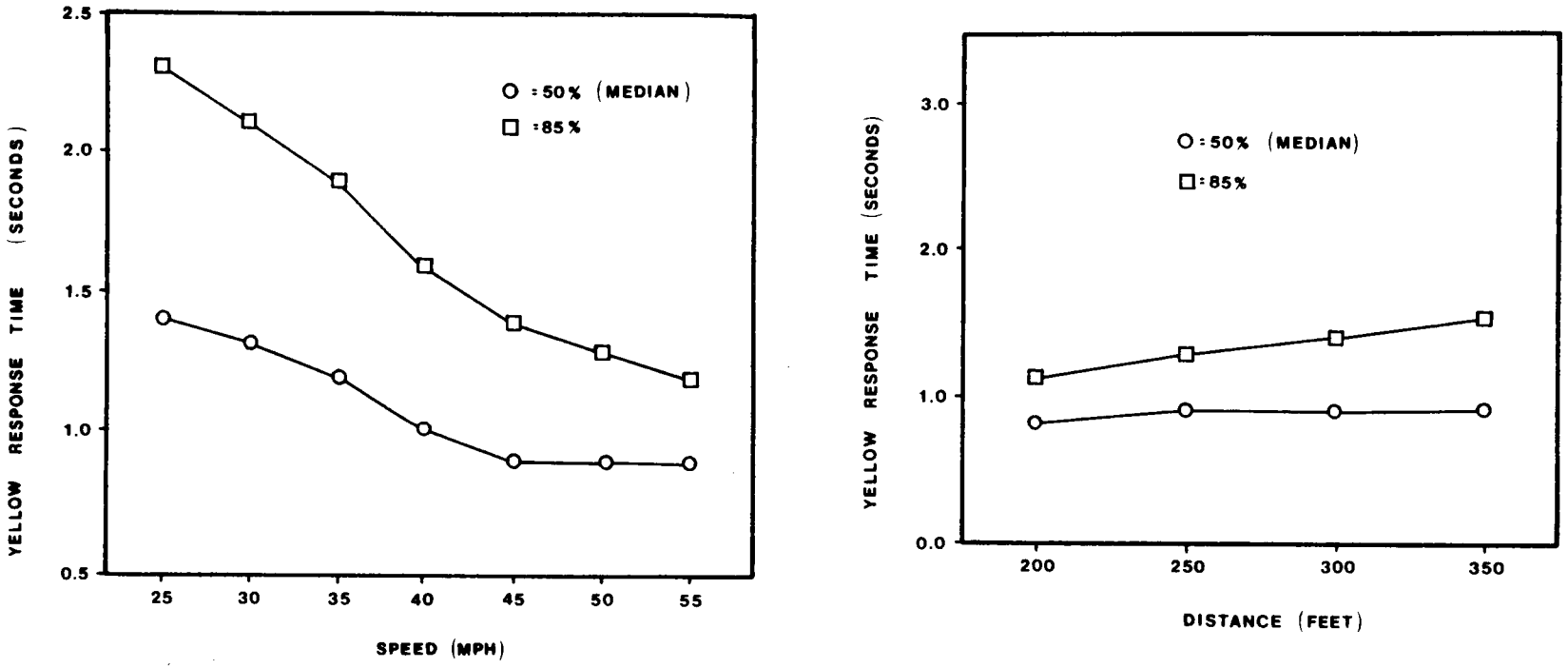


FIGURE 9. PERCEPTION-BRAKE REACTION TIME IN RESPONSE TO ONSET OF YELLOW AS A FUNCTION OF SPEED AND DISTANCE

most drivers were familiar with the traffic signals and expected them to change on a regular basis. If the signals had been complex and/or their change unexpected, such as at an isolated rural intersection or a railroad-highway grade crossing, the drivers may not have been as alert and longer PBRT's would have been observed. The American Association of State Highway and Transportation Officials (AASHTO) recognizes this fact and recommends a PBRT of 2.5 seconds be used for design so as to accommodate most drivers under most conditions (37).

Deceleration. Some researchers recommend a deceleration of 10 feet per second per second (fps^2) for use in calculating the length of a traffic signal change interval (38, 39). In fact, this value is recommended in the 1982 Transportation and Traffic Engineering Handbook (40). A study with field observations reported that when the required deceleration was 8 fps^2 or less, virtually all drivers stopped. When the required deceleration was between 8 and 12 fps^2, some drivers stopped while others proceeded through the intersection. When the required deceleration was greater than 12 fps^2, few drivers stopped (41). It should be noted that deceleration levels observed in field studies are primarily a result of comfort or a "practical" level of deceleration. They are not an indication of whether the driver/vehicle can perform certain decelerations.

Deceleration is governed by the "basic laws of motion" from physics. It is affected by speed, distance, and time, as shown in the following equations:

$$d = (v^2 - v_0^2)/2s$$

or

$$d = (v - v_0)/t$$

where:

d = deceleration, fps^2;

v = initial velocity, fps;

v_0 = final velocity, fps;

s = distance over which change in velocity occurs, ft; and

t = time over which change in velocity occurs, sec.

At an intersection, the distance and time available for deceleration is dependent upon the distance traveled during PBRT in response to onset of the yellow indication. Thus, because of the relatively stable mean PBRT time of 0.9 seconds, drivers of faster vehicles must accept higher deceleration levels than drivers of slower vehicles if they are both to stop at the intersection. This relationship is illustrated in Figure 10 (36). Note that 85 percent of the higher speed drivers utilized deceleration levels of 10.6 fps^2 or less. The 10 fps^2 deceleration level assumed by the ITE Handbook represents 90 percent of this value (40). Therefore, a deceleration of 10.5 fps^2 was suggested as normal behavior on level grade (36).

Several other factors might have an effect on deceleration, one of which is grade. Supposedly, drivers will accept higher than normal deceleration levels on an upgrade and lower than normal deceleration levels on a downgrade. One study quantified this effect in the following equation (36):

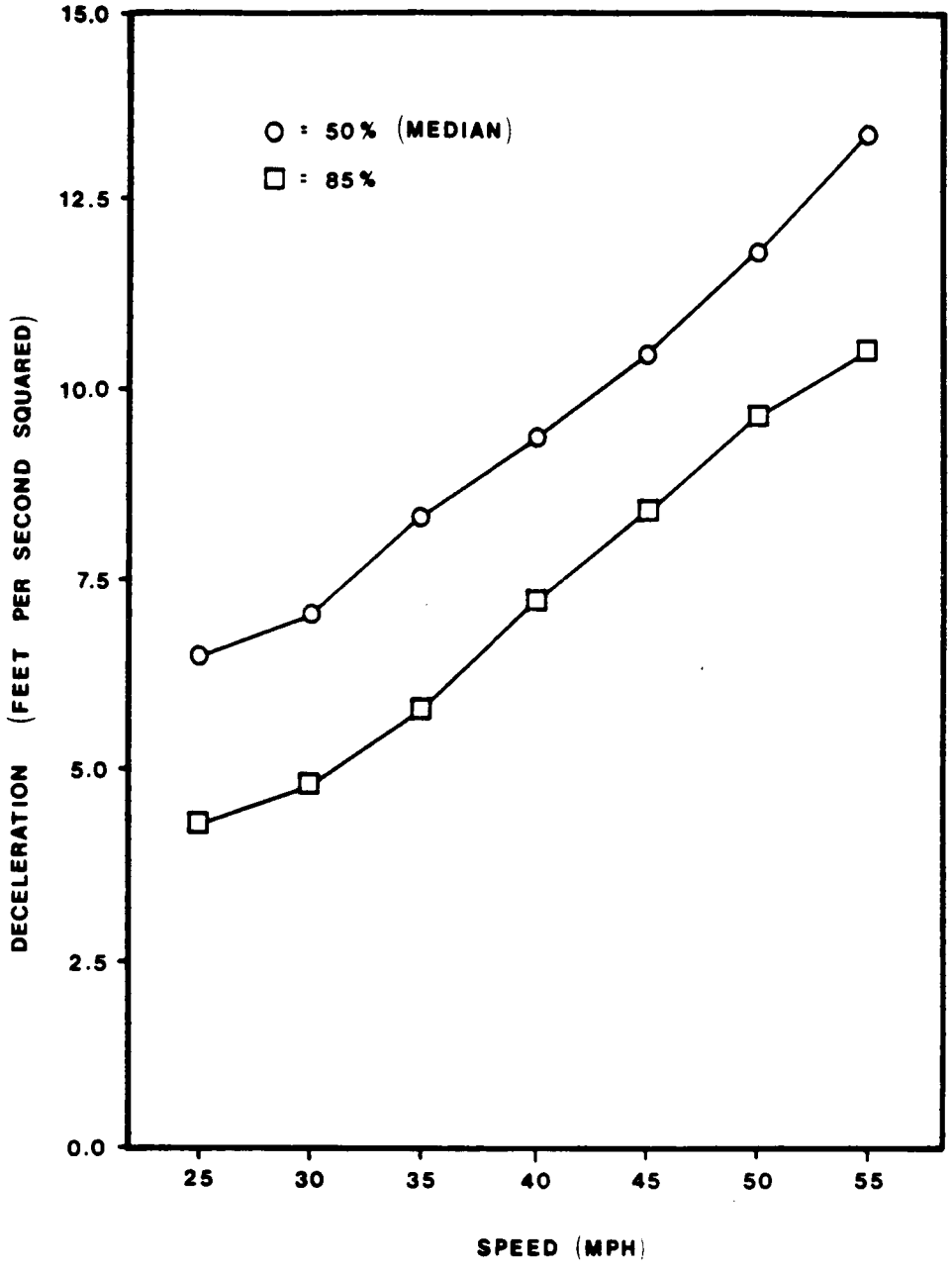


FIGURE 10. DECELERATION LEVELS IN RESPONSE TO ONSET OF YELLOW AS A FUNCTION OF SPEED

$$d = 10.5 \pm 0.75\ g$$

where:

d = normal deceleration level, fps^2; and

g = percent grade divided by 100.

This same study found no significant differences in drivers' selected deceleration levels between day versus night or dry versus wet pavement conditions.

Probability of Stopping. It is thought that a driver's perceived time to reach the stop line may influence his/her decision to stop or go. Several studies have collected data to verify this tenet; however, they were generally limited to either a single intersection (33) or several intersections with similar approach speeds (31). The findings from a study which looked at a range of conditions are presented in Figure 11 (36). As shown in the figure, practically no drivers stopped when they were less than 2 seconds away from the intersection at the onset of the yellow indication, and 85 percent of the drivers that did stop were three seconds or more away from the intersection. Furthermore, 85 percent of the drivers that did not stop were less than 3.7 seconds from the intersection; and 95 percent were less than 4.5 seconds from the intersection. These times were relatively stable across all speed categories.

These findings are somewhat surprising since the current practice is to provide a minimum yellow time for low approach speeds and to increase its length as the approach speed increases until some maximum value is reached (12). However, as shown in Figure 10, approach speed

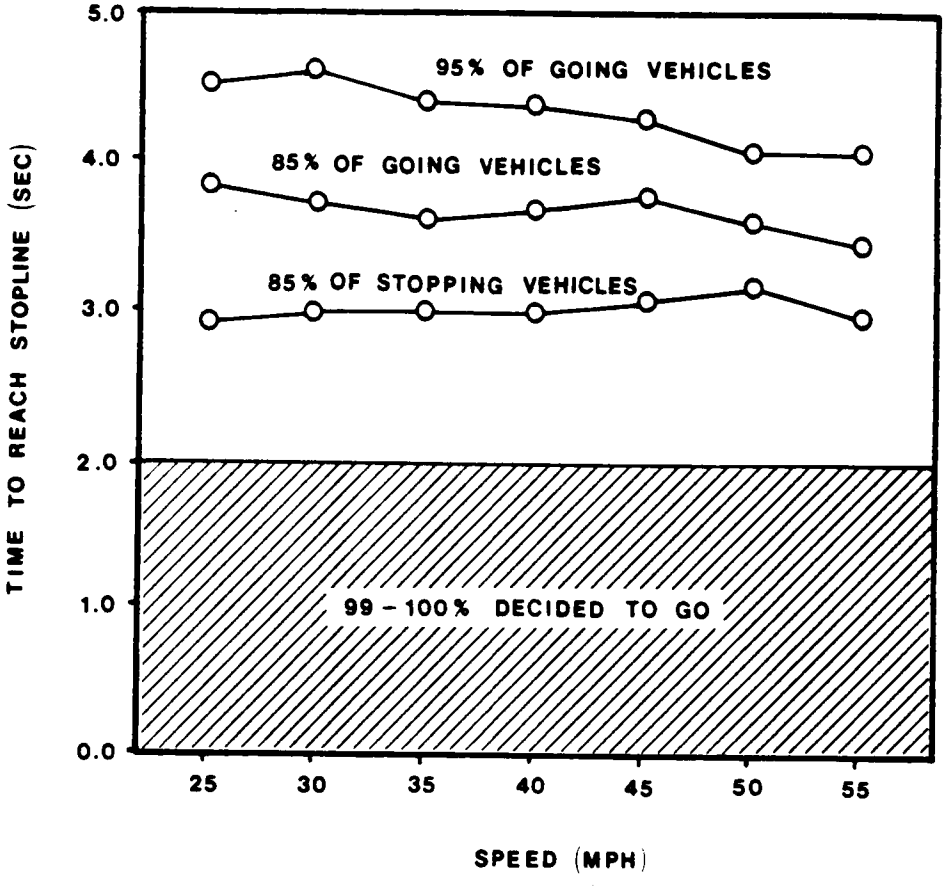


FIGURE 11. DRIVER'S DECISION TO STOP OR GO IN RESPONSE TO YELLOW AS A FUNCTION OF TIME TO REACH THE STOP LINE

has no discernible effect on the probability that a driver will stop in response to the onset of a yellow indication. Apparently, the decision to stop or go is based upon the perceived time to reach the stop line. This would mean that the real danger associated with change intervals may be with short yellow times found at lower speed intersections. In these cases, a significant number of drivers are going to enter the intersection after the yellow has terminated. To alleviate this problem, one researcher has suggested a constant yellow time of 4.5 seconds be used at all intersections (36).

Conflicts. As with grade crossings, conflicts are driver actions which place the driver in a dangerous position, i.e., in a position where a collision is imminent, unless an evasive maneuver is undertaken. Several studies have documented the relationships between different types of accidents and conflicts at signalized intersections (42). Generally, the best results have been obtained when the intersections were stratified by volume levels. Such relationships are desirable, as conflicts can be easily counted and are much more frequent than accidents. Thus, accidents can be predicted and hazardous locations identified without waiting for accidents to occur, provided the conflicts that are observed are in some way related to the type of accidents that are being predicted.

Unfortunately, conflict rates at intersections cannot be compared directly to those at grade crossings for two reasons. First, a conflict at a signalized intersection typically involves two vehicles, both of which can take evasive action. A conflict at a grade crossing also

involves two vehicles, but only one of them, the motor vehicle, can take evasive action. Second, train volumes and number of accidents at railroad-highway grade crossings are so low that there are not enough potential conflicts to develop statistically significant relationships without collecting data for long periods of time. Conflicts at highway intersections with comparable volume levels have not been studied for the same reason.

Summary of Previous Research

There are two types of warning devices for use at railroad-highway grade crossings--passive devices and active devices. Passive devices provide static warning of a grade crossing's location and are required at virtually all at-grade crossings. Active devices supplement passive ones at locations where the accident potential is high so as to warn drivers of the approach or presence of a train. The active warning devices currently in use were developed over 50 years ago. Guidelines for their use and some practical interpretations are offered in the MUTCD (12) and Traffic Control Devices Handbook (16); however, the responsibilities the different warning devices place on approaching drivers are not well understood by the general public.

Driver performance measures are a means of assessing the adequacy of a traffic control system in meeting a driver's needs. The better those needs are met, the better the driver performs. The challenge lies in defining what constitutes good driver behavior. Surprisingly, few studies have attempted to quantify driver behavior at railroad-highway grade crossings. Those that did looked at such measures as looking

behavior, speed profiles and changes, deceleration levels, conflicts, and violations. As a result of these studies, several interesting and somewhat unexpected conclusions were reached.

Looking behavior is a poor measure of driver performance for the reason that just because drivers look, one does not know why or if they even see specific things in their field of view. In addition, looking behavior appears to be more related to past experience than the need to look, i.e., at different crossings, familiar drivers tend to look more when train volumes are high, and at the same crossing they tend to look less than unfamiliar drivers (22). Speed profiles of familiar drivers on the approach to a grade crossing are a function of the crossing surface making it virtually impossible to compare different crossings; however, they are useful when comparing different warning systems at the same crossing.

When studying approach speed profiles, drivers should be grouped into categories of similar expected behavior based on the stimulus for stopping at the crossing. Basically, the greater the stimulus, the sooner and more gradual drivers will begin to slow down. Lowered gate arms result in the smoothest speed profiles and surprisingly, activated flashing lights result in speed profiles similar to those at passive crossings. As for speed changes of individual vehicles approaching the crossing, there are no apparent patterns other than the fact that their variance increases as the vehicles get closer to the crossing.

Observance of extreme deceleration levels and large numbers of conflicts and violations are good indicators of potential grade crossing safety problems. Unfortunately, very few drivers exceed a practical

deceleration level when stopping, thus requiring large data bases. Conflicts and violations are more common and easily observed. The key to their use is a clearly defined behavior that can be measured in the field. This point is discussed further in Section V.

Driver behavior at signalized intersections is different from that at railroad-highway grade crossings in that changes in right-of-way are expected at intersections and unexpected at grade crossings; however, several research findings are worth noting. The 85th percentile perception-brake reaction time in response to a yellow signal can be estimated as 1.2 seconds. This value does not change with either distance from the intersection, or day-night or wet-dry conditions. The 85th percentile deceleration level is 10.5 fps^2 which also is unchanged for all conditions other than approach grade. As with grade crossings, few drivers select higher than practical deceleration levels when stopping. Ninety-five percent of the drivers that do not stop enter the intersection within 4.5 seconds of the onset of yellow regardless of their approach speed.

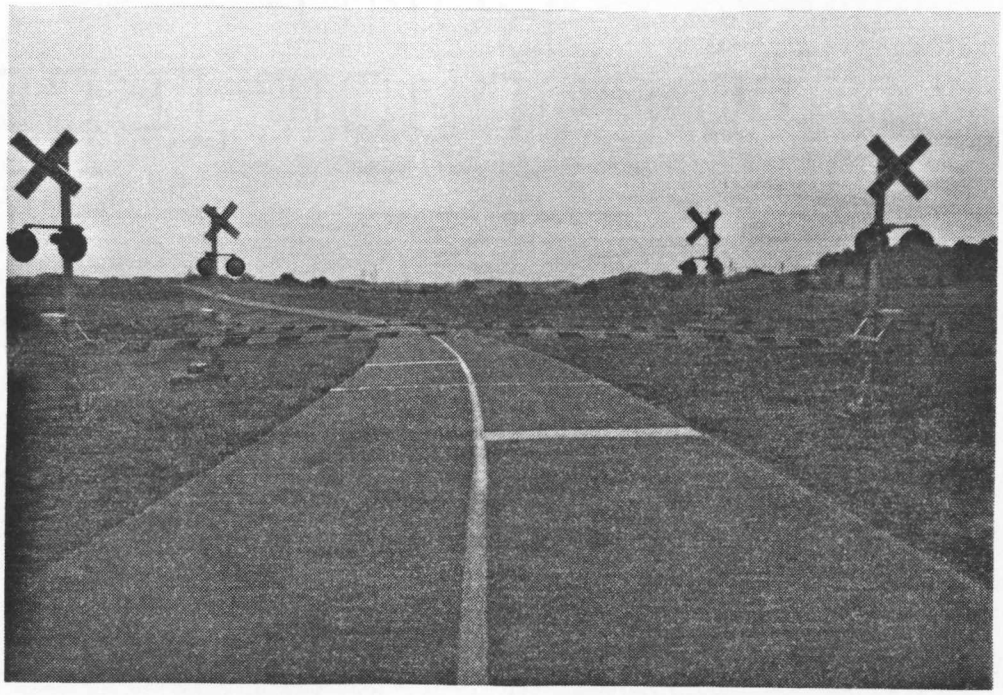
III. LABORATORY EVALUATION STUDY PLAN

The objectives of the laboratory study were to design, construct, and evaluate six innovative active warning devices for use at railroad-highway grade crossings. The design and construction process involved input from a panel of experts to select between several alternative designs and is documented in a research report (43). The evaluation process involved testing the performance of each of the six devices in a near real world environment so as to identify the three most desirable devices for field testing under normal traffic conditions at existing crossings.

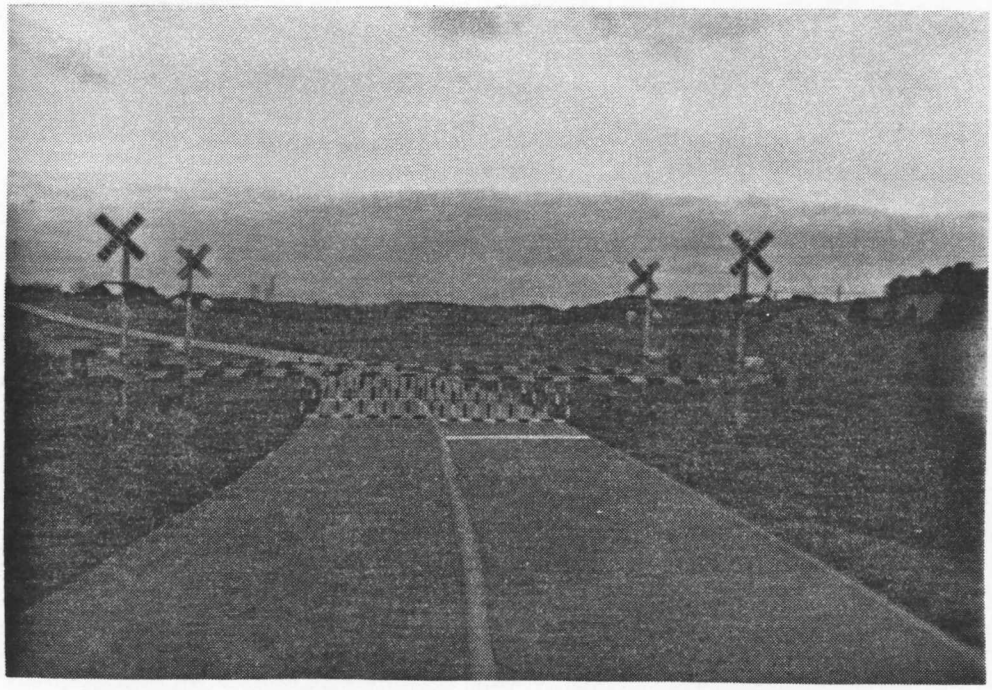
The configurations for each of the six prototype devices evaluated were in accordance with the Manual on Uniform Traffic Control Devices (MUTCD) (12) and/or standard highway engineering practice. When specific aspects of any of the six devices were not covered by either the manual or standard practice, engineering judgement was exercised. As described in Section I, the six candidate devices were:

1. Four-quadrant flashing light signals and automatic gates with and without skirts;
2. Four-quadrant flashing light signals with and without overhead strobes; and
3. Highway traffic signals with white bar strobes in one or all red lenses.

Figures 12 through 14 show the installation of these six devices as they were evaluated in the laboratory study.

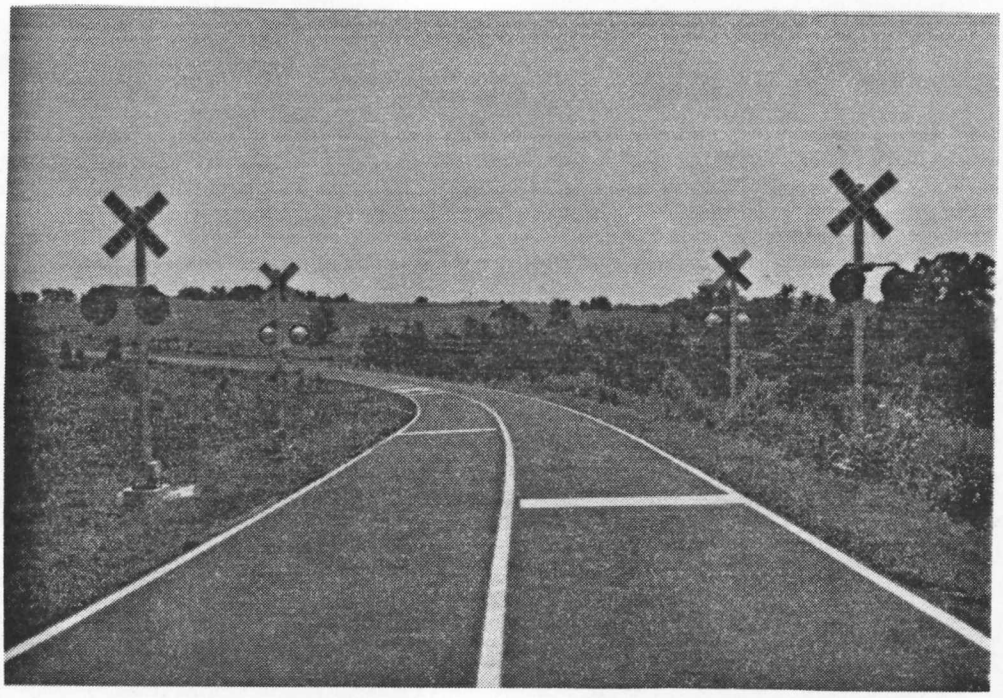


Alternative A--Without Skirts on Gate Arms

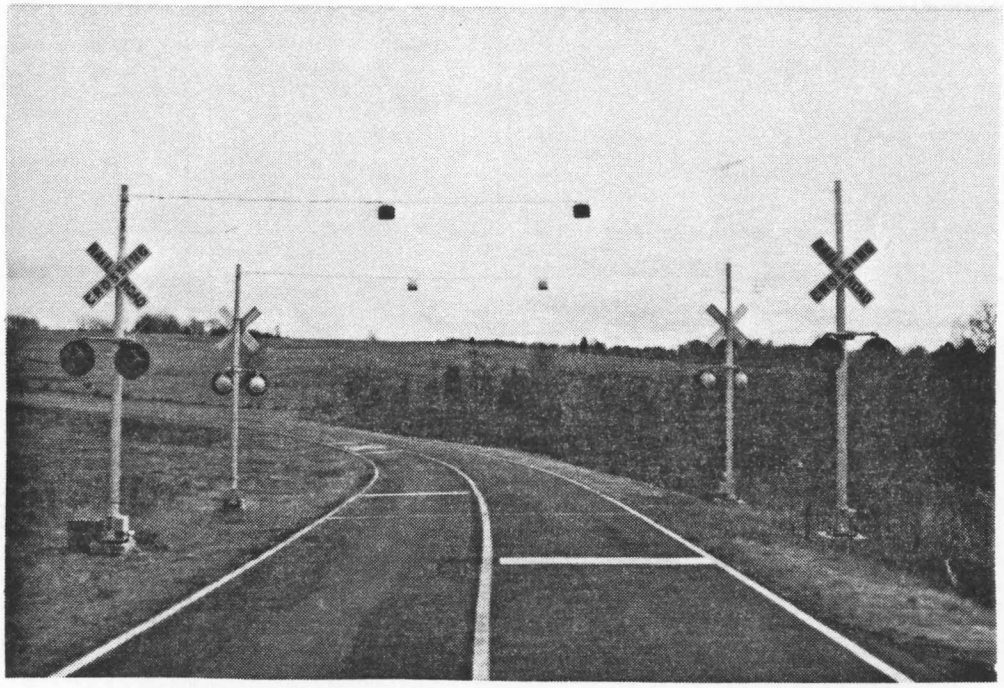


Alternative B--With Skirts Added to all Gate Arms

FIGURE 12. FOUR-QUADRANT GATE SYSTEM

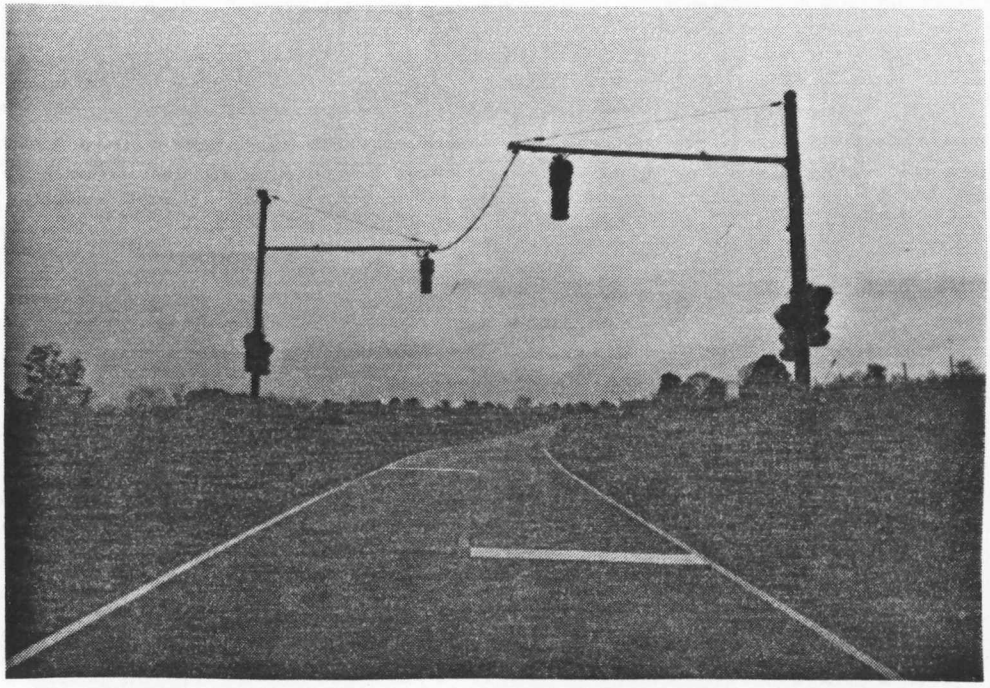


Alternative A--Without Strobes

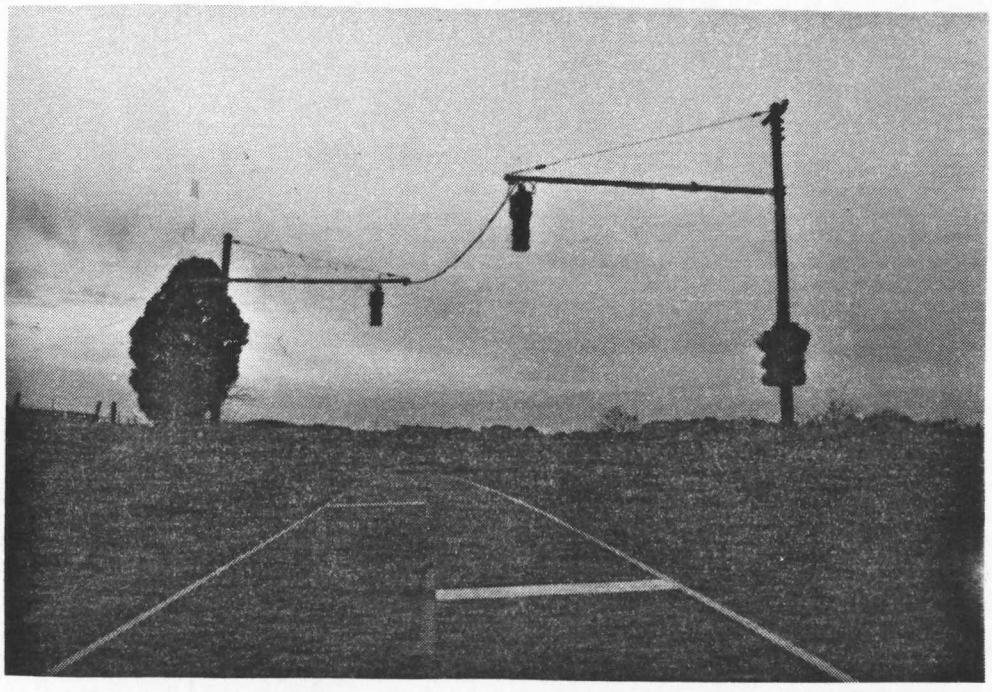


Alternative B--With Red Strobe Lights Over Traffic Lanes

FIGURE 13. FOUR-QUADRANT FLASHING LIGHT SIGNAL SYSTEM



Alternative A--White Bar Strobe in Overhead Red Signal Lens



Alternative B--White Bar Strobe in Each Red Signal Lens

FIGURE 14. HIGHWAY TRAFFIC SIGNAL SYSTEM

Many variables can and do influence driver behavior at railroad-highway grade crossings with active warning devices. However, because of the time and fiscal constraints of this research, it was not feasible to design an experiment that investigated the effects of all possible variables. Therefore, the final experimental plan reflects the more important variables that could be treated given the constraints of the overall study. This chapter presents the approach that was used in the laboratory evaluation study.

Study Approach

The laboratory evaluation of the active warning devices involved 32 test subjects each of whom repeatedly drove an instrumented vehicle at approximately 40 miles per hour over a 1.5-mile stretch of private two-lane highway. On each trip down the roadway, the test driver encountered three full-scale active railroad-highway grade crossing warning devices, any one of which may or may not have been activated as the vehicle approached. The determination of where and when the devices were activated had been randomly determined prior to the start of the study. A quasi-randomized block experimental design was employed in which the effects of the following independent variables were evaluated:

1. Three basic active warning systems (System A versus System B versus System C);
2. Two alternative active warning devices (Alternative A versus Alternative B for each system);
3. Four signal activation distances (null, long, medium, and short); and

4. Two lighting conditions (day versus night).

Each subject experienced two replications for each of the 48 treatment combinations. The basic experimental design may be conceptualized as shown in Figure 15.

Test Subjects. The 32 test subjects utilized in this research were selected so as to match as closely as possible the characteristics illustrated in Table 4. Subject recruitment was made through friends and associates of the Transportation Center staff. As shown, the subject population was divided equally between males and females, and each of these groups was further divided into an equal number of younger and older drivers. For this study, younger drivers were viewed as those under 25 years of age, while the older drivers were viewed as those over 60 years of age. By selecting subjects in these two age groups, it was anticipated that the two extremes of the driving population would be included and that the remaining portion of the population would not exhibit worse driving characteristics than those of the test subjects. An attempt was also made to stratify the subjects in each age group by their educational level so as to avoid any educational bias. While the exact distribution of subject characteristics was not obtained, a close approximation was secured, as shown in Table 4.

Instrumented Vehicle. The instrumented vehicle shown in Figures 16 and 17 was used to measure each subject's response to the activation of the warning devices. The car was equipped with sensors on both the brake and accelerator pedals so that a change in the status of either

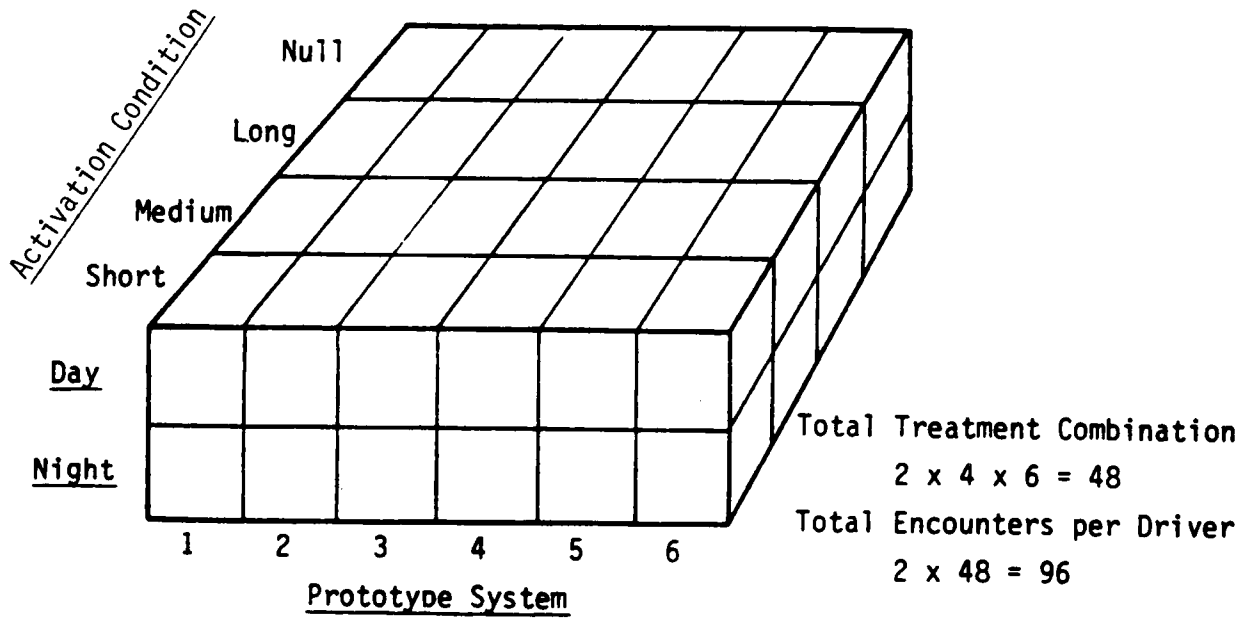


FIGURE 15. BASIC EXPERIMENTAL DESIGN FOR EVALUATING THE ACTIVE WARNING DEVICES

TABLE 4. DESIRABLE CHARACTERISTICS OF TEST SUBJECTS

Education Level	Males		Females		Total
	Younger	Older	Younger	Older	
Did not graduate from high school	2 (3)	2 (2)	2 (2)	2 (3)	8 (10)
High school graduate--no college	2 (1)	2 (1)	2 (1)	2 (2)	8 (5)
One to three years of college	2 (2)	2 (3)	2 (2)	2 (2)	8 (9)
College graduate	2 (2)	2 (2)	2 (3)	2 (1)	8 (8)
TOTAL	8 (8)	8 (8)	8 (8)	8 (8)	32 (32)

Note: Numbers in parentheses reflect actual distribution of test subjects.

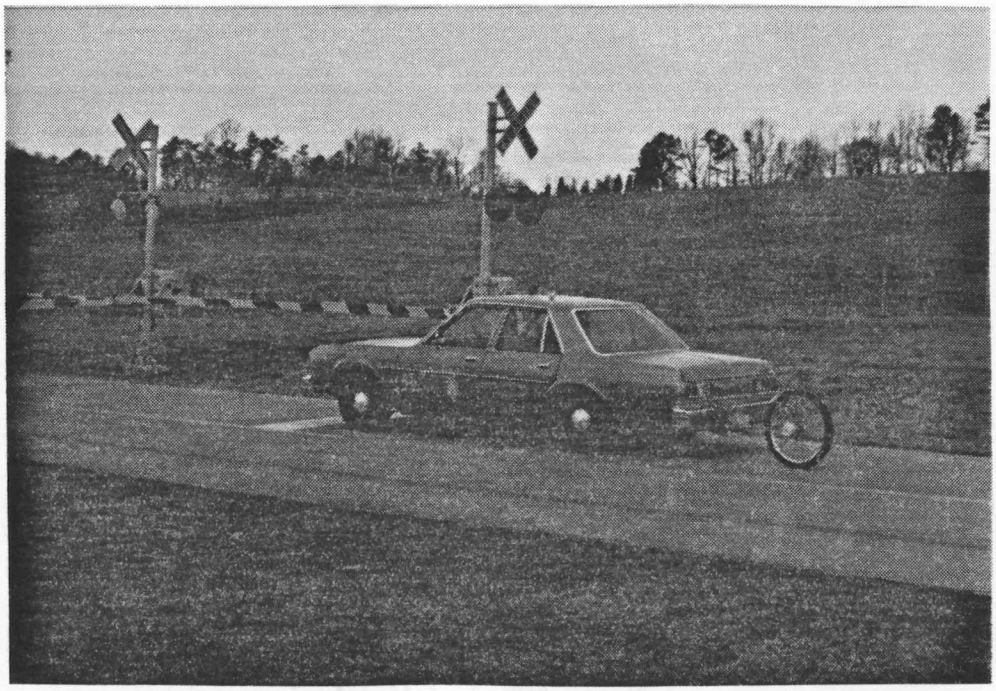


FIGURE 16. INSTRUMENTED VEHICLE USED IN THE LABORATORY TESTING

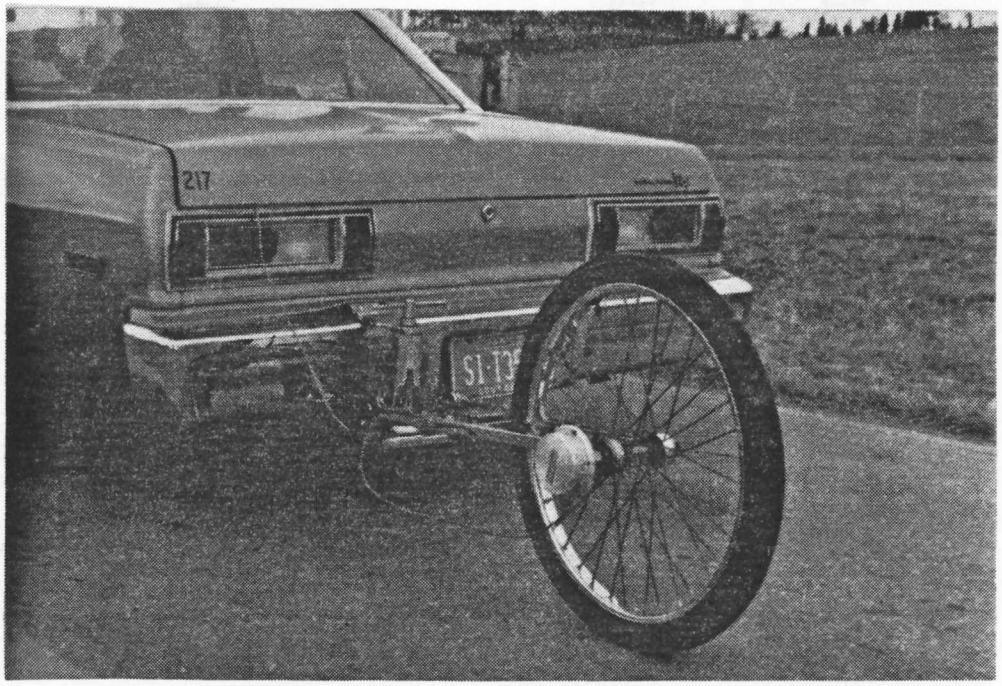


FIGURE 17. FIFTH WHEEL ATTACHED TO REAR BUMPER OF THE TEST CAR

pedal caused a signal to be sent to a small DEC LSI-11 computer in the vehicle's trunk. These signals were kept electrically independent from the computer's electrical system so as to preclude the possibility of automobile engine interference with the computer. The interface box that was used contained two relays which were driven by the brake and accelerator signals. The brake signal was from a low impedance source and could easily drive its 12-volt relay. However, the accelerator signal had a much higher impedance, so an amplifier was added in the engine compartment to ensure proper closure of its 12-volt relay.

In order to record locations on the roadway accurately, a fifth wheel was attached to the rear bumper of the car and interfaced with the computer (see Figure 17). This connection required a few integrated circuits which basically divided the output of the wheel by 25 so as to allow the computer to be interrupted once for every foot of forward motion. This arrangement permitted the travel time and the position of both the brake and accelerator pedals to be recorded for each linear foot along the test course. This information (approximately 18,000 bits of data for each of 1,024 runs through the test course) was stored on cassette tapes and later used to calculate vehicular speeds, acceleration/deceleration levels, and reaction times in reference to the distance from a given active warning device.

To test the accuracy of the data collection system, the fifth wheel was attached to the car and used to measure the distance between the two ends of the test course. Two runs were made in each direction, and the largest error in any of the four approximately 6,000-foot runs was one foot. By crossing the center line, the error could be increased to 30

feet. Therefore, each driver was instructed to stay to the right of the centerline. Because this behavior was relatively easy to both carry out and monitor, resultant measurement errors should have been small.

A computer program which was responsible for activating the three crossing installations at the proper time was written. The original plans were to use the computer software to generate two simultaneous tones to modulate a CB transmitter at a predetermined location. However, the tones could not be generated in the software because the computer had a dynamic memory which needed periodic refreshing. This refreshing caused anomalies in the tones which prevented their proper detection. Therefore, a hardware tone encoder was constructed and interfaced to the computer.

Each of the three crossing devices was activated by a different pair of tones. The exact locations (short, medium, and long) at which the tones were transmitted for each individual run had been determined prior to the experiment on a quasi-random basis. This sequence was stored in the computer and "looked up" at the start of each one-way trip through the course. Toggle switches on an external control box were used to enter the appropriate person and run numbers and to set all counters equal to zero. These identification numbers were recorded on the data tapes and provided a match between the subject's behavioral data and the conditions which the subject encountered.

Test Site. The laboratory testing was conducted on a 1.5-mile stretch of private two-lane roadway located on the McGhee-Tyson Air National Guard Base. Except for three short periods during each day,

gates at either end of the roadway were closed and the facility became a controlled environment. Thus, this roadway provided an excellent facility to test the candidate warning devices without having to be concerned with exposure to the general public. In addition, the test site was located close to The University of Tennessee and both the Executive Director of the McGhee-Tyson Airport and the Commander of the McGhee-Tyson Air National Guard Base welcomed the use of their facilities and provided all possible cooperation.

Study Procedure

Entrance and Exit Survey. Before beginning the driving test, each subject completed both a biographical data form describing the subject's driving experience, accident record, personal health, and other attributes, and a short entrance examination related to the subject's knowledge of traffic control devices used at railroad-highway grade crossings (see Figure 18). In addition, each subject's simple reaction time was measured using the American Automobile Association Portable Reaction Time Tester, and each subject's vision was checked using the Titmus Professional Vision Tester (see Figure 19). Results from these tests gave an indication of any serious reaction or visual deficiencies in any of the subject population. Copies of each data recording form as well as a copy of the entrance examination are included in Appendix A.

In addition to the above tests, a brief exit survey using semantic differential scaling and Thurstone's method of paired comparisons (44) was used to determine attitudinal responses to the effectiveness of each

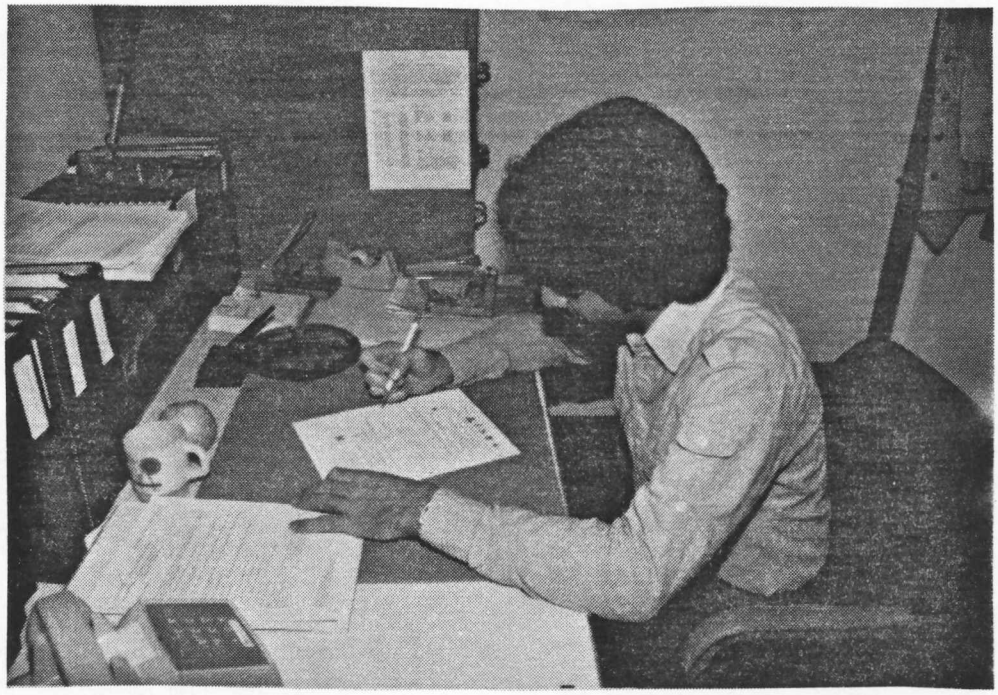


FIGURE 18. TEST SUBJECT COMPLETING DRIVER KNOWLEDGE SURVEY

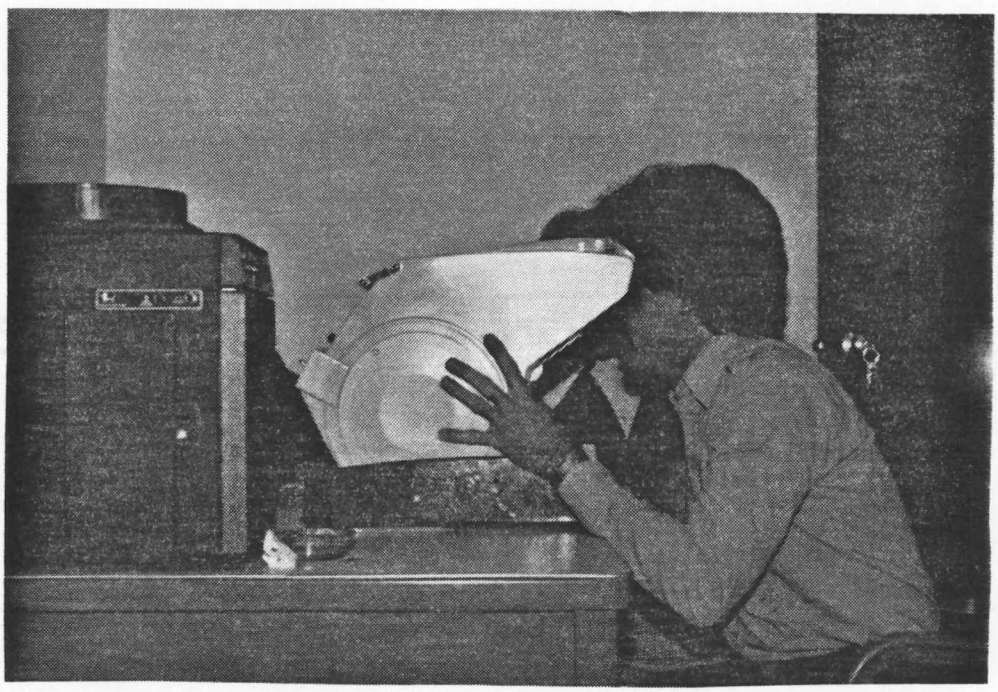


FIGURE 19. TEST SUBJECT COMPLETING VISION TEST

of the prototype devices. This survey was given after each test subject had finished all of the driving tests. Results of these procedures provided absolute as well as relative rankings of each device's effectiveness as perceived by the test subjects. Photographs of each device during both the day and the night were used in the ranking procedures. A copy of the survey form is included in Appendix B.

Study Variables. Three levels of signal activation distance were selected in an attempt to determine the effects of the active warning devices at distances representative of the continuum found in the real world. Activation distance (see Figure 20) was defined as the distance the test vehicle was from the device when the device communicated a changing of the right-of-way, i.e., flashing light signals were activated or the highway traffic signal changed from green to yellow. These three distances were long, medium, and short. In addition, there was a fourth condition (the null) wherein the devices were not activated upon approach by the test subject.

For the long distance the signal was activated when the vehicle was 670 feet from the crossing (approximately 2.5 times the minimum stopping sight distance for 40 mph). At this distance, with the test vehicle traveling at 40 miles per hour, the vehicle was approximately 11.5 seconds away from the crossing. Obviously, for these conditions, an immediate subject response was not needed in order to reasonably stop the vehicle. However, the effect of the device in terms of the subject's latent response and subsequent deceleration profile were of interest.

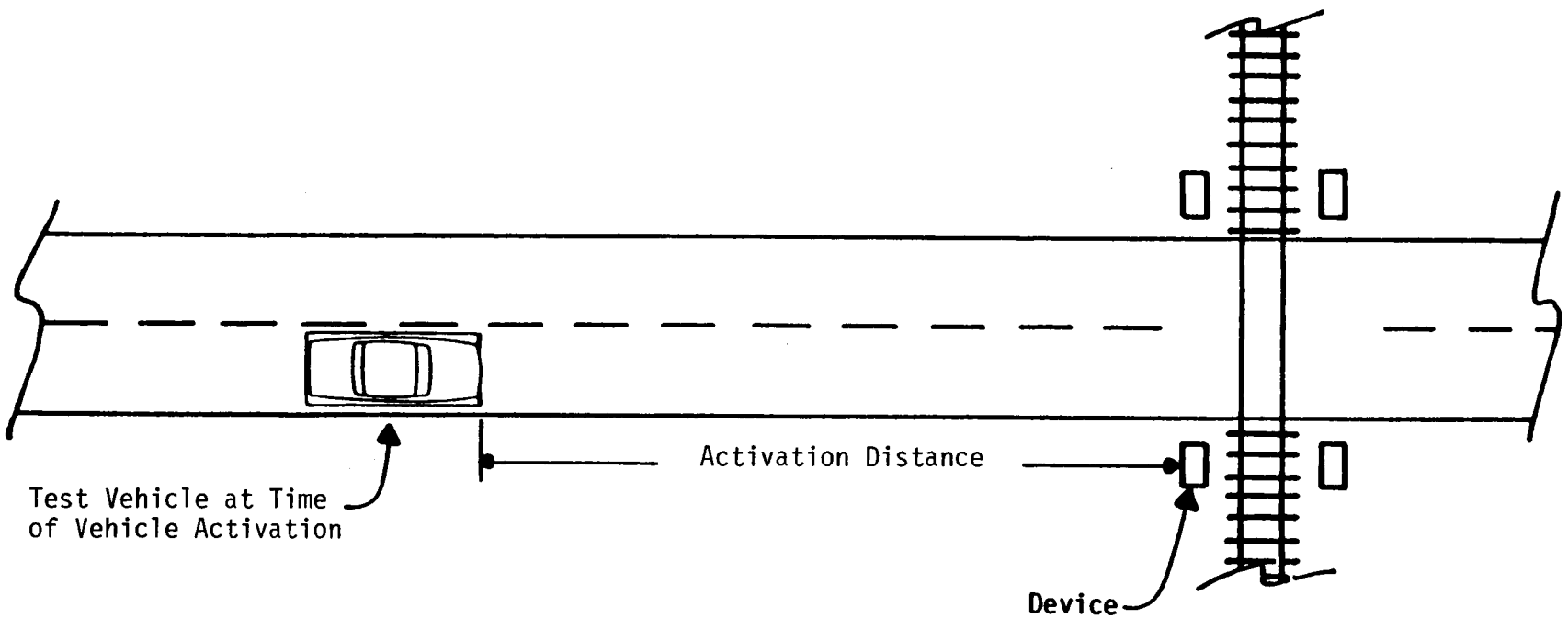


FIGURE 20. ACTIVATION OF ACTIVE WARNING DEVICE FOR TEST VEHICLE

For the medium distance, the device was activated when the vehicle was 440 feet or approximately 7.5 seconds from the crossing (approximately 1.5 times the minimum stopping sight distance). At this distance, and assuming a 2.5-second perception-reaction time and constant deceleration, the subject had to decelerate the test vehicle at about 5.9 feet per second per second in order to stop. This level of deceleration corresponds with moderate braking and is near the deceleration levels commonly observed in unconstrained vehicle operation.

For the short distance, the signal was activated when the vehicle was 330 feet or approximately 5.5 seconds from the crossing (approximately 1.2 times the minimum stopping sight distance). Again, assuming a 2.5-second perception-reaction time and constant deceleration, the subject had to decelerate the test vehicle at about 9.4 feet per second per second in order to stop. This level of deceleration corresponds with moderate to heavy braking and is near the threshold point at which an average driver would "run" the crossing.

With respect to ambient illumination, the two conditions included in this study were simply day and night. Although it would have been desirable to investigate the effects of twilight or dusk on the performance of these active warning devices, it was not feasible to do so given the constraints of the project. In addition, the main concern of the research was that of the near steady state illumination conditions found during day or night driving and not that of the relatively short transition periods in between.

Test Procedure. Immediately prior to beginning the driving test, brief instructions were read to each subject. Subjects were requested to drive at approximately 40 miles per hour and to respond to the traffic control devices as they would under normal driving conditions. In addition, they were told that they were not being asked to do anything that might be dangerous and that they should drive safely at all times. A copy of these instructions is included in Appendix C.

As previously noted, the basic experimental design involved each of the 32 subjects receiving two replications for each of the 48 treatment combinations (i.e., six prototype devices x four activation distances x two lighting conditions) for a total of 96 encounters with the active warning devices. Each subject drove in four 60-minute blocks of time, twice during the day and twice at night. This approach was compatible with the need to test one configuration of each of the three basic systems before modifying them to their alternative configurations. To reduce any learning effect that might occur, half of the subjects began with the first alternative of a basic system, while the other half began with the second alternative.

Data Analysis

The dependent variables collected during the laboratory study were as follows:

1. Travel time along each linear foot of the test roadway;
2. Position of the brake pedal;
3. Position of the accelerator pedal; and

4. Times and distances traveled until subject response following a signal activation as determined by a change in vehicle brake or accelerator pedal positions.

These variables were then used to calculate brake and accelerator reaction times as well as peak and average deceleration levels. In addition, average speed profiles were prepared for each of the 48 treatment combinations. Each of these variables was analyzed by analysis of variance (ANOVA) techniques in order to determine significant differences in the effects on subject behavior of each of the six prototype device taking into account the activation distance and lighting condition. The basic model that was used in this analysis is as follows:

$$y_{ijkl} = \mu + \alpha_j + \beta_k + \gamma_l + (\alpha\beta)_{jk} + (\alpha\gamma)_{jl} + (\beta\gamma)_{kl} + (\alpha\beta\gamma)_{jkl} + \epsilon_{ijkl}$$

where:

μ = the overall mean response from all observations.

α = the main effect for the jth device type, j = 1, 6.

β = the main effect for the kth activation distance, k = 1, 4.

γ = the main effect for the lth lighting condition, l = 1, 2.

$(\alpha\beta)$ = the interaction effect for the jth device and the kth activation distance.

$(\alpha\gamma)$ = the interaction effect for the jth device and lth lighting condition.

$(\beta\gamma)$ = the interaction effect for the kth activation distance and the lth lighting condition.

$(\alpha\beta\gamma)$ = the interaction effect for the jth device, the kth activation distance, and the lth lighting condition.

Recorded values for each of the response variables were entered into a data file and analyzed with the GLM (General Linear Models) procedure in the 1979 version of the SAS (Statistical Analysis System) computer program (45). Output from this procedure was an ANOVA table containing computed F-ratios and their associated significance probabilities for each main and interaction effect in the model. The basic hypothesis tested was that there was no difference between treatments at the 95 percent confidence level. The basic procedure followed in this analysis was to first evaluate the interaction effects and to then test each of the three main effects. Specifically, if the computed F-value (mean square effect/mean square error) for any factor did not exceed the appropriate F-statistic, the null hypothesis was not rejected, i.e., there was not a statistically significant effect on subject behavior due to this factor. If the computed F-value exceeded the appropriate F-statistic, the null hypothesis was rejected, i.e., there was a statistically significant effect on subject behavior due to this factor. For those factors having a significant effect, Duncan's multiple range test (46) was used to identify the significant differences between the individual treatments within that factor. After testing the interaction effects, the following comparisons were made:

1. Response due to different devices;
    a. Four-quadrant gates with skirts versus four-quadrant gates without skirts (Figure 12, Page 46);
    b. Four-quadrant flashing light signals with overhead strobes versus four-quadrant flashing light signals without strobes (Figure 13, Page 47); and

c. Three highway traffic signal heads each with white bar strobes versus three highway traffic signal heads, one with a white bar strobe (Figure 14, Page 48).

2. Response due to basic systems;
   a. Four-quadrant gates versus four-quadrant flashing light signals;
   b. Four-quadrant gates versus highway traffic signals; and
   c. Four-quadrant flashing light signals versus highway traffic signals.
3. Response due to activation distance; and
   a. Short versus medium (330 feet versus 440 feet);
   b. Short versus long (330 feet versus 670 feet); and
   c. Medium versus long (440 feet versus 670 feet).
4. Response due to lighting condition.
   a. Day versus night.

IV. RESULTS OF LABORATORY TESTS

Each of the 32 subjects traveled along the test roadway a total of 32 times--eight times during the day and eight times at night for each of the two alternatives. Thus, data were recorded for 1,024 trips (32 x 32) along the test roadway. As mentioned previously, travel times for each linear foot along the roadway as well as the position of the brake and accelerator pedals were automatically recorded. This activity resulted in the acquisition of over five million items of subject behavioral data and made working with the entire data set extremely difficult and very time consuming.

In addition to the subject behavioral data, entrance examinations and exit surveys were administered to each of the 32 subjects. The initial inquiry tested the subjects' vision, their simple reaction times, and their general knowledge of traffic control devices at railroad-highway grade crossings. In the exit survey, the subjects were asked to rank each of the alternatives under day and night conditions on both an absolute and a relative scale. This chapter discusses the results of these activities.

Entrance Examination

Biographical Data. The 32 test subjects were divided equally between males and females, and each of the groups was further divided into an equal number of younger (under 25) and older (over 60) subjects. As shown in Table 5, the younger subjects had been driving an average of 4.1 years and the older drivers an average of 45.8 years. In both age

TABLE 5. AVERAGE CHARACTERISTICS OF THE SAMPLE POPULATION, X

Subject Characteristics	Drivers (<25) Males (n=8)	Drivers (<25) Females (n=8)	Group Avg. (n=16)	Drivers (>60) Males (n=8)	Drivers (>60) Females (n=8)	Group Avg. (n=16)
Years driving	3.8	4.4	4.1	52.0	39.6	45.8
Miles/year (1000s)	17.8	8.3	13.1	13.1	7.6	10.4
Education (years)	12.7	13.5	13.1	13.5	12.5	13.0
License restrictions	2	2	2	1	0	0.5
Traffic violations	0	3	1.5	1	0	0.5
Knowledge (percent)	72.9	70.3	71.6	59.4	62.4	60.5
Reaction times (seconds)	0.414	0.441	0.448	0.486	0.481	0.484
Visual acuity (X/20)	17.50	19.875	18.6875	37.125	26.625	31.875

groups, the males drove almost twice as many miles per year as their female counterparts. The average educational level of the subject population was similar for each of the four groups; however, the individual subjects within the groups ranged from those who did not complete high school to college graduates. Five of the subjects noted a corrective lenses restriction on their current driver's license; four of the five were in the younger category. Interestingly, during the vision test, 17 of the 32 subjects stated that they wore glasses. Four of the subjects had received moving traffic citations in the past three years; three of the four were in the young female category. Individual responses to the biographical data survey are contained in Appendix A.

Subject Knowledge. A short entrance examination was developed in order to test the subjects' knowledge of the proper behavior at railroad-highway grade crossings. As shown in Table 5, the younger subjects scored about 10 percent higher than did the older ones. Of particular interest at this point in time are the questions which dealt specifically with the correct reaction to the three prototype systems being tested. The most understood of these devices was the standard flashing light signals with gates as 31 of the 32 test subjects indicated the proper response--stop and remain stopped until the gate arms are raised. The next most understood of the devices was the highway traffic signal as 26 of the 32 test subjects indicated the proper response--stop at the signal and wait for it to turn green before proceeding. The least understood of the devices was the standard flashing light signals as only four of the 32 subjects indicated the proper response--stop their

vehicle and proceed over the crossing if a train is not near. This order of understanding may be significant when compared to the subjects' preferences for the same devices. Individual responses to the driver knowledge survey are contained in Appendix A.

Reaction Times and Visual Characteristics. The young male subjects had the fastest reaction times (0.414 seconds) of any of the four groups. Times for the other three categories were all about 0.48 seconds. Surprisingly, the oldest subject in the study (79 years of age) was quicker than all but three of the other subjects. When vision was tested, the average corrected visual acuity of the younger subjects was about 20/20. For the older subjects, the average was about 20/30, which is the legal requirement for operating a motor vehicle in Tennessee. Seven of the drivers did not meet this criterion, with five of them being in the older categories. Seven of the subjects had trouble with their depth perception. Again, five of these were in the two older groups. Nine of the subjects had some deficiencies in perceiving colors. Eight of these were over 60. Individual responses to the reaction and vision tests are contained in Appendix A.

Exit Survey

Absolute Rankings. After completing all of the test runs, each subject was asked to compare the effectiveness of the six alternative devices encountered with the effectiveness of existing signals. An absolute scale of 1 to 5 was utilized for this purpose, with 3 being about the same as existing signals, 1 being much less effective, and 5

being much more effective (see Appendix B). Responses were solicited for both day and night driving conditions. As shown in Table 6, all six of the devices were ranked higher than existing signals for both conditions. The Wilcoxon signed-rank test (47) was used to determine whether the differences in the rankings for either the day or night driving conditions were statistically significant at the 95 percent confidence level. The results are as follows:

1. For day conditions, the four-quadrant gates with skirts had a significantly higher ranking than all of the other devices except for the four-quadrant gates without skirts; the four-quadrant flashing light signals without strobes had a significantly lower ranking than all of the other devices; and there were no significant differences in the rankings for the other four devices.
2. For night conditions, the four-quadrant gates with skirts had a significantly higher ranking than all of the other devices; the four-quadrant flashing light signals without strobes had a significantly lower ranking than all of the other devices; and there were no significant differences in the rankings for the other four devices.

It is interesting to note that the rank order of the other four alternatives varied by time of day. Perhaps, coincidentally, the devices were ranked for day driving in the same order as they were understood--four-quadrant gates, highway traffic signals, and four-quadrant flashing light signals. However, this was not true for night driving as one of the four-quadrant flashing light signal alternatives

TABLE 6. PERCEIVED EFFECTIVENESS OF THE SIX ALTERNATIVE DEVICES

Type of Traffic Control	Much Less Effective (1)	Less Effective (2)	Same as Existing Signals (3)	More Effective (4)	Much More Effective (5)	Avg. Rating (X)
Day Driving						
Four-quadrant gates without skirts	-	1	2	15	14	4.313
Four-quadrant flashing light signals without strobes	-	1	16	12	3	3.531
Highway traffic signal--one white bar strobe	-	-	3	20	9	4.188
Four-quadrant gates with skirts	-	-	3	7	22	4.594
Four-quadrant flashing light signals with overhead strobes	-	1	4	17	10	4.125
Highway traffic signals--three white bar strobes	-	1	1	17	13	4.313
Night Driving						
Four-quadrant gates without skirts	-	1	1	20	9	4.194
Four-quadrant flashing light signals without strobes	-	3	14	11	4	3.500
Highway traffic signal--one white bar strobe	-	3	1	19	9	4.063
Four-quadrant gates with skirts	-	-	2	4	25	4.742
Four-quadrant flashing light signals with overhead strobe	-	1	3	16	11	4.194
Highway traffic signals--three white bar strobes	-	3	5	9	14	4.097

was ranked as the second most effective device. It should also be noted that, although not statistically significant, the effectiveness for four of the six devices was perceived to decrease at night. The two exceptions were the four-quadrant gates with skirts and the four-quadrant flashing light signals with overhead strobes.

Relative Rankings. In addition to the absolute rankings, the subjects were asked to pick the more effective device (A or B) from a series of two alternatives. Thurstone's method of paired comparisons (44) was used to determine a relative ranking of the six alternative devices. Figure 21 shows the results of these rankings for both day and night conditions. The rankings were computed such that the higher the ranking, the higher the preference. As shown, the two highest ranked alternatives involved four-quadrant gates with and without skirts. The third ranked device was the four-quadrant flashing light signals with overhead strobes. The next two ranked devices involved the highway traffic signal. The lowest ranked alternative was the four-quadrant flashing light signals without strobes. Using the relative ranking technique of Thurstone, one can clearly see that the gate system with skirts is much preferred over the other systems.

Driver Behavioral Data

Data Preparation. As the first step in the data reduction process, each subject's driving behavioral data from the on-board computer was transferred from the cassette tapes to 5 3/4-inch floppy disks. It was then transferred via a modem to a magnetic tape that was compatible with

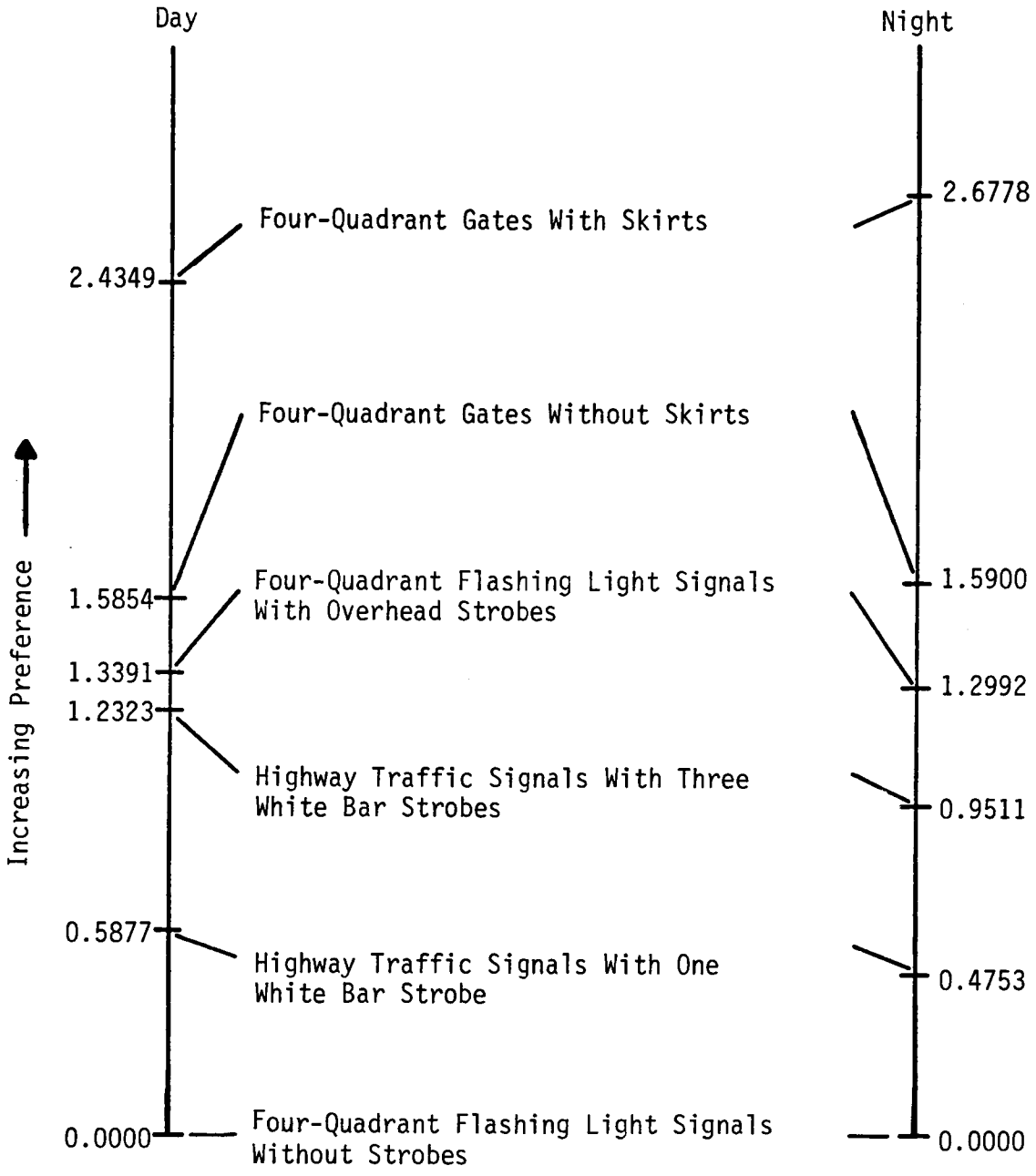


FIGURE 21. RELATIVE RANKING OF THE SIX ALTERNATIVE ACTIVE WARNING DEVICES

the University's PDP-11 and DEC-10 computers. The enormous size of the data set caused this to be a very time consuming activity. After the transfer was completed, some minor editorial work was necessary in order to place the data in the proper format for analysis. The resultant data files were further edited by a second program, and the output stored on magnetic tape. The information contained in this modified file was as follows:

1. Person number;
2. Run number;
3. Person's age;
4. Person's sex;
5. System;
6. Device;
7. Activation mode;
8. First brake, distance;
9. First brake, time;
10. Second brake, distance;
11. Second brake, time;
12. First accelerator, distance;
13. First accelerator, time;
14. Second accelerator, distance;
15. Second accelerator, time;
16. Maximum deceleration, location;
17. Maximum deceleration, levels; and
18. Velocities.

Items 1 through 7 deal with record keeping. The first four of these items are straightforward and therefore self-explanatory. System refers to whether the device being tested conformed to Alternative A or Alternative B for that particular system. Device refers to which of the six innovative devices the subject encountered. Activation mode refers to the location of the test car when the traffic control device was activated. Mode was used as a classification variable rather than an actual distance because hardware limitations allowed activation within a range of plus or minus 20 feet of the desired activation distance. For ease of presentation, activation distances of 330 feet, 440 feet, and 670 feet are used throughout the remainder of this report; however, the actual distance at which the device was activated was recorded and used in all calculations.

Items 8 through 18 deal with the subject's behavior. First and second brake distances and times refer to the number of feet traveled, and the time in seconds between the activation point and the first and second brake applications. If the brakes were applied only once, the same values were recorded for each variable. A zero occurs whenever the subject anticipated an activation and braked before the device was activated. On the other hand, values which approach the activation distance indicate a situation wherein the subject did not brake at all. First and second accelerator distance and time refer to distances and times between the activation point and the first and second times the subject's foot was removed from the gas pedal. These variables were set up in the same manner as were the brake variables and could take on the same set of values. Maximum deceleration location and level refer to

the location and level of the subject's maximum braking effort in response to the device being activated. Velocities refer to the average speed over each 10-foot interval of the 750 linear feet in advance of the traffic control device.

Once the data were in this format, the 1979 version of SAS (45) was used for preliminary data manipulation. A partial data set for one of the subjects is shown in Table 7. The information shown in Table 7 (with the 75 accompanying speeds) represents approximately 1 percent of the final data set and illustrates the magnitude of the problems facing the analyst. As mentioned in Section III, the data were analyzed by ANOVA techniques in order to determine significant differences in the effects on driver behavior of each of the six prototype devices taking into account the activation distance and lighting condition. The results from this activity are discussed in the following sections.

Response Due to Different Devices. To investigate the effects of the six innovative devices on subject behavior, each observation was classified according to device type, activation mode, and lighting condition. This process resulted in a model with 48 cells (six devices x four distances x two conditions). The total number of observations in the data set was 3,024. Table 8 breaks these down into the sample size per cell. The numbers are not equal because of the loss of some data due to equipment malfunctions and/or failures; however, there are at least 30 observations in each cell, and most of them contain at least 60 observations.

TABLE 7. PARTIAL DATA SET FOR TEST SUBJECT 30

OBS	PER	RUN	CAT	SEX	SYS	DVC	MDE	BR1	PR1	BR2	PR2	AC1	RE1	AC2	RE2	DLOC	DMAX
1	30	1	YOUNG	F	SYSTA	GATES	SHRT	0	0.00	0	0.00	0	0.00	0	0.00	555	6.43
2	30	2	YOUNG	F	SYSTA	FLSHR	SHRT	61	1.15	61	1.15	29	0.54	29	0.54	545	6.40
3	30	1	YOUNG	F	SYSTA	SGNL1	NULL	750	14.57	750	14.57	750	14.57	750	14.57	485	1.51
4	30	2	YOUNG	F	SYSTA	SGNL1	MEDM	114	1.91	114	1.91	32	0.52	32	0.52	705	5.66
5	30	2	YOUNG	F	SYSTA	FLSHR	NULL	750	14.90	750	14.90	750	14.90	750	14.50	605	1.30
6	30	2	YOUNG	F	SYSTA	GATES	LONG	249	4.43	249	4.43	70	1.22	652	21.05	555	4.08
7	30	3	YOUNG	F	SYSTA	GATES	MEDM	80	1.47	80	1.47	0	0.00	0	0.00	454	4.51
8	30	3	YOUNG	F	SYSTA	FLSHR	MEDM	91	1.76	91	1.76	37	0.71	37	0.71	625	4.23
9	30	3	YOUNG	F	SYSTA	SGNL1	NULL	750	16.12	750	16.12	750	16.12	750	16.12	425	2.09
10	30	4	YOUNG	F	SYSTA	SGNL1	LONG	291	5.41	291	5.41	227	4.19	227	4.19	695	4.66
11	30	4	YOUNG	F	SYSTA	FLSHR	SHRT	127	2.60	127	2.60	79	1.59	79	1.59	625	5.20
12	30	4	YOUNG	F	SYSTA	GATES	NULL	750	13.56	750	13.56	750	13.56	750	13.56	375	1.11
13	30	5	YOUNG	F	SYSTA	GATES	MEDM	89	1.62	89	1.62	6	0.11	6	0.11	525	5.15
14	30	5	YOUNG	F	SYSTA	FLSHR	MEDM	114	2.40	114	2.40	34	0.71	34	0.71	565	3.93
15	30	5	YOUNG	F	SYSTA	SGNL1	LONG	427	9.35	427	9.35	315	6.73	315	6.73	685	4.59
16	30	6	YOUNG	F	SYSTA	SGNL1	SHRT	73	1.36	73	1.36	25	0.47	25	0.47	615	5.54
17	30	6	YOUNG	F	SYSTA	FLSHR	LONG	468	10.24	468	10.24	383	8.22	383	8.22	705	4.53
18	30	6	YOUNG	F	SYSTA	GATES	NULL	750	14.70	750	14.70	750	14.70	750	14.70	345	0.61
19	30	7	YONNG	F	SYSTA	GATES	SHRT	107	2.11	107	2.11	0	0.00	80	1.57	555	5.71
20	30	7	YOUNG	F	SYSTA	FLSHR	LONG	379	8.77	379	8.77	0	0.00	134	3.07	675	3.67
21	30	7	YOUNG	F	SYSTA	SGNL1	SHRT	94	2.00	94	2.00	32	0.65	32	0.66	655	4.80
22	30	8	YOUNG	F	SYSTA	SGNL1	MEDM	156	3.02	156	3.02	44	0.82	44	0.82	695	5.28
23	30	8	YOUNG	F	SYSTA	FLSHR	NULL	750	16.31	750	16.31	750	16.31	750	16.31	365	1.32
24	30	8	YOUNG	F	SYSTA	GATES	LONG	311	6.33	311	6.33	189	3.81	189	3.81	555	3.62
25	30	9	YOUNG	F	SYSTA	GATES	MEDM	47	0.93	0	0.00	0	0.00	0	0.00	525	3.75
26	30	9	YOUNG	F	SYSTA	FLSHR	LONG	141	3.40	141	3.40	0	0.00	27	0.65	685	3.40
27	30	9	YOUNG	F	SYSTA	SGNL1	SHRT	86	1.65	86	1.65	44	0.83	44	0.83	575	5.81
28	30	10	YOUNG	F	SYSTA	SGNL1	NULL	750	15.47	750	15.47	750	15.47	750	15.47	615	0.57
29	30	10	YOUNG	F	SYSTA	FLSHR	SHRT	105	2.09	105	2.09	51	0.99	51	0.99	675	6.03
30	30	10	YOUNG	F	SYSTA	GATES	LONG	143	2.80	143	2.80	72	1.41	652	23.11	525	2.78
31	30	11	YOUNG	F	SYSTA	GATES	SHRT	47	1.00	47	1.00	0	0.00	0	0.00	525	2.32
32	30	11	YOUNG	F	SYSTA	FLSHR	MEDM	72	1.56	72	1.56	27	0.58	27	0.58	605	3.56
33	30	11	YOUNG	F	SYSTA	SGNL1	SHRT	74	1.52	74	1.52	31	0.61	31	0.61	615	5.03
34	30	12	YOUNG	F	SYSTA	SGNL1	LONG	360	7.65	360	7.65	274	5.77	274	5.77	475	3.32
35	30	12	YOUNG	F	SYSTA	FLSHR	NULL	750	15.13	750	15.13	750	15.13	750	15.13	365	1.36
36	30	12	YOUNG	F	SYSTA	GATES	NULL	750	14.40	750	14.40	257	5.03	257	5.03	345	1.28
37	30	13	YOUNG	F	SYSTA	GATES	MEDM	37	0.72	36	0.72	0	0.00	0	0.00	695	4.60
38	30	13	YOUNG	F	SYSTA	FLSHR	LONG	158	3.08	158	3.08	0	0.00	66	1.28	695	3.71
39	30	13	YOUNG	F	SYSTA	SGNL1	SHRT	85	1.75	85	1.75	545	0.91	45	0.91	605	5.51
40	30	14	YOUNG	F	SYSTA	SGNL1	LONG	268	4.76	268	4.76	202	3.56	202	3.56	615	3.79
41	30	14	YOUNG	F	SYSTA	FLSHR	SHRT	109	1.94	109	1.94	40	0.69	40	0.69	695	8.09
42	30	14	YOUNG	F	SYSTA	GATES	LONG	240	4.31	240	4.31	102	1.81	102	1.81	615	4.66
43	30	15	YOUNG	F	SYSTA	GATES	NULL	750	15.56	750	15.56	109	2.26	440	9.09	255	0.31
44	30	15	YOUNG	F	SYSTA	FLSHR	MEDM	0	0.00	0	0.00	0	0.00	0	0.00	615	4.22
45	30	15	YOUNG	F	SYSTA	SGNL1	NULL	750	15.71	750	15.71	750	15.71	750	15.71	435	2.19
46	30	16	YOUNG	F	SYSTA	SGNL1	SHRT	102	1.98	102	1.98	43	0.83	43	0.83	665	5.86
47	30	16	YOUNG	F	SYSTA	FLSHR	NULL	750	15.92	750	15.92	0	0.00	0	0.00	705	0.54
48	30	16	YOUNG	F	SYSTA	GATES	SHRT	76	1.37	76	1.37	39	0.70	39	0.70	535	6.16
49	30	17	YOUNG	F	SYSTB	SKRTS	MEDM	64	1.38	64	1.38	0	0.00	0	0.00	605	3.77
50	30	17	YOUNG	F	SYSTB	STRBS	SHRT	59	1.35	59	1.35	7	0.16	7	0.16	675	3.76
51	30	17	YOUNG	F	SYSTB	SGNL3	NULL	750	18.37	750	18.37	750	18.37	750	18.37	465	1.55
52	30	18	YOUNG	F	SYSTB	SGNL3	LONG	409	9.42	409	9.42	99	2.12	99	2.12	705	4.14
53	30	18	YOUNG	F	SYSTB	STRBS	MEDM	153	3.13	153	3.13	0	0.00	92	1.86	665	4.90
54	30	18	YOUNG	F	SYSTB	SKRTS	NULL	750	18.54	750	18.54	124	2.87	586	14.61	635	1.01
55	30	19	YOUNG	F	SYSTB	SKRTS	NULL	750	15.49	750	15.49	750	15.49	750	15.49	655	0.32

TABLE 8. DEVICE BY ACTIVATION DISTANCE BY LIGHTING CONDITION CLASSIFICATION PROCESS (NUMBER OF OBSERVATIONS)

Type of Traffic Control	Activation Distance				Total
	Short 330′	Medium 440′	Long 670′	Null 0′	
Day Driving					
Four-quadrant gates without skirts	63	63	63	63	252
Four-quadrant flashing light signals without strobes	63	62	63	64	252
Highway traffic signals--one white bar strobe	88	34	66	64	252
Four-quadrant gates with skirt	65	64	61	65	255
Four-quadrant flashing light signals with overhead strobes	65	63	65	62	255
Highway traffic signals--three white bar strobes	96	31	63	65	255
TOTAL (Day)	440	317	381	383	1,521
Night Driving					
Four-quadrant gates without skirts	63	63	59	63	248
Four-quadrant flashing light signals without strobes	62	63	60	63	248
Highway traffic signals--one white bar strobe	92	31	64	61	248
Four-quadrant gates with skirt	67	61	64	61	253
Four-quadrant flashing light signals with overhead strobes	60	64	66	63	258
Highway traffic signals--three white bar strobes	94	37	60	62	253
TOTAL (Night)	438	319	373	374	1,503
GRAND TOTAL	878	636	754	756	3,024

After an initial screening, brake reaction time and maximum deceleration level were selected as the most meaningful from the candidate list of variables describing a subject's reaction to a traffic control device. The cell means for these two variables are shown in Tables 9 and 10, and frequency distributions for the same two variables are contained in Appendix C. An attempt was made to analyze the number of extreme deceleration levels in the data set. However, only 58 of the 3,024 observed decelerations could be classified as undesirable or worse (greater than 8 fps^2). Because of this small sample size, a further analysis was not conducted.

A visual examination of the data in Tables 9 and 10 reveals several interesting trends. First, reaction times and deceleration levels appear to have been less at night than they were during the day. Second, reaction times seem to have increased and deceleration levels appear to have decreased with an increase in activation distance. Finally, subjects appear to have responded quicker to the two types of four-quadrant gates than to the two types of four-quadrant flashing light signals, and they appear to have responded quicker to the two types of four-quadrant flashing light signals than to the two types of highway traffic signals. It should be noted that reaction to the traffic signal was measured with regard to the start of the yellow interval because it communicates a forthcoming change of right-of-way to the driver. Removal of this time (3.6 seconds) from the reported brake reaction times would have a noticeable effect on the results, especially at the longer activation distances.

TABLE 9. AVERAGE BRAKE REACTION TIME (SECONDS) FOR THE SIX ALTERNATIVE DEVICES

Type of Traffic Control	Activation Distance			
	Short 330′	Medium 440′	Long 670′	Null 0′
Day Driving				
Four-quadrant gates without skirts	1.199[a]	1.647	3.747	10.977
Four-quadrant flashing light signals without strobes	1.339	2.494[a]	4.015	9.588
Highway traffic signals--one white bar strobe	1.777	2.286	8.393	15.355
Four-quadrant gates with skirts	1.123[a]	1.687	3.676[a]	10.718
Four-quadrant flashing light signals with overhead strobes	1.292	2.519	3.833	8.975
Highway traffic signals--three white bar strobes	2.002	2.798	7.583[b]	15.567
Night Driving				
Four-quadrant gates without skirts	0.768[a]	1.300	2.861	10.227
Four-quadrant flashing light signals without strobes	1.181	1.689[a]	3.479	9.240
Highway traffic signals--one white bar strobe	1.988	2.337	7.297	16.445
Four-quadrant gates with skirts	0.734[a]	1.285	2.422[a]	10.421
Four-quadrant flashing light signals with overhead strobes	1.222	2.167	3.287	9.983
Highway traffic signals--three white bar strobes	1.979	2.412	8.883[b]	16.670

[a]Significant decrease in brake reaction time between day and night.
[b]Significant increase in brake reaction time between day and night.

TABLE 10. MAXIMUM DECELERATION LEVELS (FEET PER SECOND SQUARED) FOR THE SIX ALTERNATIVE DEVICES

Type of Traffic Control	Activation Distance			
	Short 330′	Medium 440′	Long 670′	Null 0′
Day Driving				
Four-quadrant gates without skirts	4.994	3.926	3.563[a]	1.686
Four-quadrant flashing light signals without strobes	5.090	4.692	4.005[a]	1.896[a]
Highway traffic signals--one white bar strobe	4.812	4.162	3.612	1.310
Four-quadrant gates with skirts	5.217[a]	4.313	3.466[a]	1.571
Four-quadrant flashing light signals with overhead strobes	5.024	4.548	3.883	1.969
Highway traffic signals--three white bar strobes	5.199	3.825	3.564[a]	1.431
Night Driving				
Four-quadrant gates without skirts	5.376	3.876	3.202[a]	1.369
Four-quadrant flashing light signals without strobes	4.958	4.304	3.568[a]	1.499[a]
Highway traffic signals--one white bar strobe	4.935	4.094	3.305	1.468
Four-quadrant gates with skirts	4.514[a]	4.342	3.130[a]	1.252
Four-quadrant flashing light signals with overhead strobes	4.842	4.113	3.580	1.752
Highway traffic signals--three white bar strobes	4.680	3.650	3.204[a]	1.345

[a]Significant decrease in maximum deceleration levels between day and night.

In order to determine whether or not the differences in the means of the two variables were real or simply a result of chance, three-way ANOVA tests for statistical significance were performed. These tests resulted in calculated overall F-values of 134.49 for the first brake reaction variable and 50.57 for the maximum deceleration level variable. Both values are significant at the 0.0001 significance level which indicates that at least two of the 48 cells in the model have significantly different means. After determining that the interaction effects were not large enough to place conditions on the interpretation of the main effects, Duncan's test (at the 95 percent confidence level) was used to test the differences that existed within each of the three main effects in the full model. The results were as follows:

1. When response to the six device types was averaged across all levels of activation distance and lighting condition, there was not a significant difference between the two gate systems and the two flashing light systems; however, the difference in response between these four devices and the two highway traffic signal systems was significant.
2. When response to the four activation distances was averaged across all levels of device type and lighting condition, there were significant differences between each of the four distances.
3. When response to the two lighting conditions was averaged across all levels of device type and activation distance, there was a significant difference between day and night;

however, the magnitude of the difference (0.23 seconds) was very small.

As activation distance explained most of the variation in the data set, it was decided to run separate two-way ANOVA tests for each of the four activation distances. The results are summarized in Table 11. Interpretation of this table is rather complex as both variables are represented and each column depicts a separate ANOVA test. There are only 12 cells (six devices x two conditions) in each model, and there are four models for each variable. For each model, cells with the same letter were not significantly different.

As an example, for the brake reaction time variable and the medium activation distance, response to the two types of four-quadrant gates was significantly different (faster) than response to the other four devices; however, differences within the two groups (two types of gates and the other four devices) were not statistically significant. For the short activation distance, response to the four-quadrant gates with skirts was significantly different from response to the two types of signals. In addition, response to the two types of four-quadrant gate systems and the two types of four-quadrant flashing light signal systems was significantly different from the response to the two types of highway signals. Because the four-quadrant gates without skirts belong to both Groups A and B, there was no significant difference between the four-quadrant gate systems and four-quadrant flashing light signal systems.

Basically, the four-quadrant gates with skirts always belonged to the fastest group, and the two types of highway traffic signals were

TABLE 11. COMPARISON OF AVERAGE BRAKE REACTION TIMES AND MAXIMUM DECELERATION LEVELS FOR VARIOUS ACTIVATION DISTANCES (CELLS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT)

Type of Traffic Control	Activation Distance			
	Short 330′	Medium* 440′	Long* 670′	Null 0′
Variable: First Brake, Time				
Four-quadrant gates without skirts	A,B	A	A	A
Four-quadrant flashing light signals without strobes	B	B	A	A
Highway traffic signals--one white bar strobe	C	B	B	B
Four-quadrant gates with skirts	A	A	A	A
Four-quadrant flashing light signals with overhead strobes	B	B	A	A
Highway traffic signals--three white bar strobes	C	B	B	B
Variable: Maximum Deceleration, Level				
Four-quadrant gates without skirts	A	A,B	A	A,B
Four-quadrant flashing light signals without strobes	A	C	B	B,C
Highway traffic signals-one white bar strobe	A	A,B,C	A	A
Four-quadrant gates with skirts	A	B,C	A	A
Four-quadrant flashing light signals with overhead strobes	A	B,C	B	C
Highway traffic signals--three white bar strobes	A	A	A	A

*Significant differences between day and night.

always associated with the slowest group. The placement of the four-quadrant gates without skirts and the two types of four-quadrant flashing light signals varied with activation distance--sometimes they belonged to the fastest group, sometimes they belonged to the slowest group, and sometimes they belonged to an intermediate group. In addition, at both the medium and long distances, response to the devices was significantly different between day and night conditions.

Interpretation of the maximum deceleration levels was not as clear-cut. Interestingly, there was not a significant difference in deceleration levels at the short activation distance, but at the other distances there were differences. However, there appeared to be no pattern to the results. As with the brake reaction variable, response to the devices at the long and medium activation distances was significantly different between day and night conditions.

In order to better understand these results, average velocity profiles of the 32 drivers were plotted for several conditions. Figures 22 through 27 represent the average response of the test subjects to each of the six innovative devices. Vertical lines represent the three activation distances--short, medium, and long. Because of the previously-mentioned hardware limitations, it should be noted that these lines are plotted at 310, 420, and 650 feet as this represents the closest distances at which the device could have been activated. The symbols represent the first letter of the activation distance--short, medium, long, and null. As shown in these figures, reactions to the different devices were very similar. Basically, the test subjects began to slow to a stop shortly after the device was activated. This slowing occurred

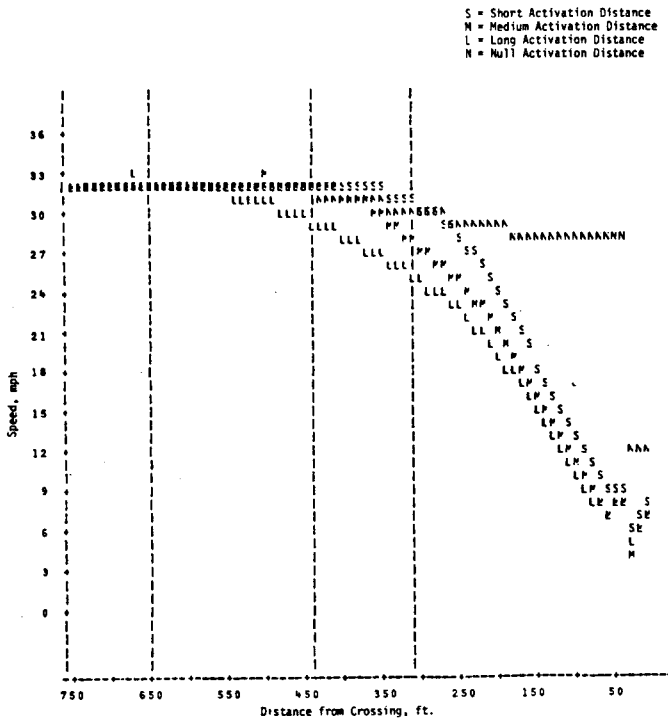


FIGURE 22. AVERAGE RESPONSE OF ALL MOTORISTS TO THE FOUR-QUADRANT GATES WITHOUT SKIRTS (ALL ACTIVATION DISTANCES)

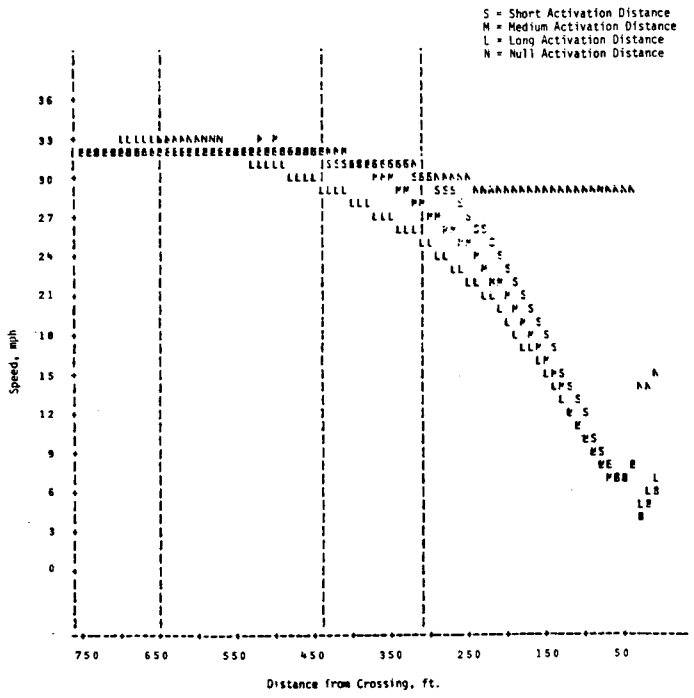


FIGURE 23. AVERAGE RESPONSE OF ALL MOTORISTS TO THE FOUR-QUADRANT GATES WITH SKIRTS (ALL ACTIVATION DISTANCES)

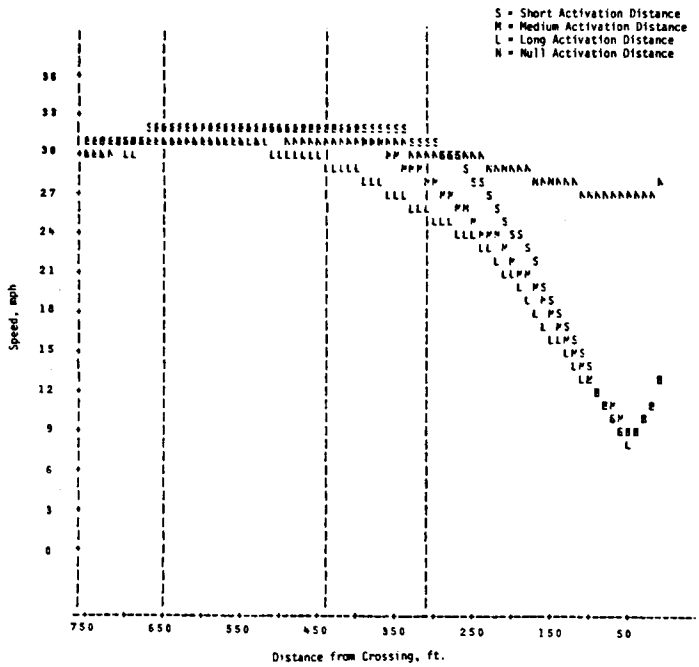


FIGURE 24. AVERAGE RESPONSE OF ALL MOTORISTS TO THE FOUR-QUADRANT FLASHING LIGHT SIGNALS WITHOUT STROBES (ALL ACTIVATION DISTANCES)

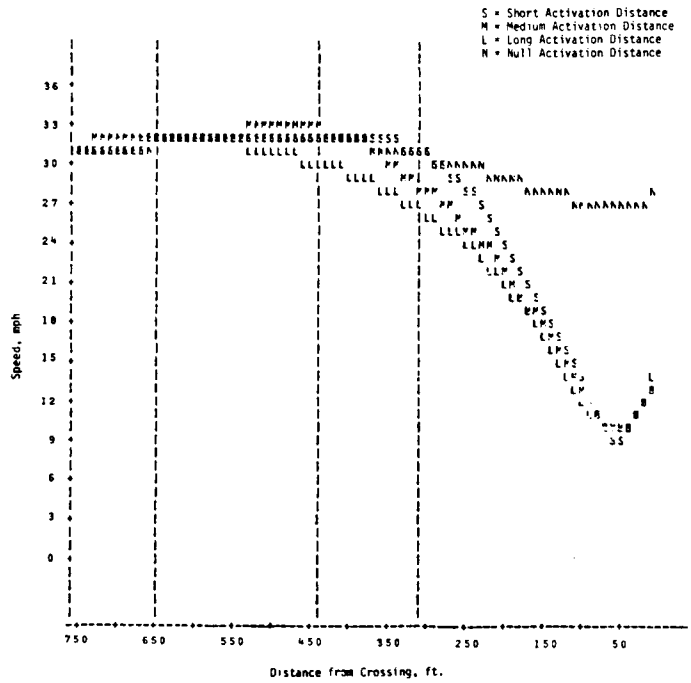


FIGURE 25. AVERAGE RESPONSE OF ALL MOTORISTS TO THE FOUR-QUADRANT FLASHING LIGHT SIGNALS WITH OVERHEAD STROBES (ALL ACTIVATION DISTANCES)

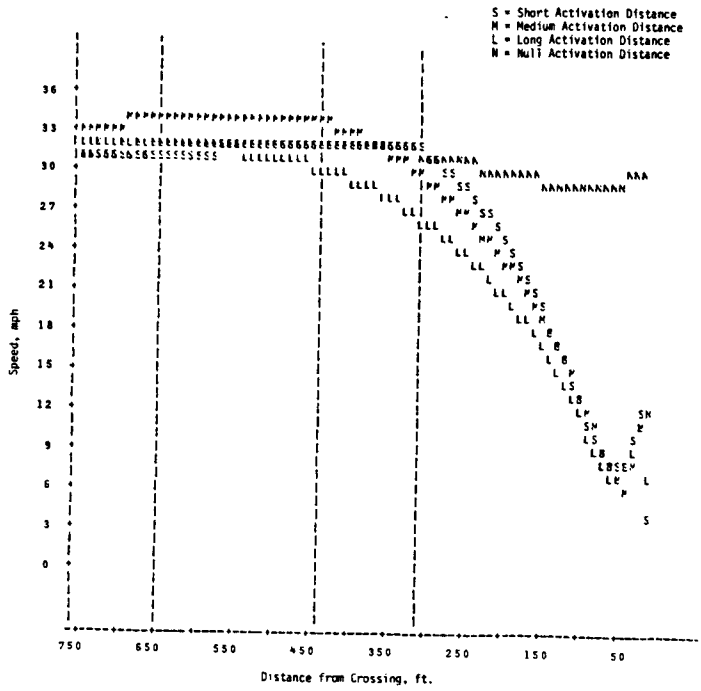


FIGURE 26. AVERAGE RESPONSE OF ALL MOTORISTS TO THE HIGHWAY TRAFFIC SIGNALS WITH ONE WHITE BAR STROBE (ALL ACTIVATION DISTANCES)

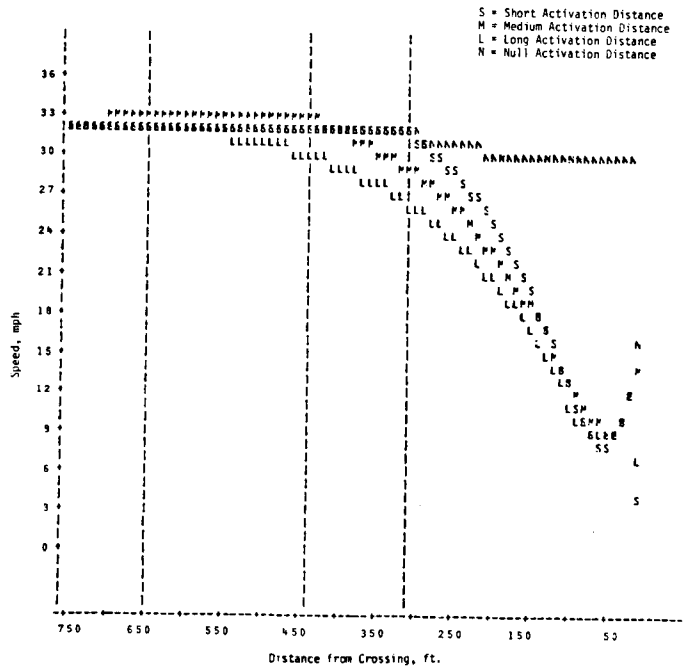


FIGURE 27. AVERAGE RESPONSE OF ALL MOTORISTS TO THE HIGHWAY TRAFFIC SIGNALS WITH THREE WHITE BAR STROBES (ALL ACTIVATION DISTANCES)

at about 300 feet for the short activation distance, at about 350 feet for the medium activation distance, and at about 500 feet for the long activation distance. Thus, the shorter the activation distance, the sooner the subject responded. It is also easy to see that higher deceleration levels were associated with the shorter activation distances. These observations reinforce the premise that different activation distances have a significant impact on a motorist's behavior.

Figures 28 through 31 represent the subjects' response to one of the four activation distances. As before, vertical lines represent the activation distances. The letters represent the six different devices as follows: A--four-quadrant gates without skirts; B--four-quadrant flashing light signals without strobes; C--highway traffic signals with one white bar strobe; D--four-quadrant gates with skirts; E--four-quadrant flashing light signals with overhead strobes; and F--highway traffic signals with three white bar strobes. Several observations can be made by looking at these figures. First, type of device did not appear to have a large effect on subject behavior, especially at short activation distances. Second, as the activation distance increased, differences in response due to device type appear to have increased. Finally, although no large differences existed, driver response to four-quadrant gates with (D) and without (A) skirts was noticeably faster than driver response to the other devices at each of the four activation distances. These observations also confirm the results from the ANOVA tests.

Comparisons of the velocity profiles in response to Alternatives A and B for the three basic devices at each of the four activation distances are contained in Appendix C. At the short activation distance,

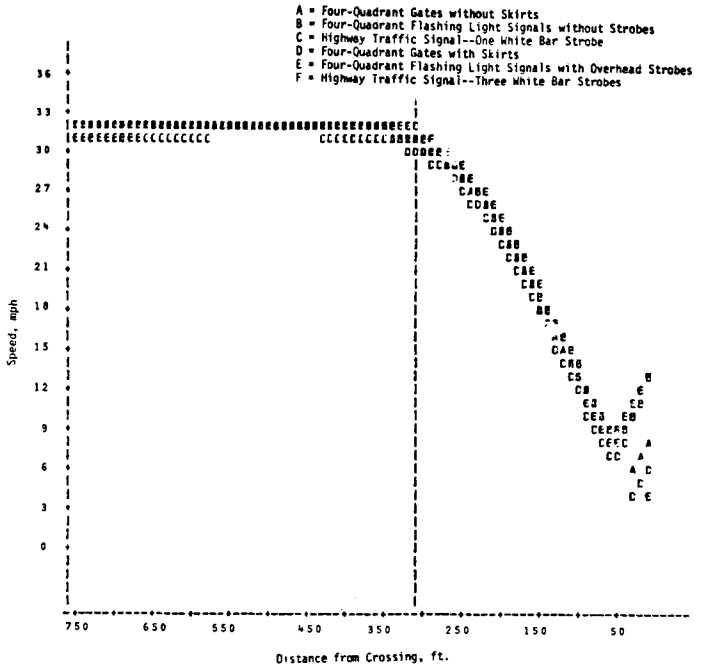


FIGURE 28. AVERAGE RESPONSE OF ALL MOTORISTS TO THE SHORT ACTIVATION DISTANCE (ALL DEVICES)

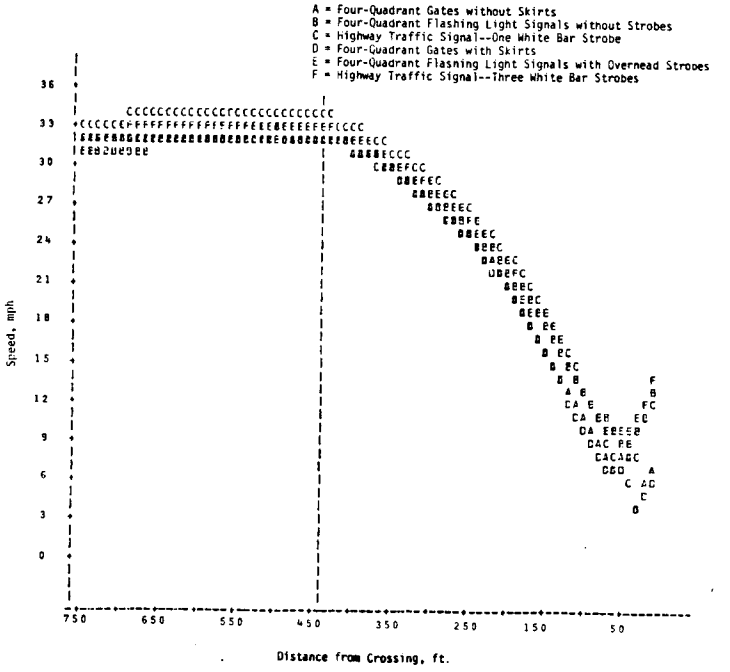


FIGURE 29. AVERAGE RESPONSE OF ALL MOTORISTS TO THE MEDIUM ACTIVATION DISTANCE (ALL DEVICES)

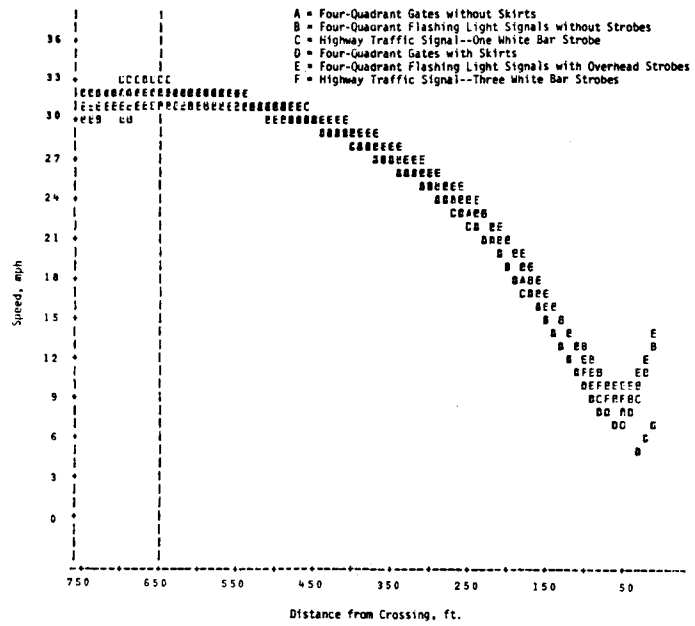


FIGURE 30. AVERAGE RESPONSE OF ALL MOTORISTS TO THE LONG ACTIVATION DISTANCE (ALL DEVICES)

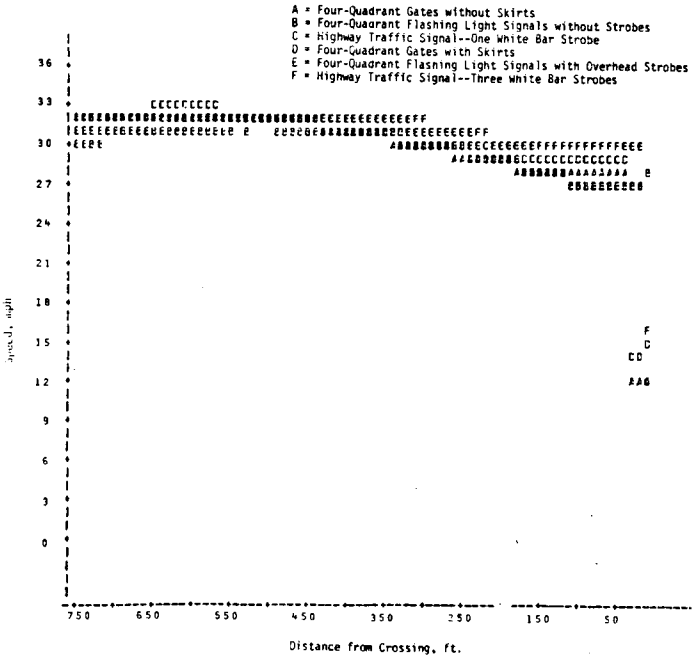


FIGURE 31. AVERAGE RESPONSE OF ALL MOTORISTS TO THE NULL ACTIVATION DISTANCE (ALL DEVICES)

response to Alternative B for the four-quadrant gate system (with skirts) appears to be a little faster than that for alternative A (without skirts). However, for both the four-quadrant flashing light signal systems and highway traffic signals systems, there are no discernible differences between alternatives. In addition, there is no obvious difference in response due to alternatives at either the medium or long activation distances. The plots for the null condition also illustrate basically consistent behavior between alternatives.

Response Due to Basic Systems. Similar analyses (ANOVA tests and speed profiles) were conducted in order to determine the effect on driver behavior of the three basic systems. As a result, a model was built which contained 24 cells (three systems x four distances x two lighting conditions). The sample size per cell is approximately double that of the other model. Tables 12 and 13 contain the means for the first brake reaction time and maximum deceleration levels for the reduced three-way model. Generally, reaction times and deceleration levels appear to be less at night than during the day; however, reaction time to the highway traffic signal systems show a slight increase from day to night. As with the full three-way model, reaction times tend to increase and deceleration levels tend to decrease with an increase in activation distance. Finally, subjects appear to have responded quicker to gates than to flashing light signals, and they appear to have responded quicker to flashing light signals than to highway traffic signals. Deceleration levels for the different systems were approximately the same.

TABLE 12. AVERAGE BRAKE REACTION TIMES (SECONDS) FOR THE THREE ALTERNATIVE SYSTEMS

Type of Traffic Control	Activation Distance			
	Short 330′	Medium 440′	Long 670′	Null 0′
Day Driving				
Four-quadrant gate systems	1.161	1.667	3.712	10.846
Four-quadrant flashing light signal systems	1.315	2.506	3.923	9.286
Highway traffic signal systems	1.894	2.530	7.998	15.462
Night Driving				
Four-quadrant gate systems	0.751	1.293	2.632	10.323
Four-quadrant flashing light signal systems	1.201	1.930	3.379	9.611
Highway traffic signal systems	1.984	2.378	8.064	16.558

TABLE 13. MAXIMUM DECELERATION LEVELS (FEET PER SECOND SQUARED) FOR THE THREE ALTERNATIVE SYSTEMS

Type of Traffic Control	Activation Distance			
	Short 330′	Medium 440′	Long 670′	Null 0′
Day Driving				
Four-quadrant gate systems	5.107	4.121	3.515	1.627
Four-quadrant flashing light signal system	5.056	4.620	3.943	1.932
Highway traffic signal systems	5.013	4.001	3.588	1.371
Night Driving				
Four-quadrant gate systems	4.932	4.105	3.165	1.311
Four-quadrant flashing light signal systems	4.901	4.208	3.574	1.625
Highway traffic signal systems	4.806	3.852	3.256	1.406

Three-way ANOVA tests were conducted in order to determine whether or not these differences were statistically significant. These tests resulted in calculated overall F-values of 274.94 for the first brake reaction time variable and 102.05 for the maximum deceleration level variable. Both values are significant at the 0.0001 significance level. As stated before, this result indicated that at least two of the 24 cells in the reduced model had significantly different means. After determining that the interaction effects were not large enough to place conditions on the interpretation of the main effects, Duncan's test (at the 95 percent confidence level) was used to test the differences that existed within each of the three main effects in the full model. The results were as follows:

1. When response to the three basic systems was averaged across all levels of activation distance and lighting condition, there was a significant difference between the highway traffic signals and the other two systems (four-quadrant gates and four-quadrant flashing light signals).
2. When response to the four activation distances was averaged across all levels of system type and lighting condition, there were significant differences between each of the four distances.
3. When response to the two lighting conditions was averaged across all levels of system type and activation distance, there was a significant difference between day and night. The magnitude of this difference was very small (0.23 seconds).

Because activation distance again explained most of the variance in the data set, separate two-way ANOVA tests were run for each of the four activation distances. The results are summarized in Table 14. For the two variables analyzed, each column represents a separate ANOVA test. There are only six cells (three systems x two conditions) for each model, and there are four models for each variable. For each model, cells with the same letter are not significantly different.

Interpretation of these results was relatively straightforward. Basically, the four-quadrant gate systems always belonged in the fastest reacting group, and the highway traffic signal systems were always in the slowest reacting group. The ranking for the four-quadrant flashing light signal systems varied with activation distance. For the maximum deceleration level variable, the four-quadrant gate systems and highway traffic signal systems generally belonged to the same group. Response to the four-quadrant flashing light signal systems indicated significantly different (higher) deceleration levels. In addition, there were differences in response between day and night for both the medium and long activation distances. All differences were significant at the 95 percent confidence level.

Several velocity profile plots were made in order to compare the average subject's response to the three basic systems. Figures 32 through 39 present the results of this activity. As before, vertical lines represent the activation distances and the symbols represent particular devices as follows: A--four-quadrant gates, B--four-quadrant flashing light signals, and C--highway traffic signals. For discussion purposes, these eight figures should be viewed as four sets of two

TABLE 14. COMPARISON OF AVERAGE BRAKE REACTION TIMES AND MAXIMUM DECELERATION LEVELS FOR VARIOUS ACTIVATION DISTANCES (CELLS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT)

Type of Traffic Control	Activation Distance			
	Short 330′	Medium* 440′	Long* 670′	Null 0′
Variable: First Brake, Time				
Four-quadrant gate systems	A	A	A	B
Four-quadrant flashing light signal systems	B	B	A	A
Highway traffic signal systems	C	B	B	C
Variable: Maximum Deceleration, Level				
Four-quadrant gate systems	A	A,B	A	A
Four-quadrant flashing light signal systems	A	B	B	B
Highway traffic signal systems	A	A	A	A

*Significant differences between day and night.

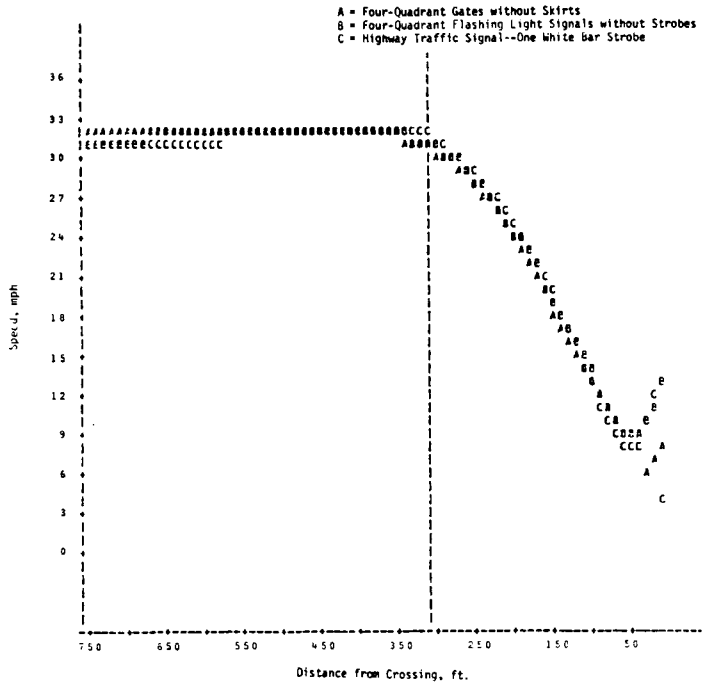


FIGURE 32. AVERAGE RESPONSE OF ALL MOTORISTS TO ALTERNATIVE A OF EACH SYSTEM (SHORT ACTIVATION)

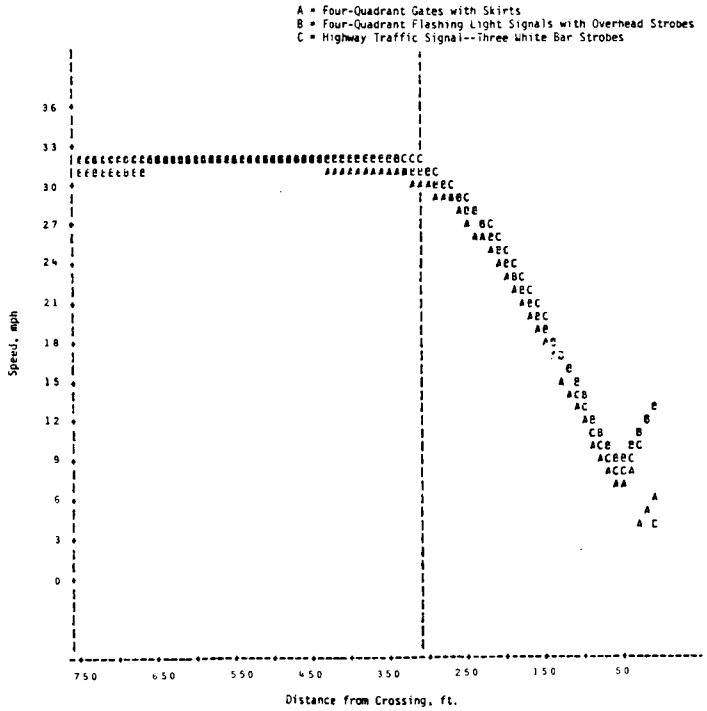


FIGURE 33. AVERAGE RESPONSE OF ALL MOTORISTS TO ALTERNATIVE B OF EACH SYSTEM (SHORT ACTIVATION)

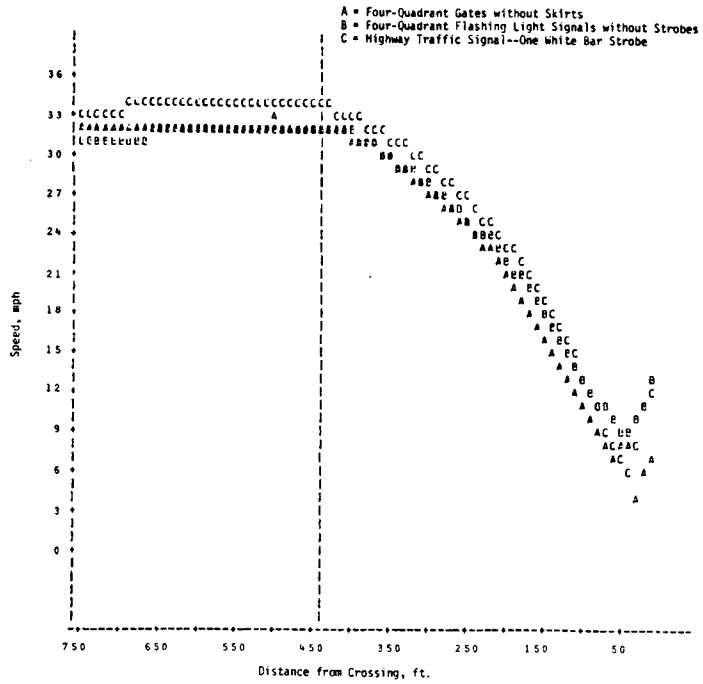


FIGURE 34. AVERAGE RESPONSE OF ALL MOTORISTS TO ALTERNATIVE A OF EACH SYSTEM (MEDIUM ACTIVATION)

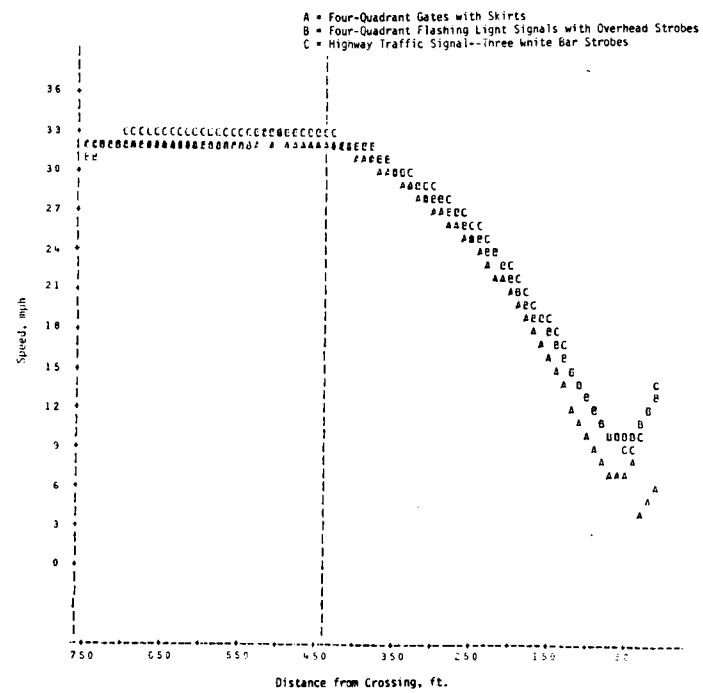


FIGURE 35. AVERAGE RESPONSE OF ALL MOTORISTS TO ALTERNATIVE B OF EACH SYSTEM (MEDIUM ACTIVATION)

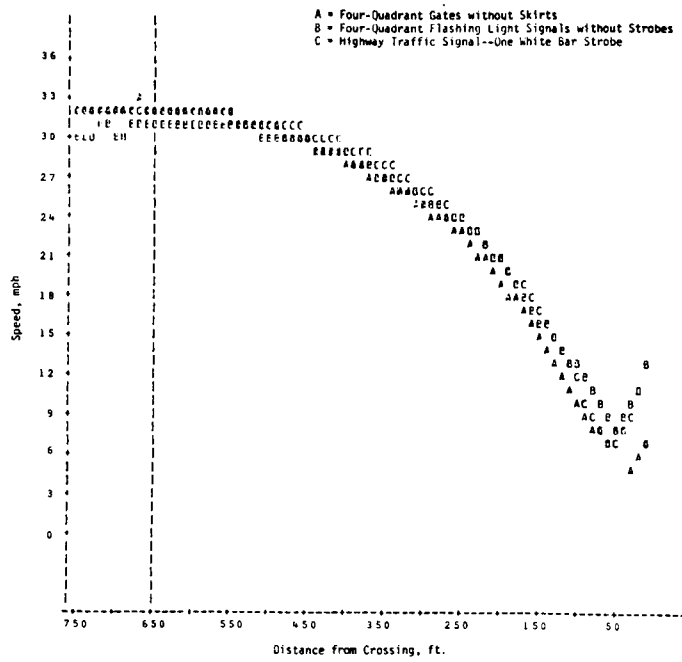


FIGURE 36. AVERAGE RESPONSE OF ALL MOTORISTS TO ALTERNATIVE A OF EACH SYSTEM (LONG ACTIVATION)

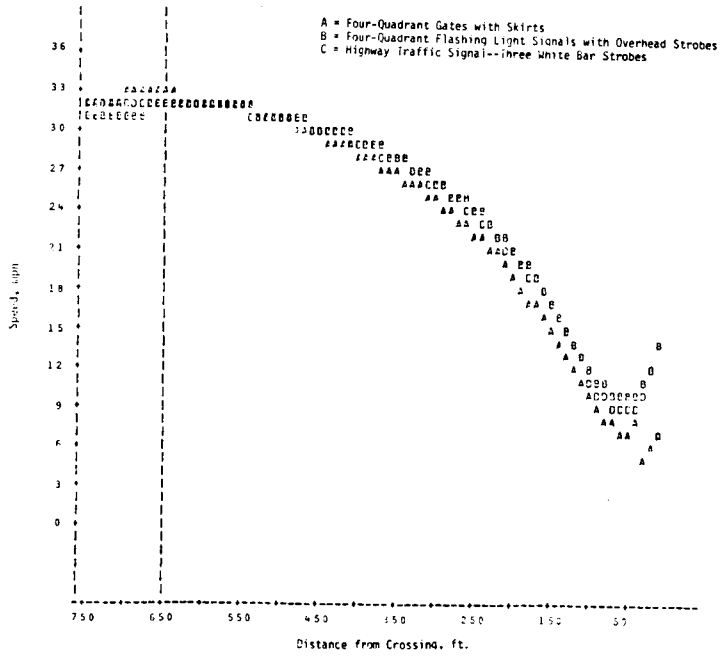


FIGURE 37. AVERAGE RESPONSE OF ALL MOTORISTS TO ALTERNATIVE B OF EACH SYSTEM (LONG ACTIVATION)

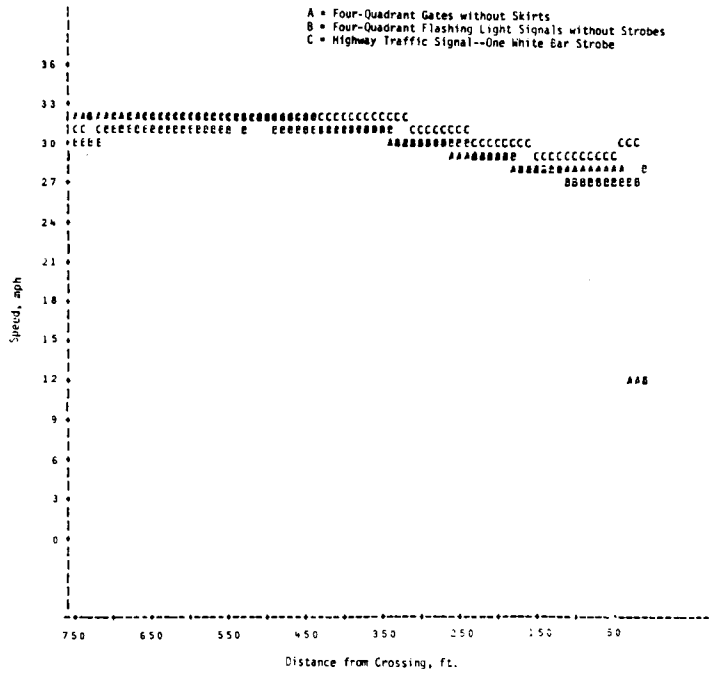


FIGURE 38. AVERAGE RESPONSE OF ALL MOTORISTS TO ALTERNATIVE A OF EACH SYSTEM (NULL ACTIVATION)

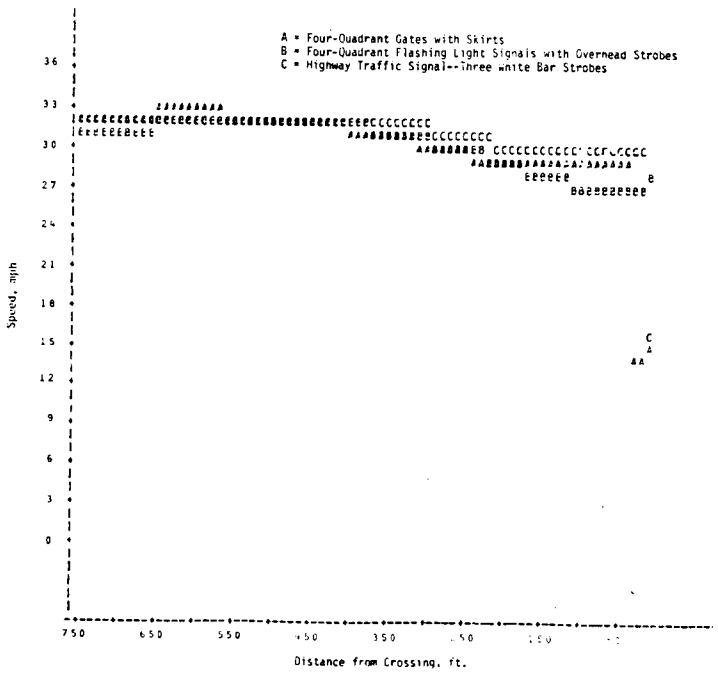


FIGURE 39. AVERAGE RESPONSE OF ALL MOTORISTS TO ALTERNATIVE B OF EACH SYSTEM (NULL ACTIVATION)

figures, one set for each of the four activation distances. The first figure in each set depicts the subject's response to the first alternative for each system, and the second figure depicts the subject's response to the second alternative for each of the three systems.

Similar response patterns are evident between each pair of drawings. Reaction to the four-quadrant gate systems was almost always the quickest. This is followed in order by reaction to the four-quadrant flashing light signal systems and then reaction to the highway traffic signal system. As the subject slowed to a stop, the velocity profiles in reaction to the highway traffic signal systems began to overlay those in reaction to the four-quadrant flashing light signal systems. The velocity profile for the four-quadrant gate systems generally remained lower throughout the entire stopping process. These observations are consistent with the results from the ANOVA tests. The quickest response was in reaction to the four-quadrant gate systems, and the slowest response was in reaction to the highway traffic signal systems. Response in reaction to the four-quadrant flashing light signal systems ranked somewhere between the other two, with its exact position varying with distance.

Summary

In terms of driver preference, all six innovative devices were perceived as superior to the standard active warning devices currently in use at railroad-highway grade crossings. The test subjects always perceived the four-quadrant gates with skirts as the most effective and four-quadrant flashing light signals without strobes as the least

effective on both an absolute and relative ranking basis. The perceived effectiveness of the other four devices tended to cluster together and was not significantly different on the absolute ranking basis for either day or night conditions. However, on the relative ranking basis, there was a consistent order of perceived effectiveness for both conditions.

In terms of driver behavior, four-quadrant gates with skirts resulted in significantly quicker brake reaction times than either highway traffic signals or four-quadrant flashing light signals at both the short and medium activation distance. In addition, the two highway traffic signal alternatives resulted in significantly slower brake reaction times than either of the other two systems at all three activation distances. There was no significant difference in the resultant deceleration levels for any of the devices at the short activation distance. Although there were significant differences at the medium and long activation distances, there was no apparent pattern to the results.

Generally speaking, Alternative B of each system (i.e., with skirts, with overhead strobes, and with three white bar strobes) was more effective. Four-quadrant gates with skirts tended to be a superior system in all performance measures. However, the relative effectiveness of flashing light signals and highway traffic signals varied depending on the measure being considered; there was not a consistent ordering of effectiveness between the two systems.

Because the overall research effort was directed toward determining the cost effectiveness of alternative active warning devices and the cost of each basic system varied over a wide range, it was decided that one alternative of each basic system should be field tested at an actual

crossing. Because Alternative B of each system was generally superior, it was the one chosen for testing.

V. FIELD EVALUATION PLAN

The objective of the field studies was to evaluate the three most promising innovative active warning devices, identified in the laboratory study, under normal traffic conditions at existing railroad-highway grade crossings. The three devices selected for field evaluation were: (a) the four-quadrant gate and flashing light signal system with skirts added to all gate arms; (b) the four-quadrant flashing light signal system with red strobe lights over the traffic lanes; and (c) the highway traffic signal system with a white bar strobe in front of each red signal lens. This chapter presents the study approach used in the field evaluation study as well as the plan for data collection and reduction.

Study Approach

A before-and-after study approach was used to evaluate the three innovative active warning devices. That is, several types of performance data were collected at existing crossings with standard active warning devices and then again at the same crossings after the standard warning devices had been replaced with the innovative devices. This approach minimized the effects of site differences, and allowed a direct comparison between the innovative devices and the standard devices currently in use at the crossings.

Data Collection Plan. Each of the innovative devices was evaluated at one of three railroad-highway grade crossings in the Knoxville, Tennessee area (Section VI describes the study crossings and presents details on design and installation of the innovative devices). Table 15

TABLE 15. DATA COLLECTION PLAN FOR FIELD STUDY

Crossing	Existing Condition (Spring and Summer 1985)	Improved Condition (Winter and Spring 1986)	Improved Condition (Summer 1986)
Cherry Street	Two-Quadrant Gate and Flashing Light Signal System	Four-Quadrant Gate and Flashing Light Signal System	-
Ebenezer Road	Two-Quadrant Flashing Light Signal System	Four-Quadrant Flashing Light Signal System with Overhead Strobes	Four-Quadrant Flashing Light Signal System with Overhead Strobes
Cedar Drive	Two-Quadrant Flashing Light Signal System without Predictors	Two-Quadrant Flashing Light Signal System with Predictors	Highway Traffic Signal System with Predictors

summarizes the before-and-after data collection plan, showing the device assignment to the study sites and the schedule for collection of the driver behavioral data at the three crossings.

The first set of studies was termed "existing condition studies" and was conducted prior to the installation of the new active warning devices. This phase of the data collection was used to quantify existing driver behavior and served as a reference point to which future observations could be compared. The second and/or third set of studies were termed "improved condition studies" and were conducted after the installation of the new active warning devices. Results from the improved condition studies were compared to the existing condition studies (to determine whether the new devices were more or less effective than the old ones) and for certain performance measures, to each other (to determine the relative effectiveness of the new devices).

The first set of crossing studies was conducted in the spring and summer of 1985. The new devices were then installed. After a one- to two-month familiarization period, the second set of studies was conducted in the winter and spring of 1986. The purpose of this delay was to ensure that the behavioral data being collected did not contain driver responses due to unfamiliarity with the new devices. The third set of studies was conducted during the summer of 1986 for the purpose of determining whether the effectiveness of the new devices changed with time.

Care was taken to ensure that conditions at the study crossings did not change during the studies. Traffic and train volumes were continuously monitored. Also, before any data were collected, all advance

warning signs and pavement markings were upgraded so as to be in compliance with the guidelines contained in the MUTCD (12). In addition, all active warning devices were properly aligned and subjected to routine maintenance prior to the conduct of each study.

Sample Size Considerations. For each study at a particular crossing, data were collected for a minimum of 30 train crossings. Including equipment setup and takedown time, a minimum of one month (two person-months) was estimated for each of the data collection periods at the three sites. However, larger samples, weather delays, and/or equipment malfunctions significantly increased the time requirements, and two to three months (four to six person-months) were actually expended for data collection during each study phase at each of the three sites. Also, a minimum of two months (four person-months) was required to reduce and analyze the data from an individual study. Therefore, approximately five months (ten person-months) were required for each study period.

Environmental Conditions. Although it would have been desirable to evaluate the effectiveness of each device under a wide range of weather and/or ambient light conditions, it was not feasible to do so given the fiscal and time constraints of the project. To start with, one cannot accurately predict the weather. For example, there was no guarantee that it would not rain on the days scheduled for data collection. Even if it did, there might have been a difference in the rainfall's intensity and its corresponding effect on visibility. To wait for usable wet weather conditions to occur might have resulted in an endless study. On the other hand, waiting for good weather during certain time periods

would also have delayed the data collection effort. Therefore, as both conditions occurred in the real world, data were collected under whatever weather conditions existed at that time.

Ambient lighting conditions were a little easier to control as the two conditions studied were simply day and night. There was no attempt to change the external lighting level at any of the three crossings. As a result, the final data set contained observations during both day and night conditions in proportion to the number of train arrivals during these time periods. It was anticipated that the night time sample sizes would be smaller because of lower train and traffic volumes; however, their size was expected to be adequate for comparison purposes. It was also anticipated that even if the total number of train crossings in the before and after conditions were not equal, the day and night proportions of the two data sets would be approximately the same.

Measures of Effectiveness

Realistic field evaluation of the three innovative active traffic control devices was dependent upon selection of suitable measures of effectiveness (MOE's). To avoid influencing drivers and hence influencing their responses, MOE's were selected which could be obtained with a minimum of interference and detection by drivers. In addition, only commonly-accepted and safety-oriented driver performance measures were considered. As a result of these considerations, the measures of effectiveness selected for evaluation were as follows:

1. Speed profiles;
2. Perception-brake reaction times;
3. Maximum deceleration levels;

4. Violations; and

5. Vehicles crossing.

Looking behavior, the other grade crossing MOE cited in the literature, was not used in this study as it is not particularly meaningful in evaluating active warning devices. Looking behavior data would also have been very difficult and costly to obtain.

The general hypotheses tested in the field studies were that when compared to the existing warning devices, the innovative devices would result in: (a) quicker driver perception-brake reaction times, (b) fewer undesirable and/or uncomfortable decelerations, (c) fewer violations, and (d) fewer vehicles crossing in front of the train. Thus, the overall null hypothesis was that there was no difference in driver performance measures when comparing response to the existing standard device with response to the innovative device under study. Rejection of this null hypothesis would suggest an increase in the conspicuity of and respect for the innovative active warning device. The specific comparisons that were made and procedures that were followed in determining the effectiveness of the different devices are described in the following sections.

Speed Profiles. Speed profile data were evaluated for each of the innovative devices and compared to similar data collected before installation of the device (i.e., under the existing conditions). In addition, a maximum deceleration level was computed from each individual speed-profile. These values were then tabulated and plotted as a cumulative frequency distribution. The number of drivers accepting an

undesirable level of deceleration (greater than 8 fps^2) was also used for evaluation purposes.

In each of the previously described comparisons, the Kolmogorov-Smirnov (KS) goodness of fit test (48) was used to determine whether or not any observed differences in distributions were statistically significant. This test was selected over the chi-square test because of its treatment of individual observations separately--thus, not losing information (and power) because of grouping as the chi-square test must sometimes do. The KS two-sample test is a test of whether or not two independent samples have been drawn from populations with the same distribution. If in fact they have, the cumulative distribution of the two samples should be fairly close to one another. If on the other hand they have not, the differences in the distributions should exceed a critical value at some point. The latter condition suggests that the samples come from different populations and was evidence for rejecting the null hypothesis, i.e., there was no difference in driver performance between existing and improved conditions.

Perception-Brake Reaction Time. In addition to the average speed profiles for the different categories of device type and improvement condition, each driver's total perception-brake reaction time (PBRT) was calculated. PBRT was defined as the difference in time between activation of the warning device and activation of the vehicle's brake lights. It was computed by counting the number of frames on the videotape between these two points in time and dividing by 60 (60 frames per second). Only those vehicles whose brake lights were activated were included in the data set. As the observations were not necessarily

expected to be normally distributed, nonparametric techniques in the Statistical Analysis Systems (SAS) program (45) were used to ascertain whether or not observed differences were statistically significant.

Nonparametric techniques such as the Mann-Whitney U test for two independent samples and the Kruskal-Wallis test for two or more independent samples are good and relatively powerful alternatives to the usual "t" and analysis of variance tests for equality of means (49). These nonparametric tests assume that the underlying variable on which the samples are being compared is continuously distributed and avoid the assumption that they also be normally distributed. The null hypothesis to be tested is that the population distributions are identical. Rejection of this hypothesis indicates that the samples came from different populations, i.e., differences in mean perception-brake reaction times observed in response to alternative active warning devices are statistically significant. For this particular driver performance measure, the following comparisons were made:

1. Existing and improved conditions at the Cherry Street crossing;
2. Existing and improved conditions at the Ebenezer Road crossing;
3. Existing and improved conditions at the Cedar Drive crossing;

Violations. Violations were evaluated for each innovative device; however the definition of a "violation" was different for each type of device. For the gate and skirt system, violations occurred whenever motorists either drove around the gate arm in the down position or collided with the gate arms as they were coming down. For the flashing

light signal system, a violation occurred whenever drivers that could reasonably stop in response to the warning device failed to do so. In this analysis, it was assumed that vehicles farther than five seconds from the crossing at the time of device activation were capable of reasonably stopping (36); however, because of the difficulty in determining whether or not a vehicle came to a complete stop, violations were not counted for the flashing light signal systems. For the highway traffic signal system, violations occurred whenever vehicles proceeded through the crossing when the signal head displayed a red light.

The number of violations (i.e., motorists driving around a lowered gate arm or crossing when the highway traffic signal displayed a red) that occurred for each train crossing were manually counted from videotapes. Like conditions were aggregated, and average violation rates per crossing were computed for each application. As with the other measures of effectiveness, comparisons were made between the different conditions at each crossing. The analysis procedure for this measure was exactly the same as that described for perception-brake reaction times.

Vehicles Crossing. The number of vehicles crossing was the final MOE used to evaluate the relative performance of the innovative active warning devices. It was defined as the total number of vehicles crossing the tracks between activation of the warning devices and the train's arrival at the crossing. The number of vehicles crossing was manually counted from the videotapes and then for comparison purposes, subdivided into those that occurred within 10 and 20 seconds of the train's arrival at the crossing. Specifically, vehicles which crossed within 10 seconds of an oncoming train (CL10) were considered an indication of risky

behavior as this represents a level of driver performance in which there is little, if any room for error. This value was based on 2.5 seconds of perception reaction time (50), and a 20 foot long vehicle starting from a stop 20 feet away from the crossing, accelerating at a normal rate of 4.8 fps^2 (51), and clearing a point 20 feet on the far side of the crossing, 2.5 seconds before the train's arrival. Vehicles which crossed within 20 seconds of an oncoming train (CL20) were considered an indication of aggressive behavior as this was thought to represent a level of driver performance in which there is some, but not much room for a driver, vehicle, and/or warning system error. The MUTCD (12) appears to address this point by requiring a minimum warning time of 20 seconds.

Using the aforementioned definitions, it was possible for a single maneuver to be classified as a CL10 and a CL20 as well as a violation. For example, driving around a lowered gate arm within 10 seconds of a train's arrival would be counted as a CL10, a CL20, and a violation; driving around a lowered gate arm between 10 and 20 seconds of the train's arrival would be counted as a CL20 and a violation; and driving around a lowered gate arm at least 20 seconds prior to the train's arrival would be a violation. The analysis procedures for CL10's and CL20's were the same as that described for the perception-brake reaction times.

Data Collection and Reduction

The key to determining motorist response to the activation of an active warning device was to obtain accurate and pertinent data on driver behavior in the decision zone, i.e., that area where the driver

must decide to either stop or proceed through the crossing. Previous behavioral studies have relied on data from field observers (21), tape switches (23), and/or time-lapse movie cameras (24, 25) to determine looking behavior, reaction times, and speed distance profiles of drivers in this zone. Each of these techniques was limited by the fact that usable data could only be collected when the warning device was activated by an approaching train, and this may only happen 10 to 15 times per day. Thus, either large amounts of extraneous data are collected, or the data collection team spends most of their time waiting for something to happen. In addition, the collected data must be reduced manually. Consequently, the gathering of large data bases is very costly and time consuming.

The data collection and reduction procedures used in this study were an attempt to overcome some of these limitations; however, as is explained later, the procedures actually used were far more labor intensive than originally anticipated. Basically, data were automatically recorded on portable video recorders whenever a train was approaching the crossing and partially reduced by an image processing and pattern recognition process. The following sections describe the equipment that was utilized and the methodology that was employed for data collection and reduction.

Video Recording System. Three complete video recording systems were used for the field studies. Each system could be operated on rechargeable storage batteries or, with the appropriate adaptor, from either a 110-volt AC or 12-volt DC power source. Fully charged batteries provided approximately two hours of continuous recorder

operation, and alternative power sources provided for even longer periods of operation. As this last option was desirable and because of their portability, deep-charge marine batteries were chosen as the power source for the data collection system. The recorders were also portable and used standard 1/2-inch T120 VHS cassettes. They could operate in temperature and relative humidity ranges of approximately 32 to 104 degrees Fahrenheit and 35 to 80 percent, respectively.

The video cameras used with the recorders were black and white closed circuit television cameras that weighed two pounds each. They utilized vidicon tubes with an automatic light range of 100,000 to 1, thus providing high quality video under both day and night lighting conditions. The cameras operated on 12-volts DC and used the recorders as a power source; therefore, they were only energized when the recorders were activated. The cameras were more rugged than the recorders as evidenced by their operating environment of zero to 140 degrees Fahrenheit and zero to 95 percent relative humidity.

Detection System. It was necessary to obtain a train presence signal in advance of the railroad's train detection signal in order to record the events immediately prior to the activation of the warning device. For this reason, a train detector which emitted an infrared light beam and detected its return from a reflector located across the tracks was utilized. To minimize vandalism, the train detector was located eight to ten feet above the tracks. When a train broke the beam, the detector transmitted an encoded camera activation signal followed by an audio timing signal. Detectors were located on each approach to the crossing such that the activation signal was transmitted

at least ten seconds prior to the train activating the active warning device at the crossing. The detectors were powered by batteries and as shown in Figure 40, their construction was such that they could be transported between study sites.

The video recorders and cameras were activated by the receipt and decoding of the encoded activation signals from the train detectors. Minor modifications to the three decoders used in the laboratory study allowed them to be used in the field study. Each decoder consisted of a command tone decoder and several timing circuits. One decoder and one CB receiver were placed with each of the video recording systems. Four to five seconds after the recorders were activated, the timing signal was received and recorded on the audio track of the video tape so as to provide a known reference point for the three video records. This eliminated the possibility of analysis errors due to any differences in start-up times between the three systems. The recorders remained on for approximately 2 1/2 to 3 minutes, allowing time for slow trains to reach the crossing. In addition, the recorders could only be activated once each ten minutes so that the activation signal transmitted as the train reached the downstream detector would not cause a second activation of the video recording system. A detailed description of the electronic and communication aspects of this system is contained in a research report (52).

Equipment Set-Up. Each camera was located at as high an elevation and as far from the centerline of the roadway as possible. Physical constraints limited the mounting height to about 20-feet and the lateral distance to about 60 feet; therefore, three 20-foot mounting poles were

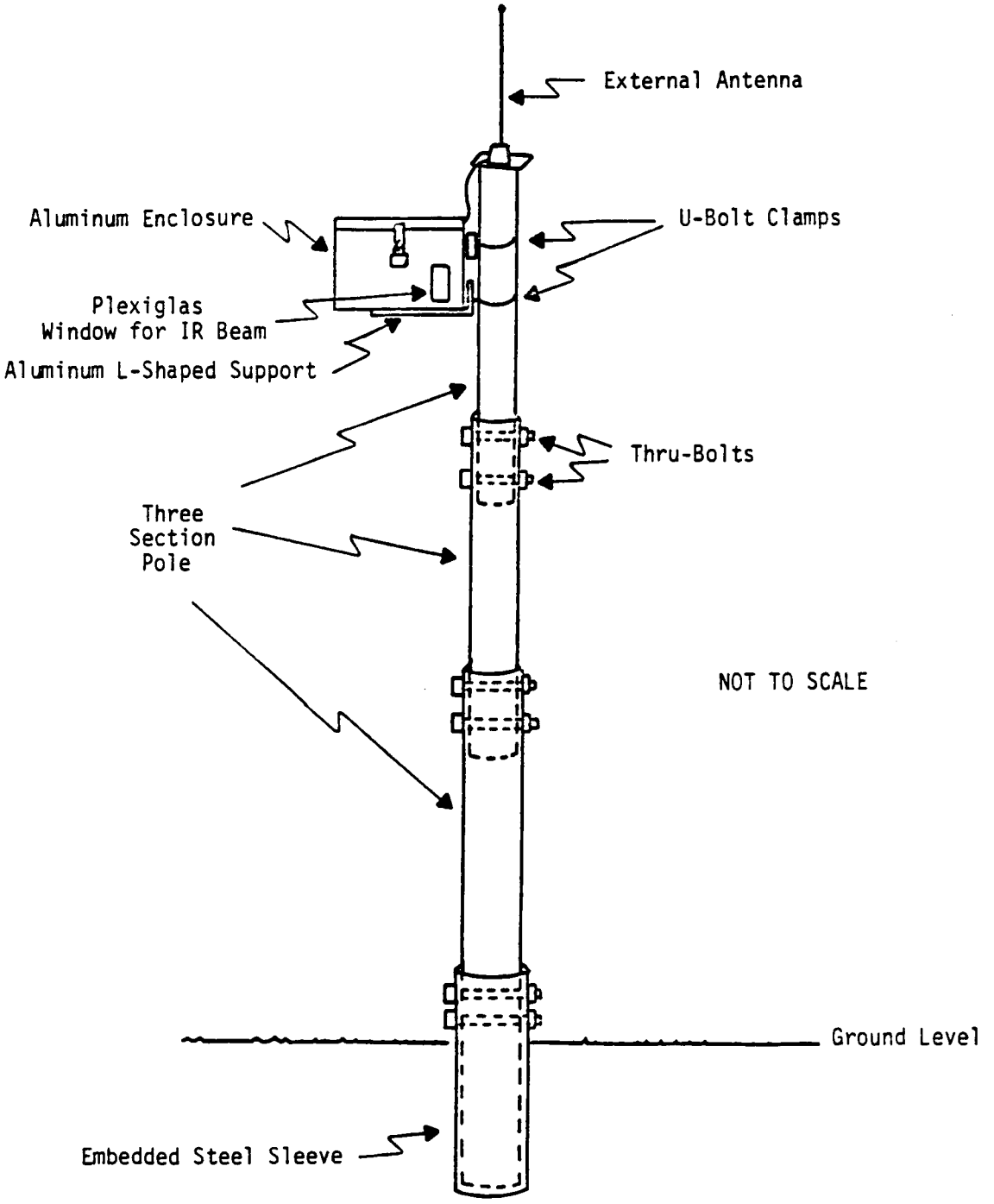


FIGURE 40. TRAIN DETECTOR UNIT

built. As shown in Figure 41, each pole was mounted on a combination box- and pyramid-shaped base. The camera was mounted inside the weather-proof housing at the top of the pole so as to protect it from the environment. The pole itself was hollow and served as a conduit for the connecting cables between the camera and recorder, and the antenna and CB receiver. The base at the bottom of the pole provided a secure location for the video recorder, command tone decoder, CB radio, and 12-volt battery. Construction was such that the entire setup could be easily dismantled and transported between field study sites. At the individual sites, concrete anchors were pre-installed so that the poles could be bolted into place.

All three video recording systems and mounting poles were used at each field site. The first unit was located approximately 300 feet from the crossing, the second approximately 500 feet from the crossing, and the third approximately 700 feet from the crossing. The cameras were aimed towards the crossing and had overlapping fields of view. This arrangement allowed for maximum video resolution in the areas where drivers were expected to react to the activated signals. A typical setup for the field studies is illustrated in Figure 42. Note that physical conditions at the crossing required that one or more of the mounting poles be located on the left side of the roadway. In fact, the three crossings selected for this study required three different combinations of right and left mountings.

Data Reduction. Tapes were removed from the recorders and blank ones loaded at intervals dependent upon the train volumes at the crossing. For example, if each tape could store 30 to 40 train arrivals and

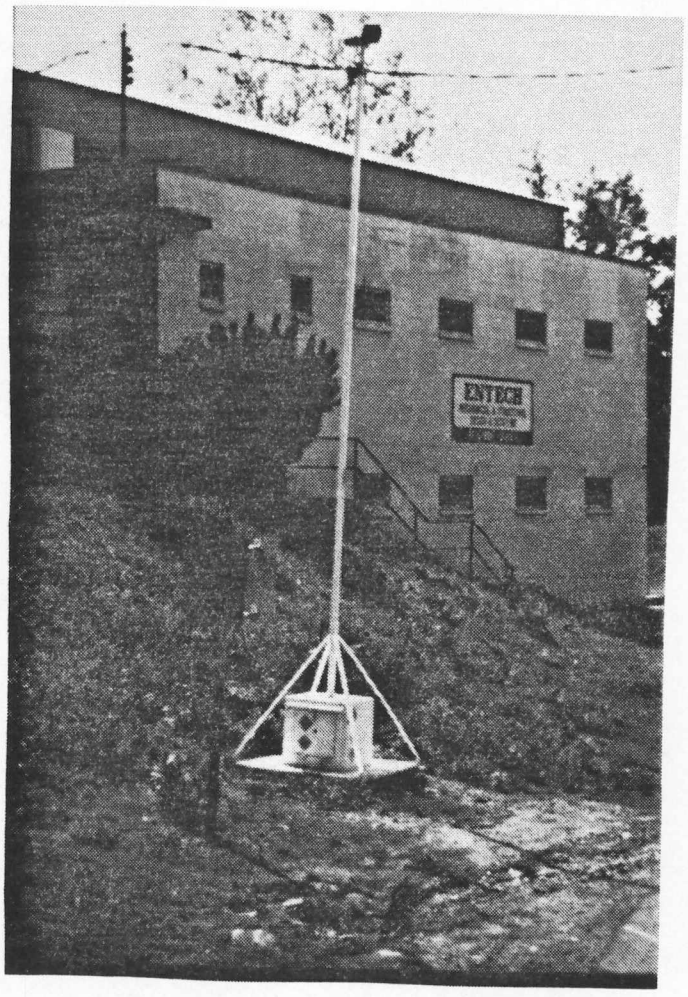


FIGURE 41. POLE-MOUNTED CAMERA INSTALLATION

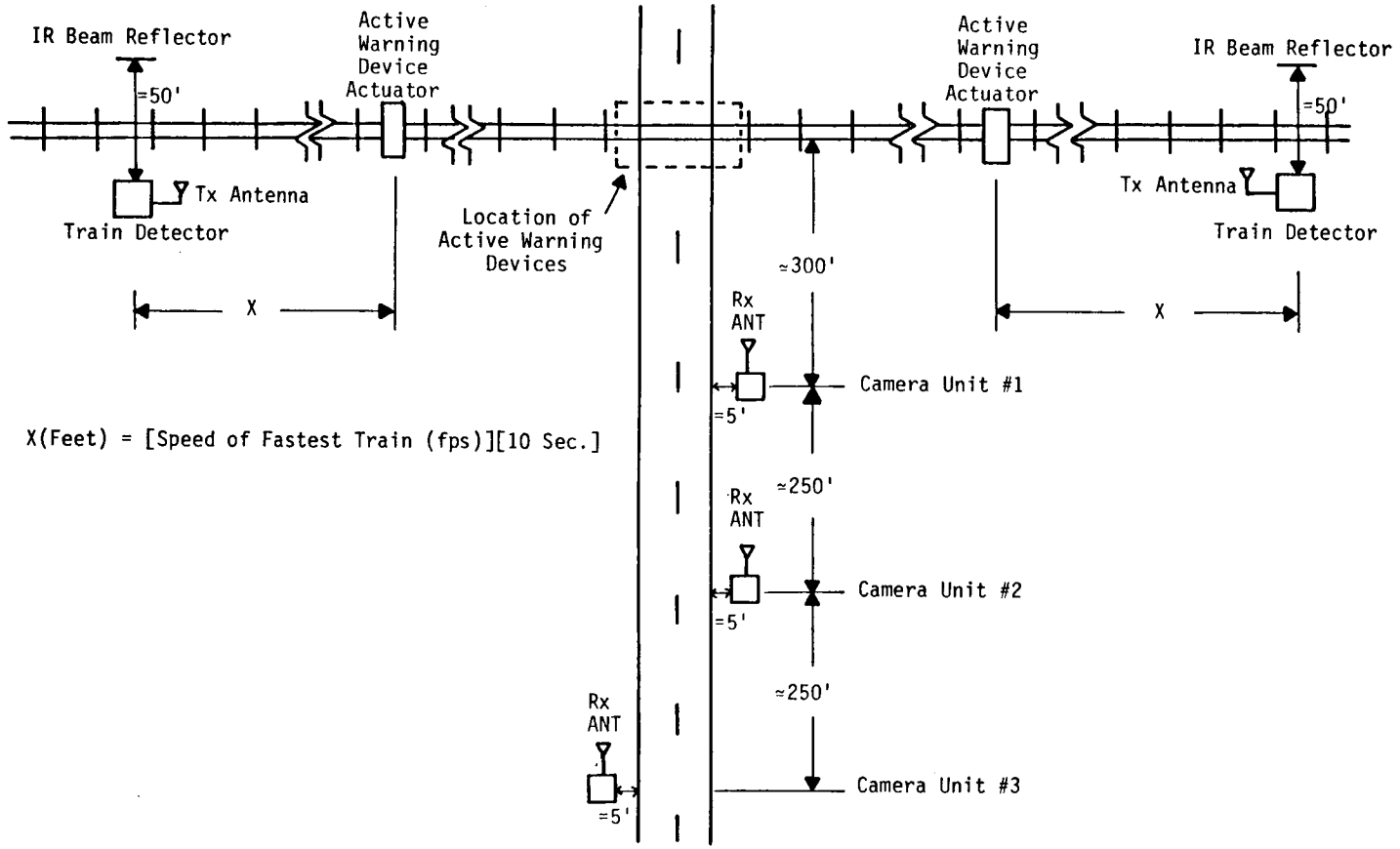


FIGURE 42. TYPICAL EQUIPMENT SETUP FOR THE FIELD STUDIES

the expected arrival rate was 15 trains per day, tapes would have to be changed every other day. Such a schedule worked well as the batteries for the train detectors and video recording system had to be swapped out and recharged at least every two to three days. However, even though it was possible to operate unattended for several days, all parts of the data collection system were checked on a daily basis so as to ensure their proper operation. Once a tape had been picked up, it was taken to the University's TI-990/42 computer lab for processing.

The first step in the data reduction process involved logging the basic information that was on the tapes. This included items such as whether the activation was a result of a train or a false alarm, the lighting and environmental conditions, and the train's direction of travel and time to arrive at the crossing after the warning devices were activated. Those activations recorded by all three cameras were copied onto master tapes in the order in which they were observed. Activations not recorded by all three cameras were copied onto a separate set of master tapes. The master tapes were then used to obtain the driver behavioral data of interest.

The master tapes were replayed on one of the video recorders and viewed on a specially modified video monitor. The only requirement placed on the recorder/playback unit by this activity was that it have the capability to freeze action by viewing a single frame on the tape. The recorder was connected to the video monitor and a small electronic control box that generated a visible marker or cross hair on the monitor's screen. A set of light-emitting diodes displayed the x-y coordinates of the cross hair's position on the screen to an accuracy of

8 bits (one point in 128). Four push buttons allowed the user to move the cross hair to any position on the screen.

When viewing the individual activations (records) on the master tapes, the tape was advanced until the warning devices were activated. The frame number at which this occurred was recorded and served as the reference point for further calculations. An outstanding feature of the vehicle closest to the crossing at this point in time was selected, and the cross hair moved to that point on the screen. The vehicle's identification number, the coordinates of the cross hair, and the picture's frame number were recorded on a supplementary data sheet. The cross hair was then moved to a position which corresponded to a fixed distance on the roadway, and the tape was advanced until the identifying feature on the vehicle reached the same position, whereupon the new coordinates and frame number were recorded. This procedure was repeated until the vehicle either cleared the crossing or stopped for the train. If the vehicle did not stop, the tape was rewound to the reference point, and the same data were entered for the next vehicle approaching the crossing. These steps were repeated until the first stopping vehicle was observed. Further data was of no interest as subsequent vehicles had no choice of whether to stop or go.

As there was a constant time between frames (1/60 of a second), speed was determined by using the known distance between coordinates on the screen and dividing by the number of frames it took the vehicle to travel between these points. Matching physical distances on the roadway to coordinates on the screen was accomplished by driving a test car through each camera's field of view at a constant speed. The test

vehicle's position was recorded every five to ten frames as it moved across the screen, and the known speeds and time were used to calculate the distances for those coordinates. To account for user error, several readings were made and a curve fitted to the resultant data set, thus creating a map of the screen.

Other types of driver behavioral measures such as perception-brake reaction time and the number of violations and vehicles crossing were manually recorded as the master tapes were being viewed. Perception-brake reaction time was simply the number of frames between activation of the warning device and activation of the vehicle's brake light divided by 60. Violations and vehicles crossing (i.e., CL10 and CL20) are defined in a previous section and refer to the closeness of a vehicle's crossing in front of the train's arrival. By using these definitions and noting the vehicle's crossing time and the train's arrival time, their number and rate were calculated.

Summary

Driver behavioral data at three crossings were collected with the use of three pole-mounted video cameras, with each of the camera covering approximately 300 feet of roadway with overlapping fields of view. The video recorders were automatically turned on prior to the activation of the warning devices and ran for approximately two and one-half to three minutes. For each study at a particular crossing, data were collected for a minimum of 30 trains. One existing and one improved condition study was conducted at each of the three study sites.

Data tapes were taken to the University's computer lab for processing. The tapes were transferred to and played back on a high

quality video reproductive machine that could stop action and produce sequential scenes separated by 1/60 of a second. Speed profiles were determined by using successive frames and noting the distances that the vehicle had traveled between frames. Since the cameras were fixed, any point on the vehicle moved on a surface dictated by the roadway. By use of an electronic cross hair, the coordinates of this reference point were calculated for successive frames and manually recorded. This information was used to construct each individual vehicle's speed-distance profile.

Other measures of driver performance that were obtained included perception-brake reaction times and violation and vehicle crossing rates in response to device activation. Statistical comparisons of these measures were made between both devices and conditions. The general hypotheses tested were that installation of these new devices improved the conspicuity of and compliance with active warning devices at railroad-highway grade crossings, thus providing for safer operations at the crossing.

VI. FIELD SITE SELECTION AND STUDY PREPARATION

In order to evaluate the three active warning devices selected for field study under normal traffic conditions at existing crossings, three railroad-highway grade crossings were necessary. Initially, potential field study sites were considered from a list of candidate crossings in Illinois, Tennessee, and Texas; however, after careful review and several site visits, it was decided that the more remote sites should be dropped from further consideration, as suitable crossings existed in the Knoxville area. Benefits of this decision were the ability to minimize the costs of the data collection effort and more importantly, to respond rapidly to any mechanical and/or electrical problems which might occur. This chapter describes the study sites and the design, construction, and installation of the new warning devices.

Field Study Sites

For a crossing to be considered in the initial phase of the field test, it was necessary that it have a relatively high train and traffic volume, a history of at least some accidents, and active warning devices already in place (at least one site had to have automatic gates at the crossing). Several sites which met these criteria were identified, and requests for permission to use them were made to the responsible railroad. Favorable response for use of three crossings in the Knoxville area was received from the Southern Railway System. Each of these locations was within seven percent of the top of the hazard ranking for the 4,168 public railroad-highway grade crossings in Tennessee.

A tabular description of the characteristics of these sites is contained in Table 16. The following sections describe the three crossings in greater detail.

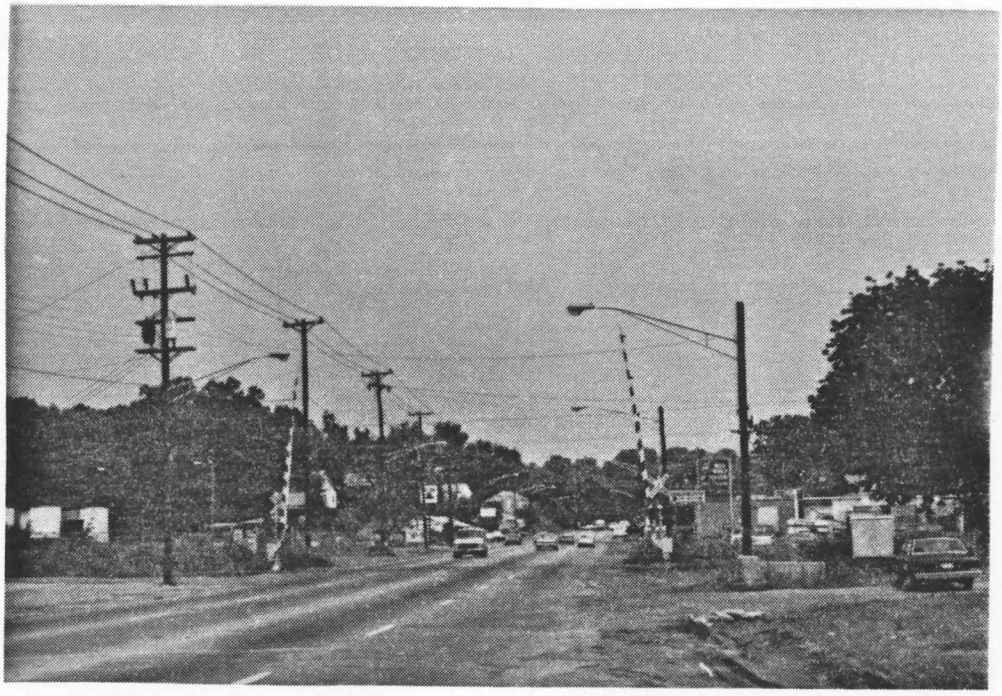
Cherry Street Crossing. The crossing (Inventory Number 730584K) selected for the four-quadrant gate and flashing light signal system was located in the eastern part of Knoxville on Cherry Street. The existing active warning devices at the crossing were automatic gates, standard railroad flashing light signals, and a bell. It was ranked as the 223rd most dangerous crossing in the state. As shown in Figure 43, the roadway was four lanes wide, and both approaches to the crossing were straight and level. There was a building in the southwest quadrant which could obstruct a northbound driver's view of eastbound trains. The average daily traffic at this site was approximately 14,000 vehicles per day, and the average thru train volume was approximately 20 trains per day. The speed limit on Cherry Street was 30 miles per hour, and train speeds at the crossing ranged from 20 to 40 miles per hour. Although only one car-train accident had occurred at this location in the past five years, there were large numbers of motorists observed driving around lowered gate arms at this site. This type of behavior made the Cherry Street crossing a potentially dangerous crossing. The four-quadrant gate and flashing light signal system with skirts added to all gate arms was installed at this location.

Implementation of the new system required the installation of an additional pole, electric motor, and gate arm support and counterweights in both the southwest and northeast quadrants. A 30-foot gate arm with

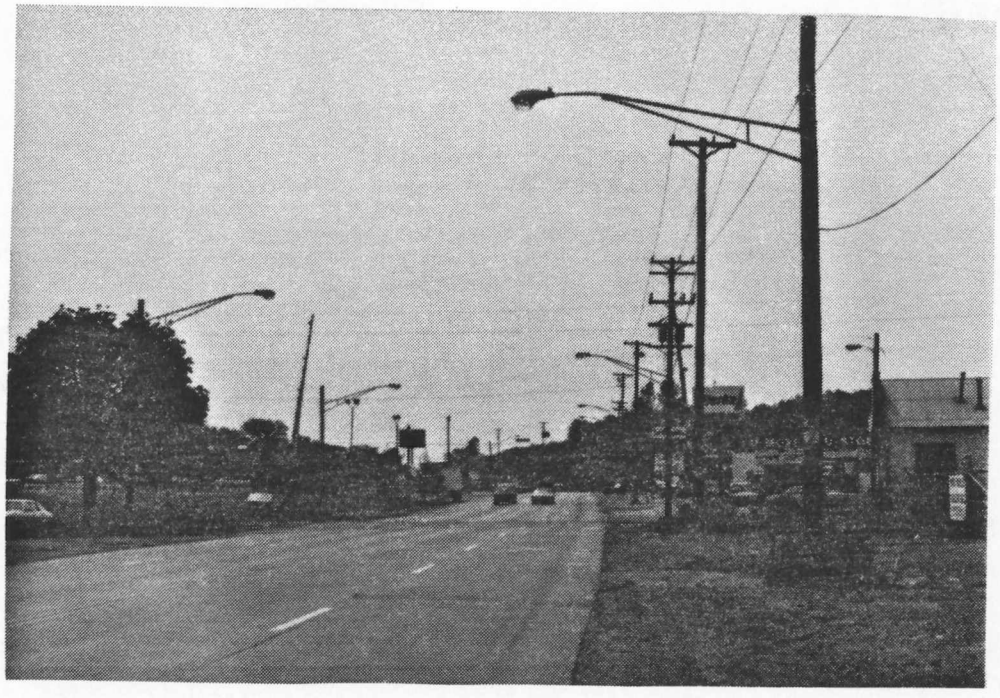
TABLE 16. SUMMARY DESCRIPTION OF THREE FIELD STUDY LOCATIONS

Descriptions	Crossing Location		
	Cherry Street	Cedar Drive	Ebenezer Road
Number of Traffic Lanes	4--2 in each direction	2--1 in each direction	2--1 in each direction
Horizontal Alignment	S--straight N--straight	E--straight W--straight	N--curves S--curve
Vertical Alignment	S--level N--level	E--level W--downhill	N--uphill S--level
Sight Distance Obstructions	N--1 quadrant S--none	E--1 quadrant W--2 quadrant	N--1 quadrant S--2 quadrant
Average Daily Traffic	14,000 vpd	14,000 vpd	10,000 vpd
Posted Speed Limit	30 mph	40 mph	40 mph
Number of Tracks	2	1	1
Thru Train Volume	20 tpd	10 tpd	10 tpd
Train Speeds	20-40 mph	5-40 mph	5-55 mph
Number of Accidents	1	3	1
Warning Devices	Flashing Lights, Bell, Automatic Gates, and Pavement Markings	Flashing Lights, Bell, and Pavement Markings	Flashing Lights and Bell

Note: N, S, E, and W refer to direction of vehicular traffic. Number of accidents refers to previous five-year period as this was the reporting requirement for the national inventory.



Looking North

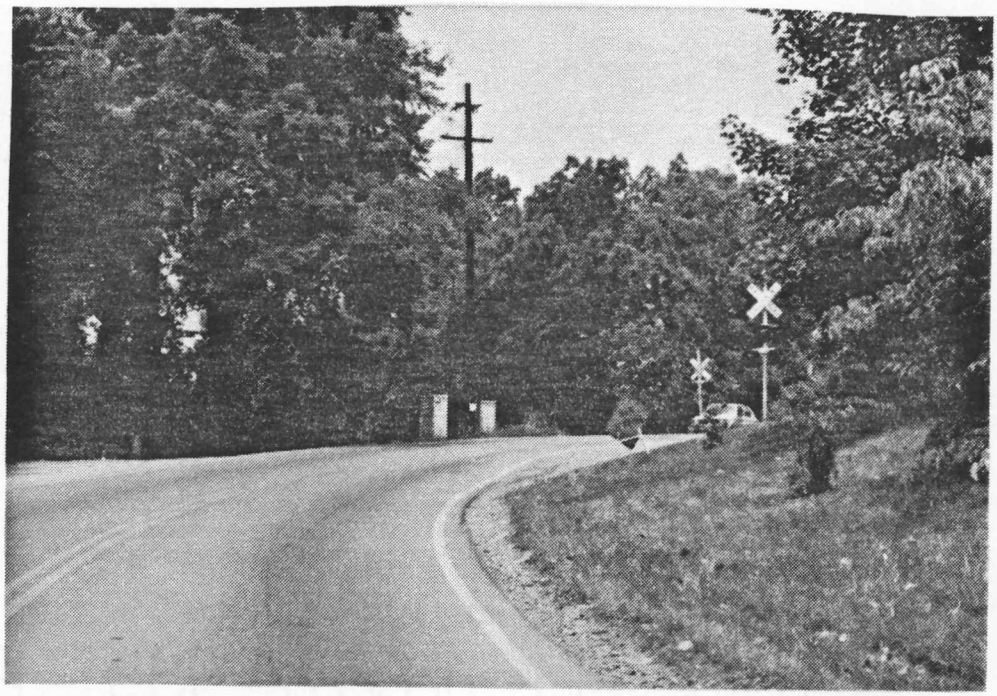


Looking South

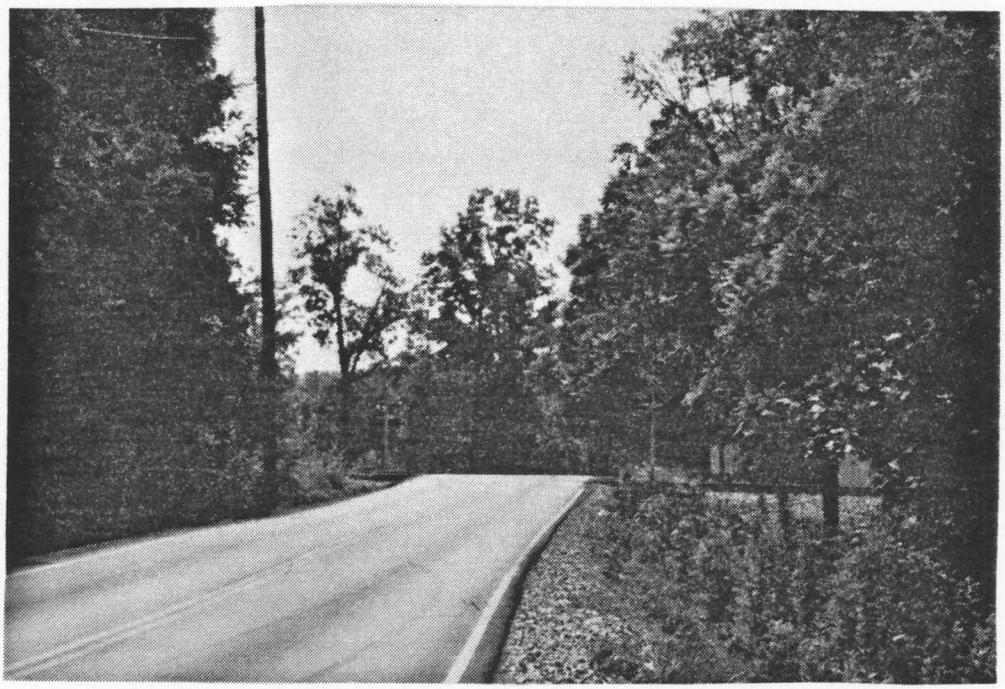
FIGURE 43. CHERRY STREET CROSSING

skirts was then attached to each of the four support arms. Thus, the entire roadway was blocked in both directions whenever the gates were down. To avoid the possibility of trapping vehicles between the gates, a delay in the downward motion of the offside gate arm was incorporated into the system. In addition to the changes in the gate arms, railroad flashing light signals with 12-inch roundels were installed in all four quadrants. The existing bell and railroad advance warning signs were left as they were; however, the pavement markings were repainted so as to be more visible to approaching motorists.

Ebenezer Road Crossing. The crossing (Inventory Number 731461C) selected for the four-quadrant flashing light signal system was located in the western part of Knox County on Ebenezer Road. The existing active warning devices at the crossing were standard railroad flashing light signals with 8-3/8 inch roundels and a bell. It was ranked as the 276th most dangerous crossing in the state. As shown in Figure 44, the roadway was two lanes wide, and its horizontal and vertical alignment limited the crossing's visibility from both directions. There were also several other sight distance obstructions on both approaches which limited the driver's view of approaching trains. The average daily traffic at this site was approximately 10,000 vehicles per day, and the average thru train volume was approximately 10 trains per day. The speed limit on Ebenezer Road was 40 miles per hour, and train speeds at the crossing ranged from 5 to 55 miles per hour. Additionally, one car-train accident had occurred at this location in the past five years.



Looking North



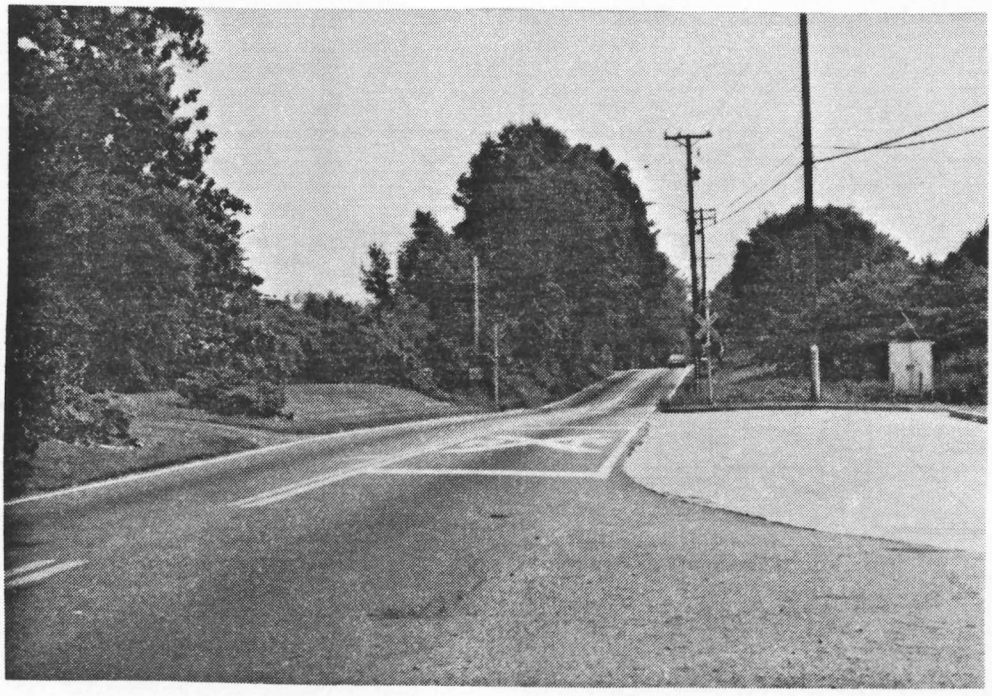
Looking South

FIGURE 44. EBENEZER ROAD

The four-quadrant flashing light system (with overhead strobes) was installed at this crossing.

Implementation of the new system required the existing 8-3/8 inch flashing lights located on the right of approaching motorists to be replaced by 12-inch flashing lights. Two new post-mounted 12-inch flashing lights were installed on the left of approaching motorists. An additional pole for mounting the strobes was installed in each quadrant, and were cables strung above and at the right angles to the roadway. Two red strobe lights per approach, one centered over each traffic lane, were attached to each cable. As neither railroad advance warning signs nor pavement markings were present, they were installed in accordance with the guidelines contained in the MUTCD (12) prior to any data being collected.

Cedar Drive Crossing. The crossing (Inventory Number 730643K) selected for the highway traffic signal system was located in the northern part of Knoxville on Cedar Drive. The existing active warning devices at the crossing were standard railroad flashing light signals with 8-3/8 inch roundels and a bell. It was ranked as the 31st most dangerous crossing in the state. As shown in Figure 45, the highway was two lanes wide and straight on both approaches to the crossing. The vertical alignment on the westbound approach limited a motorist's visibility of the crossing itself. In addition, the thick vegetation in the vicinity of the crossing restricted the driver's view of approaching trains. The average daily traffic at this site was approximately 14,000 vehicles per day, and the average thru train volume was approximately 10



Looking East



Looking West

FIGURE 45. CEDAR DRIVE CROSSING

trains per day. The speed limit on Cedar Drive was 40 miles per hour, and train speeds at the crossing ranged from 5 to 40 miles per hour. As evidenced by its hazard ranking and the three car-train accidents that occurred at this site in the past five years, this was an extremely hazardous location. The highway traffic signal system with white bar strobes in front of each red signal lens was installed at this crossing.

Implementation of the new system required the installation of two new poles and mast arms for mounting the traffic signals. The existing poles, crossbucks, flashing light signals, bell, and pavement markings were removed. The railroad advance warning signs were replaced by active advance warning signs indicating a signal ahead. Each sign was supplemented by two continuously flashing yellow light signals. For improved visibility, a 12-inch lens was used in all signal heads, i.e., traffic signals and flashers. An automatic-start, 5,000-watt electric generator was installed as the backup power source for this system. In addition, predictors were installed prior to the traffic signal's installation so as to provide shorter and more consistent warning times at the crossing.

Prototype Construction

Although the three active warning devices selected for field evaluation had been operated in a laboratory environment, several improvements in their design were necessary before they could be installed at an actual crossing. The guidelines followed in constructing the prototypes for the new warning devices were that, where possible, they be similar and in conformance with existing traffic control devices, simple

to maintain and construct, and at least as operationally reliable as existing active warning devices, i.e., fail-safe. Thus, whenever possible, commercially available and field proven components were used in each system's construction. Additional benefits of this philosophy were the relatively low development cost for the three new warning systems and the subsequent prompt approval by the National Advisory Committee on Uniform Control Devices for their installation and evaluation over a 12-month time period. Design and construction of the three warning systems are discussed in the following sections.

Four-Quadrant Gate and Flashing Light Signal System. The four-quadrant gate and flashing light signal system selected for field evaluation in the laboratory phase of the project is illustrated in Figure 46. As shown, standard post-mounted flashing light signal assemblies with 12-inch roundels and short-arm gates were installed in each of the four quadrants. In addition, railroad advance warning signs and pavement markings were placed in conformance with guidelines in the MUTCD (12). However, because of the four-quadrant configuration, the recommended flash pattern for the three lamps on each gate arm was changed from steady burn for the "tip" lamp and alternate flash for the other two lamps to steady burn for the roadside edge lamp and alternate flash for the two over roadway lamps. Each of these components were incorporated in the prototype's design.

The only significant change between laboratory and field studies was in the design of the gate-arm and skirt assemblies shown in Figure 47. In the laboratory study, the skirt assembly utilized uniformly

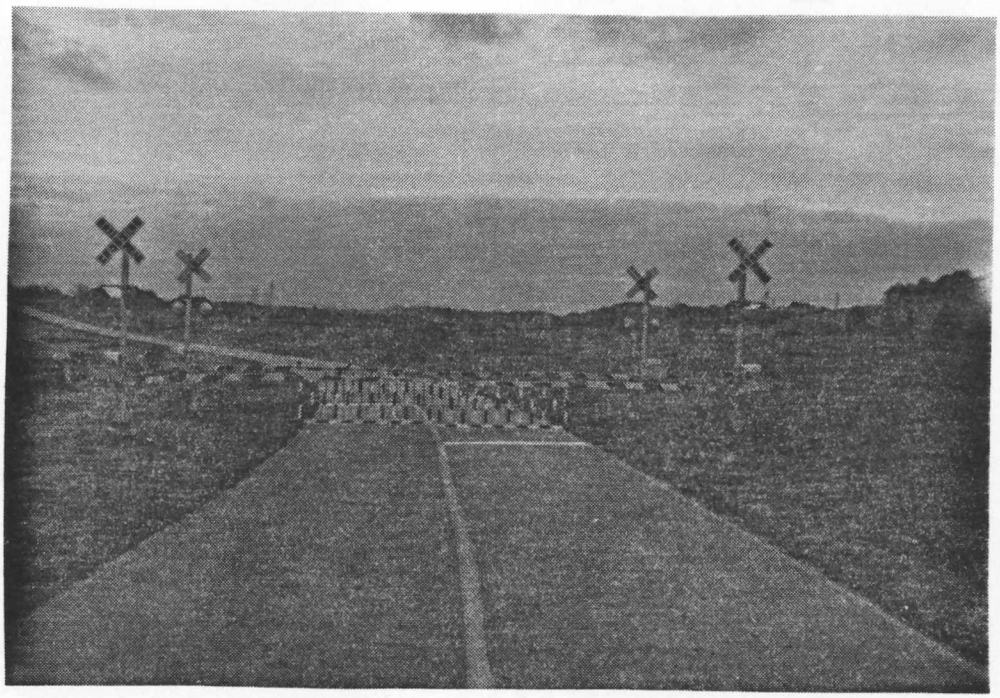


FIGURE 46. FOUR-QUADRANT GATE AND FLASHING LIGHT SIGNAL SYSTEM RECOMMENDED FOR FIELD EVALUATION

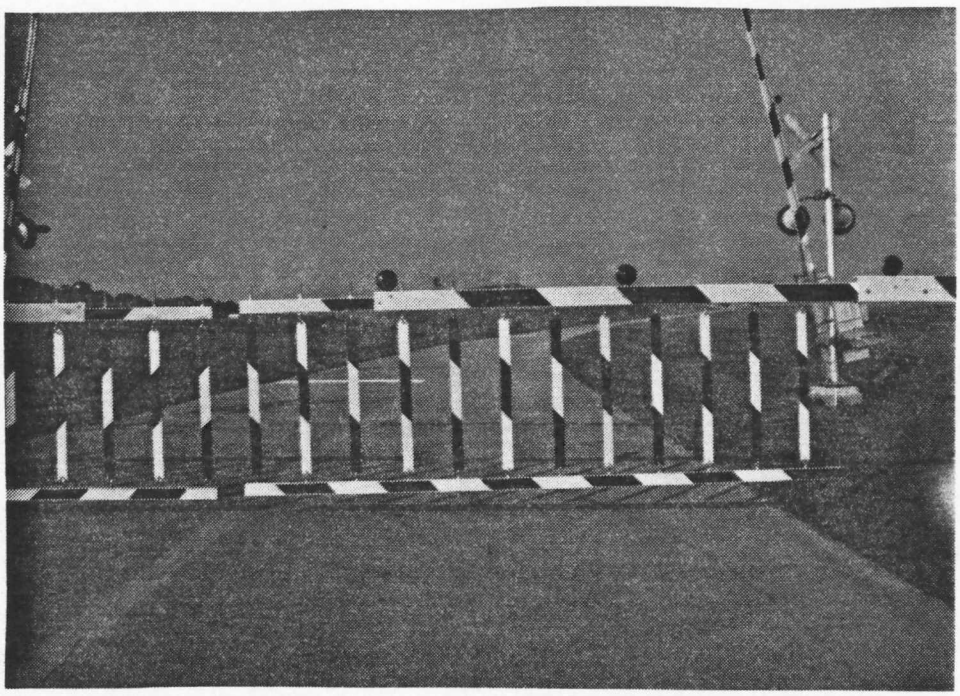


FIGURE 47. CLOSE-UP OF THE SKIRT ASSEMBLY FOR THE FOUR-QUADRANT GATE AND FLASHING LIGHT SIGNAL SYSTEM

spaced vertical strips and a horizontal bar at the bottom. The top horizontal bars were standard fiberglass gate-arms which could be adjusted from 20 to 26 feet in length. Vertical strips were spaced eight inches apart (ten inches from center to center) and made of 1/8-inch thick aluminum plating. Each strip was two inches wide and 30 inches long. The bottom horizontal bars were made of two-inch by four-inch aluminum studding ten feet in length. Sixteen-inch strips of red and white reflectorized, high-intensity sheeting were taped onto the vertical strips as well as the bottom horizontal bar. Thus, in addition to the skirt assembly appearing as a more formidable obstacle than a normal gate arm, the additional reflectorized material greatly increased the warning devices' conspicuity, i.e., the reflective surface of the gates with skirts is approximately six times greater than that of a normal gate arm.

Although this particular design worked well in the laboratory study, there were several reasons it was not suited for field evaluation at an actual railroad-highway grade crossing. First, because the connectors for the horizontal bars and vertical strips were designed to facilitate changing between alternative configurations in the laboratory study, they were not reliable, on a day-to-day basis, i.e., the whipping action caused by gusts of high wind would routinely disconnect several of the vertical strips. In addition, repeated use tended to twist and subsequently bind the connectors such that the skirt assembly would not drop properly when the gate arm was lowered. Second, in the upright position, the vertical strips tended to overlap and lay on top of one another; thus creating numerous long, flat surfaces susceptible to snow

and ice accumulations, and possible adhesion to one other. Such an event could hinder their dropping properly and also add significantly to the weight of the gate arm and skirt assembly. Finally, standard aluminum or fiberglass gate arms (single bar designs) were not rigid enough to support the length of skirt assembly (24 feet) required at the Cherry Street crossing. However, standard wooden gate arms (dual bars with steel cross bracing) could provide the necessary rigidity.

To overcome these shortcomings, the design shown in Figures 48 and 49 were adopted. The top horizontal bar was identical in shape and size to a standard wooden gate arm. This insured that special mounting and/or adaptor brackets would not have to be fabricated for the field studies. The gate arms' existing X-shaped cross braces were replaced by U-shaped ones so as to allow the entire skirt assembly to fold inside the gate-arm when they were in the upright position (See Figure 48). All horizontal and vertical members were made of kiln dried redwood, sealed and painted to industry standards, and covered with 16-inch strips of red and white high-intensity reflective sheeting. Connections between members made use of bushings, spacers, and lock washers to insure reliable operation of the entire assembly. The number of vertical strips was reduced, and the remainder's spacing adjusted such that there was no contact between them when the gate arm was in the upright position. The resultant loss of reflectorized vertical surface area was compensated for by the addition of a second horizontal bar (See Figure 49). To preclude the horizontal bars touching one another in the upright position, they were mounted on opposite sides of the vertical strips. The prototype device was 30 feet in length, three and one-half

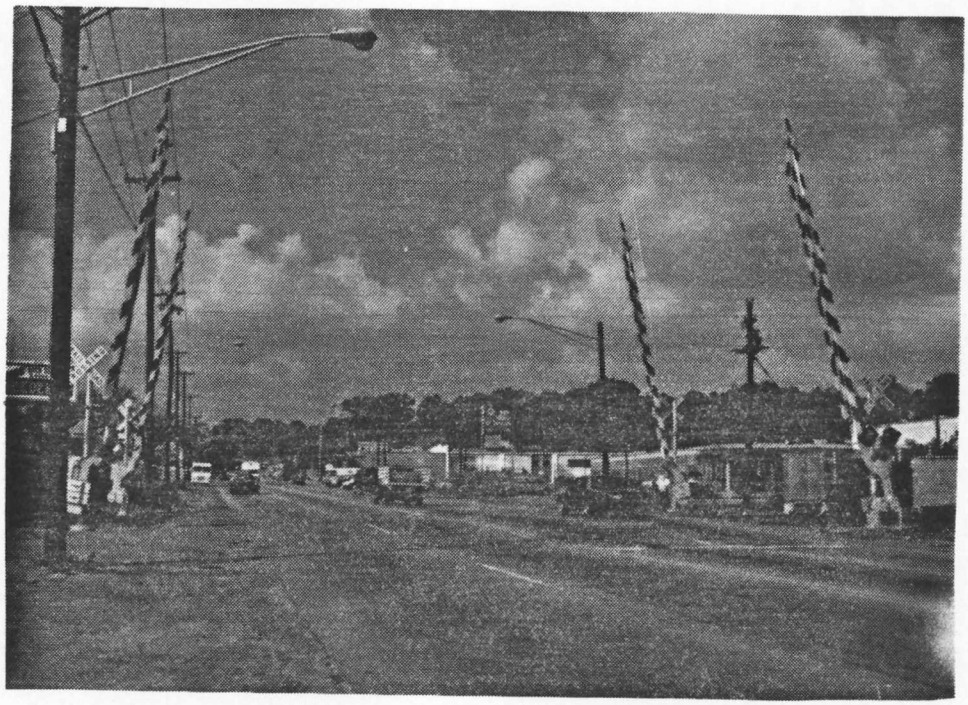


FIGURE 48. GATE ARMS IN UP-RIGHT POSITION AT THE CHERRY STREET CROSSING

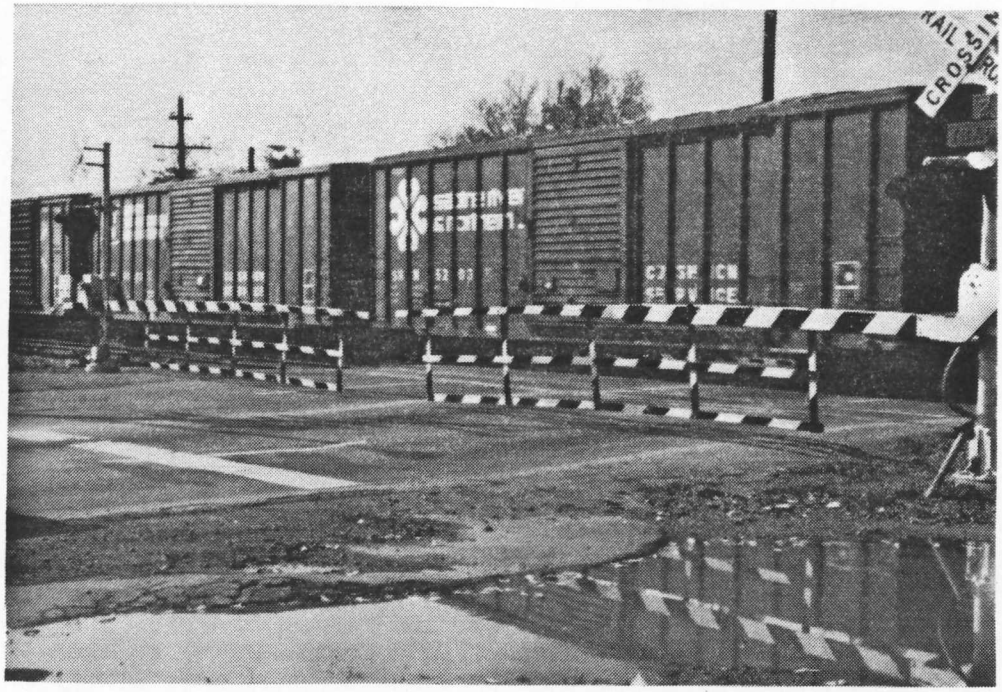


FIGURE 49. PROTOTYPE GATE ARM AND SKIRT ASSEMBLY INSTALLED AT THE CHERRY STREET CROSSING

feet in height (when in the down position) and weighed approximately 140 pounds.

Four-Quadrant Flashing Light Signal System With Overhead Strobes. The four-quadrant flashing light signal system selected for field evaluation in the laboratory phase of the project is illustrated in Figure 50. As shown, standard post-mounted flashing light signal assemblies with 12-inch roundels were installed in each of the four-quadrants. Railroad advance warning signs and pavement markings were placed in conformance with guidelines contained in the MUTCD (12). In addition to these standard devices, a rectangular shaped (approximately five inches high by seven inches wide) red strobe light with a 120-degree horizontal spread was mounted over each lane of traffic (two per approach). Such a mounting required the addition of a three-foot extension tube to each of the signal poles and a pair of messenger cables above and at right angles to the traffic lanes to support the strobes.

The strobe lights were powered by a 12-volt marine battery and activated at the same time as were the flashing light signals. Each directional pair of strobe lights flashed alternately at 60 flashes per minute and 15 joules per flash. The only difference between the devices used in the laboratory and field studies was in the design of the strobes' mounting poles and their power supplies. The railroad would not permit the extension tubes to be added atop their poles or the strobes to be connected to the power supply for their flashing light signals. Therefore, as shown in Figure 51, the prototype's design required, in addition to the poles for the flashing light signal assemblies, that a wooden pole, 20 feet in height, also be installed in

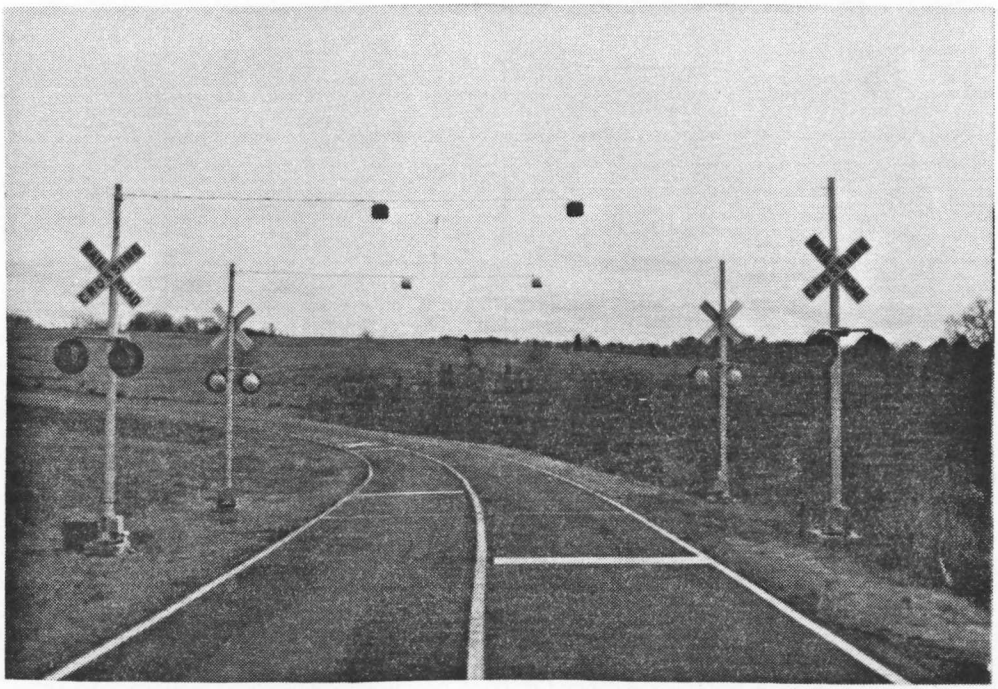


FIGURE 50. FOUR-QUADRANT FLASHING LIGHT SIGNAL SYSTEM WITH OVERHEAD STROBES RECOMMENDED FOR FIELD EVALUATION

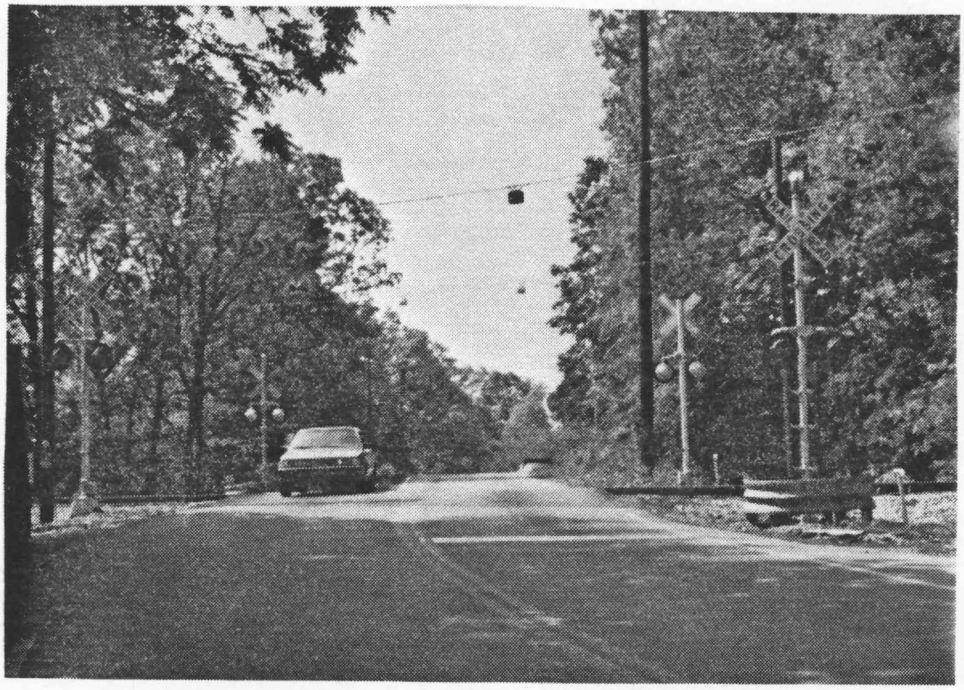


FIGURE 51. FOUR-QUADRANT FLASHING LIGHT SIGNAL SYSTEM WITH OVERHEAD STROBES INSTALLED AT THE EBENEZER ROAD CROSSING

each of the four quadrants. The wooden poles were located about five feet further from the roadway and tracks than were the railroad's signal assemblies. Messenger and power cables were hung 18 feet above each approach to the crossing, and the power cables were connected to each other by running them down the poles and underneath the tracks. Power for the strobes' operation was provided by a 12-volt marine battery which was continuously trickle charged by a 110-volt AC power drop. The battery provided protection against a commercial power failure.

Highway Traffic Signal System with White Bar Strobes in All Red Lenses. The highway traffic signal system selected for field evaluation in the laboratory phase of the project is illustrated in Figure 52. As shown, three signal heads faced each direction of traffic; two of the signal heads were pole mounted, and the remaining one was cantilevered over a traffic lane. Active advance warning signs indicating a signal ahead and stop bars placed at the test installation were located in conformance with the guidelines in the MUTCD (12) and were the same as would be found at a regular street intersection. Each signal head consisted of a 12-inch red lens and 8-inch yellow and green lenses. The signal rested in green until it was activated whereupon it changed to a 3.6 second yellow interval, and then rested in red until it was deactivated. The red signal lenses had horizontal white bar strobes in front of them that flashed 60 times per minute whenever the red signal was illuminated.

As shown in Figure 53, there were several minor differences between the prototypes used in the laboratory and field studies. First, to

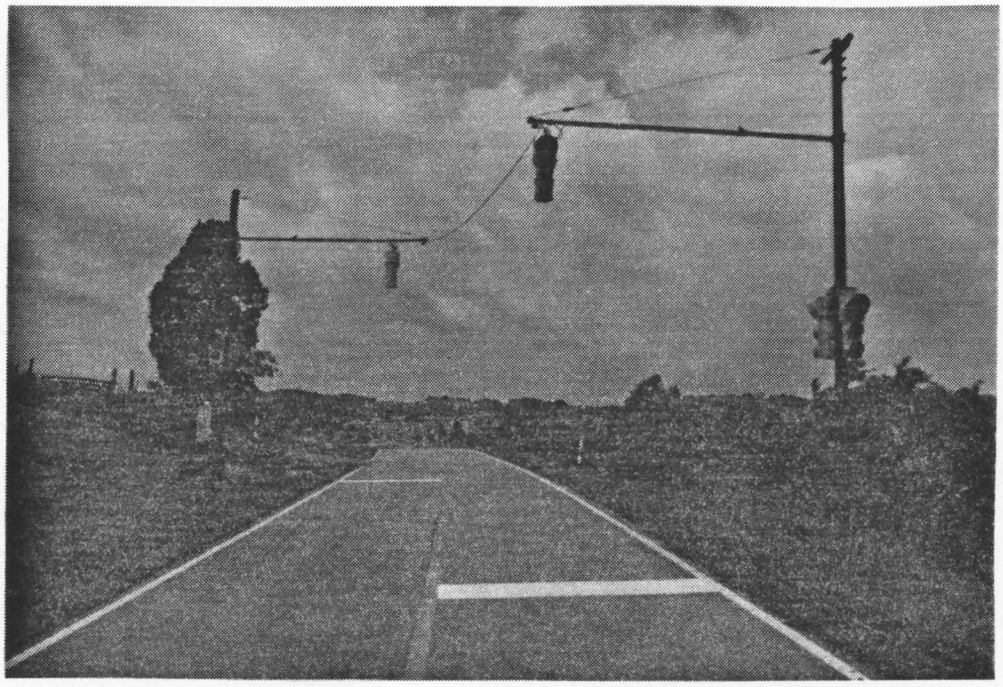


FIGURE 52. HIGHWAY TRAFFIC SIGNAL SYSTEM RECOMMENDED FOR FIELD EVALUATION

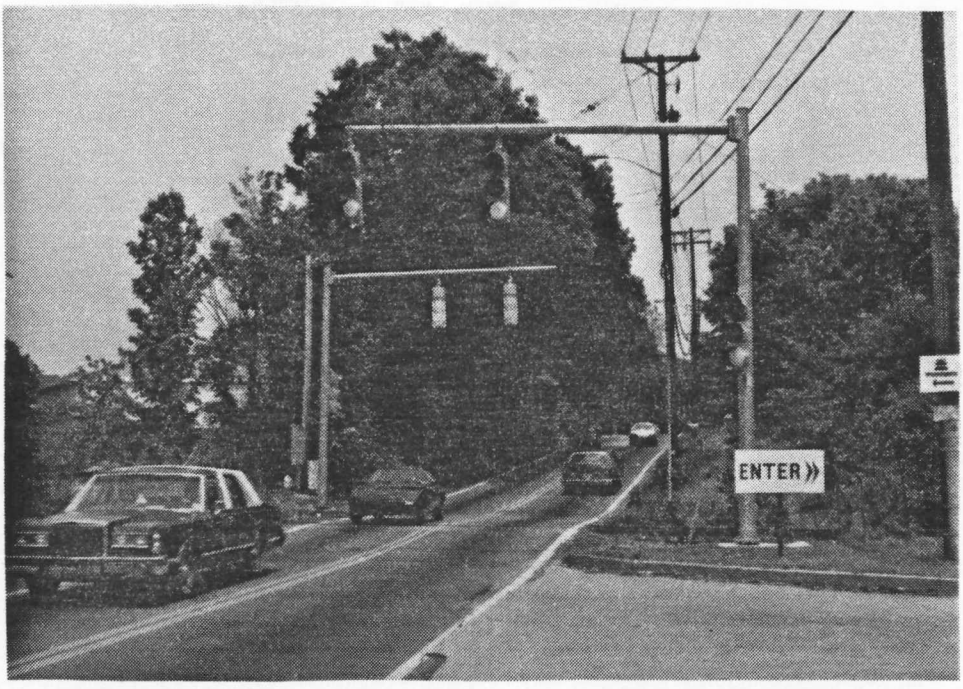


FIGURE 53. HIGHWAY TRAFFIC SIGNAL SYSTEM INSTALLED AT THE CEDAR DRIVE CROSSING

increase conspicuity of the signal itself, 12-inch yellow and green signal lenses were used in the field installation. In addition, the far-side pole-mounted signal was moved to a near-side cantilever mount. Thus, none of the signal heads were blocked by a train's presence at the crossing. Second, to eliminate the possibility of the controller's timing dials "sticking in green," a NEMA eight phase actuated controller was used for the field study installation. Power for this installation was provided by a 110-volt AC power drop. Finally, to protect against a commercial power failure, an automatic start, propane powered generator provided a minimum of 24 hours of back-up power. An exercise clock routinely recharged the generator's ignition battery so as to keep it in top operating condition. Refueling and preventive maintenance were done on a regular basis. Two additional changes were a four second yellow clearance interval and a ten minute maximum for a solid red indication, after which the signal would change to a flashing red indication. This latter feature was intended to address the problems associated with stopped trains and/or detector malfunctions.

Summary

Three active warning devices for use at railroad-highway grade crossings were identified by a detailed laboratory evaluation process as candidates for field testing under normal conditions at actual crossings. Three crossings in the Knoxville area were identified as potential study sites. Currently, standard railroad flashing light signals in conjunction with an automatic gate system are installed at one of the crossings, and standard railroad flashing light signals are installed at

the other two crossings. A four-quadrant gate system (with skirts added to all gate arms) will be installed at the first crossing. A four-quadrant flashing light signal system (with red strobe lights over the traffic lanes) and a highway traffic signal system (with white bar strobes in each red signal lens) will be installed at the latter two crossings.

VII. FOUR-QUADRANT GATES WITH SKIRTS

As discussed in Section VI, a large number of motorists disregarded the standard two-quadrant automatic gates and flashing light signals at the Cherry Street crossing by driving around lowered gate arms. Not only was this behavior illegal, it was also dangerous in many cases. The primary change in driver performance that was expected as a result of the installation of the four-quadrant gates with skirts was the elimination of this type of behavior. As a result of this expected change in behavior, the average clearance time between the last vehicle to cross and the trains' arrival at the crossing should also increase. Both behavioral modifications have implied safety benefits in that they provide greater spatio temporal separation between trains and motor vehicles. The anticipated secondary change in driver performance was better response to the new devices (i.e., quicker perception-brake reaction times and lower deceleration levels) as a result of their greater conspicuity and more formidable appearance; however, differences in these performance measures were not expected to be as easy to quantify, and the related safety benefits were not as straightforward.

The four-quadrant automatic gates with skirts and flashing light signals (four-quadrant gates with skirts) were installed at the Cherry Street railroad-highway grade crossing during the week of October 14, 1985. Prior to this time, the active warning devices at the crossing were standard two-quadrant automatic gates and flashing light signals (two-quadrant gates). Both train movement and driver behavior data were collected for approximately two months before (March and April, 1985)

and two months after (December, 1985 and January, 1986) the new devices were installed. During these two time periods, a total of 169 train movements were observed. There were 105 train movements observed in the before study (two-quadrant gates) and 64 train movements observed in the after study (four-quadrant gates with skirts). For each observation, the environmental and lighting conditions, trains' direction of travel and warning time, and approaching vehicles' clearance times, speed profiles and brake reaction times were recorded and subsequently analyzed.

This section describes the evaluation of two active warning devices at the Cherry Street crossing, i.e., the original two-quadrant gates and the subsequent four-quadrant gates with skirts. The first step in this process was an assessment of the level-of-service at which the active warning devices were operating. This determination was based on average waiting time at the crossing and was similar to the level-of-service criteria for average delay at signalized intersections presented in the 1985 Highway Capacity Manual (1985 HCM) (53). Secondly, the driver performance measures for the two warning devices were summarized and compared from both a statistical and practical standpoint. Finally, the safety implications of utilizing four-quadrant gates with skirts is discussed.

Crossing Measures

Warning Time. Warning time was defined as the difference in time between activation of the flashing light signals and the train's arrival at the crossing. It is the same as the maximum time a motorist would

have to wait between activation of the flashing light signals and a train's arrival at the crossing. As there were no changes to the train detection system itself when the four-quadrant gates with skirts were installed, there should have been no difference in the average warning time observed in the two studies. To verify this premise, the total data set from each study was first subdivided into observations that occurred during the day and observations that occurred during the night so as to ensure that similar train and traffic volume conditions were compared. These two subsets, together with the total data set, were then analyzed.

As shown in Table 17, the mean and standard deviation of the warning times from all three data sets were slightly less during the after study (four-quadrant gates with skirts); however, the Mann-Whitney U test for two independent, continuously distributed populations (49) indicated that these differences were not statistically significant at the 95 percent confidence level for either the day, night, or total data sets. This means that, as expected, installation of the four-quadrant gates with skirts had no effect on the warning times at the crossing. The Mann-Whitney U test also indicated that there was not a statistically significant difference at the 95 percent confidence level between the day and night data sets from either of the two studies. Thus, warning times were not different during day and night operation for either the two-quadrant gates or four-quadrant gates with skirts.

It was hypothesized that the warning times observed at a railroad-highway grade crossing have a major influence on driver performance, i.e., the longer the warning times, the larger the number of drivers

TABLE 17. WARNING TIMES AT THE CHERRY STREET CROSSING[1]

	Summary Statistics				Warning Times (seconds)							
	Sample Size	Mean (vehicles)	Standard Deviation	Range (seconds)	<20	20-30	30-40	40-50	50-60	60-90	>90	Total
Two-Quadrant Gates												
Day	71	55.81	14.05	30-106	--	--	--	--	--	--	--	--
Night	34	61.49	19.80	29-118	--	--	--	--	--	--	--	--
Total	105	57.65	16.26	29-118	--	--	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	0	2	12	16	39	33	3	105
Percent of Observations	--	--	--	--	0.0	1.9	11.4	15.2	37.2	31.4	2.9	
Cumulative Percentage	--	--	--	--	0.0	1.9	13.3	28.5	65.7	97.1	100.0	
Four-Quadrant Gates with Skirts												
Day	30	51.64	8.58	38-75	--	--	--	--	--	--	--	--
Night	34	60.06	16.16	30-94	--	--	--	--	--	--	--	--
Total	64	56.11	13.73	30-94	--	--	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	0	0	2	23	22	16	1	64
Percent of Total Arrivals	--	--	--	--	0.0	0.0	3.1	36.0	34.4	25.0	1.5	
Cumulative Percentage	--	--	--	--	0.0	0.0	3.1	39.1	73.5	98.5	100.0	

[1]Time between activation of flashing lights and train's arrival at the crossing.

that will exhibit dangerous and/or illegal behavior. Unfortunately, there was no method in the literature for assessing the adequacy of the warning times at a railroad-highway grade crossing from the driver's perspective; however, level-of-service concepts have been well established in the highway field for the past 30 years. As a result, level-of-service criteria, similar to those for signalized intersections in the 1985 HCM (53), were developed for active warning devices at grade crossings. The proposed criteria are shown in Table 18. They were based on the premise that a grade crossing is very similar to a signalized intersection, albeit that one interrupts vehicular flow only a few times each day. This is not an unreasonable assumption given the fact that at both a signalized intersection and a railroad-highway grade crossing, drivers are primarily concerned with how long they have to wait.

As shown in Table 18, 20 seconds is the minimum warning time currently required by the MUTCD (12), and 60 seconds is defined by the 1985 HCM (53) as the limit of acceptable delay to most motorists. These two points clearly define the limits of adequate or acceptable motorist service, i.e., warning times less than 20 seconds are inadequate (as currently defined by the MUTCD), and warning times greater than 60 seconds are unacceptable and thus, Level-of-Service "F". The 40 second range between these two limits was subdivided in 10 second increments so as to create four warning time categories for Levels-of-Service "A", "B", "C", and "D". By using these definitions, the majority of the warning times observed in both studies could be classified as Level-of-Service "D" or better--65.7 percent in the before study

TABLE 18. PROPOSED LEVEL OF SERVICE CRITERIA FOR RAILROAD-HIGHWAY GRADE CROSSINGS

Level of Service	Average Warning Time Before Train's Arrival[1]
-	<20[2]
A	20 to 30
B	30 to 40
C	40 to 50
D	50 to 60
F	>60[3]

[1]Average time between activation of the flashing light signals and the train's arrival at the crossing.

[2]20 seconds is the minimum warning time allowed by the MUTCD.

[3]60 seconds is the limit of acceptable delay to most motorists as defined by the 1985 HCM.

(two-quadrant gates) and 73.5 percent in the after study (four-quadrant gates with skirts). However, a much smaller percentage of the warning times observed could be classified as Level-of-Service "C" or better--28.5 percent in the before study and 39.1 percent in the after study. This relatively small percentage of warning times less than 40 seconds and the 34.3 percent of the warning times that were classified as Level-of-Service "F" (unacceptable) might explain why so many motorists drove around the lowered two-quadrant gates. In other words, the warning times were perceived as unacceptable (i.e., too long), and the motorists performed in an unacceptable (i.e., dangerous and illegal) manner by driving around the lowered two-quadrant gate arms.

Clearance Time. Clearance time was defined as the difference in time between the last vehicle to cross and the train's arrival at the crossing. As the four-quadrant gates with skirts prohibit driving around the gates by physically blocking the roadway, their installation should result in significantly longer clearance times. In other words, if motorists could drive around the gate arms, they could cross closer to the train's arrival at the crossing. This additional temporal separation between cars and trains is a definite safety benefit of the four-quadrant gate system.

Clearance times were only recorded for those arrivals wherein a vehicle arrived at the crossing between the activation of the flashing light signals and the train's arrival at the crossing, i.e., there was an opportunity for a vehicle to cross in front of the train. Thus, the number of clearance times will always be less than or equal to the

number of train arrivals. As shown in Table 19, there were 90 clearance times observed in the before study (two-quadrant gates) and 29 clearance times observed in the after study (four-quadrant gates with skirts). As with the warning time data set, the total data from each study was subdivided into observations that occurred during the day and observations that occurred during the night so as to ensure that similar train and traffic volume conditions were compared. These two subsets, together with the total data set, were then analyzed.

The mean and standard deviation of the clearance times from the day, night, and total data sets were noticeably longer during the after study. Additionally, the Mann-Whitney U test for two independent, continuously distributed populations (49) indicated that these differences were statistically significant at the 99 percent confidence level. This means that installation of the four-quadrant gate with skirts significantly increased the average time between the last vehicle to cross and the train's arrival at the crossing (from 24.5 seconds to 48.9 seconds). In addition to being statistically significant, this change in driver performance was large enough to be considered meaningful from a practical point of view. This finding is shown clearly in the illustration of the frequency and cumulative frequency distributions of the clearance times from the two data sets in Figure 54. The Mann-Whitney U test failed to indicate a statistically significant difference at the 95 percent confidence level between the day and night data sets from either of the two studies. This means that there was no evidence suggesting that clearance times were different between day and night operation for either the two-quadrant gates or four-quadrant gates with skirts.

TABLE 19. CLEARANCE TIMES AT THE CHERRY STREET CROSSING[1]

	Summary Statistics						Clearance Times (seconds)				
	Sample Size[2]	Mean (seconds)	Standard Deviation	Percent <20 Seconds	Percent <10 Seconds	Range (seconds)	<10	10-20	20-30	>30	Total
Two-Quadrant Gates											
Day	70	23.96	11.18	41.4	5.7	6-62	--	--	--	--	--
Night	20	26.62	17.23	35.0	5.0	4-72	--	--	--	--	--
Total	90	24.55	12.71	40.0	5.6	4-72	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	5	31	36	18	90
Percent of Total Arrivals	--	--	--	--	--	--	5.6	34.4	40.1	19.9	
Cumulative Percentage	--	--	--	--	--	--	5.6	40.0	80.1	100.0	
Four-Quadrant Gates with Skirts											
Day	18	44.39	9.10	0.0	0.0	34-68	--	--	--	--	--
Night	11	56.27	16.27	0.0	0.0	34-81	--	--	--	--	--
Total	29	48.90	13.39	0.0	0.0	34-81	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	0	0	0	29	29
Percent of Total Arrivals	--	--	--	--	--	--	0.0	0.0	0.0	100.0	
Cumulative Percentage	--	--	--	--	--	--	0.0	0.0	0.0	100.0	

[1]Time between last vehicle to cross and the train's arrival at the crossing.

[2]Includes only those observations in which vehicles were present before the train's arrival.

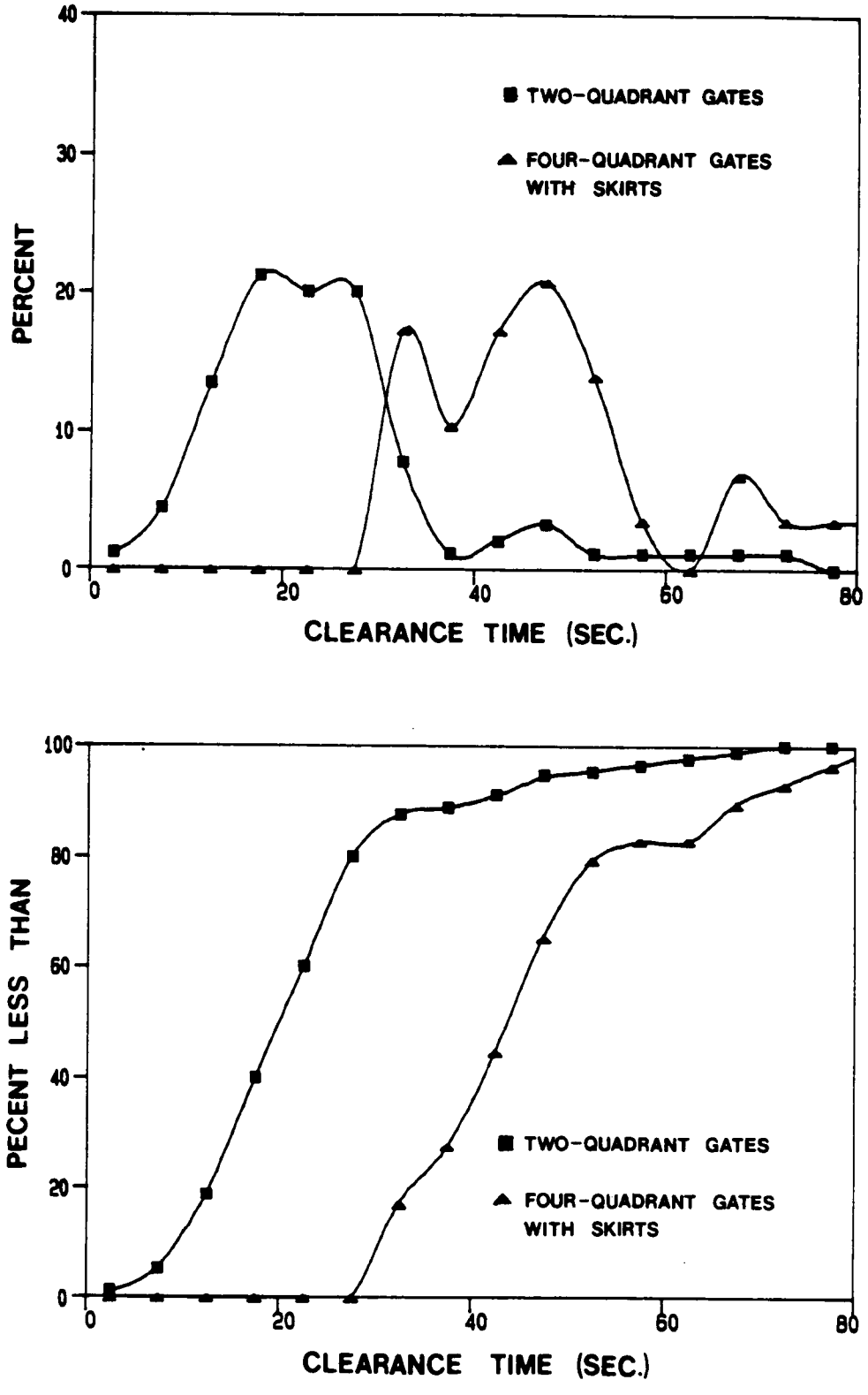


FIGURE 54. FREQUENCY AND CUMULATIVE FREQUENCY DISTRIBUTIONS OF THE OBSERVED CLEARANCE TIMES AT THE CHERRY STREET CROSSING

It was hypothesized that even though warning times have a major influence on driver performance, a small percentage of drivers would exhibit undesirable (dangerous or illegal) behavior no matter how "good" the warning times were. This type of behavior is similar to those drivers that exceed properly set speed limits. In other words, there will always be a few drivers that will take risks at railroad-highway grade crossings just as there will always be a few drivers that take risks at regular intersections as well as on the open highway. The problem then becomes one of defining risky behavior. To solve this problem, four categories of driver performance and associated clearance times were defined as follows:

1. Risky - less than 10 seconds;
2. Aggressive - from 10 to 20 seconds;
3. Normal - from 20 to 30 seconds; and
4. Cautious - greater than 30 seconds.

Risky behavior represents a level of driver performance in which there is little, if any, room for error. A judgmental mistake by the driver or a mechanical failure by the vehicle will probably result in an accident. Aggressive behavior represents a level of driver performance in which there is some, but not much, room for error. A small misestimation of the train's arrival time at the crossing will probably still allow time for most drivers to clear safely; however, vehicles that stall or have poor acceleration characteristics may be involved in an accident. The MUTCD (12) appears to address this point by currently requiring a minimum warning time of 20 seconds. Normal behavior represents a level of driver performance in which most reasonable and prudent

drivers fall. Most minor judgmental mistakes and poorly accelerating vehicles will not result in an accident. Cautious behavior represents a level of driver performance in which drivers probably rely totally on the warning device and not on their own judgement of the train's arrival at the crossing. Although these drivers are in no danger of an accident, they may be unnecessarily delayed when the warning times are long.

Using the preceding definitions, 40 percent of the clearance times in the before study (Table 19) were classified as either risky or aggressive whereas in the after study, no clearance times were classified in these categories. In fact, all of the clearance times in the after study were classified as cautious; however, this finding is not a result of a different train or driver population. Instead, as stated previously, it is a result of the four-quadrant gates with skirts prohibiting motorists from driving around the gates by completely blocking the road. Thus, all, rather than just a part of the drivers, were forced to rely on the warning device. In other words, the potential for drivers to make a judgement as to whether or not it was safe to cross was removed from their possible set of options. Reliance on active warning devices is especially important at crossings with limited sight distance, high speed trains, and multiple tracks, because it is at these locations where drivers often make mistakes in judgement. However, to avoid unnecessarily delaying drivers at these crossings, it is imperative that the warning devices operate reliably and at as high a level-of-service as possible.

Approach Measures

Speed Profiles. The average speed at which drivers approach the Cherry Street crossing whenever the warning devices are activated may or may not be different after the installation of the four-quadrant gates with skirts. Hypothetically, the greater conspicuity and more imposing presence of the four-quadrant gates with skirts should cause drivers to see them quicker and slow down sooner. Even if this behavior change occurs it may not be large enough to be statistically significant, and even if it were, it still might not be large enough to be practically significant (i.e., a difference in speeds of one or two miles per hour might be statistically significant because of a large sample size; however, from a practical standpoint, such a difference would be meaningless (54)).

In order to compare characteristics of similar vehicles, approach speed profiles for the first vehicle to stop at the crossing in both the before and after studies were plotted as shown in Figure 55. Each data point represents average speeds over 50-foot sections of roadway in advance of the stop bar at the crossing and are plotted at the midpoint of the section. As mentioned in Chapter V, data in the range of 50 to 200 feet from the stop bar were obtained from Camera 1, in the range of 250 feet to 450 feet from the stop bar from Camera 2, and in the range from 500 to 700 feet in advance of the stop bar from Camera 3. Unfortunately, there was such a small amount of available data from Camera 3, that a significant number of average speeds could not be

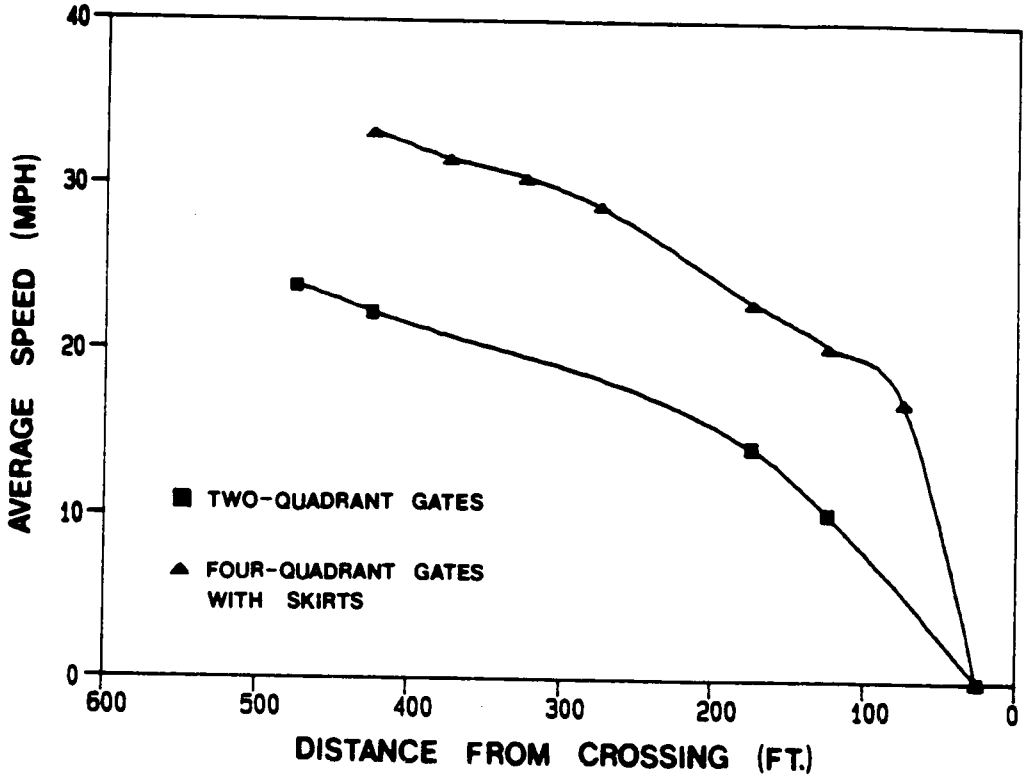


FIGURE 55. AVERAGE APPROACH SPEED PROFILES FOR VEHICLES IN ADVANCE OF THE CHERRY STREET CROSSING

calculated at the far distances. Therefore, only data from the first two cameras are shown in Figure 55.

Several observations can be made concerning the average approach speed profiles in the before and after data sets. First, the average speeds in the after study (four-quadrant gates with skirts) were about 10 miles per hour faster than they were in the before study (two-quadrant gates). This was contradictory to the initial premise of drivers slowing down or at least maintaining their speed in response to the four-quadrant gates with skirts. As a result, an investigation into why drivers speeded up was begun. In the after study, the first vehicle to stop at the crossing did so because the four-quadrant gates with skirts completely blocked the roadway. However, in the before study, visual observation of the video tapes indicated that the first vehicle to stop was oftentimes following a queue of slow moving vehicles that were driving around the gate arms; thus, its speed was limited by the vehicles in front of it. In other words, approach speeds of the first vehicle to stop in the after study would be characterized as free-flow, and approach speeds of the first vehicle to stop in the before study would be characterized as constrained.

Because of the unanticipated difference in stimuli and conditions, it was not surprising that the average approach speeds for the first vehicle to stop in the after study were faster than they were in the before study. Even with these unexpected results, several conclusions can be drawn from the approach speed profiles shown in Figure 55. First, in both studies, the first vehicle to stop began slowing about 450 feet from the stop bar. Second, stopping vehicles did so in a safe,

gradual, and consistent manner. Finally, although installation of the four-quadrant gate with skirts failed to cause the first vehicle to stop to begin slowing down sooner, the resultant speed profiles appeared to pose no safety problem for approaching motorists.

Perception-Brake Reaction Time and Deceleration. Perception-brake reaction time was defined as the difference in time between activation of the flashing light signals and the illumination of the vehicle's brake lights. It was expected that the greater conspicuity and more imposing presence of the four-quadrant gates with skirts would cause motorists to brake quicker and as a result, slow down more gradually. It was also expected that if these differences did exist, they would be small and very difficult to measure. To compound this problem, braking for a flashing light signal is an unexpected event and does not represent a pressure situation unless a train is also visible. Thus, driver response will probably be highly variable.

Average perception-brake reaction times in response to the activation of the flashing light signals at the Cherry Street crossing were 18.4 seconds in the before study and 15.4 seconds in the after study. In both cases, the standard deviations were larger than the mean. These differences were small and as indicated by the results of the Mann-Whitney U test (49), were not statistically significant at the 95 percent confidence level. These data confirm the premise that braking in response to a flashing light signal did not represent a pressure situation (i.e., long reaction times) and because of this, was highly variable (i.e., large standard deviations). An additional complication

with measuring perception-brake reaction times was the difficulty in determining whether the vehicle of interest was braking in response to the activation of the warning device, a slower moving vehicle ahead of it, or simply a rough spot in the road.

In terms of deceleration, the Traffic Engineering Handbook (28) defines several deceleration categories as follows:

1. Emergency - greater than 20 ft/sec^2;
2. Very uncomfortable - 14 to 20 ft/sec^2;
3. Uncomfortable - 11 to 14 ft/sec^2;
4. Undesirable - 8 to 11 ft/sec^2; and
5. Practical - less than 8 ft/sec^2.

Previous studies have concluded that nearly all drivers approaching an activated flashing light signal decelerate to a stop at a practical level (24, 25). The drivers approaching the Cherry Street crossing were no different. In the before study, only 5 percent of the vehicles exceeded a practical deceleration level while they were stopping, and in the after study, 12 percent of the vehicles did so. In both cases, none of the vehicles exceeded an undesirable deceleration. These differences are small, and any differences which existed were probably the result of the differences in stimuli for the first vehicle which stopped in each of the two studies, i.e., in the after study, they stopped in response to the activation of the warning devices; whereas in the before study, they may have been traveling slower and stopping more gradually because of slower moving vehicles in front of them. However, in neither study

did the maximum observed decelerations indicate a potential safety problem.

Safety Measures

Violations. At a crossing with flashing light signals and automatic gates, violations occur whenever motorists drive around the gate arms when they are in the down position. As stated previously, many motorists drove around the lowered two-quadrant gate arms at the Cherry Street crossing even though it was illegal to do so. Installation of the four-quadrant gates with skirts should eliminate this apparent disregard for the warning devices by completely blocking the roadway and making it physically impossible to drive around lowered gate arms.

For the aforementioned reasons, the average number of motorists per train arrival who drove around the gate arms went from 2.6 in the before study (two-quadrant gates) to 0.0 in the after study (four-quadrant gates with skirts) (see Table 20); however, what was not expected was the magnitude of the number of motorists that drove around the two-quadrant gates--at least one in 83.9 percent of the train arrivals, at least two in 62.4 percent of the train arrivals, and as many as 14 in a single train arrival. Clearly, driver performance in response to the two-quadrant gates at Cherry Street was not good. Although it is fairly obvious that these differences were significant, a Pearson's chi-square statistic calculated from a two by five contingency table (two studies by five violation rate categories) indicated that these differences were statistically significant at the 99 percent confidence level.

TABLE 20. VIOLATIONS AT THE CHERRY STREET CROSSING[1]

	Summary Statistics						Violations (vehicles)					
	Sample Size[2]	Mean (vehicles)	Standard Deviation	Percent >0 Violations	Percent >1 Violations	Range (vehicles)	0	1	2	3	>3	Total
Two-Quadrant Gates												
Day	71	2.76	2.40	87.3	67.6	0-14	--	--	--	--	--	--
Night	22	2.09	2.29	72.7	45.5	0-9	--	--	--	--	--	--
Total	93	2.60	2.38	83.9	62.4	0-14	--	--	--	--	--	--
Number of Observations	--	--	--	--	--	--	15	20	18	17	23	93
Percent of Observations	--	--	--	--	--	--	16.1	21.5	19.4	18.3	24.7	
Cumulative Percentage	--	--	--	--	--	--	16.1	37.6	57.0	75.3	100.0	
Four-Quadrant Gates with Skirts												
Day	28	0.00	0.00	0.0	0.0	0-0	--	--	--	--	--	--
Night	25	0.00	0.00	0.0	0.0	0-0	--	--	--	--	--	--
Total	53	0.00	0.00	0.0	0.0	0-0	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	53	0	0	0	0	53
Percent of Total Arrivals	--	--	--	--	--	--	100.0	0.0	0.0	0.0	0.0	
Cumulative Percentage	--	--	--	--	--	--	100.0	100.0	100.0	100.0	100.0	

[1]Vehicles driving around a lowered gate arm at the crossing.

[2]Include only those observations in which vehicles were present before the train's arrival.

One of the more interesting and expected findings from the before study was that the average number of violations per train arrival increased with an increase in warning time. These data are shown in Table 21 and illustrated in Figure 56. Notice that when the warning times were less than 40 seconds (Level-of-Service "B" or better), one or less motorists drove around the gates; however, when the warning times were between 40 and 60 seconds (Levels-of-Service "C" and "D"), two to three motorists drove around the gates, and when the warning times were longer than 60 seconds (Level-of-Service "F"), three or more motorists drove around the gates. Thus, a 40 to 50 second warning time might be considered as the threshold at which two or more motorists will drive around a gate arm, and a 60 second warning time as the threshold at which three or more motorists will drive around the gate arm. Therefore, it does not appear reasonable to expect the average motorist to wait any longer than 40 seconds at a railroad-highway grade crossing. These observations support the premise that the worse the performance of the warning device (i.e., the longer the warning time), the larger the number of illegal and dangerous maneuvers that will take place.

Vehicles Crossing. The average number of vehicles crossing between activation of the flashing light signals and the train's arrival at the crossing is shown in Table 22. It should be noted that these numbers include not only the motorists who drove around the gate arms when they were in the down position (i.e., a violation), but also those motorists who drove through the crossing while the gate arms were descending. Installation of the four-quadrant gates with skirts was expected to

TABLE 21. EFFECTS OF WARNING TIMES ON VIOLATION RATES AT THE CHERRY STREET CROSSING

Study	Warning Time (Sec.)[1]	Observed Train Arrivals[2]	Average Violations (Per Arrival)
Two-Quadrant Gates	<20	-	-
	20-30	2	0.00
	30-40	10	1.00
	40-50	15	1.60
	50-60	37	2.54
	60-90	27	3.44
	>90	2	9.00
		Total 93	2.60
Four-Quadrant Gates with Skirts	<20	1	0.00
	20-30	-	-
	30-40	1	0.00
	40-50	18	0.00
	50-60	21	0.00
	60-90	11	0.00
	>90	1	-
		Total 53	0.00

[1]Time between activation of flashing lights and train's arrival at the crossing.

[2]Includes only those observations in which vehicles are present.

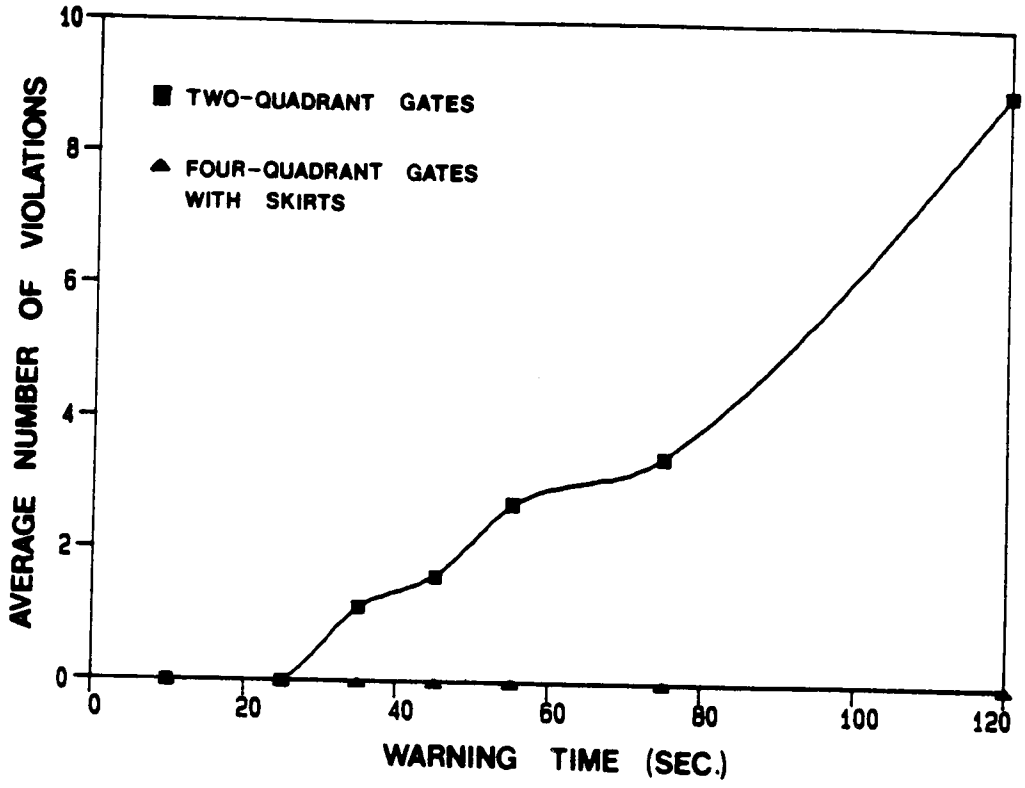


FIGURE 56. AVERAGE NUMBER OF VIOLATIONS AS A FUNCTION OF THE WARNING TIMES AT THE CHERRY STREET CROSSING

TABLE 22. VEHICLES CROSSING AT THE CHERRY STREET CROSSING[1]

	Summary Statistics						Crossings					
	Sample Size[2]	Mean (vehicles)	Standard Deviation	Percent >0 Violations	Percent >1 Violations	Range (vehicles)	0	1	2	3	>4	Total
Two-Quadrant Gates												
Day	71	4.32	2.93	98.6	88.7	0-19	--	--	--	--	--	--
Night	22	2.95	2.87	90.9	63.6	0-11	--	--	--	--	--	--
Total	93	4.01	2.96	96.8	82.8	0-19	--	--	--	--	--	--
Number of Observations	--	--	--	--	--	--	3	13	20	10	47	93
Percent of Observations	--	--	--	--	--	--	3.2	14.0	21.5	10.8	50.5	
Cumulative Percentage	--	--	--	--	--	--	3.2	17.2	38.7	49.5	64.5	
Four-Quadrant Gates with Skirts												
Day	28	1.50	1.50	64.3	42.9	0-5	--	--	--	--	--	--
Night	25	0.72	0.98	44.0	20.0	0-3	--	--	--	--	--	--
Total	53	1.13	1.33	54.7	32.1	0-5	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	24	12	7	7	3	53
Percent of Total Arrivals	--	--	--	--	--	--	45.3	22.6	13.2	13.2	5.7	
Cumulative Percentage	--	--	--	--	--	--	45.3	67.9	81.1	81.1	100.0	

[1]Vehicles driving around a lowered gate arm at the crossing.

[2]Includes only those observations in which vehicles were present before the train's arrival.

reduce the frequency of such behavior by completely blocking the roadway and making it physically impossible to drive around the lowered gate arms. Additionally, the more formidable appearance of the four-quadrant gates with skirts may have discouraged some motorists from crossing while the gate arms were descending.

For the aforementioned reasons, the average number of vehicles crossing per train arrival and the percentage of train arrivals with at least one vehicle crossing went from 4.01 and 96.8 in the before study (two-quadrant gates) to 1.13 and 54.7 in the after study (four-quadrant gates with skirts). As with the observed violations, it is fairly obvious that these differences were significant. This observation was verified by the results of the Mann-Whitney U test and a Pearson's chi-square statistic from a two by six contingency table (two studies by six crossing rate categories) which indicated that these differences were significant at the 99 percent confidence level. These findings support the premise that the four-quadrant gates with skirts improved safety at the Cherry Street crossing by reducing the number of vehicles crossing in front of an oncoming train.

Crossings Less Than 20 Seconds (CL20). Vehicles crossing within 20 seconds of a train's arrival at a crossing has previously been defined as an indication of aggressive behavior, i.e., there is some, but not much, room for driver and/or vehicular error. Because motorists had to drive around lowered gate arms in order to cross within 20 seconds, this behavior was illegal. Additionally, this measure represents those drivers who choose to cross within the 20 second minimum warning time

presently required by the MUTCD (11). Installation of the four-quadrant gates with skirts was expected to eliminate this type of behavior by completely blocking the roadway at least 20 seconds prior to the train's arrival at the crossing.

As shown in Table 23, the average number of vehicles crossing within 20 seconds of the train's arrival at the crossing went from 0.60 in the before study to 0.00 in the after study. Additionally, over 40 percent of the observations in the before study resulted in at least one CL20, and over 10 percent of the observations resulted in multiple CL20's. Results from the Mann-Whitney U test indicated that these differences were significant at the 95 percent confidence level. Thus, as expected, installation of the four-quadrant gates with skirts significantly decreased the CL20 rate (i.e., aggressive behavior) at the Cherry Street crossing.

A frequency distribution of the observed CL20's at the Cherry Street crossing is also shown in Table 23. In the before study there were 55 observations with zero CL20's, 27 observations with one CL20, six observations with two CL20's, and five observations with three or more CL20's. In the after study, there were no CL20's in any of the 53 observations. A Pearson's chi-square statistic calculated from a two by four contingency table substantiates the fact that these differences were significant at the 99 percent confidence level.

Crossings Less Than 10 Seconds (CL10). While it is illegal to drive around gate arms when they are in the down position (i.e., a violation), it also becomes extremely risky to do so whenever a train is

TABLE 23. CL20'S AT THE CHERRY STREET CROSSING[1]

	Summary Statistics						CL20s (vehicles)					
	Sample Size[2]	Mean (vehicles)	Standard Deviation	Percent >0 Violations	Percent >1 Violations	Range (vehicles)	0	1	2	3	>3	Total
Two-Quadrant Gates												
Day	71	0.65	0.97	42.3	12.7	0-4	--	--	--	--	--	--
Night	22	0.45	0.67	36.4	9.1	0-2	--	--	--	--	--	--
Total	93	0.60	0.91	40.9	11.8	0-4	--	--	--	--	--	--
Number of Observations	--	--	--	--	--	--	55	27	6	3	2	93
Percent of Observations	--	--	--	--	--	--	59.1	29.0	6.5	3.2	2.2	
Cumulative Percentage	--	--	--	--	--	--	59.1	88.1	94.6	97.8	100.0	
Four-Quadrant Gates with Skirts												
Day	28	0.0	0.0	0.0	0.0	0-0	--	--	--	--	--	--
Night	25	0.0	0.0	0.0	0.0	0-0	--	--	--	--	--	--
Total	53	0.0	0.0	0.0	0.0	0-0	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	53	0	0	0	0	53
Percent of Total Arrivals	--	--	--	--	--	--	100.0	0.0	0.0	0.0	0.0	
Cumulative Percentage	--	--	--	--	--	--	100.0	100.0	100.0	100.0	100.0	

[1]Vehicles driving around a lowered gate arm at the crossing.

[2]Includes only those observations in which vehicles were present before the train's arrival.

in close proximity to the crossing. There was a portion of the data set that was also in potential conflict (i.e., at risk) with a train's arrival at the crossing. Clearance times that leave little room for either driver or vehicular error have previously been defined as crossing within 10 seconds of an oncoming train's arrival (CL10). It was anticipated that installation of the four-quadrant gates with skirts would eliminate this type of behavior by completely blocking the roadway at least 20 seconds prior to the train's arrival at the crossing.

As shown in Table 24, five CL10's (risky crossings) were observed at the Cherry Street crossing in the before study--four during the day and one during the night; five motorists drove around the gate arms and crossed the tracks within 10 seconds of the train's arrival. As expected, no similar behavior was observed in the after study. A Pearson's chi-square statistic calculated from a two by two contingency table indicated that these differences were significant at the 95 percent confidence level for the day, night, and total data sets. Thus, it is fairly obvious that installation of the four-quadrant gates with skirts removed the possibility of risk-taking from the driver's set of options.

Summary

The average warning times at the Cherry Street crossing are near the limit of acceptable delay for most motorists, i.e., near Level-of-Service "F". Because of this and the fact that the roadway was not physically "blocked," many drivers disregarded the two-quadrant gates at the crossing by driving around lowered gate arms. Installation of the

TABLE 24. CL1O'S AT THE CHERRY STREET CROSSING[1]

Summary Statistics	Two-Quadrant Gates			Four-Quadrant Gates with Skirts		
	Day	Night	Total	Day	Night	Total
Sample Size[2]	71	22	93	28	25	53
Mean (vehicles)	0.06	0.05	0.05	0.0	0.0	0.0
Standard Deviation	0.23	0.21	0.23	0.0	0.0	0.0
Percent with Conflicts	5.6	4.6	5.4	0.0	0.0	0.0
Range (vehicles)	0-1	0-1	0-1	0-0	0-0	0-0
0 Conflicts/Arrival	67	21	89	28	25	53
1 Conflict/Arrival	4	1	5	0	0	0

[1]Vehicle's crossing within 10 seconds of the train's arrival.

[2]Includes only those observations in which vehicles were present prior to the train's arrival.

four-quadrant gates with skirts had no effect on the crossing's level-of-service, but had a very positive effect on driver behavior at the crossing by eliminating all risky and illegal behavior at the crossing, thus, resulting in a definite safety benefit. Such benefits are especially important at crossings with limited sight distance, high speed trains, and/or multiple tracks because it is at these locations where drivers often make mistakes in judgement. Performance measures such as speeds, perception-brake reaction times, and deceleration levels failed to indicate a change in driver behavior. This was not surprising as any anticipated changes were small.

VIII. FOUR-QUADRANT FLASHING LIGHT SIGNALS WITH OVERHEAD STROBES

As discussed in Section VI, the approach roadway's horizontal and vertical alignments limit visibility of the Ebenezer Road crossing from both directions. Thus, the visibility of the standard two-quadrant flashing light signals at the crossing was also limited. The primary change in driver performance that was expected as a result of the installation of the four-quadrant flashing light signals with overhead strobes was an earlier reaction to the active warning devices. As a result of this change in behavior, the approach speeds were expected to be slower, the brake reaction times were expected to be quicker, and the deceleration levels were expected to be more gradual; however, as previously discussed, differences in these driver performance measures are not easy to quantify and the related safety benefits are not straightforward.

Driver behavior at the crossing itself (i.e. clearance times, violation rates, and vehicle crossing rates) was not expected to change, as the new device neither changed the train detection system nor physically blocked the roadway. It should be noted that there was a fundamental difference in the definition of a violation at crossings with flashing light signals and at those with automatic gates. For example, violations at the Cherry Street crossing were defined in terms of illegal behavior, i.e., driving around the gate-arms while they were in the down position; however, violations at the Ebenezer Road Crossing could not be defined in a similar manner because the only legal requirements placed on motorists approaching a flashing light signal are that

they bring their vehicle to a stop in advance of the crossing and then proceed when it is safe to do so. Thus, violations at a crossing with flashing light signals were defined as drivers that could reasonably stop in response to the warning device, failing to do so. However, because of the difficulty in determining whether or not a vehicle came to a complete stop, violations were not counted for the flashing light signal systems.

The four-quadrant flashing light signals with overhead strobes were installed at the Ebenezer Road crossing during the week of October 14, 1985. Prior to this time, active warning devices at the crossing were standard two-quadrant flashing light signals. Both train movement and driver behavior data were collected for approximately two months before (July and August 1985) and two months after (May and August 1986) the new devices were installed. During these two time periods, a total of 226 train movements were observed. There were 157 trains observed in the before study (two-quadrant flashing light signals), and 79 trains observed in the after study (four-quadrant flashing light signals with overhead strobes); however, the after study consisted of two one-month studies separated by a 60-day waiting period. This was done so as to determine whether driver behavior in response to the four-quadrant flashing light signals with overhead strobes changed with time, i.e., a learning effect. Thus, the results from the Ebenezer Road crossing will be reported as three studies: before, first after, and second after. For each observation in the three studies, the environmental and lighting conditions, train's direction of travel and warning time, and

approaching vehicle's clearance time, speed profile and brake reaction time were recorded and subsequently analyzed.

This section describes the evaluation of the two active warning devices at the Ebenezer Road crossing, i.e., the original two-quadrant flashing light signals and the subsequent four-quadrant flashing light signals with overhead strobes. The first step in this process was an assessment of the level-of-service at which the active warning devices were operating. This determination was based on average waiting time at the crossing and was similar to the level-of-service criteria for average delay at signalized intersections presented in the 1985 Highway Capacity Manual (1985 HCM) (53). Secondly, the driver performance measures for the two warning devices were summarized and compared from both a statistical and practical standpoint. Finally, the safety implications of utilizing four-quadrant flashing signals with overhead strobes is discussed.

Crossing Measures

Warning Time. Warning time was defined as the difference in time between activation of the flashing light signals and the train's arrival at the crossing. It is the same as the maximum time a motorist would have to wait between activation of the flashing light signals and a train's arrival at the crossing. As there were no changes to the train detection system when the four-quadrant flashing light signals with overhead strobes were installed, there should have been no difference in the average warning times observed in the before and either of the two after studies. To verify this premise, the total data set from each

study was first subdivided into observations that occurred during the day and observations that occurred during the night so as to insure that similar train and traffic volume conditions were compared. These two subsets, together with the total data set, were then analyzed.

As shown in Table 25, the mean and standard deviation of the warning times from all three data sets were slightly lower in the first after study (flashing light signals with strobes-spring 1986); however, the Kruskal-Wallis test for two or more independent, continuously distributed populations (49) indicated that these differences were not significantly different at the 95 percent confidence level for either the day, night, or total data sets. This means that, as expected, installation of the four-quadrant flashing light signals with overhead strobes had no effect on the warning times at the crossing. The Kruskal-Wallis test also indicated that there was not a statistically significant difference at the 95 percent confidence level between the day and night data sets from either of the three studies. Thus, warning times were not different during day and night operations for either the two-quadrant flashing light signals or the four-quadrant flashing light signals with overhead strobes.

It was hypothesized in Section VII that the warning times observed at a railroad-highway grade crossing have a major influence on driver performance at the crossing, i.e., the longer the warning times, the larger the number of drivers that will exhibit dangerous and/or illegal behavior. By using the level-of-service definitions developed in Section VII (Table 18 on page 150), approximately 90 percent of the observed warning times for each of the three studies at the Ebenezer

TABLE 25. WARNING TIMES AT THE EBENEZER ROAD CROSSING[1]

	Summary Statistics				Warning Times (seconds)							
	Sample Size	Mean (vehicles)	Standard Deviation	Range (seconds)	<20	20-30	30-40	40-50	50-60	60-90	>90	Total
Flashing Light Signals												
Day	106	42.2	15.6	24-153	--	--	--	--	--	--	--	--
Night	51	38.1	11.1	26-106	--	--	--	--	--	--	--	--
Total	157	40.8	14.4	24-153	--	--	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	0	13	84	45	6	6	3	157
Percent of Total Arrivals	--	--	--	--	0.0	8.3	53.5	28.6	3.9	3.8	1.9	
Cumulative Percentage	--	--	--	--	0.0	8.3	61.8	90.4	94.3	98.1	100.0	
Flashing Light Signal with Strobes (Spring 1986)												
Day	18	36.3	7.1	19-45	--	--	--	--	--	--	--	--
Night	5	38.3	4.7	36-47	--	--	--	--	--	--	--	--
Total	23	36.7	6.6	19-47	--	--	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	2	0	15	6	0	0	0	23
Percent of Total Arrivals	--	--	--	--	8.7	0.0	65.2	26.1	0.0	0.0	0.0	
Cumulative Percentage	--	--	--	--	8.7	8.7	73.9	100.0	100.0	100.0	100.0	
Flashing Light Signals with Strobes (Summer 1986)												
Day	43	41.0	10.0	14-623	--	--	--	--	--	--	--	--
Night	13	43.4	22.4	82-116	--	--	--	--	--	--	--	--
Total	56	41.6	13.7	14-116	--	--	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	1	4	25	19	4	2	1	56
Percent of Total Arrivals	--	--	--	--	1.8	7.1	44.6	33.9	7.1	3.6	1.8	
Cumulative Percentage	--	--	--	--	1.8	8.9	53.6	87.5	94.6	98.2	100.0	

[1]Time between activation of the flashing light signal and the train's arrival at the crossing.

Road crossing could be classified as Level-of-Service "A", "B", or "C". In fact, over sixty percent of the observed warning times in all three studies could be classified as Level-of-Service "A" or "B". Additionally the very small number of unacceptable (greater than 60 seconds) warning times in the three data sets means that the active warning devices at the Ebenezer Road crossing are operating at a good level-of-service. Thus, it would be expected that driver behavior at the crossing itself would be relatively good (e.g., few dangerous or illegal maneuvers) and that, because the warning times did not change between studies, driver behavior at the crossing itself also would not change between studies.

Clearance Time. Clearance time was defined as the difference in time between the last vehicle to cross and the train's arrival at the crossing. As the four-quadrant flashing signals with overhead strobes changed nothing at the crossing itself, their installation was expected to have no affect on the clearance times observed in any of the three studies. Thus, there was no expected increase in the temporal separation between cars and trains as a result of the new devices being installed.

Clearance times were only recorded for those train arrivals wherein a vehicle arrived at the crossing between the activation of the flashing light signals and the train's arrival at the crossing, i.e., there was an opportunity for a vehicle to cross in front of the train while the signals were activated. Thus, the number of clearance times will always be less than or equal to the number of train arrivals. As shown in

Table 26, there were 109 clearance times observed in the before study (two-quadrant flashing light signals), 18 clearance times observed in the first after study (four-quadrant flashing light signals with strobes--spring 1986), and 45 clearance times observed in the second after study (four-quadrant flashing light signals with strobes--summer 1986). As with the warning time data set, the total data from each study was subdivided into observations that occurred during the day and observations that occurred during the night so as to insure that similar train traffic volume conditions were compared. The two subsets along with the total data set were then analyzed.

The mean and standard deviation of the clearance times from all three data sets were slightly shorter in the second after study. However the Kruskal-Wallis test (51) indicated that these differences were not statistically significant at the 95 percent confidence level for either the day, night, or total data sets. This means that installation of the four-quadrant flashing light signals with overhead strobes had no effect on the average time between the last vehicle to cross and the train's arrival at the crossing. This finding is shown clearly in the illustration of the frequency and cumulative frequency distributions of the clearance times from the three data sets in Figure 57. The Kruskal-Wallis test also failed to indicate a statistically significant difference at the 95 percent confidence level between the day and night data sets from either of the three studies. This means that the clearance times were no different between day and night operation for either the two-quadrant flashing light signals or the four-quadrant flashing light signals with overhead strobes.

TABLE 26. CLEARANCE TIMES AT THE EBENEZER ROAD CROSSING[1]

	Summary Statistics						Clearance Times (seconds)				
	Sample Size[2]	Mean (seconds)	Standard Deviation	Percent <20 Seconds	Percent <10 Seconds	Range (seconds)	<10	10-20	20-30	>30	Total
Flashing Light Signals											
Day	92	19.1	9.9	66.3	12.0	7-64	--	--	--	--	--
Night	17	27.9	20.5	41.2	5.9	8-99	--	--	--	--	--
Total	109	20.5	12.4	62.4	11.0	7.99	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	12	56	26	15	109
Percent of Total Arrivals	--	--	--	--	--	--	11.0	51.4	23.9	13.8	
Cumulative Percentage	--	--	--	--	--	--	11.0	62.4	86.2	100.0	
Flashing Light Signals with Strobes (Spring 1986)											
Day	15	19.1	6.9	53.3	0.0	10-31	--	--	--	--	--
Night	3	19.1	17.3	66.7	33.3	4-38	--	--	--	--	--
Total	18	19.1	8.6	55.6	5.6	4-38	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	1	9	6	2	18
Percent of Total Arrivals	--	--	--	--	--	--	5.6	50.0	33.3	11.1	
Cumulative Percentage	--	--	--	--	--	--	5.6	55.6	88.9	100.0	
Flashing Light Signals with Strobes (Summer 1986)											
Day	38	14.3	6.3	86.8	23.7	5-36	--	--	--	--	--
Night	7	27.2	6.0	14.3	0.0	18-37	--	--	--	--	--
Total	45	16.3	7.8	75.6	20.0	5-37	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	9	25	8	3	45
Percent of Total Arrivals	--	--	--	--	--	--	20.0	55.6	17.8	6.6	
Cumulative Percentage	--	--	--	--	--	--	20.0	75.6	93.4	100.0	

[1]Time between activation of the flashing light signal and the train's arrival at the crossing.

[2]Includes only those observations in which vehicles were pesent before the train's arrival.

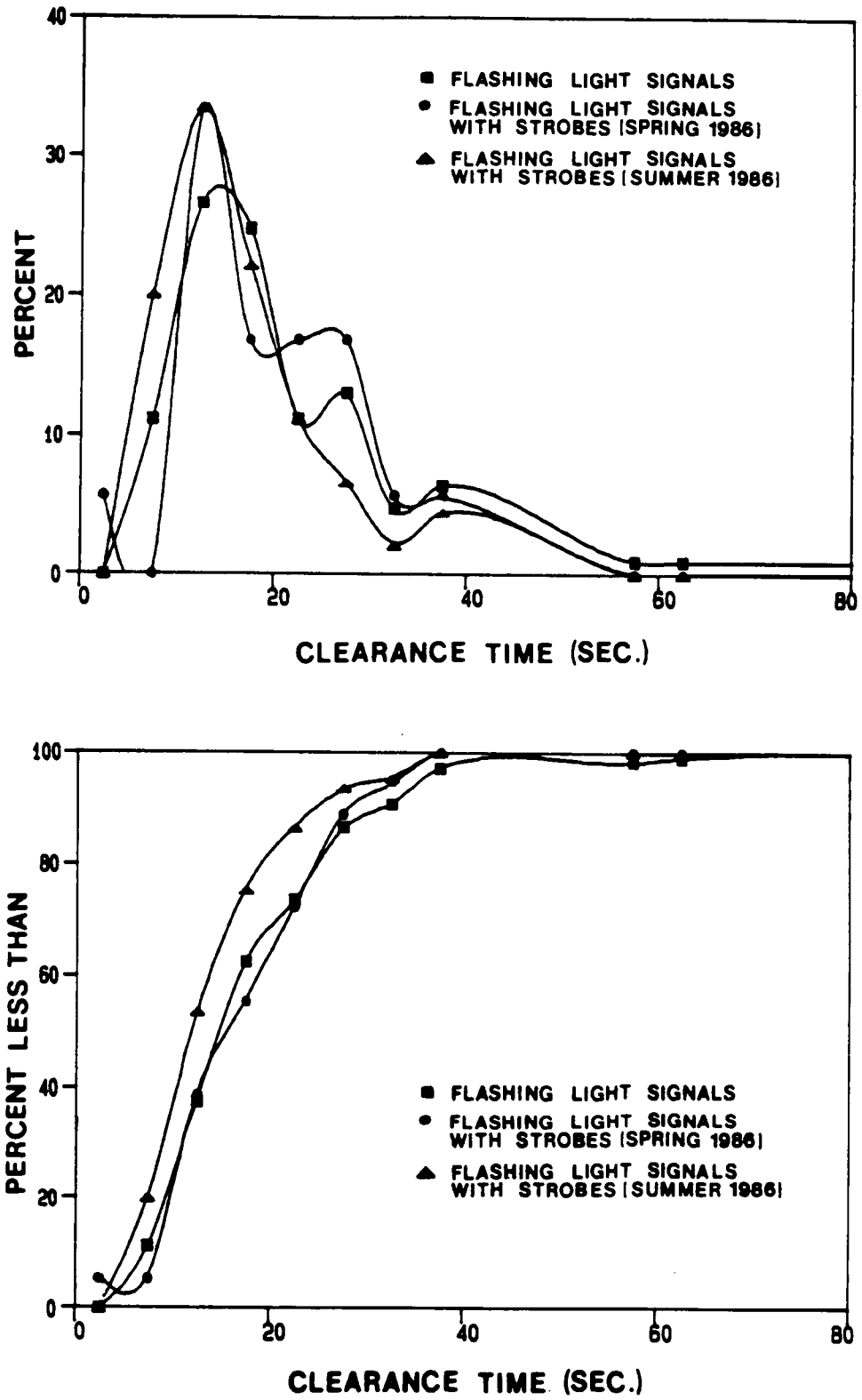


FIGURE 57. FREQUENCY AND CUMULATIVE FREQUENCY DISTRIBUTIONS OF OBSERVED CLEARANCE TIMES AT THE EBENEZER ROAD CROSSING

It was also hypothesized in Section VII that no matter how short the warning times, a small percentage of drivers would exhibit dangerous and/or illegal behavior. To assess the magnitude of this problem at the Ebenezer Road crossing, the observed vehicle clearance times were classified into the four categories previously defined in Section VII:

1. Risky - less than ten seconds;
2. Aggressive - from 10 to 20 seconds;
3. Normal - from 20 to 30 seconds; and
4. Cautious - greater than 30 seconds.

By using these definitions, approximately 50 percent of the observed clearance times in all three studies could be classified as either risky or aggressive, i.e., they were less than the minimum warning time currently required by the MUTCD (12). In addition, only about ten percent of the clearance times could be classified as cautious even though the active warning devices were operating at Level-of-Service "B" or "C". These data indicate that motorists will drive through a crossing while the signals are flashing as long as a train does not appear to be in close proximity. Interestingly, the frequency with which short clearance times occur indicate that drivers and the MUTCD (12) may have different ideas as to what the necessary warning time should be.

Approach Measures

Speed Profiles. The average speed at which drivers approach the Ebenezer Road crossing whenever the warning devices were activated may or may not have been different after the installation of the four-quadrant flashing light signals with overhead strobes.

Hypothetically, the greater conspicuity of the new warning devices, especially that of the overhead strobes, should cause drivers to see the warning devices earlier and slow down sooner. However, even if this behavioral change occurs, it may not be large enough to be statistically significant; even if it were, it still might not be large enough to be meaningful from a practical point of view. In addition, the safety benefits of such a speed change are not easily quantified.

In order to compare characteristics of similar vehicles, approach speed profiles for the first vehicle to stop at the crossing in both the before and each of the two after studies were plotted as shown in Figure 58. Each data point represents average speeds over 50-foot sections of roadway in advance of the stop bar at the crossing and are plotted at the mid-point of the section. Data in the range of 50 to 200 feet from the stop bar were obtained from Camera 1, in the range of 250 feet to 450 feet from the stop bar from Camera 2, and in the range of 500 to 700 feet in advance of the stop bar from Camera 3. Unfortunately, there was such a small amount of data from Camera 3, that a significant number of average speeds could not be calculated at the far distances. In addition, the curvilinear nature of the approach roadway rendered much of the data unusable for speed calculations, and Camera 2 was the only camera used in the second after study. Therefore, only partial data from the first two cameras in the before and first after study and data from Camera 2 in the second after study are shown in Figure 58.

Several observations can be made concerning the average approach speed profiles in the before and after data sets. First, the average

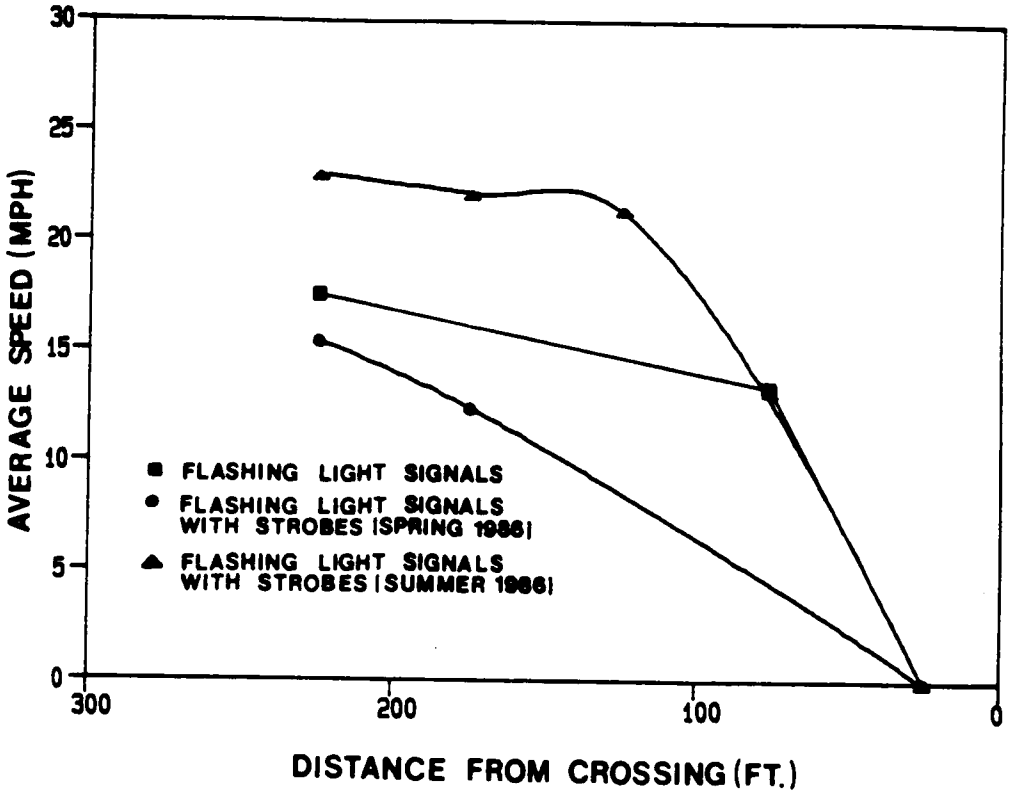


FIGURE 58. AVERAGE APPROACH SPEED PROFILES FOR VEHICLES IN ADVANCE OF THE EBENEZER ROAD CROSSING

speeds in the first after study (four-quadrant flashing light signals with strobes-spring 1986) were lower than the average speeds in either of the other two studies. However, close examination of the data reveals that the average speeds in the before study and the first after study were relatively close to one another; i.e., for practical purposes, they were the same. In other words, even if the differences were statistically significant, the magnitude of the difference was so small that it was not meaningful from a practical point of view (54). Vehicles stopping in response to either the two-quadrant flashing light signals or the four-quadrant flashing light signals with overhead strobes did so in a safe, gradual, and consistent manner. As a result, the resultant speed profiles appeared to pose no safety problems for approaching motorists.

Perception-Brake Reaction Time and Deceleration. Perception-brake reaction time was defined as the difference in time between activation of the flashing light signals and the illumination of a vehicle's brake lights. It was expected that the greater conspicuity of the four-quadrant flashing light signals with overhead strobes would cause motorists to brake sooner and as a result decelerate more gradually. It was also expected that if these differences did exist, they would be very small and difficult to measure. To compound this problem, braking for a flashing light signal is an unexpected event and also does not represent a pressure situation unless a train is also visible. Thus, driver response can be relatively long and highly variable.

Average brake reaction times in response to the activation of the flashing light signals at the Ebenezer Road crossing were 15.6 seconds in the before study, 21.7 in the first after study, and 11.5 in the second after study. These differences were large enough to be meaningful, but because of the relatively small sample size, the results from the Kruskal-Wallis test (49) indicated that these differences were not large enough to be statistically significant at the 95 percent confidence level. This means that installation of the flashing light signals with overhead strobes had no measurable effect on the perception-brake reaction time of approaching motorists. As at the other crossings, it was very difficult to determine whether the vehicle of interest was braking in response to activation of the warning device, a slower moving vehicle in front of it, or in the case of the Ebenezer Road crossing, for a curve in the road.

In terms of deceleration, drivers approaching activated flashing light signals at the Ebenezer Road crossing were no different than those reported in the literature (24, 25) or observed at the other two crossings. None of the observed deceleration levels in the first after study exceeded a practical deceleration level, again indicating nonemergency stops. However, it could also indicate that drivers had already slowed their vehicles because of the horizontal alignment of the road, and continuance of this initial slow down in order to stop resulted in low decelerations. Whatever the reason, the maximum deceleration levels observed at the Ebenezer Road crossing did not indicate a potential safety problem for either the two-quadrant flashing light signals or the four-quadrant flashing light signals with overhead strobes.

Safety Measures

Violations. At a crossing with flashing light signals, violations were defined as motorists that could reasonably stop in response to the warning device, failing to do so. However, because of the difficulty in determining whether or not a vehicle came to a complete stop, violations were not counted for the flashing light signal systems. Even if the number of violations had been counted, installation of the four-quadrant flashing light signals with overhead strobes was not expected to change their frequency of occurrence because there were no changes to either the train detection system or the crossing itself.

Vehicles Crossing. The average number of vehicles crossing between activation of the flashing light signals and the train's arrival at the crossing are shown in Table 27. As there was no statistically significant difference in the warning times observed during the three studies, there should have been no difference in the number of vehicles crossing. The results of the Kruskal-Wallis test verified this premise at the 95 percent confidence level. Interestingly, almost 28 percent of the total observations resulted in five or more vehicles crossing after the flashing light signals were activated. As stated before, this is a clear indication that motorists will drive through a crossing while the signals are flashing as long as a train is not believed to be in close proximity.

The effects of warning times on the number of vehicles crossing while the flashing light signals were activated is shown in Table 28. Even though the majority of the warning time observations are still in

TABLE 27. VEHICLES CROSSING AT THE EBENEZER ROAD CROSSING[1]

	Summary Statistics						Crossings (vehicles)						
	Sample Size[2]	Mean (vehicles)	Standard Deviation	Percent >1 Crossing	Percent >0 Crossing	Range (vehicles)	0	1	2	3	4	>4	Total
Flashing Light Signals													
Day	101	3.83	3.41	91.1	74.3	0-21	--	--	--	--	--	--	--
Night	22	1.59	1.37	77.3	45.5	0-5	--	--	--	--	--	--	--
Total	123	3.43	3.26	88.6	69.1	0-21	--	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	14	24	25	14	15	31	123
Percent of Total Arrivals	--	--	--	--	--	--	11.4	19.5	20.3	11.4	12.2	25.2	
Cumulative Percentage	--	--	--	--	--	--	11.4	30.9	51.2	62.6	74.8	100.0	
Flashing Light Signals with Strobes (Spring 1986)													
Day	16	2.81	1.64	93.8	81.3	0-6	--	--	--	--	--	--	--
Night	4	1.25	1.26	75.0	25.0	0-3	--	--	--	--	--	--	--
Total	20	2.50	1.67	90.0	70.0	0-6	--	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	2	4	5	4	2	3	20
Percent of Total Arrivals	--	--	--	--	--	--	10.0	20.0	25.0	20.0	10.0	15.0	
Cumulative Percentage	--	--	--	--	--	--	10.0	30.0	55.0	75.0	85.0	100.0	
Flashing Light Signals with Strobes (Summer 1986)													
Day	42	4.24	2.82	90.5	81.0	0-11	--	--	--	--	--	--	--
Night	7	2.71	1.38	100.0	71.4	1-4	--	--	--	--	--	--	--
Total	49	4.02	2.70	91.8	79.5	0-11	--	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	4	6	8	3	8	20	49
Percent of Total Arrivals	--	--	--	--	--	--	8.2	12.3	16.3	6.1	16.3	40.8	
Cumulative Percentage	--	--	--	--	--	--	8.2	20.5	36.8	42.9	59.2	100.0	

[1]Vehicles crossing between activation of the flashing light signals and the train's arrival at the crossing.

[2]Includes only those observations in which vehicles were present before the train's arrival.

TABLE 28. EFFECTS OF WARNING TIMES ON NUMBER OF VEHICLES CROSSING AT THE EBENEZER ROAD CROSSING

Study	Warning Time (Sec.)[1]	Observed Train Arrivals[2]	Average No. Crossing (Per Arrival)
Flashing Light Signals	<20	0	-
	20-30	7	1.29
	30-40	63	2.79
	40-50	38	3.82
	50-60	6	3.83
	60-90	6	7.00
	>90	3	9.00
		Total 123	
Flashing Light Signals with Strobes (spring 1986)	<20	1	0.00
	20-30	-	-
	30-40	13	2.46
	40-50	6	3.00
	50-60	-	-
	60-90	-	-
	>90	-	-
		Total 20	
Flashing Light Signals with Strobes (summer 1986)	<20	1	1.00
	20-30	4	1.50
	30-40	22	3.45
	40-50	16	4.63
	50-60	4	6.25
	60-90	2	7.50
	>90	-	-
		Total 49	

[1]Time between activation of flashing lights and train's arrivals at the crossing.

[2]Includes only those observations in which vehicles were present.

the 30 to 40 second range, there is clearly an identifiable trend--the longer the warning time, the greater the number of vehicles that will cross while the signal is flashing. This relationship is illustrated in Figure 59. Note that if the warning time is less than 30 seconds, an average of one driver will cross in front of the train; whereas, if the warning time is longer than 30 seconds, an average of three to four drivers will cross in front of the train. Even though none of the drivers in any of these observations were in immediate danger, the more of them that have to make the decision of whether or not it is safe to cross, the greater the probability of one of them making the wrong decision.

Crossings Less Than 20 Seconds (CL20). Vehicles crossing within 20 seconds of a train's arrival at the crossing have previously been defined as an indication of aggressive behavior, i.e., there is some, but not much, room for driver and/or vehicular error. Although such behavior is not illegal, it represents those drivers that choose to cross within the 20-second minimum warning time presently required by the MUTCD (12). Installation of the four-quadrant flashing light signals with overhead strobes should have no effect on this driver performance measure as nothing was changed at the crossing itself.

As shown in Table 29, the average number of vehicles crossing within 20 seconds of a train's arrival at the crossing was not noticeably different for any of the three studies. Additionally, the Kruskal-Wallis test (49) indicated that there were no statistically significant differences at the 95 percent confident level. Thus, as expected, installation of the four-quadrant flashing light signals with

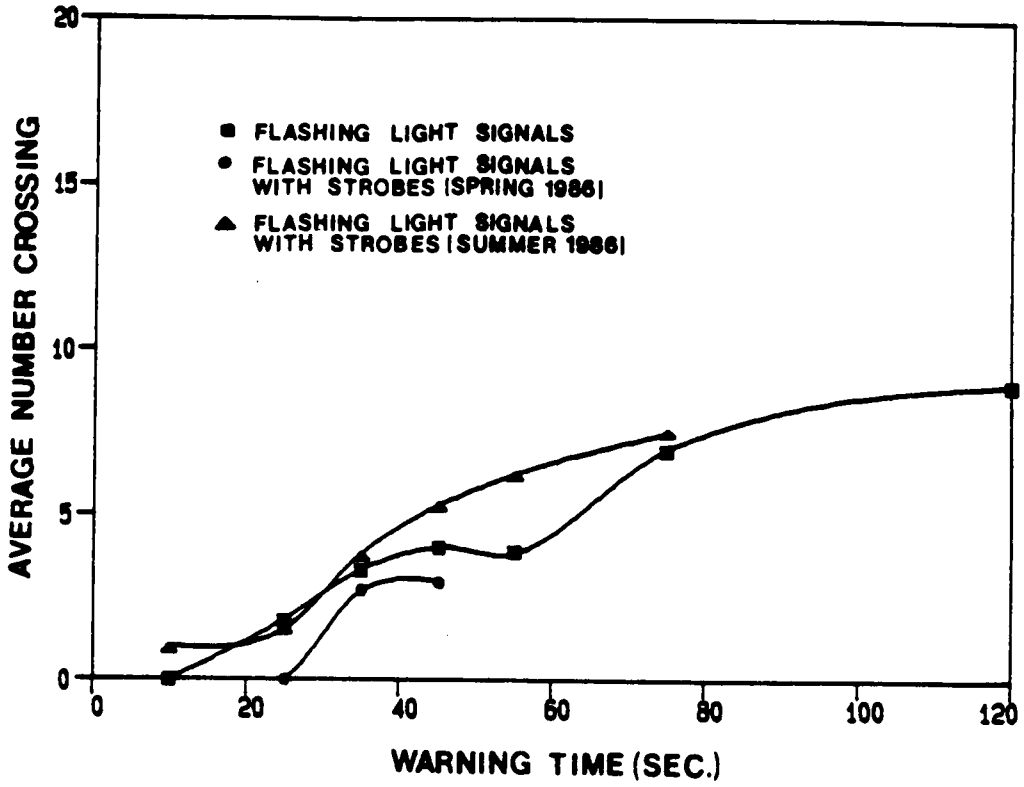


FIGURE 59. AVERAGE NUMBER OF VEHICLES CROSSING AS A FUNCTION OF WARNING TIME AT THE EBENEZER ROAD CROSSING

TABLE 29. CL20'S AT THE EBENEZER ROAD CROSSING[1]

	Summary Statistics						CL20s (vehicles)					
	Sample Size[2]	Mean (vehicles)	Standard Deviation	Percent >0 Violations	Percent >1 Violations	Range (vehicles)	0	1	2	3	>3	Total
Flashing Light Signals												
Day	101	1.30	1.50	70.3	36.6	0-7	--	--	--	--	--	--
Night	22	0.41	0.67	31.8	4.6	0-2	--	--	--	--	--	--
Total	123	1.14	1.43	55.3	30.9	0-7	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	55	30	20	10	8	123
Percent of Total Arrivals	--	--	--	--	--	--	44.7	24.4	16.3	8.1	6.5	
Cumulative Percentage	--	--	--	--	--	--	44.7	69.1	85.4	93.5	100.0	
Flashing Light Signals with Strobes (Spring 1986)												
Day	16	0.94	1.12	50.0	31.3	0-3	--	--	--	--	--	--
Night	4	0.50	0.58	50.0	0.0	0-1	--	--	--	--	--	--
Total	20	0.85	1.04	50.0	25.0	0-3	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	10	5	3	2	0	20
Percent of Total Arrivals	--	--	--	--	--	--	50.0	25.0	15.0	10.0	0.0	
Cumulative Percentage	--	--	--	--	--	--	50.0	75.0	90.0	100.0	100.0	
Flashing Light Signals with Strobes (Summer 1986)												
Day	42	1.64	1.45	78.6	45.2	0-5	--	--	--	--	--	--
Night	7	0.43	0.79	28.6	14.3	0-2	--	--	--	--	--	--
Total	49	1.47	1.43	71.4	40.8	0-5	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	14	15	12	2	6	49
Percent of Total Arrivals	--	--	--	--	--	--	28.6	30.6	24.5	4.1	12.2	
Cumulative Percentage	--	--	--	--	--	--	28.6	59.2	83.7	87.8	100.0	

[1]Vehicles crossing within 20 seconds of the train's arrival at the crossing.

[2]Includes only those observations in which vehicles were present before the train's arrival.

overhead strobes had no effect on the CL20 rate (i.e., aggressive behavior) at the Ebenezer Road crossing. Surprisingly, over 60 percent of the observations in each study resulted in at least one CL20 and more than 35 percent of the observations resulted in multiple CL20's.

A frequency distribution of the observed CL20's at the Ebenezer Road crossing is also shown in Table 29. In the before study, there were 41 observations with no CL20's, 30 observations with one CL20, 20 observations with two CL20's, ten observations with three CL20's, and eight observations with four or more CL20's. Although the number of observations in each category were smaller in the after studies, the percentages are almost identical to that of the before study. A Pearson's chi-square statistic calculated from a three by four contingency table (three studies by four CL20 rate categories) substantiates the fact there were no significant differences at the 95 percent confidence level between the three data sets.

The effects of warning times on the CL20 rates at the Ebenezer Road crossing are shown in Table 30. As mentioned previously, and as shown in the table, most of the observed warning times were in the 30 to 50 second range. This left very few observations in the other warning time ranges and precluded any development of trends. An additional complication in the development of relationships was the fact that the time available for CL20's to occur did not increase with an increase in warning time, i.e., it was defined to always be 20 seconds. However, it is interesting to note that in the 30 to 40 second warning time range, there were approximately 1.27 CL20's per train arrival in the before study and 1.00 to 1.64 CL20's per train arrival in the two after

TABLE 30. EFFECTS OF WARNING TIMES ON CL20 RATES AT THE EBENEZER ROAD CROSSING

Study	Warning Time (Sec.)[1]	Observed Train Arrivals[2]	Average CL20's (Per Arrival)
Flashing Light Signals	<20	0	-
	20-30	7	0.57
	30-40	63	1.27
	40-50	38	1.16
	50-60	6	0.17
	60-90	6	0.67
	>90	3	2.33
		Total 123	
Flashing Light Signals with Strobes (spring 1986)	<20	1	0.00
	20-30	-	-
	30-40	13	1.00
	40-50	6	0.67
	50-60	-	-
	60-90	-	-
	>90	-	-
		Total 20	
Flashing Light Signals with Strobes (summer 1986)	<20	1	1.00
	20-30	4	1.25
	30-40	22	1.64
	40-50	16	1.31
	50-60	4	1.75
	60-90	2	1.00
	>90	-	-
		Total 49	

[1]Time between activation of flashing lights and train's arrivals at the crossing.

[2]Includes only those observations in which vehicles were present.

studies. Again, this is an indication that motorists and the MUTCD (12) may have different ideas as to what the necessary warning times at a railroad-highway grade crossing should be.

Crossings Less Than 10 Seconds (CL10). Vehicles crossing within 10 seconds of a train's arrival at the crossing have previously been defined as an indication of risky behavior, i.e., there is little room for either driver and/or vehicular error. Although also not illegal, such behavior intuitively increases the likelihood of an accident occurring. It was expected that installation of the four-quadrant flashing light signals with overhead strobes would have no effect on this driver performance measure as nothing was changed at the crossing itself.

As shown in Table 31, 14 CL10's were observed at the Ebenezer Road crossing in the before study--13 during the day and 1 during the night, i.e., 14 motorists crossed the tracks within ten seconds of the train's arrival. In fact, in at least one case, two motorists crossed the tracks within ten seconds of a train's arrival. Because the small number of observed CL10's (i.e., risky behavior) in the two after studies did not allow meaningful statistical comparisons to be made between the three studies, the two after studies were combined and compared to the before study. Thus, a total of 12 CL10's were observed in the two after studies--11 during the day and 1 during the night. A Pearson's chi-square statistic calculated from a two by two contingency table indicated that the observed CL10's in the before (i.e., two-quadrant flashing light signals) and after (i.e., four-quadrant

TABLE 31. CL1O'S AT THE EBENEZER ROAD CROSSING[1]

Summary Statistics	Flashing Light Signals			Flashing Light Signals with Strobes (Spring 1986)			Flashing Light Signals with Strobes (Summer 1986)		
	Day	Night	Total	Day	Night	Total	Day	Night	Total
Sample Size	101	22	123	16	4	20	42	7	49
Mean (seconds)	0.13	0.05	0.11	0.00	0.25	0.05	0.26	0.00	0.22
Standard Deviation	0.37	0.21	1.34	0.00	0.50	0.22	0.54	0.00	0.51
Percent with Conflicts	11.9	4.6	10.6	0.0	25.0	5.0	21.4	0.0	18.4
Range (vehicles)	0-2	0-1	0-2	0-0	0-1	0-1	0-2	0-0	0-2
0 CL1Os/Arrival	89	21	110	16	3	19	33	7	40
1 CL1Os/Arrival	11	1	12	0	1	1	7	0	7
2 CL1Os/Arrival	1	0	1	0	0	0	2	0	2

[1]Vehicles crossing within 10 seconds of the train's arrival at the crossing.

[2]Includes only those observations in which vehicles were present prior to the train's arrival.

flashing light signals with overhead strobes) data sets were not significantly different at the 95 percent confidence level. It is interesting to note however that 24 of the 26 observed CL10's occurred during the day. The obvious conclusion is that CL10's were more likely to occur during this period of time; however, the reasons why are not so clear. For example, do fewer drivers take risk at night because they have poorer visibility of approaching trains, or do fewer drivers take risk at night because there are fewer of them in a position to take the risk, i.e., less exposure?

One interesting observation from this data set is that the CL10 rates and percentages were more than twice as high at Ebenezer Road than they were at Cherry Street. Even though driver performance measures at the two crossings are not directly comparable because of differences in location, crossing surfaces, and warning devices, one point is worth mentioning--the maximum train speeds at the Ebenezer Road crossing are almost twice as high as at the Cherry Street crossing (i.e., 55 miles per hour as compared to 30 miles per hour). Motorists crossing in front of a train a fixed distance from the crossing will result in shorter clearance times at the higher speed crossing. Thus, these data might be an indication of the difficulty motorists have in estimating a train's speed, especially if the speed is high, and its subsequent arrival at the crossing.

Summary

The active warning devices at the Ebenezer Road crossing are operating at Level-of-Service "B" or "C" (i.e., at an acceptable level to

most motorists). As the intent of the additional flashing light signals with overhead strobes was to provide increased conspicuity of the active warning devices, performance measures such as clearance times, violations, and vehicle crossing rates were not expected to change. The resultant analysis substantiated this premise. Performance measures such as approach speed profiles, perception-brake reaction times, and maximum deceleration levels were expected to change. Unfortunately, there were a number of additional variables, such as horizontal and vertical curvature and restrictive right-of-way, that added extraneous variability to the measurement process. This variability was so great that it probably hid any positive or negative effects on driver behavior that might have occurred. Thus, from the data collected and analyzed, the four-quadrant flashing light signals with overhead strobes had no discernible effect on driver behavior at the Ebenezer Road crossing.

IX. HIGHWAY TRAFFIC SIGNAL

As discussed in Section VI, the Cedar Drive crossing had severe safety problems as evidenced by its high hazard ranking (31st most dangerous crossing in the state) and the three car-train accidents that occurred at this site during the past five years. It was hypothesized that these safety problems were a result of a combination of the relatively high train and traffic volumes, limited sight distance at the crossing, and long warning times, resulting in numerous motorists crossing in front of approaching trains. Because highway traffic signals have a relatively high level of driver credibility and respect, their installation at the Cedar Drive crossing should discourage most motorists from crossing in front of approaching trains.

Because the highway traffic signals legally prohibit crossing rather than physically doing so, the average clearance time between the last vehicle to cross and the train's arrival at the crossing may or may not increase. However, the average number of vehicles crossing per train arrival was expected to decrease. These behavioral modifications have implied safety benefits in that they provide greater spatiotemporal separation between trains and motor vehicles. The anticipated secondary change in driver performance was better response to the new devices (i.e., quicker perception-brake reaction times and lower deceleration levels) as a result of the greater conspicuity of the white bar strobes and credibility of the traffic signal. As noted previously, differences in these performance measures were not expected to be as

easy to quantify, and the related safety benefits were not expected to be as straightforward.

It should be noted that there was a fundamental difference in the definition of a violation at a crossing with flashing light signals (before study) and with highway traffic signals (after study). For example, violations at a crossing with flashing light signals were defined as vehicles that could reasonably stop in response to the activated warning devices, failing to do so. However, because of the difficulty in determining whether or not a vehicle came to a complete stop, violations were not counted for flashing light signal systems. Violations at a crossing with a highway traffic signal were defined in terms of illegal behavior (i.e., running a red light) and could easily be counted. Thus, violation rates between the two conditions at the Cedar Drive crossing were not directly comparable.

The highway traffic signals were installed at the Cedar Drive crossing during April 1986. Prior to this time, the active warning devices at the crossing were standard two-quadrant flashing light signals; however, because it was felt that long warning times at this crossing might lessen the traffic signal's credibility, predictors were installed during November 1985 so as to provide shorter and more consistent warning times. Both train movement and driver behavior data were collected for approximately two months before the predictors were installed (May and June, 1985), two months after the predictors were installed and before the highway traffic signals were installed (February and March, 1986), and two months after the highway traffic signals were installed (July and August, 1986).

The results from the Cedar Drive crossing will be reported as three studies--first before study (i.e., flashing light signals without predictors), second before study (i.e., flashing light signals with predictors) and after study (i.e., highway traffic signals with predictors). During these three studies, there were a total of 231 train movements observed. There were 89 train movements observed in the first before study, 50 train movements observed in the second before study, and 92 train movements observed in the after study. For each observation, the environmental and lighting conditions, train's direction of travel and warning time, and approaching vehicle's clearance time, speed profile, and perception-brake reaction time were recorded and subsequently analyzed.

This section describes the evaluation of the three combinations of active warning devices that were installed at the Cedar Drive crossing. The first step in this process was an assessment of the level-of-service at which the active warning devices were operating. As before, this determination was based on average waiting time at the crossing and was similar to the level-of-service criteria for average delay at signalized intersections presented in the 1985 Highway Capacity Manual (1985 HCM) (53). Secondly, the driver performance measures for the two warning devices were summarized and compared from both a statistical and a practical standpoint. Finally, the safety implications of installing predictors and/or highway traffic signals is discussed.

Crossing Measures

Warning Time. Warning time was defined as the difference in time between activation of either the flashing light signals or the traffic signal's clearance interval (yellow interval) and the train's arrival at the crossing. It is the same as the maximum amount of time a motorist would have to wait between activation of the warning devices and the train's arrival at the crossing. Installation of the predictors at the Cedar Drive crossing should have resulted in shorter and more consistent warning times. In other words, the warning times should have been shorter in the second before study (i.e., four-quadrant flashing light signals with predictors) than they were in the first before study (i.e., four-quadrant flashing light signals without predictors). However, because the same predictors were used in the two latter studies, there should have been no differences in the warning times between the second before study and the after study (i.e., highway traffic signals with predictors).

To verify these premises, the total data set from each study was subdivided into observations that occurred during the day and observations that occurred during the night so as to ensure that similar train and traffic volume conditions were compared. These two subsets, together with the total data set, were then analyzed. As shown in Table 32, the mean warning time from all three data subsets was significantly longer in the first before study. The Kruskal-Wallis test for two or more independent, continuously distributed populations (49) indicated that these differences were statistically significant at the 99 percent

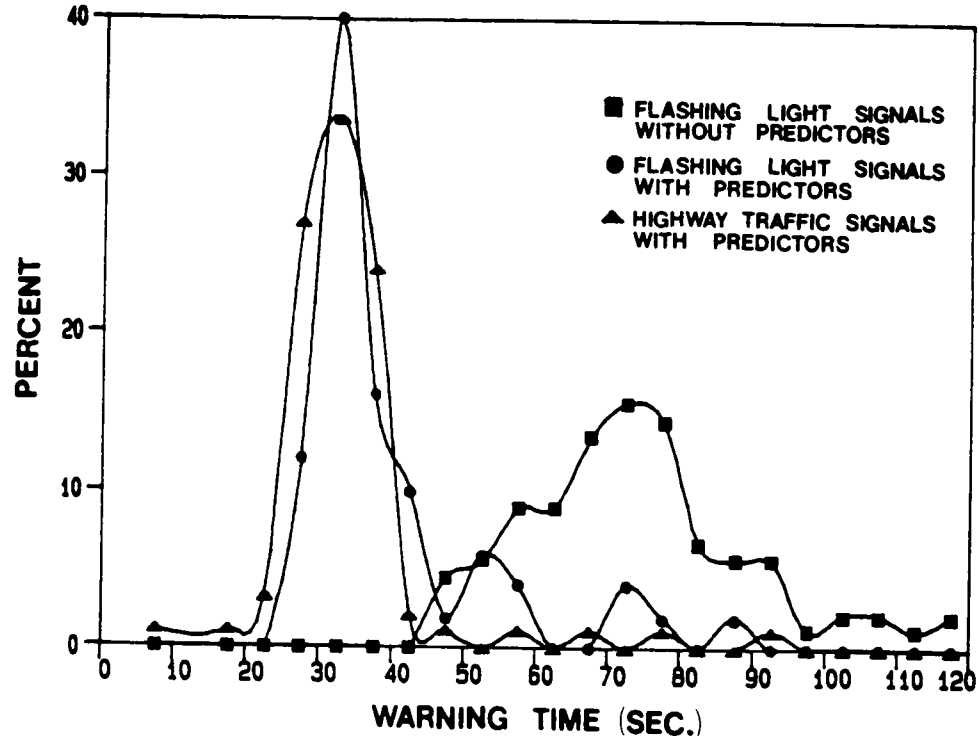
TABLE 32. WARNING TIMES AT THE CEDAR DRIVE CROSSING[1]

	Summary Statistics				Warning Times (seconds)							
	Sample Size	Mean (vehicles)	Standard Deviation	Range (seconds)	<20	20-30	30-40	40-50	50-60	60-90	>90	Total
Flashing Light Signals without Predictors												
Day	53	73.7	20.6	47-141	--	--	--	--	--	--	--	--
Night	36	77.6	13.4	56-119	--	--	--	--	--	--	--	--
Total	89	75.2	17.9	47-141	--	--	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	0	0	0	4	13	57	15	89
Percent of Observations	--	--	--	--	0.0	0.0	0.0	4.4	14.5	64.5	16.6	
Cumulative Percentage	--	--	--	--	0.0	0.0	0.0	4.4	18.9	83.4	100.0	
Flashing Light Signal with Predictors												
Day	22	40.5	15.5	27-89	--	--	--	--	--	--	--	--
Night	28	42.7	19.9	28-121	--	--	--	--	--	--	--	--
Total	50	41.7	18.0	27-121	--	--	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	0	6	28	6	5	4	1	50
Percent of Total Arrivals	--	--	--	--	0.0	12.0	56.0	12.0	10.0	8.0	2.0	
Cumulative Percentage	--	--	--	--	0.0	12.0	68.0	80.0	90.0	98.0	100.0	
Highway Traffic Signals with Predictors												
Day	67	38.1	21.7	23-161	--	--	--	--	--	--	--	--
Night	25	31.5	8.4	8-57	--	--	--	--	--	--	--	--
Total	89	75.2	17.9	47-141	--	--	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	2	28	53	3	1	2	3	92
Percent of Observations	--	--	--	--	2.2	30.4	57.6	3.3	1.0	2.2	3.3	
Cumulative Percentage	--	--	--	--	2.2	32.6	90.2	93.5	94.5	96.7	100.0	

[1]Time between activation of flashing lights or onset of yellow and the train's arrival at the crossing.

confidence level. This means that, as expected, installation of the predictors decreased the average warning time at the crossing and that, once the predictors were in place, installation of the highway traffic signal had no further effect on the average warning time at the crossing. This finding is shown clearly in the illustration of the frequency and cumulative frequency distributions of the warning times from the three data sets in Figure 60. In addition, the Mann-Whitney U test indicated that there was not a statistically significant difference at the 95 percent level between the day and night data sets from any of the three studies.

As with the other two crossings, it was hypothesized that the warning times observed at the Cedar Drive crossing would have a major influence on driver performance, i.e., the longer the warning time, the larger the number of drivers that will exhibit dangerous and/or illegal behavior. By using the level of service criteria developed in Section VII (Table 18 on Page 150), less than five percent of the observed warning times in the first before study (without predictors) were Level-of- Service "C" or better; whereas, over 80 percent of the observed warning times were Level-of-Service "F" (unacceptable). However, after the predictors were installed, almost 80 percent of the observed warning times were Level-of-Service "C" or better, and only 10 percent were Level-of-Service "F". In fact, over 68 percent of the observed warning times were Level-of-Service "B" or better. When the highway traffic signals were installed in conjunction with the predictors, over 90 percent of the observed warning times were Level-of-Service "B" or better, and only 5.5 percent were Level-of-Service "F." Clearly,



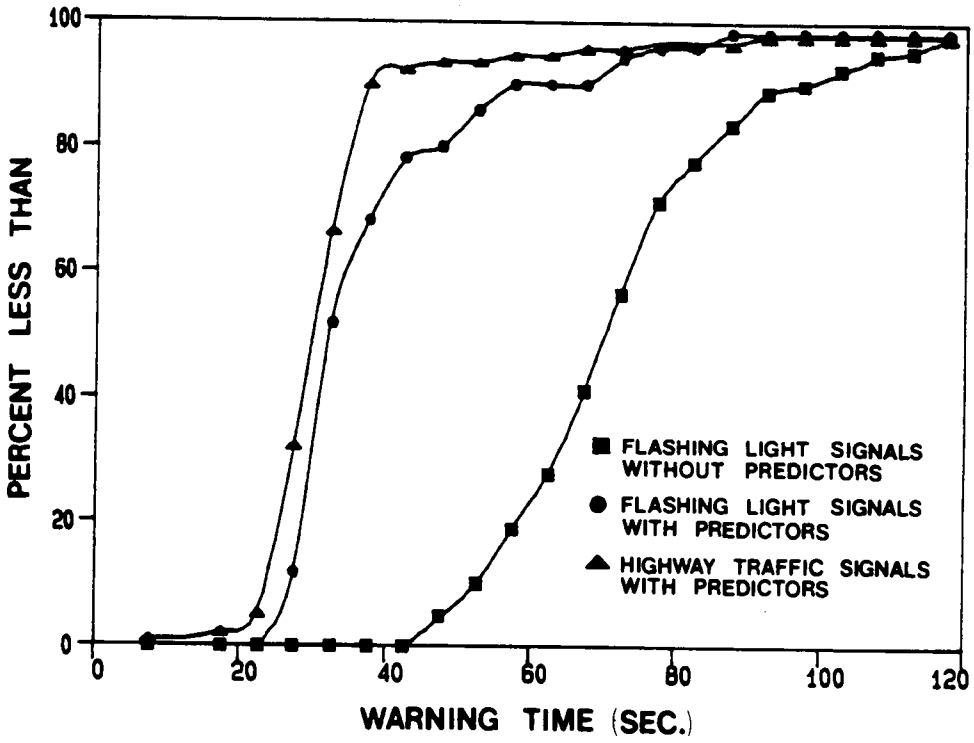


FIGURE 60. FREQUENCY AND CUMULATIVE FREQUENCY DISTRIBUTIONS OF OBSERVED WARNING TIMES AT THE CEDAR DRIVE CROSSING

installation of the predictors greatly improved the level-of-service of the active warning devices at the Cedar Drive crossing, and as a result should have improved driver behavior at the crossing by reducing the number of dangerous and/or illegal maneuvers that took place.

Clearance Time. Clearance time was defined as the difference in time between the last vehicle to cross and the train's arrival at the crossing. As neither the predictors nor the highway traffic signals physically blocked the road, their installation separately would probably not result in an increase in average clearance times; however, because the predictors significantly shortened the average warning time at the crossing, they in combination with the traffic signal may give enough credibility to the warning devices to increase average clearance times at the crossing. If in fact this does occur, the additional temporal separation between the cars and trains would be a definite safety benefit. It should be noted that this benefit is expected to be the result of both the predictors and highway traffic signal being installed at the Cedar Drive crossing.

Clearance times were only recorded for those train arrivals wherein a vehicle arrived at the crossing between the activation of the flashing light signals and the train's arrival at the crossing, i.e., there was an opportunity for a vehicle to cross in front of the train. Thus, the number of clearance times observed will always be less than or equal to the number of train arrivals. As shown in Table 33, there were 82 clearance times observed in the first before study (two-quadrant flashing lights without predictors), 39 clearance times observed in the

TABLE 33. CLEARANCE TIMES AT THE CEDAR DRIVE CROSSING[1]

	Summary Statistics						Clearance Times (seconds)				
	Sample Size[2]	Mean (seconds)	Standard Deviation	Percent <20 Seconds	Percent <10 Seconds	Range (seconds)	<10	10-20	20-30	>30	Total
Flashing Light Signals without Predictors											
Day	53	15.7	13.2	79.3	37.7	4-73	--	--	--	--	--
Night	30	28.2	15.0	31.0	10.3	6-66	--	--	--	--	--
Total	83	20.1	15.0	62.6	27.7	4-73	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	23	29	15	16	83
Percent of Total Arrivals	--	--	--	--	--	--	27.7	34.9	18.1	19.3	
Cumulative Percentage	--	--	--	--	--	--	27.7	62.6	80.7	100.0	
Flashing Light Signals with Predictors											
Day	19	16.2	5.8	73.7	15.8	7-28	--	--	--	--	--
Night	20	26.3	18.9	50.0	5.0	6-96	--	--	--	--	--
Total	39	21.4	14.9	61.5	10.3	6-96	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	4	20	10	5	39
Percent of Total Arrivals	--	--	--	--	--	--	10.3	51.3	25.6	12.8	
Cumulative Percentage	--	--	--	--	--	--	10.3	61.5	87.2	100.0	
Highway Traffic Signals with Predictors											
Day	20	20.7	8.4	45.0	15.0	5-34	--	--	--	--	--
Night	9	21.4	10.5	55.6	11.1	10-45	--	--	--	--	--
Total	29	20.9	8.9	48.3	13.8	5-45	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	4	10	11	4	29
Percent of Total Arrivals	--	--	--	--	--	--	13.8	34.5	37.9	13.8	
Cumulative Percentage	--	--	--	--	--	--	13.8	48.3	86.2	100.0	

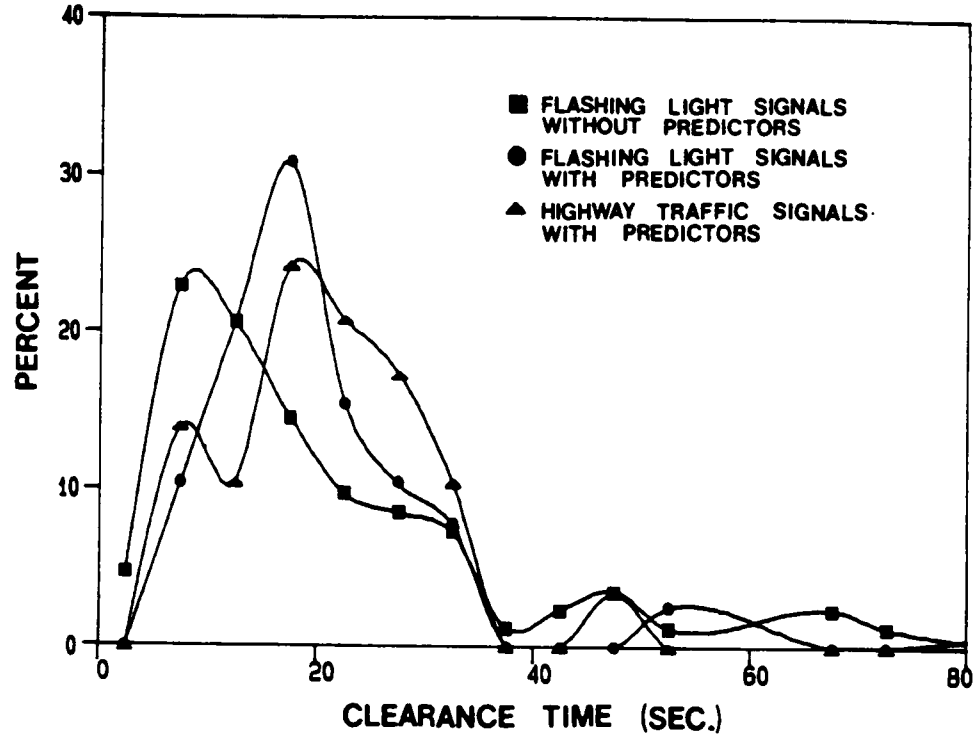
[1]Time between the last vehicle to cross and the train's arrival at the crossing.

[2]Includes only those observations in which vehicles were pesent before the train's arrival.

second before study (two-quadrant flashing light signals with predictors), and 29 clearance times observed in the after study (highway traffic signals with predictors). As with the warning time data set, the total data from each study was subdivided into observations that occurred during the day and observations that occurred during the night so as to insure that similar train and traffic volume conditions were compared. These two subsets, together with the total data set, were then analyzed.

The mean clearance times from the total data sets were approximately the same for all three studies. The Kruskal-Wallis test for two or more independent, continuously distributed populations (49) confirmed that these differences were not statistically significant at the 95 percent confidence level. However, there was a significant difference (at the 98 percent confidence level) between the daytime data sets from the two before studies and the daytime data set from the after study. This means that installation of the predictors had no effect on the daytime clearance times observed at the crossing. However, installation of the highway traffic signals in combination with the predictors did lengthen the clearance times observed in the daytime data sets.

The frequency and cumulative frequency distributions of clearance times from the three data sets are shown in Figure 61. Interestingly, the Mann-Whitney test indicated a statistically significant difference at the 99 percent confidence level between the day and night data sets from the two before studies. There was not a difference between the day and night data sets from the after study. This means that the clearance times observed were different between day and night operation for both



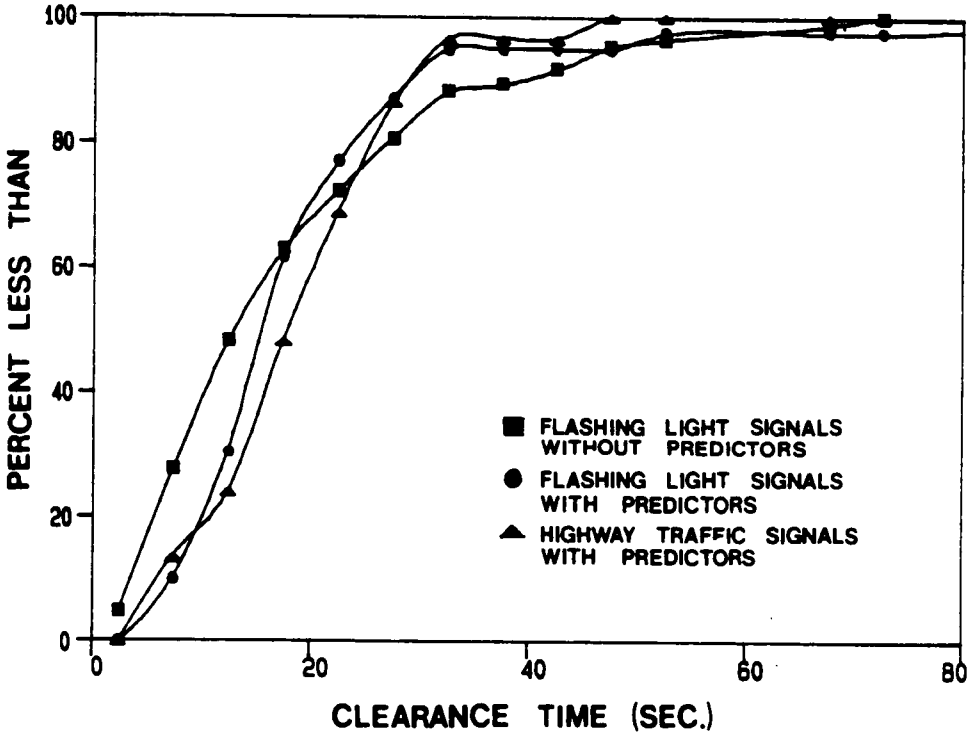


FIGURE 61. FREQUENCY AND CUMULATIVE FREQUENCY DISTRIBUTIONS OF OBSERVED CLEARANCE TIMES AT THE CEDAR DRIVE CROSSING

the flashing light signals without predictor study and the flashing light signals with predictor study; however, there was no difference between day and night operation for the highway traffic signal with predictor study.

As at the other two crossings, it was hypothesized that even though warning times have a major influence on driver behavior, a small percentage of drivers would exhibit undesirable (dangerous or illegal) behavior no matter how short the warning times were. Therefore, it was expected at the Cedar Drive crossing that there would be many dangerous and/or illegal maneuvers made during the first before study when the warning times were long, and there would be much fewer dangerous and/or illegal maneuvers made when the warning times were shorter as in the second before study and the after study.

By using the four categories of driver performance and associated clearance times defined in Section VII, almost 30 percent of the clearance times in the first before study would be classified as risky whereas only about 10 to 15 percent of the clearance times observed in the second before study and the after study would be classified as risky. Additionally, over 60 percent of the observed clearance times in the first two before studies would be classified as either risky or aggressive, but only about 50 percent of the observed clearance times in the after study would be classified as risky or aggressive. This seems to indicate that the shorter warning times that resulted from the installation of the predictors were very successful in eliminating or greatly reducing risky behavior at the Cedar Drive crossing, and the installation of the highway traffic signals in combination with the

predictors was able to further reduce the aggressive behavior exhibited by motorists at the Cedar Drive crossing.

Approach Measures

Speed Profiles. The average speed at which drivers approach the Cedar Drive crossing whenever the warning devices are activated may or may not be different after the installation of either the predictors or the highway traffic signals with predictors. Hypothetically, the predictors should have had no effect on approach speeds and the greater conspicuity of the white bar strobes and the additional credibility of the highway traffic signal should cause drivers to see the warning devices quicker and begin decelerating sooner. However, as mentioned previously, even if this behavioral change occurs it may not be large enough to be statistically significant, and even if it were, it still might not be large enough to be meaningful from a practical point of view.

In order to compare characteristics of similar vehicles, approach speed profiles for the first vehicle to stop at the crossing in each of the two before studies as well as the after study were plotted as shown in Figure 62. Each data point represents average speeds over 50-foot sections of roadway in advance of the stop bar at the crossing, and are plotted at the midpoint of the section. As mentioned in Section V, data in the range of 50-200 feet from the stop bar were obtained from Camera 1, in the range of 250 feet to 450 feet from the stop bar from Camera 2, and in the range from 500 to 700 feet in advance of the stop bar from Camera 3. However, as with the other crossings, there was such a small

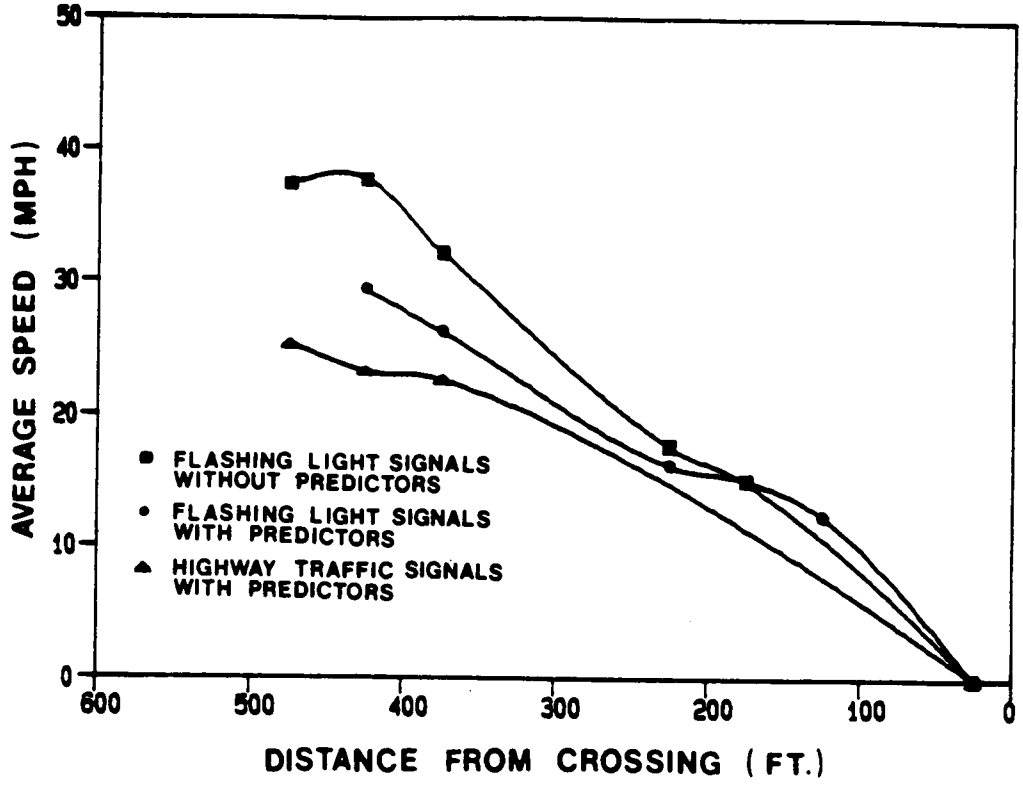


FIGURE 62. AVERAGE APPROACH SPEED PROFILES FOR VEHICLES IN ADVANCE OF THE CEDAR DRIVE CROSSING

amount of available data from Camera 3 that a significant number of average speeds could not be calculated at the far distances. Additionally, Camera 2 was the only one used in the after study. Therefore, only data from the first two cameras in the two before studies and data from the second camera in the after study are shown in Figure 62.

Several observations can be made concerning the average approach speed profiles in the before and after data sets. First, the average speeds in the first before study were about five miles per hour faster than they were in the second before study and as expected about ten miles per hour faster than they were in the after study. This indicates that the highway traffic signals with the white bar strobes in front of the red lenses may have been visible farther from the crossing than were the flashing light signals. It is interesting to note that in all three studies, the first vehicle to stop began slowing about 450 feet from the stop bar and that stopping vehicles did so in a safe, gradual, and consistent manner. In addition, the resultant speed profiles appeared to pose no safety problems for approaching motorists.

Perception-Brake Reaction Time and Deceleration. Perception-brake reaction time was defined as the difference in time between activation of the flashing light signals and the illumination of the vehicle's brake lights. It was expected that the greater conspicuity and additional credibility of the highway traffic signals would cause motorists to brake quicker and as a result slow down more gradually. It was also expected that if these differences did exist, they would be small and very difficult to measure. To compound this problem, braking for a

flashing light signal is an unexpected event and does not represent a pressure situation to a driver unless a train is also visible, i.e., drivers know that there is at least some length of time before a train's arrival at the crossing; thus, driver response to activation of a flashing light signal will be relatively long and probably highly variable.

Average perception-brake reaction times in response to the activation of either the flashing light signals or onset of the traffic signal's red indication were 26.6 seconds in the first before study, 17.1 seconds in the second before study, and 19.2 seconds in the after study. In all three cases the standard deviation was almost as large or larger than the mean. These differences appear significant; however, the Kruskal-Wallis test indicated that they were not statistically significant at the 95 percent confidence level. In other words, the variability in the brake time data precluded being able to find any significant differences that might exist. These data do confirm the premise that braking in response to either a flashing light signal or a highway traffic signal at a railroad highway grade crossing did not represent a pressure situation (i.e., long reaction times) and, because of this, was highly variable (i.e., large standard deviations). As at the other crossings, an additional complication with measuring brake reaction times was the difficulty in determining whether the vehicle of interest was braking in response to the activation of the warning device, a slower moving vehicle ahead of it, or simply because of the roughness of the crossing itself.

Safety Measures

Violations. At a crossing with flashing light signals, violations were defined as motorists that could reasonably stop in response to the warning device, failing to do so. However, as mentioned previously, because of the difficulty in determining whether or not a vehicle came to a stop, violations were not counted for the flashing light signal systems. At a crossing with highway traffic signals, violations were defined as a motorist driving through the crossing while the signal displayed a red indication, i.e., a violation of the motor vehicle laws. As the highway traffic signals did not physically block the roadway, their installation was not expected to eliminate violations at the Cedar Drive crossing; however, installation of the predictors and/or installation of the predictors in combination with the highway traffic signals may provide enough credibility in the warning devices to significantly reduce the number of violations at the crossing. Unfortunately, because of the different definitions, a direct comparison of the violation rates between the two conditions was not possible.

When the highway traffic signal was installed at the Cedar Drive crossing, the average and maximum number of motorists per train arrival who "ran the red" (illegal behavior) was 0.68 and six respectively. These statistics were based on the 78 observations where vehicles were in the crossing area prior to the train's arrival. Of this total there were 50 observations in which no motorists behaved illegally, 15 observations in which one motorist behaved illegally, and only 13 observations in which more than one motorist behaved illegally. Although not

comparable, it is interesting to note that at two crossings with approximately the same vehicular traffic volumes, the rate and frequency of violations at the crossing with highway traffic signals (Cedar Drive) were much lower than they were at the crossing with two-quadrant gates (Cherry Street). However, it should also be noted that the highway traffic signals were operating at Level-of-Service "B" whereas the two-quadrant gates were operating at Level-of-Service "D." Thus, it is not clear whether the difference in driver behavior is a result of differences in warning devices or differences in their operational level-of-service.

Vehicles Crossing. The average number of vehicles crossing between activation of either the flashing light signals or the traffic signal's clearance interval and the train's arrival at the crossing are shown in Table 34. As there was a statistically significant difference in the warning times observed during the three studies, it was hypothesized that there would be a significant difference in the number of vehicles crossing. The Kruskal-Wallis test verified this premise at the 99 percent confidence level for the day, night, and total data sets, i.e., a significant reduction in the number of vehicles crossing was realized as a result of the predictors being installed. In addition, the predictors in combination with the highway traffic signal reduced the average number of vehicles crossing per train arrival from four to two. Thus, the additional credibility of the highway traffic signal further reduced the number of vehicles that crossed in front of an oncoming train.

TABLE 34. VEHICLES CROSSING AT THE CEDAR DRIVE CROSSING[1]

	Summary Statistics						Crossings (vehicles)						
	Sample Size[2]	Mean (vehicles)	Standard Deviation	Percent >0 Crossing	Percent >1 Crossing	Range (vehicles)	0	1	2	3	4	>4	Total
Flashing Light Signals without Predictors													
Day	53	13.38	7.74	100.0	98.1	1-40	--	--	--	--	--	--	--
Night	30	6.40	6.28	97.6	86.7	0-24	--	--	--	--	--	--	--
Total	83	10.86	7.91	98.6	94.0	0-40	--	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	1	4	5	8	2	63	83
Percent of Total Arrivals	--	--	--	--	--	--	1.2	4.8	6.0	9.7	2.4	75.9	
Cumulative Percentage	--	--	--	--	--	--	1.2	6.0	12.0	21.7	24.1	100.0	
Flashing Light Signals with Predictors													
Day	21	3.86	3.34	90.5	71.4	0-12	--	--	--	--	--	--	--
Night	24	2.92	2.50	83.3	62.5	0-9	--	--	--	--	--	--	--
Total	45	3.35	2.92	86.7	66.7	0-12	--	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	6	9	6	6	7	11	45
Percent of Total Arrivals	--	--	--	--	--	--	13.3	20.0	13.3	13.3	15.7	24.4	
Cumulative Percentage	--	--	--	--	--	--	13.3	33.3	46.6	59.9	75.6	100.0	
Highway Traffic Signals with Predictors													
Day	59	0.80	1.47	33.3	20.30	0-7	--	--	--	--	--	--	--
Night	19	0.53	0.61	47.4	5.3	0-2	--	--	--	--	--	--	--
Total	78	0.73	1.32	37.2	16.7	0-7	--	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	49	16	6	4	0	3	78
Percent of Total Arrivals	--	--	--	--	--	--	62.8	20.5	7.7	5.1	0.0	3.9	
Cumulative Percentage	--	--	--	--	--	--	62.8	83.3	91.0	96.1	96.1	100.0	

[1]Vehicles crossing after either activation of the flashing light signals or the traffic signal changing to yellow and the train's arrival at the crossing.

[2]Includes only those observations in which vehicles were present before the train's arrival.

The effects of warning times on the number of vehicles crossing while the flashing light signals were activated or the traffic signals were red is shown in Table 35. Even though the total observations are not distributed evenly throughout the warning time categories, there is clearly an identifiable trend, i.e., the longer the warning time, the greater the number of vehicles that will cross while the warning devices are activated. This relationship is illustrated in Figure 63. These results were expected; however, what was not expected were the differences between the flashing light signals with and without predictors. For example, in the without predictor study, warning times in the 40 to 60 second range resulted in an average of 9.3 vehicles crossing per train arrival whereas in the with predictor study, the same warning times resulted in an average of 4.8 vehicles crossing per train arrival. This difference is attributed to the shorter and more consistent warning times in the with predictor study. In other words, simply installing the predictors at the Cedar Drive crossing improved the warning device's operation from Level-of-Service "F" to Level-of-Service "C" and resulted in fewer drivers crossing in front of oncoming trains for the same range of warning times.

Interestingly, in the with predictor study, the average number of vehicles crossing compares favorably to the results from the Ebenezer Road crossing--if the warning time is less than 30 seconds, an average of one driver will cross in front of an oncoming train whereas if the warning time is as long as 50 seconds, an average of three to four vehicles will cross in front of the train. This is not altogether surprising as the active warning devices at both the Ebenezer Road

TABLE 35. EFFECTS OF WARNING TIMES ON NUMBER OF VEHICLES CROSSING AT THE CEDAR DRIVE CROSSING

Study	Warning Time (Sec.)[1]	Observed Train Arrivals[2]	Average No. Crossing (Per Arrival)
Flashing Light Signals without Predictors	<20	-	-
	20-30	-	-
	30-40	-	-
	40-50	4	10.00
	50-60	11	9.17
	60-90	53	9.24
	>90	15	19.00
		Total 83	
Flashing Light Signals with Predictors	<20	-	-
	20-30	5	1.60
	30-40	24	2.75
	40-50	6	4.33
	50-60	5	4.40
	60-90	4	6.75
	>90	1	2.00
		Total 45	
Highway Traffic Signals with Predictors	<20	1	0.00
	20-30	24	0.21
	30-40	46	1.00
	40-50	2	1.00
	50-60	1	1.00
	60-90	1	0.00
	>90	3	1.00
		Total 78	

[1]Time between activation of flashing lights and train's arrival at the crossing.

[2]Includes only those observations in which vehicles were present.

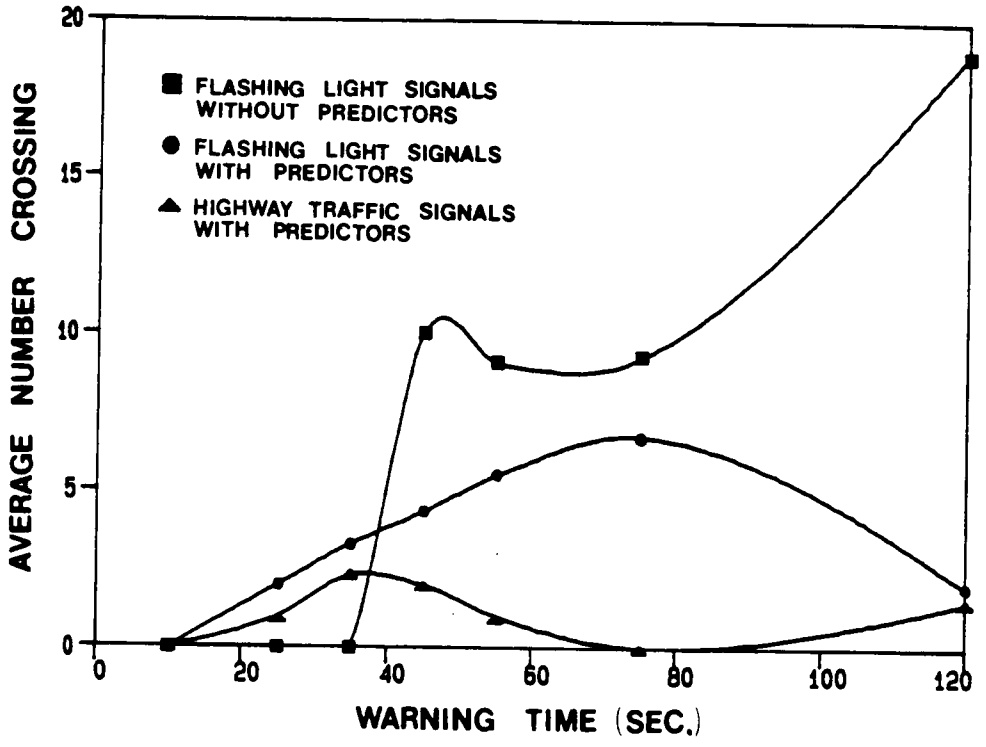


FIGURE 63. AVERAGE NUMBER OF VEHICLES CROSSING AS A FUNCTION OF WARNING TIME AT THE CEDAR DRIVE CROSSING

crossing and the Cedar Drive crossing with predictors were exposed to similar traffic volumes and were both operating at Level-of-Service "B" or "C". Thus, it appears that traffic volume and the level-of-service at which the flashing light signals are operating may be a good indication of the average number of vehicles that will cross in front of an oncoming train.

Crossings Less Than 20 Seconds (CL20). Vehicles crossing within 20 seconds of a train's arrival at the crossing have previously been defined as an indication of aggressive behavior, i.e., there is some, but not much, room for driver and/or vehicular error. Although such behavior is not illegal, it represents those drivers that choose to cross within the 20-second minimum warning time presently required by the MUTCD (12). Installation of the predictors may have no effect on this driver performance measure as nothing was changed at the crossing itself; however, installation of the predictors in combination with the highway traffic signal should have an effect because of the traffic signals additional credibility.

As shown in Table 36, the average number of vehicles crossing within 20 seconds of the train's arrival at the Cedar Drive crossing was noticeably lower in both studies where the predictors were installed. The Kruskal-Wallis test (49) indicated that these reductions were statistically significant for both the day and total data sets at the 99 percent confidence level. Thus, as expected, installation of the predictors and of the predictors in combination with the highway traffic signals significantly reduced the number of CL20's at the crossing.

TABLE 36. CL20'S AT THE CEDAR DRIVE CROSSING[1]

	Summary Statistics						CL20s (vehicles)					
	Sample Size[2]	Mean (vehicles)	Standard Deviation	Percent >0 Violations	Percent >1 Violations	Range (vehicles)	0	1	2	3	>3	Total
Flashing Light Signals without Predictors												
Day	53	2.34	1.74	79.2	67.9	0-6	--	--	--	--	--	--
Night	30	0.83	1.60	34.5	17.3	0-6	--	--	--	--	--	--
Total	83	1.82	1.84	63.9	50.6	0-6	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	30	11	13	12	17	83
Percent of Total Arrivals	--	--	--	--	--	--	36.1	13.3	15.7	14.5	20.4	
Cumulative Percentage	--	--	--	--	--	--	36.1	49.4	65.1	79.6	100.0	
Flashing Light Signals with Predictors												
Day	21	0.95	0.86	66.7	33.8	0-3	--	--	--	--	--	--
Night	24	0.63	1.10	41.7	8.3	0-5	--	--	--	--	--	--
Total	45	0.78	1.00	53.3	15.5	0-5	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	21	17	5	1	1	45
Percent of Total Arrivals	--	--	--	--	--	--	46.7	37.8	11.1	2.2	2.2	
Cumulative Percentage	--	--	--	--	--	--	46.7	84.5	95.6	97.8	100.0	
Highway Traffic Signals with Predictors												
Day	59	0.24	0.63	15.3	6.8	0-3	--	--	--	--	--	--
Night	19	0.26	0.45	26.3	0.0	0-1	--	--	--	--	--	--
Total	78	0.24	0.59	18.0	5.2	0-3	--	--	--	--	--	--
Observed Train Arrivals	--	--	--	--	--	--	64	10	3	1	0	78
Percent of Total Arrivals	--	--	--	--	--	--	82.0	12.8	3.9	1.3	0.0	
Cumulative Percentage	--	--	--	--	--	--	82.0	94.8	98.7	100.0	100.0	

[1]Vehicles crossing within 20 seconds of the train's arrival at the crossing.

[2]Includes only those observations in which vehicles were pesent before the train's arrival.

There was no difference in the average CL20 rates for any of the nighttime data sets.

A frequency distribution of the observed CL20's at the Cedar Drive crossing is also shown in Table 36. In the first before study (i.e., flashing light signals without predictors), there were 29 observations with no CL20's, 11 observations with one CL20, and 42 observations with two or more CL20's. The number of observations in each category were smaller and the percentages different in the two studies with predictors present. A Pearson's chi-square statistic calculated from a three by three contingency table (three studies by three CL20's rate categories) substantiates the fact that these differences (i.e., fewer multiple CL20's) were significant at the 95 percent confidence level. The most effective warning device as far as preventing CL20's was the predictors in combination with the highway traffic signal--82 percent of the observations in the after data set resulting in no CL20's.

The effects of warning times on the CL20 rates at the Cedar Drive crossing are shown in Table 37. As mentioned previously, and as shown in the table, the distribution of the observed warning times was significantly different between the first before study and the two studies with predictors, i.e., flashing light signals with predictors and highway traffic signals with predictors. Notice that the average CL20 rate was approximately 1.82 before predictors were installed, 0.78 after predictors were installed, and 0.24 after both predictors and traffic signals were installed; however, there does not appear to be a relationship between warning time and CL20 rates. It should be noted that in the 30 to 40 second warning time range for the flashing light signal with

TABLE 37. EFFECTS OF WARNING TIMES ON CL20 RATES AT THE CEDAR DRIVE CROSSING

Study	Warning Time (Sec.)[1]	Observed Train Arrivals[2]	Average CL20's (Per Arrival)
Flashing Light Signals without Predictors	<20	-	-
	20-30	-	-
	30-40	-	-
	40-50	4	3.75
	50-60	11	2.45
	60-90	53	1.63
	>90	15	1.53
		Total 83	
Flashing Light Signals with Predictors	<20	-	-
	20-30	5	0.80
	30-40	24	0.83
	40-60	6	1.00
	50-60	5	0.60
	60-90	4	0.50
	>90	1	0.00
		Total 45	
Highway Traffic Signals with Predictors	<20	1	0.00
	20-30	24	0.17
	30-40	46	0.33
	40-50	2	0.00
	50-60	1	0.00
	60-90	1	0.00
	>90	3	0.00
		Total 78	

[1]Time between activation of flashing lights and train's arrivals at the crossing.

[2]Includes only those observations in which vehicles were present.

predictor study, there were approximately 0.83 CL20's per train arrival, and whenever traffic signals were installed, the CL20 rate in this warning time range was approximately 0.33. This seems to indicate that highway traffic signals with predictors are more effective in reducing CL20's (i.e., aggressive behavior) than are standard active warning devices currently found at railroad-highway grade crossings.

Crossings Less Than 10 Seconds (CL10). Vehicles crossing within 10 seconds of a train's arrival at the crossing have previously been defined as an indication of risky behavior, i.e., there is little room for either driver or vehicular error. Although not illegal at a flashing light signal, such behavior intuitively increases the likelihood of an accident occurring. It was anticipated that installation of the predictors might reduce this type of behavior by providing shorter and more consistent warning times, i.e., increased credibility of the warning devices. Furthermore, it was anticipated that the additional credibility of the highway traffic signal might further reduce the number of CL10's crossing within 10 seconds of the train's arrival (i.e., risky behavior).

As shown in Table 38, 29 CL10's (15 single CL10's and seven multiple CL10's) were observed at the Cedar Drive crossing in the first before study--25 during the day and four during the night, i.e., 29 motorists crossed the tracks within 10 seconds of the train's arrival. In fact, in seven different cases, at least two motorists crossed the tracks within 10 seconds of the train's arrival. A Pearson's chi-square statistic calculated from a three by three contingency table (three

TABLE 38. CL10'S AT THE CEDAR DRIVE CROSSING[1]

Summary Statistics	Flashing Light Signals without Predictors			Flashing Light Signals with Predictors			Highway Traffic Signals with Predictors		
	Day	Night	Total	Day	Night	Total	Day	Night	Total
Sample Size[2]	53	30	83	21	24	45	59	19	78
Mean (vehicles)	0.53	0.13	0.39	0.19	0.08	0.13	0.05	0.05	0.05
Standard Deviation	0.77	0.43	0.69	0.51	0.41	0.46	0.22	0.22	0.22
Percent with Conflicts	35.9	10.0	26.5	14.3	4.2	8.9	5.1	5.3	5.1
Range (vehicles)	0-3	0-2	0-3	0-2	0-2	0-2	0-1	0-1	0-1
0 CL10s/Arrival	34	27	61	18	23	41	56	18	74
1 CL10s/Arrival	13	2	15	2	0	2	3	1	4
2 CL10s/Arrival	6	1	7	1	1	2	0	0	0

[1]Vehicle's crossing within 10 seconds of the train's arrival.

[2]Includes only those observations in which vehicles were present prior to the train's arrival.

studies by three CL10 categories) indicated that the observed CL10's in the first before study (i.e., flashing light signals without predictors) and the two studies with predictors (i.e., flashing light signals with predictors and highway traffic signals with predictors) were significantly different at the 95 percent confidence level. This means that installation of the predictors appears to have been successful in reducing the amount of risky behavior that took place at the crossing. Unfortunately, there was such a small number of observed CL10's in the two studies with predictors that meaningful statistical comparison could not be made between them. Therefore, the premise that the additional credibility of the highway traffic signal might further reduce the number of CL10's could not be tested.

One observation from this data set is that the CL10 rates and percentages for the flashing light signals without predictors study were more than twice as high at Cedar Drive than they were at Ebenezer Road and more than five times as high as they were at Cherry Street. This large amount of risk-taking behavior is a direct result of the poor level-of-service at which the warning devices at Cedar Drive were operating, i.e., the worse the warning device's operation, the more risks a motorist will take. To substantiate this hypothesis, note that when the predictors were installed at the Cedar Drive crossing, so as to improve the level-of-service of the active warning devices, the observed CL10 rates (i.e., risky behavior) were comparable to those at Ebenezer Road. Interestingly, the additional installation of the highway traffic signal reduced the number of observed CL10's to a rate comparable to that

observed at the Cherry Street crossing when it was protected by two-quadrant flashing light signals with automatic gates.

Summary

The existing active warning system at the Cedar Drive Crossing (i.e., flashing light signals without predictors) was originally operating at Level-of-Service "F". Installation of predictors and the predictors in combination with the highway traffic signals at this crossing improved the operation of the active warning devices to "Level-of-Service" "B" or "C" (i.e., at an acceptable level to most motorists). As the intent of both the predictors and also the highway traffic signal was to provide additional credibility and respect for the active warning devices, performance measures such as clearance times, violations and vehicles crossing were expected to improve. The resultant analysis concluded that clearance times increased and risky behavior decreased when either the predictors or the predictors in combination with the highway traffic signals were installed, thus resulting in a definite safety benefit. Performance measures such as speeds, reaction times, and deceleration levels failed to indicate a change of driver behavior. This was not surprising as any anticipated changes were small.

X. COMPARISONS AND APPLICATIONS OF THE THREE ACTIVE WARNING DEVICES

Based on the results of the field studies, all three of the innovative active warning devices for use at the railroad-highway grade crossings proved feasible both from a technical and practical standpoint. In addition, all three of the systems were seemingly well accepted and understood by the motoring public as there were no accidents, complaints, and/or inquiries while the innovative devices were in operation. Two of the warning systems, the four-quadrant flashing light signals and gates with skirts and the highway traffic signals with white bar strobes in front of all red lenses, were effective in improving driver behavior at the crossings where they were installed (i.e., the frequencies of illegal and dangerous maneuvers were reduced). The third system, four-quadrant flashing light signals with overhead strobes, had no measurable effect on driver behavior at the crossing where it was installed; however, as will be discussed later, it shows some promise for limited applications.

This section compares the effectiveness of the various active warning devices that were evaluated by this research. Presented first is a comparison of driver performance measures both before and after the new devices were installed. Second, cost estimates for installing, operating, and maintaining the three innovative devices and for "retrofitting" various percentages of existing crossings with the innovative devices are discussed. Finally, applications wherein the innovative devices show the greatest potential for improving safety are discussed.

Driver Performance Measures

As described in Sections VII, VIII, and IX, driver behavior data were obtained for three crossings in the Knoxville, Tennessee area both before and after innovative active warning devices were installed. Data collected include warning and clearance times at the crossing; speed profiles, brake reaction times, and maximum deceleration levels approaching the crossing; and, average violation, and vehicle crossing rates per train arrival at the crossing. There were no discernible differences in speed profiles, perception-brake reaction times, and maximum deceleration levels in response to any of the new devices; however, as discussed in the following sections there were significant differences in the other performance measures.

Crossing Measures. The crossing measures of interest were warning and clearance times, where warning time was defined as the time between activation of the flashing light signals and the train's arrival at the crossing, and clearance time was defined as the time between the last vehicle to cross and the train's arrival at the crossing. Average values for each of the eight individual studies at the three crossings are shown in Table 39. Also included in the table are the estimated levels-of-service at which the warning devices were operating during each study.

In regard to warning times, installation of the new warning devices had no measurable effect except for the two studies which added predictors to the existing train detection system. In those studies (i.e., Cedar Drive with predictors) the average warning time was reduced by

TABLE 39. COMPARISON OF DRIVER PERFORMANCE MEASURES IN RESPONSE TO VARIOUS ACTIVE WARNING DEVICES

Type of Warning Device	Warning Time[1] Mean	LOS	Clearance[2] Time (sec)	Violations[3] Mean/Frequency		Crossings[4] Mean/Frequency		CL20's[5] Mean/Frequency		CL10's[6] Mean/Frequency	
Cherry Street Crossing											
Two-Quadrant Gates	57.6	D	24.5	2.60	83.9	4.00	96.8	0.6	40.9	0.05	5.4
Four-Quadrant Gates with Skirts	56.1	D	48.9	0.00	0.0	1.13	54.7	0.0	0.0	0.00	0.0
Ebenezer Road Crossing											
Flashing Light Signals	40.8	C	20.5	-	-	3.43	88.6	1.14	55.3	0.11	10.6
Flashing Light Signals with Strobes (Spring 1986)	36.7	B	19.1	-	-	2.50	90.0	0.85	50.0	0.05	5.0
Flashing Light Signals with Strobes (Summer 1986)	41.6	C	16.3	-	-	4.02	91.8	1.47	71.4	0.22	18.4
Cedar Drive Crossing											
Flashing Light Signals without Predictors	75.2	F	20.1	-	-	10.86	98.8	1.82	63.9	0.39	26.5
Flashing Light Signals with Predictors	41.7	C	21.4	-	-	3.35	86.7	0.78	53.3	0.13	8.9
Highway Traffic Signals with Predictors	36.3	B	20.9	0.68	35.9	0.73	37.2	0.24	18.0	0.05	5.1

[1]Time between activation of the flashing light signals and the train's arrival at the crossing.

[2]Time between the last vehicle to cross and the train's arrival at the crossing.

[3]Vehicles driving around lowered gate arms or crossing after the traffic signal changed to red.

[4]Vehicles crossing between activation of the active warning devices and the train's arrival at the crossing.

[5]Vehicles crossing within 20 seconds of the train's arrival at the crossing.

[6]Vehicles crossing within 10 seconds of the train's arrival at the crossing.

almost 50 percent and was comparable to the average warning time for the three studies at the Ebenezer Road crossing. In other words, installing predictors at the Cedar Drive crossing eliminated the excess warning times resulting from a fixed-distance warning system having to handle both thru trains at 30 miles per hour and switching trains at five miles per hour, and made its operation comparable to the Ebenezer Road crossing where a fixed-distance warning system had to handle only thru trains at 50 miles per hour. Interestingly, both studies at the Cherry Street crossing where motion sensors existed to partially compensate for switching trains had significantly shorter warning times than the Cedar Drive study without predictors, but significantly greater warning times than the other five studies. Thus, it appears that although motion sensors can reduce excessive warning times caused by switching trains, predictors are necessary if the warning devices are to be operated at an acceptable level-of-service.

In regard to clearance times, installation of the new warning devices had no effect except for the Cherry Street study where the four-quadrant gates with skirts completely blocked the roadway at least 30 seconds prior to the train's arrival at the crossing. In this case, the average clearance time was more than double the before condition (i.e., two-quadrant gates). Note that the average clearance times for the five studies at the other two crossings were all approximately 20 seconds, which coincidently is the minimum warning time required by the MUTCD (12); however, a number of drivers accepted shorter clearance times and violated this requirement. Interestingly, the average clearance times with two-quadrant gates were also very close to 20 seconds. Thus, even

though the two-quadrant gates at the Cherry Street crossing partially blocked the roadway, they had about the same effect on the average driver's clearance time as did the flashing light signals or highway traffic signals at the other two crossings.

Safety Measures. As no car-train accidents occurred during any of the studies, surrogate safety measures such as violations (i.e., illegal behavior), and vehicles crossing (i.e., dangerous behavior), were collected for each of the eight studies. As each of the basic devices placed different requirements on approaching motorists, violations were defined as driving around lowered gate arms at the Cherry Street crossing, crossing without stopping at crossings with flashing light signals, and running the red light at a highway traffic signal; however, because of the difficulty in determining whether or not vehicles came to a complete stop, violations were not counted at crossings with flashing light signals.

Because of the differences in definitions, violations were not readily comparable between studies; however, it should be noted that with the exception of the four-quadrant gates with skirts which physically prohibited violations, installation of the highway traffic signal resulted in violation rates of 0.68 vehicles per train arrival, and the two-quadrant gates resulted in violation rates of 2.6 vehicles per train arrival.

Vehicles crossing was defined as crossing between activation of the flashing light signal and the train's arrival at the crossing. This performance measure was subdivided into those vehicles crossing within

10 seconds (CL10's) and those vehicles crossing within 20 seconds (CL20's) of the train's arrival at the crossing. Average values and frequencies of occurrence for each of these measures are presented in Table 39.

In terms of number of vehicles crossing, the lowest rate observed was 0.73 per train arrival during the highway traffic signal study. For four of the five flashing light signal studies, the average crossing rates ranged from 2.50 to 4.02 per train arrival. The one exception was the Cedar Drive study without predictors where the average crossing rate was 10.86 per train arrival, where not surprisingly the longest warning times were observed. It should also be noted that in four of the five studies with flashing light signals, the average number of crossings within 20 seconds of the train's arrival were between 0.78 and 1.47. Again, the exception was the Cedar Drive study without predictors. Similar trends were observed when comparing the CL10 rates (risky behavior) in that the without predictor study had the highest rate; however, the highway traffic signal did not have the lowest rate. Thus, even though the highway traffic signal was able to reduce the average number of vehicles crossing, those that did cross were willing to take the same risks as at a flashing light signal. However, the 30 to 50 percent reduction in crossings is still a major safety improvement.

Cost Comparison

As cost considerations govern whether and where the innovative active warning devices are advantageous, the life cycle costs for the two existing and the three innovative devices evaluated in this study

were determined. As shown in Table 40, these data (55, 56) include installation and/or upgrading costs as well as operating and maintenance costs. Installation includes costs for pre-engineering, labor, materials, equipment, and miscellaneous expenses. Operating and maintenance costs include power consumption, routine service checks, minor repairs, and battery maintenance. All costs have been converted to 1987 dollars and assume a useful life for the warning device of 30 years, with a 10 percent salvage value at the end of that period and a five percent annual interest rate.

If it is assumed that the innovative devices described in Table 40 would only be installed at crossings where active warning devices already existed, the costs shown could be referred to marginal costs, i.e., those costs incurred over and above the cost of providing whatever standard active warning device would normally be used. For example, marginal costs of four-quadrant flashing light signals and gates with skirts would be those costs over and above the costs of providing standard two-quadrant flashing light signals and automatic gates. The marginal costs of the four-quadrant flashing light signals with strobes would be over and above the costs of providing standard two-quadrant flashing light signals. However, marginal costs for the highway traffic signal would include the costs to install, operate, and maintain the traffic signal installation as it is completely replacing a standard two-quadrant flashing light signal system.

Using the above definition of marginal cost and the average driver performance measures developed in this study to estimate benefits, Heathington, Fambro, and Richards (55) have determined benefit/cost

TABLE 40. LIFE CYCLE COSTS FOR ACTIVE WARNING DEVICES AT RAILROAD-HIGHWAY GRADE CROSSINGS

Active Warning Device	Installation Cost ($1,000)	Maintenance Cost ($1,000)	Total Cost ($1,000)
Highway Traffic Signal	11.2	21.5	32.7
Flashing Light Signals	42.3	23.0	65.3
Flashing Light Signals Upgraded to Flashing Light Signals with Strobes	19.2	6.9	26.1
Two-Quadrant Gates	63.8	37.8	101.6
Two-Quadrant Gates Upgraded to Four-Quadrant Gates	32.8	11.4	44.2

Note: All costs are in 1987 dollars and assume a useful life for the warning device of 30 years, a 10 percent salvage value at the end of that time and a 5 percent annual interest rate.

ratios for installing the four-quadrant gate and highway traffic signal systems. For both systems, the reported benefit/cost ratios were generally favorable over a wide range of potential accident reduction and train, traffic, and crossing conditions. In fact, ratios of 2.0 or more were reported for many of the crossing conditions that were evaluated. Interestingly, if the highway traffic signal was installed at a passive crossing, the marginal installation cost would be negative, i.e., the installation costs are less for a highway traffic signal than they are for a flashing light signal system. In this case, the reported benefit/cost ratios of installing a new device were as high as 20 to 1. The primary reason for this discrepancy was the 10 times greater labor cost for installing the flashing light signals, a fact which reflects the noncompetitive labor forces in the railroad signal industry (55).

Based on the aforementioned cost analyses, it appears that the four-quadrant gates and highway traffic signals would be cost-effective at certain crossings. This suggests that some type of funding program be set up at the national level; however, in formulating such a program, an important issue which must be considered is the total cost to install the innovative devices at a number of crossings around the country. Costs for upgrading various percentages of existing crossings are shown in Table 41 (55). Note that to upgrade one percent of the existing crossings to four-quadrant gates and highway traffic signals would cost approximately 18.2 million dollars, and to upgrade five percent of existing crossings would cost approximately 91 million dollars. Given the current federal spending of 190 million dollars per year for grade crossing improvement projects (13) these percentages probably bracket

TABLE 41. ESTIMATED NATIONWIDE INSTALLATION COSTS FOR THE THREE INNOVATIVE SYSTEMS

Existing Traffic Control	Number of Crossings[1]	Alternative Innovative System	Installation (Retrofit) Cost[2]	Total Nationwide Cost (in million $) to Convert Given Percentages of Existing Crossings			
				1%	5%	10%	20%
Standard Flashing Light Signals	32,788	Four-Quadrant Flashing Light Signals with Strobes	$19,200	6.3	31.4	63.0	125.9
		Highway Traffic Signals	$11,200	3.7	18.4	36.7	73.4
Standard Gates With Flashing Light Signals	22,066	Four-Quadrant Gate/Skirt with Flashing Light Signals	$32,750	7.2	36.1	72.3	144.5
Other Active Devices	9,023	Highway Traffic Signals	$11,200	1.0	5.1	10.1	20.2

[1]Source: "Rail-Highway Crossing Accident/Incident and Inventory Bulletin" (3).

[2]Source: Innovative Railroad-Highway Crossing Active Warning Devices (55).

the number of upgrades per year that are affordable on a national level. The total number of upgrades that would be beneficial is unknown at this time, but it is not expected to exceed the 20 percent values shown in Table 41.

Implementation Guidelines

The field studies assessed the effects of three innovative active warning devices on driver behavior and safety at three railroad-highway grade crossings. However, other considerations are important to the success and acceptance of these devices for general use. These include hardware, installation, operation, maintenance, and power requirements. The following sections are summaries from a research report by Heathington, Fambro, and Richards (55) and describe those conditions wherein the innovative devices have the biggest potential for improving safety at grade crossings.

Four-Quadrant Flashing Light Signals and Gates with Skirts. Four-quadrant gates were the most effective device in terms of driver response and safety. They provide a level of control somewhere between standard two-quadrant gates and a grade separated crossing, i.e., they physically prohibit car-train conflicts without physical separation of the highway and crossing surface. They should be used where two-quadrant gates fail to provide the level of safety required and a full grade separation cannot be economically justified. Four-quadrant gates would be the most effective at those crossings where motorists routinely violate motor vehicle laws by driving around lowered gate arms. They would also be effective at crossings where the potential for extremely serious

accidents exist. Crossings with characteristics that tend to encourage violations or crossings where potential violations are extremely hazardous are as follows:

1. Crossings on multilane undivided roadways and/or with two or more tracks, i.e., the wider the roadway and/or crossing area, the easier it is to drive around the gate arms;
2. Crossings with large variations in train speeds (i.e., both thru and switching trains) and no predictors to provide reasonably consistent warning times;
3. Crossings for which motor vehicle-train collisions pose the potential for extremely serious safety problems such as crossings with large numbers of hazardous materials carriers, crossings with large numbers of school buses, crossings with high speed passenger trains, and crossings with continuing accident occurrence over three or more years; and
4. Crossings with consistent gate arm violations and inadequate site distance along the tracks.

While it is acknowledged that the design of the gate arm and skirts could be improved, the prototype device was constructed of commercially available components and worked well in a variety of environmental conditions. The four-quadrant gate system can be installed and maintained by regular railroad field personnel within the normal scope of their duties and union contracts. Therefore, no special training or equipment is necessary. The marginal costs for upgrading to a four-quadrant system have previously been discussed and were less than half of the cost of the initial two-quadrant system; however, it should be

noted that the power requirements for the four-quadrant gate system were approximately 50 percent more than for the two-quadrant gate system. Additional operational concerns are that alternative emergency vehicle routes exist in the event the four-quadrant gates malfunction.

Four-Quadrant Flashing Light Signals with Overhead Strobes. Although the four-quadrant flashing light signals with strobes had no measurable impact on driver behavior at the Ebenezer Road crossing, intuitively, the additional flashing lights (i.e., overhead strobes) and physical relocation of existing flashing lights (i.e., nearside installation of left-hand lights) had to have improved the conspicuity of the active warning devices at the crossing. Unfortunately, the data collection and analysis process was not sensitive enough to quantify the differences that might have occurred. This particular system would be best suited for crossings where horizontal and/or vertical or other types of sight distance obstructions limit the driver's visibility of the crossing itself. The flashing light signals and overhead strobes are commercially available hardware that could easily be installed and maintained by the railroads' regular field crews. Due to the low cost and ease of implementation of this particular system, it would be an alternative at restricted sight distance crossings for both low and high exposures of train-traffic volumes (55).

Highway Traffic Signals. The enhanced highway traffic signal system was much more successful than the standard flashing light signal system in discouraging unacceptable track crossings. Furthermore, as discussed earlier, the highway traffic signals were less expensive than

the flashing light signals and much less expensive than the flashing light signals and automatic gates. Therefore, when compared to standard flashing light signals, highway traffic signals have the potential for improving safety at certain types of grade crossings, and at a reduced overall cost.

Highway traffic signals are suited for any crossing where flashing light signals are warranted. However, they should not be installed haphazardly and maintained poorly as doing so will destroy driver's credibility in and respect for the warning device. Therefore, highway traffic signals should only be installed at crossings with either uniform train speeds or predictors (i.e., constant warning times) and high maintenance standards for both the train detection system and traffic signals themselves. This last requirement would require either retraining of railroad maintenance personnel or contracting traffic signal maintenance to outside agencies.

Situations where highway traffic signals seem best suited are crossings in the vicinity of other signalized intersections and crossings with complex geometrics, such as multiple intersections where drivers are unable to make proper judgments on whether or not it is safe to proceed across the tracks, and where gates would be impractical or too costly. In the first case, drivers are familiar with the traffic signals in the area and thus should respond appropriately when the signal changes. On the other hand, traffic signals at the grade crossing may change so infrequently that drivers may be lulled into a false sense of security and overlook the signal changing to red. Thus, the

attention-grabbing properties of the white bar strobes are particularly advantageous for this type of installation.

At grade crossings with complex geometrics, highway traffic signals offer an alternative warning device for locations which are difficult to control with standard flashing light signals and automatic gates. Improvements can be accomplished through the use of louvered signal heads and/or protected turning movements as well as arrows for directional movement and guidance. In either case, power for the highway traffic signal requires a 110-volt power supply and sufficient back-up power to cover all but the most extensive power outages caused by storms. Again, it must be emphasized that highway traffic signals should not be installed at crossings without constant warning time devices, else the traffic signal's credibility might be destroyed not only at the crossing, but also at adjacent signalized intersections.

XI. CONCLUSIONS

This section summarizes the major conclusions and recommendations emanating from the field evaluation studies. They are listed by device and discussed in order of presentation in this dissertation, i.e., four-quadrant flashing light signals and gates with skirts, four-quadrant flashing light signals with overhead strobes, and highway traffic signals with white bar strobes in all red lenses. Included at the end of this section are conclusions and recommendations concerning the train predictors that were evaluated in conjunction with the highway traffic signal.

Four-Quadrant Flashing Light Signals and Gates with Skirts

The four-quadrant flashing light signals and gates with skirts were field tested for approximately one year at the Cherry Street crossing in Knoxville, Tennessee. As part of the evaluation, their performance was compared to that of the standard two-quadrant flashing light signals and gates which had been in regular use at the crossing.

Based on the field test results, the four-quadrant gate system outperformed standard gates on several key safety and driver response measures, and proved to be practical under a variety of conditions. The specific conclusions and recommendations for four-quadrant flashing light signals and gates with skirts are summarized below:

Conclusions.

1. Compared to standard gates, four-quadrant gates with skirts reduced the number of gate violations per train at the test crossing from an average of 2.6 to zero.
2. Compared to standard gates, four-quadrant gates with skirts reduced the risky behavior per 100 trains at the test crossing from 5.4 to zero. (Risky behavior occurred when a car or truck drove around the lower gate arms and crossed within 10 seconds of an approaching train.)
3. Four-quadrant gates with skirts did not significantly affect drivers' perception-brake reaction time or their maximum deceleration levels at the test crossing.
4. Four-quadrant gates with skirts had no significant effects on drivers' speed profiles as they approached the test crossing.
5. During the entire time that the four-quadrant gates with skirts were in place at the test crossing, no motorists were trapped on the tracks. Four-quadrant gates do not increase the risk of a vehicle being trapped on the tracks, provided the lowering of the far side gates is delayed by a few seconds to allow vehicle clearance.
6. At the test crossing, the four-quadrant gates with skirts did not create unreasonable delays for motorists.
7. The wooden gate arms with skirts fabricated for the research performed adequately even under very adverse weather conditions, e.g., high winds, heavy snow and ice.

8. The added cost of installing four-quadrant gates with skirts, compared to the cost of a standard two-quadrant gate system, is approximately $32,750. The additional maintenance cost is approximately $740 per year (30 percent higher), and the additional operating (power) cost is approximately 50 percent higher.
9. Four-quadrant gates with skirts can be easily retrofitted to a crossing with a standard two-quadrant gate system. Railroad crews already have the necessary equipment and training.
10. There were no public complaints concerning the use of the four-quadrant gates with strobes and flashing light signals; the news media was very supportive of the research.

Recommendations.

1. Since experience with four-quadrant gate systems in this research and abroad has been excellent, FHWA should immediately initiate steps to have them adopted into the MUTCD (12).
2. Four-quadrant gate systems should be considered for the following types of crossings:
   a. Crossings on four-lane, undivided roads;
   b. Multi-track crossings where the distance between tracks is greater than the length of a vehicle;
   c. Crossings without train predictors where train warning times are long and variable;

d. Crossings where there is a reasonable number of hazardous materials carriers, school buses, or high-speed passenger trains; and/or

e. Crossings with a number of recurring accidents or gate violations.

3. Research should be conducted to determine if skirts are beneficial and cost effective.

4. Provided that skirts prove to be beneficial, a better gate/skirt design should be developed and tested.

5. When four-quadrant gates are used, the lowering of far side gates should be delayed to provide clearance time for vehicles crossing the tracks as the gates are starting down.

Four-Quadrant Flashing Light Signals with Overhead Strobes

Four-quadrant flashing light signals with overhead strobes were field tested for approximately one year at the Ebenezer Road Crossing in Knoxville. This crossing is characterized by severe sight restrictions of the crossing itself. The performance of the four-quadrant flashing light signals with strobes was compared to that of the standard two-quadrant flashing signals which had been in regular use at the crossing.

Based on the test results, there were no significant differences in driver response or safety measures between the four-quadrant flashing signals with overhead strobe lights and the standard flashing light signals. However, the innovative system was found to be feasible, though it may have some limited application. The specific conclusions

and recommendations regarding four-quadrant flashing light signals with strobes are summarized below:

Conclusions.

1. Four-quadrant flashing light signals with strobes offered no apparent safety or driver response advantages over standard two-quadrant flashing signals at the test crossing.
2. Four-quadrant flashing light signals with strobes did not significantly effect violations, clearance times, approach speed profiles, maximum deceleration levels or perception-brake reaction times at the test crossing.
3. There were no accidents, confusion, or motorist diversions while the four-quadrant flashing light signals with strobes were installed.
4. The overhead strobes performed adequately throughout the 12-month test period. Their alignment was not critical to visibility, and their brightness did not "wash out" other traffic control devices. They produced no known hypnotic effects on drivers.
5. The retrofit installation cost is approximately $19,200. Almost 70 percent of this cost is labor while 25 percent is equipment cost.
6. The maintenance cost of four-quadrant flashing light signals with strobes is approximately $450 per year more than for standard two-quadrant flashing light signals. Operating (power) costs are the same.

7. Because they require about twice as much power as standard flashing light signals, four-quadrant flashing light signals with strobes would require additional battery capacity for the same level of fail-safe operation.

Recommendations.

1. Based on the results of this research, four-quadrant flashing light signals with strobes are generally not recommended as an enhancement of standard two-quadrant flashing light signals.
2. No further research or wide-scale implementation of four-quadrant flashing light signals with strobes is recommended.
3. Four-quadrant flashing light signals with strobes may be considered for use at special problem crossings where visibility to the crossing is restricted; however, cantilever signals would probably be a better or equally effective alternative.

Highway Traffic Signal

The highway traffic signal was field tested for approximately four months at the Cedar Drive crossing in Knoxville. The crossing is characterized by variable train speeds and several sight restrictions at the crossing itself. The performance of the highway signal was compared to that of the standard flashing light signals which had been in regular use at the crossing.

The highway traffic signal proved to be both feasible and effective as a grade crossing traffic control device. Driver response to the highway traffic signal was excellent, with the highway traffic signal out-performing standard flashing light signals on several key safety and

driver response measures. Below is a summary of the specific conclusions and recommendations for the highway traffic signal based on the field study results:

Conclusions.

1. Compared to flashing light signals with predictors, the highway traffic signal reduced the number of crossings per signal activation from 3.35 to 0.73.
2. Compared to flashing light signals with predictors, the highway traffic signal reduced the risky behavior per train arrival from 0.13 to 0.05. (Risky behavior refers to the number of vehicles crossing while the flashing light signals are activated and within 10 seconds of the train).
3. The highway traffic signal did not significantly change drivers' perception-brake reaction time, maximum deceleration level, or speed profile at the test crossing.
4. The highway traffic signal appeared to be well understood and respected at the test crossing by the overwhelming majority of motorists.
5. During the entire time that the highway traffic signal was installed at the test crossing, there were no accidents, confusion, diversions or unnecessary delays to motorists.
6. The cost to install a new highway traffic signal installation at a simple crossing, or to retrofit a crossing with flashing light signals, is estimated to be $11,200. Eighty-four

percent of these costs are equipment costs and, on the average, 12 percent are labor costs.

7. The added maintenance cost of a highway signal, compared to standard flashing light signals, is approximately $200 per year. The added operating (power) cost is approximately $1200 per year.
8. Credibility problems would be expected if traffic signals were used at crossings where detector malfunctions were frequent or where train warning times were long and highly variable.
9. There was no evidence that the use of traffic signals at grade crossings would in any way diminish their effectiveness at highway intersections.
10. There were no public complaints concerning the use or operation of the four-quadrant gates with strobes and flashing light signals; the news media was very supportive of the research.

Recommendations.

1. Highway traffic signals should be tested at additional crossing sites under varying conditions and in different parts of the country. Research is needed to evaluate the long-term performance of highway traffic signals.
2. Research should be undertaken to determine if the inherent fail-safe mode of highway signals is sufficient for grade crossing applications and, if it is, if back-up power requirements can be eliminated.

3. If highway traffic signals are adopted, and every indication is that they should be, then responsibility for the signal installation and upkeep should be given to the state or local highway agency in the interests of efficiency and economy.

Train Predictors

Train speeds at the Cedar Drive crossing, where the highway traffic signal was field tested, are highly variable. In order to eliminate the variable and sometimes long warning times resulting from these variable train speeds, train predictors were installed at the crossing prior to the installation of the highway traffic signal. This installation provided the opportunity to evaluate the effects of train predictors and constant warning on crossing safety and driver response measures. Thus, as part of the field studies, the effects of train predictors used with standard flashing light signals were evaluated. The resulting conclusions and recommendations are summarized below:

Conclusions.

1. At the test crossing, the installation of train predictors reduced the average length of the observed warning times from 75 seconds to about 42 seconds.
2. Train predictors reduced the average number of vehicles crossing the tracks per signal activation from 10.86 to 3.35.
3. At the test crossing, the predictors reduced the risky behavior per train arrival from 0.39 to 0.13. (Risky behavior refers to the number of vehicles crossing while the flashing

light signals are activated and within 10 seconds of the train.)

4. Predictors did not significantly affect speed profiles, perception-brake reaction times or deceleration rates at the test crossing.
5. There have been no train-car accidents at the test crossing since the predictors were installed. (The predictors are still in use at the crossing.)

Recommendations.

1. Predictors should be installed at active crossings which have highly variable and long train warning times.
2. Research is needed to determine the optimal "constant" warning time at crossings equipped with predictors.
3. Warrants/guidelines need to be developed for determining when and where to use predictors, i.e., under what conditions are predictors cost effective.

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APPENDICES

APPENDIX A

BIOGRAPHICAL DATA, DRIVER KNOWLEDGE SURVEY, AND REACTION AND VISION TESTS

BIOGRAPHICAL DATA

1. Driver No: _____
2. Age: _____
3. Sex: _____
4. Education Level: (Check the appropriate blank)
   a. Non-high school graduate _____
   b. High school graduate _____
   c. College (1-3 years) _____
   d. College graduate _____
   e. Graduate Degree _____
5. Driving Experience (Please answer each question)
   a. Do you have a valid driver's license in Tennessee? Yes ____ No ____
   b. In what states have you held a valid driver's license?

      _____

   c. Are there any restrictions on your current license? If so, please list.

      _____

   d. How many years have you been driving a motor vehicle?

      _____

   e. What is the average number of miles you drive in one year?

      _____

   f. Estimate the percentage of this mileage that is driven on rural roads.

      _____
6. What is your occupation?

   _____
7. Do you have any type of heart disease? Yes _____ No _____
8. Do you have any type of circulatory disease? Yes _____ No _____
9. Are you presently on any type of medication? Yes _____ No _____
   If yes, what is the medication for? _____
10. Have you received any tickets for moving traffic violations in the past three years? If yes, please give number and the reason for each.

    _____

BIOGRAPHICAL DATA

Driver Number	Age	Sex	Education	Driver's License	Restrictions	Years Driving	Miles Per Year x 1,000	Percent Rural	Occupation	Heart Disease	Circulatory Disease	Medication	Tickets in Past 3 Years
1	18	M	b	TN	none	3	6-7	50	College Student	no	no	no	no
2	24	F	d	NC,TN	Glasses, Seat Cushion	8	10	30	Transportation Planner	no	no	no	no
3	19	F	c	TN	none	3	8.5	70	College Student	no	no	no	no
4	65	F	c	FL,KY,TN	none	48	8	25	Secretary	no	no	no	no
5	79	M	b	GA,TN,WI	none	65	15	3	Real Estate Broker	no	no	Thyroid	no
6	23	M	c	TN	Glasses	6	12-15	15	Student/Musician	no	no	no	no
7	63	M	e	DE,IL,PA TN,VA	Glasses	51	15	20	Manager Financial Serv.	no	no	no	Speeding
8	61	F	e	CO,IL,TN	none	43	10	5	Nurse Educator	no	no	no	no
9	17	M	a	TN	none	1.5	10	90	High School Student	no	no	no	no
10	22	F	d	TN	Glasses	6	8	75	High School Teacher	no	no	no	Speeding
11	68	F	a	TN	none	45	10	50	Assistant Plant Manager	no	yes	Arthritis, Blood Pressure	no
12	68	M	a	TN	none	45	20	50	Retired	no	no	no	no
13	61	F	b	TN	none	40	30	10	Housewife	no	no	Colon	no
14	64	M	c	TN	none	50	2-3	20	Retired	no	no	Blood Pressure	no
15	22	M	d	IN	none	6	8	5	Graduate Student	no	no	no	no
16	21	F	c	TN	none	5	8	10	College Student	no	no	no	Speeding
17	20	F	b	TN	none	4	7	60	Secretary	no	no	no	Speeding
18	20	M	c	TN	none	6	30	50	Deli Clerk	no	no	no	no
19	17	F	a	TN	none	1	9	50	Student	no	no	no	no
20	63	M	d	GA,IL,MD MO,NJ,NY, INTL	none	45	20	10	Building Management	no	no	no	no
21	17	M	a	TN	none	1.5	9	85	Stock Clerk	no	no	no	no
22	72	M	c	TN	none	50	12	10	Retired	no	no	Blood Pressure	no
23	20	M	d	TN	none	4	15	75	Stock Clerk	no	no	no	no
24	63	F	a	CA,NB,TN	none	40	15-20	25	Housewife	no	no	no	no
25	63	M	a	CA,NB,TN	none	48	10	30	Retired	no	no	no	no
26	67	F	c	TN	none	51	12	1	Housewife	no	no	no	no
27	74	M	c	TN	none	62	10	5	Retired	no	no	no	no
28	65	F	a	TN	-	15	7	75	Retired	no	no	Blood Pressure	no
29	65	F	b	IL,TN	none	35	6	15	Retired	no	no	no	no
30	24	F	d	VA	none	7	11	10	Graduate Student	no	no	no	no
31	16	F	a	TN	none	1	5	10	High School Student	no	no	no	no
32	17	M	a	TN	Glasses	2	50	85	High School Student	no	no	no	no

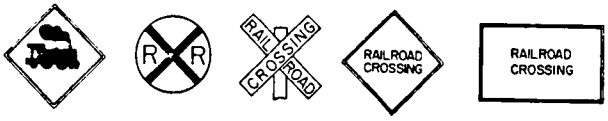
DRIVER SURVEY

Your answers to the following questions will be used in a research project which is attempting to find a way to improve highway safety. We need to have all questions answered, so please answer to the best of your present knowledge. Thank you for your assistance.

1. Do you recall specific instructions concerning driving safety at railroad crossings from any of the following sources? Check only those you remember something from.

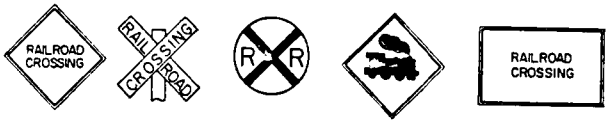
___ Safety Campaign (Radio, TV, etc.)
___ Driver's Education Course
___ Tennessee Driver's Handbook
___ Don't recall any instructions
Other _____
(please specify)

2. Which of the following is usually placed just at the point where the railroad tracks cross the highway?



___ ___ ___ ___ ___ Don't know ___

3. Which of the following is usually located several hundred feet in advance of a railroad crossing? Check only one.



___ ___ ___ ___ ___ Don't know ___

4. What does it mean when this railroad signal is flashing?

___ This is a warning primarily for trucks
___ Slow down for rough crossing
___ A train is coming
___ This is a warning only for train engineer
___ Don't know



5. What should you do when you see this railroad signal flashing?

___ Nothing as it is for the train engineer
___ Stop my vehicle only if it is a truck
___ Stop my vehicle and wait until the flashing stops before proceeding over the crossing
___ Stop my vehicle and proceed over the crossing if a train is not near
___ Don't know



6. Does this flashing signal appear at all crossings?

Yes ___ No ___

7. How long does it generally take for a train to reach the crossing after the railroad signal begins to flash?

___ A flashing signal has nothing to do with a train coming
___ 10 seconds
___ 20 seconds
___ 30 - 60 seconds
___ Always over 1 minute
___ Don't know



8. In general, how does the distance needed to stop a train compare with that needed to stop a large truck traveling at the same speed?

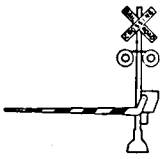
___ Same
___ Truck needs more distance to stop
___ Train needs more distance to stop
___ Don't know

9. What does this sign mean?



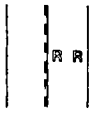
___ Slow down to 20 miles per hour (mph) due to crossing ahead
___ There is a crossing ahead of you
___ There are signals ahead at the crossing
___ You will have to stop at the crossing
___ Don't know

10. What should you do when the gates are down at a crossing?

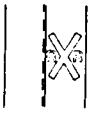


___ Stop and remain stopped until the gate arms are raised
___ Stop and then proceed around the gates if no train is coming
___ Only slow down and then proceed around the gates if no train is coming
___ Don't know

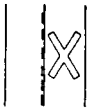
11. Which of the following are the standard markings painted on the pavement in advance of some railroad crossings?



a. _____



b. _____



c. _____

Don't know

d. _____

12. What should you do when approaching a crossing that does not have a railroad signal?

___ Not applicable, since all crossings have railroad signals
___ Be ready to stop if you see or hear a train
___ Speed up and cross the tracks quickly to avoid an accident
___ Stop, look, and listen at the crossing for a train
___ Don't know

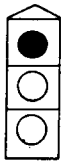
13. Approximately how many motorists were killed in accidents at railroad crossings last year in the United States?

___ 10 ___ 100 ___ 1,000 ___ 5,000 ___ 25,000 ___ Don't know

14. Are you satisfied with the current signs, signals, and pavement markings used at railroad crossings? If not, what additional traffic related measures would you like to see taken to improve safety at railroad crossings?

___ Present system satisfactory
___ Other measures needed _____ (please specify)

15. What should you do when the steady red light is illuminated on a traffic signal?



___ Slow down and proceed with caution
___ Stop at the signal and proceed when it is safe to do so
___ Stop at the signal and wait for signal to turn green before proceeding
___ Nothing if it is not located at an intersection
___ Don't know

16. Which of the following is usually located several hundred feet in advance of a traffic signal?



___ ___ ___ ___ ___

Don't know ___

SUMMARIZED RESPONSES TO DRIVER KNOWLEDGE SURVEY
(Correct Answer is Checked ✓)

DRIVER SURVEY

Your answers to the following questions will be used in a research project which is attempting to find a way to improve highway safety. We need to have all questions answered, so please answer to the best of your present knowledge. Thank you for your assistance.

1. Do you recall specific instructions concerning driving safety at railroad crossings from any of the following sources? Check only those you remember something from.

   9 Safety Campaign (Radio, TV, etc.)
   13 Driver's Education Course
   17 Tennessee Driver's Handbook
   6 Don't recall any instructions
   Other 2 _____ (please specify)

2. Which of the following is usually placed just at the point where the railroad tracks cross the highway?










___ 9 26 ✓ 2 ___ Don't know ___

3. Which of the following is usually located several hundred feet in advance of a railroad crossing? Check only one.










7 5 22 ✓ ___ ___ Don't know ___

4. What does it mean when this railroad signal is flashing?



   ___ This is a warning primarily for trucks
   Slow down for rough crossing
   ✓ 32 A train is coming
   ___ This is a warning only for train engineer
   ___ Don't know

5. What should you do when you see this railroad signal flashing?



   ___ Nothing as it is for the train engineer
   ___ Stop my vehicle only if it is a truck
   28 Stop my vehicle and wait until the flashing stops before proceeding over the crossing
   ✓ 4 Stop my vehicle and proceed over the crossing if a train is not near
   ___ Don't know

6. Does this flashing signal appear at all crossings?

   Yes 3 No 28 ✓

7. How long does it generally take for a train to reach the crossing after the railroad signal begins to flash?



   ___ A flashing signal has nothing to do with a train coming
   1 10 seconds
   6 20 seconds
   ✓ 10 30 - 60 seconds
   7 Always over 1 minute
   8 Don't know

8. In general, how does the distance needed to stop a train compare with that needed to stop a large truck traveling at the same speed?

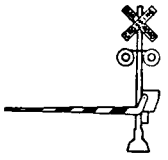
___ Same
1 Truck needs more distance to stop
✓ 28 Train needs more distance to stop
3 Don't know

9. What does this sign mean?



___ Slow down to 20 miles per hour (mph) due to crossing ahead
✓ 29 There is a crossing ahead of you
___ There are signals ahead at the crossing
3 You will have to stop at the crossing
___ Don't know

10. What should you do when the gates are down at a crossing?



✓ 31 Stop and remain stopped until the gate arms are raised
1 Stop and then proceed around the gates if no train is coming
___ Only slow down and then proceed around the gates if no train is coming
___ Don't know

11. Which of the following are the standard markings painted on the pavement in advance of some railroad crossings?



a. 2 b. ✓ 24 c. 4 d. Don't know 3

12. What should you do when approaching a crossing that does not have a railroad signal?

___ Not applicable, since all crossings have railroad signals
✓ 5 Be ready to stop if you see or hear a train
___ Speed up and cross the tracks quickly to avoid an accident
27 Stop, look, and listen at the crossing for a train
___ Don't know

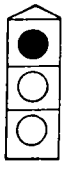
13. Approximately how many motorists were killed in accidents at railroad crossings last year in the United States?

___ 10 2 100 ✓ 6 1,000 4 5,000 ___ 25,000 20 Don't know

14. Are you satisfied with the current signs, signals, and pavement markings used at railroad crossings? If not, what additional traffic related measures would you like to see taken to improve safety at railroad crossings?

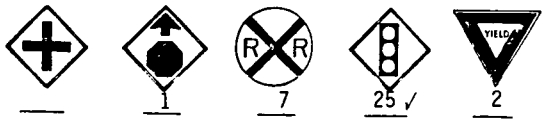
9 Present system satisfactory
22 Other measures needed _____ (please specify)

15. What should you do when the steady red light is illuminated on a traffic signal?



___ Slow down and proceed with caution
6 Stop at the signal and proceed when it is safe to do so
✓ 26 Stop at the signal and wait for signal to turn green before proceeding
___ Nothing if it is not located at an intersection
___ Don't know

16. Which of the following is usually located several hundred feet in advance of a traffic signal?



___ 1 7 25 ✓ 2 Don't know ___

INDIVIDUAL RESPONSES TO DRIVER
KNOWLEDGE SURVEY

Driver Number	Question Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	b,c	c	c	c	c	Y	f	c	b	a	b	d	f	a	c	d
2	b,c	c	a	c	d	N	e	c	b	a	b	d	f	b	c	d
3	b,c	c	c	c	c	N	f	c	b	a	d	d	f	b	c	d
4	c	c	c	c	c	N	d	c	b	a	b	b	b	b	c	d
5	a,c	b	b	c	c	N	f	c	b	a	b	d	f	-	c	c
6	b,e	c	c	c	c	N	c	c	b	a	b	d	f	a	c	d
7	d	c	c	c	c	N	d	c	b	a	b	d	f	b	b	c
8	a	c	c	c	c	N	f	c	b	a	d	d	f	b	c	d
9	b,c	b,c	a	c	c	N	b	c	b	a	b	d	d	a	c	b,d
10	a,b	c	c	c	c	N	e	c	a	a	b	d	c	b	c	d
11	b,c	b,d	b,c	c	c	N	c	b	d	a	a	d	f	b	c	c,d,e
12	a,c	b,c	a,c	c	c	N	c	c	b	a	b	b	c	b	c	c
13	a,c	c	c	c	c	N	e	c	b	a	b	d	c	b	c	d
14	a,c	b,c,d	a,b	c	c	-	c	c	b,d	a	a,b	d	d	a	c	d
15	b,c	c	c	c	c	N	f	c	b	a	b	d	f	b	c	d
16	d	b	c	c	c	N	d	c	b	a	b	d	f	a	c	d
17	b	c	c	c	c	N	d	c	b	a	c	d	f	b	c	d
18	b,c	c	c	c	d	N	d	c	b	a	b	b	f	b	c	d
19	c	c	c	c	c	N	d	c	b	a	b	d	b	a	b	d
20	b,c	b	a	c	c	N	d	c	b	a	b	d	d	b	c	d
21	b,c	c	c	c	c	N	c	c	b	a	c	d	c	b	c	d
22	a	c	a	c	c	N	d	c	b	a	b	d	f	a	c	c
23	d	c	c	c	d	N	c	c	b	a	d	d	f	b	c	d
24	-	c	c	c	c	N	e	d	b	a	b	b	c	b	b	c
25	c	c	c	c	d	N	f	d	b	a	b	d	f	b	c	d
26	a	c	c	c	c	N	d	c	b	a	b	d	f	b	c	d
27	d	c	a	c	c	N	e	c	b	a	b	b	d	b	b	e
28	d	b	b	c	c	Y	e	d	b	a	b	d	f	a	b	d
29	-	b	b	c	c	N	e	c	d	a	c	d	f	a	b	c
30	d	c	c	c	c	Y	d	c	b	a	b	d	f	b	c	d
31	c	c	a	c	c	N	f	c	b	a	c	d	c	b	c	d
32	a,b,c	c	c	c	c	N	f	c	b	b	b	d	f	b	c	d

QUESTION NO. 14: WHAT ADDITIONAL TRAFFIC RELATED MEASURES WOULD YOU LIKE TO SEE TAKEN IN ORDER TO IMPROVE SAFETY AT RAILROAD CROSSINGS?

Driver Number	Comment
1	-
2	More eye-catching signs or signals
3	More warning because some tracks are not marked
4	All crossings should have flashing signals
5	-
6	Satisfactory provided the signs of crossing are not obscured by trees
7	More advance warning
8	Longer approach--always gates
9	-
10	All crossings need lights and gates
11	Should be lights at crossings
12	Signal lights or gates
13	-
14	-
15	Two arms on each side of tracks to prohibit crossing altogether when arms are down
16	-
17	More crossings need to be marked
18	A person must come to a complete stop before crossing
19	-
20	Flashers at all crossings
21	Lights and gates at all crossings
22	-
23	All crossings need signal lights
24	Flashing signal at each light; ample space to get to safety on other side
25	More consistent signals at all crossings
26	Some crossings need stricter signals; especially near rural schools
27	More railroad gates
28	-
29	-
30	Better visibility of oncoming trains
31	Sounds of notice, etc.
32	Gates at all crossings

FORM FOR RECORDING SIMPLE REACTION TIMES

Driver No._____ Date_____ Hour_____

Trial	Time (hundredths of seconds)
1	_____
2	_____
3	_____
4	_____
5	_____
6	_____
7	_____
8	_____
9	_____
10	_____

Average Time _____

Std. Deviation _____

PROFESSIONAL FORM
T/O VISION TESTER
RECORD OF

Driver No._____ Date_____

Last Exam by Doctor_____

Rx_____ None_____ Always_____ Bifocal_____ Far Near_____ Special_____ Safety_____

Difficulty with Vision? Yes_____ No_____

Comments of Subject_____

Test No.	Target	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Both Eyes	T	R	R	L	T	B	L	R	L	B	R	B	T	R
2	Right	T	L	T	T	B	B	L	B	R	T	R	L	B	R
3	Left	L	R	L	B	R	T	T	B	R	T	B	R	T	L
	Snellen Equivalents	20/200	20/100	20/70	20/50	20/40	20/35	20/30	20/25	20/22	20/20	20/18	20/17	20/15	20/13
4	Stereo Depth	1 B		2 L		3 B		4 T		5 T	6 L		7 R	8 L	9 R
5	Color	A 12		B 5			C 26			D 6		E 16		F ◯	
6	Vertical		1		2		3		4		5		6		7
7	Lateral	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
8	Demonstration Slide														
	Alternate														

	Target	1	2	3	4	5	6	7	8	9	10	11	12	13	14
9	Both Eyes	R	L	T	R	B	R	T	L	T	L	B	R	B	L
10	Right	T	B	T	B	R	T	R	L	B	L	R	R	L	T
11	Left	B	L	B	R	T	L	T	B	R	R	L	R	T	L
12	Lateral	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

RESPONSES TO REACTION AND VISION TESTS

Driver Number	Reaction Test: Time (sec.)	Reaction Test: Standard Deviation	Vision Test: Last Eye Exam	Vision Test: Wears Glasses	Vision Test: Type of Correction	1	2	3	4	5	6	7	9	10	11	12	Comments Concerning Difficulty with Vision Comment
1	.390	.020	1978	No	-	14	14	13	9	8	4	9	11	14	14	3	-
2	.549	.064	10/82	Yes	Near	7	6	14	2	5	4	11	5	6	7	10	-
3	.564	.055	1979	No	-	6	5	11	9	6	4	10	11	8	8	5	Glare when it rains
4	.456	.022	1975	-	Far	7	8	14	9	5	4	6	7	4	4	10	Night glare
5	.392	.023	10/82	Yes	Far & Near	6	0	8	2	5	4	8	14	0	2	9	Right eye--looking straight ahead vision very dim
6	.393	.045	1980	Yes	Near	14	14	8	9	8	4	8	14	14	14	1	Bright lights at night cause pain if tired
7	.424	.029	1980	Yes	Far & Near	9	8	8	9	6	5	8	14	14	4	10	-
8	.396	.033	1981		Far	11	14	8	6	6	4	8	14	10	7	9	-
9	.460	.063	7/82	No	-	11	2	11	8	7	4	8	14	13	13	5	-
10	.446	.026	3/82	Yes	Near	12	12	10	9	8	4	7	14	10	10	6	-
11	.491	.096	1980	Yes	Far & Near	5	3	3	9	8	5	9	1	7	6	11	-
12	.516	.026	2/81	Yes	Far & Near	8	4	0	7	6	6	3	4	3	0	3	-
13	.450	.033	1980	Yes	Far & Near	11	4	7	9	8	4	9	12	7	7	8	-
14	.489	.021	1975	Yes	Far & Near	4	5	4	1	5	1	7	5	4	0	11	-
15	.489	.059	7/78	No	-	14	14	12	9	6	4	10	14	14	12	10	-
16	.456	.052	1981	No	-	12	10	13	9	8	4	10	14	12	14	5	-
17	.421	.021	1976	-	Near	12	10	11	9	8	4	9	13	12	12	6	Supposed to wear glasses for driving, movies, etc., but does not
18	.434	.028	1977	No	-	14	14	14	9	8	4	9	14	14	14	5	-
19	.481	.024	1981	No	-	13	12	12	9	8	4	9	14	11	9	7	-
20	.524	.062	1980	Yes	Far & Near	11	9	5	5	8	5	9	9	9	5	15	-
21	.424	.037	1980	No	-	14	12	11	4	8	4	9	13	11	14	7	-
22	.588	.092	1980	-	Far	2	4	1	3	4	4	3	2	3	3	5	-
23	.366	.025	1980	Yes	Near	6	6	4	9	8	4	9	11	5	5	7	In summer, eyes get blurry due to sinuses
24	.458	.035	9/81	-	Far	8	4	3	7	5	4	5	8	7	10	12	-
25	.465	.032	1978	Yes	Far	8	8	5	3	5	5	9	1	1	1	9	-
26	.539	.082	1980	Yes	Far & Near	7	5	7	4	5	3	8	5	5	3	8	Sometimes when reading, seems dim
27	.493	.019	1980	Yes	Far & Near	9	6	14	6	7	4	10	9	6	8	10	-
28	.605	.091	3/82	Yes	Far & Near	6	6	11	9	7	4	3	14	11	5	3	Sometimes sees spots
29	.451	.068	1980	Yes	Far	12	4	8	3	5	3	1	11	4	9	2	-
30	.442	.051	7/82	No	-	14	14	14	9	8	4	13	13	12	12	12	-
31	.489	.025	2/82	-	Far	13	13	13	9	6	4	9	14	10	14	7	-
32	.354	.027	6/82	Yes	Near	9	13	5	3	8	4	9	14	11	12	8	-

APPENDIX B

EXIT SURVEY

I

Please compare the effectiveness of the following devices with the effectiveness of existing signals during DAYTIME driving:

	Much less effective	Less effective	About the same as existing signals	More effective	Much more effective
1. Highway traffic signals with overhead bar strobe light	1	2	3	4	5
2. Railroad flashing light signals in all four quadrants	1	2	3	4	5
3. Gates with flashing light signals in all four quadrants	1	2	3	4	5
4. Highway traffic signals with three bar strobe lights	1	2	3	4	5
5. Railroad flashing light signals in all four quadrants with red strobe lights over traffic lanes	1	2	3	4	5
6. Gates with flashing light signals and skirts in all four quadrants	1	2	3	4	5

II

Please compare the effectiveness of the following devices with the effectiveness of existing signals during NIGHTTIME driving:

	Much less effective	Less effective	About the same as existing signals	More effective	Much more effective
1. Highway traffic signals with overhead bar strobe light	1	2	3	4	5
2. Railroad flashing light signals in all four quadrants	1	2	3	4	5
3. Gates with flashing light signals in all four quadrants	1	2	3	4	5
4. Highway traffic signals with three bar strobe lights	1	2	3	4	5
5. Railroad flashing light signals in all four quadrants with red strobe lights over traffic lanes	1	2	3	4	5
6. Gates with flashing light signals and skirts in all four quadrants	1	2	3	4	5

III

Which of the following traffic control devices (A or B) seems more effective to you during DAYTIME driving? Please circle the letter A or B which represents the more effective traffic control device.

1. A. Highway traffic signals with overhead bar strobe light
   or
   B. Gates with flashing light signals and skirts in all four quadrants

2. A. Railroad flashing light signals in all four quadrants
   or
   B. Railroad flashing light signals in all four quadrants with red strobe lights over traffic lanes

3. A. Highway traffic signals with three bar strobe lights
   or
   B. Gates with flashing light signals and skirts in all four quadrants

4. A. Gates with flashing light signals in all four quadrants
   or
   B. Railroad flashing light signals in all four quadrants with red strobe lights over traffic lanes

5. A. Railroad flashing light signals in all four quadrants
   or
   B. Highway traffic signals with three bar strobe lights

6. A. Gates with flashing light signals in all four quadrants
   or
   B. Gates with flashing light signals and skirts in all four quadrants

7. A. Highway traffic signals with overhead bar strobe light
   or
   B. Highway traffic signals with three bar strobe lights

8. A. Railroad flashing light signals in all four quadrants
   or
   B. Gates with flashing light signals in all four quadrants

9. A. Highway traffic signals with three bar strobe lights
   or
   B. Railroad flashing light signals in all four quadrants with red strobe lights over traffic lanes

10. A. Railroad flashing light signals in all four quadrants
    or
    B. Highway traffic signals with overhead bar strobe light

11. A. Railroad flashing light signals in all four quadrants with red strobe lights over traffic lanes
    or
    B. Gates with flashing light signals and skirts in all four quadrants

12. A. Highway traffic signals with overhead bar strobe light
    or
    B. Gates with flashing light signals in all four quadrants

13. A. Railroad flashing light signals in all four quadrants
    or
    B. Gates with flashing light signals and skirts in all four quadrants

14. A. Gates with flashing light signals in all four quadrants
    or
    B. Highway traffic signals with three bar strobe lights

15. A. Highway traffic signals with overhead bar strobe light
    or
    B. Railroad flashing light signals in all four quadrants with red strobe lights over traffic lanes

IV

Which of the following traffic control devices (A or B) seems more effective to you during NIGHTTIME driving? Please circle the letter A or B which represents the more effective traffic control device.

1. A. Railroad flashing light signals in all four quadrants
   or
   B. Gates with flashing light signals and skirts in all four quadrants

2. A. Gates with flashing light signals in all four quadrants
   or
   B. Highway traffic signals with three bar strobe lights

3. A. Highway traffic signals with overhead bar strobe light
   or
   B. Gates with flashing light signals and skirts in all four quadrants

4. A. Gates with flashing light signals in all four quadrants
   or
   B. Railroad flashing light signals in all four quadrants with red strobe lights over traffic lanes

5. A. Railroad flashing light signals in all four quadrants
   or
   B. Highway traffic signals with overhead bar strobe light

6. A. Railroad flashing light signals in all four quadrants with red strobe lights over traffic lanes
   or
   B. Gates with flashing light signals and skirts in all four quadrants

7. A. Railroad flashing light signals in all four quadrants
   or
   B. Gates with flashing light signals in all four quadrants

8. A. Highway traffic signals with overhead bar strobe light
   or
   B. Highway traffic signals with three bar strobe lights

9. A. Gates with flashing light signals in all four quadrants
   or
   B. Gates with flashing light signals and skirts in all four quadrants

10. A. Railroad flashing light signals in all four quadrants
    or
    B. Railroad flashing light signals in all four quadrants with red strobe lights over traffic lanes

11. A. Highway traffic signals with three bar strobe lights
    or
    B. Gates with flashing light signals and skirts in all four quadrants

12. A. Highway traffic signals with overhead bar strobe light
    or
    B. Railroad flashing light signals in all four quadrants with red strobe lights over traffic lanes

13. A. Railroad flashing light signals in all four quadrants
    or
    B. Highway traffic signals with three bar strobe lights

14. A. Highway traffic signals with overhead bar strobe light
    or
    B. Gates with flashing light signals in all four quadrants

15. A. Highway traffic signals with three bar strobe lights
    or
    B. Railroad flashing light signals in all four quadrants with red strobe lights over traffic lanes

V

1. How old were you when you obtained your first driver's license? _____ years

2. Have you been tested for a driver's license since receiving your first license?

   Written test: Yes ___ If yes, how long ago? ___ years
   No ___

   Driving test: Yes ___ If yes, how long ago? ___ years
   No ___

3. How long has it been since you had an eye examination for a driver's license? Please circle appropriate number of years.

   1 2 3 4 5 6 7 8 9 10 Over 10 Never

RESPONSES TO EXIT SURVEY

Driver Number	Age for First Driver's License (yr.)	Tested Since First Written Test (yr.)	Tested Since First Driving Test (yr.)	Last Eye Exam for License (yr.)	Daytime Driving Device Number 1	2	3	4	5	6	Nighttime Driving Device Number 1	2	3	4	5	6
1	15	N	N	2	4	4	4	4	5	5	5	4	4	5	5	5
2	16	Y,<1	Y,8	<1	4	3	5	4	3	3	4	4	5	4	3	4
3	16	N	N	3	4	4	4	4	3	4	4	4	4	4	4	5
4	27	Y,1	N	1	5	5	5	5	5	5	5	5	5	5	5	5
5	33	Y,40	Y,30	>10	4	3	5	4	3	3	4	3	4	2	3	3
6	18	N	N	3	4	3	4	4	4	4	2	3	4	2	4	4
7	16	Y,6	Y,6	6	3	2	2	4	2	5	2	2	4	3	2	5
8	14	Y,10	Y,10	Never	5	3	3	4	4	4	4	3	4	4	4	5
9	16	N	N	1	5	3	5	5	4	5	5	4	5	5	4	5
10	16	N	N	6	4	3	5	4	3	5	4	3	5	4	3	5
11	21	Y,20	Y,20	>10	4	3	5	5	4	5	4	3	4	3	4	5
12	21	Y,43	Y,43	>10	4	3	5	5	4	5	4	3	4	3	4	5
13	18	Y,15	Y,15	>10	4	4	4	4	4	5	2	2	2	2	4	5
14	18	Y,39	Y,39	>10	4	4	4	4	5	5	5	4	-	-	-	-
15	16	Y,2	N	2	4	4	4	5	5	5	4	4	4	5	5	5
16	16	N	N	5	5	3	4	5	4	5	5	5	4	5	5	5
17	17	N	N	3	4	3	5	5	5	5	4	3	4	5	5	5
18	16	N	N	4	4	3	4	5	4	5	4	3	4	5	4	5
19	15	N	N	2	5	5	5	4	5	4	4	5	5	5	5	5
20	17	Y,2	Y,2	2	5	3	4	5	4	4	5	4	4	5	5	5
21	16	N	N	2	5	3	4	5	4	5	4	3	4	5	4	5
22	20	N	N	Never	4	4	4	4	4	5	4	4	4	4	4	4
23	16	N	N	4	3	3	5	3	4	5	5	3	5	3	5	5
24	27	Y,25	Y,25	>10	4	5	5	4	4	5	4	5	5	4	4	5
25	17	Y,28	Y,28	>10	4	4	3	4	4	3	3	4	4	3	4	3
26	16	N	N	Never	4	4	5	5	5	5	5	3	5	5	5	5
27	24	N	N	Never	4	4	4	4	4	5	4	4	4	4	4	5
28	49	N	N	>10	4	4	4	2	4	4	4	2	4	4	4	5
29	30	N	N	>10	4	3	4	4	4	4	4	4	4	4	4	4
30	16	N	N	1	5	4	4	5	5	5	5	3	3	5	5	5
31	16	N	N	1	3	4	5	5	5	5	4	3	5	5	4	5
32	16	N	N	1	5	3	5	4	5	5	4	3	4	5	5	5

RESPONSES TO EXIT SURVEY: DAYTIME DRIVING

Driver Number	Comparison Number														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	B	B	B	A	B	B	B	B	B	A	B	A	B	B	B
2	B	B	B	A	B	B	B	B	A	A	B	B	B	A	A
3	B	A	B	A	A	A	A	B	B	A	B	B	B	A	B
4	B	B	B	B	A	B	B	B	B	A	B	B	B	A	B
5	B	A	A	A	A	A	B	B	B	B	B	B	B	A	A
6	B	B	B	A	A	B	A	B	B	A	B	B	B	A	B
7	B	B	B	A	B	B	B	B	A	B	B	B	B	A	A
8	B	B	B	B	B	B	B	B	A	B	B	A	B	B	A
9	A	B	B	A	B	B	B	B	A	A	B	B	B	B	A
10	B	B	B	B	B	B	B	B	A	B	B	B	B	A	A
11	B	B	B	A	B	B	B	B	B	B	B	B	B	A	B
12	B	B	B	A	B	B	B	B	B	B	B	B	B	A	B
13	B		B	B	B	B	B	B	B	B	B	B	B	B	B
14	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
15	B	A	B	A	B	B	B	B	B	B	B	B	B	A	B
16	B	B	B	B	B	B	B	B	B	B	B	A	B	B	B
17	B	B	B	B	B	B	B	B	A	B	B	B	B	B	A
18	B	B	A	B	B	B	B	B	A	B	B	B	B	B	B
19	A	A	A	A	B	B	B	B	B	B	B	B	B	B	B
20	A	B	A	B	B	B	B	B	A	B	A	A	B	B	B
21	B	B	A	B	B	B	A	B	B	B	B	B	B	B	B
22	B	A	B	B	A	B	B	B	B	B	B	B	B	A	B
23	B	B	B	A	B	B	A	B	A	B	B	B	B	A	A
24	B	B	B	A	B	B	B	B	B	A	B	B	B	A	B
25	A	A	A	B	A	A	B	A	B	A	A	B	A	A	B
26	B	B	B	A	B	B	B	B	B	B	B	B	B	A	A
27	B	B	B	A	A	B	B	B	B	A	B	B	B	A	B
28	B	B	B	A	B	B	B	B	B	B	B	B	B	A	B
29	A	B	A	B	B	B	B	B	B	B	A	B	B	B	B
30	B	B	B	B	B	B	A	B	B	B	A	A	B	A	B
31	B	B	B	A	B	B	B	B	B	B	B	B	B	A	B
32	B	B	B	A	B	B	B	B	B	B	B	B	B	B	B

RESPONSES TO EXIT SURVEY: NIGHTTIME DRIVING

Driver Number	Comparison Number														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	B	B	B	B	A	A	B	B	B	B	B	B	B	B	B
2	B	A	B	A	A	B	B	B	B	B	B	B	A	B	A
3	B	A	B	A	B	B	B	B	B	B	B	B	B	B	A
4	B	A	B	A	A	B	B	B	B	B	B	B	A	B	B
5	B	A	B	A	A	B	B	A	A	B	B	B	A	B	B
6	B	A	B	A	A	B	A	A	B	B	B	B	A	B	B
7	B	A	B	A	B	B	B	B	B	B	B	A	B	B	A
8	B	B	B	A	B	B	B	B	B	B	B	A	B	B	A
9	B	B	B	A	B	B	B	A	B	B	B	A	B	A	A
10	B	A	B	A	B	B	B	B	B	B	B	A	B	B	A
11	B	A	B	A	B	B	B	B	B	B	B	B	A	B	B
12	B	A	B	A	B	B	B	B	B	B	B	B	A	B	B
13	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
14	B	B	B	B	B	B	B	B	B	B	B	B	B	A	B
15	B	B	B	A	B	B	B	B	B	B	B	B	B	B	B
16	B	A	B	A	B	B	B	B	B	B	B	B	B	B	B
17	B	A	B	A	B	B	B	B	B	B	B	A	B	B	A
18	B	B	B	B	B	B	B	B	B	B	A	B	B	B	A
19	B	B	B	A	B	B	B	A	B	B	B	A	B	B	A
20	B	B	A	B	B	A	B	B	B	B	A	B	B	A	A
21	B	A	B	B	B	B	B	B	B	B	B	B	B	B	B
22	B	A	B	A	A	B	B	A	B	A	B	B	A	B	B
23	B	A	B	A	B	B	B	A	B	B	B	A	B	B	A
24	B	A	B	A	A	B	B	A	B	B	B	B	A	B	B
25	A	A	B	B	A	A	A	A	A	B	A	B	A	B	B
26	B	A	B	A	B	B	B	B	B	B	B	B	B	B	B
27	B	A	B	A	A	B	B	B	B	A	B	B	A	B	B
28	B	A	B	A	B	B	B	B	B	B	B	B	B	B	A
29	B	A	B	B	B	B	B	B	B	B	B	B	B	B	B
30	B	B	A	B	B	B	B	A	B	B	B	B	B	A	B
31	B	A	B	A	A	B	B	B	B	B	B	B	B	B	A
32	B	A	B	B	A	B	B	A	B	B	B	A	B	B	B

APPENDIX C

DRIVING INSTRUCTIONS, BRAKE-REACTION AND MAXIMUM DECELERATION DISTRIBUTIONS, AND AVERAGE VELOCITY PROFILES

INSTRUCTIONS TO DRIVERS

Hello, my name is _____ and I would like to explain to you what we will be doing this afternoon. You are participating in a study of motorist reaction to several traffic control devices that we are testing. We have installed these devices on the road down which you are about to drive. As you drive along the highway, you will encounter the traffic control devices one at a time. Respond to each situation as you would under normal driving conditions. The speed limit on the road is 40 mph; however, only drive as fast as feels comfortable for you. Let me add, that we are not asking you to do anything that might be dangerous, and we ask that you drive safely at all times.

Let me explain a few things about the car you will be driving. Because of the instrumentation we have installed in the car, it should not be driven in reverse during the study. Therefore, we ask that you do not try to back-up as this would damage our equipment. I will assist you in turning the car around. Now, if you will start the car we will drive to the starting point.

(Drive to the starting point)

See the orange flag on the right side of the road. Stop the car so that its front bumper is even with the flag. Remember, you should not back up. In order for us to adequately measure your reaction to the different traffic control devices, we will need you to drive down this highway four times during each of your visits to the airbase. However, the first thing we will do is drive once through the course so that you can become familiar with the roadway. So, whenever you are ready we can begin.

Driver No.: _____

	Run No.	Binary Eq.	Completed
Daytime	1	000001	____
	2	000010	____
System 1	3	000011	____
	4	000100	____
Date: _____	5	000101	____
	6	000110	____
Time: _____	7	000111	____
	8	001000	____
Nighttime	9	001001	____
	10	001010	____
System 1	11	001011	____
	12	001100	____
Date: _____	13	001101	____
	14	001110	____
Time: _____	15	001111	____
	16	010000	____
Daytime	17	010001	____
	18	010010	____
System 2	19	010011	____
	20	010100	____
Date: _____	21	010101	____
	22	010110	____
Time: _____	23	010111	____
	24	011000	____
Nighttime	25	011001	____
	26	011010	____
System 2	27	011011	____
	28	011100	____
Date: _____	29	011101	____
	30	011110	____
Time: _____	31	011111	____
	32	100000	____

DISTRIBUTION OF BRAKE REACTION TIMES FOR THE SIX ALTERNATIVE WARNING DEVICES (SHORT ACTUATION, DAYTIME)

Device	Brake-Reaction Time, Seconds											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	30	15	11	3	0	0	3	1	0	0	0	63
Four-Quadrant Flashing Light Signals Without Strobes	12	28	14	5	1	2	1	0	0	0	0	63
Highway Traffic Signal-- One White Bar Strobe	5	39	33	7	0	1	3	0	0	0	0	88
Four-Quadrant Gates With Skirts	27	17	12	7	1	0	1	0	0	0	0	65
Four-Quadrant Flashing Light Signals With Strobes	14	32	11	5	1	1	1	0	0	0	0	65
Highway Traffic Signal-- Three White Bar Strobes	0	37	43	8	5	0	2	1	0	0	0	96
Total	88	168	124	35	8	4	11	2	0	0	0	440

DISTRIBUTION OF BRAKE REACTION TIMES FOR THE SIX ALTERNATIVE WARNING DEVICES (SHORT ACTUATION, NIGHTTIME)

Device	Brake-Reaction Time, Seconds											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	25	33	4	0	0	1	0	0	0	0	0	63
Four-Quadrant Flashing Light Signals Without Strobes	10	32	15	4	1	0	0	0	0	0	0	62
Highway Traffic Signal-- One White Bar Strobe	2	33	39	7	5	5	1	0	0	0	0	92
Four-Quadrant Gates With Skirts	30	27	9	1	0	0	0	0	0	0	0	67
Four-Quadrant Flashing Light Signals With Strobes	12	31	14	1	0	0	2	0	0	0	0	60
Highway Traffic Signal-- Three White Bar Strobes	3	38	32	11	7	0	3	0	0	0	0	94
Total	82	194	113	24	13	6	6	0	0	0	0	438

DISTRIBUTION OF BRAKE REACTION TIMES FOR THE SIX ALTERNATIVE WARNING DEVICES (MEDIUM ACTUATION, DAYTIME)

Device	Brake-Reaction Time, Seconds											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	16	18	20	3	2	2	0	0	0	1	1	63
Four-Quadrant Flashing Light Signals Without Strobes	9	15	14	8	5	4	2	4	0	1	0	62
Highway Traffic Signal-- One White Bar Strobe	0	12	13	4	2	1	2	0	0	0	0	34
Four-Quadrant Gates With Skirts	17	19	17	4	1	1	4	0	0	1	0	64
Four-Quadrant Flashing Light Signals With Strobes	9	18	13	7	3	5	5	2	0	0	1	63
Highway Traffic Signal-- Three White Bar Strobes	0	9	9	6	1	3	1	1	1	0	0	31
Total	51	91	86	32	14	16	14	7	1	3	2	317

DISTRIBUTION OF BRAKE REACTION TIMES FOR THE SIX ALTERNATIVE WARNING DEVICES (MEDIUM ACTUATION, NIGHTTIME)

Device	Brake-Reaction Time, Seconds											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	13	30	18	0	0	0	0	2	0	0	0	63
Four-Quadrant Flashing Light Signals Without Strobes	12	24	14	5	3	3	2	0	0	0	0	63
Highway Traffic Signal-- One White Bar Strobe	0	7	17	2	1	1	2	1	0	0	0	31
Four-Quadrant Gates With Skirts	10	31	15	3	1	0	1	0	0	0	0	61
Four-Quadrant Flashing Light Signals With Strobes	9	20	17	7	3	3	2	1	1	1	0	64
Highway Traffic Signal-- Three White Bar Strobes	0	12	11	8	3	1	1	1	0	0	0	37
Total	44	124	92	25	11	8	8	5	1	1	0	319

DISTRIBUTION OF BRAKE REACTION TIMES FOR THE SIX ALTERNATIVE WARNING DEVICES (MEDIUM ACTUATION, DAYTIME)

Device	Brake-Reaction Time, Seconds											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	2	8	13	12	11	5	4	4	1	0	3	63
Four-Quadrant Flashing Light Signals Without Strobes	12	6	8	4	6	10	3	2	3	4	5	63
Highway Traffic Signal-- One White Bar Strobe	0	0	3	2	3	3	6	9	5	8	27	66
Four-Quadrant Gates With Skirts	1	3	20	15	7	4	3	4	1	0	3	61
Four-Quadrant Flashing Light Signals With Strobes	13	6	10	7	8	5	2	2	4	1	7	65
Highway Traffic Signal-- Three White Bar Strobes	0	1	5	4	2	8	3	10	3	8	19	63
Total	28	24	59	44	37	35	21	31	17	21	64	381

DISTRIBUTION OF BRAKE REACTION TIMES FOR THE SIX ALTERNATIVE WARNING DEVICES (LONG ACTUATION, NIGHTTIME)

Device	Brake-Reaction Time, Seconds											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	5	10	19	8	7	3	5	0	0	0	2	59
Four-Quadrant Flashing Light Signals Without Strobes	11	11	10	8	4	5	1	0	1	1	8	60
Highway Traffic Signal-- One White Bar Strobe	0	2	4	5	5	9	7	4	5	8	15	64
Four-Quadrant Gates With Skirts	8	11	22	8	5	6	2	1	1	0	0	64
Four-Quadrant Flashing Light Signals With Strobes	15	7	15	10	2	3	5	1	0	1	7	66
Highway Traffic Signal-- Three White Bar Strobes	0	1	6	4	0	2	4	8	5	4	26	60
Total	39	42	76	43	23	28	24	14	12	14	58	370

DISTRIBUTION OF BRAKE REACTION TIMES FOR THE SIX ALTERNATIVE WARNING DEVICES (NULL ACTUATION, DAYTIME)

Device	Brake-Reaction Time, Seconds											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	1	0	1	1	0	7	8	1	5	1	38	63
Four-Quadrant Flashing Light Signals Without Strobes	10	1	1	3	4	2	2	1	1	4	35	64
Highway Traffic Signal-- One White Bar Strobe	0	0	0	0	0	0	2	0	1	1	60	64
Four-Quadrant Gates With Skirts	1	0	3	1	3	5	2	3	6	3	38	65
Four-Quadrant Flashing Light Signals With Strobes	12	0	3	1	1	3	2	3	3	3	31	62
Highway Traffic Signal-- Three White Bar Strobes	0	0	0	0	0	0	1	0	0	0	64	65
Total	24	1	8	6	8	17	17	8	16	12	266	383

DISTRIBUTION OF BRAKE REACTION TIMES FOR THE SIX ALTERNATIVE WARNING DEVICES (NULL ACTUATION, NIGHTTIME)

Device	Brake-Reaction Time, Seconds											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	4	1	2	1	4	2	5	3	3	3	35	63
Four-Quadrant Flashing Light Signals Without Strobes	16	3	0	3	0	0	2	3	1	0	35	63
Highway Traffic Signal-- One White Bar Strobe	1	0	0	0	0	0	1	0	0	1	58	61
Four-Quadrant Gates With Skirts	2	1	0	3	4	7	3	3	2	1	35	61
Four-Quadrant Flashing Light Signals With Strobes	9	0	3	1	2	1	1	5	1	2	38	63
Highway Traffic Signal-- Three White Bar Strobes	0	0	0	0	0	0	0	0	1	0	61	62
Total	32	5	5	8	10	10	12	14	8	7	262	373

DISTRIBUTION OF MAXIMUM DECELERATION RATES FOR THE SIX ALTERNATIVE DEVICES (SHORT ACTUATION, DAYTIME)

Device	Maximum Deceleration Rate, feet per second per second											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	0	2	1	6	17	17	10	7	0	1	2	63
Four-Quadrant Flashing Light Signals Without Strobes	0	0	0	5	18	17	15	8	0	0	0	63
Highway Traffic Signal-- One White Bar Strobe	1	2	0	7	26	27	21	2	1	1	0	88
Four-Quadrant Gates With Skirts	0	1	1	4	17	22	11	5	1	0	3	65
Four-Quadrant Flashing Light Signals With Strobes	0	0	0	6	18	19	13	7	2	0	0	65
Highway Traffic Signal-- Three White Bar Strobes	0	0	1	12	24	18	17	18	5	1	0	96
Total	1	5	3	40	120	120	87	47	9	3	5	440

DISTRIBUTION OF MAXIMUM DECELERATION RATES FOR THE SIX ALTERNATIVE DEVICES (SHORT ACTUATION, NIGHTTIME)

Device	Maximum Deceleration Rate, feet per second per second											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	0	0	1	8	17	18	10	3	4	1	1	63
Four-Quadrant Flashing Light Signals Without Strobes	0	0	1	9	19	16	7	3	6	0	1	62
Highway Traffic Signal-- One White Bar Strobe	1	0	2	10	25	30	11	6	3	3	1	92
Four-Quadrant Gates With Skirts	0	0	0	18	22	9	11	5	2	0	0	67
Four-Quadrant Flashing Light Signals With Strobes	0	0	2	4	19	22	7	3	1	2	0	60
Highway Traffic Signal-- Three White Bar Strobes	0	0	3	15	23	34	5	9	5	0	0	94
Total	1	0	9	64	125	129	51	29	21	6	3	438

DISTRIBUTION OF MAXIMUM DECELERATION RATES FOR THE SIX ALTERNATIVE DEVICES (MEDIUM ACTUATION, DAYTIME)

Device	Maximum Deceleration Rate, feet per second per second											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	1	1	0	19	26	14	1	0	1	0	0	63
Four-Quadrant Flashing Light Signals Without Strobes	0	0	0	9	25	16	8	2	1	0	1	62
Highway Traffic Signal-- One White Bar Strobe	0	0	0	8	15	8	3	0	0	0	0	34
Four-Quadrant Gates With Skirts	0	0	1	18	22	16	4	2	0	0	1	64
Four-Quadrant Flashing Light Signals With Strobes	0	1	1	12	18	16	9	5	1	0	0	63
Highway Traffic Signal-- Three White Bar Strobes	0	1	0	10	14	4	2	0	0	0	0	31
Total	1	3	2	76	120	74	27	9	3	0	2	317

DISTRIBUTION OF MAXIMUM DECELERATION RATES FOR THE SIX ALTERNATIVE DEVICES (MEDIUM ACTUATION, NIGHTTIME)

Device	Maximum Deceleration Rate, feet per second per second											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	0	0	3	22	24	11	1	2	0	0	0	63
Four-Quadrant Flashing Light Signals Without Strobes	0	0	2	16	25	11	4	4	0	0	1	63
Highway Traffic Signal-- One White Bar Strobe	0	0	1	9	13	6	1	1	0	0	0	31
Four-Quadrant Gates With Skirts	0	0	4	22	21	11	0	2	0	0	1	61
Four-Quadrant Flashing Light Signals With Strobes	0	1	2	15	26	11	7	2	0	0	0	64
Highway Traffic Signal-- Three White Bar Strobes	0	0	6	10	14	6	1	0	0	0	0	37
Total	0	1	18	94	123	56	14	11	0	0	2	319

DISTRIBUTION OF MAXIMUM DECELERATION RATES FOR THE SIX ALTERNATIVE DEVICES (LONG ACTUATION, DAYTIME)

Device	Maximum Deceleration Rate, feet per second per second											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	0	0	2	32	23	6	0	0	0	0	0	63
Four-Quadrant Flashing Light Signals Without Strobes	0	0	2	19	22	15	5	0	0	0	0	63
Highway Traffic Signal-- One White Bar Strobe	0	0	3	28	27	6	2	0	0	0	0	66
Four-Quadrant Gates With Skirts	0	1	7	23	23	6	1	0	0	0	0	61
Four-Quadrant Flashing Light Signals With Strobes	0	0	1	24	24	12	3	0	0	1	0	65
Highway Traffic Signal-- Three White Bar Strobes	0	1	6	23	23	9	1	0	0	0	0	63
Total	0	2	21	149	142	54	12	0	0	1	0	381

DISTRIBUTION OF MAXIMUM DECELERATION RATES FOR THE SIX ALTERNATIVE DEVICES (LONG ACTUATION, NIGHTTIME)

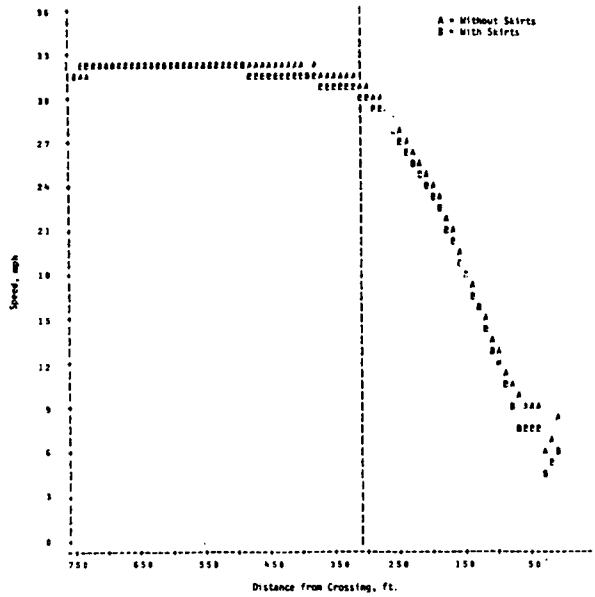
Device	Maximum Deceleration Rate, feet per second per second											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	1	0	11	26	15	6	0	0	0	0	0	59
Four-Quadrant Flashing Light Signals Without Strobes	1	0	7	20	23	7	1	1	0	0	0	60
Highway Traffic Signal-- One White Bar Strobe	0	0	14	26	14	10	0	0	0	0	0	64
Four-Quadrant Gates With Skirts	0	0	12	36	13	2	1	0	0	0	0	64
Four-Quadrant Flashing Light Signals With Strobes	0	1	9	21	21	11	3	0	0	0	0	66
Highway Traffic Signal-- Three White Bar Strobes	0	0	14	30	11	5	0	0	0	0	0	60
Total	2	1	67	159	97	41	5	1	0	0	0	373

DISTRIBUTION OF MAXIMUM DECELERATION RATES FOR THE SIX ALTERNATIVE DEVICES (NULL ACTUATION, DAYTIME)

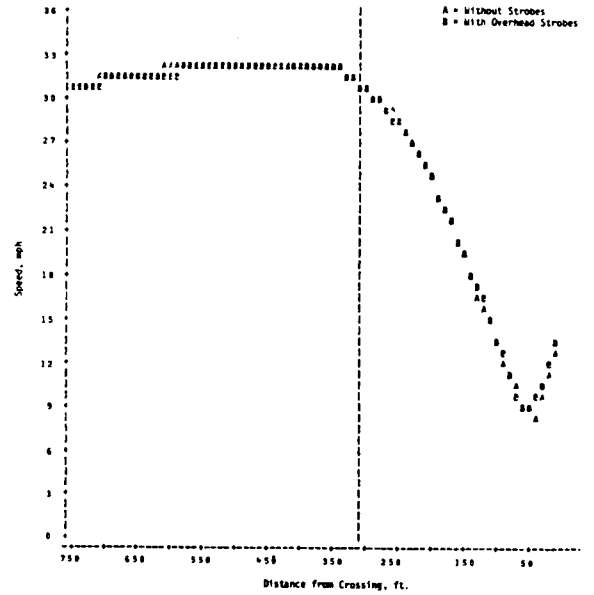
Device	Maximum Deceleration Rate, feet per second per second											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	4	34	16	3	3	1	1	0	1	0	0	63
Four-Quadrant Flashing Light Signals Without Strobes	0	36	14	6	5	2	1	0	0	0	0	64
Highway Traffic Signal-- One White Bar Strobe	2	44	13	2	3	0	0	0	0	0	0	64
Four-Quadrant Gates With Skirts	5	30	18	9	3	0	0	0	0	0	0	65
Four-Quadrant Flashing Light Signals With Strobes	1	25	21	8	6	0	1	0	0	0	0	62
Highway Traffic Signal-- Three White Bar Strobes	6	40	15	2	1	0	0	0	0	0	1	65
Total	18	209	97	30	21	3	3	0	1	0	1	383

DISTRIBUTION OF MAXIMUM DECELERATION RATES FOR THE SIX ACTIVATION DEVICES (NULL ACTUATION, NIGHTTIME)

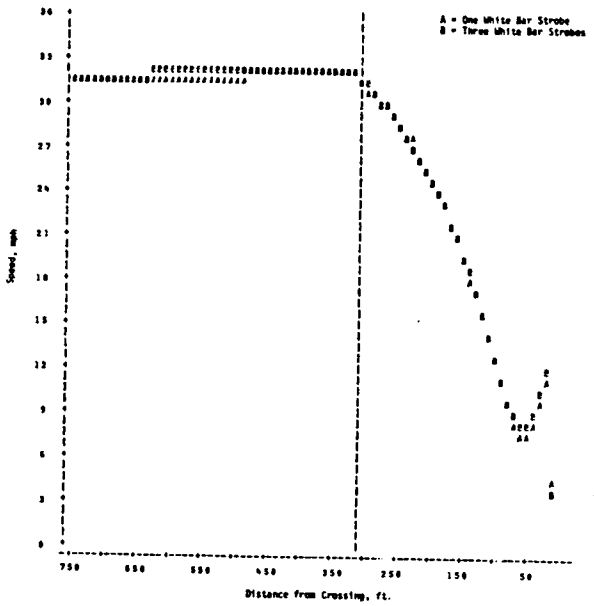
Device	Maximum Deceleration Rate, feet per second per second											
	0.0-0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5	Total
Four-Quadrant Gates Without Skirts	10	39	4	7	2	0	1	0	0	0	0	63
Four-Quadrant Flashing Light Signals Without Strobes	2	38	16	5	1	1	0	0	0	0	0	63
Highway Traffic Signal-- One White Bar Strobe	3	34	19	3	1	1	0	0	0	0	0	61
Four-Quadrant Gates With Skirts	7	38	11	5	0	0	0	0	0	0	0	61
Four-Quadrant Flashing Light Signals With Strobes	2	29	20	10	1	0	0	0	1	0	0	63
Highway Traffic Signal-- Three White Bar Strobes	2	42	13	4	1	0	0	0	0	0	0	62
Total	26	220	83	34	6	2	1	0	1	0	0	373



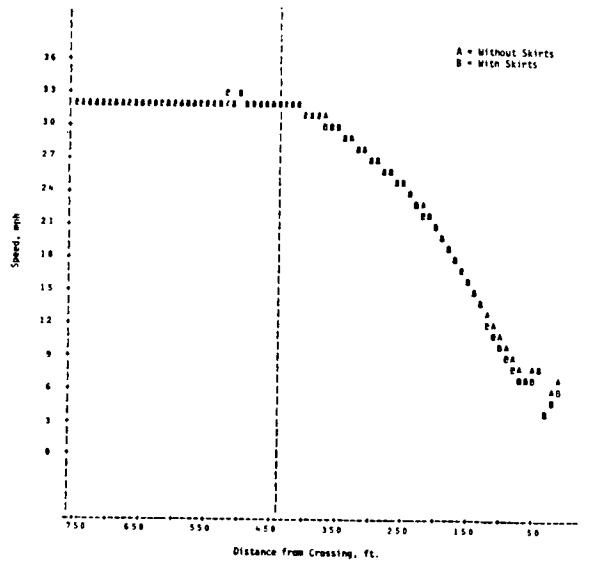
AVERAGE RESPONSE OF ALL MOTORISTS TO THE TWO TYPES OF FOUR-QUADRANT GATE SYSTEMS (SHORT ACTUATION)



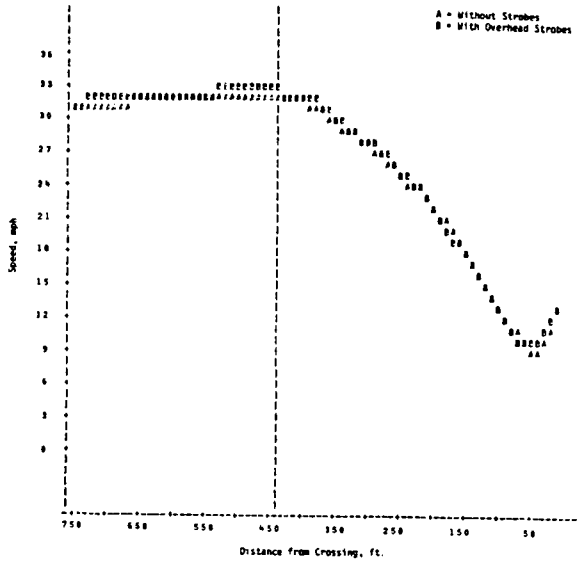
AVERAGE RESPONSE OF ALL MOTORISTS TO THE TWO TYPES OF FOUR-QUADRANT FLASHING LIGHT SIGNAL SYSTEMS (SHORT ACTUATION)



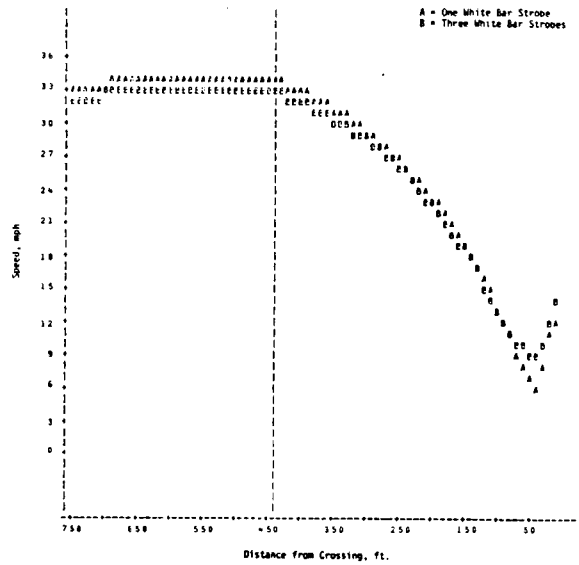
AVERAGE RESPONSE OF ALL MOTORISTS TO THE TWP TYPES OF HIGHWAY TRAFFIC SIGNAL SYSTEMS (SHORT ACTUATION)



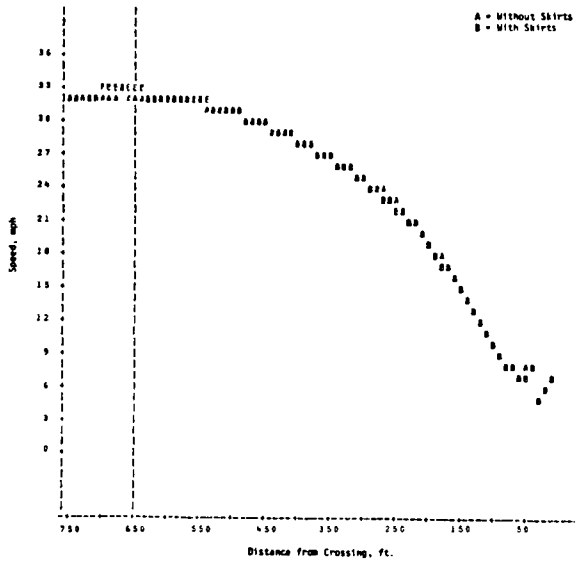
AVERAGE RESPONSE OF ALL MOTORISTS TO THE TWO TYPES OF FOUR-QUADRANT GATE SYSTEMS (MEDIUM ACTUATION)



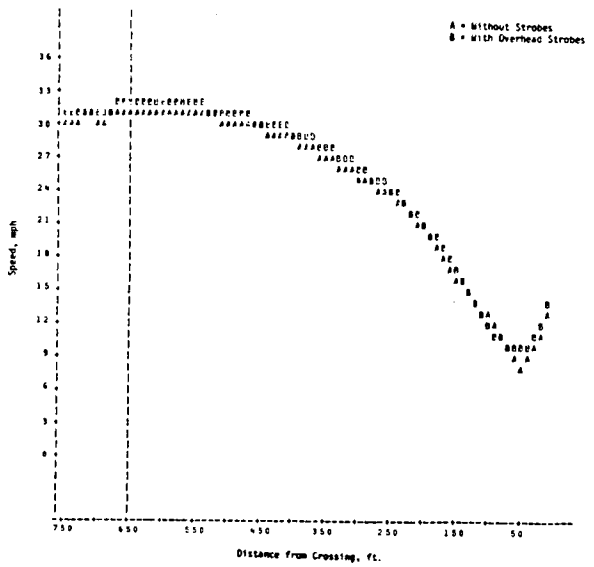
AVERAGE RESPONSE OF ALL MOTORISTS TO THE TWO TYPES OF FOUR-QUADRANT FLASHING LIGHT SIGNAL SYSTEMS (MEDIUM ACTUATION)



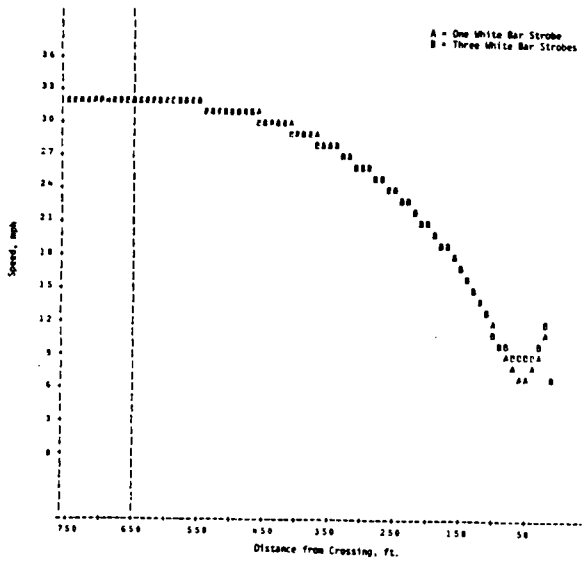
AVERAGE RESPONSE OF ALL MOTORISTS TO THE TWO TYPES OF HIGHWAY TRAFFIC SIGNAL SYSTEMS (MEDIUM ACTUATION)



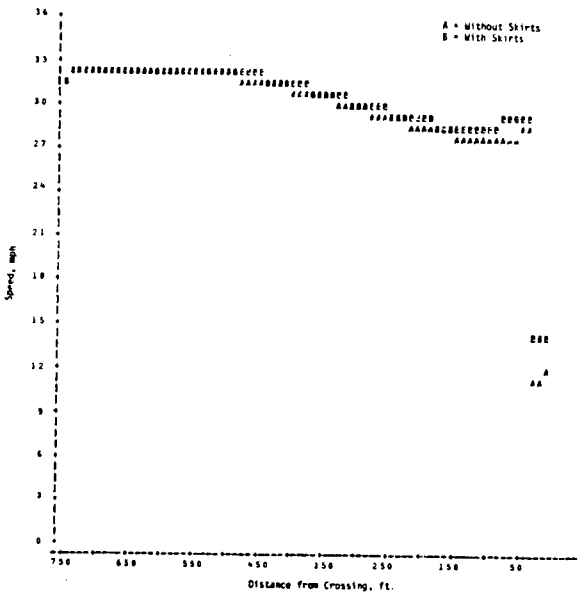
AVERAGE RESPONSE OF ALL MOTORISTS TO THE TWO TYPES OF FOUR-QUADRANT GATE SYSTEMS (LONG ACTUATION)



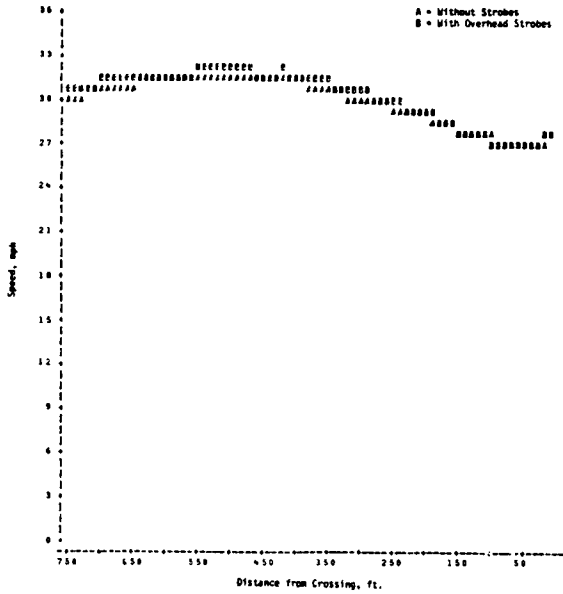
AVERAGE RESPONSE OF ALL MOTORISTS TO THE TWO TYPES OF FOUR-QUADRANT FLASHING LIGHT SIGNAL SYSTEMS (LONG ACTUATION)



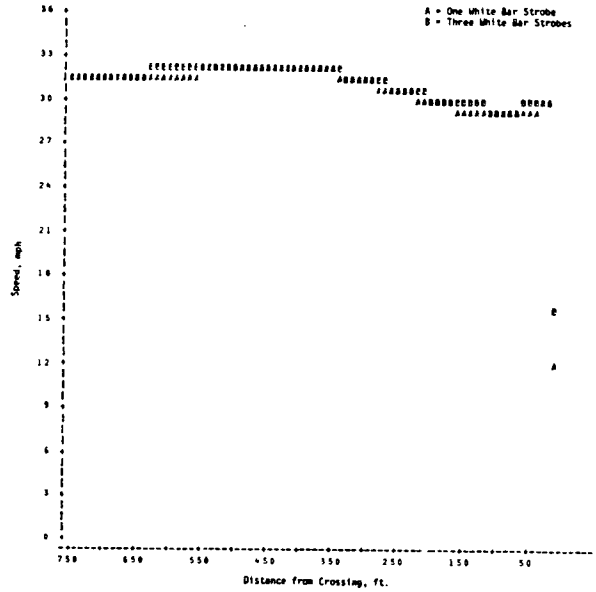
AVERAGE RESPONSE OF ALL MOTORISTS TO THE TWO TYPES OF HIGHWAY TRAFFIC SIGNAL SYSTEMS (LONG ACTUATION)



AVERAGE RESPONSE OF ALL MOTORISTS TO THE TWO TYPES OF FOUR-QUADRANT GATE SYSTEMS (NULL ACTUATION)



AVERAGE RESPONSE OF ALL MOTORISTS TO THE TWO TYPES OF FOUR-QUADRANT FLASHING LIGHT SIGNAL SYSTEMS (NULL ACTUATION)



AVERAGE RESPONSE OF ALL MOTORISTS TO THE TWO TYPES OF HIGHWAY TRAFFIC SIGNAL SYSTEMS (NULL ACTUATION)

VITA

Daniel Bruce Fambro was born in Breckenridge, Texas on February 14, 1951. He attended elementary and secondary schools in that city and graduated from Breckenridge High School in May 1969. The following September, he entered Texas A&M University and in May 1973 he received a Bachelor of Science degree in Civil Engineering. In September 1973, he accepted a research assistantship with the Texas Transportation Institute at Texas A&M University and began study toward a Master's of Engineering degree in Civil Engineering. This degree was awarded in December 1974.

After working seven years as a lecturer with Texas A&M's Civil Engineering Department and a researcher with the Texas Transportation Institute, Mr. Fambro entered the Graduate School of The University of Tennessee, Knoxville in September 1981. While there he worked as a research engineer and program manager for the University's Transportation Center. He received the Doctor of Philosophy degree with a major in Civil Engineering in March 1988.

The author is a member of Phi Kappa Phi, Sigma Xi, the American Society of Civil Engineers, the Institute of Transportation Engineers, and the Transportation Research Board. He is also a registered Professional Engineer in the State of Texas. After graduation, Mr. Fambro will be employed as an Assistant Professor with the Civil Engineering Department and Assistant Research Engineer with the Texas Transportation Institute, both at Texas A&M University.