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Field Evaluation of Innovative Active Warning Devices for Use at Railroad-Highway Grade Crossings

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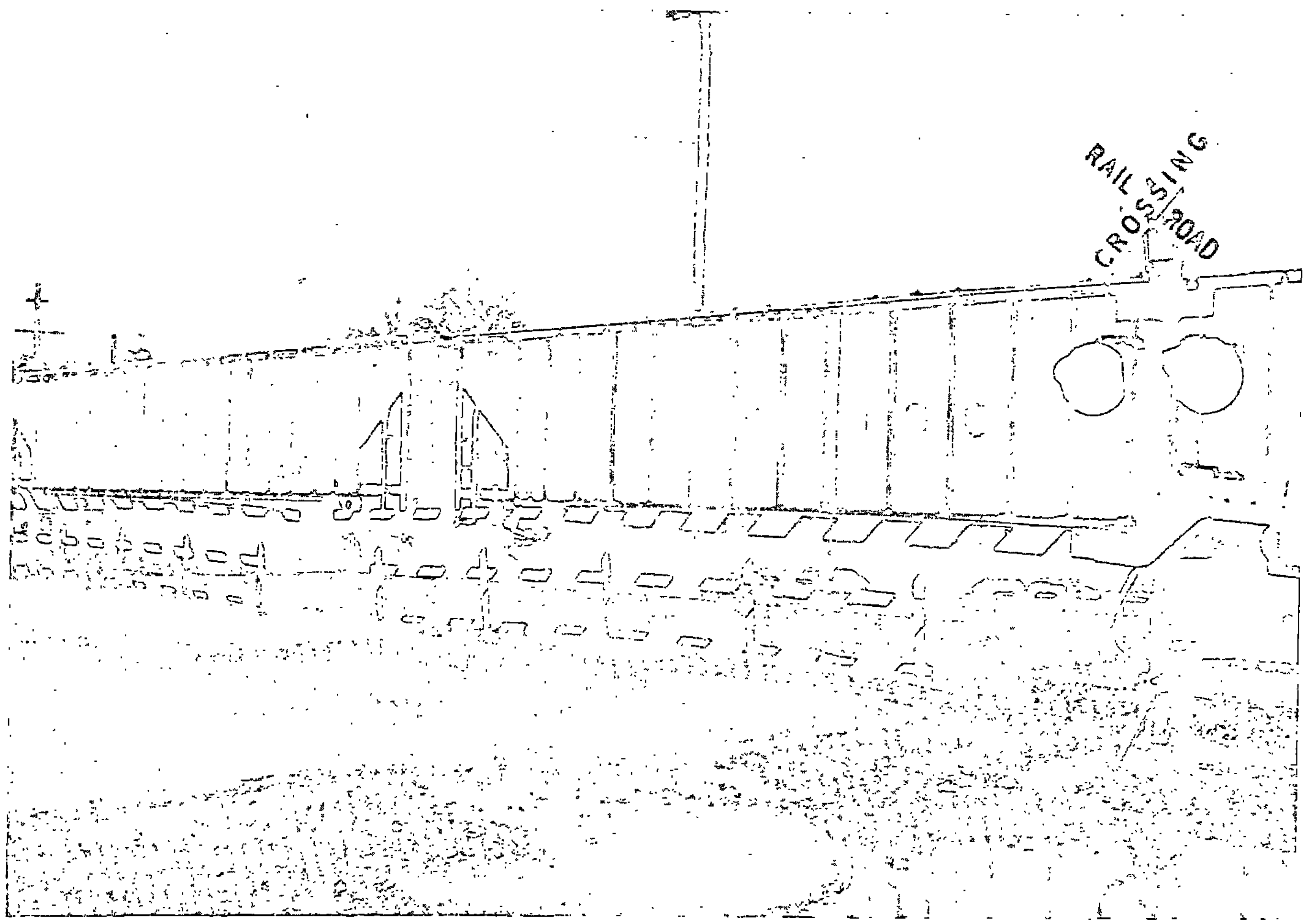

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
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McLean, Virginia 22101-2296

FOREWORD

This report documents the methodology and results of the field evaluation of a research project aimed at improving railroad-highway grade crossing safety by applying innovative active warning devices. The investigation evaluated three innovative warning systems: (1) 4-quadrant gates with skirts, (2) highway traffic signals with strobes, and (3) 4-quadrant flashing lights with overhead strobes. The 4-quadrant gates with skirts eliminated all violations at the test crossing by physically blocking the railroad tracks from highway traffic. With conventional 2-quadrant gates, 1 or more vehicles drove around the closed gates during 84 out of every 100 train arrivals. Fewer 10-second crossings and violations occurred with the highway traffic signals than the flashing light signals. While the observed violations were greatly reduced with the highway traffic signals, they were higher than intersection use and are a cause for general concern. No traffic signal violation problems, however, were found at nearby intersections. The 4-quadrant flashing light signals with overhead strobes did not produce measurable improvements in safety compared to the "before" 2-quadrant flashing light signals at the test crossing. The study found predictors, which provide constant warning times of train arrivals, had a positive effect on motorist behavior at the crossing.

Sufficient copies of the report are being distributed to provide one copy to each Regional office, Division office, and State highway agency. Direct distribution is being made to the Division offices. Additional copies are available from the National Technical Information Service (NTIS), U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

R. J. Betsold
Director, Office of Safety and Traffic
Operations Research and Development

NOTICE

Technical Report Documentation Page

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16. Abstract

Research was conducted to identify and evaluate innovative active warning devices with potential for improving safety at railroad-highway grade crossings. Candidate devices were identified and/or developed, and the most promising devices were evaluated in a detailed laboratory study. Three of the devices were chosen for field evaluation: (1) four-quadrant gates with skirts and flashing light signals; (2) four-quadrant flashing light signals with overhead strobes; and (3) highway traffic signals with white bar strobes in all red lenses.

The report documents the methodology and results of the field evaluations, presents a summary of the research leading up to the field evaluations, and presents the results of benefit-cost analyses for the innovative devices and guidelines for their implementation.

All three of the innovative devices proved to be technically feasible and practical, and all three devices were accepted and understood by the driving public. Two of the systems, the four-quadrant gates with skirts and the highway traffic signals, significantly improved crossing safety at the test crossings. The third system, four-quadrant flashing light signals with strobes, did not produce measurable improvements in safety at the test crossing. Train predictors (and the constant warning time they provide) can have significant positive effects on safety at crossings where flashing light signals or highway traffic signals are used.

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METRIC (SI*) CONVERSION FACTORS

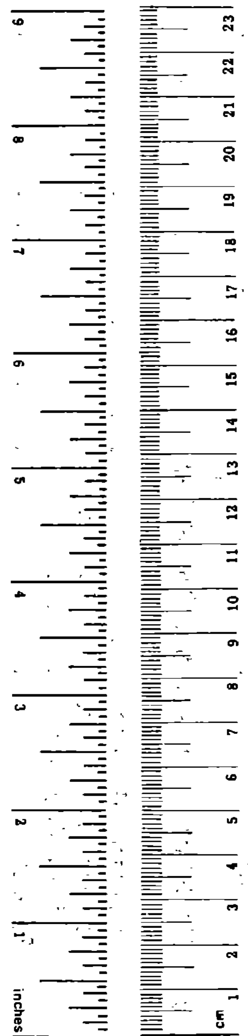
APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

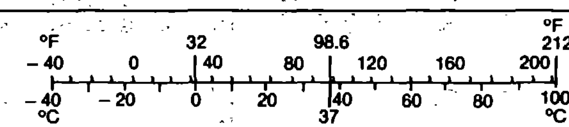
* SI is the symbol for the International System of Measurements



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

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LIST OF ABBREVIATIONS

A	accelerate
AAR	Association of American Railroads
AASHTO	American Association of State Highway and Transportation Center
AC	alternating current
ADT	average daily traffic
C	constant speed
CB	citizens' band
CL10	clearance time of less than 10 seconds before a train's arrival
CL20	clearance time of less than 20 seconds before a train's arrival
D	decelerate
DC	direct current
°F	degrees Fahrenheit
ft/s	feet per second
ft/s^2	feet per second per second
ft	foot/feet
in	inch/inches
IR	infrared
km/h	kilometers per mile
KS	Kolmogorov-Smirnov
LOS	level of service
MOE	measure of effectiveness
mi/h	miles per hour
MUTCD	<u>Manual on Uniform Traffic Control Devices for Streets and Highways</u>
PBRT	perception-brake reaction times

LIST OF ABBREVIATIONS (continued)

s	second
sec.	seconds
tpd	trains per day
UVC	Uniform Vehicle Code
vpd	vehicles per day
VHS	Video Home System

I. INTRODUCTION

During the 10-year period from 1977 through 1986, injuries and fatalities resulting from motor vehicle accidents at railroad-highway grade crossings have decreased from 4,452 and 846 to 2,227 and 507, respectively.(1) Much of this safety improvement may be attributed to the availability of Federal funds for grade crossing improvement projects.(2) The majority of the Federal funding has been used to upgrade passive crossings to active ones and has resulted in over one in four of the 192,454 public grade crossings in 1986 being equipped with active warning devices. In 1986, there were 22,066 crossings (11.5 percent) equipped with automatic gates and 32,778 crossings (17.0 percent) equipped with flashing light signals.(3)

Even with these improvements, over 50 percent of all car-train accidents in 1986 occurred at 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 these active traffic control 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 time, many innovative warning devices have been developed for use both at and in advance of crossings, yet field implementation of new concepts has been minimal.

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 to identify and evaluate innovative active warning devices with potential for improving safety at railroad-highway grade crossings. As part of the research, candidate devices were identified and/or developed, and the most promising devices were evaluated in detailed laboratory studies. Based upon the results of the laboratory evaluation, three of the devices were chosen for field evaluation at actual crossings. The three innovative active warning devices selected were: (1) four-quadrant gate and flashing light signal system with skirts; (2) a four-quadrant flashing light signal system with overhead strobes; and (3) a highway traffic signal system with white bar strobes in all red lenses.

The objectives of the field evaluations were to determine the effects of alternative active warning devices on driver behavior and crossing safety, and to assess the cost-effectiveness of the three candidate devices. In order to accomplish these objectives, the following tasks were performed:

1. The existing driver performance measures at three selected railroad-highway grade crossings were identified and quantified.
2. Driver performance measures at the three crossings before and after the innovative devices were installed were compared.
3. The cost-benefit relationships for the three innovative devices were evaluated.

This report documents the field evaluations and presents the final project results. Chapter I presents background information on the overall project and research objectives. Chapter II reviews the history and performance of warning devices used at railroad-highway grade crossings, including previous driver performance studies at railroad-highway grade crossings. It also reviews the history and performance of highway traffic signals. The plan for field evaluation is described in chapter III. Chapter IV summarizes the field site selection and study preparation. The field evaluation of the four-quadrant gates with skirts and flashing light signals is discussed in chapter V. Chapter VI describes the field evaluation of the four quadrant flashing light signals with overhead strobes. Chapter VII provides the results of the field testing of the highway traffic signals. Chapter VIII presents the benefit-cost relationships for the three innovative active warning devices. Chapter IX provides guidelines for implementation of the innovative active warning devices in selected field situations. The summary of results and conclusions are presented in chapter X. Appendix A briefly summarizes the results of earlier tasks of this research project.

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 at times may 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:

- Approaching the crossing.
- Within the critical stopping distance zone.
- 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, by 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. The drivers' 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 drivers' 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, i.e., 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, shown in figure 1, was a signalman on horseback preceding the train, waving a flag, and shouting "a train is coming" to warn people away from the tracks.[(6)] 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 to activate a visual device known as a "wig-wag" which simulated the action of a signalman waving his flag or lantern.[(7)] 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.[(8)] Basically, the unit consisted of two alternately-flashing

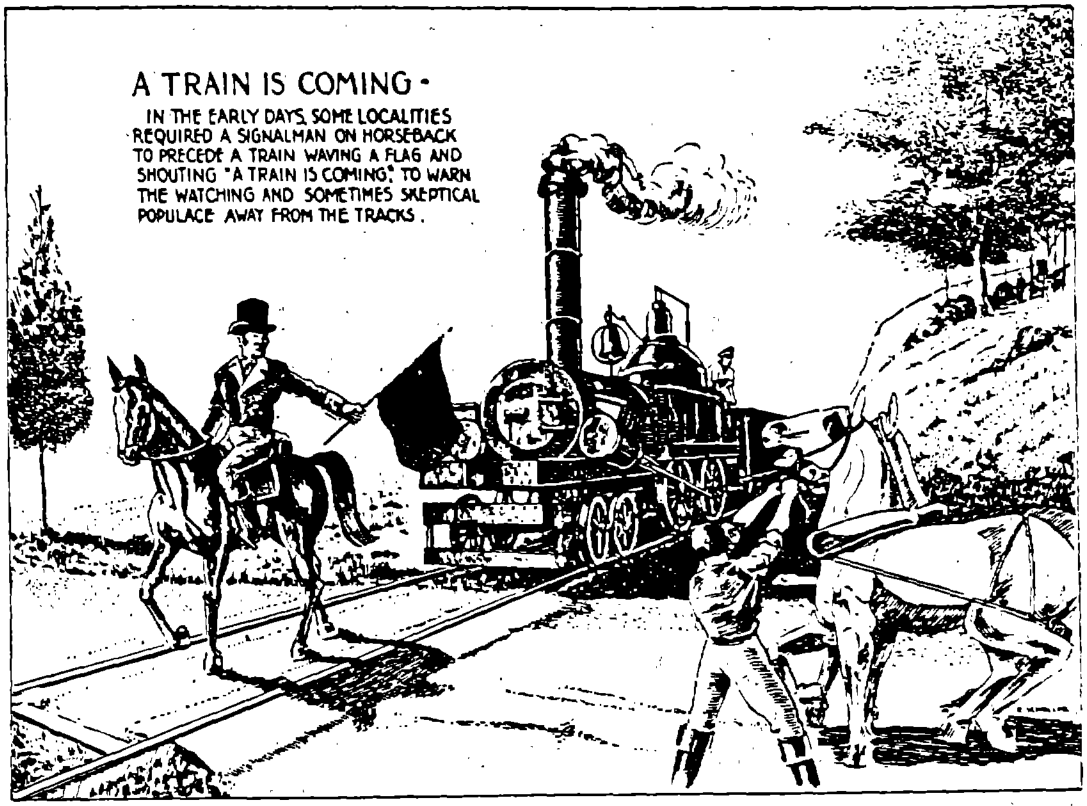


Figure 1. An early active warning device for use at railroad-highway grade crossings.

horizontal red lights each with 5-3/8-in diameter lenses. The use of this device spread rapidly and operational experience soon revealed a need for much stronger lights; as a result, the 8-3/8-in diameter lens was introduced in 1923. By 1930, over 60 different warning devices were 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, be adopted as standard. 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.[9] In the same year, 26 automatic gates were installed nationwide in an effort to provide more protection and to reduce labor costs. Interestingly, both the manual and early automatic gates blocked the entire roadway as is currently done in much of Europe.[10] 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 10 years short-arm gates were being installed at approximately 1,000 new crossings per year.[9]

Flashing Light Signals. A standard flashing light signal assembly is illustrated in figure 2.[11] 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-mounted or cantilevered. 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 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

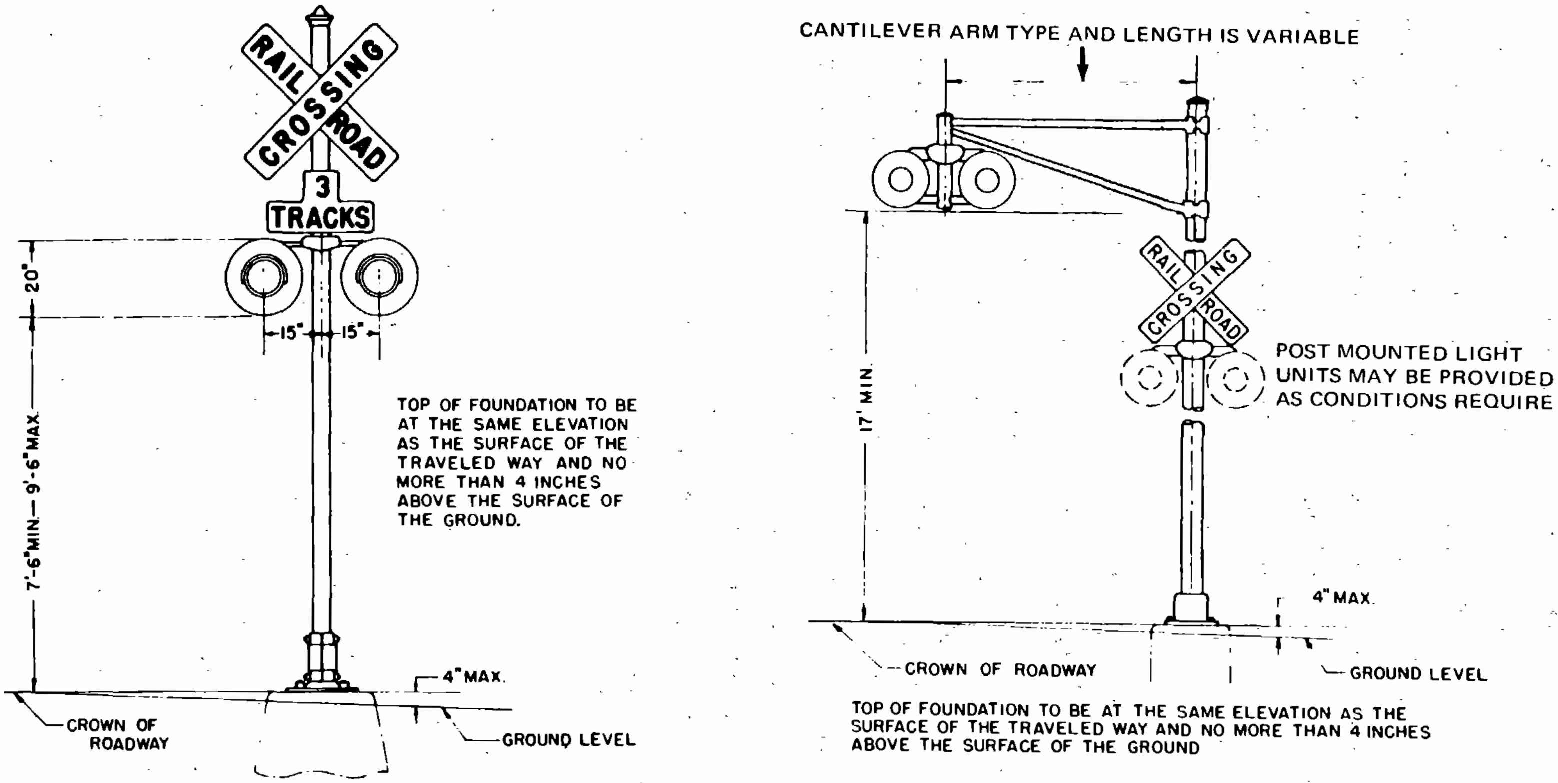


Figure 2. Typical flashing light signal assemblies as illustrated in the MUTCD.

used to provide backup power, in most cases, for 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.[12] They continue to flash until after the train has cleared the crossing. The two lights are spaced 30 in apart on a horizontal crossarm and consist of either two 8-3/8-in or two 12-in diameter red lenses, or roundels as they are more commonly called, each surrounded by 20-in 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.[11] 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 of approximately 4 feet above the pavement's surface. The red and white stripes are 16 in in length and are cut such that they slope down toward the center of the roadway at a 45 degree angle. The gate arm tip end light burns steadily and the two inside lights flash alternately. 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 5 to 10 seconds. Gate arms can be made of aluminum, fiberglass, or wood. Their generally acceptable maximum practical length is 44 ft.

Guidelines for Use. Guidelines for the conditions under which different warning devices should be installed are contained in three documents--(1) the <u>Manual of Uniform Traffic Control Devices</u> (MUTCD); (2) the <u>Railroad-Highway</u>

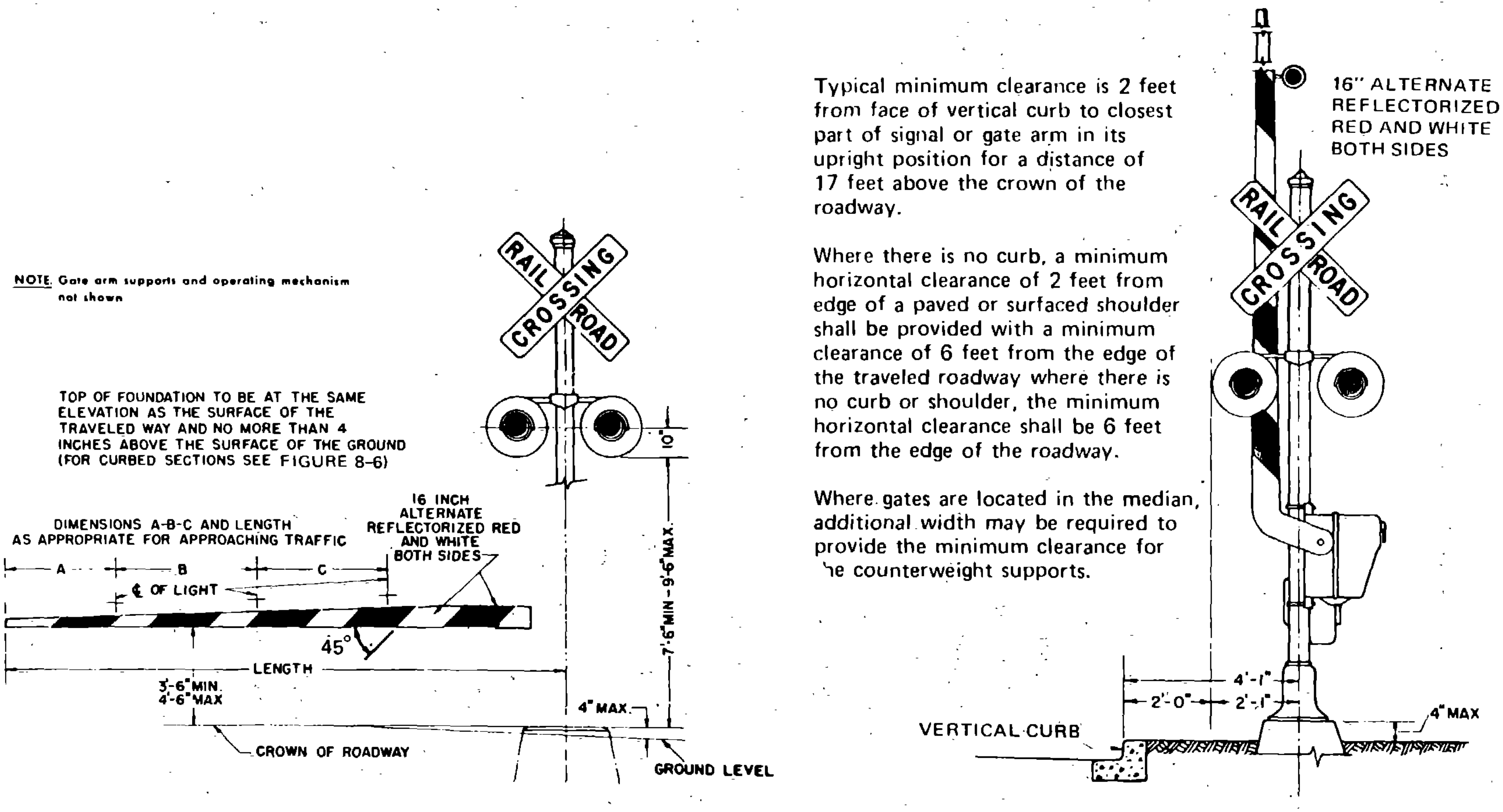


Figure 3. Typical automatic short-arm gate installation as shown in the MUTCD.

Grade Crossing Handbook; and (3) the Traffic Control Devices Handbook.[11,12,13,14,15] The MUTCD 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 and illustrated in table 1.[13,14]

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 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.[16] However, only 11 percent of the crossings were not in compliance with the Railroad-Highway Grade Crossing Handbook guidelines 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.[13,14] Thus, it appears that the "Handbook" guidelines are being adhered to fairly well whereas strict compliance with the MUTCD standards is 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) and in various State traffic regulations. Following is an excerpt from the UVC, Section 11-701, establishing driver duties at grade crossings.[17]

> "(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;

Table 1. Factors used in determining the need for active traffic control devices at railroad-highway grade crossings.(9,10)

- Vehicular traffic volume--an ADT of less than 1,000 would require other significant warrants;
- Railroad traffic volume--less than 6 trains per day would normally represent light exposure except where passenger train operations exist;
- Maximum train speeds--speeds greater than 50 miles per hour in rural areas or 35 miles per hour in urban areas deserve careful consideration;
- 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;
- Pedestrian volumes--pedestrian volumes of 150 or more per hour may be a significant determinant;
- Accident record--occurrence of a train-involved accident within a three year period indicates a need for careful analysis;
- Reduced sight distance--limited view of tracks should be checked for limited driver reaction; and
- Elimination potential--closing lightly used crossings and installing active deveices at more heavily used crossing should be considered.

Additional factors should be considered for automatic gate

- Multiple main line railroad tracks;
- Multiple tracks where a train on or near the crossing can obscure the movement of another train approaching the crossing;
- High-speed train operations combined with limited sight distance;
- Combination of high speed and moderately high volume highway and railroad traffic;
- Presence of school buses, transit buses, or farm worker vehicles in the traffic flow;
- Presence of trucks carrying hazardous materials, particularly when the view down the track from a stopped vehicle is obstructed;
- Presence of passenger trains; and
- Continuance of accidents after installation of flashing lights.

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; . . .

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, at least nine States do not expressly prohibit driving under or around a lowered gate arm, 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.(18)

Indeed, not all drivers understand their responsibilities at a grade crossing. In a study of 829 subjects, 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.(19) Approximately 30 percent of the respondents did not recognize the standard MUTCD 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.(11) 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 (MOEs) reported in these studies include looking behavior, speed profiles, speed changes, deceleration levels, and conflicts and violations. These MOEs are discussed individually in the following sections:

Looking Behavior. Looking behavior refers to whether and where the driver looks when approaching 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.[20] 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.[21] 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.[22] 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

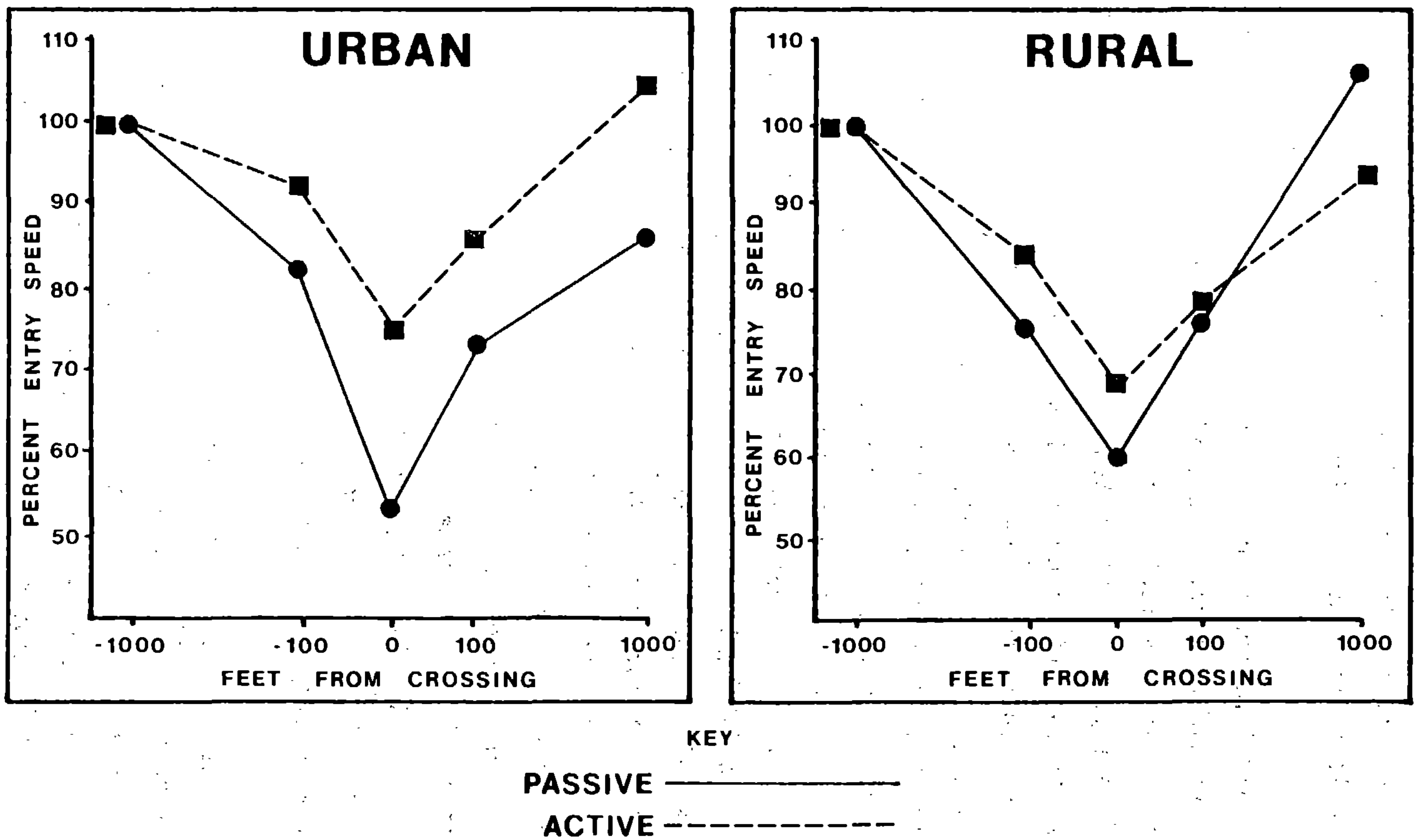
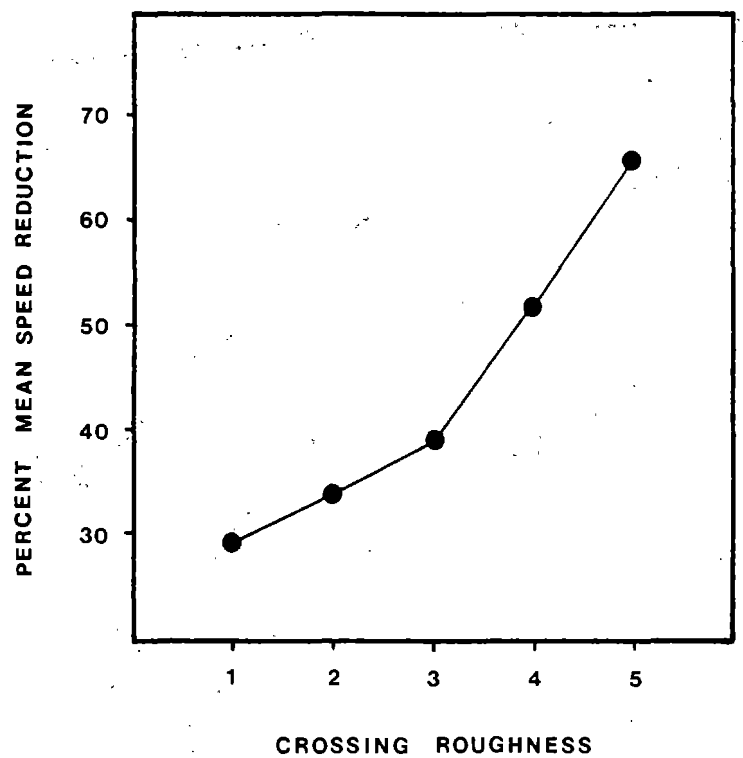


Figure 4. Speed profiles by protection type for all vehicles at two-lane urban and rural crossings.

active crossings. This was true for 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.[22]

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.[23,24] 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.[23] Note that free-flow vehicles entered the crossing area at about the same speed as the first unobstructed 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



Crossing roughness was estimated by field observers subjectively as:

$$\text{Crossing Roughness} = \frac{50 \text{ mi/h} - \text{"Test Driver Safe Speed" in mi/h}}{10}$$

Figure 5. Percent speed reduction as related to crossing roughness.

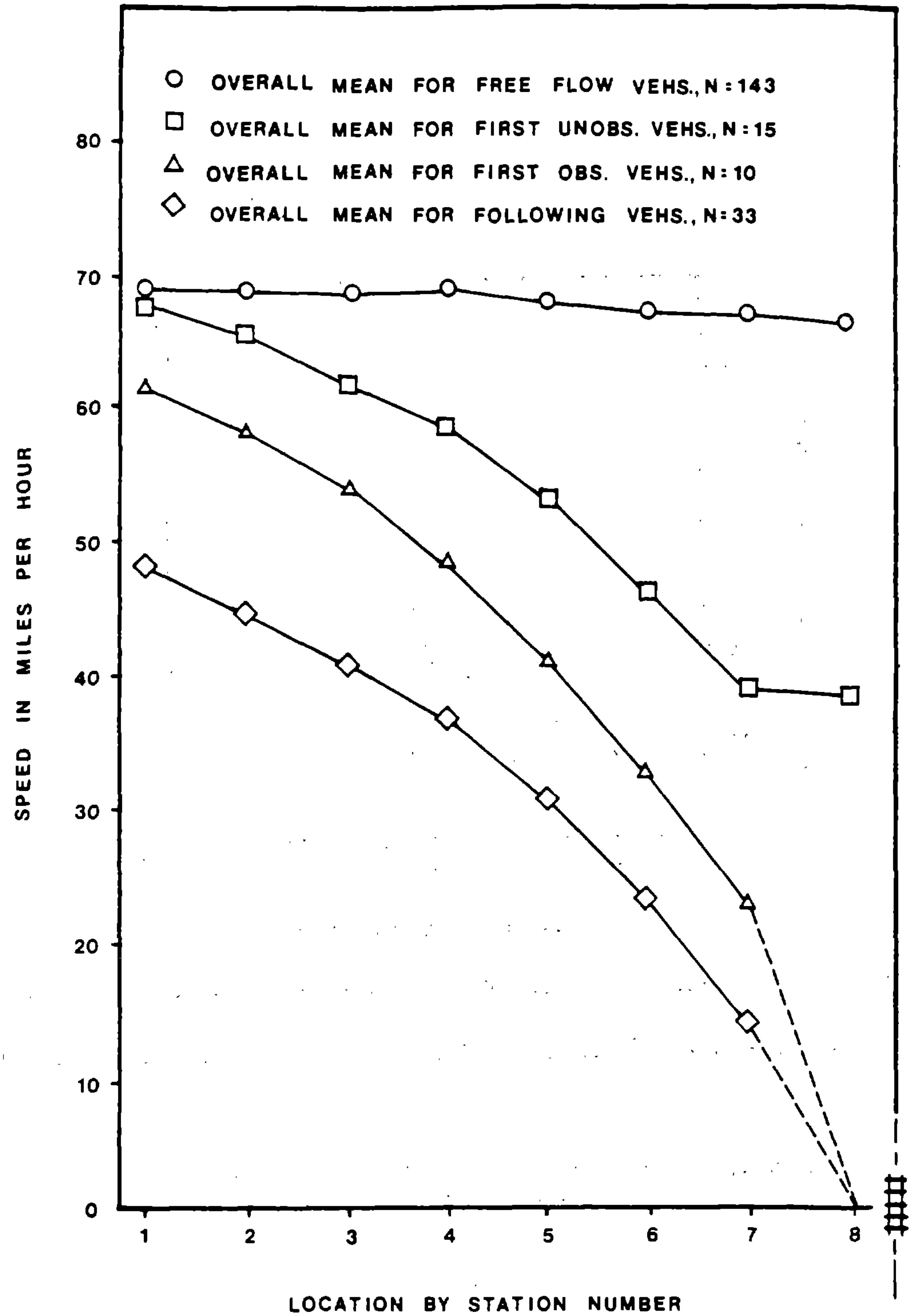


Figure 6. Approach speed profiles for different categories of entering vehicles.

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 immediately present, are not commanding enough to cause unobstructed drivers to decrease their speed until they are relatively close to the crossing. In other words, drivers 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.[23]

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. Figure 7 presents the speed profile results from this study.[24] 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 mi/h. 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 drivers. 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.

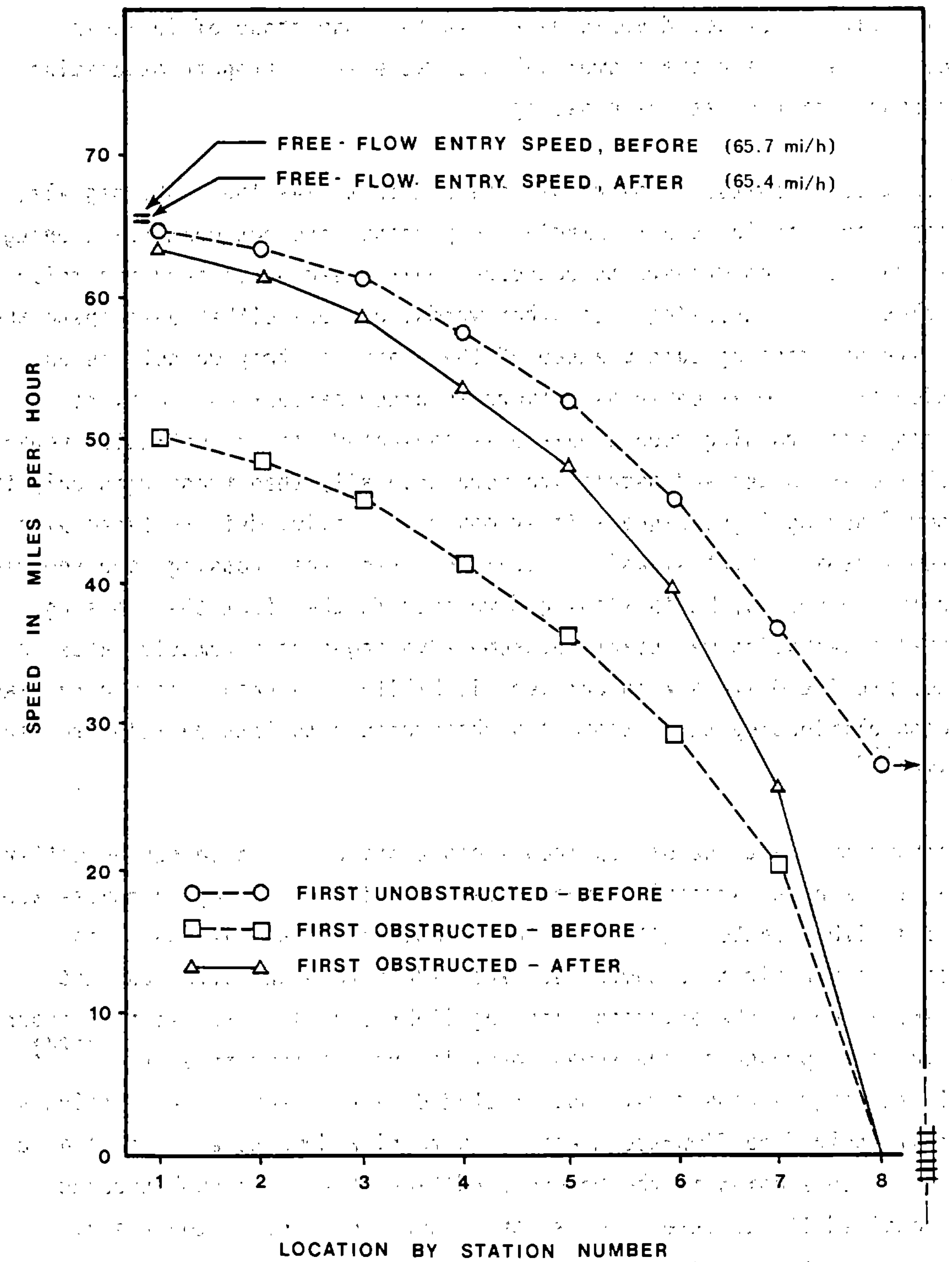


Figure 7. Approach speed profiles before and after flashing lights were replaced by automatic gates.

The other comparative study evaluated five warning device conditions at the same site:[25]

- Passive signs and markings.
- Nonactivated flashing light signals.
- Activated flashing light signals.
- Nonactivated flashing light signals and raised automatic gates.
- Activated flashing light signals and lowered automatic gates.

Table 2 and figure 8 summarize the results from this study.[25] 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 great enough to stop the vehicles 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.[26] 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.[20] From this

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 (4,326)
Speed at 200 m						
Mean (km/h)	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/h)	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/h)	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: 1.0 km/hr = 0.6214 mi/hr; 1.0 meter = 3.281 feet; * = significant at 0.05 level; and ** = significant at the 0.0001 level.

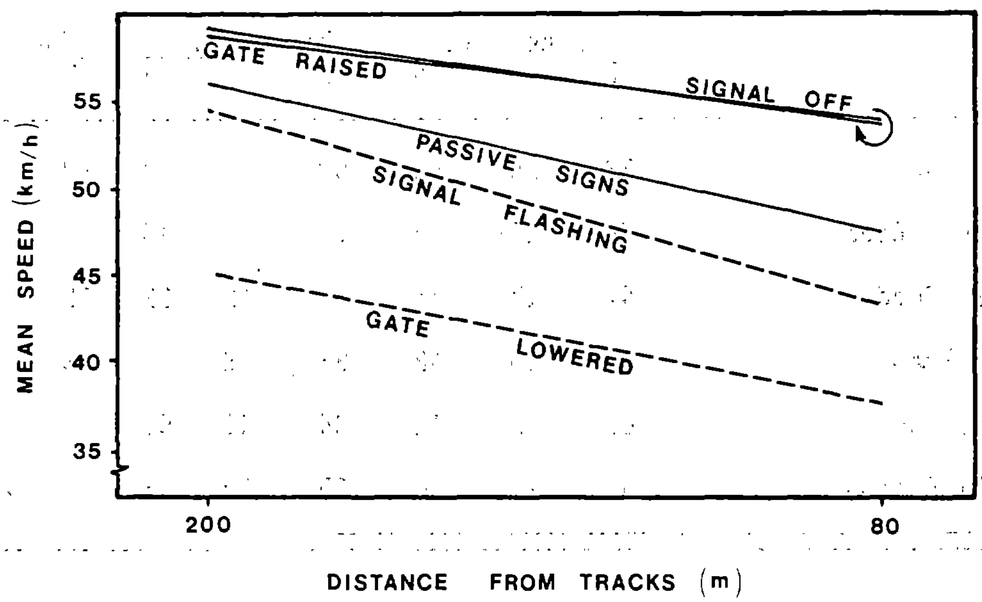


Figure 8. Mean speed approaching a railroad-highway grade crossing with different warning devices.

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.

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 nonactivated conditions. Also, variance of the mean speed change 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 that 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 defines several deceleration levels as follows:(27)

- Emergency--greater than 20 ft/s^2.
- Very uncomfortable--14 to 20 ft/s^2.
- Uncomfortable--11 to 14 ft/s^2.
- Undesirable--8 to 11 ft/s^2.
- Practical--less than 8 ft/s^2.

Two studies have analyzed deceleration levels at grade crossings and reached similar conclusions.(23,24) In the first study, 13 drivers out of 520 exceeded the practical deceleration level when approaching an activated flashing light signal.(23) 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.(24) 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.[28] It is not reported how many of those who did not stop, crossed unsafely; however, dependent upon State law, those who drove around the lowered gates probably did so illegally.[18] Other studies have reported from 15 percent to 60 percent of approaching drivers crossing in front of a train while the flashing light signals were activated.[22,25]

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.[20] 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.[22]

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.(29) 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.(30) The Traffic Engineering Handbook assumes a PBRT in response to a yellow indication of one second; however, actual intersection stopping distance data revealed a much higher value of PBRT when stopping was made.(27,32,33) When these data were analyzed using deceleration levels ranging from 8 to 15 feet per second per second, three categories of driver behavior emerged as follows:(34)

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.[35] 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 mi/h. In situations requiring immediate reaction (e.g., approach speeds greater than 40 mi/h), 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.[35] 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 PBRTs reported in the aforementioned studies are representative of operationally alert conditions in that 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 PBRTs 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.[36]

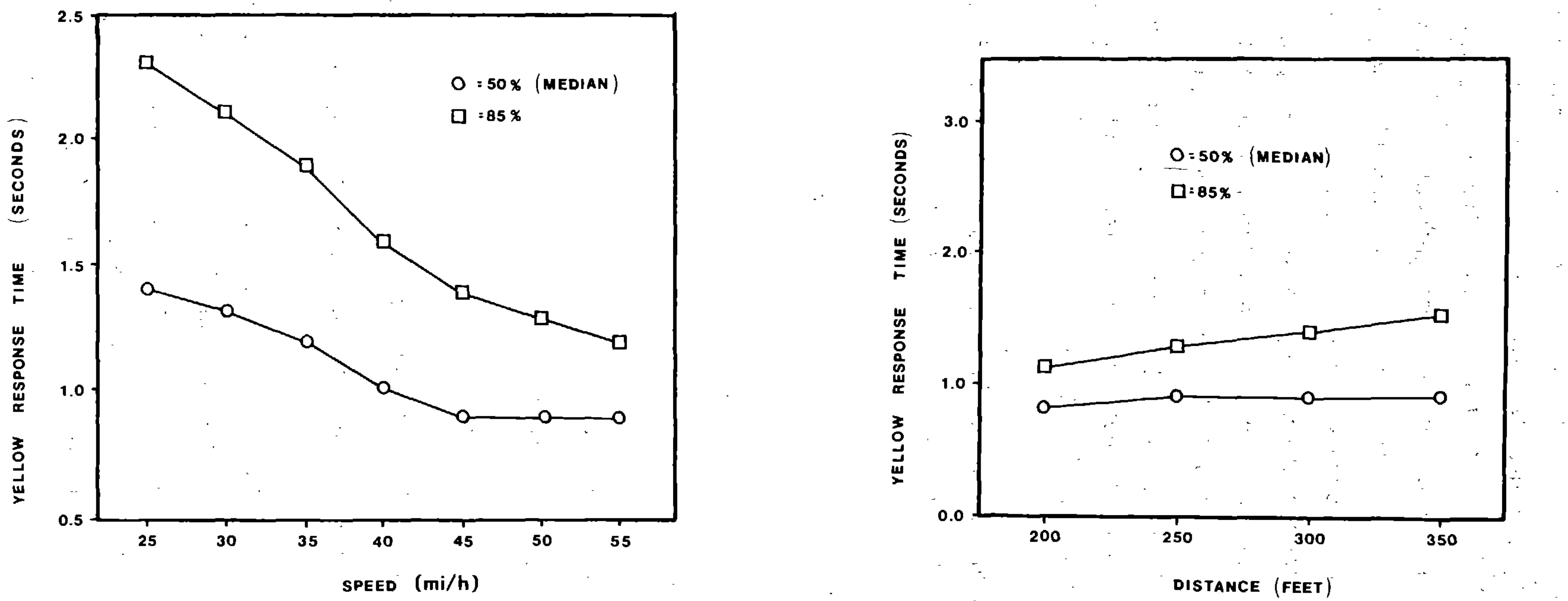


Figure 9. Perception-brake reaction time in response to onset of yellow as a function of speed and distance.

Deceleration. Some researchers recommend a deceleration of 10 feet per second per second (ft/s^2) for use in calculating the length of a traffic signal change interval.[37,38] In fact, this value is recommended in the 1982 Transportation and Traffic Engineering Handbook.[39] A study with field observations reported that when the required deceleration was 8 ft/s^2 or less, virtually all drivers stopped. When the required deceleration was between 8 and 12 ft/s^2, some drivers stopped while others proceeded through the intersection. When the required deceleration was greater than 12 ft/s^2, few drivers stopped.[40] 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:

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

or

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

where:

d = deceleration, ft/s^2.

v = initial velocity, ft/s.

v_o = final velocity, ft/s.

s = distance over which change in velocity occurs, ft.

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.[35] Note that

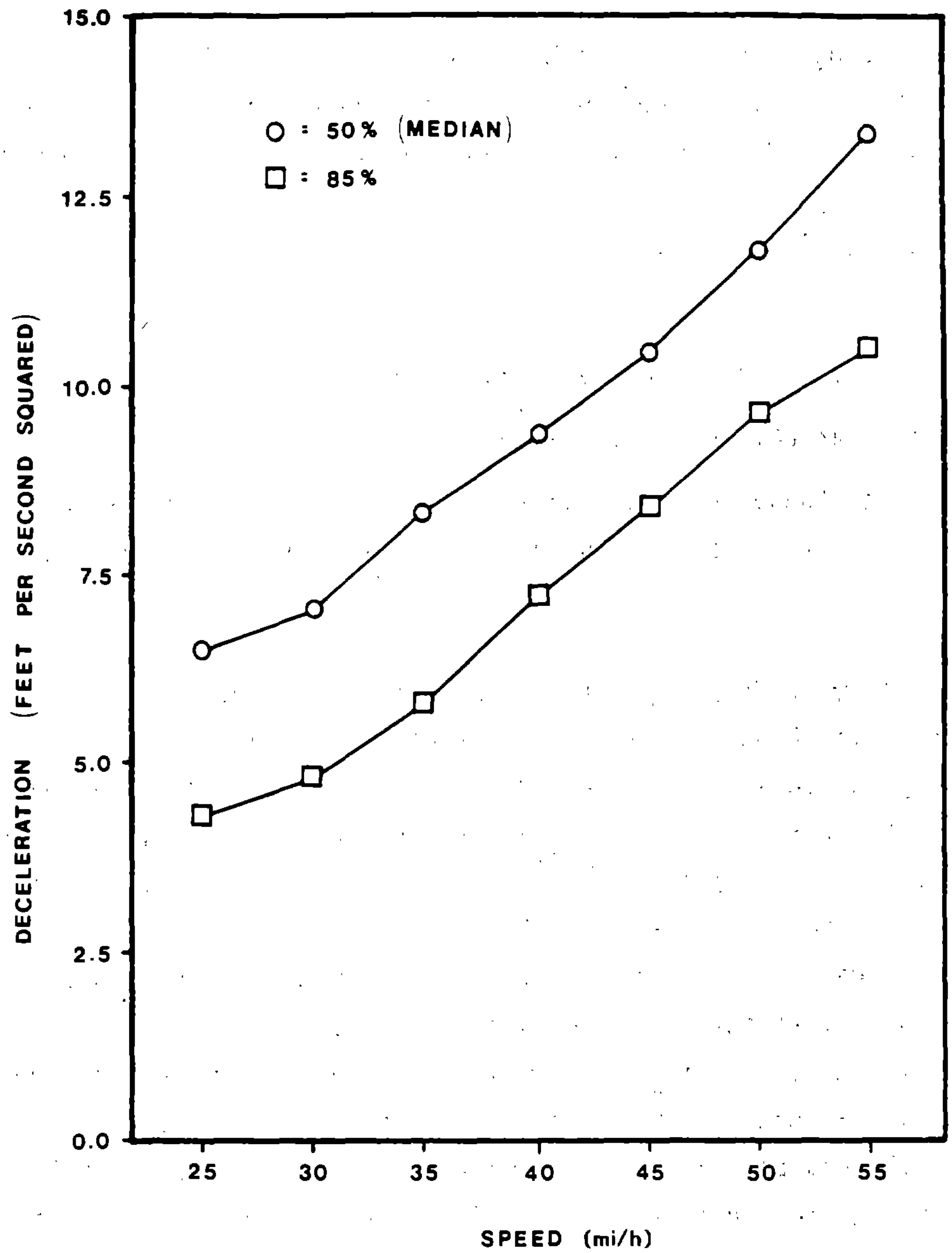


Figure 10. Deceleration rate in response to onset of yellow as a function of speed.

85 percent of the higher speed drivers utilized deceleration levels of 10.6 ft/s^2 or less. The 10 ft/s^2 deceleration level assumed by the Transportation and Traffic Engineering Handbook represents 90 percent of this value.[39] Therefore, a deceleration of 10.5 ft/s^2 was suggested as normal behavior on level grade.[35]

Several other factors might have an effect on deceleration, one of which is grade. Supposedly, drivers will accept higher than normal deceleration levels on a downgrade. One study quantified this effect in the following equation:[35]

$$d = 10.5 + 0.75\ g$$

where:

d = normal deceleration level, ft/s^2.

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 or several intersections with similar approach speeds.[30,32] The findings from a study which looked at a range of conditions are presented in figure 11.[35] 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 3 seconds or more away from the intersection. Furthermore, 85 percent of the drivers who 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

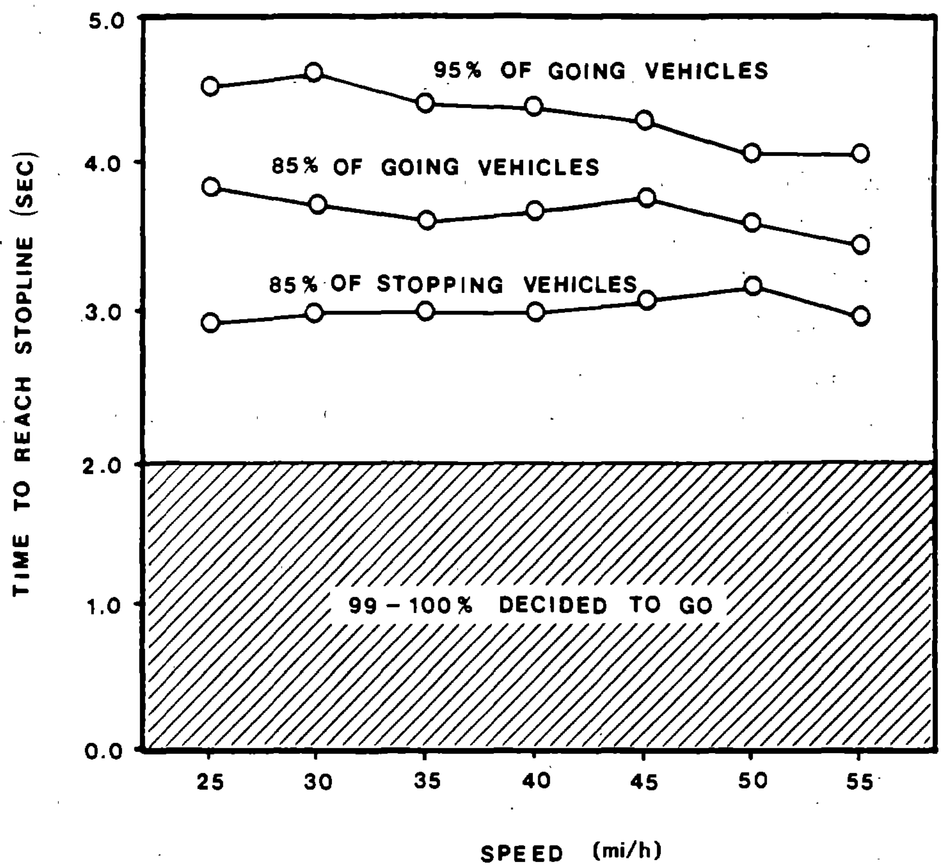


Figure 11. Driver's decision to stop or go in response to yellow as a function of time to reach the stop line.

reached.[11] However, as shown in figure 10, approach speed 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.[35]

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.[41] 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 can be 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 and Traffic Control Devices Handbook; however, the responsibilities the different warning devices place on approaching drivers are not well understood by the general public.[11,15]

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.[21] 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, speed profiles 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 gradually 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.

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 ft/s^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 who do not stop enter the intersection within 4.5 seconds of the onset of yellow regardless of their approach speed.

III. 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: (1) the four-quadrant gates with skirts; (2) the four-quadrant flashing light signal system with red strobe lights over the traffic lanes; and (3) 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, 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 used 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 (chapter IV describes the study crossings and presents details on design and installation of the innovative devices). Table 4 summarizes the before-and-after data collection plan, showing the device assignment to the study sites and the schedule for collection of the driver behavior 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

Table 4. Data collection plan for field study.

Crossing	Existing Condition (Spring 1985)	Improved Condition (Spring 1986)	Improved Condition (Summer 1986)
Cherry Street	Two-Quadrant Gate and Flashing Light Signal System	Four-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

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 1- to 2-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.[11] 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 1 month (2 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 3 to 4 months (6 to 8 person-months) were actually expended for data collection during each study phase at each of the three sites. Also, a minimum of 2 months (4 person-months) was required to reduce and analyze the data from an individual study. Therefore, approximately 5 months (10 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 the time as long as visibility was such that the data could be collected.

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 MOEs. To avoid influencing drivers and hence influencing their responses, MOEs were selected which could be obtained with a minimum of interference and detection by drivers. In addition, only commonly-accepted, safety-oriented driver performance measures were considered. As a result of these considerations, the MOEs selected for evaluation were as follows:

- Speed profiles.
- PBRTs.
- Maximum deceleration levels.
- Violations.
- 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 PBRTs; (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 ft/s^2) was also used for evaluation purposes.

In each of the previously described comparisons, the Kolmogorov-Smirnov (KS) goodness of fit test was used to determine whether or not any observed differences in distributions were statistically significant.[42] 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 hypotheses, 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 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. A clock superimposed on the film permitted the calculation of elapsed time. 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 were used to ascertain whether or not observed differences were statistically significant.[43]

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.[44] These 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 PBRTs observed in response to alternative active warning devices are statistically significant. For this particular driver performance measure, the following comparisons were made:

- Existing and improved conditions at the Cherry Street crossing.
- Existing and improved conditions at the Ebenezer Road crossing.
- 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 four-quadrant gates with skirts, 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 who could reasonably stop in response to the warning device failed to do so. In this analysis, it was assumed that vehicles farther than 5 seconds from the crossing at the time of device activation were capable of reasonably stopping; 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.(35) 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 those described for PBRTs.

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 were 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, a 20 foot long vehicle starting from a stop 20 feet away from the crossing, accelerating at a normal rate of 4.8 ft/s^2, and clearing a point 20 feet on the far side of the crossing, 2.5 seconds before the train's arrival.[45,46] 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 driver, vehicle, and/or warning system error. The MUTCD appears to address this point by requiring a minimum warning time of 20 seconds.[11]

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 CL10s and CL20s were the same as those described for PBRTs.

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, tape switches, and/or time-lapse movie cameras to determine looking behavior, reaction times, and speed distance profiles of drivers in this zone.[20,22,23,24] 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 subsections 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 2 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-in T120 VHS cassettes. The recorders could operate in a temperature range of 32-104 °F and relative humidity range of approximately 32-80 percent.

The video cameras used with the recorders were black and white closed circuit television cameras that weighed 2 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 0-140 °F and 0-95 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 8 to 10 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 10 seconds prior to the train activating the active warning device at the crossing. The detectors were powered by batteries and as shown in figure 12, 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 5 seconds after the recorders were activated, the timing signal was received and recorded on the audio track of the videotape 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 startup 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.[47]

Equipment Setup. 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 built. As shown in figure 13, each pole was mounted on a combination box- and pyramid-shaped base. The camera was mounted inside the weatherproof 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

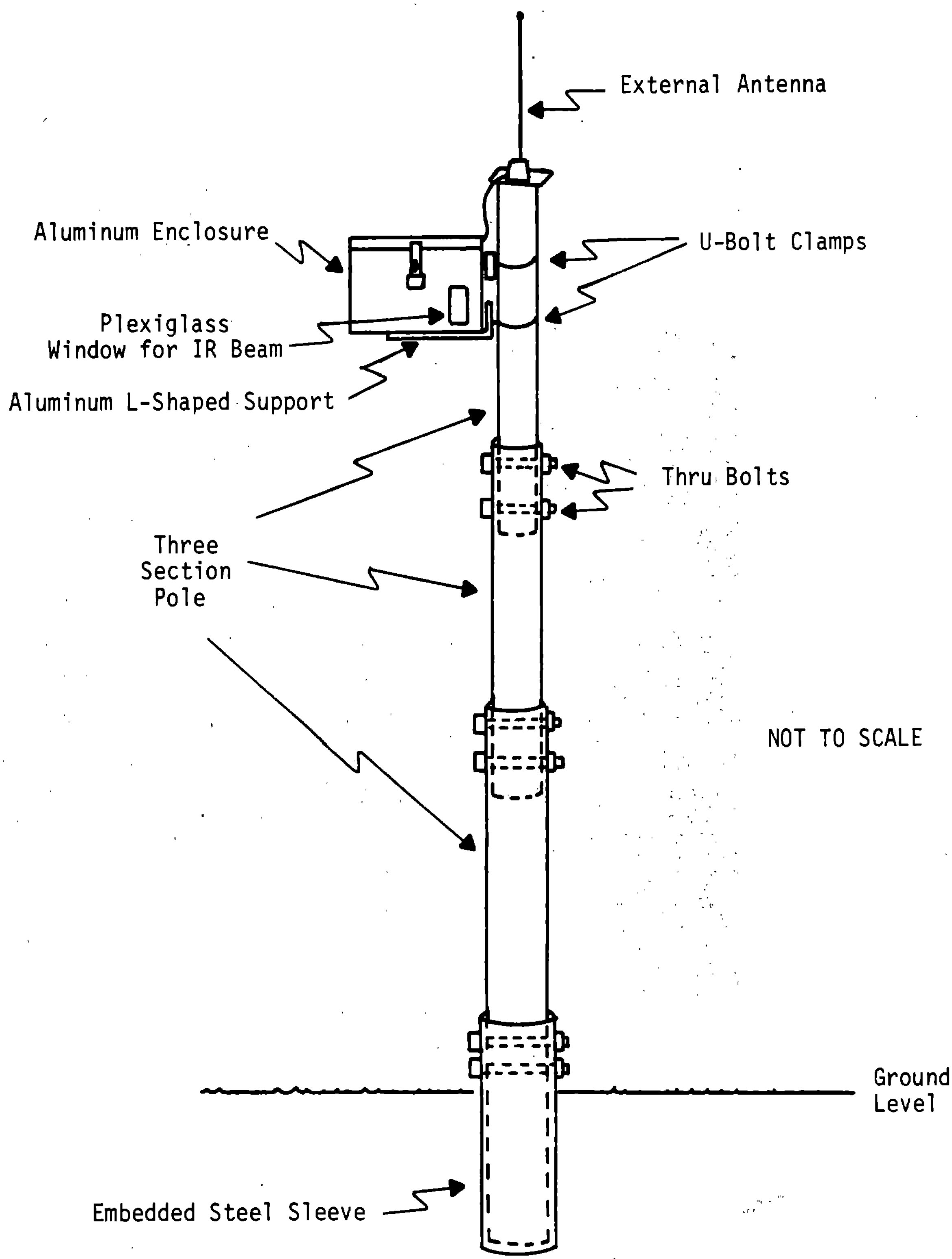


Figure 12. Train detector unit.

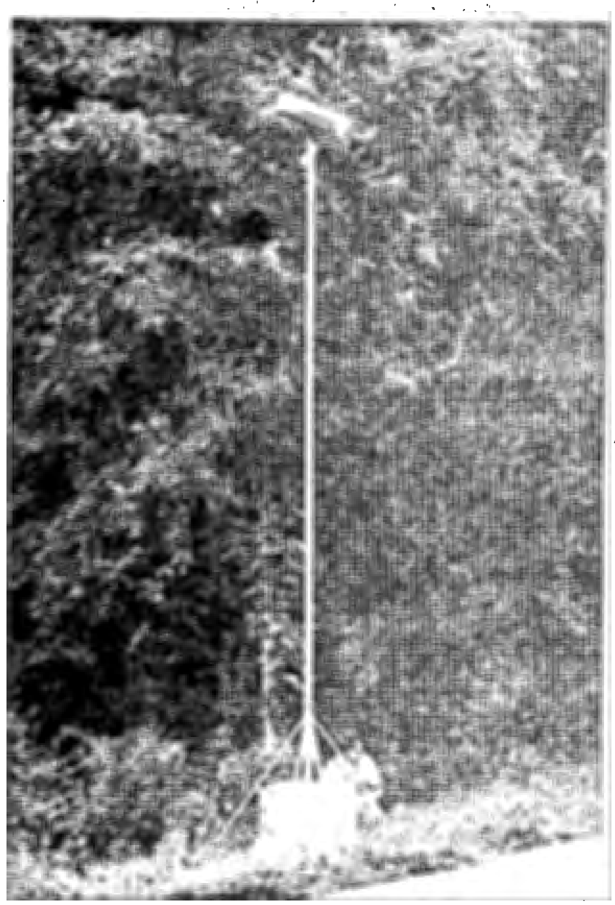


Figure 13. Pole-mounted camera installation.

and recorder, and the antenna and CB receiver. The base 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 14. 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 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 2-3 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

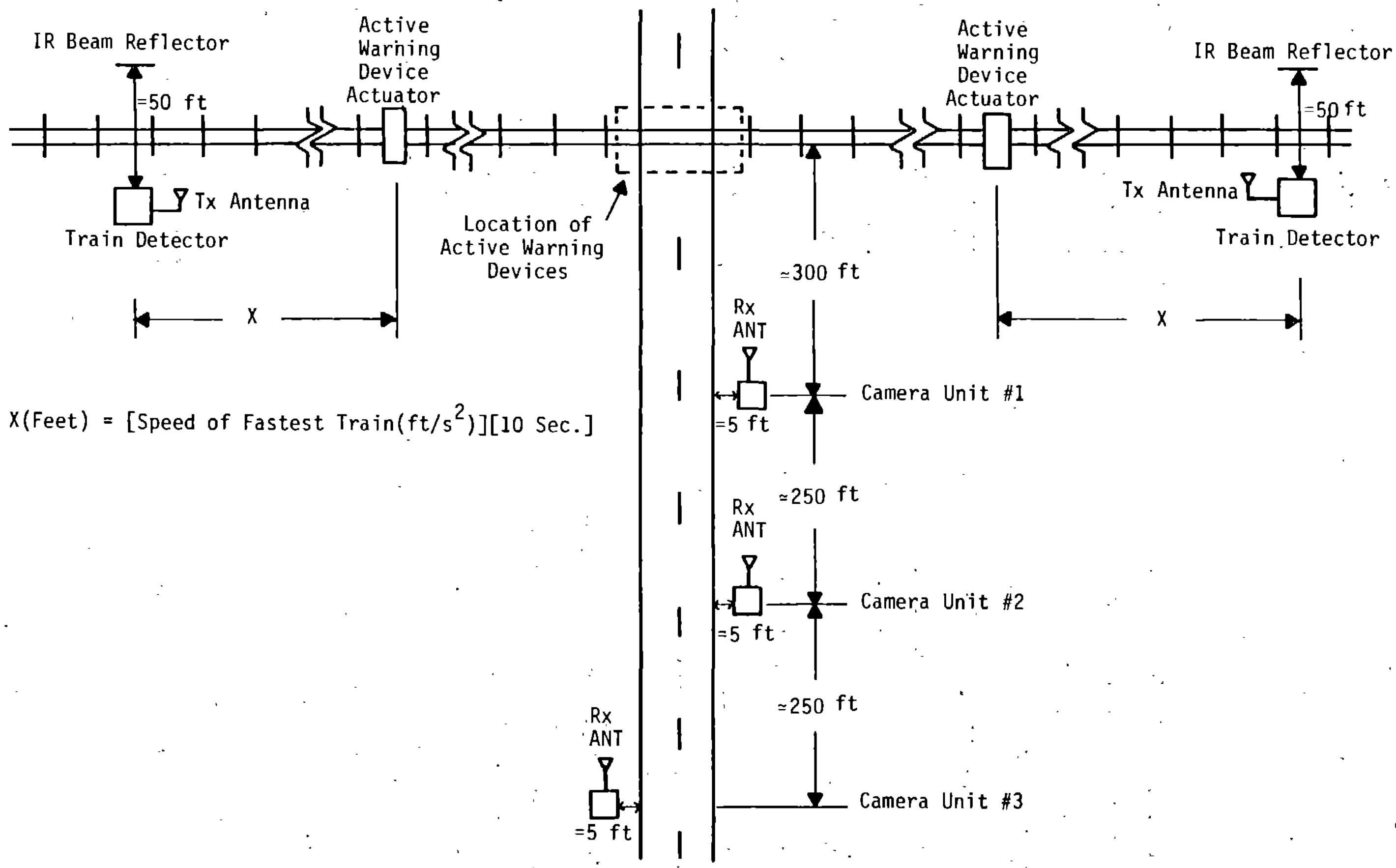


Figure 14. Typical equipment setup for the field studies.

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 fields (1/60 of a second), speed was determined by using the known distance between coordinates on the screen and dividing by the number of fields it took the vehicle to travel between these points. (In the National Television Standards Committee format, two fields constitute one frame.). 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 5 to 10 fields 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 PBRT and the number of violations and vehicles crossing were manually recorded as the master tapes were being viewed. PBRT was simply the number of fields 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 behavior data at three crossings were collected with the use of three pole-mounted video cameras, with each 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 2-1/2 to 3 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 PBRTs 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.

IV. 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 have been considered in the initial phase of the field test, it was necessary that it have a relatively high train and traffic volume, have a history of at least some accidents, and have 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 7 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 5. The following subsections describe the three crossings in greater detail.

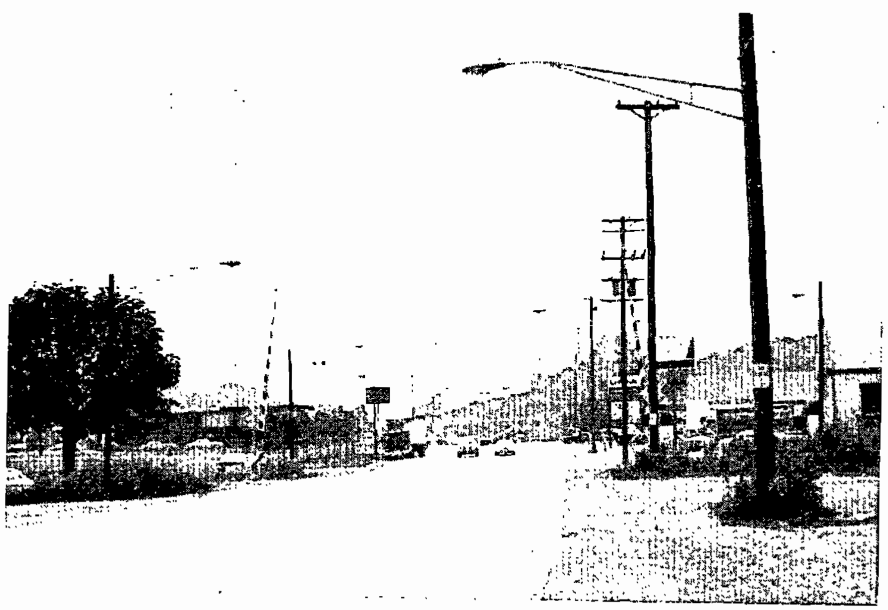
Cherry Street Crossing. The crossing (Inventory Number 730584K) selected for four-quadrant gates is located in the eastern part of Knoxville on Cherry Street. The existing active warning devices at the crossing were automatic gates, standard railroad flashing light signals, and a bell. It was ranked as the 223rd most dangerous crossing in the State. As shown in figure 15, the roadway was four lanes wide and straight and level on both

Table 5. Summary description of three field study locations.

Physical Descriptions	Crossing Location: Cherry Street	Cedar Drive	Ebeneezer 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 mi/h	40 mi/h	40 mi/h
Number of Tracks	2	1	1
Thru Train Volume	10 tpd	16 tpd	10 tpd
Train Speeds	20-40 mi/h	5-40 mi/h	5-55 mi/h
Number of Accidents (previous 5 years)	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 5-year period as this was the reporting requirement for the national inventory.

Looking north



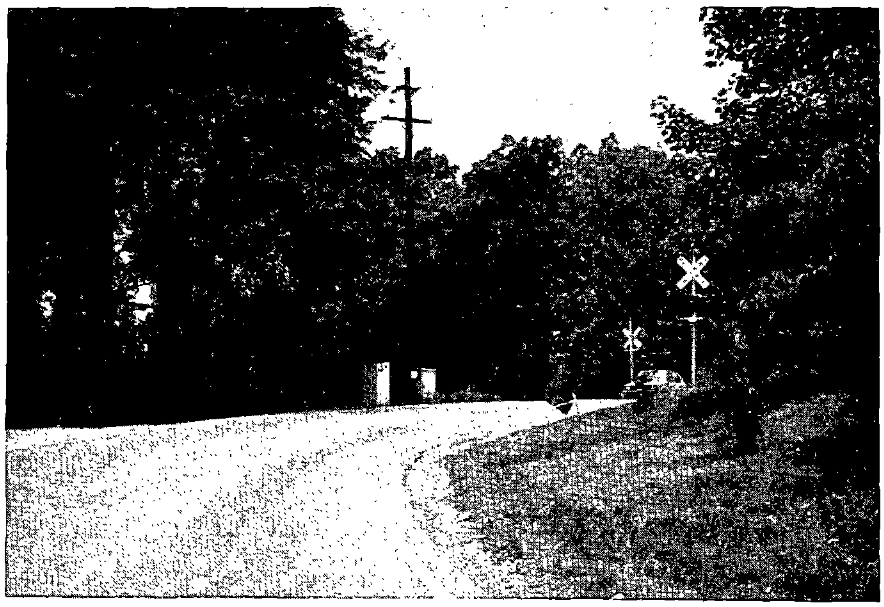
Looking south

Figure 15. Cherry Street crossing.

approaches to the crossing. 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 mi/h, and train speeds at the crossing ranged from 20 to 40 mi/h. Although only one car-train accident had occurred at this location in the past 5 years, large numbers of motorists were observed driving around lowered gate arms at this site. This type of behavior made the Cherry Street crossing a potentially dangerous crossing. Four-quadrant gates with skirts were 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 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-in 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 is 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-in roundels and a bell. It was ranked as the 276th most dangerous crossing in the State. As shown in figure 16, the roadway was two lanes wide and its horizontal and vertical alignments limited the crossing's visibility from both directions. Several other sight distance obstructions on both approaches also 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 mi/h, and train speeds at the crossing ranged from 5 to 55 mi/h. Additionally, one car-train accident had occurred at this



Looking north

Looking south

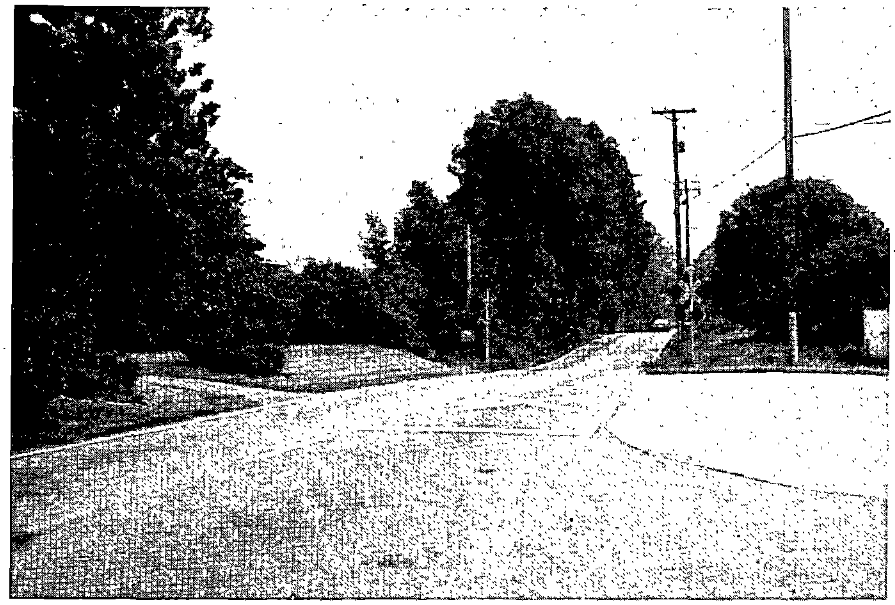
Figure 16. Ebenezer Road.

location in the past 5 years. 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-in flashing lights located on the right of approaching motorists to be replaced by 12-in flashing lights. Two new post-mounted 12-in flashing lights were installed on the left of approaching motorists. An additional pole for mounting the strobes was installed in each quadrant, and cables were strung above and at 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 prior to any data being collected.[11]

Cedar Drive Crossing. The crossing (Inventory Number 730643K) selected for the highway traffic signal system is 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 in roundels and a bell. It was ranked as the 31st most dangerous crossing in the State. As shown in figure 17, the highway is 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 trains per day. The speed limit on Cedar Drive was 40 mi/h, and train speeds at the crossing ranged from 5 to 40 mi/h. As evidenced by its hazard ranking and the three car-train accidents that occurred at this site in the past 5 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



Looking east

Looking west

Figure 17. Cedar Drive crossing.

signs indicating a signal ahead. Each sign was supplemented by two continuously flashing yellow light signals. For improved visibility, a 12-in 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 to 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 Traffic 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 Gates with Skirt System. The four-quadrant gates with skirts system selected for field evaluation in the laboratory phase of the project is illustrated in figure 18. 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.(11) 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

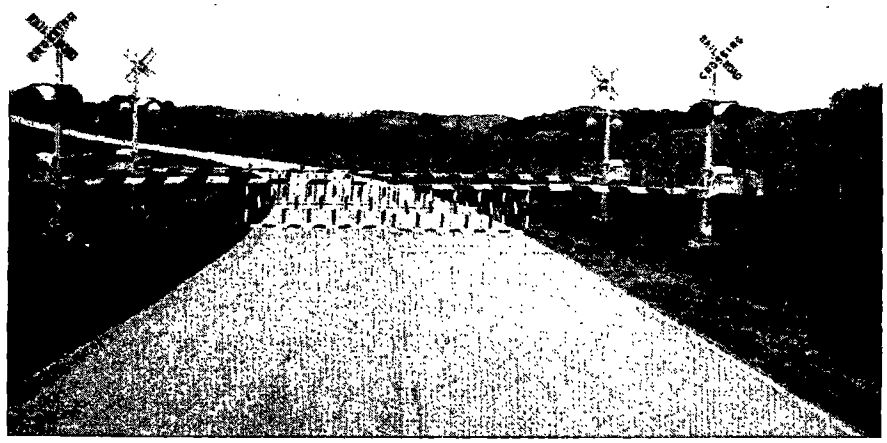


Figure 18. Four-quadrant gate and flashing light signal system recommended for field evaluation.

the two over roadway lamps. Each of these components was 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 19. In the laboratory study, the skirt assembly utilized uniformly 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 8 inches apart (10 inches from center to center) and made of 1/8-in thick aluminum plating. Each strip was 2 inches wide and 30 inches long. The bottom horizontal bars were made of 2-in by 4-in aluminum studding 10 feet in length. Sixteen-in 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 device's conspicuity (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, it was not suited for field evaluation at an actual railroad-highway grade crossing for several reasons. 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; 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 another. Such an event could hinder their dropping properly and add significant weight to 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

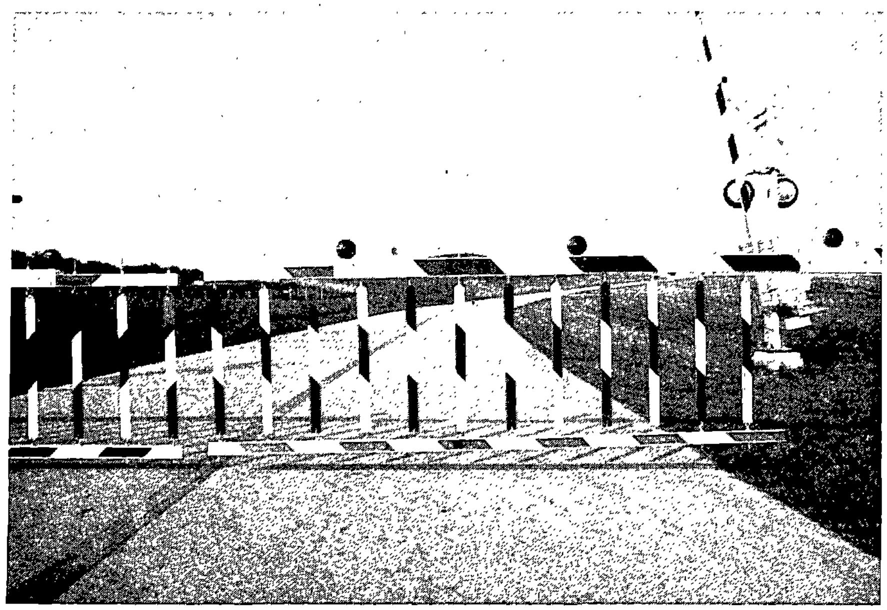


Figure 19. Close-up of the skirt assembly for the four-quadrant gate and flashing light signal system.

wooden gate arms (dual bars with steel cross bracing) could provide the necessary rigidity.

To overcome these shortcomings, the design shown in figures 20 and 21 were adopted. The top horizontal bar was identical in shape and size to a standard wooden gate arm. This ensured 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 to allow the entire skirt assembly to fold inside the gatearm when in the upright position (see figure 20). All horizontal and vertical members were made of kiln-dried redwood, sealed and painted to industry standards, and covered with 16-in 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 21). 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, 3-1/2 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 22. As shown, standard post-mounted flashing light signal assemblies with 12-in 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.[11] In addition to these standard devices, a rectangular shaped (approximately 5 inches high by 7 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 3-ft 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.

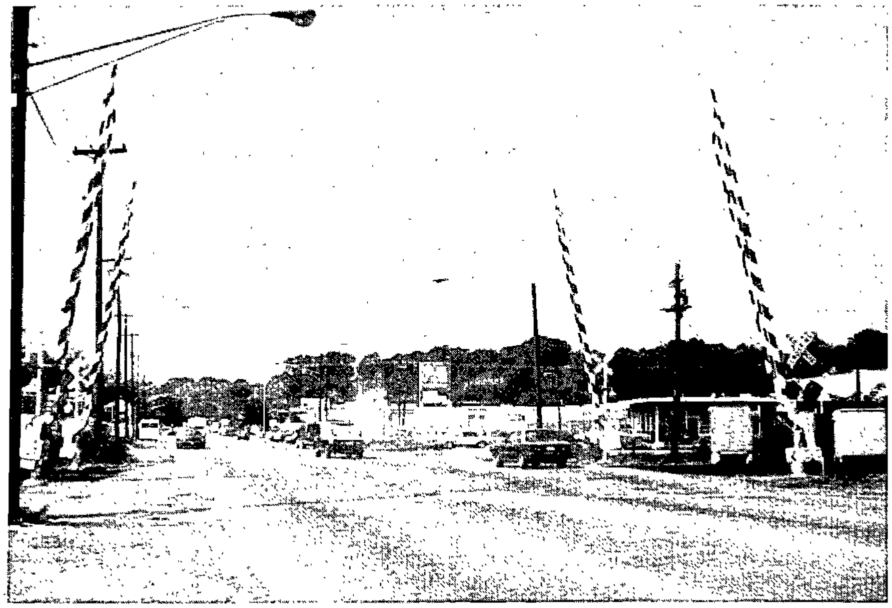


Figure 20. Gate arms in upright position at the Cherry Street crossing.

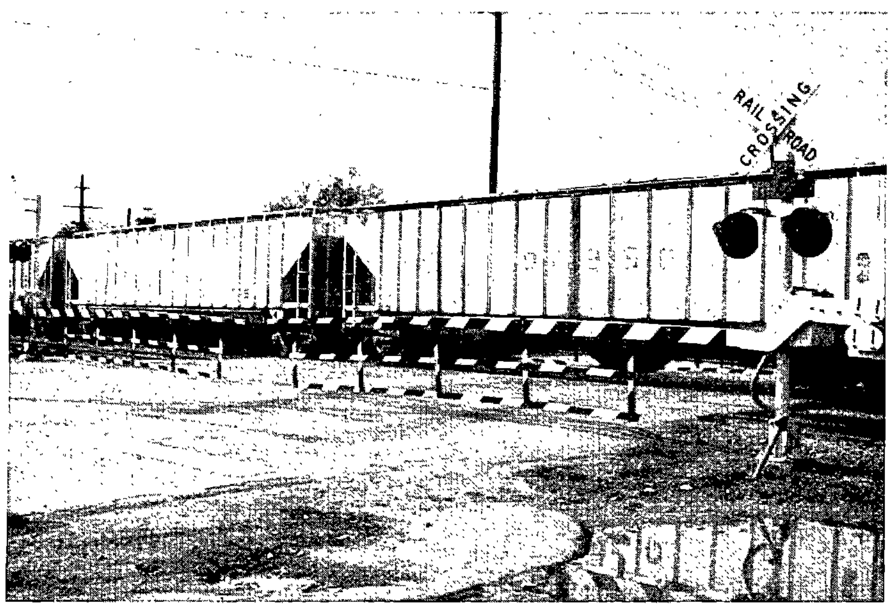


Figure 21. Prototype gate arm and skirt assembly installed at the Cherry Street crossing.

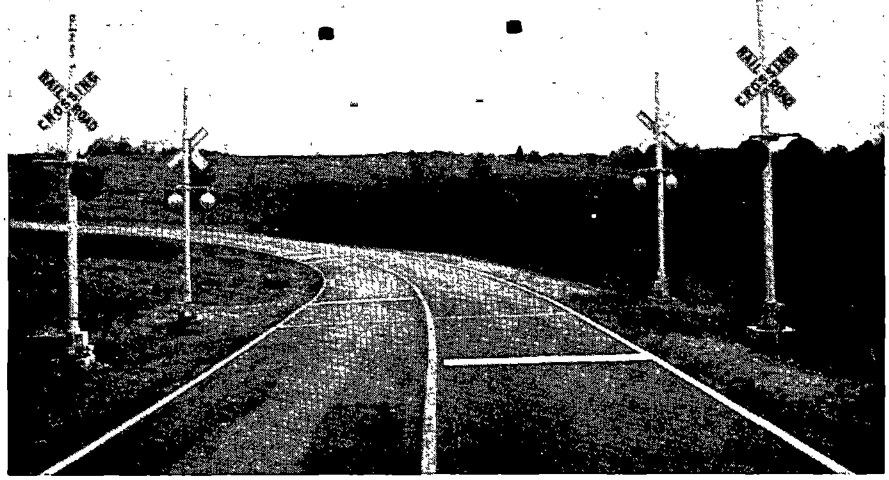


Figure 22. Four-quadrant flashing light signal system with overhead strobes recommended for field evaluation.

The strobe lights were powered by a 12-volt marine battery and activated at the same time as 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, the prototype's design required that, in addition to the poles for the flashing light signal assemblies, a wooden pole, 20 feet in height, also be installed in each of the four quadrants. As shown in figure 23, the wooden poles were located approximately 5 feet further from both 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 connected to each other by running them down the poles and underneath the tracks. Power for the strobe's 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 24. 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 and were the same as would be found at a regular street intersection.[11] Each signal head consisted of a 12-in red lens and 8-in 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.

There were several minor differences between the prototypes used in the laboratory and field studies. First, to increase conspicuity of the signal

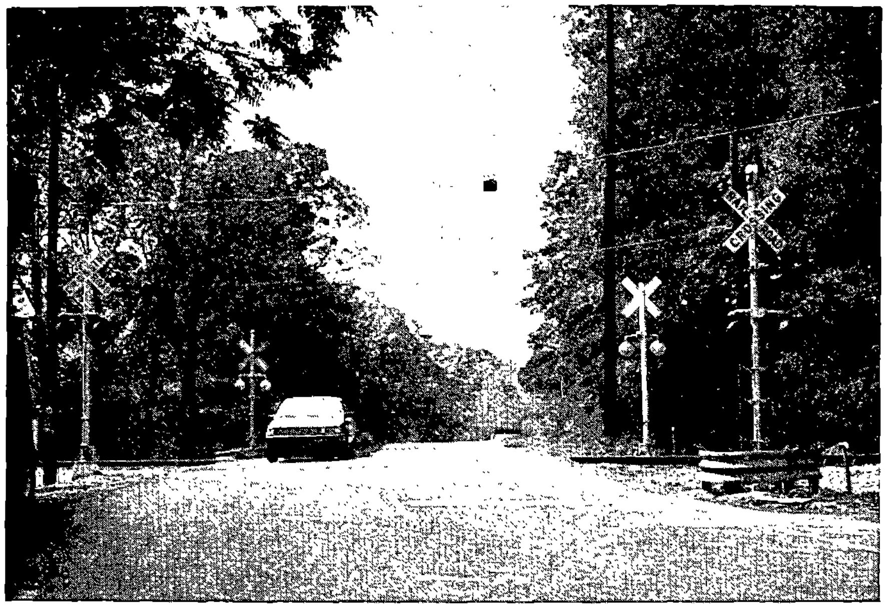


Figure 23. Four-quadrant flashing light signal system with overhead strobes installed at the Ebenezer Road crossing.

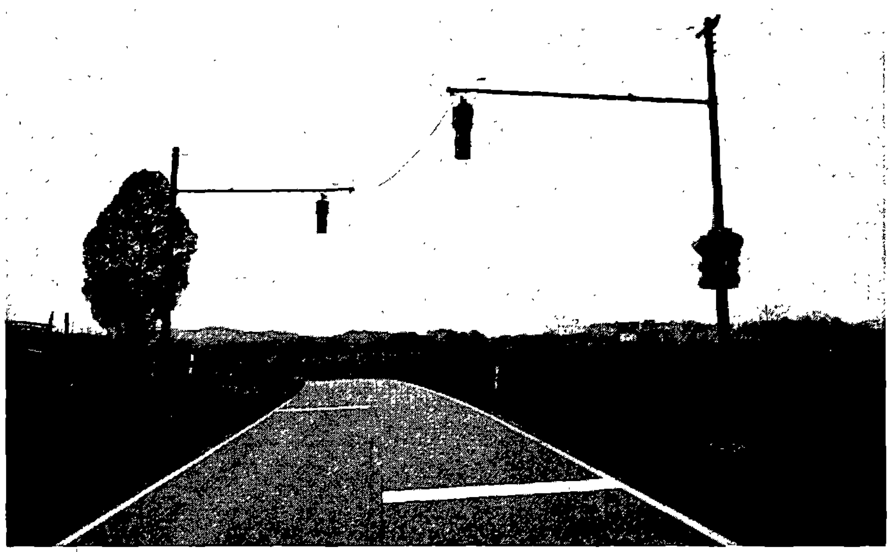


Figure 24. Highway traffic signal system recommended for field evaluation.

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 as shown in figure 25. Thus, none of the signal heads were blocked by a trains' presence at the crossing. Second, to eliminate the possibility of the controller's timing dials "sticking in green," a National Electrical Manufacturers Association 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 backup 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 4-second yellow clearance interval and a 10-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.

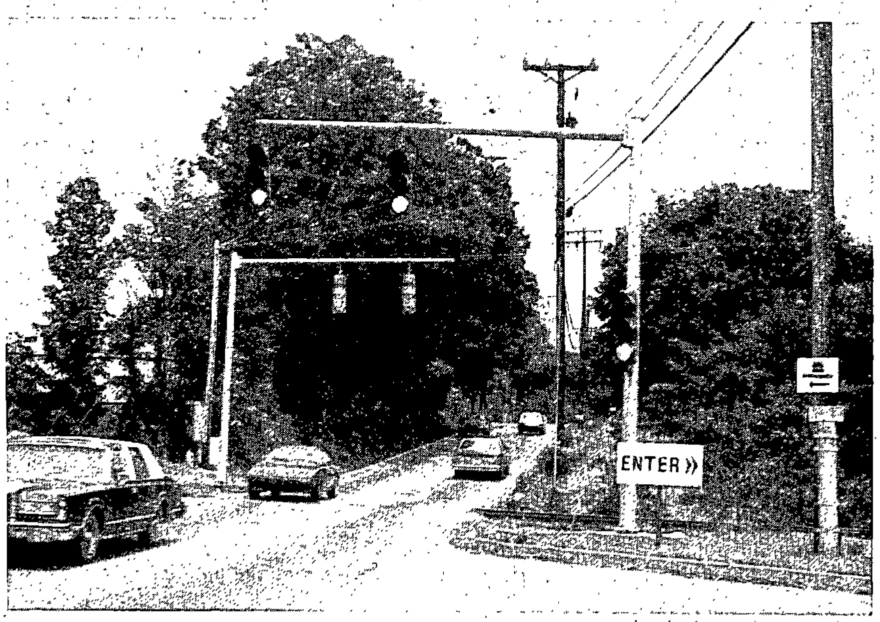


Figure 25. Highway traffic signal system installed at the Cedar Drive crossing.

V. FOUR-QUADRANT GATES WITH SKIRTS

As discussed in chapter IV, a large number of motorists disregarded the standard two-quadrant gates at the Cherry Street crossing by driving around lowered gate arms. Not only was this behavior illegal, it was also dangerous. 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 train's 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 PBRTs 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 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 gates. Both train movement and driver behavior data were collected for approximately 2 months before (March and April 1985) and 2 months after (December 1985 and January 1986) the new devices were installed. During these two time periods, 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; train's direction of travel and warning time; and approaching vehicles' clearance times, speed profiles, and brake reaction times were recorded and subsequently analyzed.

This chapter describes the evaluation of the 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 part in this process is 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.(48) Second, the driver performance measures for the two warning devices are summarized and compared from both a statistical and practical standpoint. Third, the safety implications of utilizing four-quadrant gates with skirts are 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 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 6, 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 indicated that these differences were not statistically significant at the 95 percent confidence level for either the day, night, or total data sets.(44) 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.

Table 6. Warning times at the Cherry Street crossing.[1]

Summary Statistics	Two-Quadrant Gates Day	Two-Quadrant Gates Night	Two-Quadrant Gates Total	Four-Quadrant Gates with Skirts Day	Four-Quadrant Gates with Skirts Night	Four-Quadrant Gates with Skirts Total
Sample Size	71	34	105	30	34	64
Mean (seconds)	55.81	61.49	57.65	51.64	60.06	56.11
Standard Deviation	14.05	19.80	16.26	8.58	16.16	13.73
Range (seconds)	30-106	29-118	29-118	38-75	30-94	30-94

Warning Time (seconds)	Two-Quadrant Gates Observed Train Arrivals	Two-Quadrant Gates Percent of Total Arrivals	Two-Quadrant Gates Cumulative Percentage	Four-Quadrant Gates with Skirts Observed Train Arrivals	Four-Quadrant Gates with Skirts Percent of Total Arrivals	Four-Quadrant Gates with Skirts Cumulative Percentage
<20	0	0.0	0.0	0	0.0	0.0
20-30	2	1.9	1.9	0	0.0	0.0
30-40	12	11.4	13.3	2	3.1	3.1
40-50	16	15.2	28.5	23	36.0	39.1
50-60	39	37.2	65.7	22	34.4	73.5
60-90	33	31.4	97.1	16	25.0	98.5
>90	3	2.9	100.0	1	1.5	100.0
Total	105			64		

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

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 who 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 Highway Capacity Manual, were developed for active warning devices at grade crossings.[48] The proposed criteria are shown in table 7. The levels of service are 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 7, 20 seconds is the minimum warning time currently required by the MUTCD, and 60 seconds is defined by the 1985 Highway Capacity Manual as the limit of acceptable delay to most motorists.[11,48] 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 defined as 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. As can be seen from table 6, 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 (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 gate arms. In other words, the warning times

Table 7. Proposed level of service criteria for railroad highway grade crossings.

Level of Service	Warning Time Category	Before Train's Arrival[1]
-	Inadequate[2]	<20
A	Desirable	20 to 30
B	Marginal	30 to 40
C	Poor	40 to 50
D	Maximum	50 to 60
F	Unacceptable[3]	>60

[1]Average time (in seconds) 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 Highway Capacity Manual.

were perceived as unacceptable (too long) and the motorists performed in an unacceptable (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 in which a vehicle arrived at the crossing between the activation of the flashing light signals and the train's arrival at the crossing; 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 8, 90 clearance times were observed in the before study (two-quadrant gates) and 29 clearance times were observed in the after study (four-quadrant gates with skirts). As with the warning time data set, the total data from each study were subdivided into observations that occurred during the day and observations that occurred during the night 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, indicating greater temporal separation between vehicles and trains. Additionally, the Mann-Whitney U test for two independent, continuously distributed populations indicated that these differences were statistically significant at the 99 percent confidence level.[44] This means that installation of the four-quadrant gates 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

Table 8. Clearance times at the Cherry Street crossing.[1]

Summary Statistics	Two-Quadrant Gates Day	Two-Quadrant Gates Night	Two-Quadrant Gates Total	Four-Quadrant Gates with Skirts Day	Four-Quadrant Gates with Skirts Night	Four-Quadrant Gates with Skirts Total
Sample Size[2]	70	20	90	18	11	29
Mean (seconds)	23.96	26.62	24.55	44.39	56.27	48.90
Standard Deviation	11.18	17.23	12.71	9.10	16.27	13.39
Percent <20 Seconds	41.4	35.0	40.0	0.0	0.0	0.0
Percent <10 Seconds	5.7	5.0	5.6	0.0	0.0	0.0
Range (seconds)	6-62	4-72	4-72	34-68	34-81	34-81

Clearance Time (seconds)	Two-Quadrant Gates Observed Train Arrivals	Two-Quadrant Gates Percent of Total Arrivals	Two-Quadrant Gates Cumulative Percentage	Four-Quadrant Gates with Skirts Observed Train Arrivals	Four-Quadrant Gates with Skirts Percent of Total Arrivals	Four-Quadrant Gates with Skirts Cumulative Percentage
<10	5	5.6	5.6	0	0.0	0.0
10-20	31	34.4	40.0	0	0.0	0.0
20-30	36	40.1	80.1	0	0.0	0.0
>30	18	19.9	100.0	29	100.0	100.0
Total	90			29		

[1] Time between last vehicle to cross and the trains arrival at the crossing.

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

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 26. 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 which suggested that clearance times were different between day and night operation for either the two-quadrant gates or four-quadrant gates with skirts.

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 short the warning times were. This type of behavior is similar to that of those drivers who exceed properly set speed limits. In other words, there will always be a few drivers who will take risks at railroad-highway grade crossings just as there will always be a few drivers who 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:

- Risky--less than 10 seconds.
- Aggressive--from 10 to 20 seconds.
- Normal--from 20 to 30 seconds.
- 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 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

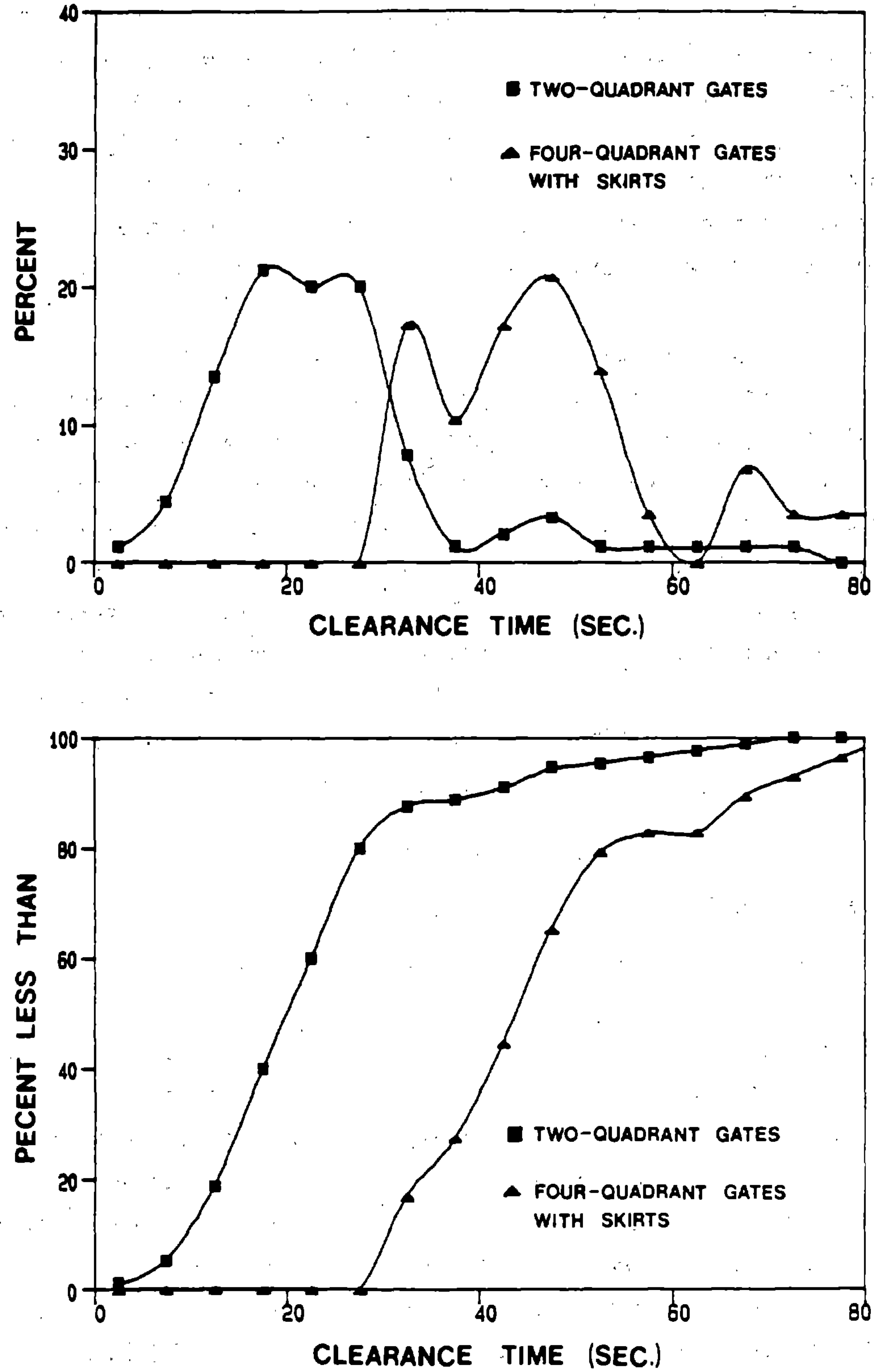


Figure 26. Frequency and cumulative frequency distributions of the observed clearance times at the Cherry Street crossing.

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.

Using the preceding definitions, 40.0 percent of the clearance times in the before study (see table 8) 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 gate arms by completely blocking the road. Thus, all drivers rather than just a few 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 that drivers often make mistakes in judgement. However, to avoid unnecessarily delaying drivers at these crossings and to reduce risky and/or aggressive behavior, 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 approached the Cherry Street crossing whenever the warning devices were activated could or could 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 earlier and slow down sooner. Even if this behavior change occurred it may not be large enough to be statistically significant. If it is statistically significant, 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).[49]

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 27. 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 earlier, 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 calculated at the far distances. Therefore, only data from the first two cameras are shown in figure 27.

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 videotapes indicated that the first vehicle to stop was often following a queue of slow moving vehicles that were driving around the gate arms and, 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 27. First, in both studies, the first vehicle to stop began slowing about 450 feet from the stop bar.

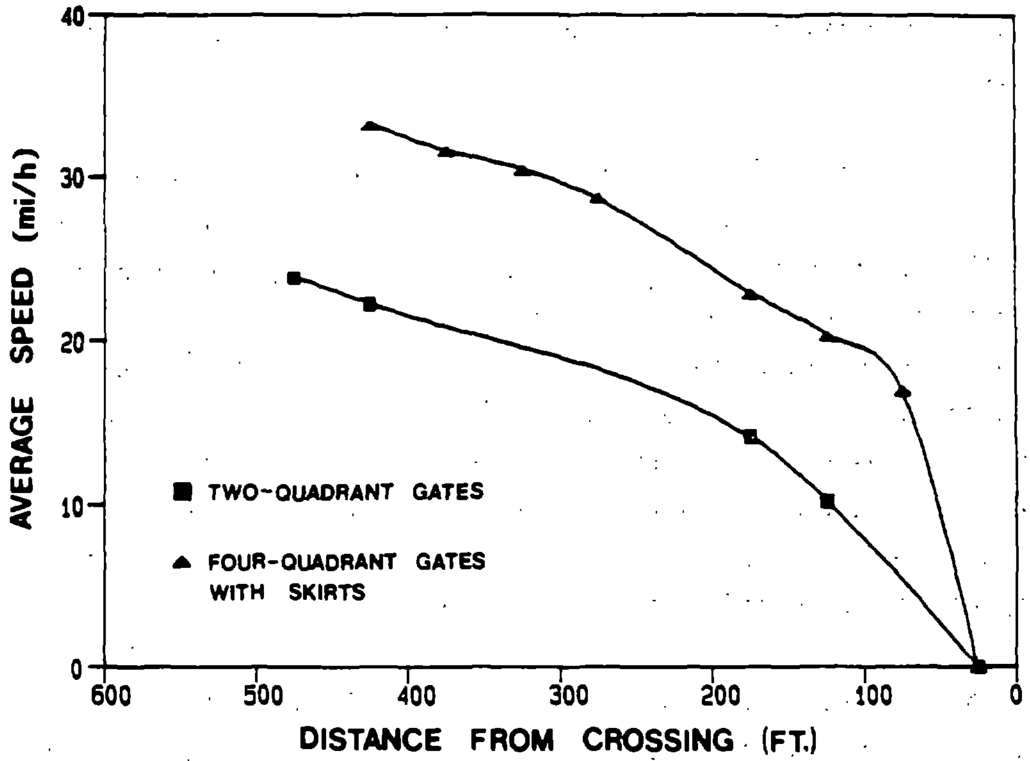


Figure 27. Average approach speed profiles for vehicles in advance of the Cherry Street crossing.

Second, stopping vehicles did so in a safe, gradual, and consistent manner. Finally, although installation of the four-quadrant gates with skirts failed to cause the first stopping vehicle to begin slowing down sooner, the resultant speed profiles appeared to pose no safety problem for approaching motorists.

Perception-Brake Reaction Time and Deceleration. PBRT 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 sooner 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 was expected to be highly variable.

Average PBRTs 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, were not statistically significant at the 95 percent confidence level.[44] These long reaction times confirm the premise that braking in response to a flashing light signal did not represent a pressure situation (short reaction times) and, because of this, was highly variable (large standard deviations). An additional complication with measuring PBRTs 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 approaching a recognized railroad-highway grade crossing.

In terms of deceleration, the Traffic Engineering Handbook defines several deceleration categories as follows:[27]

1. Emergency--greater than 20 ft/s^2.

2. Very uncomfortable--14 to 20 $ft./s^2$.

3. Uncomfortable--11 to 14 ft/s^2.

4. Undesirable--8 to 11 ft/s^2.

5. Practical--less than 8 ft/s^2.

Previous studies have concluded that nearly all drivers approaching an activated flashing light signal decelerate to a stop at a practical level.[23,24] 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 exist are probably the result of the differences in stimuli for the first vehicle which stopped in each of the two studies; in the after study, they may have stopped in response to the activation of the warning devices, whereas in the before study, they may have been traveling more slowly 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 gates, violations occur whenever motorists drive around the gate arms in the down position. As stated previously, many motorists drove around the lowered two-quadrant gates at the Cherry Street crossing even though it was illegal to do so. Installation of the four-quadrant gates with skirts was expected to eliminate this apparent disregard for the warning devices by completely blocking the roadway and making it physically impossible to drive around lowered gate arms.

Table 9 shows the number of violations observed at the Cherry Street crossing. As can be seen from table 9, for those observations in which a motor vehicle was present prior to the train's arrival at the crossing, the average number of motorists per train arrival who drove around the gate arms

Table 9. Violations 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)	2.76	2.09	2.60	0.00	0.00	0.00
Standard Deviation	2.40	2.29	2.38	0.00	0.00	0.00
Percent >0 Violations	87.3	72.7	83.9	0.0	0.0	0.0
Percent >1 Violation	67.6	45.5	62.4	0.0	0.0	0.0
Range (vehicles)	0-14	0-9	0-14	0-0	0-0	0-0

Violations (vehicles)	Two-Quadrant Gates			Four-Quadrant Gates with Skirts		
	Number of Observations	Percent of Observations	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage
0	15	16.1	16.1	53	100.0	100.0
1	20	21.5	37.6	0	0.0	100.0
2	18	19.4	57.0	0	0.0	100.0
3	17	18.3	75.3	0	0.0	100.0
>3	23	24.7	100.0	0	0.0	100.0
Total	93			53		

[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.

went from 2.6 in the before study (two-quadrant gates) to 0.0 in the after study (four-quadrant gates with skirts). What was not expected was the high number of motorists who drove around the two-quadrant gates--at least one in 83.9 percent of the train arrivals in which vehicles were present before the train's arrival, 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 2 by 5 contingency table (two studies by five violation rate categories) indicated that these differences were statistically significant at the 99 percent confidence level.

One of the expected findings from the before study was that the average number of violations per train arrival would increase with an increase in warning time. These data are shown in table 10 and illustrated in figure 28. Notice that when the warning times were less than 40 seconds (level of service B or better), one or fewer 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. These observations support the premise that the longer the warning time, the larger the number of illegal and dangerous maneuvers which will take place.

The four-quadrant gates with skirts simply eliminated all violations as can be seen in table 10. Obviously, this is a significant safety benefit.

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 11. 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

Table 10. 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	0	-
	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	2	0.00
		Total 53	0.00

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

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

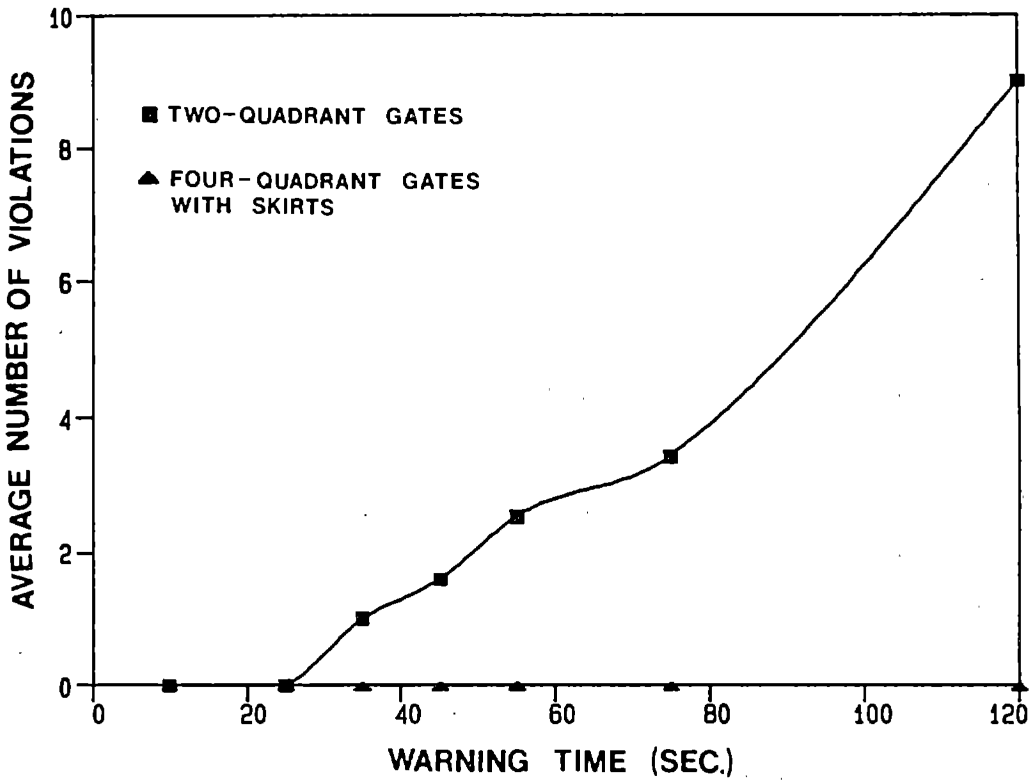


Figure 28. Average number of violations as a function of the warning times at the Cherry Street crossing.

Table 11. Vehicle crossings at the Cherry Street crossing.[1]

Summary Statistics	Two-Quadrant Gates Day	Two-Quadrant Gates Night	Two-Quadrant Gates Total	Four-Quadrant Gates with Skirts Day	Four-Quadrant Gates with Skirts Night	Four-Quadrant Gates with Skirts Total
Sample Size[2]	71	22	93	28	25	53
Mean (vehicles)	4.32	2.95	4.01	1.50	0.72	1.13
Standard Deviation	2.93	2.87	2.96	1.50	0.98	1.33
Percent >0 Violations	98.6	90.9	96.8	64.3	44.0	54.7
Percent >1 Violation	88.7	63.6	82.8	42.9	20.0	32.1
Range (vehicles)	0-19	0-11	0-19	0-5	0-3	0-5

Crossings (vehicles)	Two-Quadrant Gates Observed Train Arrivals	Two-Quadrant Gates Percent of Total Arrivals	Two-Quadrant Gates Cumulative Percentage	Four-Quadrant Gates with Skirts Observed Train Arrivals	Four-Quadrant Gates with Skirts Percent of Total Arrivals	Four-Quadrant Gates with Skirts Cumulative Percentage
0	3	3.2	3.2	24	45.3	45.3
1	13	14.0	17.2	12	22.6	67.9
2	20	21.5	38.7	7	13.2	81.1
3	10	10.8	49.5	7	13.2	94.3
>4	47	50.5	100.0	3	5.7	100.0
Total	93			53		

[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.

four-quadrant gates with skirts was expected to 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 2 by 6 contingency table (two studies by six crossing categories rate) 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 trains' arrival at a crossing has previously been defined as an indication of aggressive bahavior, 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 12, 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 0.0 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 CL20s. Results from the Mann-Whitney U test indicated that these differences were significant at the 95

Table 12. CL2Os 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)	0.65	0.45	0.60	0.0	0.0	0.0
Standard Deviation	0.97	0.67	0.91	0.0	0.0	0.0
Percent >0 Violations	42.3	36.4	40.9	0.0	0.0	0.0
Percent >1 Violation	12.7	9.1	11.8	0.0	0.0	0.0
Range (vehicles)	0-4	0-2	0-4	0-0	0-0	0-0

CL2Os (vehicles)	Two-Quadrant Gates			Four-Quadrant Gates with Skirts		
	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage
0	55	59.1	59.1	53	100.0	100.0
1	27	29.0	88.1	0	0.0	100.0
2	6	6.5	94.6	0	0.0	100.0
3	3	3.2	97.8	0	0.0	100.0
>3	2	2.2	100.0	0	0.0	100.0
Total	93			53		

[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.

percent confidence level. Thus, as expected, installation of the four-quadrant gates with skirts significantly decreased the CL20 rate (aggressive behavior) at the Cherry Street crossing.

A frequency distribution of the observed CL20s at the Cherry Street crossing is also shown in table 12. In the before study there were 55 observations with zero CL20s, 27 observations with one CL20, 6 observations with two CL20s, and 5 observations with three or more CL20s. In the after study, there were no CL20s in any of the 53 observations. A Pearson's chi-square statistic calculated from a 2 by 4 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 (a violation), it also becomes extremely risky to do so whenever a train is in close proximity to the crossing. There was a portion of the data set that was also in potential conflict (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 13, five CL10s (risky crossings) were observed at the Cherry Street crossing in the before study--four during the day and one during the night. Thus, 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 with the four-quadrant gates with skirts in the after study. A Pearson's chi-square statistic calculated from a 2 by 2 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 obvious that installation of the four-quadrant gates with skirts removed the possibility of risk-taking from the driver's set of options.

Table 13. CL10s 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.

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.

With the installation of four-quadrant gates with skirts, performance measures such as speeds, PBRTs, and deceleration levels did not indicate a change in driver behavior. Thus, there were no measurable safety disadvantages to the four-quadrant gates with skirts. Installation of the 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 as well as violations at the crossing, thus resulting in a superb safety benefit. Such benefits are especially important at crossings with limited sight distance, high-speed trains, and/or multiple tracks.

VI. FOUR-QUADRANT FLASHING LIGHT SIGNALS WITH OVERHEAD STROBES

The approach roadway's horizontal and vertical alignments limit visibility of the Ebenezer Road crossing from both directions. Thus, the visibility of standard two-quadrant flashing light signals at the crossing is 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 expected 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 crossings with gates or highway traffic signals. 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. Violations at the Cedar Drive crossing were also defined in terms of illegal behavior, i.e., driving through the crossing after the signal had changed to red. Violations at the Ebenezer Road crossing could not be defined in a similar manner because the only legal requirements placed on motorists approaching a crossing with an activated flashing light signal are that they bring their vehicles 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 would be defined as drivers who could reasonably stop in response to the warning device, but failed to do so. However, because of the difficulty in determining whether or not a vehicle came to a complete stop, violations could not be counted for the flashing light signal systems at the Ebenezer Road crossing.

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 2 months before (July and August 1985) and 2 months after (May and August 1986) the new devices were installed. During these two time periods, 226 train movements were observed. There were 157 trains observed in the before study (two-quadrant flashing light signals) and 79 trains were observed in the after study (four-quadrant flashing light signals with overhead strobes). The after study consisted of two 1-month studies separated by a 60-day waiting period. This was done 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 chapter 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 part 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 previously discussed.[48] Second, the driver performance measures for the two warning devices were summarized and compared from both a statistical and practical standpoint. Third, the safety implications of utilizing four-quadrant flashing light signals with overhead strobes are 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, no difference was expected 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 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 14, the mean and standard deviation of the warning times 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 indicated that these differences were not significantly different at the 95 percent confidence level for either the day, night, or total data sets.[44] 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 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 who will exhibit dangerous and/or illegal behavior. By using the level of service definitions developed in chapter V, approximately 90 percent of the observed warning times for each of the three studies at the Ebenezer Road crossing could be classified as level of service A, B, or C. In fact, over 60 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

Table 14. Warning times at the Ebenezer Road crossing.[1]

Summary Statistics	Flashing Light Signals			Flashing Light Signal with Strobes (Spring 1986)			Flashing Light Signals with Strobes (Summer 1986)		
	Day	Night	Total	Day	Night	Total	Day	Night	Total
Sample Size	106	51	157	18	5	23	43	13	56
Mean (seconds)	42.2	38.1	40.8	36.3	38.3	36.7	41.0	43.4	41.6
Standard Deviation	15.6	11.1	14.4	7.1	4.7	6.6	10.0	22.4	13.7
Range (seconds)	24-153	26-106	24-153	19-45	36-47	19-47	14-62	82-116	14-116

Warning Times (seconds)	Flashing Light Signals			Flashing Light Signal with Strobes (Spring 1986)			Flashing Light Signals with Strobes (Summer 1986)		
	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage
<20	0	0.0	0.0	2	8.7	8.7	1	1.8	1.8
20-30	13	8.3	8.3	0	0.0	8.7	4	7.1	8.9
30-40	84	53.5	61.8	15	65.2	73.9	25	44.6	53.6
40-50	45	28.6	90.4	6	26.1	100.0	19	33.9	87.5
50-60	6	3.9	94.3	0	0.0	100.0	4	7.1	94.6
60-90	6	3.8	98.1	0	0.0	100.0	2	3.6	98.2
>90	3	1.9	100.0	0	0.0	100.0	1	1.8	100.0
Total	157			23			56		

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

sets means that the active warning devices at the Ebenezer Road crossing were 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 light 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 are only reported 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 15, 109 clearance times were observed in the before study (two-quadrant flashing light signals), 18 clearance times were observed in the first after study (four-quadrant flashing light signals with strobes--Spring 1986), and 45 clearance times were 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 were subdivided into observations that occurred during the day and observations that occurred during the night to ensure 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 indicated that these differences were not statistically significant at the 95 percent confidence interval for either the day, night, or total data sets.[46] This means that installation of the four-quadrant

Table 15. Clearance times at the Ebenezer Road crossing.[1]

Summary Statistics	Flashing Light Signals: Day	Flashing Light Signals: Night	Flashing Light Signals: Total	Flashing Light Signals with Strobes (Spring 1986): Day	Flashing Light Signals with Strobes (Spring 1986): Night	Flashing Light Signals with Strobes (Spring 1986): Total	Flashing Light Signals with Strobes (Summer 1986): Day	Flashing Light Signals with Strobes (Summer 1986): Night	Flashing Light Signals with Strobes (Summer 1986): Total
Sample Size[2]	92	17	109	15	3	18	38	7	45
Mean (seconds)	19.1	27.9	20.5	19.1	19.1	19.1	14.3	27.2	16.3
Standard Deviation	9.9	20.5	12.4	6.9	17.3	8.6	6.3	6.0	7.8
Percent <20 seconds	66.3	41.2	62.4	53.3	66.7	55.6	86.8	14.3	75.6
Percent <10 seconds	12.0	5.9	11.0	0.0	33.3	5.6	23.7	0.0	20.0
Range (seconds)	7-64	8-99	7-99	10-31	4-38	4-38	5-36	18-37	5-37

Clearance Times (seconds)	Flashing Light Signals: Observed Train Arrivals	Flashing Light Signals: Percent of Total Arrivals	Flashing Light Signals: Cumulative Percentage	Flashing Light Signals with Strobes (Spring 1986): Observed Train Arrivals	Flashing Light Signals with Strobes (Spring 1986): Percent of Total Arrivals	Flashing Light Signals with Strobes (Spring 1986): Cumulative Percentage	Flashing Light Signals with Strobes (Summer 1986): Observed Train Arrivals	Flashing Light Signals with Strobes (Summer 1986): Percent of Total Arrivals	Flashing Light Signals with Strobes (Summer 1986): Cumulative Percentage
<10	12	11.0	11.0	1	5.6	5.6	9	20.0	20.0
10-20	56	51.4	62.4	9	50.0	55.6	25	55.6	75.6
20-30	26	23.9	86.2	6	33.3	88.9	8	17.8	93.4
>30	15	13.8	100.0	2	11.1	100.0	3	6.6	100.0
Total	109			18			45		

[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 present before the train's arrival.

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 shown in figure 29. 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.

It was also hypothesized 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.

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

By using these definitions, the percentage of the observed clearance times in all three studies that could be classified as either risky or aggressive, ranged from 55.6 percent to 75.6 percent. In addition, from 6.6 percent to 13.8 percent of the clearance times could be classified as cautious. 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 may have different ideas as to what the necessary warning time should be.[11]

Approach Measures

Speed Profiles. The average speed at which drivers approached the Ebenezer Road crossing whenever the warning devices were activated may or may

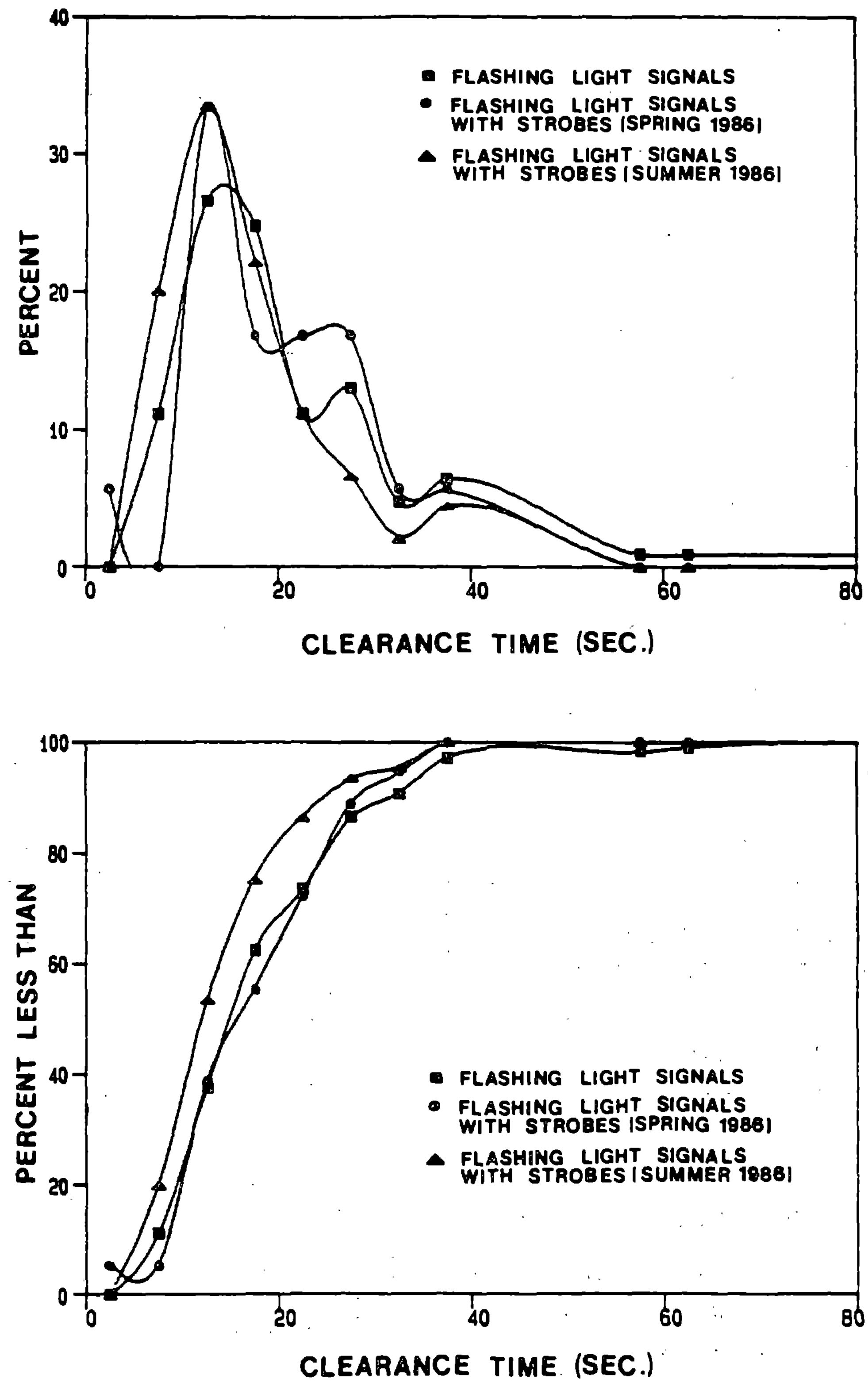


Figure 29. Frequency and cumulative frequency distributions of observed clearance times at the Ebenezer Road crossing.

not be different after the installation of the four-quadrant flashing light signals with overhead strobes. Hypothetically, the greater conspicuity of the new warning devices, and 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 occurred, it may not be large enough to be statistically significant; and even if it is statistically significant, 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 vehicles to stop at the crossing in both the before and each of the two after studies were plotted as shown in figure 30. Each data point represents average speeds over 50-foot sections of roadway in advance of the stop bar at the crossing and is 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 from 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 unsuitable for speed calculations. 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 the Camera 2 in the second after study are shown in figure 30.

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 after study (four-quadrant flashing light signals with strobes--May 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; for practical purposes, they were the same. In other words, even if the differences were statistically significant, they were so small that they were not meaningful from a practical point of view.[49] Vehicles stopping in

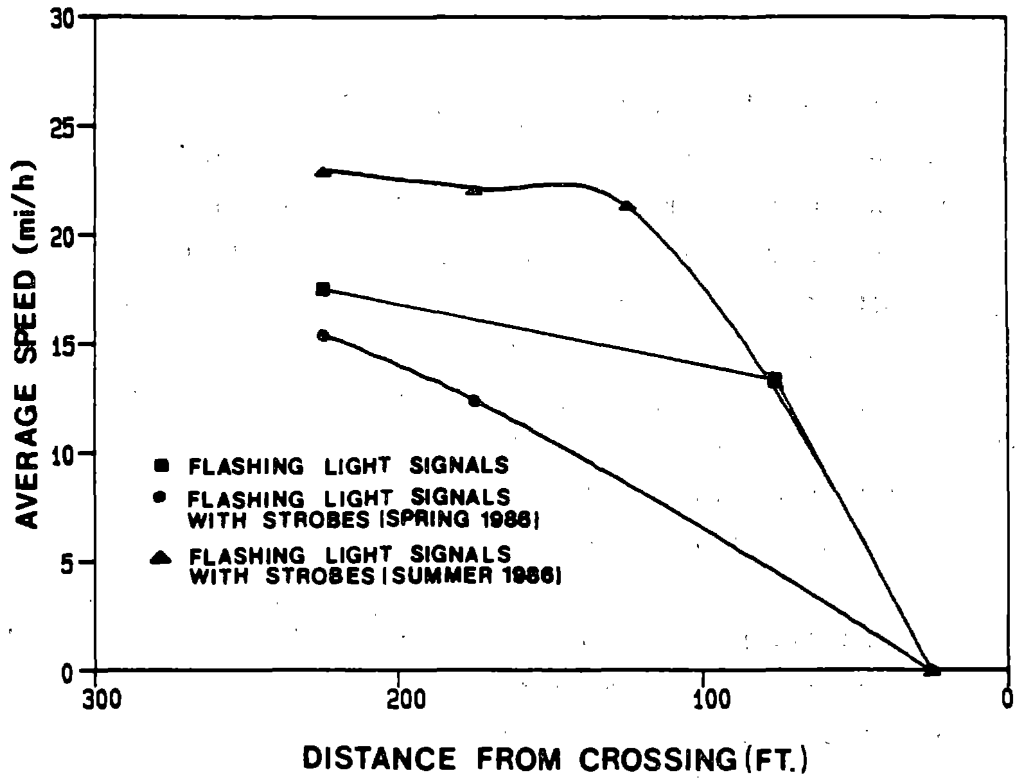


Figure 30. Average approach speed profiles for vehicles in advance of the Ebenezer Road crossing.

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. PBRT 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 but 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 seconds in the first after study, and 11.5 seconds 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 indicated that these differences were not large enough to be statistically significant at the 95 percent confidence level.(44) This means that installation of the flashing light signals with overhead strobes had no measurable effect on the PBRT 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, the horizontal or vertical alignment of 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 or observed at the other two crossings.(23,24) 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, as stated earlier, were defined as motorists who could reasonably stop in response to the warning device but failed 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 is shown in table 16. The average number of vehicles crossing ranged from 2.5 to 4.24 in these studies. 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, 40.8 percent of the total observations had five or more vehicles crossing after the flashing light signals were activated (Summer 1986). 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 are activated are shown in table 17. Even though the majority of the warning time observations are still in the 30- to 40-second range, there is clearly an identifiable trend--the longer the warning

Table 16. Vehicles crossing 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[2]	101	22	123	16	4	20	42	7	49
Mean (vehicles)	3.83	1.59	3.43	2.81	1.25	2.50	4.24	2.71	4.02
Standard Deviation	3.41	1.37	3.26	1.64	1.26	1.67	2.82	1.38	2.70
Percent >0 Crossings	91.1	77.3	88.6	93.8	75.0	90.0	90.5	100.0	91.8
Percent >1 Crossing	74.3	45.5	69.1	81.3	25.0	70.0	81.0	71.4	79.5
Range (vehicles)	0-21	0-5	0-21	0-6	0-3	0-6	0-11	1-4	0-11

Crossings (vehicles)	Flashing Light Signals			Flashing Light Signals with Strobes (Spring 1986)			Flashing Light Signals with Strobes (Summer 1986)		
	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage
0	14	11.4	11.4	2	10.0	10.0	4	8.2	8.2
1	24	19.5	30.9	4	20.0	30.0	6	12.3	20.5
2	25	20.3	51.2	5	25.0	55.0	8	16.3	36.8
3	14	11.4	62.6	4	20.0	75.0	3	6.1	42.9
4	15	12.2	74.8	2	10.0	85.0	8	16.3	59.2
>4	31	25.2	100.0	3	15.0	100.0	20	40.8	100.0
Total	123			20			49		

[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 17. 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.

time, the greater the number of vehicles that will cross while the signal is flashing. This relationship is illustrated in figure 31. 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 greater the number who have to make the decision of whether or not it is safe to cross, the greater the probability of a wrong decision.

Crossings Less Than 20 Seconds (CL20). Vehicles crossing within 20 seconds of a train's arrival at the 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. Although such behavior is not illegal, it 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 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 18, 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, ranging from 0.94 to 1.47. Additionally, the Kruskal-Wallis test indicated that there were no statistically significant differences at the 95 percent confident level.(44) Thus, as expected, installation of the four-quadrant flashing light signals with overhead strobes had no effect on the CL20 rate (i.e., aggressive behavior) at the Ebenezer Road crossing. Surprisingly, over 50 percent of the observations in each study resulted in at least one CL20, and more than 25 percent of the observations in each study resulted in multiple CL20s.

A frequency distribution of the observed CL20s at the Ebenezer Road crossing is also shown in table 18. In the before study, there were 55 observations with no CL20s, 30 observations with one CL20, 20 observations with two CL20s, 10 observations with three CL20s, and 8 observations with four or more CL20s. Although the number of observations in each category was smaller in the after studies, the percentages are almost identical to that of

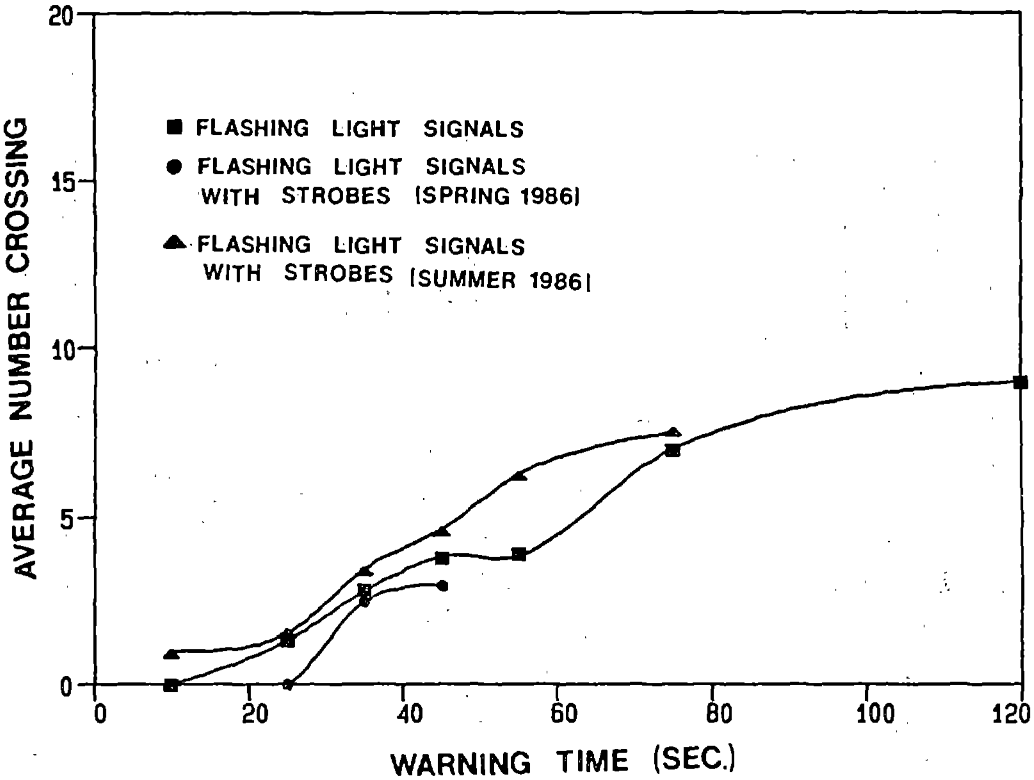


Figure 31. Average number of vehicles crossing as a function of warning times at the Ebenezer Road crossing.

Table 18. CL20s 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[2]	101	22	123	16	4	20	42	7	49
Mean (vehicles)	1.30	0.41	1.14	0.94	0.50	0.85	1.64	0.43	1.47
Standard Deviation	1.50	0.67	1.43	1.12	0.58	1.04	1.45	0.79	1.43
Percent >0 Violations	70.3	31.8	55.3	50.0	50.0	50.0	78.6	28.6	71.4
Percent >1 Violations	36.6	4.6	30.9	31.3	0.0	25.0	45.2	14.3	40.8
Range (vehicles)	0-7	0-2	0-7	0-3	0-1	0-3	0-5	0-2	0-5

CL20s (vehicles)	Flashing Light Signals			Flashing Light Signals with Strobes (Spring 1986)			Flashing Light Signals with Strobes (Summer 1986)		
	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage
0	55	44.7	44.7	10	50.0	50.0	14	28.6	28.6
1	30	24.4	69.1	5	25.0	75.0	15	30.6	59.2
2	20	16.3	85.4	3	15.0	90.0	12	24.5	83.7
3	10	8.1	93.5	2	10.0	100.0	2	4.1	87.8
>3	8	6.5	100.0	0	0.0	100.0	6	12.2	100.0
Total	123			20			49		

[1]Vehicles crossing with 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.

the before study. A Pearson's chi-square statistic calculated from a 3 by 4 contingency table (three studies by four CL20 rate categories) substantiates the fact there were no siginificant 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 19. 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 CL20s 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 1.27 CL20s per train arrival in the before study and 1.00 to 1.64 CL20s per train arrival in the two after studies. Again, this is an indication that motorists and the MUTCD may have different ideas as to what the necessary warning time at a railroad-highway grade crossing should be.[11]

Crossings Less Than 10 Seconds (CL10). Vehicles crossing within 10 seconds of a train's arrival at the crossing has previously been defined as an indication of risky behavior, i.e., there is little room for either driver and/or vehicular error. Although not necessarily 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 20, 14 CL10s (12 single CL10s and 1 double CL10) were observed at the Ebenezer Road crossing in the before study, i.e., 14 motorists crossed the tracks within 10 seconds of the train's arrival. Thirteen of the CL10s (11 single CL10s and 1 double CL10) occurred during the day and 1 CL10 occured at night. In fact, in at least one case, two motorists crossed the tracks within 10 seconds of a train's arrival. Because the small number of observed CL10s (risky behavior) in the two after studies did not

Table 19. Effects of warning times on CL20 rates at the Ebenezer Road crossing.

Study	Warning Time (Sec.)[1]	Observed Train Arrivals[2]	Average CL20s (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.

Table 20. CL10s 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 (vehicles)	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 CL10s/Arrival	89	21	110	16	3	19	33	7	40
1 CL10s/Arrival	11	1	12	0	1	1	7	0	7
2 CL10s/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.

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 CL10s 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 2 by 2 contingency table indicated that the observed CL10s in the before (two-quadrant flashing light signals) and after (four-quadrant 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 CL10s occurred during the day. The obvious conclusion is that CL10s 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 with two-quadrant gates. 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 (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 have 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 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, PBRTs, and maximum deceleration levels were expected to change. Unfortunately, a number of additional variables such as horizontal and vertical alignment added extraneous variability in the measurement process. This variability was so great that it may have hidden any positive or negative effects on driver behavior that might have occurred. From the data collected and analyzed, four-quadrant flashing light signals with overhead strobes had no discernible effect on driver behavior at the Ebenezer Road crossing; driver behavior was essentially the same as when standard flashing light signals were used and no quantifiable improvements in safety could be ascertained.

VII. HIGHWAY TRAFFIC SIGNAL

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 5 years. It was hypothesized that these safety problems were due to a combination of 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 was expected to discourage 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 was not expected to 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 spatio-temporal separation between trains and motor vehicles for a larger number of motorists. The anticipated secondary change in driver performance was better response to the new devices (quicker PBRTs 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 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 one 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 but failed 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. 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. Because of the different definitions, 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. Because it was felt that long warning times at this crossing might lessen the traffic signal's credibility, predictors were installed during November 1985 to provide shorter and more consistent warning times. Both train movement and driver behavior data were collected for approximately 2 months before the predictors were installed (May and June 1985), 2 months after the predictors were installed and before the highway traffic signals were installed (February and March 1986), and 2 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 (flashing light signals without predictors), second before study (flashing light signals with predictors), and after study (highway traffic signals with predictors). During these three studies 231 train movements were 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 PBRT were recorded and subsequently analyzed.

This chapter 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, based on average waiting time at the crossing, was similar to the level-of-service criteria for average delay at signalized intersections presented in the 1985 Highway Capacity Manual and previously discussed.[48] Second, the driver performance measures for the two warning devices were summarized and compared from both statistical and practical standpoints. Third, the safety implications of installing predictors and/or highway traffic signals are discussed.

Crossing Measures

Warning Time. Warning time was defined as the difference in time between activation of either the flashing light signals or the highway traffic signals' yellow 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. It was expected that the installation of the predictors at the Cedar Drive crossing would result in shorter and more consistent warning times. In other words, the warning times should be shorter in the second before study (four-quadrant flashing light signals with predictors) than they were in the first before study (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 (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 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 21, the mean warning time from all three data subsets was significantly longer in the first before study. The mean warning time in the first before study was 75.2 seconds, in the second before study was 41.7 seconds, and in the after study was 36.3 seconds. The Kruskal-Wallis test for two or more independent, continuously distributed populations indicated that these differences were statistically significant at the 99 percent confidence level.[44] 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 shown in figure 32. In addition to the between study results, 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.

Table 21. Warning times 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	53	36	89	22	28	50	67	25	92
Mean (seconds)	73.7	77.6	75.2	40.5	42.7	41.7	38.1	31.5	36.3
Standard Deviation	20.6	13.4	17.9	15.5	19.9	18.0	21.7	8.4	19.2
Range (seconds)	47-141	56-119	47-141	27-89	28-121	27-121	23-161	8-57	8-161

Warning Times (seconds)	Flashing Light Signals without Predictors			Flashing Light Signals with Predictors			Highway Traffic Signals with Predictors		
	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage
<20	0	0.0	0.0	0	0.0	0.0	2	2.2	2.2
20-30	0	0.0	0.0	6	12.0	12.0	28	30.4	32.6
30-40	0	0.0	0.0	28	56.0	68.0	53	57.6	90.2
40-50	4	4.4	4.4	6	12.0	80.0	3	3.3	93.5
50-60	13	14.5	18.9	5	10.0	90.0	1	1.0	94.5
60-90	57	64.5	83.4	4	8.0	98.0	2	2.2	96.7
>90	15	16.6	100.0	1	2.0	100.0	3	3.3	100.0
Total	89			50			92		

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

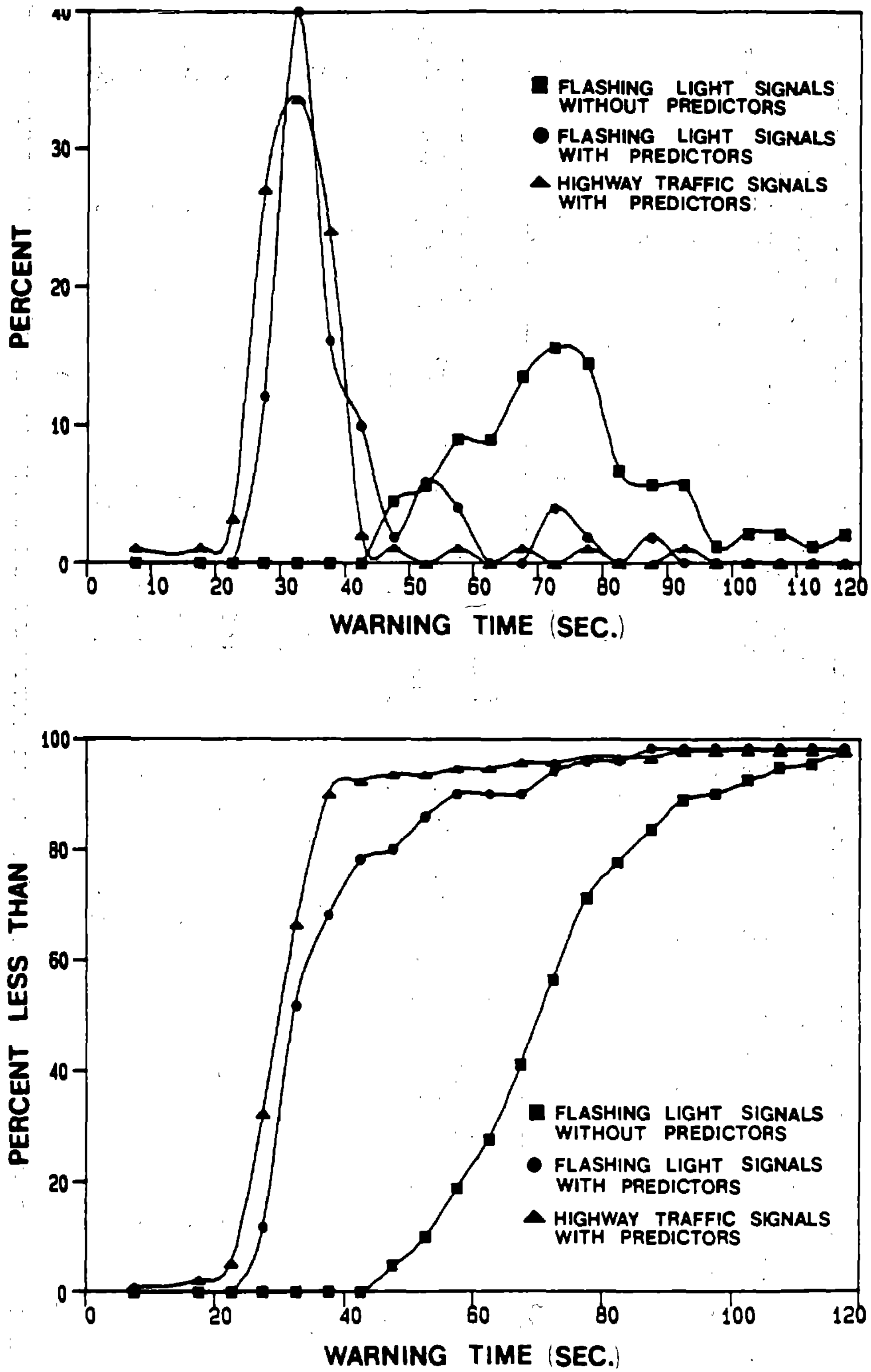


Figure 32. Frequency and cumulative frequency distributions of observed warning times at the Cedar Drive crossing.

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 would exhibit dangerous and/or illegal behavior. By using the level of service criteria previously developed, less than 5 percent of the observed warning times in the first before study (without predictors) were level of service C or better, and over 80 percent of the observed warning times were level of service F (unacceptable). However, after the predictors were installed, 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, 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 were expected to give enough credibility to the warning devices to increase average clearance times at the crossing. If in fact this was to 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 signals being installed at the Cedar Drive crossing.

Clearance times were only recorded for those train arrivals in which a vehicle arrived at the crossing between the activation of the flashing light signals and the train's arrival at the crossing; 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 22 there were 83 clearance times observed in the first before study (two-quadrant flashing lights without predictors), 39 clearance times observed in the 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 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 clearance times from the total data sets were approximately the same for all three studies, ranging from 20.1 to 20.9 seconds. The Kruskal-Wallis test for two or more independent, continuously distributed populations confirmed that these differences were not statistically significant at the 95 percent confidence level.[44] 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 an effect on the daytime clearance times observed at the crossing. Installation of the highway traffic signals in combination with the predictors did lengthen the clearance times observed in the daytime data sets.

Interestingly, the Mann-Whitney test indicated a statistically significant difference for clearance times 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 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. The frequency and cumulative frequency distributions of clearance times from the three data sets are shown in figure 33.

As at the other two crossings, it was hypothesized that even though warning times have a major influence on driver behavior, a small percentage

Table 22. Clearance times 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	19	20	39	20	9	29
Mean (seconds)	15.7	28.2	20.1	16.2	26.3	21.4	20.7	21.4	20.9
Standard Deviation	13.2	15.0	15.0	5.8	18.9	14.9	8.4	10.5	8.9
Percent <20 seconds	79.3	31.0	62.6	73.7	50.0	61.5	45.0	55.6	48.3
Percent <10 seconds	37.7	10.3	27.7	15.8	5.0	10.3	15.0	11.1	13.8
Range (seconds)	4-73	6-66	4-73	7-28	6-96	6-96	5-34	10-45	5-45

Clearance Times (seconds)	Flashing Light Signals without Predictors			Flashing Light Signals with Predictors			Highway Traffic Signals with Predictors		
	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage
<10	23	27.7	27.7	4	10.3	10.3	4	13.8	13.8
10-20	29	34.9	62.6	20	51.3	61.5	10	34.5	48.3
20-30	15	18.1	80.7	10	25.6	87.2	11	37.9	86.2
>30	16	19.3	100.0	5	12.8	100.0	4	13.8	100.0
Total	83			39			29		

[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 present before the train's arrival.

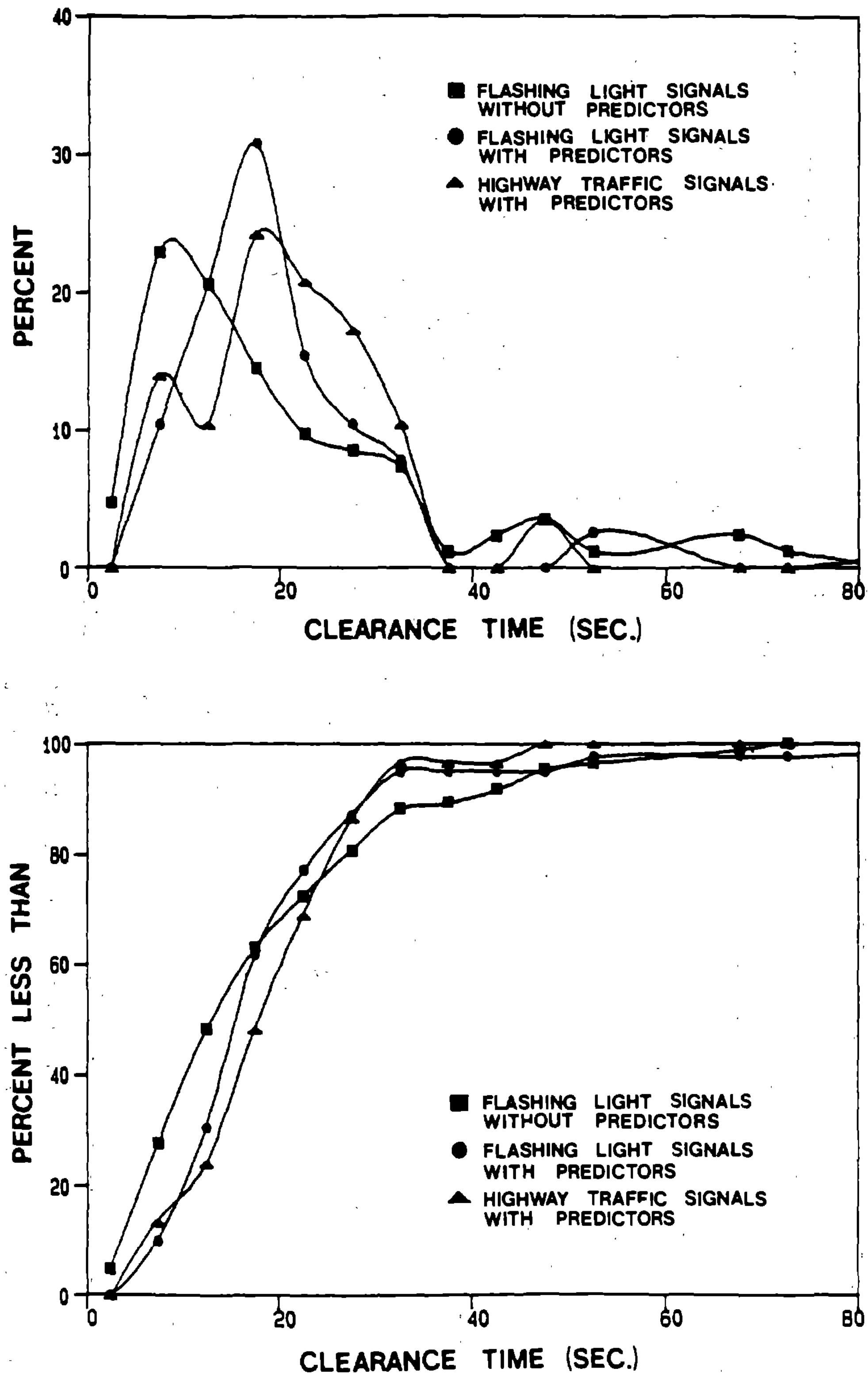


Figure 33. Frequency and cumulative frequency distributions of observed clearance times at the Cedar Drive crossing.

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 many dangerous and/or illegal maneuvers would be made during the first before study when the warning times were long and fewer dangerous and/or illegal maneuvers would be 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, 27.7 percent of the clearance times in the first before study would be classified as risky, whereas only 10.3 to 13.8 percent of the clearance times observed in the second before study and the after study, respectively, 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 under 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 which resulted from the installation of the predictors were successful in 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 aggressive behavior exhibited by motorists at the Cedar Drive crossing.

Approach Measures

Speed Profiles. The average speed at which drivers approached the Cedar Drive crossing whenever the warning devices were 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 have caused drivers to see the warning devices earlier and begin decelerating sooner. However, as mentioned previously, even if this behavioral change occurred it may not be large enough to be statistically significant, and even if it is statistically significant, 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 34. Each data point represents average speeds over 50-foot sections of roadway in advance of the stop bar at the crossing and is plotted at the midpoint 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 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 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 34.

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 5 miles per hour faster than they were in the second before study and as expected about 10 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. PBRT 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 sooner 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 but does not represent a pressure situation to a driver unless a train is also visible. Drivers know that

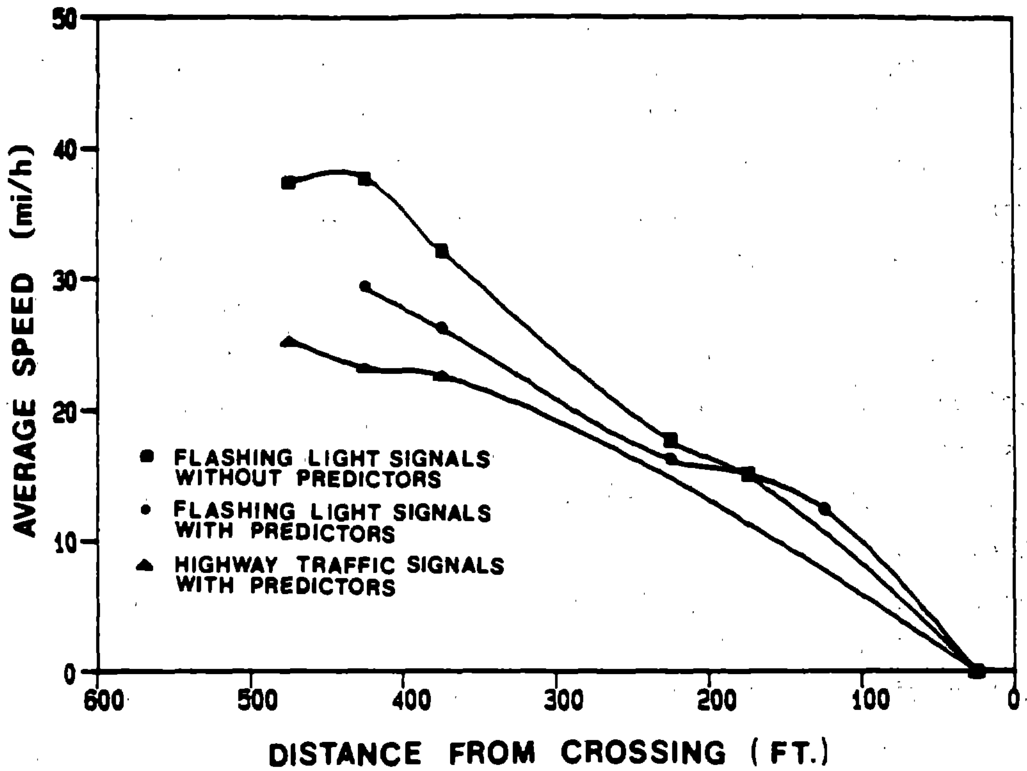


Figure 34. Average approach speed profiles for vehicles in advance of the Cedar Drive crossing.

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 should be relatively long and probably highly variable.

Average PBRTs in response to the activation of either the flashing light signals or onset of the traffic signals' 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. The Kruskal-Wallis test indicated that the differences 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 long reaction times 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 (short reaction times) and, because of this, was highly variable (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, the roughness of the crossing itself, or something else.

Safety Measures

Violations. At a crossing with flashing light signals, violations were defined as motorists who could reasonably stop in response to the warning device but failed to do so. However, as mentioned previously, 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. 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. Installation of the predictors and/or installation of the predictors in combination with the highway traffic signals was expected to 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 highway traffic signals were 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 6 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 49 observations in which no motorists behaved illegally, 16 observations in which one motorist behaved illegally, and only 13 observations in which more than one motorist behaved illegally. Thus, in 35.9 percent of train arrivals in which a motor vehicle was at the crossing, one or more vehicles proceeded through a red indication on the signal head. 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 90 percent of the time at level of service B, whereas the two quadrant gates were operating over 70 percent of the time at level of service D or F. Thus, it is not clear whether the differences in driver behavior are 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 highway traffic signals and the train's arrival at the crossing are shown in table 23. 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. The predictors in combination with the highway traffic signals reduced the average number of vehicles crossing per train arrival from 3.35

Table 23. Vehicles crossing 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)	13.28	6.40	10.86	3.86	2.92	3.35	0.80	0.53	0.73
Standard Deviation	7.74	6.28	7.91	3.34	2.50	2.92	1.47	0.61	1.32
Percent >0 Crossing	100.0	97.6	98.8	90.5	83.3	86.7	33.3	47.4	37.2
Percent >1 Crossing	98.1	86.7	94.0	71.4	62.5	66.7	20.3	5.3	16.7
Range (vehicles)	1-40	0-24	0-40	0-12	0-9	0-12	0-7	0-2	0-7

Crossings (vehicles)	Flashing Light Signals without Predictors			Flashing Light Signals with Predictors			Highway Traffic Signals with Predictors		
	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage
0	1	1.2	1.2	6	13.3	13.3	49	62.8	62.8
1	4	4.8	6.0	9	20.0	33.3	16	20.5	83.3
2	5	6.0	12.0	6	13.3	46.6	6	7.7	91.0
3	8	9.7	21.7	6	13.3	59.9	4	5.1	96.1
4	2	2.4	24.1	7	15.7	75.6	0	0.0	96.1
>4	63	75.9	100.0	11	24.4	100.0	3	3.9	100.0
Total	83			45			78		

[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.

to 0.73 when compared to flashing light signals with predictors. Thus, the highway traffic signals reduced the number of vehicles that crossed in front of an oncoming train by a factor of five (80 percent) compared to the flashing light signals when both systems had a predictor installed.

The effects of warning times on the number of vehicles crossing while the flashing light signals were activated or the highway traffic signals were red also are shown in table 24. 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 35. These results were expected; however, what was not expected was the differences between the flashing light signals with and without predictors. For example, without predictors warning times in the 40- to 50-second range resulted in an average of 10.0 vehicles crossing per train arrival, whereas with predictors, the same warning times resulted in an average of 4.33 vehicles crossing per train arrival. This difference is attributed to the shorter and more consistent warning times with predictors. 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, with predictors, 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 3 to 4 vehicles will cross in front of the train. This is not altogether surprising as the active warning devices at both the Ebenezer Road 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.

Table 24. 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	0	-
	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 arrivals at the crossing.

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

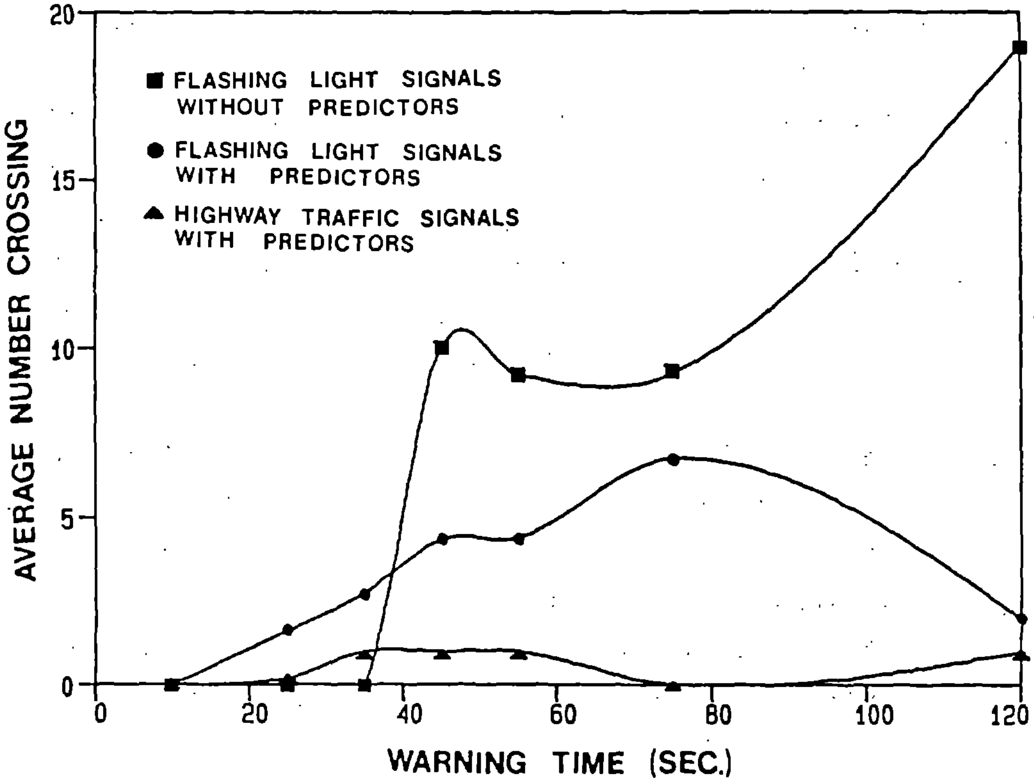


Figure 35. Average number of vehicles crossing as a function of warning time at the Cedar Drive crossing.

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 necessarily illegal, it represents those drivers who choose to cross within the 20-second minimum warning time presently required by the MUTCD.[11] As shown in table 25, 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, being reduced from an average of 1.81 to 0.24. The Kruskal-Wallis test indicated that these reductions were statistically significant for both the day and total data sets at the 99 percent confidence level.[44] Thus, as expected, installation of the predictors and of the predictors in combination with the highway traffic signals significantly reduced the number of CL20s at the crossing. The installation of the highway traffic signals reduced the CL20s from 0.78 (with flashing light signals) to 0.24 when predictors were used with both systems. There was little difference in the average CL20 rates for any of the nighttime data sets.

A frequency distribution of the observed CL20s at the Cedar Drive crossing is also shown in table 25. In the first before study (flashing light signals without predictors), there were 30 observations with no CL20s, 11 observations with one CL20, and 42 observations with two or more violations. The number of observations in each category were smaller and the percentages were different in the two studies with predictors present. A Pearson's chi-square statistic calculated from a 3 by 3 contingency table (three studies by three CL20 rate categories) substantiates the fact that these differences (fewer multiple CL20s) were significant at the 95 percent confidence level. Interestingly, the most effective warning device as far as preventing CL20s was the predictors in combination with the highway traffic signal; 82 percent of the observations in the after data set resulting in no CL20s. This compares with 46.7 percent for flashing light signals with predictors.

The effects of warning times on the CL20 rates at the Cedar Drive crossing are shown in table 26. As mentioned previously, and as shown in

Table 25. CL20s 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)	2.34	0.83	1.82	0.95	0.63	0.78	0.24	0.26	0.24
Standard Deviation	1.74	1.60	1.84	0.86	1.10	1.00	0.63	0.45	0.59
Percent >0 Violations	79.2	34.5	63.9	66.7	41.7	53.3	15.3	26.3	18.0
Percent >1 Violations	67.9	17.3	50.6	33.8	8.3	15.5	6.8	0.0	5.2
Range (vehicles)	0-6	0-6	0-6	0-3	0-5	0-5	0-3	0-1	0-3

CL20s (vehicles)	Flashing Light Signals without Predictors			Flashing Light Signals with Predictors			Highway Traffic Signals with Predictors		
	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage
0	30	36.1	36.1	21	46.7	46.7	64	82.0	82.0
1	11	13.3	49.4	17	37.8	84.5	10	12.8	94.8
2	13	15.7	65.1	5	11.1	95.6	3	3.9	98.7
3	12	14.5	79.6	1	2.2	97.8	1	1.3	100.0
>3	17	20.4	100.0	1	2.2	100.0	0	0.0	100.0
Total	83			45			78		

[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.

Table 26. Effects of warning times on CL20 rates at the Cedar Drive crossing.

Study	Warning Time (Sec.)[1]	Observed Train Arrivals[2]	Average CL20s (per Arrival)
Flashing Light Signals without Predictors	<20	0	-
	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	0	-
	20-30	5	0.80
	30-40	24	0.83
	40-50	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.

table 25, 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. The average CL20 rate was 1.82 before predictors were installed, 0.78 after predictors were installed, and 0.24 after both predictors and highway 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 predictor study, there were 0.83 CL20s per train arrival. When traffic signals were installed, the CL20 rate in this warning time range was approximately 0.33. This seems to indicate that the highway traffic signals with predictors are more effective in reducing CL20s than flashing light signals when predictors are used with both systems.

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; there is little room for either driver or vehicular error. Although not necessarily 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 and 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 conflicts.

As shown in table 27, 29 CL10s (15 single CL10s and 7 double CL10s) were observed at the Cedar Drive crossing in the before study, i.e., 29 motorists crossed the tracks within 10 seconds of the train's arrival. Twenty-five CL10s (13 single CL10s and 6 double CL10s) occured during the day and four CL10s (2 single CL10s and 1 double CL10) occured at night. 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 3 by 3 contingency table (three studies by three CL10 categories) indicated that the observed CL10s in the first before study (flashing light signals without predictors) and the two studies with predictors (flashing light signals with predictors and highway traffic signals with predictors) were significantly

Table 27. CL10s 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.

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 CL10s 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 CL10s could not be tested.

One observation from this data set is that the CL10 rates and percentages for the flashing light signals without predictors 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; 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 to improve the level of service of the active warning devices, the observed CL10 rates were comparable to those at Ebenezer Road. Interestingly, the additional installation of the highway traffic signal reduced the number of observed CL10s to a rate comparable to that observed at the Cherry Street crossing when two-quadrant gates were used.

Summary

The existing active warning system at the Cedar Drive crossing (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 (an acceptable level to most motorists). As the intent of both the predictors and the highway traffic signals was to provide additional credibility and respect for the active warning devices, performance measures such as clearance times, violations, and conflicts 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 did not change significantly. When holding the variable predictors constant, highway traffic signals substantially outperform flashing light signals in categories having an impact on safety.

VIII. BENEFIT-COST EVALUATION

Based on the results of the field studies, all three of the innovative traffic control systems proved to be feasible, both from a technical and practical standpoint. In addition, all three systems were accepted and understood by the driving public. Two of the systems, the four-quadrant gates with skirts and the highway traffic signals, show great promise for improving crossing safety. The third system, four-quadrant flashing light signals with strobes, did not produce measurable improvements in safety at the test crossing, but may have some limited applications.

Having confirmed that the innovative systems are feasible and effective, the issue of system cost becomes important. Cost considerations govern whether and where the innovative traffic control devices are economically advantageous.

This chapter identifies and discusses the primary cost considerations for each of the innovative systems. Presented first are cost estimates for installing, operating, and maintaining the three systems. The results of benefit-cost analyses are then presented for the two most promising systems, the four-quadrant gates with skirts and the highway traffic signals. Lastly, estimates are developed for the cost of "retrofitting" various percentages of the existing crossings in the country with the innovative devices.

Cost Estimates

For each of the three innovative systems, the following cost components were considered in assessing total system cost: (1) installation costs; (2) operating costs; and (3) maintenance costs. Installation costs include the cost of materials, equipment, labor, and miscellaneous expenses (travel, worker per diem, contingency costs, etc.). Operating costs are the system power consumption costs. Maintenance costs include the cost of routine service checks, cleaning, repairs, minor hardware replacement, and battery maintenance for those systems with battery backup power.

Use of Marginal Costs. In developing cost estimates for the three innovative systems, marginal costs were used. "Marginal costs" refer to those costs incurred above and beyond the cost of providing whichever standard active warning system would normally be used. For example, the marginal costs of four-quadrant gates with skirts would be those costs above and beyond the costs of providing standard two-quadrant gates. The marginal costs of the four-quadrant flashing light signals with strobes would be the costs above and beyond the costs of providing standard two-quadrant flashing light signals.

Marginal costs for highway traffic signals would be the costs to install, operate, and maintain the traffic signal installation after subtracting the costs for a standard two-quadrant flashing light signal system. The highway traffic signal system is unique in that it does not incorporate any of the traffic control hardware used in its standard counterpart and because its marginal installation cost is actually a negative number. That is, the cost of installing traffic signals is actually less than the cost of installing flashing light signals.

Note that marginal costs do not include the following:

- The cost of installing, operating, or maintaining the train detection system.
- The cost of installing that portion of the traffic control equipment which would also be required for the standard active warning system.
- The costs of operating and maintaining that portion of the equipment which would be required for a standard active warning system.

The use of marginal costs as opposed to total costs is appropriate for several reasons. First of all, it is reasonable to assume that, if adopted, the innovative systems would be used most often at crossings which already have standard active control devices. In these cases, the retrofit (or add-on) costs would be of primary interest, and these retrofit costs are essentially the same as marginal costs. (A retrofit traffic signal installation is an exception in that the retrofit costs are not essentially the same as the marginal costs. The cost evaluations take this fact into account as discussed later.)

For a new installation at a passive crossing, it is also logical to use marginal costs to assess the economics of installing one of the innovative systems. Generally speaking, the innovative devices would be considered for use only at existing passive crossings where one of the standard active devices was also warranted and would be installed. Thus, the decision which must be made is whether to employ a standard device or to opt for one of the innovative devices. Marginal costs provide the needed input for this decision.

In addition, the costs of providing train detection, initial site preparation, and power connections are highly variable depending on the location of the crossing, terrain, number of tracks, type of detection system, etc. However, marginal costs, as defined, should be fairly consistent from one crossing to the next; thus, they provide a more consistent and accurate means of comparing alternatives than if comparisons are made on total costs.

Installation Cost Estimates. Although much was learned about the economics of constructing and installing the innovative traffic control systems during the field studies, the three test installations did not give a complete and accurate indication of "typical" installation costs. First of all, the systems were designed, constructed, and operated in a research setting where minimizing cost was secondary to successfully completing the research. Second, some of the components of the innovative systems were not intergrated into the existing active warning systems at the test crossings, but rather were operated independently. The flashing light signals with strobes are an example. The strobe lights were mounted on different poles from the flashing light signals, and they had their own primary and secondary power supply systems. The strobe controller and batteries were even housed in a separate cabinet.

To develop more reliable and accurate installation costs for the innovative systems, actual construction estimates were solicited from two railroads, three highway agencies, and a traffic engineering consultant. The details of the solicitation are described in the following section.

Construction Estimates. To obtain the needed installation cost estimates, three hypothetical projects were conceived, one for each of the innovative systems. Each of the projects involved "retrofitting" one of the innovative systems to a grade crossing which had a standard active warning device and a train detection system already in place. The exception was the project for the highway traffic signal. For this project, it was assumed that a train detection system was in place, but there were no existing active warning devices at the crossing.

A project description was prepared, along with an estimate worksheet, for each project. The descriptions and corresponding worksheets are shown in Appendix B. All three hypothetical projects involved the same basic crossing situation--a single mainline track crossing a two-lane roadway. This simple type of crossing was chosen to promote consistency and ease of cost estimation. The cost of installing standard devices at more complex crossings would be higher, but the basic relationship between standard and innovative system costs, as reflected by the marginal costs, should remain fairly constant (or at least proportional) for the more complex crossing situations.

Two railroads, three highway agencies, and one consulting firm agreed to participate in the artificial bid exercise. The railroad companies provided cost estimates for two of the projects--installing four-quadrant gates with skirts and installing four-quadrant flashing light signals with strobes. The highway agencies and consulting firm provided cost estimates for the project to install highway traffic signals.

Table 28 shows the resulting average estimated costs for the three hypothetical projects, broken down by expense category. From the table, the average cost to install the four-quadrant gates with skirts was $32,763, the average cost to install highway traffic signals was $11,196, and the average cost for the four-quadrant flashing light signals with strobes was $19,196. It should be emphasized that the cost estimates shown in the table assume that train detection systems were already in place. Also, for the four-quadrant

Table 28. Average installation cost estimates.

Expense Category	Four-Quadrant Gates with Flashing Light Signals[1]	Highway Traffic Signals[2]	Four-Quadrant Flashing Light Signals with Strobes[2]
Material/ Supply Costs	$12,314	$ 9,373	$4,793
Equipment Costs	1,550	425	1,175
Labor Costs	13,676	1,092	10,161
Other Costs (Travel, Per Diem, Contingencies, etc.)	5,223	306	3,067
Total Installation Costs	$32,763	$11,196	$19,196

[1]Average of two estimates.

[2]Average of four estimates.

gates with skirts and the four-quadrant flashing signals with strobes, it is assumed that standard two-quadrant gates and two-quadrant flashing light signals, respectively, were already in place.

It is significant to note in table 28 that the highway traffic signal cost estimates were considerably lower than the estimates for the other two innovative systems. The major reason for the relatively low cost of highway traffic signals is the much lower estimated labor costs. From the table, the average estimated cost of labor for highway traffic signals was $1,092. In contrast, the average estimated cost for labor for the four-quadrant gates with skirts was $13,676, and for the four-quadrant flashing light signals with strobes it was $10,161. These labor costs are about ten times greater than the labor costs for installing highway traffic signals.

Marginal Installation Costs. Marginal installation cost estimates for each of the innovative systems are presented in table 29. For the four-quadrant gates with skirts and the four-quadrant flashing light signals with strobes, the marginal installation cost was taken to be the average total estimated cost shown in table 28. (The costs have been appropriately rounded off.)

For the highway traffic signals, two marginal costs are given in table 29, one for a retrofit installation and the other for a new installation. The retrofit installation cost was taken to be the average installation cost from table 28. The marginal cost for a new highway traffic signal installation was estimated by subtracting the average cost for installing standard flashing light signals (excluding the train detection system) from the average estimated cost for highway traffic signals as shown in table 27. The average cost for installing standard flashing light signals (excluding the train detection system) was assumed to be $17,300, based on cost estimates furnished by Southern Railroad and Union Pacific Railroad.

Operating and Maintenance Cost Estimates. The experience gained in the field studies provided a basis to estimate annual operating and maintenance costs for the innovative systems. Based on the field experience, Southern Railroad supplied estimates for the annual costs of operating and maintaining

Table 29. Marginal installation costs.

Innovative System	Marginal Installation Cost[1]
Four-Quadrant Gates with Skirts	$32,750
Highway Traffic Signals (New Installation)	- 6,100[2]
Highway Traffic Signals (Retrofit)	11,200[3]
Four-Quadrant Flashing Light Signals with Strobes	19,200

[1]Marginal costs refer to added cost to install innovative system in lieu of appropriate standard active warning system, i.e., two-quadrant flashing light signals with or without gates.

[2]Negative cost indicates a cost savings compared to the cost of installing standard two-quadrant flashing light signals.

[3]Cost to remove existing flashing light signals and install highway traffic signals in their place.

the four-quadrant gates with skirts and the four-quadrant flashing light signals with strobes (excluding the strobe lights). Operating and maintenance cost estimates for the strobe lights were developed by the researchers based on actual power company billings and service records. The City of Knoxville supplied estimates for the annual costs of operating and maintaining the highway traffic signals.

To compute marginal operating and maintenance costs for the innovative systems (compared to standard active warning systems), the costs of operating/maintaining standard gates and/or flashing light signals had to be subtracted out. Appropriate annual operating and maintenance costs for gates and flashing light signals were based on national averages for these standard systems.[50]

Marginal Operating Costs. Table 30 summarizes the annual marginal operating costs for the three innovative systems. The cost figures in the table are for a single-track crossing on a two-lane roadway, and they assume that the innovative systems have unified power supply systems which minimize power costs.

From table 30, the marginal operating (power) costs of the four-quadrant gates with skirts and the four-quadrant flashing light signals with strobes would be expected to be zero (0). Both of these systems operate on 12-volt battery systems, and the batteries are trickle charged using commercial power or through a special railroad power transmission line. Power consumption and power costs associated with battery charging are small and relatively insignificant compared to other costs. (Battery service costs are significant, but these costs are included in maintenance costs.)

Highway traffic signals, which operate on 110-volt commercial power, consume considerably more power than their conventional counterpart, flashing light signals. As shown in table 30, the annual marginal operating (power) cost of highway traffic signals is estimated to be $1,200 for a retrofit installation. This figure includes the cost of operating the highway traffic signals and the advanced sign flashing lights above the power cost

Table 30. Annual marginal operating costs of the three innovative systems.

Innovative System	Annual Marginal Operating Cost
Four-Quadrant Gates with skirts	$ 0
Highway Traffic Signals	1,200
Four-Quadrant Flashing Light Signals with Strobes	0

associated with trickle charging the battery system for the train detection circuitry.

Marginal Maintenance Costs. Table 31 presents annual marginal maintenance costs for the three innovative traffic control systems. As noted previously, the maintenance cost estimates were developed based on data provided by Southern Railroad and the City of Knoxville, national averages and field study maintenance records.[50] The cost estimates in the table are for a single-track crossing on a two-lane highway. The cost estimates also assume that the innovative systems are fully unified, i.e., all the system components including the train detection system, the active warning devices, and power supply system are designed and operated in the most efficient and cost effective manner.

From table 31, the four-quadrant gates with skirts would cost approximately $740 more per year to maintain than standard two-quadrant gates. The added costs would be incurred in maintaining the two additional poles, two additional gates and gate mechanisms, and the four skirts.

Also from table 31, the annual marginal maintenance costs of highway traffic signals would be approximately $200. The additional maintenance costs for highway traffic signals (compared to standard flashing light signals) are incurred in maintaining the traffic signal controller and the flashing light units on the advanced signs.

It would cost approximately $450 more per year to maintain four-quadrant flashing light signals with strobes compared to standard two-quadrant flashing light signals (see table 31). The added costs are for maintaining the two additional poles, the four strobe lights, and strobe power supply units.

Benefit-Cost Analyses

This section analyzes the relationships between cost and safety performance for the two most promising innovative systems, i.e., the four-quadrant gates and skirts and the highway traffic signals. In the analyses, system cost data from the previous sections are combined with accident cost

Table 31. Annual marginal maintenance costs of the three innovative systems.

Innovative System	Annual Marginal Maintenance Cost
Four-Quadrant Gates with Skirts	$740
Highway Traffic Signals	200
Four-Quadrant Flashing Light Signals with Strobes	450

estimates to generate benefit-cost ratios. Surrogate safety measures are also identified and discussed to justify the assumptions made regarding predicted accident reductions and to further illustrate the magnitude of the improvements which may be achieved through use of the innovative systems.

It should be noted that the cost and accident data used in the analyses are based on a number of simplifying assumptions, and that the data are admittedly somewhat limited and site specific. Nevertheless, the data are sufficient to illustrate the anticipated costs and safety benefits of the innovative systems in typical applications. Agencies contemplating using the innovative devices are encouraged to develop and use their own cost and accident data to yield more accurate benefit-cost estimates for their circumstances.

A benefit-cost analysis for the third innovative system, the four-quadrant flashing light signals with strobes, was not attempted. The specific improvements in safety afforded by this system could not be sufficiently quantified at the test crossing to make a reliable benefit-cost assessment. It should be noted, however, that four-quadrant flashing light signals with strobes might enhance safety at some types of crossings (see chapter IX), and since their marginal costs are relatively low, the system might be cost effective at these locations.

Analysis Approach. For a particular innovative system, the benefit-cost analyses consisted of the following four steps:

1. The annual marginal costs to install, operate, and maintain the innovative system were estimated.
2. Surrogate accident measures were identified from the field studies. These measures were quantified for a variety of crossing conditions using a simple simulation model developed specifically for this project. The surrogate safety measures were then subjectively evaluated to predict the likely impacts of the innovative system on crossing safety.
3. The reductions in crossing accidents produced by the innovative systems were estimated for a variety of crossing conditions using an accident prediction model from the literature.

4. Savings in accident costs were generated based on the accident reductions predicted in step 3. These savings in accident costs were compared with system installation/operation costs (step 1) to generate appropriate benefit-cost ratios.

Each of these steps is discussed in detail below, and then the results of the cost-effectiveness analyses are presented.

Cost Estimates. Marginal costs, expressed on an annual basis, were used in the analyses. The annual marginal costs of a particular innovative system were estimated by summing the annual marginal installation, operating, and maintenance costs of that system.

Annual marginal operating and maintenance costs were taken directly from tables 30 and 31. Annual marginal installation costs were calculated from the installation costs presented in table 29. The total costs from table 29 were converted to annual costs using the Capital Recovery Cost Method for annualizing an initial expenditure over an assumed future time period.[51] For the purpose of this evaluation, it was assumed the innovative systems would have a useful life of 20 years, when retrofitted to a crossing which already had standard active devices. A 10.0 percent annual interest rate was also assumed. For new installations at crossings which previously had passive control, a useful life of 30 years was assumed, along with the 10 percent annual interest rate.

Surrogate Accident Measures. The innovative systems are intended to reduce the number of train-auto accidents at grade crossings. Thus, the most appropriate measures of effectiveness are accident reduction and accident cost savings. However, since there were no accidents during any of the field studies and since the field studies were relatively short in duration, it was not possible to directly measure the long-term accident reduction potential of the innovative systems. Instead, accident reduction potential had to be subjectively assessed from surrogate accident measures.

In the case of the four-quadrant gates with skirts, the number of vehicles driving around the gate arms (violations) was used as the surrogate accident measure. This measure was selected for two reasons. First, it is reasonable to assume that if the number of gate arm violations can be substantially reduced at a crossing, then the crossing's accident potential should also be reduced. Second, the field studies provided the data needed to estimate the number of gate arm violations which could be eliminated through the use of four-quadrant gates with skirts.

In comparing highway traffic signals with flashing light signals, signal violations could not be used as a surrogate accident measure since no violation data were available for flashing light signals. Instead, the number of vehicles crossing the tracks within 10 seconds of a train arrival (CL10s) was used as a surrogate accident measure. This crossing safety measure should be directly related to accident potential at a crossing. That is, if the number of vehicles crossing the tracks within 10 seconds of a train arrival can be substantially reduced at a crossing, then it follows that the potential for accidents should decrease (provided all other factors remain constant). In addition, CL10 data were available from the field studies for all the traffic control devices at the crossings.

To estimate and assess surrogate accident measures for the innovative devices, a simple simulation model was developed by the researchers. The model incorporates basic traffic flow theory and characteristics, along with performance data from the field studies, to estimate the numbers of gate violations or CL10 crossings which could be eliminated by installing four-quadrant gates or highway traffic signals, respectively. A description of the model, including its assumptions, inputs, and outputs, follows:

1. The model generates (simulates) train and vehicle traffic at a grade crossing for a range of crossing conditions specified as model inputs. Specifically, the model predicts how many vehicles (per year) arrive at the crossing while a train is approaching, and how many of these vehicles will attempt to cross in front of the train.

2. The variable inputs to the model include daily train and vehicular volumes at the crossing, the assumed train warning time distribution (mean and standard deviation), type of traffic control, and the percentage of drivers who would be expected to violate the gates or cross within 10 seconds of train arrival. (The violation and CL10 crossing rates were estimated from the field studies.)

3. The model assumes that train arrivals are randomly distributed throughout the day, and that vehicle traffic varies by time of

day in a pattern typical of a State highway route. During a specific train event, vehicle arrivals at the crossing are assumed to have a Poisson distribution.

4. The model further assumes that train warning times (the time between device activation and train arrival) are normally distributed. (The mean and standard deviation warning times are variable inputs.) For the analyses, the following warning time conditions were assumed: (1) 60-second mean warning time with a 20-second standard deviation; and (2) 40-second mean warning time with a 15-second standard deviation. (These warning times are typical of those observed in the field studies and provide a suitable range of conditions for the evaluation.)

5. A Bernoulli Process is incorporated into the model to predict how many arriving motorists would elect to cross in front of an approaching train.

6. The model incorporates several limiting factors to account for crossing capacity, minimum warning times used by the railroads, and the times at the beginning and end of the warning periods in which motorists are restricted in their crossing behavior.

Accident Reduction Estimates. A critical aspect of the benefit-cost analyses was estimating the number of accidents which would be prevented by the innovative systems. In the absence of any accident experience with the new systems, the following approach was used. First, the numbers of accidents which would be expected for standard devices (gates and/or flashing light signals) were predicted. These accident frequencies for standard systems were then multiplied by the assumed percentage reduction in accidents which would be achieved by installing the appropriate innovative system.

To predict accident frequencies at crossings with standard devices, the grade crossing accident prediction model developed by Coleman and Stewart was used.[52] The Coleman-Stewart model is a regression model developed from empirical data gathered at over 32,000 crossings in 15 States. The model is expressed as follows:

$$\log (A) = C_0 + C_1 \log (V) + C_2 \log (T) + C_3 (\log (T))^2$$

where:

A = Average accidents per year per crossing

V = Average daily traffic

T = Trains per day

C_0, C_1, C_2, C_3 are regression coefficients which vary depending on the location and type of crossing and the type of traffic control.

The model, by varying the coefficients, distinguishes between rural and urban crossings, and between single- and multi-track crossings. It also can handle several types of standard traffic control; however, for this study only two levels of standard traffic control were of interest (gates and flashing light signals).

The Coleman-Stewart model was used to generate estimates of the number of accidents per crossing per year under various assumed conditions for crossings with flashing light signals and for crossings with gates. To predict the number of accidents prevented by the innovative systems, these estimates were multiplied by the percentage reduction in accidents which could be achieved by installing the appropriate innovative system. Obviously, a single, precise percentage of accidents which would be prevented by installing one of the innovative systems could not be made based on the limited field experience. Therefore, in the absence of accident experience, ranges in accident reduction potential had to be used.

It was assumed that the four-quadrant gates with skirts could reduce the number of accidents by 40 to 100 percent compared to standard two-quadrant gates. It was assumed the highway traffic signals could reduce train-auto accidents by 20 to 80 percent compared to standard flashing light signals. It should be stressed that these accident reductions are merely estimates made by the researchers based on their experience and intuition. Wide ranges in reductions were purposely selected since there are no accident reduction data on the innovative systems. By using wide ranges, the benefit-cost analyses considered high, medium, and low accident reduction potentials.

Accident Cost Savings. Before benefit-cost ratios could be computed, the number of accidents prevented by the innovative systems had to be equated to a cost savings. To accomplish this, the estimated number of prevented accidents was multiplied by the fatality and injury rates for grade crossing accidents shown in table 32.(3) This generated the numbers of deaths and injuries prevented by installing the innovative systems. It was then assumed that each prevented fatality resulted in a total cost savings of $1,450,000, and each prevented serious injury resulted in a savings of $39,000. These fatality and injury costs are based on Federal Highway Administration estimates.(53)

The accident cost savings were expressed in annual savings and were divided by the annual marginal system costs to generate benefit-cost ratios. Benefit-cost ratios were generated for both the four-quadrant gates with skirts and for the highway traffic signals for a wide range of volume conditions and crossing types.

Cost Evaluation of Four-Quadrant Gates with Skirts. This section presents the results of the benefit-cost evaluation of the four-quadrant gates with skirts. The procedure described in the preceding sections was used for this evaluation. Presented first are cost estimates for the innovative gate system. Next, the reductions in crossing violations which can be achieved by using the innovative system are quantified and discussed relative to the impacts on safety. Lastly, benefit-cost ratios are presented for the innovative gate system for various crossing conditions and types.

System Cost Estimates. As shown in table 33 the annual marginal cost to install, operate, and maintain four-quadrant gates with skirts is $4,590. That is, it would cost $4,590 more per year to provide four-quadrant gates with skirts compared to standard two-quadrant gates. This cost includes $3,850 in annualized installation marginal costs and $740 in maintenance marginal costs.

It should be noted that the cost estimates in table 33 are applicable to an "ordinary" installation. Both installation and maintenance costs would be higher at crossings with complex traffic control or geometric conditions, e.g., at multi-track crossings or crossings at or near a highway

Table 32. Fatality and injury rates for accidents at railroad-highway grade crossings.

Traffic Control	Fatalities per Accident	Injuries per Accident
Gates	0.09	0.37
Flashing Light Signals	0.08	0.41

Table 33. Annual marginal costs of four-quadrant gates with skirts.

Cost Component	Annual Marginal Costs[1]
Annualized Installation Costs	$3,850[2]
Annual Operating Costs	0
Annual Maintenance Costs	740
Total	$4,590

[1]Cost estimates apply to ordinary crossing conditions. Costs may increase at crossing with complex traffic control requirements.

[2]Capital recovery costs assuming a 20-year useful life and 10 percent interest rate.

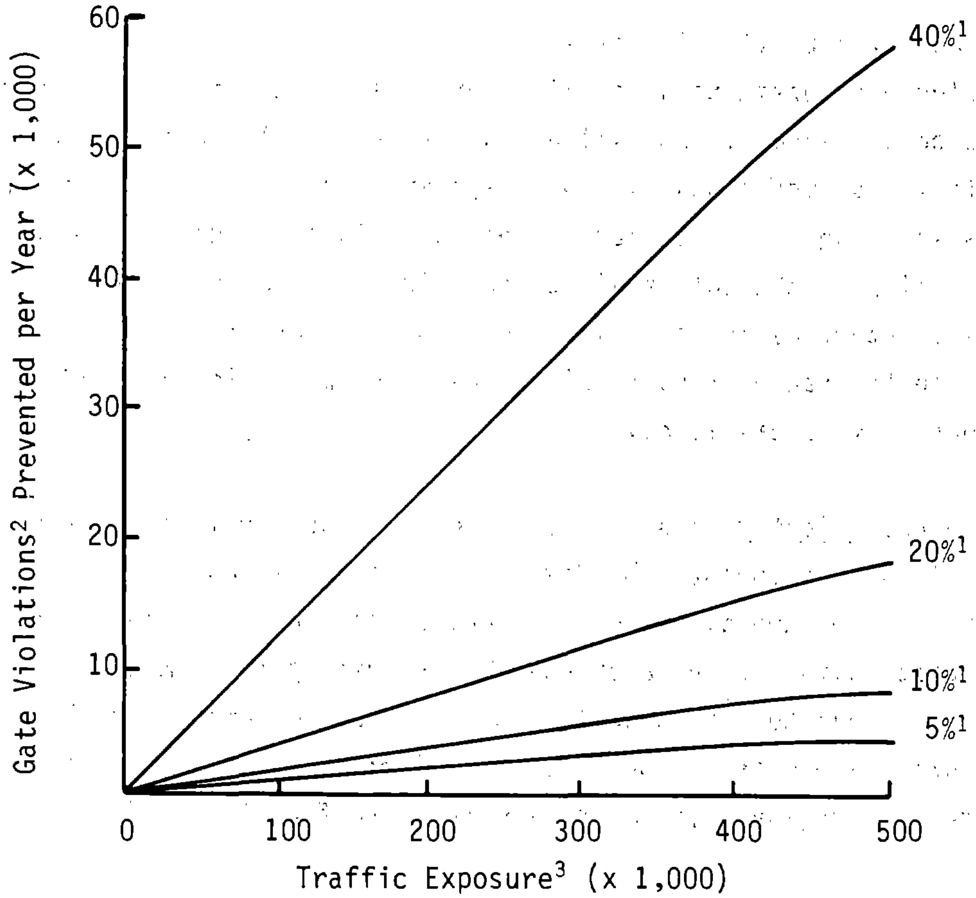
intersection. In fact, in generating benefit-cost ratios for the innovative gate system at multi-track crossings, the total marginal annual cost was increased by 10 percent to $5,050.

Reductions in Crossing Violations. Based on the results of the field studies, four-quadrant gates with skirts eliminate virtually all gate violations. This "zero" violation rate compares to violation rates ranging from 5 to 40 percent at crossings with standard gates. Thus, it is reasonable to conclude that four-quadrant gates with skirts should have a significant impact on crossing safety, especially at existing gated crossings with high violation rates and corresponding high numbers of accidents.

Figure 36 illustrates the impact of four-quadrant gates with skirts on crossing violations. The data shown in the figure were generated using the simulation model described earlier, and they represent a typical assumed crossing situation. For the particular simulation run used to generate figure 36, an average train warning time of 60 seconds was assumed. (The Cherry Street Crossing had an approximate average warning time of 60 seconds, thus making this assumed warning time particularly pertinent.) It was also assumed that the innovative gate system would effectively eliminate all crossing violations, as was observed in the field studies.

In figure 36, the number of prevented violations is related to traffic exposure (trains per day x average daily traffic [ADT]) and to the initial violation rate (the violation rate for standard gates). As shown in the figure, the number of violations which would be eliminated increases as traffic exposure increases. The number of violations eliminated by the use of four-quadrant gates with skirts would also be greater at crossings with a higher initial violation rate.

What is significant from figure 36 in terms of crossing safety is the magnitude of the prevented violations. For example, at a crossing with an initial violation rate of 10 percent and a traffic exposure of 500,000 (e.g., 20 trains per day and an ADT of 25,000), approximately 9,000 crossing violations per year would be eliminated by installing four-quadrant gates with skirts. For an initial violation rate of 20 percent, over 18,000 violations



[1]Percentage of motorists violating standard gates and flashing light signals.

[2]Gate violations refer to motorists driving around a lowered gate arm while a train is approaching.

[3]Traffic exposure = trains per day x ADT.

Figure 36. Annual gate violations prevented by four-quadrant gates with skirts in place of standard two-quadrant gates and flashing light signals.

would be eliminated each year by installing the innovative gate system. These reductions in crossing violations should represent a significant reduction in accident potential.

As noted previously, it is not possible based on the limited field experience to estimate a specific percentage reduction in accidents which would be achieved by installing four-quadrant gates with skirts. However, the fact that the innovative gate system completely eliminates crossing violations suggests that reductions in train-auto accidents will be very high. Simply, the potential for conflict between trains and highway vehicles is eliminated, as is the driver decision element. Therefore, accident reductions in the range of 40 to 100 percent are possible, and reductions of 80 percent or more are likely.

<u>Benefit-Cost Ratios</u>. Benefit-cost ratios for various crossing types and conditions were computed by dividing the expected annual accident cost savings by the annual system marginal costs. As discussed previously, accident cost savings were calculated by estimating the number of accidents which would be prevented by installing the innovative gates, and then calculating an appropriate cost savings resulting from having fewer crossing accidents. The annual marginal system costs were taken from table 32.

Generally, the results of the benefit-cost analyses were very favorable, suggesting that four-quadrant gates with skirts would be cost-effective in many crossing situations. In fact, benefit-cost ratios of 4.0 or more were found for many of the crossing conditions evaluated. The detailed results are discussed in the following sections broken down by type of crossing (rural single-track crossings, urban single-track crossings, and urban multi-track crossings). These crossing types were differentiated in the Coleman-Stewart accident prediction model which was used in generating the benefit-cost ratios.

Figure 37 presents the benefit-cost ratios for installing four-quadrant gates with skirts at rural single-track crossings. The figure includes benefit-cost ratios for four levels of accident reduction (40, 60, 80, and 100 percent). In each case, the ratios are plotted for a range of ADTs (from

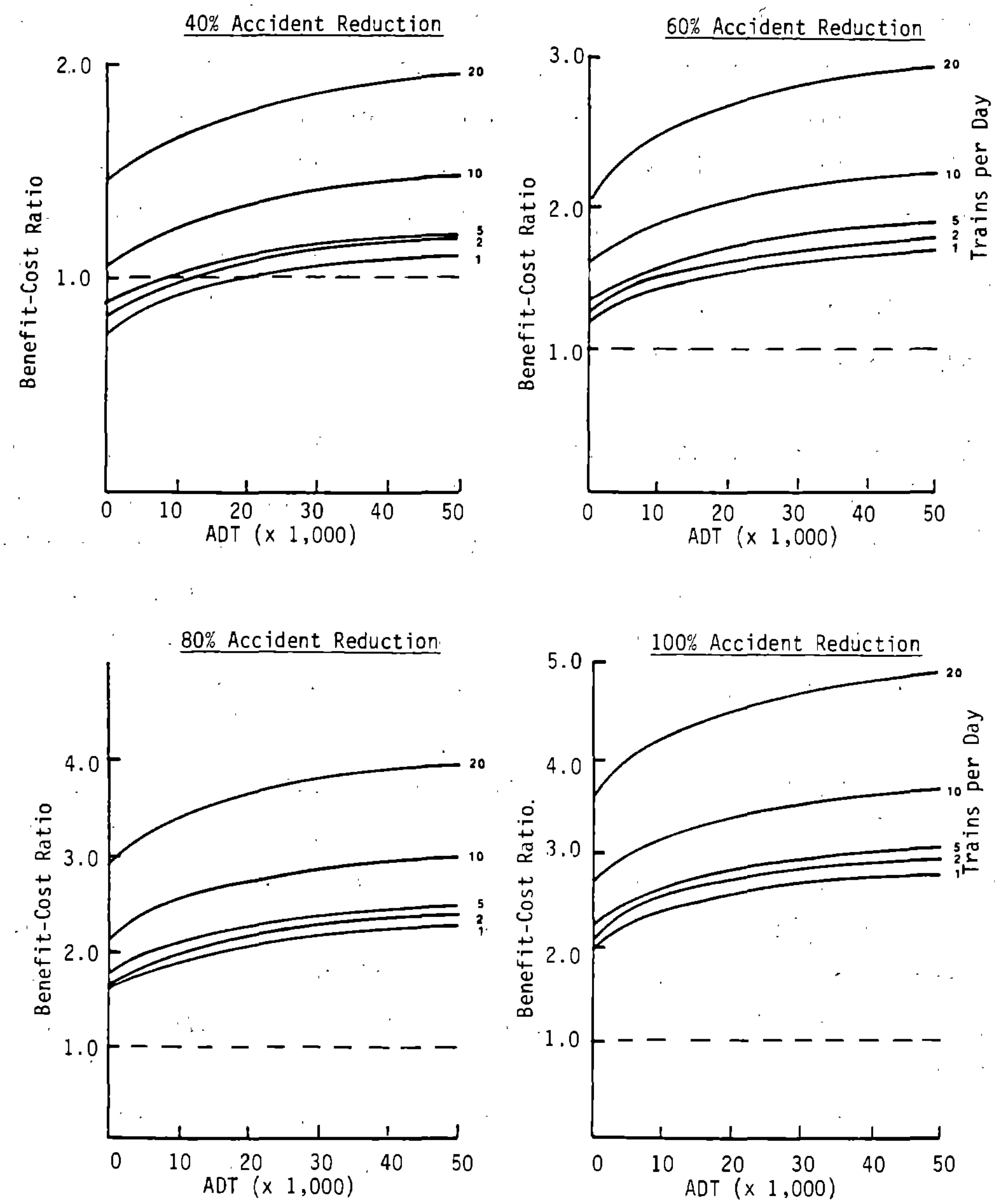


Figure 37. Benefit-cost ratios, rural single-track crossing, retrofit four-quadrant gates with skirts.

0 to 50,000 vehicles per day) and for a range of trains per day (1, 2, 5, 10, and 20 trains per day).

Generally, a benefit-cost ratio above 1.0 indicates that the savings in accident costs achieved by installing the innovative gate system would be greater than the costs of installation, operation, and maintenance for the particular conditions. However, a word of caution is necessary. The graphs are only intended to illustrate basic trends, and not to establish firmly whether or not the innovative gates are appropriate. Several other factors, besides a favorable benefit-cost ratio, have to be considered in assessing where the innovative system might be used. Many of these factors are identified and discussed in chapter IX.

Assuming a 40 percent accident reduction level, it is seen in figure 37 (upper left-hand graph) that the four quadrant gates with skirts would be cost-effective at crossings with 10 or more trains per day regardless of the traffic volume level. At lower train volumes (1 to 5 trains per day) and assuming a 40 percent accident reduction level, the innovative gate system would be cost-effective only at moderate to high traffic volumes.

If 60 percent or more of the train-car accidents could be eliminated by installing the innovative gate system, then the system would be cost-effective at virtually all train and traffic volume levels. This is illustrated in the upper right-hand and lower two graphs in figure 37. For example, if a 100 percent accident reduction could be achieved, then the innovative gates would have a benefit-cost ratio ranging from 2 to 5 depending on the train and traffic volumes (see lower right-hand graph in figure 37). If 60 percent of the accidents were prevented, benefit-cost ratios ranging between 1 and 3 could be obtained (see upper right-hand graph in figure 37).

Figure 38 presents benefit-cost ratios for installing four-quadrant gates with skirts at urban single-track crossings. As can be seen in the figure, the benefit-cost ratios for urban single-track crossings differ slightly from those for rural single-track crossings shown in figure 37. The differences are due to differences in accident rates at urban versus rural crossings as indicated in the Coleman-Stewart accident prediction model.

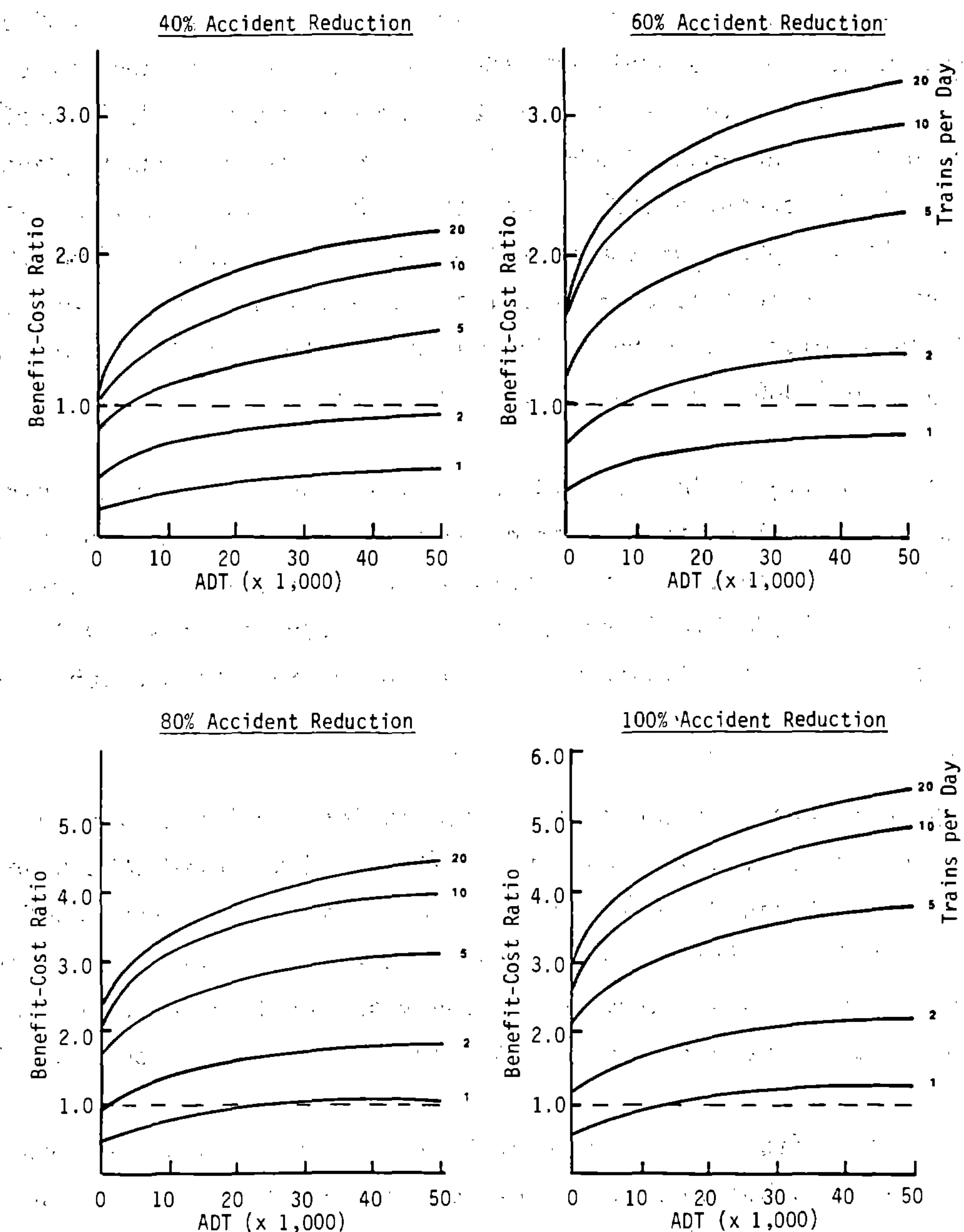


Figure 38. Benefit-cost ratios, urban single-track crossing, retrofit four-quadrant gates with skirts.

Note in figure 38 that four-quadrant gates with skirts would generally be cost-effective at any urban single-track crossing with 10 or more trains per day, regardless of the traffic volume. For example, if an 80 percent accident reduction were achieved, the innovative system would be cost-effective for train volumes of only 2 or more per day at daily traffic volumes higher than about 2,000 (refer to the lower left-hand graph in figure 38). For a 60 percent accident reduction, daily traffic volumes would have to be slightly higher for the system to be cost-effective. From the upper right-hand graph in figure 38, the innovative gates would be cost-effective at a crossing with 2 or more trains per day if the traffic volumes at the crossing were 8,000 vehicles per day or higher.

Also from figure 38, if a 100 percent accident reduction could be achieved by installing four-quadrant gates with skirts at an urban single-track crossing, then the system would be cost-effective at moderate traffic volumes (i.e., 12,000 vehicles per day or greater) for train volumes of only one per day. This is illustrated in the lower right-hand graph of the figure.

Figure 39 presents the benefit-cost ratios for installing the innovative gates at urban multi-track crossings. It should be noted that higher installation and maintenance costs were assumed in calculating the benefit-cost ratios shown in the figure due to the greater complexity of multi-track crossings. As discussed previously, the annualized installation and annual maintenance costs were inflated by 10 percent for multi-track crossings.

As seen in figure 39, the innovative gate system would achieve benefit-cost ratios up to 8.5 to 1 under some of the conditions evaluated. In fact as might be expected, urban multi-track crossings yielded the highest benefit-cost ratios among the various types of crossings considered. This is due to the generally higher accident rates at these crossings. From figure 39, it is seen that four-quadrant gates with skirts would be cost-effective at medium train volumes and low traffic volumes if only a 40 percent accident reduction was achieved. For example, assuming a 40 percent accident reduction and 5 or more trains per day, the innovative system would be

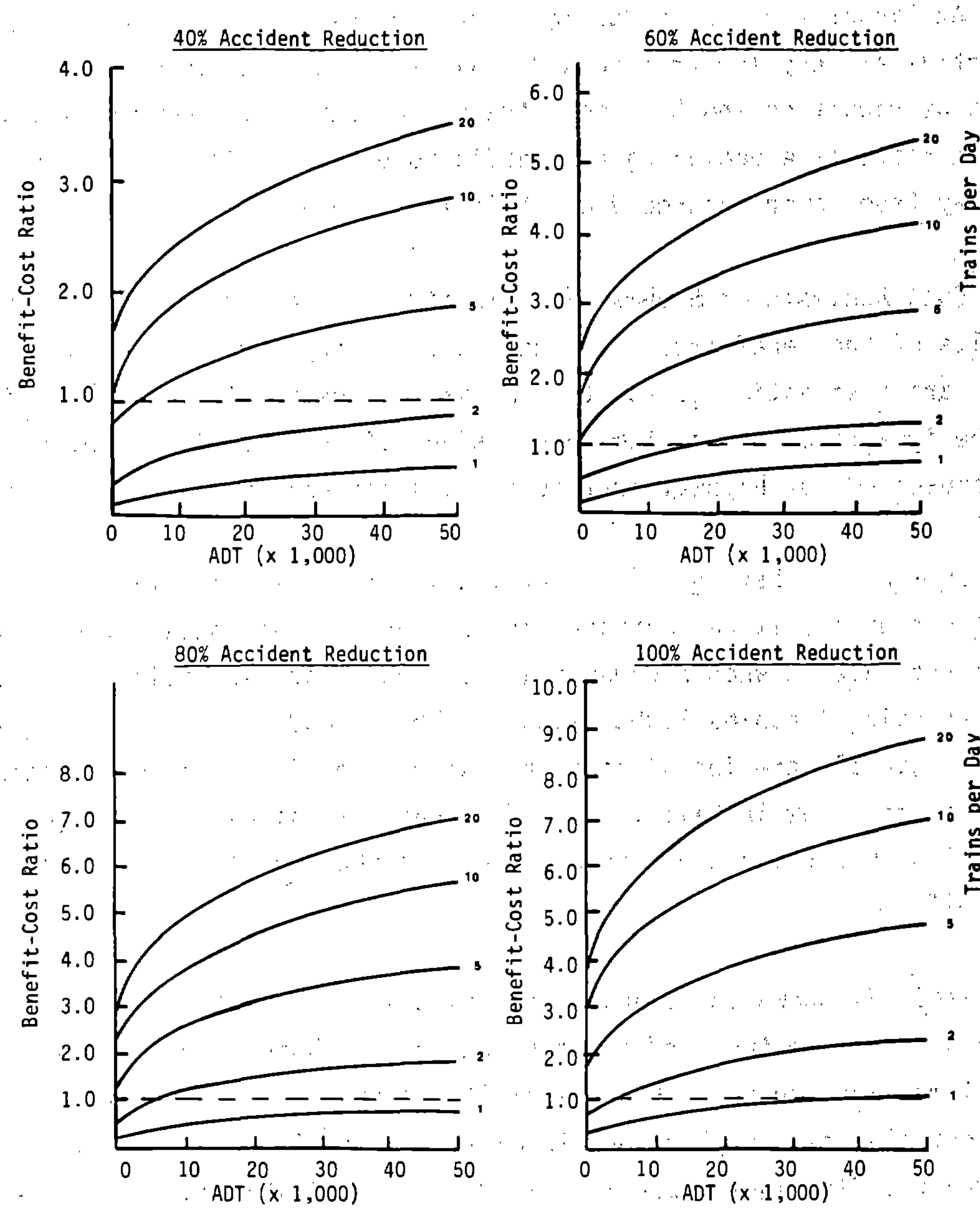


Figure 39. Benefit-cost ratios, urban multi-track crossing, retrofit four-quadrant gates with skirts.

cost-effective at traffic volumes of about 4,000 vehicles per day or higher (see top left-hand graph in figure 39).

At higher accident reductions, the innovative gates would be cost-effective at very low traffic and train volumes. Assuming an 80 percent accident reduction and 5 or more trains per day, the innovative system would be cost-effective beginning at traffic volumes of only a few hundred vehicles per day (see lower left-hand graph in figure 39).

Cost Analysis of Highway Traffic Signal. This section presents the results of the benefit-cost evaluation of highway traffic signals. Presented first are cost estimates for the innovative system, followed by a discussion of the impacts of the system on crossing safety. Lastly, benefit-cost ratios are presented for highway traffic signals for various crossing conditions.

System Cost Estimates. In evaluating the cost-effectiveness of highway traffic signals, it was appropriate to consider two installation situations. The first case is when highway traffic signals are installed at a crossing with existing flashing light signals. The second case is when highway traffic signals are installed at a passive crossing in lieu of flashing light signals (as a new installation). For these two situations, the marginal installation costs are different, and thus the overall cost-effectiveness will differ.

Table 34 shows the annual marginal costs for installing highway traffic signals under the two conditions cited above. Note from table 34 that the annual marginal costs of highway traffic signals are $2,720 when the signals are installed as a replacement to existing flashing light signals. When the highway traffic signals are installed as a new installation, however, the annual marginal costs are only $630. In both cases (retrofit and new installation), the annual system marginal costs are the sum of three cost components--annualized installation costs, annual operating costs, and annual maintenance cost. The component costs for both cases are also shown in table 34.

Table 34. Annual marginal costs of highway traffic signals.

Cost Component	Annual Marginal Costs: Retrofit Installation	Annual Marginal Costs: New Installation
Annualized Installation Costs	$1,320[1]	-$650[2]
Annual Operating Costs	1,200	1,080[3]
Annual Maintenance Costs	200	200
Total	$2,720	$630

[1]Capital recovery costs assuming a 20-year useful life and a 10 percent annual inflation rate.

[2]Captial recovery costs assuming a 30-year useful life and a 10 percent annual inflation rate.

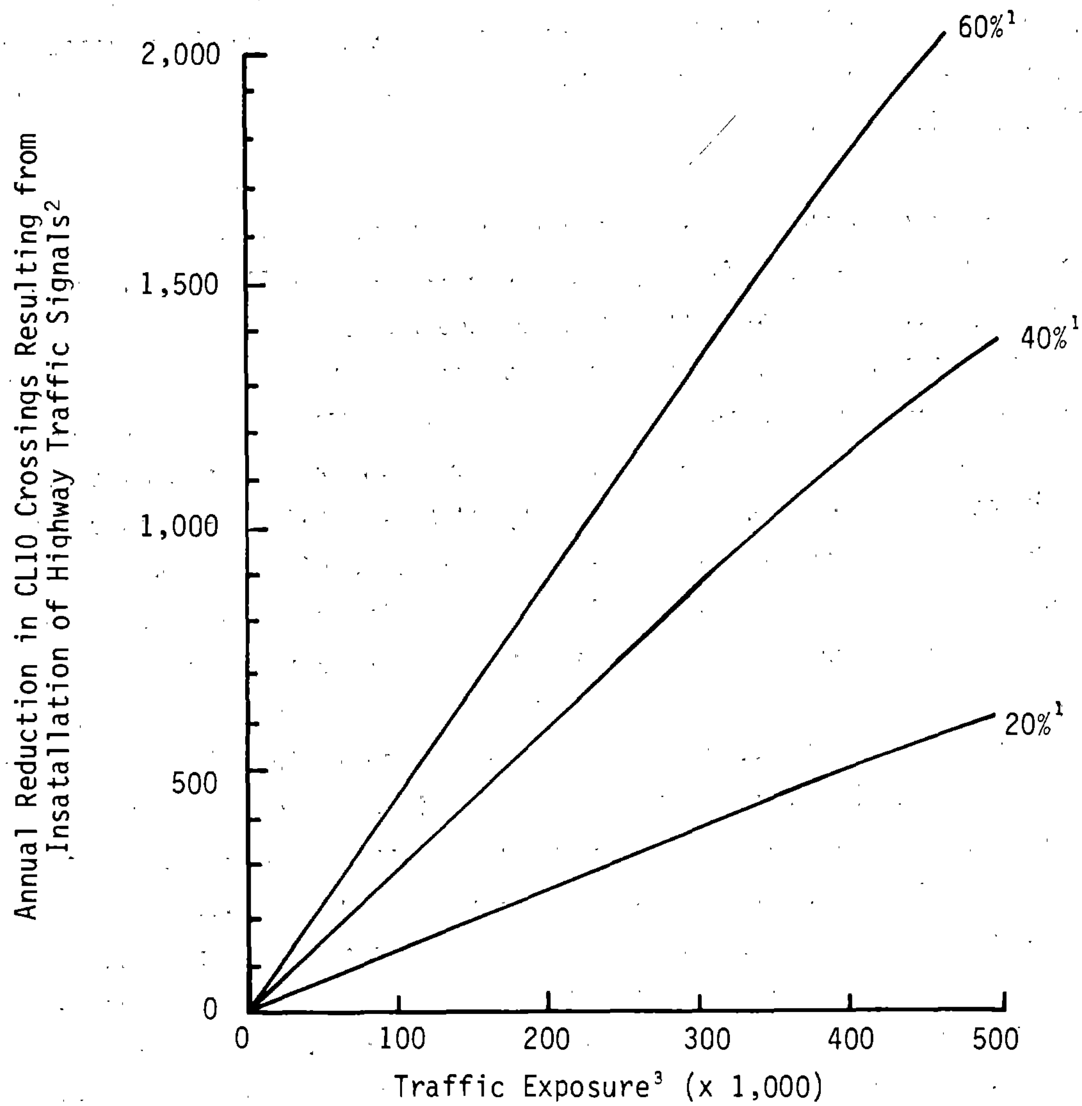
[3]Power costs for new installations are reduced through total unification of power systems.

It should be noted that the marginal cost is less for a new installation for two reasons. First of all, the cost of the original flashing light signals is saved in a new installation. Second, system power costs can minimized in a new installation, as opposed to a retrofit system, through the unification of the traffic signal, advance sign beacon, and train detection power supply systems.

As done for the four-quadrant gates with skirts, it was assumed that overall costs would be slightly higher at multi-track crossings. Thus, the marginal annual costs presented in table 34 were increased by 10 percent in computing the cost-effectiveness of highway traffic signals at rural and urban multi-track crossings.

<u>Reductions in CL10 Times</u>. As discussed earlier, the number of vehicles crossing the tracks within 10 seconds of train arrival (CL10s) was selected for assessing the potential safety impacts of highway traffic signals. From the field studies, it was observed that the percentage of motorists who cross the tracks in the last 10 seconds before train arrival was a relatively constant proportion of the total number who cross while the devices (flashing light signals) are activated. In fact, approximately 3.5 percent of the total crossings typically occur in the last 10 seconds before train arrival. Furthermore, it was found that highway traffic signals reduced total crossings during the train warning period to less than 5 percent of the total arriving traffic. These rates were used in the simulation model to predict the numbers of CL10 crossings which could be prevented under various crossing conditions by installing highway traffic signals in place of flashing light signals.

Figure 40 illustrates the impact of highway traffic signals compared to standard flashing light signals on CL10 crossings for typical crossing conditions. The data in the figure were generated assuming a 40-second train warning time (this was the approximate warning time at the Cedar Drive crossing after predictors were installed) and assuming that highway traffic signals would reduce crossings during the warning period to 5 percent of the total arriving vehicles. In figure 40, the number of prevented CL10 crossings is related to traffic exposure (trains per day x ADT) and to the



Percentage of arriving traffic crossing the tracks during the train warning period.

CL10 crossings refer to the number of motorists who cross the tracks less than 10 seconds before a train arrival.

Traffic exposure = trains per day x ADT.

Figure 40. Impact of highway traffic signals with predictors on CL10 crossings compared to standard flashing light signals with predictors.

crossing rate for standard flashing light signals. (Crossing rate is the percentage of arriving traffic which crosses the tracks while the flashing light signals are activated.) Crossing rates of 20 to 60 percent are included in the figure since these rates are typical for crossings controlled by flashing light signals.

As seen in the figure, the number of CL10 crossings which can be prevented by highway traffic signals increases as traffic exposure and initial crossing rate increase. Furthermore, the numbers of CL10 crossings which can be prevented are significant, particularly at the higher traffic exposure levels. For example, at a crossing with a traffic exposure of 300,000 (e.g., 20 trains per day and 15,000 vehicles per day) and an initial crossing rate of 60 percent, there would be over 1,300 fewer CL10 crossings per year if highway traffic signals were installed in place of the existing flashing light signals. This reduction is very significant considering the fact that CL10 crossings represent very near misses of an actual train-auto accident.

As with the innovative gate system, there is insufficient accident experience at this time to estimate a specific percentage reduction in accidents which would be realized by installing highway traffic signals at a grade crossing. However, based on the significant reductions in the CL10 which would be achieved, it is reasonable to conclude that some reduction in accidents should occur. In addition, it is reported in the literature that traffic signals used at highway intersections reduce right angle collisions by up to 80 percent. It is very possible that similar reductions in train-auto "right angle" accidents could be realized. In generating the benefit-cost ratios presented, these considerations were used as the rationale for assuming that accident reductions in the range of 20 to 80 percent could be achieved by highway traffic signals.

Benefit-Cost Ratios. Benefit-cost ratios were developed for retrofit and new highway traffic signal installations in the same manner as for the innovative gate system. That is, expected annual accident cost savings were divided by the annual system marginal costs. Generally, the resulting benefit-cost ratios were very high for a wide range of conditions. In fact, in all instances double-digit benefit-cost ratios were reported. The detailed results are presented in the following sections broken down by crossing type, and for retrofit versus new installations.

Figure 41 presents benefit-cost ratios for retrofitting rural single-track crossings with highway traffic signals (removing the existing flashing light signals and installing highway traffic signals in their place). The figure includes benefit-cost ratios for four levels of accident reduction (20, 40, 60, and 80 percent). For each level, the ratios are plotted for a range of ADTs (from 0 to 50,000 vehicles per day) and for a range of train volumes (1, 2, 5, 10, and 20 trains per day).

As seen in figure 41, it would be cost-effective to retrofit a crossing (with existing flashing light signals) with highway traffic signals under a wide range of conditions. For example, assuming a 20 percent accident reduction, it would be cost-effective to install highway traffic signals at crossings with more than about 5,000 vehicles per day and 2 trains per day or more (refer to top left-hand graph in figure 41). Assuming a 40 percent accident reduction, it would be cost-effective to install highway traffic signals at crossings with more than about 2,000 vehicles per day and 2 trains per day or more (see upper right-hand graph). At the 80 percent accident reduction level, it would even be cost-effective to install highway traffic signals at a crossing with only one train per day, provided traffic volumes were 1,000 vehicles per day or greater.

The magnitude of benefit-cost ratios for retrofitting a rural single-track crossing with highway traffic signal are also very significant. Note from figure 41 that benefit-cost ratios ranging up to 34 to 1 were estimated depending on traffic/train volumes and on the accident reduction achieved. These high ratios, if they are achieved in actual field experience, strongly support the use of highway traffic signals at some grade crossings.

Figure 42 presents benefit-cost ratios for installing highway traffic signals at a rural single-track crossing as a new installation. It should be noted that the benefit-cost ratios are "marginal" ratios since they were computed using marginal accident and system costs. In other words, the ratios represent the additional benefits (or costs) which would result if

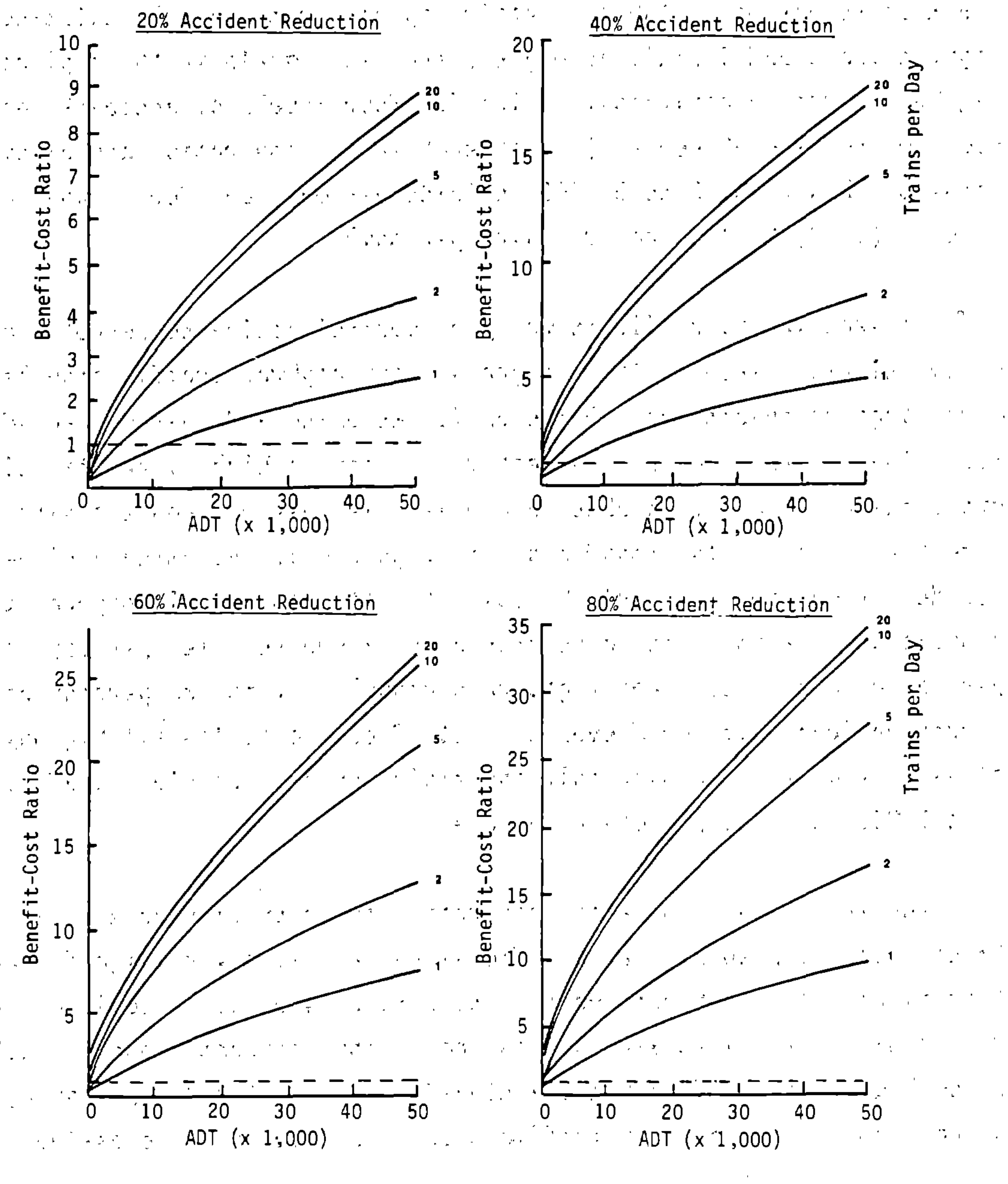


Figure 41. Benefit-cost ratios, rural single-track crossing, retrofit highway traffic signals.

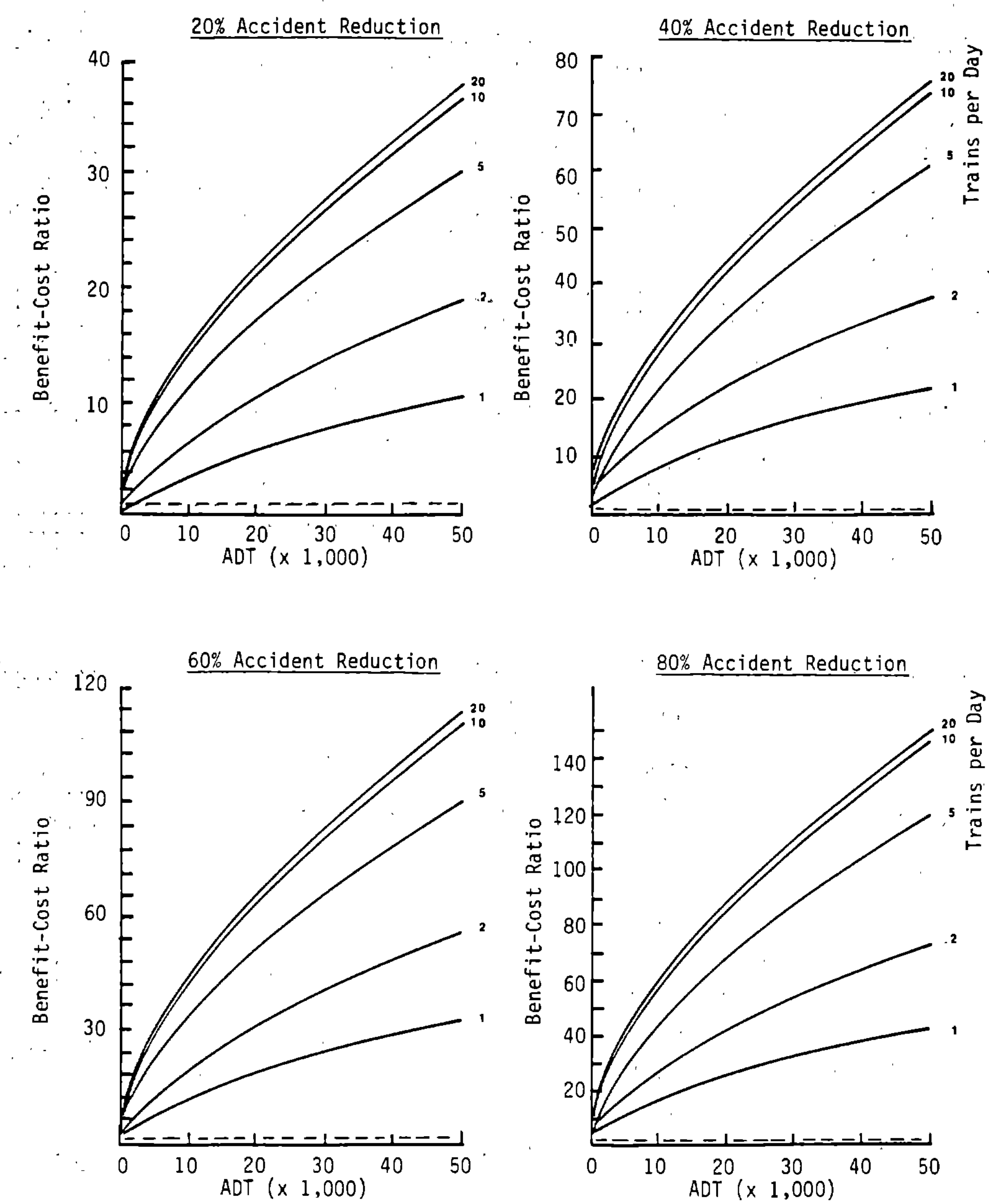


Figure 42. Benefit-cost ratios, rural single-track crossing, new highway traffic signals.

traffic signal were installed instead of flashing light signals. They do not directly reflect the cost-effectiveness of installing traffic signals versus having a passive crossing.

As seen in figure 42, the benefit-cost ratios for a new installation are even more favorable than for a retrofit installation. Even at a modest 20 percent accident reduction, highway traffic signals would be cost-effective at crossings with 1 or more trains per day and traffic volumes of 1,000 or higher (refer to top left-hand graph in figure 42). Also in figure 42 note that benefit-cost ratios of over 100 to 1 can be achieved at medium train and traffic volumes assuming a 60 to 80 percent accident reduction.

Figure 43 presents benefit-cost ratios for retrofitting urban single-track crossings with highway traffic signals. As seen in the figure, highway traffic signals would be cost-effective for very low train volumes (one or two trains per day) and moderate traffic volumes for any assumed accident reduction level. At higher train volumes, highway traffic signals are cost-effective under many conditions. For example, assuming a 40 percent accident reduction, highway traffic signals would be cost-effective at crossings with 5 or more trains per day with traffic volumes greater than about 2,000 vehicles per day (refer to top right-hand graph in figure 42). Assuming an 80 percent accident reduction and 5 or more trains per day, highway traffic signals would be cost-effective if traffic volumes were only a few hundred vehicles per day (see lower right-hand graph).

Figure 44 shows benefit-cost ratios for installing highway traffic signals as a new installation at an urban single-track crossing instead of flashing light signals. As seen in the figure, such an installation would be cost-effective under a wide range of conditions and accident reduction levels, with benefit-cost ratios approaching 90 to 1 under some circumstances. Of particular note in figure 44, is that highway traffic signals (as a new installation) would be cost-effective at crossings with 1 or more trains per day, for any traffic volume, assuming a 40 percent or greater accident reduction level.

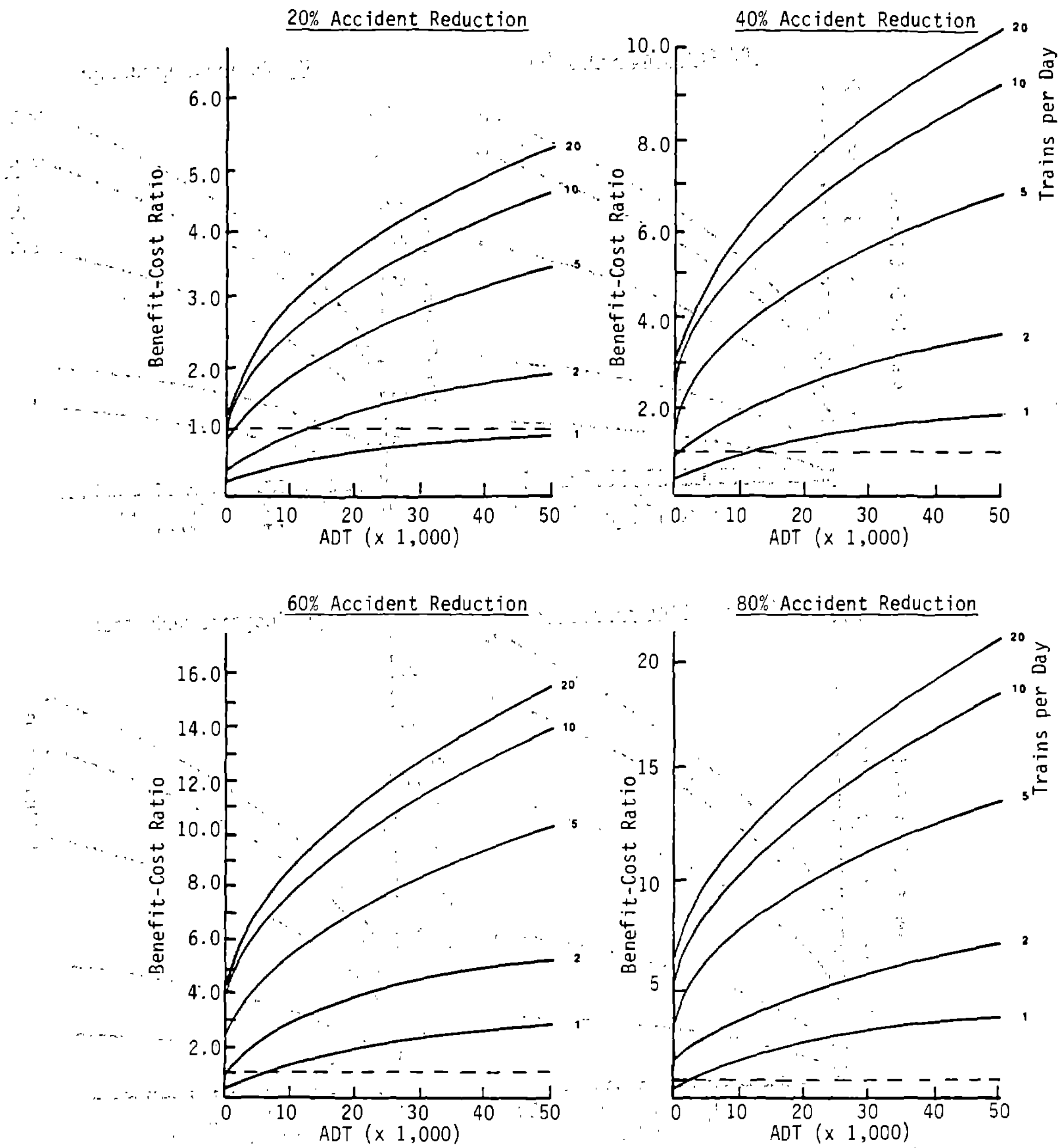


Figure 43. Benefit-cost ratios, urban single-track crossing, retrofit highway traffic signals.

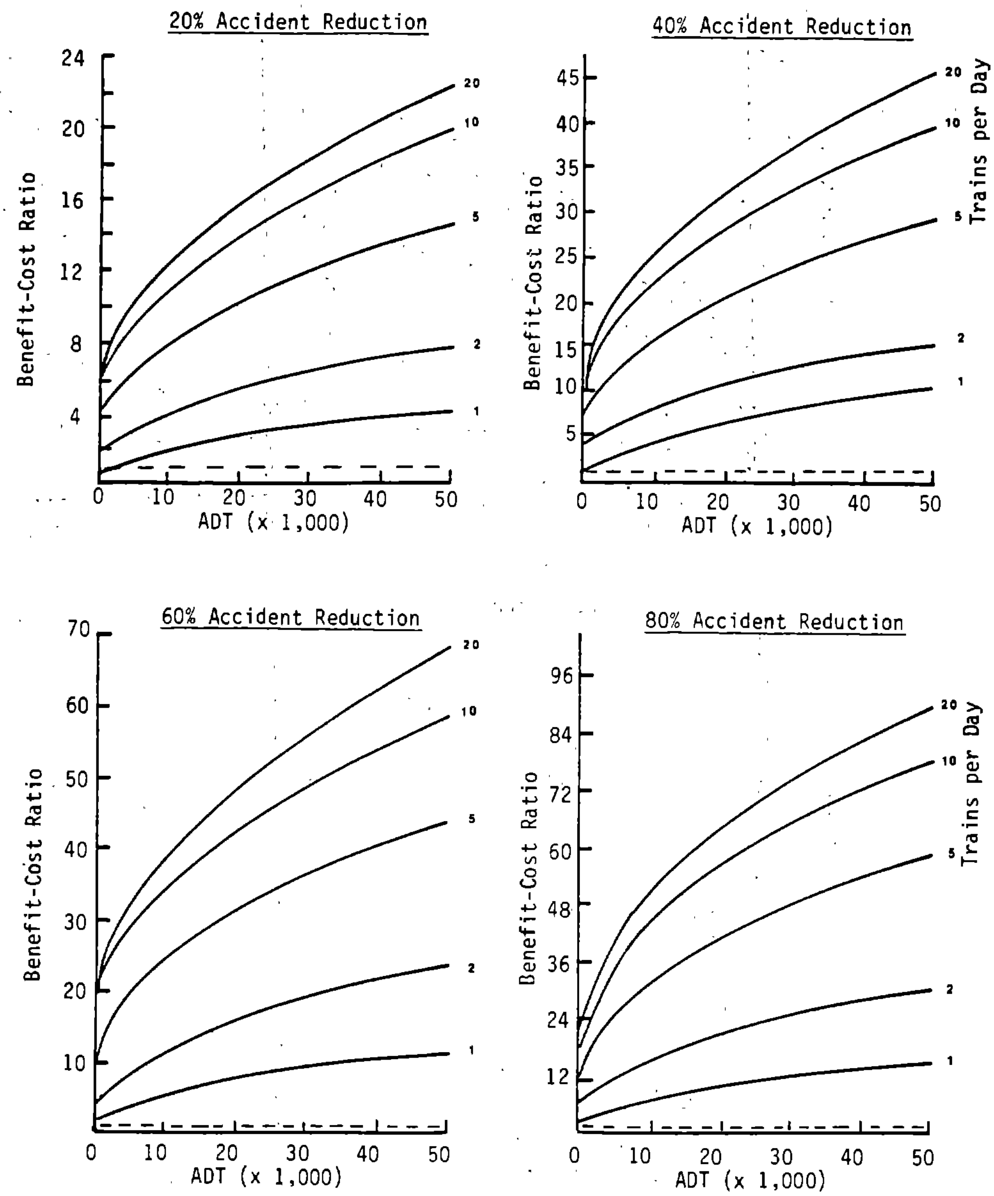


Figure 44. Benefit-cost ratios, urban single-track crossing, new highway traffic signals.

Figure 45 presents benefit-cost ratios for retrofitting rural multi-track crossings with highway traffic signals. As with the previous cases, such an installation would be cost-effective under a variety of conditions. For example, assuming a 40 percent reduction, highway traffic signals would be cost-effective at rural multi-track crossings with 1 or more trains per day and traffic volumes of 8,000 or higher (see top right-hand graph in figure 45). Assuming a 60 or 80 percent accident reduction and 1 or more trains per day, highway traffic signals would be cost-effective at traffic volumes of approximately 3,000-4,000 vehicles per day or higher (refer to the two lower graphs in figure 45).

Benefit-cost ratios for installing highway traffic signals at a rural multi-track crossing as a new installation in place of flashing light signals are presented in figure 46. Note in the figure that the benefit-cost ratios are well above 1.0 for all conditions and approach 100 to 1 in some situations.

It is also interesting to note from all the graphs in figure 46 that highway traffic signals appear to be cost-effective (provided active warning is needed) at crossings with only one train per day and very low traffic volume levels. This of course is based on the premise that the highway traffic signals would reduce accidents by at least 20 percent compared to flashing light signals.

Figure 47 presents benefit-cost ratios for retrofitting an urban multi-track crossing with highway traffic signals. Note from the figure that the benefit-cost ratios are very high ranging up to 33 to 1 for a crossing with 20 trains per day and 50,000 vehicles per day, and assuming an 80 percent accident reduction. In fact, highway traffic signals would be very cost-effective under virtually all conditions and levels of accident reduction evaluated. Also observe in figure 47 that the benefit-cost ratios are very sensitive to train volumes compared to the preceding crossing types. (A characteristic of urban multi-track crossings is that the accident rate is highly dependent of train volumes.)

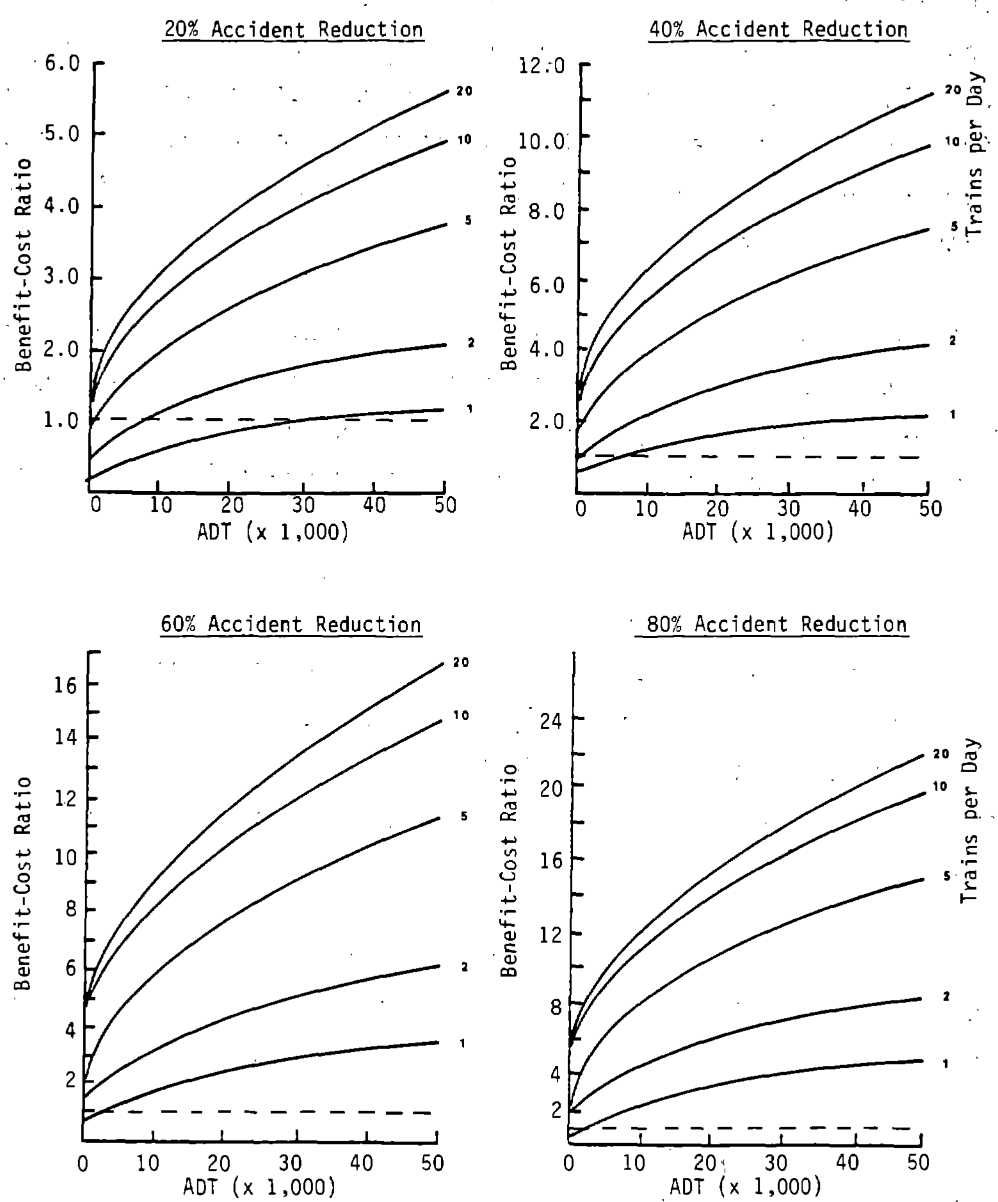


Figure 45. Benefit-cost ratios, rural multi-track crossing, retrofit highway traffic signals.

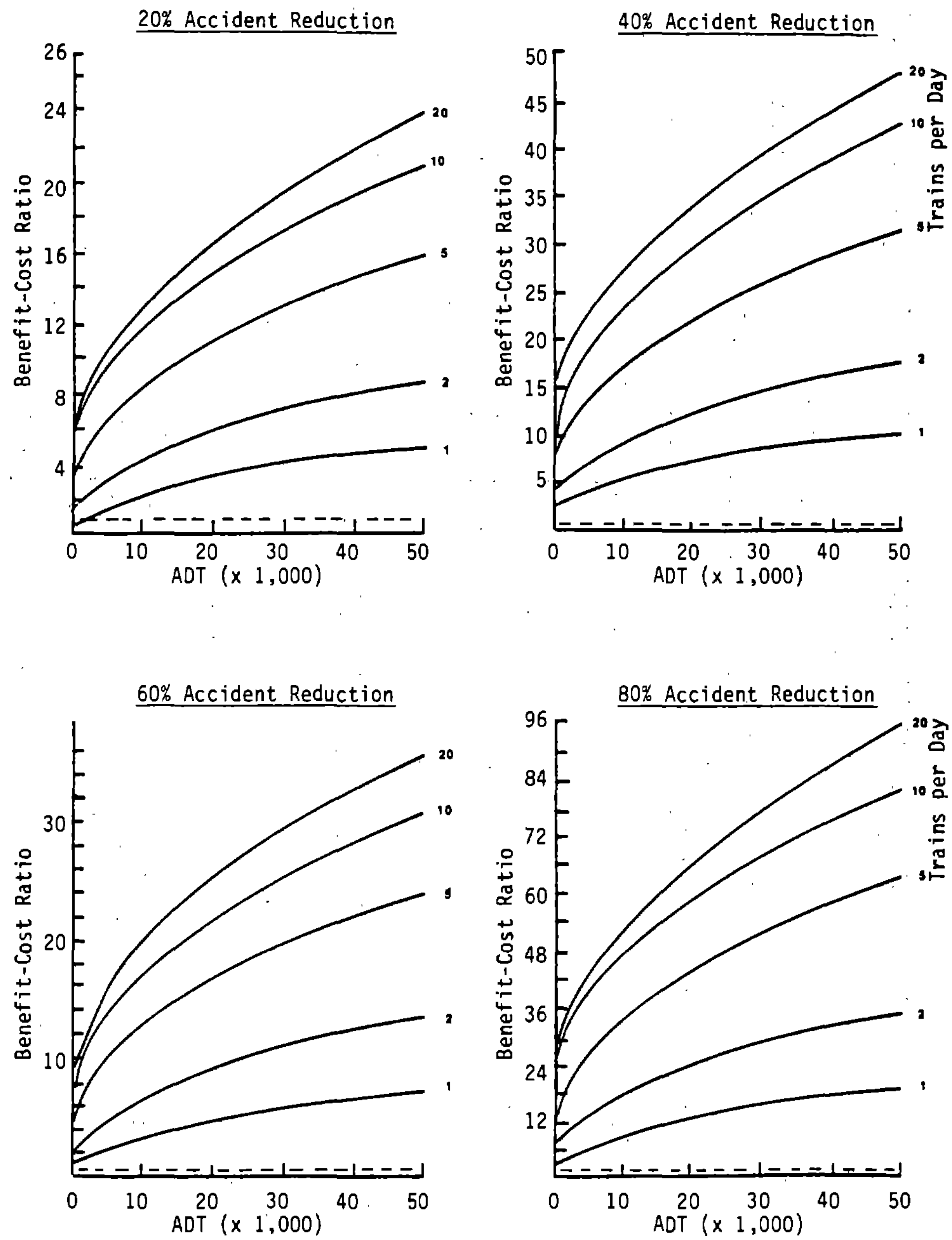


Figure 46. Benefit-cost ratios, rural multi-track crossing, new highway traffic signals.

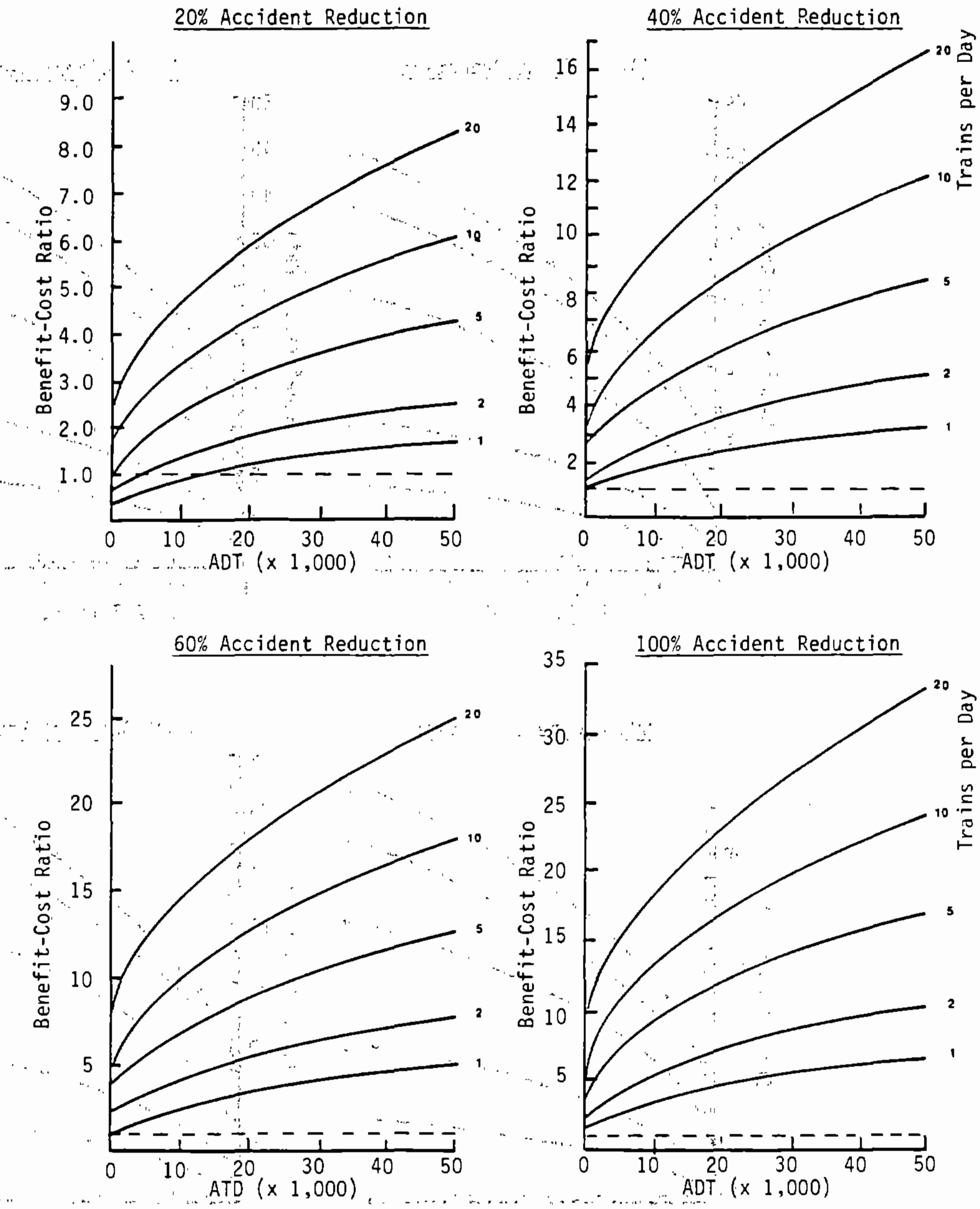


Figure 47. Benefit-cost ratios, urban multi-track crossing, retrofit highway traffic signals.

Figure 48 presents benefit-cost ratios for installing highway traffic signals at an urban multi-track crossing as a new installation in place of flashing light signals. Note from the figure that traffic signals would be cost-effective for virtually all traffic volumes and accident reduction levels, and that very high benefit-cost ratios would be achieved. For example, if only a 20 percent accident reduction were achieved, benefit-cost ratios ranging up to 35 to 1 would be possible at crossings with high train and traffic volumes (see top right-hand graph in figure 47). If an 80 percent accident reduction were achieved, benefit-cost ratios as high as 140 to 1 might be possible (see lower right-hand graph in figure 48).

National Implementation Cost Estimates

Based on the preceding cost analyses, two of the innovative systems would be cost-effective at selected crossings. This finding suggests that some type of national installation program should be considered. In formulating such a program, an important issue is the cost to implement the innovative devices at a number of crossings around the country. This cost can be roughly estimated by combining the installation cost estimates with data from the National Grade Crossing Inventory on the numbers of crossings with conventional traffic control.[3]

The resulting nationwide installation cost estimates are presented in table 35. The table shows the total costs to implement the innovative systems for various percentages of existing crossings. The installation (retrofit) costs, with the exception of the cost to convert from passive control to highway traffic signals, are from table 29. For the case of conversion from passive control to highway traffic signals, the cost of installing a train detection system had to be added to the traffic signal installation costs. An appropriate estimated cost for installing a train detection system was assumed to be $42,880.[50]

Table 35 is not meant as a recommendation that the innovative devices be implemented at a certain number of crossings nationwide. In fact, the research did not address how many crossings might be candidates for the innovative devices, although chapter IX does identify the types of crossings

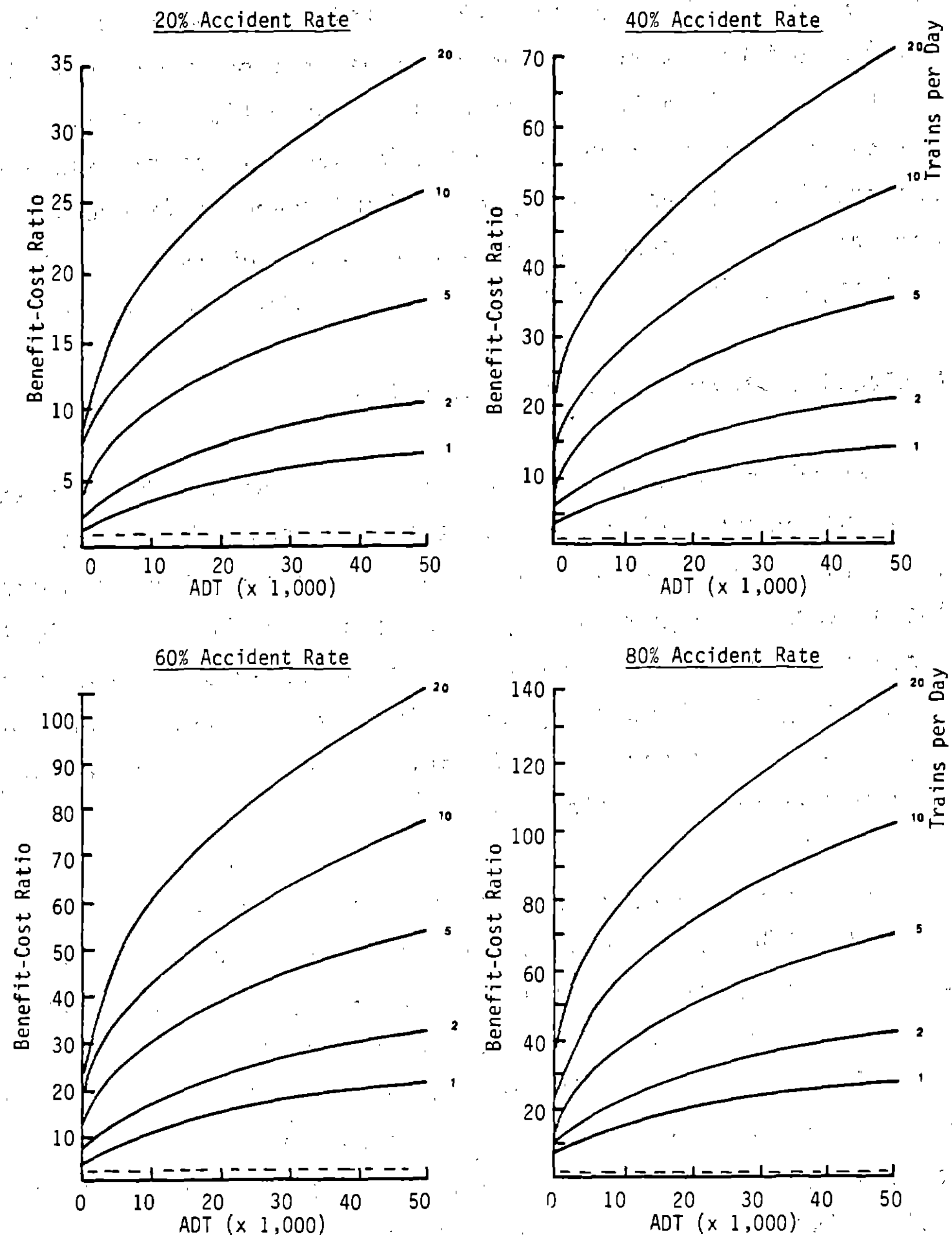


Figure 48. Benefit-cost ratios, urban multi-track crossing, new highway traffic signals.

where the various devices might be considered. Table 35 is intended to show the number of crossings which could be impacted by the innovative devices at various levels of funding. The table should be useful as a decision-making tool for administrators when establishing funding levels for railroad-highway grade crossing improvements.

For example, the field studies indicated that highway traffic signals show great promise for improving safety at certain crossings presently controlled by flashing light signals. This being the case, an administrator would want to know what it would cost to implement traffic signals at all or part of the candidate crossings. For the sake of illustration, assume that 10 percent of the nation's crossings presently controlled with flashing light signals were identified as likely candidates for highway traffic signals. From table 35, it is seen that it would cost $36.7 million to install traffic signals at 10 percent of the crossings presently controlled by flashing light signals. As another example, it would cost approximately $72.3 million to retrofit 10 percent of the nation's gated crossings with four-quadrant gates with skirts.

The reader is reminded that benefit-cost ratios for installing the innovative systems would generally be very high, ranging up to 8.7 for four-quadrant gates with skirts and up to 147 for new highway traffic signal installations. Thus, each level of investment in the innovative systems presented in table 35 would be expected to return many time the investment costs in accident cost savings.

Cost of Train Predictors

The research was not intended to evaluate the cost-effectiveness of train predictors. However, since predictors (and the constant warning time they provide) were found to be extremely beneficial at one of the study sites, a brief discussion of predictor costs is appropriate.

Based upon estimates provided by two railroads, a basic predictor unit with the redundancy feature costs between $11,500 and $14,000, depending on the supplier and purchase quantity. The cost of a train predictor unit

Table 35. Estimated nationwide installation costs for the three innovative systems.

Existing Traffic Control	Number of Crossings	Alternative Innovative System	Installation (Retrofit) Cost	Total Nationwide Costs (in millions $) to Convert Given Percentage of Existing Crossings			
				1%	5%	10%	20%
Standard Flashing Light Signals	32,778	Four-Quadrant Flashing Light Signals with Strobes	$19,200[1]	6.3	31.5	62.9	125.9
		Highway Traffic Signals	11,200[1]	3.7	18.4	36.7	73.4
Standard Gates with Flashing Light Signals	22,006	Four-Quadrant Gate with Skirts and Flashing Light Signals	32,750[1]	7.2	36.1	72.3	144.5
Other Active Devices	9,033	Highway Traffic Signals	11,200[1]	1.0	5.1	10.1	20.2
Passive Control[2]	128,577	Highway Traffic Signals	42,880[3]	55.1	275.7	551.3	1,102.7

[1]Installation (retrofit) costs assume that train detection system is in place.

[2]Crossings with no control are excluded.

[3]Intallation costs include installation of train detection system.

without redundant or backup capability is about 30 percent less. This cost does not include installation costs, battery costs, wiring and relay costs, etc. It should also be noted that a single predictor unit can normally handle both approaches of a single track crossing. Multiple-track crossings or crossings with insulated joints nearby will require multiple predictors or sets of unidirectional predictors.

One of the railroads also provided cost comparisons for installing train predictors versus motion sensors in conjunction with flashing light signals with and without gates. Based on the railroad's estimates, it would cost approximately $42,840 to install flashing light signals with train predictors, while it would cost approximately $34,240 to install the same flashing light signals with motion sensors. Thus, the use of predictors versus motion sensors would result in an increased total installation cost of approximately $8,600. For the case of gated crossings, the railroad estimates that it would cost about $61,930 to install standard two-quadrant gates and flashing light with train predictors, while it would cost $50,930 to install gates and signals with motion sensors. In this case, the use of predictors would result in an increased total installation cost of approximately $11,000. These costs estimates are for a typical single-track crossing in Tennessee, and they assume a maximum train speed of 60 mi/h.

IX. IMPLEMENTATION CONSIDERATIONS

The field studies assessed the effects of three innovative traffic control devices on driver behavior and safety at typical grade crossings. In addition to driver behavior and safety, other considerations are important to the success and acceptance of these innovative devices for general field use. These considerations include hardware, installation, system operation and maintenance, and system power requirements.

This chapter identifies the important implementation considerations for each of the three innovative traffic control devices. The information presented is based on the experience and insight gained during the field evaluation, as well as input from Southern Railway employees; City of Knoxville Traffic Engineering Department personnel; traffic signal contractors who installed, operated, and/or maintained the innovative devices; and many years of railroad-highway grade crossing experience by the project staff.

Four-Quadrant Gates with Skirts

The most effective devices, in terms of driver response and safety, are the four-quadrant gates with skirts. As discussed in chapter V, this device completely eliminates all unwanted vehicle crossings and enhances driver behavior in the crossing approach area. In addition to the obvious safety benefits, four-quadrant gates with skirts are relatively easy to install, maintain, and operate, and they are reliable and durable.

The four-quadrant gates with skirts may be thought of as a level of traffic control between standard two-quadrant gates and a grade separated crossing. If standard two-quadrant gates do not provide the level of safety desired and a full grade separation is not economically attractive, then the four-quadrant gates with skirts should be the more cost-effective alternative.

Applications. Obviously, four-quadrant gates are very appropriate for those crossings which tend to have violations of gate arms by motorists; the four-quadrant gates with skirts simply stop all violations by blocking the driving around a gate arm. However, four-quadrant gates with skirts can be used at any crossing where standard two-quadrant gates are warranted. Several types of crossings tend to have a reasonable number of motorists driving around gate arms after they have been lowered. These crossings have certain unique characteristics which tend to encourage violations and would be prime candidates for use of four-quadrant gates with skirts.

There are crossings with other characteristics that are good candidates for four-quadrant gates with skirts:

- Crossings on four-lane undivided roadways.
- Crossings with two or more tracks separated by a distance equal to or greater than the storage requirements for one or more motor vehicles.
- Crossings with large variations in train speeds and without predictors.
- Crossings for which motor vehicle-train collisions pose large potential safety problems such as: (a) crossings with large numbers of hazardous materials trucks, (b) crossings with large numbers of school buses, (c) crossings with high-speed passenger trains, and (d) crossings with continuing accident occurrences.
- Crossings with consistent gate arm violations or continuing accident occurrences.

The above listed crossings are candidates for the use of four-quadrant gates with skirts and have characteristics that tend to cause motorists to desire to drive around gate arms, or if an accident does occur from a motorist driving around a gate arm, the consequences of that accident can be very severe. The discussion below reviews the rationale for each type of crossing being a candidate for four-quadrant gates with skirts.

<u>Crossings on Four-Lane Undivided Roadways</u>. While several characteristics of crossings tend to cause motorists to desire to drive around gate arms, crossing geometrics play an important role in permitting or creating a decision to violate gate arms. With crossings on four-lane undivided roadways, one will find that there is a sufficient amount of lateral space to permit a motor vehicle to go around a gate arm that only covers two of the four lanes. An example of this characteristic is shown in figure 49. If there is sufficient space for maneuvering a motor vehicle around a gate arm

Figure 49. Four-lane, undivided roadway crossing.

with relative ease, many motorists will violate a gate arm, particularly if the driver perceives a long waiting time.

Crossings with Two or More Tracks a Substantial Distance Apart. Crossings that have two or more tracks which are separated by a distance equal to or greater than the storage requirements for one or more motor vehicles often cause motorists to desire to violate gate arms. A truck driving around a gate arm for multiple tracks separated by a substantial distance is shown in figure 50. Motorists seem to treat the distance between the tracks as a safety island to store their vehicle should they encounter a train on the downstream track. Field observations indicate that motorists will often pull around one gate arm and use the lateral space between the tracks for reassessing if there are other trains coming on the set of tracks they are now approaching. More violations are expected as the spacing between the tracks increases.

Crossings with Large Variations in Train Speeds and Without Predictors. There are crossings which have a large variation in train speeds from slow moving freight trains of 20 mi/h or lower to high-speed passenger trains of 80 mi/h or higher. When predictors are not used, obviously there is a substantial difference in the length of time that gate arms are down for approaching trains. Field observations would seem to indicate that in these types of situations drivers have difficulty recognizing these varying speeds. This is to say that if a driver frequently encounters a gate arm being down for a long period of time at a crossing, the driver has a tendency to not want to wait for a long activation and will often drive around the gate arm. Obviously, with fast moving trains, this creates a severe safety hazard.

Crossings for Which Motor Vehicle-Train Collisions Pose Large Potential Safety Problems. There are crossings where the type of motor vehicles that use the crossing create a potential for severe safety problems should a collision occur between a train and a motor vehicle. Additional safety measures are often necessary to minimize the potential for conflicts at these crossings. Four-quadrant gates with skirts could significantly improve safety at these crossings.

Figure 50. Tracks separated by sufficient distance to store motor vehicles.

Hazardous materials trucks using a crossing can pose a serious problem should a collision occur between one of those vehicles and a train (see figure 51). There have been some very serious accidents of this nature in the United States in the last few years. Some of these accidents have resulted from gasoline tank trucks driving around gate arms. The result has been disastrous. Figure 52 shows the results of a gasoline tank truck that drove around a gate arm and was hit by a train. Seven fatalities resulted from this collision, and 19 motor vehicles were destroyed by the resulting fire.

In addition, if a hazardous materials truck is stopped at a crossing and a motor vehicle-train collision occurs, the possibility of a secondary collision with the hazardous materials truck presents a serious safety problem. Thus, as the number of hazardous materials trucks using a crossing increases, this safety issue becomes more severe.

Crossings with a large number of school buses and/or public transportation buses pose certain safety problems. An example of this type of crossing is shown in figure 53. While it is very unlikely that a school bus driver or a transit bus driver would ever drive around a gate arm and place school children or adult passengers in a serious safety situation, nevertheless, a secondary collision from a hazardous materials truck can cause serious safety problems. As the number of school bus crossings and/or public transportation bus crossings increases, the magnitude of this safety issue increases.

Crossings with high-speed passenger trains pose certain safety problems due to the possibility of a train derailment as well as the speed of impact of the train with a motor vehicle. Obviously the derailment of a passenger train has the potential for creating a large number of personal injuries and fatalities. Preventing a motor vehicle from moving on to the tracks in front of a high-speed passenger train is highly desirable. In situations where the crossing characteristics are such to cause a desire to drive around a gate arm, four-quadrant gates with skirts will be very effective.

Continuing accident occurrences at crossings with two-quadrant gates tend to indicate that the standard gate system is not performing as intended.

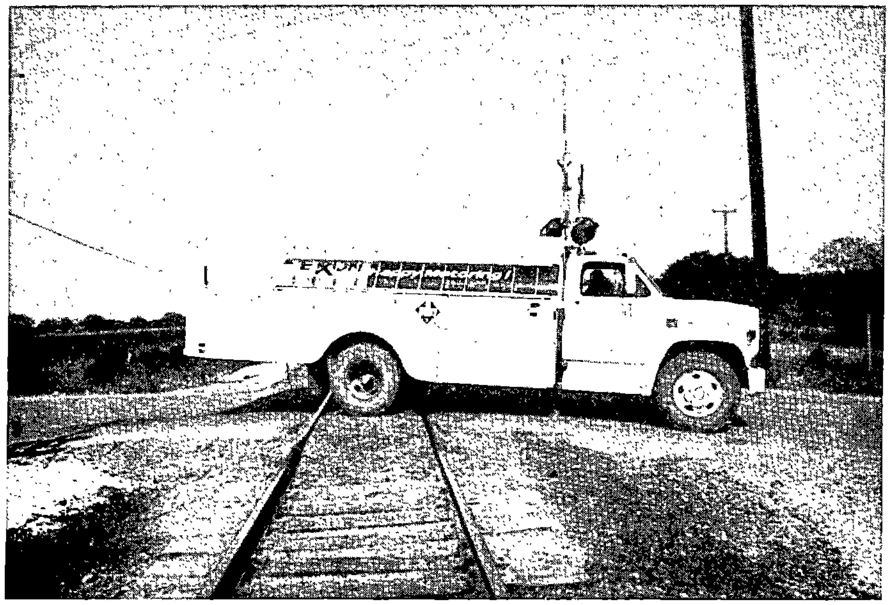


Figure 51. Hazardous materials truck using crossing.

Figure 52. Results of collision of hazardous materials truck and train.

Figure 53. School bus and transit bus using crossing.

This can be due to a number of things, some of which are not necessarily due to motorists driving around the gate arm. However, when one encounters continuing accident occurrences, one should consider using four-quadrant gates with skirts to improve the safety of the crossing.

Crossings with Consistent Gate Arm Violations. Crossings with consistent gate arm violations which do not meet one of the preceding situations also pose a continuing hazardous situation for the traveling public. An example is shown in figure 54. There seem to be some crossings that do have an abnormally high number of drivers going around gate arms. In these situations four-quadrant gates with skirts will simply eliminate the violations.

Hardware Considerations. With the exception of the gate arms and skirts, all of the hardware and equipment used in the four-quadrant gates with skirts are standard parts commercially available from several suppliers. Furthermore, the hardware/equipment is the same that is used in standard two-quadrant gates; thus, field crews are familiar with their installation, operation, and maintenance.

To minimize unnecessary or lengthy gate activations, motion sensors or constant warning time train detectors should be installed at crossings where there are switching operations or large variations in train speed. The motion sensors and constant warning time detectors will minimize the time which the gates block the crossing.

A delay relay should be installed in the gate control system in order to stagger the operation of the near- and far-side gate arms. Also, due to the added weight of the gate arm and skirt assembly, more counterweights will be required on the panarms. This added weight causes no problem in system operation.

The innovative gate arms with skirts made from kiln-dried redwood performed successfully and proved that the concept was not only technically feasible but practical and economically feasible. However, the following improvements would be desirable in a fully operational system:

Figure 54. Multiple large trucks driving around gate arms.

- The gate arms and skirts had an extreme number of support brackets, pivot joints, and bolted connections making assemblage and repair somewhat time consuming. A simpler design can be attained.

- The joints connecting the skirts to the gate arm could only accommodate movement and loading in the plane parallel to the gate arm. Thus, when a skirt "rubbed" along the top of a large truck (as happens even with standard gate arms), the skirt-gate arm connection could fail. Typically, the wood around one or more of the plastic hinge joints would crack and the plastic joint(s) would separate from the board. This of course is undesirable and could be remedied through a better, more flexible joint design that permits some lateral movement.

- At some of the pivot points in the flexible skirts, the boards would rub together as the gate arm was being raised and lowered. This rubbing damaged the retroreflective sheeting which was on the board surfaces. This problem could be easily remedied by minor changes in the joint design and/or board alignment.

One point to raise concerning the gate arms and skirts is whether the skirts are cost-effective. The field experience suggests that four-quadrant gates alone may greatly enhance driver performance and safety, and that the additional benefits of skirts may be minimal. The addition of skirts certainly complicates device construction, installation, and maintenance, and increases the cost of a four-quadrant gate installation; however, it enhances visibility considerably, especially at night.

Installation Considerations. Four-quadrant gates with skirts can be installed by regular field personnel within the normal scope of their duties and union contracts. No additional personnel training is required, nor are any special equipment, vehicles, or tools needed beyond those required for the normal installation of a gate system.

The procedures to install four-quadrant gates with skirts are basically the same as those used for standard two-quadrant gates, except for the following special requirements and concerns:

- Due to the increased weight of the skirts and gate arm, additional counterweights may need to be added to the panarms compared to the counterweights required for a standard gate arm. This additional counterweight will not affect the operation of the mechanism.

- When the gate and skirt are lowered and stopped in the horizontal position, there is a tendency for the unit to bounce or rock up and down a few times. To prevent the bottom of the skirt from striking the pavement during this bouncing, there should be 3 to 4 inches clearance between the bottom of the skirt and roadway.

System Operation and Maintenance. It is very important that the gate arms be of sufficient length to completely block the roadway. If an opening of just a few feet is left between opposing gate arms, motorcyclists and bicyclists may try to cross in front of a train.

There should be a time delay between the operation of the near- and far-side gates. That is, the near-side gate should start down first, with the far-side gate descent delayed by a few seconds. The actual delay time is based on vehicle lengths, crossing width, and vehicle operating speeds. (At the Cherry Street crossing, a 5-second offset was used.) The delay is achieved by installing a delay relay in the controller and by adjusting the circuit resistance as appropriate.

Three red lights should be used on each gate arm. Thus, a total of six gate lights across the roadway on each side of the crossing would be used. The two outside lights should be operated in the flashing mode, while the four interior lights should be steady-burn.

The type of maintenance for four-quadrant gates with skirts is essentially the same as for standard two-quadrant gates. Due to the complete roadway being closed upon a malfunction of the equipment, a reasonably quick response time is needed.

Power Requirements. The system contains two more gate mechanisms and six more gate lights, thus it uses approximately 50 percent more power. The additional weight of the gate arms and skirts does not increase energy consumption significantly because this weight is "accommodated" by adding counterweights to the panarms.

Environmental Considerations. The experimental gate arms with skirts were subjected to a variety of environmental conditions. They performed fine in high winds, in heavy rains, and under snow and ice conditions. They did not swing or sway excessively, nor did they bind up, freeze up, or snag. Also, the gates and skirts were essentially self cleaning from rain.

Emergency Vehicles. Emergency vehicles need to be considered in implementing four-quadrant gates with skirts, particularly at crossings near hospitals, near fire stations, or on routes frequented by emergency vehicles. Some ideas and issues regarding emergency vehicle handling are presented below:

- Advance notification of all affected service agencies is needed. These agencies should be informed of alternate routes and what to do if a malfunction does occur during an emergency run.
- Gate arms which could be raised or rotated out of the way by emergency personnel either manually or electronically could be installed at crossings frequented by emergency vehicles. Also, the far-side gates could be designed to raise automatically if down for more than some maximum time.
- The four-quadrant gates with skirts could simply not be considered for use at crossings that are frequented by emergency vehicles and a suitable alternate route is not available.

It should be remembered that four-quadrant gates would only be a problem for emergency vehicles if the equipment malfunctioned. Obviously, if the gate arms are down because of a train approaching or on the crossing, the emergency vehicle should not proceed over the crossing. Thus, if malfunctions occur infrequently, four-quadrant gates with skirts should not pose any problems for emergency vehicles. If a malfunction does occur and a train is not approaching the crossing, an emergency vehicle could simply break the gate arm if the situation warrants.

Highway Traffic Signals

The enhanced highway traffic signals performed better than standard flashing light signals in reducing CL10s and CL20s when predictors were used on both systems. In addition, the violation rate was low. In fact the highway traffic signals performed similar to standard short-arm gates in discouraging unacceptable track crossings. Furthermore, the traffic signals proved to be less expensive than flashing light signals and much cheaper than short-arm gates. These results suggest that enhanced highway traffic signals do indeed have application to railroad-highway grade crossings. In fact, study results indicate highway traffic signals would actually improve crossing safety over that afforded by standard flashing light signals and at a reduced overall cost.

Applications. Study results further indicate that, with appropriate revisions to the MUTCD, highway traffic signals could be used at any crossing where flashing light signals are warranted. Highway traffic signals have a high level of driver credibility and respect because they have been used prudently and have been well operated and maintained in the vast majority of cases. If highway traffic signals were to be successful at railroad-highway grade crossings, and thus, not compromise driver credibility for highway traffic signals in general, then the same high standards of operation and maintenance must be obtained. In particular, highway traffic signals should not be considered at crossings where false activations/malfunctions are common. They also should not be used at crossings where the train warning and/or occupancy times are consistently unreasonably long, i.e., above 60 seconds.

Some crossing situations where highway traffic signals would regularly afford advantages over conventional flashing light signals are identified below:

- Crossings in the vicinity of a signalized intersection or in the middle of a system of signalized intersections.
- Crossings with complex highway geometrics where drivers are unable to make proper judgements on whether it is safe to proceed across the tracks and where gates would be impractical.

<u>Crossings in Area of Signalized Intersections</u>. Motorists using a crossing that is located in the area of a number of signalized highway intersections are responding with regularity to standard highway traffic signals. To change to a new type of activated traffic control device,

generally found nonactivated, requires some adjustments for a motorist from a human factors point of view. Increased perception-reaction times can occur for motorists in these situations through receiving a different stimulus for processing. To provide a repetitive environment for a motorist, there is merit in continuing to provide a standard highway traffic signal system network across a fairly large area to reduce the number of new or different encounters by the motorists. Figure 55 shows an application of this concept in Denver, Colorado, and figure 56 shows an application in Knoxville, Tennessee.

Complex Geometrics at Crossings. Traffic encountering complex highway geometrics at crossings is difficult to control with standard railroad active traffic control devices such as flashing light signals or gates. Complex highway geometrics create complex driving maneuvers on the part of motorists. Channelization of motorists becomes critical to ensure appropriate movement of motor vehicles in a complex geometric area. In addition, perception-reaction times can be significantly increased for motorists through encountering confusing geometrics and/or a complexity of active traffic control devices. Complex geometric multileg crossings are difficult, to say the least, to actively control by flashing light signals or gates. However, highway traffic signals, through the use of protected turning movements as well as arrows for directional movement and guidance, can be effective active traffic control devices at these types of crossings. Figure 57 shows an application of this concept in Oklahoma City, Oklahoma, and figure 58 shows an application in Knoxville, Tennessee.

Hardware Considerations. Except for the Barlo strobe lights in the red signal lenses, all of the hardware used is standard, off-the-shelf highway traffic signal equipment available from numerous suppliers in all parts of the country. This includes the signal poles and foundations, mast arms, signal heads, mounting hardware, wiring, controller, and advance sign/flashing beacon units. The ready availability of this hardware and competitive price market certainly are advantages.

The Barlo lights are currently available only from a sole source, and production levels are low. Should the enhanced highway traffic signals be

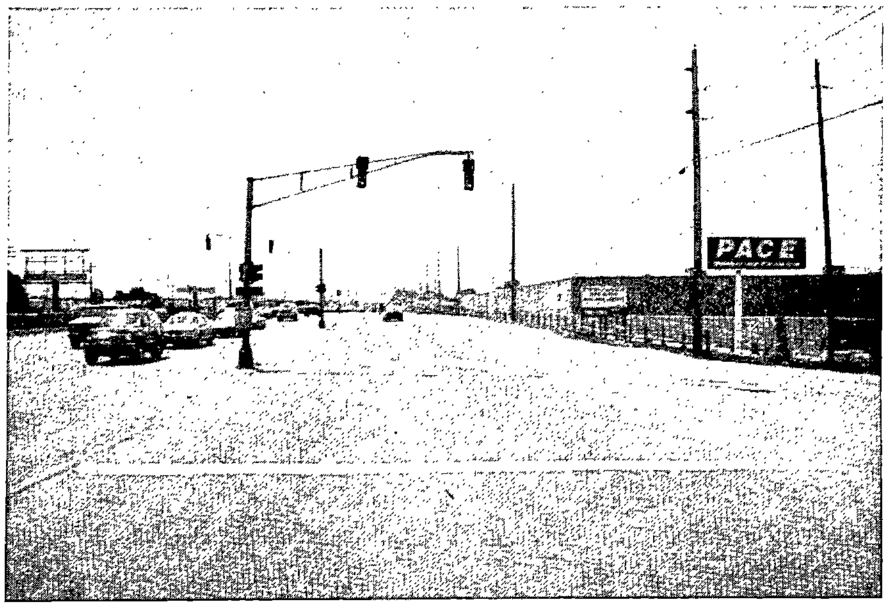


Figure 55. Highway traffic signals used at a crossing in Denver, Colorado.

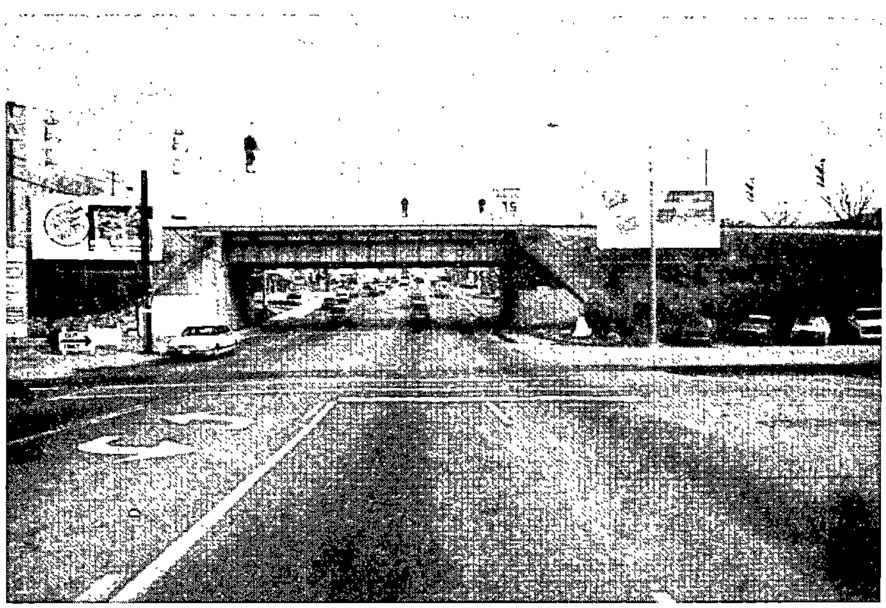


Figure 56. Highway traffic signals used at a crossing in Knoxville, Tennessee.

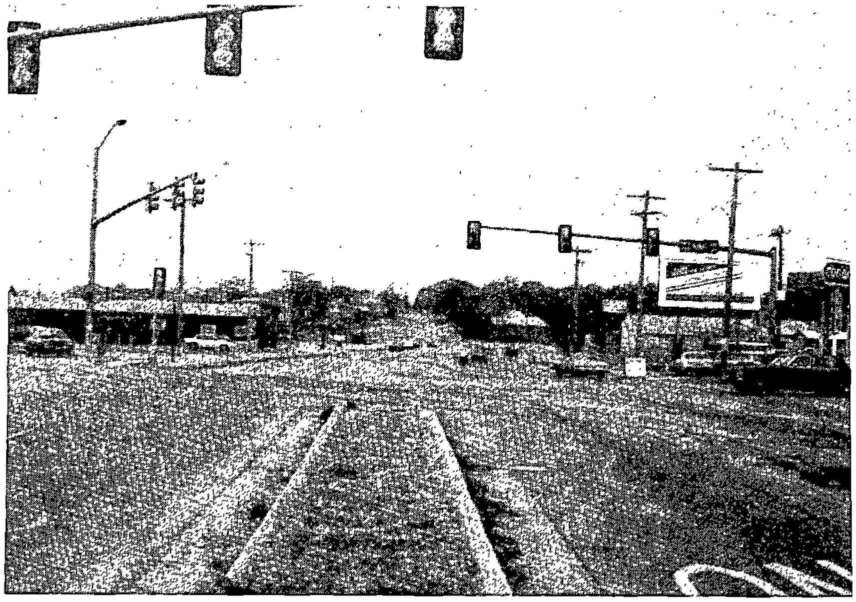


Figure 57. Highway traffic signals at crossing with complex roadway geometrics in Oklahoma City, Oklahoma.

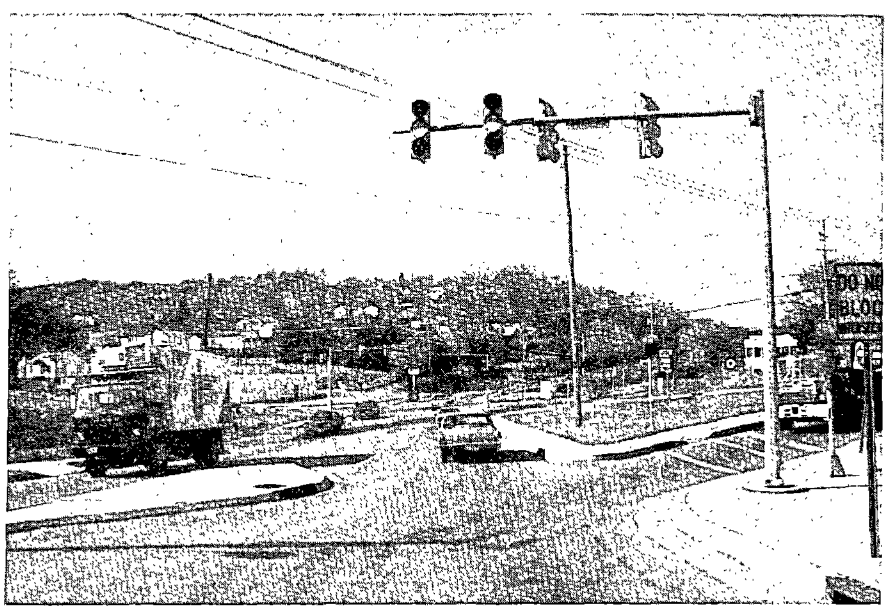


Figure 58. Highway traffic signals at crossing with complex roadway geometrics in Knoxville, Tennessee.

adopted for use, it is expected that the current supplier could meet demands at prices comparable to existing active device prices. Other manufacturers would also be expected to enter the market depending on patent restrictions.

Any type of signal controller can be used as long as it is capable of providing a three-part (red, yellow, and green), variable length cycle, along with a flashing red mode. Also, it is desirable to fully unify the signal controller with the train detection controller, placing them in the same cabinet and providing a unified power system.

Installation Considerations. Railroads have the experienced labor needed to install highway traffic signals. The alternative of using highway traffic signal contractors would also be available.

No additional right-of-way or space (above or below ground) is needed for a highway traffic signal compared to a flashing light signal. However, if advance flashing beacons are used, some additional space along the roadway right-of-way may be needed for these devices. The installation of the beacons will generally be handled by the highway agency which would require some additional coordination.

Power Considerations. The enhanced highway traffic signal is powered directly by 120-volt commercial power. The 120-volt power permits the use of higher wattage lamps (compared to flashing light signals). The higher wattage lamps are bright over a wide angle; thus alignment is not critical as is the case with flashing light signals.

For the field studies, a propane generator was used to provide backup power for the highway traffic signals in the event of a commercial power failure. (Backup power for the train detection system was provided by conventional 12-volt batteries.) The propane generator was capable of powering the traffic signal for 24 hours or more. The generator performed without incident during the months of testing.

Power backup may not be necessary for a highway traffic signal installation since, unlike flashing light signals and gates, a traffic signal has a built-in fail-safe mode. When power is lost due to a commercial power failure or malfunction, the signal indications go blank. A blank signal, in turn, warns motorists that there is a problem and that conflicts with opposing traffic are likely. Experience with conventional highway traffic signals indicates that drivers will be extremely cautious under these circumstances. Backup generators are not known to be used in the illustration shown in this chapter.

It may be appropriate to define a fail-safe mode as a flashing red for standard highway traffic signals used at a railroad-highway crossing. This mode would not be difficult to achieve with a standard battery system used with standard active control devices at a crossing. The highway traffic signal should be operated regularly on 120-volt AC power supply. However, should there be a power failure, a simple relay could be used to switch from the 120-volt AC power supply to the battery source to operate only a flashing red light by DC current. Without increasing the existing capability in standard battery installations at crossings, one could maintain a flashing red mode for a sufficient time to cover all but the most extensive power outages caused by storms. The increased safety benefits from the use of highway traffic signals should far outweigh any safety problems caused by power failures from a major storm.

Warning Time and Train Detection. The enhanced highway traffic signals can be easily and economically installed at crossings equipped with flashing light signals. However, for such retrofit installations (and for all new installations), consideration must be given to providing reasonable, uniform train warning times. Warning times (the time that the signal is yellow and then red before the train arrives at the crossing) will depend on the variability in approach train speeds and the type of train detection equipment. Reasonable and uniform warning times are essential to the successful operation of the enhanced highway traffic signals. Thus, level of service D or better should be maintained.

Experience suggests that most motorists will stop and wait for a red traffic signal for up to 60 seconds, even if there is no opposing traffic in sight. This is true at signalized highway intersections and was also observed at the crossing test site. If the wait time exceeds about 60 seconds (particularly if there is no opposing traffic), the highway traffic signal may lose credibility for the motorist and violations are likely to occur.

At crossings with variable train speeds, it is desirable to employ constant warning time train detectors to provide warning times in the range of 20 to 30 seconds. Constant warning time detectors should not be needed at crossings with uniform train speeds, since the uniform speeds should result in uniform warning times. Highway traffic signals will normally outperform flashing light signals in terms of reducing the number of motor vehicles going over the crossing after the signals are activated, even when both systems have constant warning times.

Traffic Signal Operation and Timing. The highway traffic signals should rest in green until the approach of a train is detected by the train detectors. When the train is approximately 20 seconds from the crossing, the signal should turn yellow and then red. The signal should remain red, with the white bar strobes flashing, until the train is past the crossing.

The length of the yellow vehicle change interval should be 3 to 6 seconds, depending on approach traffic speeds. Recommendations for setting yellow times for highway intersections are presented in the MUTCD and Traffic Engineering Handbook, and these guidelines are applicable to grade crossing highway traffic signal installations.(11,27)

A minimum warning time of 20 seconds is more than enough to provide adequate train-car separation. In fact, a lesser warning time might minimize motorist delay, uncertainty, and violations, while still providing adequate train-car clearances. This time may be increased where conditions of vehicle length, acceleration characteristics, grades, number of tracks, or other factors dictate.

It must be recognized that hardware malfunctions (namely false signal activations) are unavoidable. Furthermore, it would severely damage the credibility of a highway traffic signal installation at a grade crossing if the signal remained red during a lengthy malfunction period. Thus, it is desirable to have the signal change indications in the event of a malfunction. With standard signal equipment and controllers, the most practical way to accommodate false activations is to have the signal change to a flashing red indication after a sufficiently long period (long enough to know that the activation is not due to a slow train). A time of three minutes may be acceptable for most installations. This time should be based on specific conditions at the crossing such as train speeds and train lengths.

All railroad warning signs (including the crossbucks and advance warning signs) should be eliminated. In their place, intersection stop bars and signal ahead signs with flashing beacons should be installed on the crossing approaches. Stop bars are essential, since the normal intersection cues are not present at a railroad grade crossing. In fact, "STOP HERE ON RED" signs may be used to supplement the stop bars.

Maintenance Considerations. Highway traffic signal installations require similar maintenance as a standard flashing light signal system. However, flashing light signals, as opposed to highway traffic signals, do require sighting. Maintenance of highway traffic signals could be handled by railroad signal maintainers with very little additional training. Typical maintenance needs include the following: (1) the signal lamps must be changed and the lenses cleaned periodically; (2) routine service checks on wiring and the controller are recommended; and (3) pavement markings must be replaced periodically and signs should be cleaned periodically.

Four-Quadrant Flashing Light Signal System with Overhead Strobes

Based on the results of the field studies, the four-quadrant flashing light signal system with strobes did not appear to have a significant impact on the overall safety of the test crossing. However, the innovative system did encourage some drivers to begin braking sooner and to approach the crossing at slower speeds. Thus, the system may have some potential limited applications, particularly since it involves very little cost over a standard flashing light signal system.

This system does enhance the conspicuity of the crossing by adding additional lighting sources as well as physically relocating specific roundels for better visibility. The more appropriate installation would be for safety enhancement of crossings using post-mounted flashing light signals.

Applications. The four-quadrant flashing light signal system with overhead strobes is best suited for crossings where, due to the horizontal and/or vertical alignment or restricted sight distances, the visibility of the crossing itself is restricted (see figure 59). Due to the low cost and ease of implementation of the system, it would be an alternative at both low or high exposures.

Field studies suggest that the overhead strobes may actually encourage some drivers to cross the tracks, after stopping, while the device is activated. This could be a problem at crossings with inadequate sight distance down the tracks from the stopping point.

From limited observations at the test crossing, it would appear that the four-quadrant post-mounted signals may not be cost-effective, compared to two standard post-mounted signals with back-mounted lights. Thus, improvements in safety from this system might be attained through the use of strobe lights in combination with a standard two-quadrant flashing light signal system.

Installation Considerations. The four-quadrant flashing light signal system with strobes can be installed by regular field personnel familiar with the installation of a standard flashing light signal system.

Hardware Considerations. The four-quadrant flashing light signals with overhead strobes can be easily and economically retrofitted to an existing standard flashing light signal system. All of the hardware for the flashing light signals is standard crossing equipment available from several suppliers. The strobe equipment is also commercially available from multiple sources. The particular strobe lights used are commonly used at airports, on radio/TV antennas, and on ocean vessels. The strobe lights and support hardware are reliable and durable.

The strobes should be mounted above the flashing light signals on the same poles (pole height extenders will be needed), and the strobes should be

Figure 59. Crossing where sight distance to crossing is obscured.

powered and controlled by the same controller and battery-powered system used for the flashing light signals.

Alignment of the overhead strobes is not critical, i.e., strobe visibility is not particularly sensitive to alignment as is the case with roundels. There will be additional wiring and burying of wire required for the two additional post mounted signals on opposite sides of the crossing.

Power Considerations. The strobes should be powered by the same battery system used to power the flashing light signals. The overall power requirements of the four-quadrant flashing light signals with overhead strobes would be about twice the power required for a standard, two-quadrant flashing light signal system. Thus, more batteries and battery storage space may be required for this system.

System Operation and Maintenance. The four-quadrant flashing light signal system with overhead strobes is operated in the same manner as a standard two-quadrant flashing light signal system. That is, as a train approaches the crossing, the flashing lights and strobes are activated at least 20 seconds prior to arrival of the train at the crossing. Both the flashing light signals and strobes are activated at the same time, and they continue to flash until the train is past the crossing.

Two strobes per approach should be used. The use of two strobes per approach provides the desired level of conspicuity without distracting from other important visual cues at the crossing. With the dual light configuration, strobe lighting will be provided in the event that one unit fails to activate, or is burned out.

The strobes should be operated in an alternating flash mode; one strobe on an approach should be illuminated while the other is blanked. A flash rate of approximately 75 flashes per minute should be selected. Even at night the strobe flashes cause no hypnotic effects, nor do the brighter strobes "wash out" or obscure other traffic control devices/visual cues at the crossing.

Long-Range Implementation

The implementation considerations presented in this chapter have been developed through the field experience gained from the research project, consultations with the traffic engineering community, as well as many years of crossing safety experience by project staff. As these systems are implemented and are placed under additional field conditions, it is recognized that modifications to these guidelines may be needed. However, these guidelines will promote successful installation and operation of the three systems.

Based upon the results and experiences with the innovative systems to date, the systems are ready to be implemented in various geographical regions across the country in the applications identified in the preceding discussions. In fact, highway traffic signals are currently being used throughout the United States at crossings with certain characteristics. For nationwide implementation, the systems need to be adopted into the MUTCD. This will require the active support of the traffic engineering community, highway agencies, and the railroads.

X. SUMMARY OF RESULTS AND CONCLUSIONS

Summary of Results

This chapter summarizes and compares the effectiveness of the three innovative active warning devices and presents major conclusions from the research. Based on the results from the field studies, all three of the innovative active warning devices for use at the railroad-highway grade crossings proved feasible both from technical and practical standpoints. In addition, all three of the systems were seemingly well accepted by the motoring public. There were no accidents, complaints, and/or inquiries while the innovative devices were in operation.

Two of the warning systems, the four-quadrant gates with skirts and the highway traffic signals with predictors, were very effective in improving safety related driver behavior at the crossings where they were installed; 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 that would improve safety at the crossing where it was installed; however, it may have some limited applications.

As described in chapters V, VI, and VII, driver behavior data were obtained from three railroad-highway grade crossings in the Knoxville, Tennessee, area both before and after the innovative active warning devices were installed. Data collected include warning and clearance times at the crossings, speed profiles, brake reaction times, maximum deceleration levels, average violations, and vehicle crossing rates per train arrival. A summary of the major performance measures can be found in table 36.

Speed Profiles, Braking Characteristics, and Deceleration Levels. There were no major differences in speed profiles, PBRTs, and maximum deceleration levels in response to any of the new devices that would have a discernible impact on safety. All of these measures fell well within acceptable limits.

Warning and Clearance Times. Of interest were warning times and clearance times, where warning time was defined as the time between activation of

Table 36. Comparison of driver performance measures in response to various active warning devices.[1]

Type of Warning Device	Warning Time[2] Mean	LOS[8]	Clearance[3] Time (sec)	Violations[4] Mean	Violations[4] Percent[9]	Crossings[5] Mean	Crossings[5] Percent[9]	CL20s[6] Mean	CL20s[6] Precent[9]	CL10s[7] Mean	CL10s[7] Percent[9]
Cherry Street Crossing											
Two-Quadrant Gates	57.6	D	24.5	2.60	83.9	4.00	96.8	0.60	40.9	0.05	5.4
Four-Quadrant Gates with Skirts	56.1	D	48.9	0.00	0.0	1.13	54.7	0.00	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	0.05	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] All values involving motor vehicles include only train arrivals in which a motor vehicle was at the crossing.

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

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

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

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

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

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

[8] Levels of service (LOS) are defined in Table 7.

[9] Percentage of train events with the stated vehicle action.

the active traffic control device 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 36. Also included in the table are the levels of service at which the warning devices were operating during each phase of the field study.

In regard to warning times, installation of the new warning devices had no measurable effect. However, the installation of the predictors to the existing train detection system had a significant impact on the warning times at the Cedar Drive crossing. In that study (highway traffic signals with predictors at Cedar Drive) the average warning time was reduced by over 50 percent and became 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 5 mi/h. It also made the operation comparable to the Ebenezer Road crossing where a fixed-distance warning system had to handle only thru trains at 50 mi/h. 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 major effect except at 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 increased to approximately double the before condition (two-quadrant gates). Note that the average clearance times for the five studies at the other two crossings were all around 20 seconds, which coincidently is the minimum warning time required by the MUTCD; however, a number of drivers accepted a clearance time shorter than 20 seconds.[11] Interestingly, the average clearance times with two-quadrant gates was also very close to 20 seconds (24.5 seconds). Thus, even though the two-quadrant gates at the Cherry Street crossing partially blocked the roadway, they had about the same effect on a driver's average clearance time as did the flashing light signals or highway traffic signals at the other two crossings.

Violations and Vehicles Crossing. A car-train accident did not occur during any of the studies. Surrogate safety measures such as violations (illegal behavior) and vehicle crossings (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 highway traffic signals. 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.

One performance measure was defined as crossing between activation of the traffic control device and the train's arrival at the crossing. This performance measure was subdivided into those vehicles crossing within 20 seconds (CL20s) and those vehicles crossing within 10 seconds (CL10s) of the train's arrival at the crossing. Average values and frequencies of the occurrence for each of these measures are presented in table 36.

Because of the differences in definitions, obviously violations were not readily comparable between all studies; however, it should be noted that with the exception of the four-quadrant gates with skirts which physically prohibited violations, installation of highway traffic signals resulted in the lowest violation rate with an average of 0.68 violations per train arrival. This low violation rate for the highway traffic signals occurred even though there was an average of 32.3 seconds (average length of red) for violations to occur. This rate of 0.68 for the highway traffic signals can be compared with the rate of 2.60 for the two-quadrant gates. Obviously, the four-quadrant gates with skirts did not have any violations because the gate arms physically blocked the entire roadway. It should be noted that for the highway traffic signals a violation occurred in 35.9 percent of the times when a motor vehicle was at the crossing with a train arrival. However, for the two-quadrant gates, a violation occurred 83.9 percent of the times when a motor vehicle was at the crossing with the arrival of a train. The average warning time for the two-quadrant gates was 58.7 percent higher than that for the highway traffic signals (57.6 seconds as opposed to 36.3 seconds). As seen in table 36, the four-quadrant gates with skirts prohibited all violations 100 percent of the time regardless of the length of warning time.

When comparing the number of vehicles that crossed between the activation of a warning device and a train arrival, one finds that the highway traffic signals with predictors had the lowest average with a mean of 0.73. The next lowest average was for the four-quadrant gates with skirts with a mean of 1.13. The flashing light signals without predictors had the highest average with 10.86. The highway traffic signals had the lowest percentage (37.2 percent) of train arrivals in which someone crossed between the time of activation of the traffic control device and the arrival of the train. Even with the four-quadrant gates with skirts, one finds that 54.7 percent of the time a driver would cross between the activation of the traffic control device and the arrival of the train. The worst conditions were for two-quadrant gates and flashing light signals without predictors, whether they were at the Cedar Drive crossing or at the Ebenezer Road crossing. It was also noted that even with predictors, 86.7 percent of the time a driver crossed between the time of the activation of the warning device and the arrival of the train at the crossing with flashing light signals. This is an increase of 133 percent over that of highway traffic signals (86.7 percent compared to 37.2 percent) which makes the highway traffic signals with predictors a substantial improvement over flashing light signals with predictors.

When comparing CL20s, the number of vehicles crossing within 20 seconds or less of a train arrival, one finds that the four-quadrant gates with skirts perform the best with a mean of zero; however, the highway traffic signals had the next best rate with 0.24. Also, one should notice that only 18 percent of the time was there a CL20 for highway traffic signals. The flashing light signals with or without predictors had the highest rates.

ranging from 53.3 to 63.9 percent. Even the two-quadrant gates had a CL20 an average of 40.9 percent of the time.

When comparing the CL10s, a vehicle crossing within 10 seconds or less of the arrival of a train, one finds that the four-quadrant gates with skirts have the best record with zero crossings. The highway traffic signals with predictors, the two-quadrant gates, and the flashing light signals with strobes (Spring, 1986) each had a mean of 0.05 for the number of vehicles crossing within 10 seconds of the arrival of a train. It is interesting to note that the percentage of train events in which a vehicle crossed in less than 10 seconds before train arrival (CL10) was very similar for the two-quadrant gates, highway traffic signals with predictors and flashing light signals with strobes (Spring, 1986) being 5.4, 5.1, and 5.0 percent respectively. As can be seen from table 36, the flashing light signals generally performed worse than the highway traffic signals with predictors.

Benefit-Cost Analyses. As part of the research, benefit-cost analyses were performed for the two most promising systems (four-quadrant gates with skirts and highway traffic signals). In these benefit-cost analyses, the predicted savings in accident costs achieved by installing the innovative devices in lieu of standard devices were compared to the additional costs incurred in constructing, operating, and maintaining the innovative devices.

Table 37 summarizes the results of the benefit-cost analyses. For various traffic and train exposure levels, the table shows the expected ranges in benefit-cost ratios for "retrofitting" the crossings with standard two-quadrant gates with a four-quadrant gate system. The table also shows the expected ranges in benefit-cost ratios for "retrofitting" crossings with standard flashing light signals with highway traffic signals and for new highway traffic signals installations at passive crossings. It should be noted that benefit-cost ratios greater than 1.0 indicate that the innovative device would be cost-effective (the savings in accident costs would outweigh the costs of constructing, operating, and maintaining the innovative device).

As seen in table 37, both the four-quadrant gate system and highway traffic signals would be cost-effective under a wide range of train and

Table 37. Summary of benefit-cost analyses.

Exposure	Benefit-Cost Ratios[1]		
	Four-Quadrant Gates with Skirts (Retrofit Installation)	Highway Traffic Signals (Retrofit Installation)	Highway Traffic Signals (New Installation)
Low 1-5 Trains/Day 500-5000 Veh./Day	0.1-4.4	0.1-7.1	0.6-30.4
Medium 6-10 Trains/Day 5000-15,000 Veh./Day	0.8-5.2	1.9-15.8	8.3-67.7
High > 10 Trains/Day > 15,000 Veh./Day	1.7-8.7	3.6-34.4	15.3-147.4

[1]The benefit-cost ratios presented in this table represent a variety of crossing types and a wide range of accident reduction potentials. They also assume that the appropriate type of train detector equipment (e.g., predictors, motion sensors, etc.) for the crossing conditions are installed. Refer to Chapter VIII for a detailed discussion of the analysis procedures.

traffic volume conditions. In addition, very high benefit-cost ratios could be achieved under many of the conditions. For example, benefit-cost ratios for "retrofitting" with the four-quadrant gate system would range up to 4.4 at crossings with low exposure, to 5.2 at crossings with medium exposure, and to 8.7 at crossings with high exposure. Also from table 37, benefit-cost ratios for "retrofitting" with highway traffic signals would range up to 7.1 at crossings with low exposure, to 15.8 at crossings with medium exposure, and to 34.4 at crossings with high exposure. Even higher benefit-cost ratios would be achieved by new highway traffic signal installations at passive crossings. From table 37, benefit-cost ratios for new highway traffic signal installations would range up to 30.4 at crossings with low exposure, to 67.7 at crossings with medium exposure, and to 147.4 at crossings with high exposure.

A benefit-cost analysis for four-quadrant flashing light signals with strobes was not attempted since the specific improvements in safety afforded by this innovative system could not be sufficiently quantified at the test crossing. It should be noted, however, that four-quadrant flashing light signals with strobes might enhance safety at some types of crossings (see chapter IX), and since their marginal costs are relatively low, they should be cost-effective at these locations.

Conclusions

This section summarizes major conclusions drawn from the field studies. Presented first are the conclusions for each of three innovative traffic control devices which were tested (four-quadrant gates with skirts, highway traffic signals with predictors, and four-quadrant flashing light signals with overhead strobes). Presented next are the conclusions for train predictors, which were evaluated in conjunction with the highway traffic signals and the flashing light signals. The last section provides conclusions related to conducting research at railroad-highway grade crossings.

Four-Quadrant Gates with Skirts. The four-quadrant gates with skirts were field tested for approximately 1 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 gates which had been in regular use at the crossing.

Based on the field test results, the four-quadrant gate system out-performed standard two-quadrant gates on several key measures and proved to be practical and cost-effective under a variety of conditions. The specific conclusions for four-quadrant gates with skirts are summarized below:

1. The four-quadrant gate system substantially increased the safety of the crossing compared to the standard two-quadrant gate system.

2. With the two-quadrant gates, one or more motor vehicles drove around the closed gates during 84 out of every 100 train arrivals. The four-quadrant gates with skirts reduced the number of gate violations (number of vehicles crossing) from an average of 260 per 100 train arrivals to 0.

3. Compared to standard two-quadrant gates, four-quadrant gates with skirts reduced the CL20s (vehicles crossing less than 20 seconds before arrival of train) from 60 per 100 train arrivals to 0.

4. Compared to standard two-quadrant gates, four-quadrant gates with skirts reduced the CL10s (vehicles crossing less than 10 seconds before arrival of a train) from 5 per 100 trains to 0.

5. Four-quadrant gates with skirts did not significantly affect PBRT or maximum deceleration levels at the test crossing.

6. 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 gate arms is delayed by a few seconds to allow vehicle clearance.

7. The four-quadrant gates with skirts did not interfere in any way with emergency vehicle operations at the test crossing.

8. The four-quadrant gates with skirts did not create unreasonable delays for motorists.

9. No significant amount of traffic diverted to other routes to avoid the four-quadrant gates with skirts.

10. No public complaints were received concerning the use or operation of the four-quadrant gates with skirts.

11. The news media was very supportive of the four-quadrant gates with skirts.

12. The wooden gate arms with skirts fabricated for the research performed adequately even under very adverse weather conditions (high winds, heavy snow and ice).

13. Due to their simple design, the gate arms with skirts were too easily damaged when "brushed" by a vehicle. For long-term use, modifications should be made in the skirt assembly.

14. A standard two-quadrant gate system can be retrofitted easily to four-quadrant gates with skirts.

15. Worldwide experience with four-quadrant gates has been good and the need to provide for their use in the MUTCD is evident.

16. At a minimum, four-quadrant gates with skirts can 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 motor vehicle.

    c. Crossings without train predictors where train warning times are long and variable.

    d. Crossings where there are hazardous materials trucks, school buses, or high-speed passenger trains.

    e. Crossings with consistent gate arm violations or continuing accident occurrences.

17. 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. The additional power cost is minimal.

18. Four-quadrant gates with skirts would be cost-effective at many crossings with moderate to high train and/or traffic volumes.

Highway Traffic Signal. Highway traffic signals were field tested for approximately four months at the Cedar Drive crossing in Knoxville. The performance of the highway traffic signals was compared to that of the standard flashing light signals which had been in regular use at the crossing. The highway traffic signals proved to be both feasible and effective as a grade crossing traffic control device. Driver response to the highway traffic signals was excellent, with the highway signals out-performing standard flashing light signals on key safety measures when both systems had predictors installed.

The highway traffic signal costs shown below do not include the cost of predictors. If predictors are needed because of large variations in warning times, the predictor cost would be added to the cost of the highway signals or the flashing light signals. The specific conclusions for highway traffic signals based on the field study results are summarized below:

1. Highway traffic signals with predictors substantially increased the safety of the crossing compared to the flashing light signals with predictors.

2. Compared to standard flashing light signals with predictors, highway traffic signals with predictors reduced the number of crossings during signal activation at the test crossing from 335 crossings per 100 train arrivals to 73.

3. Compared to standard flashing light signals with predictors, highway traffic signals with predictors significantly reduced the number of vehicles crossing in the last 20 seconds before train arrival (CL20s) from 78 per 100 train arrivals to 24.

4. Compared to standard flashing light signals with predictors, highway traffic signals with predictors reduced the number of vehicles crossing in the last 10 seconds before train arrival (CL10s) from 13 per 100 train arrivals to 5.

5. The highway traffic signal with predictors had the second lowest number of violations. After the traffic signal turned red, an average of 68 cars crossed per 100 train arrivals. Only the four-quadrant gates with skirts performed better by reducing the number of violations to 0.

6. When a motor vehicle was at the crossing during signal activation, a violation occurred 36 percent of the time (one or more vehicles crossed for 36 out of every 100 train arrivals).

7. Highway traffic signals did not significantly change drivers' brake reaction times, maximum deceleration levels, or speed profiles at the test crossing.

8. Highway traffic signals at the test crossing appeared to be well understood and respected by motorists.

9. During the entire time that highway traffic signals were installed at the test crossing, there were no reported accidents, confusion, diversions, or unnecessary delays to motorists.

10. While there was no evidence that the use of the highway traffic signals at the Cedar Drive crossing diminished their effectiveness at nearby highway intersections, some individuals are concerned that widespread use of traffic signals at grade crossings may potentially degrade compliance at highway intersections controlled by traffic signals. The research staff does not believe that this will occur.

11. Highway traffic signals should not be used at crossings where frequent equipment malfunctions occur and cannot be remedied, or at crossings with highly variable warning times unless predictors are installed.

12. Highway traffic signals have an inherent fail-safe mode in that when there is an electrical malfunction or power outage, all the signal lenses go blank. Drivers are automatically put on alert by a blank signal head.

13. Highway traffic signals are being used at several crossings in the United States, and their performance has been good.

14. Highway traffic signals should be seriously considered at least for the following types of crossings:

    a. Crossings in signalized areas.

    b. Crossings with complex geometrics.

15. Railroads have the in-house expertise to install and operate highway traffic signals; however, installation and operation can be performed as effectively and much more economically by State or local highway agencies and/or private signal contractors.

16. Highway traffic signals can be installed at a passive crossing for less cost than flashing light signals. Also, highway traffic signals can be retrofitted economically to a crossing with existing flashing light signals.

17. The cost to install new highway traffic signals 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 12 percent are labor costs on the average.

18. The added maintenance cost of highway traffic signals, compared to standard flashing light signals, is approximately $200 per year. The added operating (power) cost is approximately $1,200 per year.

19. Highway traffic signals would be highly cost-effective even at crossings with low and moderate train and traffic volumes. Benefit-cost ratios up to 147.4 to 1 would be achieved for new installations with high train and traffic volumes.

20. 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.

21. Research should be undertaken to determine if the inherent fail-safe mode of highway signals is sufficient for grade crossing applications; if it is, backup power requirements can be eliminated.

Four-Quadrant Flashing Light Signals with Overhead Strobes. Four-quadrant flashing light signals with overhead strobes were field tested for approximately 1 year at the Ebenezer Road crossing in Knoxville. This crossing is characterized by severe sight restrictions at 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 leading to improved safety between the four-quadrant flashing light signals with overhead strobes when compared to standard flashing light signals. However, the innovative system was found to be feasible and may have some limited application. The specific conclusions for four-quadrant flashing light signals with strobes are summarized below:

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 affect vehicles crossing, clearance times, approach speed profiles, maximum deceleration levels, or brake reaction times at the test crossing.

3. There were no reported accidents, confusion, or motorist diversion while the four-quadrant flashing light signals with strobes were installed.

4. The overhead strobes performed adequately throughout the 1-year 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. Based on the research, four-quadrant flashing light signals with strobes are generally not recommended as an enhancement over standard two-quadrant flashing light signals.

6. Four-quadrant flashing light signals with strobes may be considered for use at special problem crossings where visibility approaching the crossing is restricted; however, cantilever signals may be a better or equally effective alternative.

7. Four-quadrant flashing light signals with strobes are easy to retrofit to crossings with standard two-quadrant flashing light signals.

8. The retrofit installation cost is approximately $19,200. Almost 70 percent of this cost is labor, while 25 percent is equipment cost.

9. 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 about the same.

10. 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.

11. Further research or wide-scale implementation of four-quadrant flashing light signals with strobes would not appear to be warranted.

Train Predictors. Train speeds at the Cedar Drive crossing, where the highway traffic signals were field tested, were 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 highway traffic signals. This provided the opportunity to evaluate the effects of train predictors and constant warning times 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 are summarized below:

1. Train predictors reduced the average number of vehicles crossing the tracks while the flashing light signals were activated from 1,086 crossings per 100 train arrivals to 335.

2. At the test crossing, the predictors reduced the number of CL20s from 182 per 100 train arrivals to 78.

3. At the test crossing, the predictors reduced the number of CL10s from 39 per 100 train arrivals to 13.

4. At the test crossing, the installation of train predictors reduced the average length of train warning time from 75.2 seconds to 41.7 seconds.

5. Predictors did not significantly affect speed profiles, brake reaction times, or deceleration at the test crossing.

6. 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.)

7. Predictors should be installed at active crossings which have highly variable and long train warning times.

8. Research is needed to determine the optimal "constant" warning time at crossings equipped with predictors.

9. Warrants/guidelines need to be developed for the use of predictors.

Grade Crossing Safety Research. During the course of the research project, much insight was gained into the requirements and difficulties associated with testing new and different traffic control devices under field conditions at actual grade crossings. The requirements and difficulties referred to here are not related to the particular devices under study, but rather involve the broad issues of contract negotiations, liability, insurance, equipment procurement, and union labor to name a few. Summarized below are the conclusions emanating from the research which concern these and other peripheral areas of grade crossing research.

1. Standard contract agreements and procedures for conducting research in the field at grade crossings that would be acceptable to railroad companies need to be developed by the Federal Highway Administration and the Federal Railroad Administration.

2. Standard indemnity and/or liability insurance requirements for conducting research at grade crossings need to be established by the Federal Highway Administration and the Federal Railroad Administration.

3. Once standard contract and liability issues are agreed upon, a list of railroads willing to participate in research under the standard agreements needs to be formulated.

4. Unless the Federal Highway Administration and the Federal Railroad Administration take the lead in working out the problems with testing devices at crossings, there will be little, if any, field testing conducted by organizations other than the railroads or their trade associations.

APPENDIX A

REVIEW OF PRECEDING PROJECT RESEARCH

The research activities of this long-term project have been extensive. Individual tasks addressed a large number of issues involving innovative active warning devices for use at railroad-highway grade crossings. As tasks were completed, written documentation was prepared throughout the duration of the project. This appendix briefly reviews major findings from individual tasks that have been previously reported.

Domestic and Foreign Research and Practices in Railroad-Highway Grade-Crossing Safety

The first reporting of activities on the project was a literature review report titled Domestic and Foreign Research and Practices in Railroad-Highway Grade Crossing Safety.[10] The areas addressed in this first report were: (1) studies related to driver needs; (2) studies related to signal hardware; (3) studies related to effectiveness of warning systems; and (4) studies and practices in foreign countries. Ninety abstracts, selected from over 800 references, contained major conclusions related to the areas cited above.

The report is a comprehensive summary of techniques and approaches found in the literature and other sources that relate to the improvement of safety at railroad-highway grade crossings and is directed primarily toward the use of innovative or nonstandard active warning devices. References contained in the appendices of the report address the entire spectrum of the railroad-highway grade crossing problems for the benefit of those conducting research in related areas.

Several agencies throughout the world were contacted to secure references on railroad-highway grade crossing safety improvements. In the United States, a search was made of the Railroad Research Information Service (RRIS), the Highway Research Information Service (HRIS), the National Safety Council materials, and the Northwestern University Transportation Library.

In addition, the Departments of Transportation (or Highways) in each State were contacted regarding any reports or projects related to innovative active warning devices. Committee D, Highway Grade Crossing Warning Systems, of the Association of American Railroads was also contacted for information.

Outside the United States, letters requesting information were sent to officials in Canada, Australia, The Philippines, Japan, Austria, Belgium, Denmark, France, Germany, Ireland, Italy, The Netherlands, Sweden, and the United Kingdom. The Australian Road Research Board provided a bibliographic search on grade crossings.

Reports and articles which could be obtained were reviewed, and a summary was prepared for each report or article that was related to innovative active warning devices. The report contains a summary of 90 reviewed articles and/or reports that have some bearing on the overall research project. Each brief summary furnishes the basic abstract, the major conclusions, and the source from which the document might be obtained. The report also contains a comprehensive bibliography of 803 references on railroad-highway grade crossings, both domestic and foreign. The references were included for use by researchers in the railroad-highway grade crossing safety area.

The literature review report documented that numerous approaches have been taken to improve safety at railroad-highway grade crossings. These approaches have been in the form of signs, signals, lighting, or other types of devices that would appear to better alert the motorist to a railroad-highway grade crossing. Unfortunately many of the techniques used at railroad-highway grade crossings have not been consistent with sound engineering or human factors concepts. In certain instances, these techniques may have actually reduced rather than improved the level of safety. In addition, very few formal evaluations have occurred where these techniques have been utilized. Many of the nonstandard techniques which have been utilized have risen from the belief that the present warning devices do not meet the needs of motorists.

The report documented that automobiles and trains have changed substantially over the years, while the present warning devices are essentially the same as were developed at the beginning of the automobile age. The early warning devices for motorists approaching railroad-highway grade crossings took into account two human senses--seeing and hearing. At the time these devices were developed, vehicles could not attain high rates of speed and were designed in such fashion that sound could readily enter the passenger compartment. These characteristics applied to both cars and trucks. However, over time, great improvements have been made in the speed capabilities of automobiles and in the acoustics of their interior compartments, thus making it difficult for sound to penetrate the body of the car and warn a driver. Also, visibility in certain modern vehicles may be restrictive. Truck and bus characteristics have also changed. These changes in characteristics have not necessarily improved safety at railroad-highway grade crossings.

Motor vehicle speeds on the average, increased substantially over the years, even though in more recent times the national maximum speed limit was set at 55 mi/h. Also, train speeds have increased somewhat over the years, particularly on certain tracks and with passenger trains. There are continual efforts directed toward increasing the speed capabilities of trains, not only in the United states but in foreign countries as well.

The changing characteristics of motor vehicles and trains have at times reduced the effectiveness of warning devices. With an increase in speed (which normally requires greater sight distances) and the improvement in acoustics (which reduces the effectiveness of whistles or bells), there is a need for new and innovative devices that will add to or improve safety at railroad-highway grade crossings. Arguments are that the devices developed for the early automobiles which did not have acoustical improvements, had lower speeds, and sometimes had greater visibility are not adequate for today's modern automobiles and trucks.

The literature review shows that numerous research reports, articles, and papers indicate that existing traffic control devices utilized at railroad-highway grade crossings do not "command" the obedience of drivers. The obedience to these traffic control devices is less than desirable, and the devices are violated by drivers who are familiar with the crossings (repeat drivers). In addition, many drivers simply do not understand or comprehend what is expected of them when approaching a railroad-highway grade crossing, as is evidenced from various studies. The performance of a driver at a normal highway intersection controlled by traffic devices is much better than that found at railroad-highway grade crossings with traffic control devices, either passive or active. Thus, there appears to be less respect for traffic control devices at railroad-highway grade crossings than for traffic control devices used in normal traffic operations.

There has been much research related to warning lights, gate systems, train detection equipment, interconnection and control subsystems, and vehicle warning systems. Much of the research in the hardware area has been directed toward reducing cost or improving the "attention-gettingness" of a specific device.

It would appear from the literature review that there are no significant problems with technology providing innovation in traffic control systems for railroad-highway grade crossings. Costs appear to be at an acceptable level, and the technological capabilities for the industry are such degree that industry is able to provide the technical support which is needed. However, other reasons appear to impede changes in technological improvements in traffic control devices. These relate to liability issues and other aspects of major concern to the railroad industry. Some of the past research indicated that these impediments are more of a perceived nature than of real substance.

Research has been directed toward determining the effectiveness of warning devices used at railroad-highway grade crossings. The literature in this area again would indicate that the traffic control devices used at railroad-highway grade crossings do not have the impact needed on the traveling motorist. Some would argue that this is due to the ineffectiveness of the traffic control devices, while others would argue that it is due to a lack of enforcement of traffic laws which apply at the crossings. Whatever the reason, there is a need for improvements in traffic control operations at grade crossings. Some of the literature indicates that it would be difficult to provide enforcement at levels which would have an impact on driver obedience to traffic control devices. Some argue that it is an educational problem on the part of the drivers and that drivers do not understand and comprehend what is expected of them at a grade crossing.

A reasonable amount of work has been conducted in foreign countries relative to safety at railroad-highway grade crossings. Specifically, a review was made of reports from the United Kingdom, Canada, Australia, Japan, and Europe. The practices utilized at railroad-highway grade crossings in these countries are similar to those in the United States, although there are some differences. As an example, full barrier gates are used in some foreign countries as standard practice, but not in the United States. In addition, white and green lights are used on certain open crossings. There are large numbers of crossings with manually-operated gates.

There is a concern in other countries, as well as in the United States, about improving safety at railroad-highway grade crossings. As in the United States, gates are considered to be the best technique presently used for safety. There is a use of supplemental signing and lighting to make the open crossings with active warning devices more conspicuous. It appears that certain countries allocate far more resources to safety at railroad-highway grade crossings than other countries.

A review of the literature indicates that numerous things can be done to improve the conspicuity of traffic control devices used at railroad-highway grade crossings. However, these techniques are not becoming widely used in the industry. It also appears there is a reluctance to be innovative at grade crossings because of considerations that are related not to hardware availability or cost, but to other factors. A lack of continual improvement in safety at railroad-highway grade crossings may be due not to technological aspects but more to perceived legal and other considerations.

Conceptualization and Subjective Evaluation of Innovative Railroad-Highway Crossing Active Warning Devices

The second report from the project, titled Conceptualization and Subjective Evaluation of Innovative Railroad-Highway Crossing Active Warning Devices, dealt with the identification of innovative active warning devices that could be implemented in the field.[54] The research contract required that eight innovative devices be conceptualized and subjectively evaluated. Effectiveness, public acceptance, first cost, life expectancy, power requirements, and other device attributes were to be utilized in the evaluation process. From the eight innovative devices conceptualized and subjectively evaluated, the most promising five candidates were to be selected for extensive laboratory testing. (As will be seen, six devices rather than five were selected for laboratory testing.)

Several methods could have been used to generate or conceptualize innovative railroad-highway grade crossing active warning devices. The process chosen in this portion of the research was to select approximately 30 individuals representing railroad companies, signal manufacturers, consultants, university researchers, and representatives of Federal and State government, all with expertise in the railroad-highway grade crossing safety area. These individuals were asked to help generate new concepts. It was felt that by using a small group representing various segments of the railroad-highway grade crossing safety field one could formalize the thinking from various areas of the field and bring to bear collectively many years of both practice and research experience in this area.

A 1-day workshop was held in Washington, D.C., bringing together these individuals representing a wide variety of expertise in the railroad-highway grade crossing safety area. During this all-day workshop, numerous concepts of railroad-highway crossing active warning devices were verbalized and then described in writing. In addition, these concepts were ranked by those in attendance to reduce the total number for final consideration.

After the 1-day workshop, mail questionnaires were used to further evaluate the concepts generated at the workshop and to rank each concept in both absolute and relative terms. In addition, the criteria used for evaluation of the new concepts were ranked in terms of their importance.

The candidates which were proposed for laboratory testing were not "pie in the sky" types of installations. They were pragmatic concepts which are achievable from both technology and cost perspectives. They also have a high probability of being accepted for widespread field use, provided they are improvements over existing technology used in the field.

The final rankings of the eight innovative active warning devices are shown in table 38 and figure 60. Table 38 shows the absolute rankings while figure 60 gives the relative rankings of each alternative. From these eight candidate devices, which were developed through the ranking procedures utilizing representatives from various areas of the railroad-highway grade crossing safety field, active warning devices were selected for extensive laboratory testing. The research team at the Transportation Center took the results from table 38 and figure 60 and developed the conceptual systems that were laboratory tested.

It is interesting to note from figure 60 that the eight candidate devices can be grouped into three broadly defined systems. One system can be defined as short-arm gates used in all four quadrants. A second system can be defined as the use of standard highway traffic signals. The third system can be defined as making improvements on existing railroad flashing light signals. By varying the characteristics of these three broad general systems, one can develop six (rather than five) innovative active warning systems for testing in a laboratory setting.

Four-Quadrant Short-Arm Gate System. Two alternatives of a short-arm gate system used in all four quadrants were selected for testing in the laboratory. An example of this concept is shown in figure 61. As can be seen, short-arm gates covered the entire roadway. Skirts were used on each arm as is common practice in certain European countries. The short-arm gates were elevated slightly above the hood of a standard automobile,

Table 38. Results from the analysis of likert scaling of system alternatives (n = 24).

	Form II[1]		Form III[2]	
System	Average Likert Rating	Rank Based on Average Likert Rating[3]	Average Likert Rating	Rank Based on Average Likert Rating
1	3.83	2	4.04	2
2	3.46	5(T)	3.71	7
3	3.04	6	3.25	8
4	3.46	5(T)	4.00	3
5	3.61	4(T)	3.83	6
6	3.71	3	3.96	4
7	4.08	1	4.58	1
8	3.61	4(T)	3.92	5

(1 = Much Worse; 2 = Worse; 3 = Equivalent; 4 = Better; 5 = Much Better.)

[1]All systems were compared with a standard gate with flashers.

[2]All systems were compared to a standard flasher system without gates.

[3]T indicates a tie in ranks.

Brief System Description

1. Auxiliary strobe lights added to complement existing railroad flashing signals with or without gates.

2. Standard highway traffic signal in conjunction with standard grade crossing flashers or strobes, with standard flasher-gate systems, or a combination of the above.

3. Standard highway traffic control device by itself.

4. An amber light on continuously when there is no train approaching or occupying the crossing which changes to a red light in conjunction with other red lights when a train is detected.

5. Standard highway traffic control device used in conjunction with an active advance warning signal.

6. Standard highway traffic device used in conjunction with an active advance changeable message sign.

7. Short-arm gates in all four quadrants.

8. "Second train" advisory.

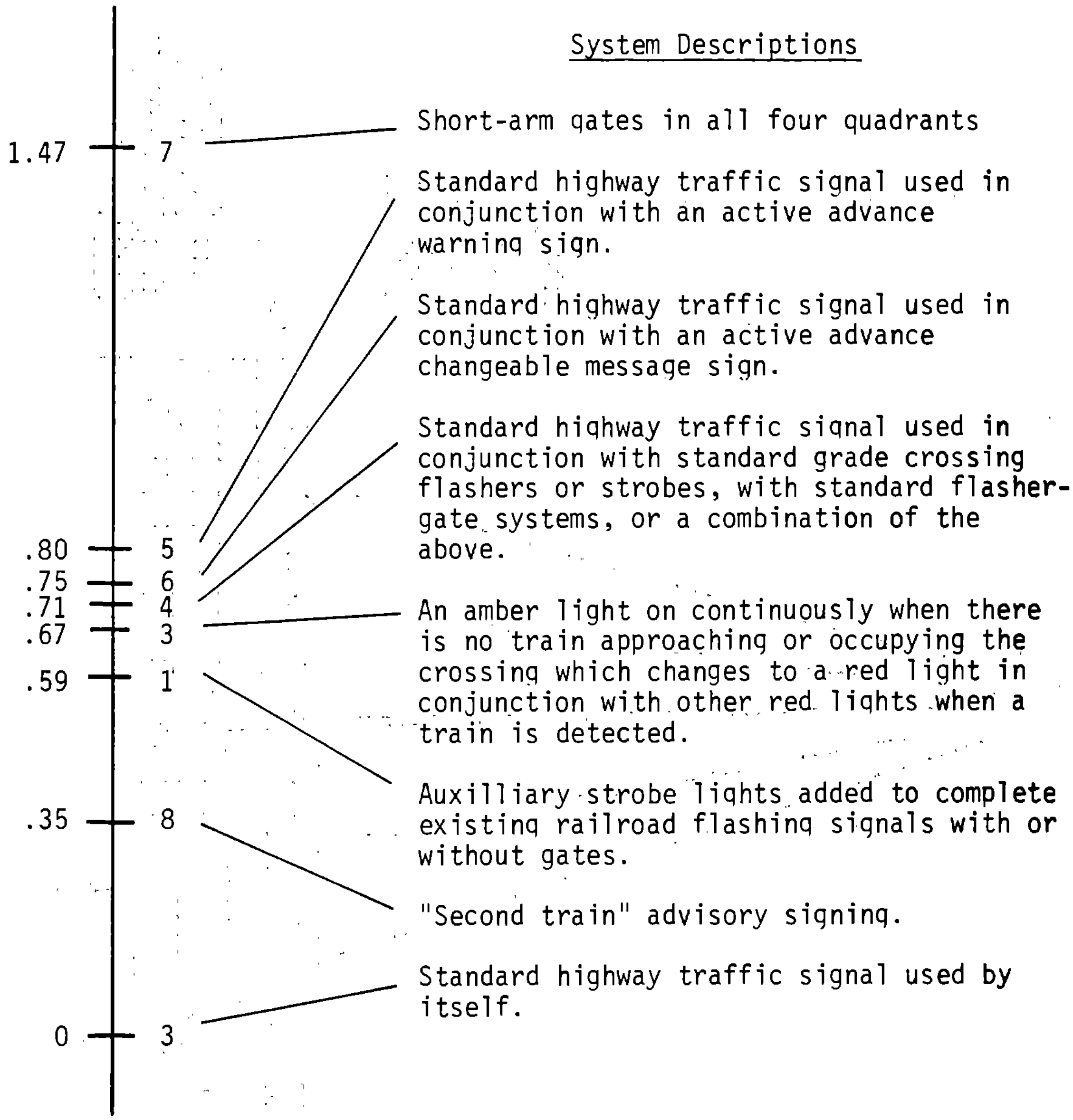


Figure 60. Results from the analysis of paired comparisons of the system alternatives (n = 25).

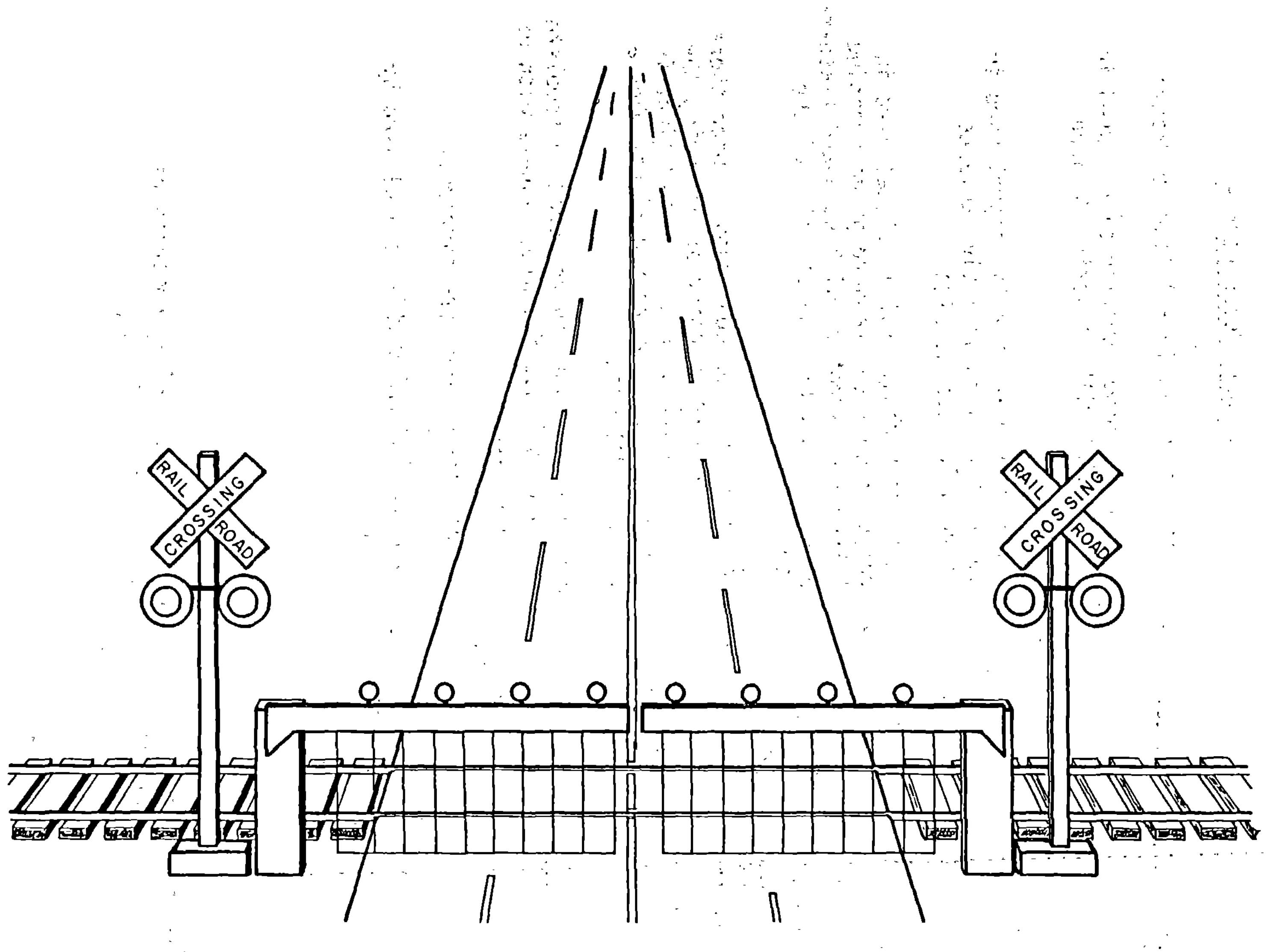


Figure 61. Proposed four-quadrant gate system (one approach shown).

incorporated wider arms, and used highly reflective material. Alternative A chosen for laboratory testing had skirts, alternative B did not.

A delay function was incorporated into the control system to delay the actuation of the far-side gate arms for some 3 to 5 seconds. This reduced the possibility of a vehicle becoming trapped on the tracks with the gate arms lowered.

Standard Highway Traffic Signal System. It is noticed from figure 60 that a standard highway traffic control device, when used by itself, had the lowest ranking of any of the eight candidate devices evaluated. However, if one adds an active advance warning sign or an active advance changeable message sign, this concept becomes second and third in importance relative to the four-quadrant short-arm gate system. A standard highway traffic signal used in conjunction with standard grade crossing flashers or with standard flasher-gate systems ranked lower than when the standard highway traffic signal was used in conjunction with an active advance warning or changeable message sign.

The second conceptual system proposed to be laboratory tested was similar to that shown in figure 62. Preliminary laboratory testing resulted in the two alternatives evaluated being with and without white bar strobes in the red signal lenses.

Flashing Light Signal System. It can also be seen from figure 60 that three conceptual systems make use of flashing light signals presently found at railroad-highway grade crossings. One of these concepts would be the use of an amber light that would be on continuously when no train was approaching or occupying the crossing but that would change to a red light in conjunction with the flashing light signals when a train was detected. Another concept would be to add strobe lights to complement existing railroad flashing light signals to increase their conspicuity. The third concept would include the use of a "second train" advisory sign. The second train advisory sign could include a word message or other types of warnings that would be easily learned and understood by the motorists.

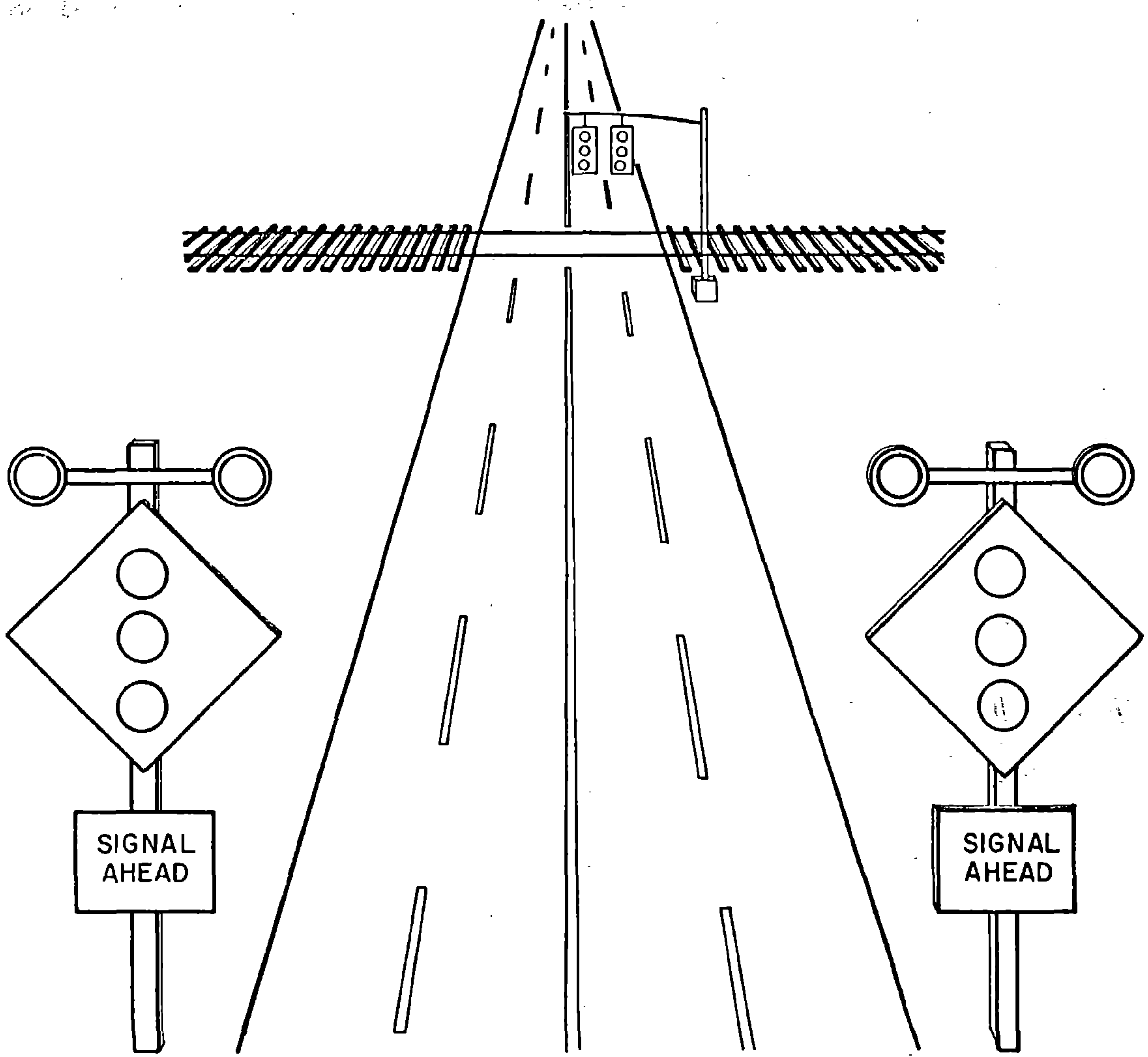


Figure 62. Proposed standard highway traffic signal with active advance warning signs (one approach shown).

Figure 63 illustrates the type of system that would represent the third concept to be tested in a laboratory setting. Two variations of improvements upon existing flashing light signal installations shown in figure 63 were recommended for testing in the laboratory to enable an evaluation to be made of these proposed improvements. In the laboratory testing, one alternative incorporated overhead strobe lights while the other alternative did not.

Resulting Systems. By combining specific characteristics of the eight candidate systems into the three systems described and shown in figures 61 through 63, one can incorporate six of the concepts that emanated from the evaluation of the eight concepts shown in figure 60. The final results are three very distinct system concepts differing in basic characteristics and costs that were laboratory tested. From the results of the laboratory testing, these six concepts (composing three systems) were reduced to three concepts which were field tested.

Even though these concepts proposed by individuals working in the railroad-highway grade crossing safety area were somewhat pragmatic in nature, some fundamental concepts are substantially different from active warning devices presently used. The use of short-arm gates in all four quadrants is a significant departure from present practice in the United States, although not from practice in certain countries in Europe. In addition, the use of standard highway traffic signals at railroad-highway grade crossings is a definite move toward placing a railroad-highway grade crossing in the same category as a highway intersection. This is a significant departure from current practice. The improvements in existing railroad flashing light signals, of course, are minor adjustments to current practice. While one may view the systems proposed to be pragmatic, the concepts provide for a fairly significant change in current philosophy and practice.

Evaluating the Effectiveness of Innovative Railroad-Highway Crossing Warning Devices

The third report from the project, titled <u>Evaluating the Effectiveness of Innovative Railroad-Highway Crossing Warning Devices</u>, was concerned with

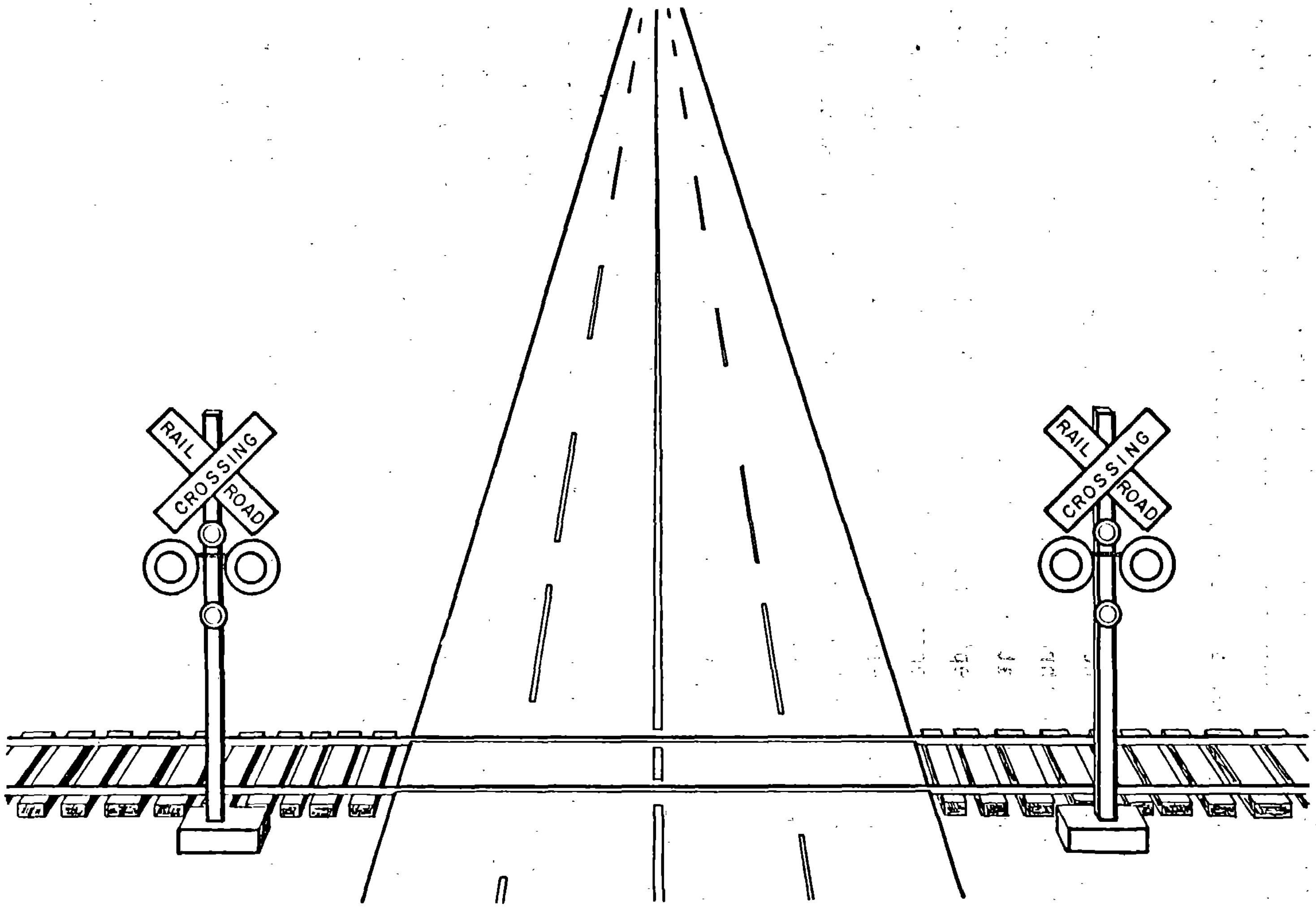


Figure 63. Proposed improvements to existing flashing light signals (one approach shown).

the current use of innovative devices at railroad-highway grade crossings in the United States and whether the effectiveness could be determined from devices in use.[55] In order to evaluate innovative (nonstandard) railroad-highway crossing warning devices which have been developed and installed in the United States, it was necessary first to ascertain where such devices had been, or are being, used. Realizing that a comprehensive before-and-after study of any one site would be difficult to achieve and may not be meaningful, it was felt that a large number of installations over considerable exposure periods would be required for a meaningful statistical analysis. If such a group of installations were identified, before-and-after accident data could, perhaps, be pooled in such a way as to evaluate the accident reduction potential of these devices. By site stratification, the effectiveness of specific devices used at specific locations (urban vs. rural, tangent vs. curved roadways, high vs. low volume) then might be determined. In this way, certain site characteristics could be identified where a particular treatment of system would produce benefits.

The data for such an analysis was taken from two sources--the National Railroad-Highway Crossing Inventory records and a survey of railroad agencies, companies, and State governments.

National Inventory. Specifically, an analysis of the listing of warning devices for the national inventory indicated five areas of "nonstandard" warning devices that are coded into the inventory. It was felt that a review of these codes for all crossings might give some indication as to the specifics of the type and location of innovative devices which are now being, or have been, used. The five identified data fields were as follows:

- Other stop signs (SS).
- Other signs (OS1, OS2).
- Other colored gates (O Gate).
- Other flashing lights (OFLS).
- Highway signals (SIG).

A brief review of the summary data, however, suggested that the number of crossings with devices in one or more of these categories was substantial. For example, 1,059 crossings had "other signs" and 7,632 crossings had special warning devices of some type. Due to the sheer volume of crossings with nonstandard devices, less that the full data set was selected for analysis. Consequently, the Federal Railroad Administration (FRA) furnished the Transportation Center with the most recent inventory files for 243 randomly-selected crossings which had entires in at least one of the appropriate fields as listed above.

From a private effort made in 1981, the Transportation Center also had access to inventory and accident history files for five crossings in Louisiana. In addition, data from three crossings in Illinois were received separately from other sources. For each of these eight crossings, at least two files were received, one reflecting the latest (or current) inventory, and one reflecting the original inventory. For one Louisiana crossing three files were received--the original, an update, and a second update (the current record).

After analyzing the combined total of 251 crossing inventory files, the research team decided that the quality of the data available from the national inventory would not permit the desired analysis. Too many discrepancies were apparent in the files to allow a meaningful analysis. Specific discrepancies were noted on such items as inventory updates, dates of charges, different incident records and inventory records, lights, and data.

Major discrepancies were noted for the eight crossings for which more than the latest (current) inventory data were available. Although no similar analyses (field tests, etc.) were made for any of the 243 randomly selected crossings, it is believed from numerous field experiences, that these are not isolated instances.

One of the basic causes for these problems just discussed which hinder rigid statistical analyses appears to lie in the method of inventory updating. Either the State or the railroad can initiate an update, but they are not required to update all items. Thus, only partial updates are available. Even though the FRA receives 50,000 updates per year, many agencies are providing few, if any, updates. While the national inventory may be useful for providing an aggregate statistical summary of grade crossing information, it has serious limitations on providing information for any detailed statistical evaluations.

State Responses to Written Inquiries. In order to survey the practices of using innovative active crossing warning devices both inside and outside the United States, letters requesting information were sent to highway and/or railway officials in all 50 States, Puerto Rico, and five provinces of Canada. Thirteen members of Committee D, Highway Grade Crossing Warning Systems, of the Association of American Railroads received the letter as well as representatives of the National Safety Council and the Railway Progress Institute. Enclosed with each letter of inquiry was a brief summary of the research project goals, objectives, and work plan. The addressee was then asked for any available information (such as papers, reports, accident data, or other materials) dealing with the use of such devices, their costs, requirements for fail-safeness, standby power requirements, maintenance requirements and practices, and motorists' responses. Also requested was information related to motorists' needs at railroad-highway grade crossings.

Thirty written responses were obtained from the initial mailout, while one additional response was received as a result of a follow-up inquiry. Twenty-eight States responded, along with Puerto Rico, the Canadian province of Ontario, the Canadian Northwest Territories, and the Southern Railway System. Of the 31 responses, 21 indicated that the responding agency had done no work in these areas. The remaining 10 reported to a varying degree devices installed or to be installed, but in general were unable to provide meaningful data relative to any evaluations.

The majority of the reported innovative devices fell into one of two categories: (1) active advance warning devices; and (2) the use of strobe lights. Reporting in this first group were the States of Florida, Maryland, Nebraska, Pennsylvania, and Texas, and the Province of Ontario. The second group included Arizona, California, Florida, Illinois, Nebraska, and New York.

The expected before-and-after analyses of pooled data to determine the effectiveness of innovative devices in use at crossings in the United States could not be completed. The identification of such devices through the use of national inventory data is considered difficult at best, and such data certainly do not lend themselves to any reasonable statistical analysis. Furthermore, data received from State and agency responses were not helpful in identifying any innovative devices where data of sufficient quantities were available for analyses.

Laboratory Specification and Testing of Alternative Active Railroad-Highway Grade Crossing Warning Devices

The fourth report from the research project, titled Laboratory Specification and Testing of Alternative Active Railroad-Highway Grade Crossing Warning Devices, outlined the specifications for laboratory testing the alternative active railroad-highway grade crossing warning devices.[56] The report did not contain "results" of any of the research but simply outlined the laboratory procedures to be used. During the laboratory testing, minor changes were made in the testing procedure due to unforeseen circumstances. The basic methodology employed in the laboratory testing involved the use of 32 subjects selected according to age and sex. These subjects operated an instrumented automobile at a target speed of 40 mi/h on a 1.5-mile section of a private two-lane roadway. As the subjects drove the research vehicle along this roadway, the prototype active railroad-highway grade crossing warning devices were activated. Driver response to these devices were observed and recorded with a computer.

Investigation of the Effectiveness of Railroad-Highway Grade Crossing Warning Devices

The fifth report of the research project, titled Investigation of the Effectiveness of Railroad-Highway Grade Crossing Warning Devices, detailed the influence certain factors had on device effectiveness, as measured by accident rates.[57] One segment of the report analyzed the influence on effectiveness of warning device type, suitability, and conformance to MUTCD standards, and the other investigated characteristics of high and low accident rate observations.

The research confirmed other research results for the past several years which indicate that there is a hierarchy of effectiveness in traffic control devices at railroad-highway grade crossings. Gates were found to be the most effective and passive devices were the least effective.

From this part of the research project, a conclusion could not be drawn that conformance or nonconformance of warning systems to MUTCD standards significantly influence device effectiveness. Differences in accident rates could not be explained by differences in conformance. However, it should be pointed out that in regard to the MUTCD standards, the nonconforming crossings often deviate only marginally from the standards. Perhaps other factors such as geometrics are more influential on accident rates than conformance to the MUTCD.

It was anticipated that warning systems at locations judged to be in need of higher level traffic control devices (for example, passive devices located where flashing light signals were apparently needed) would be less effective than devices judged to be suitable for the conditions of their locations. However, this was not found to be the case. The results suggest that this analysis, based on Federal Highway Administration guidelines, failed to assess device suitability accurately; however, it should be noted that sight distance, highway speed, number of trucks carrying hazardous materials, number of school buses, number of pedestrians using a crossing, and other variables could not be a part of the analysis in this research due to a lack of data in this area. In addition, important factors such as geometrics, visual clutter, and other environmental influences could not be taken into account.

It is interesting to note that in this analysis, high train speeds were associated with low accident rates and low train speeds were associated with high accident rates. This finding was consistent for all warning device categories considered individually and for all observations considered as a whole. Accidents did not vary linearly with train speed. These results suggest that driver behavior is influenced by train speed. Perhaps greater caution is exercised at high train speed crossings and, due to perceptions of risk, less care is taken at low train speed locations. Active traffic control devices at railroad-highway grade crossings apparently do not always compensate for these attitudes and provide the level of safety needed. Thus, it would appear in these instances that traffic control devices are not meeting the needs of the motorists.

Low accident rate observations tended to have high train volumes and high accident rate observations were associated with low train volumes. These trends were not absolute, but the tendencies were distinct. Accidents did not vary linearly with train volume. The results suggest that driver perceptions of hazards are influenced by the frequency of train arrivals and that these perceptions in turn influence safety. There are apparently certain situations where the traffic control devices are not effective in overcoming the influence of these perceptions. Thus, it would appear in certain circumstances that the traffic control devices in place at railroad-highway grade crossings are not meeting the needs of the motorists.

The extensive use of information from the National Grade Crossing Inventory reveals some limitations in that data base. These limitations were generally concerned with either the accuracy or the completeness of the available information. In terms of completeness, information such as highway speeds and sight distances as well as an accounting for each of the two highway approaches would have aided the analysis. Additional information should be added to the Inventory if a complete and thorough analysis is to be performed on the safety performance of crossings.

The National Grade Crossing Inventory contained information that had not been updated since the initiation of the data file. Therefore, certain characteristics of the crossing, including such things as highway traffic volumes and type of device in place, were not accurate. This was also in evidence from the fact that some of the accident/incident reporting files did not contain the same data for the crossing that the inventory records contained. In addition, when an inventory update does occur, it is not possible to ascertain all of the characteristics of the crossing that were examined for the update. A periodic updating of the National Grade Crossing Inventory should be established. This updating should include all operating characteristics of the railroad-highway grade crossings. In addition, whenever traffic control devices are changed at a given crossing, an update should be made immediately thereafter. There is also a need to list the specific date of the change associated with each characteristic of the crossing.

Development of Innovative Railroad-Highway Active Warning Devices

The sixth report is a paper prepared for presentation titled "Development of Innovative Railroad-Highway Active Warning Devices".[58] This paper was presented at the 1982 National Rail-Highway Crossing Safety Conference held in Kansas City and was published in the proceedings of the conference. This paper reviews the activities of the project from its beginning through the installation of the active warning devices in the laboratory testing phase. The results reported in the paper will not be repeated here as they are contained in other portions of this review of previous research project activities.

Laboratory Evaluation of Six Active Warning Devices for Use at Railroad-Highway Grade Crossings

The seventh report from the project, titled Laboratory Evaluation of Six Active Warning Devices for Use at Railroad-Highway Grade Crossings, contained the results from the laboratory testing.[59] The six active warning devices chosen for laboratory testing were:

- Four-quadrant gate system (without skirts).
- Four-quadrant gate system (with skirts).

- Four-quadrant flashing light signal system (without strobes).
- Four-quadrant flashing light signal system (with overhead strobes).
- Highway traffic signal system (with one white bar strobe).
- Highway traffic signal system (with three white bar strobes).

The testing of these six active warning devices was conducted on a private two-lane roadway at the McGhee-Tyson Air National Guard Base near the main Knoxville airport. This test facility provided a good combination of road geometry, vehicle control, security, and accessibility.

Thirty-two test subjects were chosen to participate in the laboratory testing. The test subjects were equally divided between those under 25 years of age and those over 60 years of age, and each of these groups was further divided into an equal number of males and females. 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.

A special instrumented vehicle was used to measure each subject's response to the activation of the six warning devices. The automobile was equipped with sensors on both the accelerator and brake pedals. A change in the status of either pedal caused a signal to be sent to a small DEC LS1-11 computer in the vehicle's trunk. A fifth wheel was used to record distances along the roadway. This instrumentation 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.

Upon arrival at the test site, each test subject completed both a biographical data form requesting information on the subject's driving experience, accident record, personal health, and other attributes, and a short entrance examination to determine the subject's knowledge of traffic control devices used at railroad-highway grade crossings. In addition, each subject's simple reaction time was measured using the American Automobile

Association portable model for reaction time testing, and each subject's vision was checked using the Titmus Professional Vision Tester. Results from these tests gave an indication of any serious reaction or visual deficiencies in any of the subject population.

After completing the driving portion of the laboratory testing, a brief exit survey, using semantic differential scaling and Thurstone's method of paired comparisons, was used to determine attitudinal responses to the effectiveness of each of the six prototype active warning devices. This survey was given after each test subject had finished all of the driving tests. Results of these procedures provided both absolute and relative rankings of the effectiveness of each device as perceived by the test subjects. Attitudinal responses were obtained for both day and night driving conditions.

The basic experimental design utilized three of the active warning devices for a given driving experience. Each test subject would drive a 1.5-mile course and would encounter three different active warning devices. Each device could be activated from either a short, medium, or long distance upon the approach of a test subject. In addition, the null condition was also contained in the experiment in which the active warning device would not activate upon approach by a test subject. Each test subject also negotiated this course during both day and night and was required to do two replications of each variable combination. Thus, 96 encounters with active warning devices were made by each test subject (6 [six active warning devices] x 4 [actuation distances--short, medium, long, null] x 2 [day, night] x 2 [replications] = 96). Using an analysis of variance (ANOVA) statistical technique, evaluations were made to determine the following:

- Differences in the effectiveness of each of the six active warning devices.
- Differences in the effectiveness of each of the three basic system concepts of four-quadrant gates, flashing light signals, and highway traffic signals.
- Differences in the effectiveness of each of the six active warning devices and each of the three basic systems for short, medium, and long distances of actuation.

- Differences in the effectiveness of each of the six active warning devices and each of the three basic systems under day and night driving conditions.

A large combination of factors and a variety of conditions were used to evaluate the effectiveness of the six individual active warning devices as well as the effectiveness of the three basic systems of active warning devices.

Some of the more important conclusions derived from the analysis of the data obtained in the laboratory testing were:

- All six innovative active warning devices were perceived by the test subjects to be superior to standard active warning devices currently in use at railroad-highway grade crossings.
- Four-quadrant gates (with skirts) were always perceived by the test subjects to be the most effective on both an absolute and relative ranking for both day and night driving conditions.
- Flashing light signals (without strobes) were always perceived by the test subjects to be the least effective on both an absolute and relative ranking basis for both day and night conditions.
- For short and medium actuation distances, four-quadrant gates (with skirts) resulted in quicker brake reaction times than either highway traffic signals or four-quadrant flashing light signals.
- For short, medium, long, and null actuation distances, highway traffic signals resulted in slower brake reaction times than did the other two systems.
- For short actuation distances, there were no differences in deceleration rates for any of the six active warning devices.
- There were no significant differences in brake reaction times or maximum deceleration between day and night conditions for short actuation distances, but there were differences for medium and long actuation distances.
- Four-quadrant gates (with skirts) tended to be a superior system in all categories of analysis.
- Generally speaking, Alternative B of each system (with skirts, with overhead strobes, and with three white bar strobes) was more effective.

- The effectiveness of four-quadrant flashing light signals and highway traffic signals tended to alternate relative to one another depending upon a given category of analysis--there was not a consistent ordering of effectiveness between these two systems.

Experimental Plan for Field Testing Three Active Warning Devices for Use at Railroad-Highway Grade Crossings

The eighth report, titled Experimental Plan for Field Testing Three Active Warning Devices for Use at Railroad-Highway Grade Crossings, was prepared to guide the field testing of three active warning devices.(60) This report outlined the experimental plan and the measurements of effectiveness that were to be used at the three crossings. Results from the task are not a part of this report. The results of the field testing are contained elsewhere in this presentation.

Evaluation of Six Active Warning Devices for Use at Railroad-Highway Grade Crossings

The ninth report from the research project, titled "Evaluation of Six Active Warning Devices for Use at Railroad-Highway Grade Crossings," was a paper prepared for an annual Transportation Research Board meeting.(61) The material in the paper was taken from internal reporting prepared on the laboratory testing phase of the project. The paper covered the laboratory testing and evaluation; the findings will not be repeated here as they were discussed in the paper.

Motorists' Understanding of Active Warning Devices Used at Railroad-Highway Grade Crossings

The tenth report from the project, titled "Motorists' Understanding of Active Warning Devices Used at Railroad-Highway Grade Crossings," dealt with a measurement of motorists' understanding of active warning devices used at railroad-highway grade crossings.(4) This short report was published in the ITE Journal in April 1984. To test motorists' knowledge of driver requirements at railroad-highway grade crossings, a short examination was developed and administered to 32 test subjects. The test subjects were equally divided between males and females, and each group was further divided into an equal number of younger (than 25) and older (over 60) subjects. The younger subjects had been driving an average of four years and the older subjects an average of 46 years. In both age groups, males drove almost twice as many miles per year as their female counterparts. The average educational level for each of the four groups was similar; however, individuals within the groups ranged from those who did not complete high school to college graduates.

Surprisingly, younger and less experienced drivers scored about 10 percent higher on the knowledge examination than did the older subjects. Of the 14 questions, only 4 subjects (12%) answered as many as 11 correctly; 22 (69%) answered 9 or 10 correctly, and 6 (19%) answered 8 or fewer correctly. All six of the lower scores were in the older age groups. When asked to identify those sources from which they recalled specific instruction concerning driving safety at railroad-highway grade crossings, 19 subjects (59%) checked a State driver's handbook; 13 (41%) checked a driver's education course; 9 (28%) checked some type of safety campaign; and 6 (19%) did not recall any instructions at all. These six were evenly divided between the two age groups; however, only two of the six had low test scores.

When asked what they should do when approaching a crossing that does not have a railroad signal, only 5 subjects (16%) chose the correct response--be ready to stop if you see or hear a train. The remainder of the subjects (84%) thought you should stop, look, and listen at the crossing for a train.

When asked the meaning of the Railroad Advance Warning sign, 29 subjects (91%) selected the correct response--there is a crossing ahead of you. The other 3 subjects (9%) selected "you will have to stop at the crossing" as the proper meaning. When asked which of the five signs was located several hundred feet in advance of a railroad crossing, 20 subjects (63%) selected the proper response--the railroad advance warning sign, 3 (9%) selected the crossbuck sign; and 9 (28%) selected a diamond-shape sign with the word message "Railroad Crossing." When asked which of the signs was located just at the point where the railroad tracks cross the highway, 23 subjects (72%) selected the correct response--the crossbuck sign; 5 (16%) selected the railroad advance warning sign; and 4 (12%) selected the diamondshaped sign. When asked about the standard markings painted on the pavement in advance of some railroad crossings; 24 subjects (75%) selected the RXR, 4 (13%) selected the X by itself; 1 (3%) selected the RR; and 3 (9%) selected "do not know" as their answer.

When shown a standard railroad flashing light signal and asked what does it mean when this signal is flashing, all 32 subjects (100%) chose the correct answer--a train is coming; however, when asked what they should do when this signal is flashing, only 4 subjects (12%) chose the correct answer--stop my vehicle and proceed over the crossing if a train is not near. The other 28 subjects (88%) chose "Stop my vehicle and wait until the flashing stops before proceeding over the crossing." Four subjects (12%) thought that flashing light signals appeared at all crossings, and only 16 (50%) knew that it generally takes from 20 to 60 seconds for a train to reach the crossing after the signal had begun to flash (20 seconds is the minimum requirement). One subject (3%) thought it was less than 20 seconds; 7 (22%) thought it was more than 60 seconds; and 8 (25%) did not know.

When asked what they should do when the gates at a crossing are down, 31 subjects (97%) selected the correct answer--stop and remain stopped until the gate arms are raised. The remaining subject (3%) said he would stop and then proceed around the gates if no train was coming.

When asked what additional traffic-related measures they would like to see taken in order to improve safety at railroad-highway grade crossings, 10 subjects (31%) thought the present system was satisfactory; 10 (31%) thought flashing light signals or gates should be provided at all crossings; 4 (13%) thought more advance warning signs, flashing lights, automatic gates, etc., were needed; 3 (9%) thought better visibility of warning devices and oncoming trains were needed; 2 (7%) thought consistent behavior at all crossings was needed; and 3 (9%) thought a higher level (more restrictive) warning device was needed, especially near rural schools.

It appears that a number of motorists do not fully comprehend the meaning of traffic control devices at railroad-highway grade crossings. In certain situations, the percentage of motorists who misunderstand is small, but the severity of train-automobile collisions is such that only a small fraction of the driving public making improper decisions can lead to death and serious injury. Therefore, it becomes very important to have high performance traffic control devices at railroad-highway grade crossings and to educate the motorists on the proper driving behavior at these locations. Thus, the three Es of traffic engineering (engineering, education, and enforcement) are even more important at railroad-highway grade crossings.

Facilitating Field Evaluation of New Traffic Control Devices for Railroad-Highway Grade Crossings

The eleventh report, a paper titled "Facilitating Field Evaluation of New Traffic Control Devices for Railroad-Highway Grade Crossings," was presented at the 1985 National Conference on Highway-Rail Safety in Kansas City, Missouri, and was included in the published proceedings of the conference.[62] The paper dealt with the issues involved in securing crossings to be used for field testing of the innovative devices developed in the project. A substantial amount of time had been spent in locating suitable field sites and securing permission to use those crossings for field evaluations of the new devices.

Many illustrations were given to point to the need of reexamining the way in which field testing might be pursued for traffic control devices used in railroad-highway crossings in the future. A repeat of the procedures used in this project to secure sites for field testing of traffic control devices simply adds substantially to the cost of conducting the research as well as creating substantial time delays. There can be a much better approach to the manner in which permission for the use of crossings can be secured for field evaluations. Without an improvement in the ability of a contractor to secure crossings for use in field evaluations, the cost to the sponsoring agency will continue to be far more than it should be. The additional funds required for the long duration of contract negotiations do not provide any productivity gains in safety, nor do they contribute to anything of material value other than being able to complete the project. It is a waste of resources for which little return can be identified.

There is a way in which future projects requiring field evaluations can be implemented more readily without the undue costs that have been associated with this project. It is proposed that the Association of American Railroads (AAR), in cooperation with the U.S. Department of Transportation, make formal contact with various railroad companies that would be interested in participating in research, particularly in field evaluations. For those companies that would be agreeable to having their crossings considered for use in research projects, a model agreement should be developed which would incorporate standard provisions that would be readily agreed to by any railroad company wanting to participate in a research project. This model agreement would be similar to model labor agreements which have been established at the national level for various labor organizations. AAR and the U.S. Department of Transportation should formalize this agreement in such fashion that, if a contractor for U.S. the Department of Transportation has to use crossings in research, the contractor can quickly reach an agreement by meeting the conditions of the model agreement. The model agreement should be worked out so that no additional negotiations would be required. A railroad company that has participated in the model agreement would approve an agreement upon certification that the items in the agreement have been met.

In addition, it appears that it may be very inefficient and more costly for each contractor individually to secure insurance for use in field evaluations at railroad-highway grade crossings. Since the U.S. Department of Transportation, in actuality, will pay for the premiums of the insurance that is obtained for research projects, it would appear to be more cost-effective for the U.S. Department of Transportation to work out an agreement with one or more insurance carriers to provide the insurance. Most likely, the Federal government can obtain a more favorable premium cost than can independent contractors. In addition, the Federal government could take bids on the cost of premiums for provisions required in the model agreement, and the insurance would become effective only when a model agreement was executed. By grouping projects, insurance premiums could be less than when individually purchased.

It must be realized that negotiations for the use of crossings in research require an inordinate amount of time and money. There are few, if any, incentives for a railroad company to expedite an agreement. The individuals given responsibility for negotiations on the part of the railroad companies are not the ones who are working with safety on a day-to-day basis, and their interests lie in other areas such as liability, equipment damage and other potential costs to the railroad. Unless a new approach is taken to working out agreements, similar time delays and costs associated with this project will be encountered on all future projects.

Innovative Railroad-Highway Crossings Active Warning Devices--Status Report on Installation and Field Testing

The twelfth report, titled Innovative Railroad-Highway Crossings Active Warning Devices--Status Report on Installation and Field Testing, was prepared in May 1986 on the status of the installation and field testing of the railroad-highway crossing active warning devices at the three crossings in the Knoxville area.[63] The report dealt with the installation of the traffic control devices as well as the data collection system. This report provided the reader a view of the installations found in the field. The information contained in the report is described as a part of the field evaluation discussion in this report.

Summary

As one can see, a substantial amount of research results has been reported. The material presented here provides only a brief overview of the material contained in the 12 reports.

APPENDIX B

PROJECT DESCRIPTION AND COST ESTIMATE WORKSHEETS

PROJECT DESCRIPTION

General

Upgrade existing two-quadrant gates with flashing light signals to four-quadrant gates with flashing light signals.

Existing Conditions

1. Single mainline track crossing a two-lane (24-foot) roadway without shoulders.

2. Standard two-quadrant gates with flashing light signals in place. Train detection circuitry, underground conduit, controller and power supply system (i.e., batteries) are also in place to support existing two-quadrant system.

Proposed Modifications

1. Remove backlights from existing flashing light signal assemblies.

2. Install additional conduit to connect four quadrants.

3. Install 13-1/2' x 5" masts, flashing light signals (12-inch roundels), gate mechanisms, gates (26-foot) and crossbuck signs in two empty quadrants.

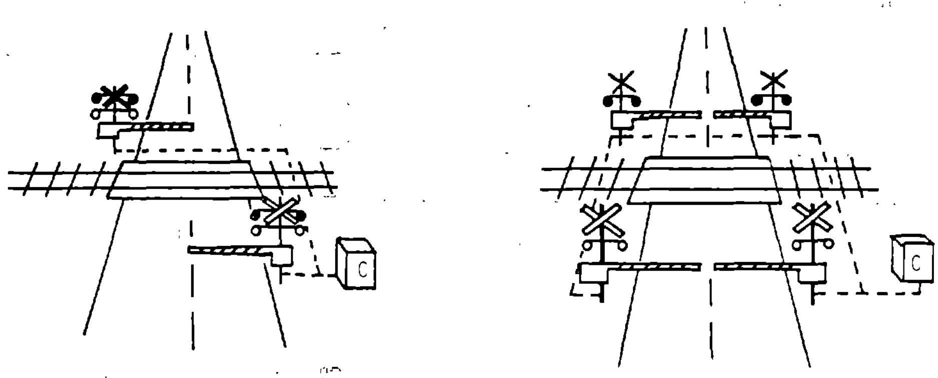
4. Modify existing controller to accomodate two additional gate/flashing light signal installations; install delay relay to stagger operation of farside gates.

Assumptions

1. Do not include the cost of installing/removing advance warning signs or pavement markings.

2. Assume that the existing conduit has excess capacity to handle additional wiring.

3. Use your own material and labor costs. (Some supplemental cost data are provided on the attached sheet, but we prefer that you use your own data if available.)



Existing installation. Proposed installation.

Figure 64. Two- and four-quadrant gates with flashing light signals.

COST ESTIMATE WORK SHEET

MATERIALS

Description	Quantity	Unit Cost	Total
Conduit			
Wiring			
Pole Foundations	2		
13-1/2 Foot Masts	2		
Flashing Light Signals	*	*	*
Mechanisms with Panarms and Counterweights	2		
26-Foot Gate Arms	2		
Crossbuck Signs	2		
Delay Relay	1		
Other			

TOTAL MATERIALS: $______

*Use back lights from existing installation

EQUIPMENT (WORK VEHICLES, ETC.)

______

______

______

______

TOTAL EQUIPMENT: $______

LABOR

______

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______

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TOTAL LABOR: $______

OTHER/MISCELLANEOUS

______

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______

______

TOTAL OTHER: $______

TOTAL PROJECT COST: $______

PROJECT DESCRIPTION

General

Upgrade existing two-quadrant flashing light signals to four-quadrant flashing light signals with overhead strobe lights

Existing Conditions

1. Single mainline track crossing a two-lane (24-foot) roadway without shoulders.

2. Standard two-quadrant flashing light signals in place. Train detection circuitry, underground conduit, controller and power supply system (i.e., batteries) are also in place to support existing two-quadrant flashing light signal system.

Proposed Modifications

1. Remove backlights from existing flashing light signal assemblies.

2. Install additional conduit to connect four quadrants.

3. Install 13-1/2' x 5" masts, flashing light signals (12-inch roundels), and crossbuck signs in two empty quadrants.

4. Install pole extenders and span wire; suspend two strobe light units per approach.

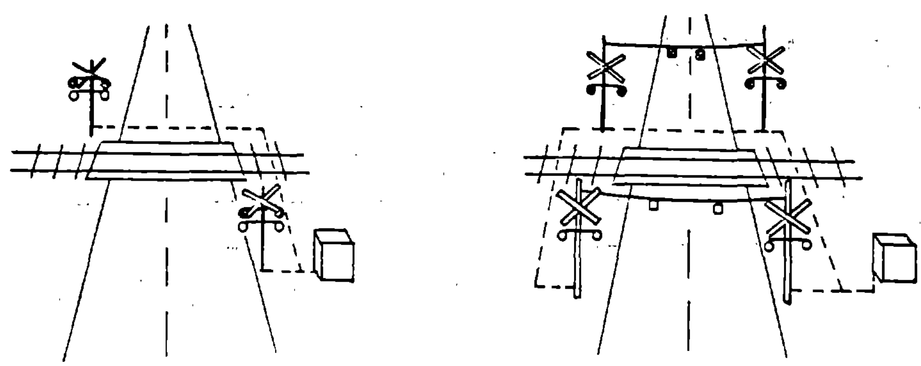
5. Modify existing controller to accomodate two additional flashing light signal installations. Install two strobe power supply units in existing controller cabinet; connect strobes into existing power (battery) system.

Assumptions

1. Do not include the cost of installing/removing advance warning signs or pavement markings.

2. Assume that the existing conduit has excess capacity to handle additional wiring.

3. Use your own material and labor costs. (Some supplemental cost data are provided on the attached sheet, but we prefer that you use your data if available.)



Existing installation. Proposed installation.

Figure 65. Two- and four-quadrant flashing light signals.

COST ESTIMATE WORK SHEET

MATERIALS

Description	Quantity	Unit Cost	Total
Conduit			
Wiring			
Pole Foundations	2		
13-1/2 Foot Masts	2		
Flashing Light Signals	*	*	*
Crossbuck Signs	2		
Pole Extenders	4		
Span Wire			
Strobe Lights	4		
Strobe Power Supplies	1		
Other			

TOTAL MATERIALS: $__________

*Use back lights from existing installation.

EQUIPMENT (WORK VEHICLES, ETC.)

TOTAL EQUIPMENT: $__________

LABOR

TOTAL LABOR: $__________

OTHER/MISCELLANEOUS

TOTAL OTHER: $__________

TOTAL PROJECT COST: $__________

PROJECT DESCRIPTION

General

Install fixed-time highway traffic signal with solid-state controller; install "SIGNAL AHEAD" advance warning signs with flashing lights.

Existing Conditions

1. Single mainline track crossing a two-lane (24-foot) roadway without shoulders.

2. Train detection circuitry and train detector controller is in place. Commercial power is available 100 feet from crossing and approximately 100 feet from the advance sign locations.

Proposed Work

1. Install two galvinized steel poles/mast arms, i.e., one per travel direction; hang one three-section head from each mast arm and mount one three-section head on each pole.

2. Install necessary conduit, pullboxes and wiring.

3. Install solid-state controller and pole-mounted controller cabinet.

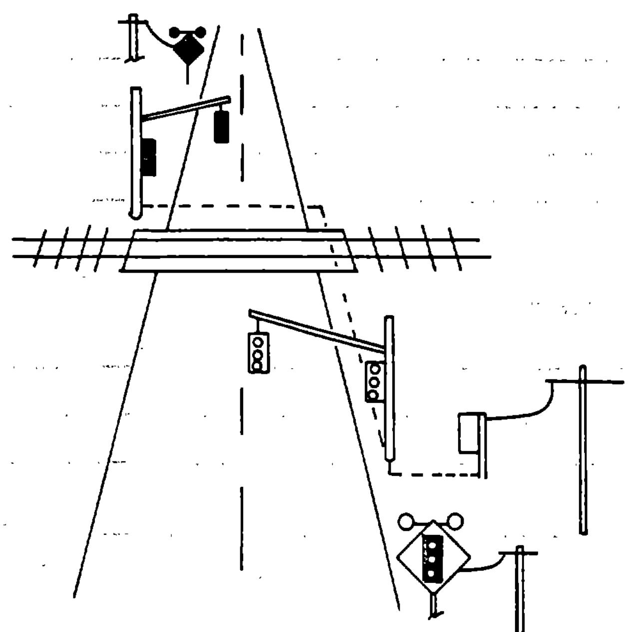
4. Provide commercial power hook-up to highway traffic signal.

5. Install a "SIGNAL AHEAD" advance warning sign with flashing lights on both approaches to the crossing; provide commercial power hook-up for the flashing lights. (Assume that the flashing lights will operate continuously and will not be interconnected with the highway traffic signal.)

Assumptions

1. Do not include the cost of installing/removing advance warning signs or pavement markings, other than the "SIGNAL AHEAD" advance warning signs.

2. Use your own material and labor costs. (Some supplemental cost data are provided on the attached sheet, but we prefer that you use your data if available.)



Proposed installation.

Figure 66. Highway traffic signal.

COST ESTIMATE WORK SHEET

MATERIALS

Description	Quantity	Unit Cost	Total
Conduit			
Wiring			
Pullboxes			
Pole Foundations	2		
Steel Pole/Mast Arms	2		
3-Section Signal Heads	4		
Solid-state Controller	1		
Controller Cabinet/Post	1		
SIGNAL AHEAD Signs	2		
Sign Posts	2		
Flashing Sign Lights	2 sets		
Other			

TOTAL MATERIALS: $______________

EQUIPMENT (WORK VEHICLES, ETC.)

____

____

____

____

TOTAL EQUIPMENT: $______________

LABOR

____

____

____

____

TOTAL LABOR: $______________

OTHER/MISCELLANEOUS

____

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____

TOTAL OTHER: $______________

TOTAL PROJECT COST: $______________

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