Assessment of Warning Time Needs at Railroad-Highway Grade Crossings with Active Traffic Control

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Research was conducted to assess the effects of warning time on driver behavior and safety at railroad-highway grade crossings with active traffic control, i.e., flashing light signals with and without automatic gates. The research included (a) an evaluation of driver response data gathered at three grade crossings in the Knoxville, Tennessee, area; and (b) a human factors laboratory study of drivers' warning time expectations and tolerance levels. In the field studies, the actions of over 3,500 motorists were evaluated during 445 train events. Based on the study results, warning times in excess of 30–40 sec caused many more drivers to engage in risky crossing behavior. The studies also revealed that the large majority of drivers who cross the tracks during the warning period do so within 5 sec from the time they arrive at the crossing. The human factors studies expanded the findings of the field evaluation. Specifically, the studies revealed that most drivers expect a train to arrive within 20 sec from the moment when the traffic control devices are activated. Drivers begin to lose confidence in the traffic control system if the warning time exceeds approximately 40 sec at crossings with flashing light signals and 60 sec at gated crossings. Based on the research, guidelines for minimum, maximum, and desirable warning times are presented. These guidelines are designed to minimize vehicles crossing during the warning period and promote driver credibility for the active control devices.

In the past two decades, over $2 billion has been allocated for improvements at the 192,454 public grade crossing locations in the country. The majority of these improvements involved converting passive crossings to active ones. As of 1986, roughly 30 percent of all crossings had active warning devices—22,066 grade crossings were equipped with automatic gates and flashing light signals and 32,778 were equipped with flashing light signals.

The upgrading of crossings to active control no doubt has contributed to improved crossing safety. Between 1977 and 1986, fatalities at grade crossings dropped from 846 to 501, and injuries decreased from 4,455 to 2,192. Still, over 50 percent of all car-train accidents in 1986 occurred at grade crossings with active devices even though only 30 percent of the total crossings have active control. It is generally recognized that much of this safety problem at active crossings is related to poor driver response to the traffic control. In fact, a study by the National Transportation Safety Board concluded that most accidents at actively controlled grade crossings resulted from drivers intentionally violating the warning device (*1*).

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SYSTEM CREDIBILITY AND WARNING TIME

The poor performance of flashing light signals with and without gates at grade crossings is due in large part to the lack of system credibility for drivers. That is, drivers may not consider these devices to be accurate or reliable, leading to eventual violation of their warning. One factor affecting system credibility is the high number of false activations at some active crossings. Certainly, every effort should be made to minimize these false activations through improvements in track circuitry, train detection equipment, and maintenance practices.

Another factor that may encourage undesirable driver behavior at crossings with active traffic control devices is the amount of time provided between device activation by a train and passage of the train through the crossing, i.e., warning time. Specifically, excessive or highly variable warning times may encourage frustrated drivers to willfully disregard the active devices. Conversely, extremely short warning times leave little margin of safety and poorly accommodate larger vehicles such as combination trucks and buses, especially if those vehicles must first come to a stop as required by many state laws. The current minimum warning time of 20 sec set forth in the *Manual on Uniform Traffic Control Devices* (MUTCD) (*2*) may not be appropriate in all cases.

The warning time issue is hardware related—certain types of train detection devices cannot provide reasonable warning times if train speeds are highly variable. However, train predictors generally can provide a relatively constant warning time at active crossings regardless of train speed. Predictors have been installed at over 6,300 sites in the United States. Studies (*3*) have shown that new train prediction hardware is operationally reliable and that violations, motorist delays, and accidents can be reduced at crossings using predictors, presumably due to the reasonable and consistent warning times they provide (*4*). Another study (*5*) estimated that up to 13,100 additional crossings can benefit from predictor installation.

With the advent of predictors, a new grade crossing traffic control issue has arisen. Now that constant, reasonable warning times can be provided, exactly what these times should be for various conditions must be determined. Also, maximum warning times have not been recommended as of yet, even though experience and intuition suggest that they would improve the credibility of traffic control at grade crossings.

RESEARCH OVERVIEW

Research was undertaken to investigate the identified warning time issues.

The objectives of the research were to

1. Identify typical driver behavior and the range of driver behavior (stopping and crossing actions) at active crossings under various conditions and situations;
2. Evaluate and determine the influence and effects of warning time length on driver crossing behavior at gated crossings and crossings with only flashing light signals;
3. Assess driver expectancies and tolerance levels with respect to warning times at active crossings; and
4. Based on the results of the first three objectives, present guidelines for minimum and maximum warning time (optimal range) for active grade crossings.

The research included two major tasks:

1. A field evaluation of driver behavior at active grade crossings; and
2. A human factors laboratory study of drivers' warning time tolerances and expectations.

FIELD STUDY DESCRIPTION

Data for the warning time evaluation were taken from videotapes of driver behavior at three crossings in the Knoxville, Tennessee, area. These videotapes had been collected as part of a recently completed FHWA study (*3*). Two of the study crossings had standard flashing light signals, whereas the third crossing had standard gates with flashing light signals.

The evaluation focused on quantifying the effects of warning time length on key driver response measures. The key driver response measures were (a) vehicles crossing during the warning period (violations); (b) clearance times between a crossing vehicle and the arrival of the train; (c) dwell times, i.e., the amounts of time that motorists waited at the crossing; and (d) exposure times, i.e., the amounts of time that crossing vehicles were on the tracks. Each of these measures intuitively could be affected by the length of the warning period, and each one is related to crossing safety or efficient operations.

Study Sites

The three study sites were all Norfolk Southern crossings. Each of the crossings had relatively high train and traffic volumes, thus affording the opportunity to collect a reasonable amount of driver response data. Also, all three crossings had a history of at least some accidents.

Cherry Street

The first crossing (Inventory No. 730584K) is located in the eastern part of Knoxville on Cherry Street. This double-track crossing has standard automatic gates, standard railroad flashing light signals, and a bell. Cherry Street is a 4-lane, undivided urban street. The roadway approaches to the crossing are straight and level. The average daily traffic at the site is approximately 14,000 veh/day, and the average through train volume is approximately 10 trains per day. The speed limit on Cherry Street is 30 mph. Train speeds at the crossing range from 20 to 40 mph, and motion sensors are installed at the crossing.

Cedar Drive

The second crossing (Inventory No. 730643K) is located in the northern part of the city on Cedar Drive. This crossing has standard railroad flashing light signals. Cedar Drive in the vicinity of the crossing is 2 lanes wide and straight on both approaches to the crossing. The vertical alignment of the roadway and thick vegetation in the vicinity of the crossing restrict drivers' view of approaching trains. The average daily traffic at this site is approximately 14,000 veh/day, and the average through train volume is approximately 16 trains per day. The speed limit on Cedar Drive is 40 mph, and train speeds at the crossing range from 5 to 40 mph.

Initially, the Cedar Drive crossing had standard train detectors, and because train speeds vary substantially at the crossing, warning times tended to be variable and often very long. Data were collected under these conditions. Train predictors were then installed at the crossing, resulting in more consistent and generally shorter warning times. Additional data were collected under these new conditions.

Ebenezer Road

The third crossing (Inventory No. 731461C) is located in the western part of Knox County on Ebenezer Road. This single-track crossing has standard railroad flashing light signals. Ebenezer Road is a 2-lane suburban road, and the roadway's horizontal and vertical alignments limit the visibility of the crossing from both directions. The average daily traffic on Ebenezer Road is approximately 10,000 veh/day, and the average through train volume is approximately 10 trains per day. The speed limit on Ebenezer Road was 40 mph at the time of the studies. Train speeds at the crossing range from 5 to 55 mph; the large majority of trains travel between 45 and 55 mph.

Data Collection

Driver response data were recorded automatically on portable video camera-recorders whenever a train was approaching. Three complete video camera-recorder systems were used at each crossing. The cameras were mounted on 20-ft poles approximately 60 ft from the centerline of the roadway. The first camera-recorder unit at each site was located approximately 300 ft from the crossing, the second approximately 500 ft from the crossing, and the third approximately 700 ft from the crossing. The cameras were aimed towards the crossing and had overlapping fields of view.

To activate the video camera-recorder systems just before activation of the traffic control devices, a train detector sys-

tem, separate from the regular track circuitry, was used. This special pole-mounted detection system projected an infrared light beam across the tracks. When a train broke the beam, the detector transmitted an audio (FM radio) signal that activated the camera-recorders. A detector was placed on each approach at each crossing such that the camera activation signal was transmitted at least 10 sec before a train activated the traffic control device at the crossing.

Data Reduction and Analysis

Information on weather condition, light condition, train direction, warning time, and type of traffic control were recorded for each train event. At the gated crossing (Cherry Street), the gate delay and descent time also was noted. Vehicle and driver response data were recorded for every vehicle which arrived at the crossing during the entire warning period. These data included vehicle arrival position (first, second, etc.), vehicle type, whether the vehicle was pulling a trailer, direction and lane of travel, whether the vehicle stopped or crossed without stopping, and, as appropriate, the times of stopping, starting up, crossing over the tracks, and clearing the crossing area.

Sample Size

Data were collected at each site for approximately 2 months to observe a sufficient number of both train events and vehicles arriving during the warning period. The sample included several hundred train events, several thousand arriving vehicles, and a wide range of warning times.

Train Events

Table 1 presents the numbers of train events observed at each of the study crossings and all crossings combined. There were 445 train events at the three crossings combined, and vehicles were present during 407 of these events. Also, 258 (66.5 percent) of the train events were in the daytime, and 149 (33.5 percent) were at night.

At Cherry Street, 129 train events were observed; 119 of these events had vehicles present. At Ebenezer Road, 179 train events were observed; vehicles were present during 159 of these events. Data for Cedar Drive are broken down into two groups, i.e., before predictors were installed at the crossing and after predictors were installed. Before installation of predictors, 74 train events were observed; vehicles were present during 70 of these events. After predictor installation, 63 train events were observed; 59 of these events had vehicles present.

Vehicles

A total of 3,555 vehicles were observed—1,030 vehicles at Cherry Street, 1,121 vehicles at Ebenezer Road, 999 vehicles at Cedar Drive before predictor installation, and 405 vehicles at Cedar Drive after predictor installation. The total sample and the samples for each individual crossing were made up predominately of passenger cars. The total sample only included 67 vehicles that were not passenger cars, pickups, or vans. The small number of other vehicle types made it difficult to evaluate the effects of warning times on large vehicles with any degree of confidence.

Warning Times

Table 2 presents the warning time conditions observed at each of the study crossings. A range of warning times was observed at each crossing, thus facilitating the evaluation. There was even a wide range of warning times observed at the Cedar Drive crossing after installation of train predictors. This occurred because train predictors were installed on the mainline track, but there was a siding without predictors just a few hundred feet from the crossing.

TABLE 1 SUMMARY OF TRAIN EVENT SAMPLE SIZES

Train Events	Cherry Street	Cedar Drive (no predictors)	Cedar Drive (predictors)	Ebenezer Road	All Crossings
Total Train Events	129	74	63	179	445
Events with Vehicles	119	70	59	159	407
Events without Vehicles	10	4	4	20	38
Total Daytime Events	87	45	29	139	296 (66.5)[1]
Total Nighttime Events	42	29	34	44	149 (33.5)[1]

[1]Percent of Total Train Events

TABLE 2 SUMMARY OF WARNING TIMES

Warning Times	Cherry Street	Ebenezer	Cedar Drive (no predictors)	Cedar Drive (predictors)
Sample Size	129	179	74	63
Mean Warning Time, sec.	57.9	40.2	75.6	39.8
Standard Deviation sec.	15.6	11.1	19.4	12.8
Range, sec.	28-120	24-110	49-139	26-83
Warning Times				
20-30	2 (1.6%)	14 (7.8%)	0 (0.0%)	5 (7.9%)
30-40	9 (7.0%)	92 (51.4%)	0 (0.0%)	39 (61.9%)
40-50	30 (23.3%)	57 (31.8%)	3 (4.1%)	11 (17.5%)
50-60	39 (30.2%)	5 (2.8%)	12 (16.2%)	2 (3.2%)
60-90	44 (34.1%)	9 (5.0%)	45 (60.8%)	6 (9.5%)
>90	5 (3.9%)	2 (1.1%)	14 (18.9%)	0 (0.0%)
Totals	129 (100.0%)	179 (100.0%)	74 (100.0%)	63 (100.0%)

The mean warning time at the Cherry Street crossing was 57.9 sec, with a range of 28–120 sec. The Ebenezer Road crossing had a mean warning time of 40.2 sec, with a range of 24–110 sec. Before predictors were installed, the Cedar Drive crossing had a mean warning time of 75.6 sec, with a range in warning times of 49–139 sec. After installation of the predictors, the mean warning time dropped to 39.8 sec, with a range of 26–83 sec. Based on a Kruskal-Wallis test, the installation of predictors did significantly lower the mean warning time at the Cedar Drive crossing.

FIELD STUDY RESULTS

General Results

In analyzing the driver behavior data, it was apparent that drivers at the crossing when the traffic control activated could not respond to the devices. Thus, a preliminary analysis was performed to assess driver response during the initial onset of the warning period and to identify those vehicles that should be excluded from the sample. In the case of the Cherry Street crossing, it was also hypothesized that drivers might respond differently during the gate delay and descent period compared to how they would respond after the gates were fully lowered. This issue was also addressed at the start of the evaluation so that the data from the Cherry Street crossing could be handled appropriately.

Onset of Warning Period

Drivers' stopping behavior immediately following device activation was evaluated at each of the study crossings. This evaluation not only served to identify appropriate vehicles to include in the study sample, but also provided insight into drivers' typical perception and brake-reaction times at active crossings.

Figure 1 shows the relationship between driver stopping behavior and arrival time for gates with flashing light signals (Cherry Street crossing) and for flashing light signals (Cedar Drive and Ebenezer Road crossings combined). Arrival time in the figure refers to a vehicle's arrival time relative to the start of the warning period. Arrival time did have a significant effect on the percent of drivers who cross without stopping at all of the crossings. In addition, there was a significant difference in stopping behavior for the two types of traffic control. (In Figure 1, data from two crossings that had flashing light signals are combined.)

With regard to flashing light signals, all drivers who were within 1 sec of the crossing at the time of device activation crossed without stopping. Obviously, these drivers simply had no chance to respond to the signals. For arrival times of 1–4 sec, the percentage of drivers crossing without stopping declined steadily. At around the 4-sec point, the percentage of drivers who crossed without stopping leveled off to approximately 15–20 percent. After this 4-sec point, the large majority of drivers could have stopped at the study crossings, but a consistent few did not. The 4-sec point therefore was selected for sample screening, i.e., vehicles arriving at the crossing less than 4 sec into the warning period were not considered in the sample.

Figure 1 shows that driver stopping behavior during the onset of the warning period is much different at gated crossings compared with crossings with flashing light signals. Most drivers at the Cherry Street crossing did not react to the initial device activation. Instead, most drivers continued to cross without stopping well into the gate delay and descent period. From the figure, 60 percent or more of the drivers crossed without stopping during the first 9 sec of the warning period. Because the average gate delay and descent time at the Cherry Street crossing was approximately 14 sec, it follows that most drivers responded to the onset of a gate with flashing light signal activation by driving to beat the gates. They only stopped when they could no longer clear before the gates were lowered.

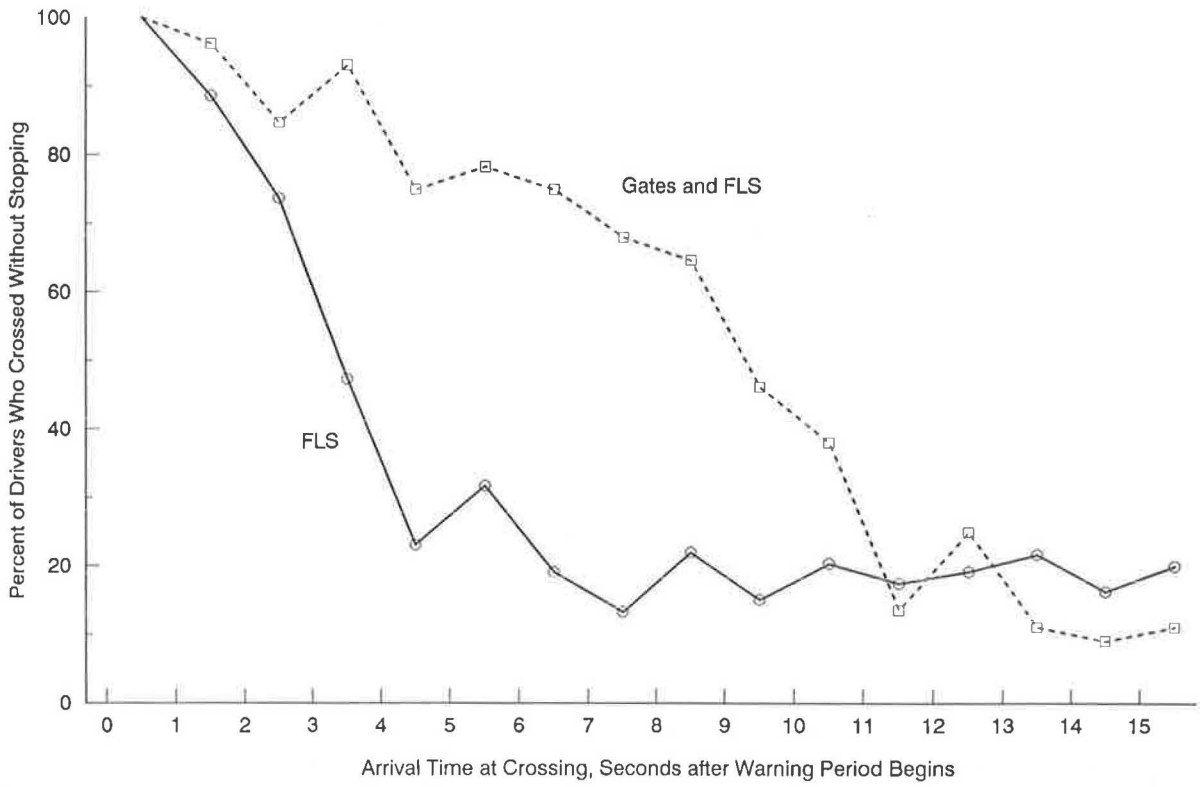


FIGURE 1 Relationship between arrival time at crossing and stopping behavior.

Gate Delay and Descent Period

For the gated crossing, it was theorized that driver behavior during the gate delay and descent period would be different from driver behavior after the gates were fully lowered. This expectation is certainly confirmed by the data for the Cherry Street crossing shown in Figure 1. Therefore, it was appropriate to break down the driver response data for the Cherry Street crossing into the two time periods: (1) before gates were fully lowered; and (2) after gates were fully lowered.

In evaluating driver response data for the gate delay and descent period, it was also noted that the length of this time period apparently had a significant effect on driver stopping behavior. Figure 2 shows the influence of gate delay and descent time on the percentage of drivers who crossed without stopping at the Cherry Street crossing. The percentage of drivers not stopping rose sharply as the gate delay and descent time increased from around 10 to 14 sec. At about 15 sec, the percentage of drivers who crossed without first stopping leveled off at approximately 50 percent. The data in Figure 2 suggest that longer gate delay and descent times may encourage drivers to try to beat the gates and discourage them from stopping. If this is the case, reasonably short times should promote overall crossing safety; however, short gate delay and descent times may also increase the frequency of gate rubs by long, slowly moving vehicles.

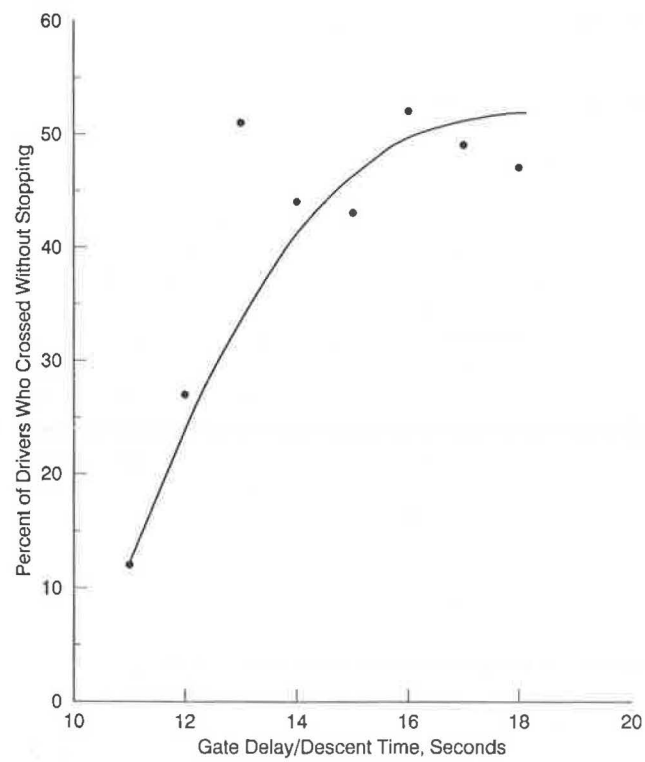


FIGURE 2 Relationship between gate delay and descent time and stopping behavior.

TABLE 3 SUMMARY OF DRIVER BEHAVIOR BY CROSSING

Crossing	Total Vehicles	Percent of Drivers: Crossed without Stopping	Stopped and Crossed	Stopped and Waited
Cherry Street (gate delay/descent)	162	56.2	11.7	32.1
Cherry Street (gates lowered)	768	11.7	28.0	60.3
Ebenezer Road	1,036	14.5	31.1	54.4
Cedar Drive (without predictors)	937	19.0	61.4	19.6
Cedar Drive (with predictors)	363	10.5	45.5	44.1

Summary of Driver Stopping and Crossing Behavior

Table 3 presents a summary of driver behavior observed at the three study crossings. The data in the table exclude those drivers who were less than 4 sec from the crossings when the traffic control was activated.

At the Cherry Street crossing, 60.3 percent of the motorists who arrived while the gates were being lowered stopped and waited; only 32.1 percent of drivers who arrived during the gate delay and descent period stopped and waited. These percentages were lower than expected, particularly the percentage for the gate delay and descent period. Note also from Table 3 that 56.2 percent of the motorists who arrived during the gate delay and descent period crossed without stopping. This relatively high percentage further illustrates that many drivers (in this case over one-half) tried to beat the gates and did not respond appropriately to the advance warning of the flashing light signals before and during gate activation.

In the case of flashing light signals, 14.5, 19.0, and 10.5 percent of the drivers crossed without stopping at the Ebenezer Road, Cedar Drive (without predictors), and Cedar Drive (with predictors) crossings, respectively. Most of these drivers slowed down considerably and looked for the train, but still their actions violated state law and safe driving behavior. The percentages of drivers who did not stop were approximately the same at both crossings with flashing light signals, and with and without predictors at the Cedar Drive crossing. Also, approximately the same percentage (11.7 percent) of drivers did not stop at the Cherry Street crossing after the gates were down. Thus, it would seem that roughly 10 percent of motorists at all the study crossings demonstrated very undesirable behavior.

Table 3 also shows that 54.4, 19.6, and 44.1 percent of drivers stopped and waited at the Ebenezer Road, Cedar Drive (without predictors), and Cedar Drive (with predictors) crossings, respectively. The percentage of drivers who did not cross was approximately the same at Ebenezer Road (which had only flashing light signals) as it was at the Cherry Street crossing (which had gates). On the positive side, this sameness shows that flashing light signals, when operated efficiently, can encourage most drivers to stop and wait. On the negative side, it indicates that driver response to the Cherry Street gates certainly needs to be improved.

The effectiveness of the train predictors installed at the Cedar Drive crossing are also highlighted by the data in Table 3. Only 19.6 percent of the drivers stopped and waited before predictors were installed and warning times were highly variable and sometimes very long. After predictors were installed, this percentage rose to 44.1 percent. This difference was statistically significant at the 0.01 conflict level.

Light Condition

Chi-square tests for independence indicated that light condition effects were significant for the Cherry Street crossing during the gate delay and descent period and for Ebenezer Road. At the Cherry Street crossing, 29.9 percent of the motorists arriving during the gate delay and descent stopped and waited in the daytime; this percentage rose to 50 percent at night. It is theorized that drivers at night were less inclined to attempt to beat the gates because of the reduced visibility and depth perception. Once drivers stopped and the gates were lowered, then the physical and legal restriction of the gates discouraged crossings.

At the Ebenezer Road crossing, 53.4 percent of the drivers stopped and waited in the day and 69.6 percent stopped and waited at night. However, further analysis revealed that the nighttime sample had a disproportionate number of shorter warning times relative to the daytime sample. The nighttime differences were attributed to warning time differences rather than light condition effects.

Weather Conditions

The impact of inclement weather (i.e., rain or snow) on driver stopping and crossing behavior was evaluated. Based on the

evaluation, inclement weather had no significant effects on the percentage of drivers who stopped and crossed during the warning period.

Warning Time Effects on Stopping and Crossing Behavior

The effects of warning time on stopping and crossing behavior are shown in Figure 3. The data from the Ebenezer Road and Cedar Drive (with predictors) crossings are combined in the figure, because these crossings had essentially warning time conditions and both had flashing light signals. Separate curves are shown for the Cherry Street crossing, which had gates, and for the Cedar Drive (without predictors) crossing, which had highly variable and long warning times. The Cherry Street crossing data do not include vehicles arriving during the gate delay and descent period.

Warning time had a very significant effect on crossing behavior at the Cherry Street, Ebenezer Road, and Cedar Drive (with predictors) crossings. Generally, a very high percentage of drivers stopped and waited at these crossings if the warning time was relatively short, i.e., 20–30 sec. However, as the warning times increased beyond 30 sec, the percentage of drivers who stopped and waited declined steadily.

At the Cherry Street crossing, approximately 90 percent of arriving motorists stopped and remained stopped for warning times of 20–25 sec. This percentage declined to about 70 percent for warning times of 25–30 sec and to approximately 60 percent for warning times of 30–35 sec. Then, the percentage of drivers who stopped and remained stopped remained fairly constant (at around 60 percent) for warning times up to about 80 sec. After 80 sec, there was again a sharp drop in driver obedience to the gates, to below 30 percent. These data indicate that relatively short warning times (20–35 sec) are desirable to minimize gate violations. They also suggest that, if warning times are greater than about 35 sec, approximately 40 percent or more of the drivers will violate the gates.

At the Ebenezer Road and Cedar Drive (with predictors) crossings, 98 percent of the drivers stopped and remained stopped for warning times of 20–25 sec. At warning times of 25–30 sec, 73 percent of the drivers stopped and remained stopped, and at warning times of 30–35 sec, approximately 90 percent stopped and remained stopped. For warning times beyond 35 sec, the percentage of motorists stopping and remaining stopped declined steadily to less than 20 percent for warning times over 80 sec. As was the case for the gated Cherry Street crossing, these data suggest that relatively short warning times (25–35 sec) are very desirable at crossings with flashing light signals. Driver crossing behavior deteriorates very rapidly for warning times greater than 35 sec.

The severe driver behavior deficiencies at the Cedar Drive (without predictors) crossing are shown in Figure 3. Because of the generally long warning times at the crossing (the mean warning time was over 75 sec), the percentage of drivers who stopped and waited never rose above 30 percent and even dropped to approximately 10–15 percent for warning times greater than 80 sec. Even at moderately long warning times of 45–60 sec, the Cedar Drive (without predictors) crossing performed significantly worse than the Ebenezer Road and Cedar Drive (with predictors) crossings, at the same warning times. This result strongly suggests that long and variable warning times at an individual crossing can have negative impacts that affect overall driver behavior at the crossing. This finding supports the need for consistently short warning times, i.e., some long warning times at a crossing may negate the positive influences of reasonably short times at the same crossing.

Train Wait Time

When drivers arrive at an active crossing too soon before the train arrives, they are unlikely to wait, regardless of the status of the active devices. This issue was addressed in the field studies by evaluating driver crossing behavior as a function

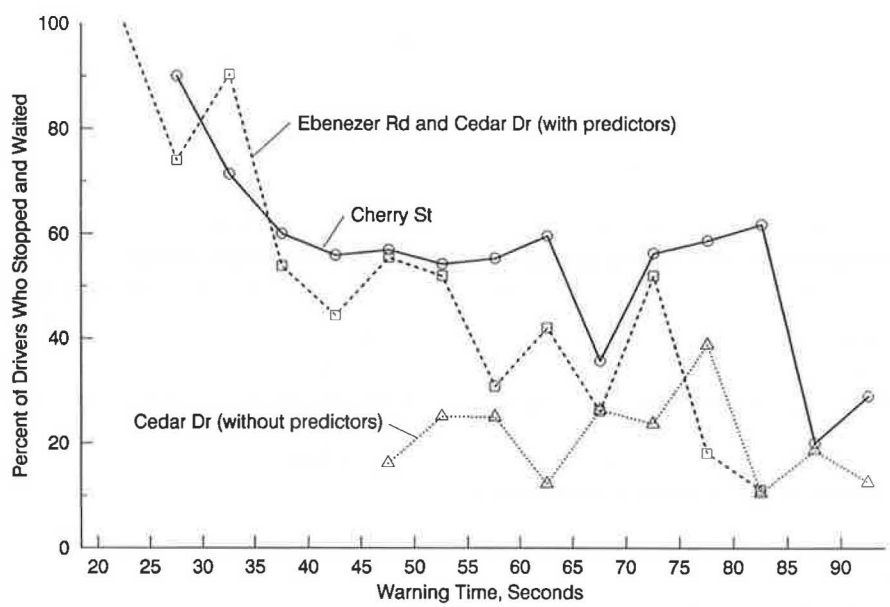


FIGURE 3 Effects of warning time on drivers' stopping and waiting behavior.

of the driver's arrival time at the crossing relative to the train's arrival (train wait time). The results are shown in Figure 4.

At the Cherry Street crossing, 98.2 percent of the drivers arriving at the crossing 10 sec or less before train arrival stopped and remained stopped, and 80.8 percent arriving 10–20 sec before the train arrival stopped and remained stopped. After 20 sec, the percentage dropped sharply. These data suggest that the maximum warning time at gated crossings should be as close to 20 sec as practical, or at least as short as large vehicle clearance requirements will allow.

At all the crossings with flashing light signals nearly all the drivers arriving at the crossing less than 10 sec before train arrival stopped and remained stopped. These percentages were 98.0 percent at the Ebenezer Road crossing, 95.2 percent at the Cedar Drive (without predictors) crossing, and 95.1 percent at the Cedar Drive (with predictors) crossing. For train wait times of 10–20 sec, the percentage of motorists who stopped and waited fell off slightly to 62.5, 51.1, and 64.1 percent, respectively. However, after 20 sec the percentages dropped sharply to below 30 percent in every case. These data suggest that the maximum warning time at crossings with flashing light signals should be near 20 sec, or as short as large vehicle clearance requirements will allow, to minimize unwanted vehicles crossing during the warning period.

Dwell Time

Another important issue related to crossing behavior is dwell time, i.e., the time that crossing drivers spend deciding to cross. Figure 5 shows the dwell time characteristics observed at the three study crossings. Dwell times at the crossings with flashing light signals ranged from around 1 to over 30 sec; however, the large majority of dwell times at these crossings were relatively short. In fact, around 90 percent were less than 5 sec, and 70 percent were less than 4 sec. Thus, the vast majority of crossing drivers at those crossings with flashing light signals stopped and then crossed after taking a quick look for the train.

At the Cherry Street crossing, dwell times tended to be longer, but still were relatively short. Dwell times ranged from 1 to over 30 sec. However, approximately 50 percent of the times were less than 5 sec, and 80 percent were less than 10 sec. At a gated crossing, drivers seem to take more time evaluating the risks, assessing the path they must take, and checking the actions of other drivers. Still, the dwell times do not suggest that drivers are crossing after they get frustrated and tired of waiting; rather they are crossing just as soon as they feel comfortable doing so. As expected, warning time had no significant effects on dwell time.

Warning Time Effects on Clearance Times

Figure 6 shows the mean clearance times observed at each of the crossings by warning time. Clearance time is the difference in train arrival time and vehicle crossing time for those vehicles that crossed. The mean clearance time tended to increase with increasing warning times at each of the crossings. This finding was expected given that most crossing drivers do so within a few seconds of arriving at the crossing. Thus, as the warning time increases, more drivers would be arriving at the crossing a longer time before train arrival. Because the earlier arriving drivers cross fairly quickly (if they are going to cross), this would cause a steady increase in the mean clearance times as the warning time increases.

In Figure 6, the mean clearance times did not differ significantly from crossing to crossing, even at the Cherry Street crossing. It is also important to note that, at the shorter warning times observed (25–35 sec), the mean clearance times were sufficiently large and near 20 sec. This finding supports the current 20-sec minimum warning time as an appropriate minimum level. Even when the warning time was relatively short, clearance times tended to remain near 20 sec, indicating

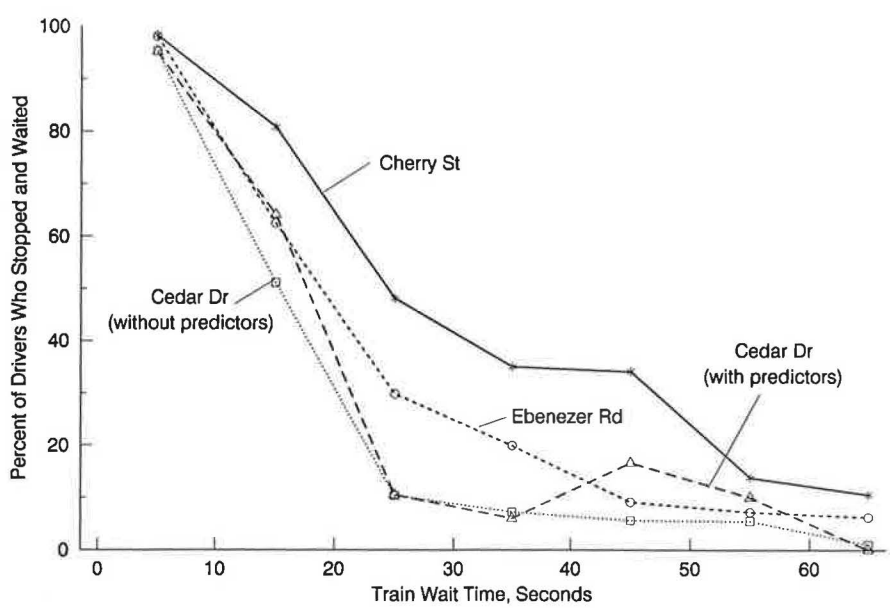


FIGURE 4 Relationship between train wait time and driver behavior.

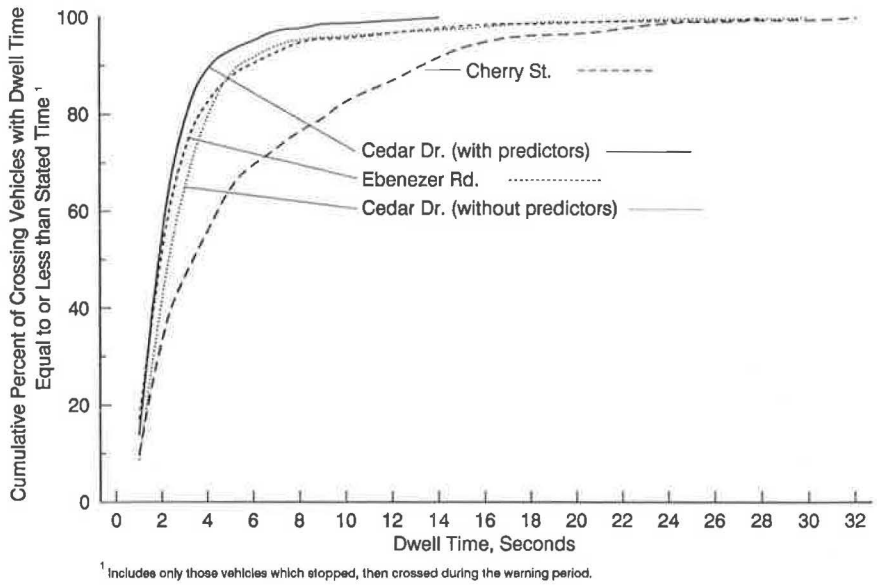


FIGURE 5 Dwell time characteristics.

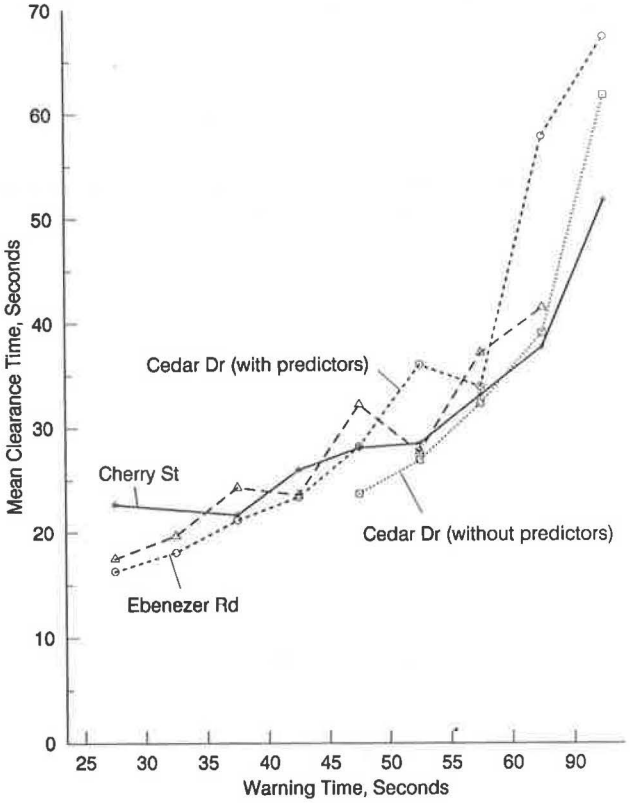


FIGURE 6 Relationship between mean clearance time and warning time.

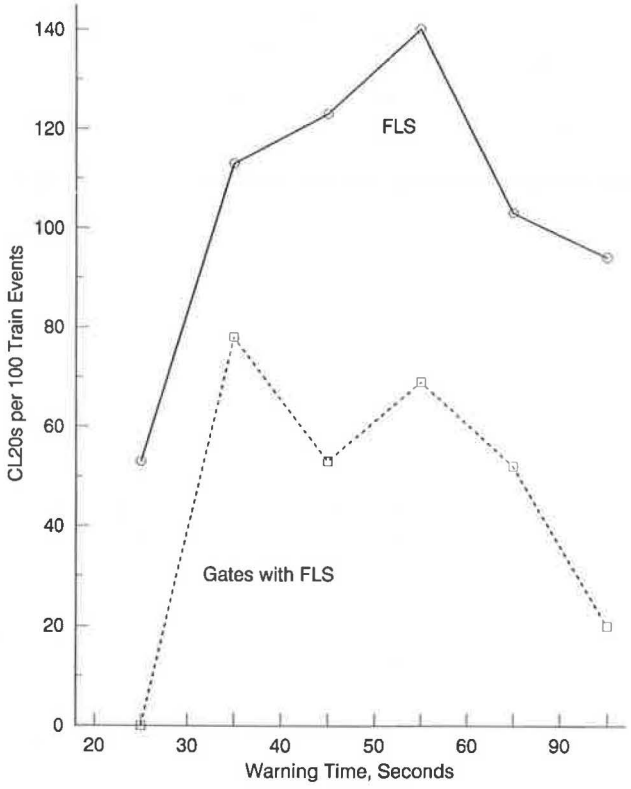


FIGURE 7 Relationship between number of CL20s and warning time.

that the majority of drivers would not regularly accept clearance times of much less than 20 sec.

CL20s

A clearance time of less than 20 sec was defined in the previous research (*3*) as an indicator of risky driver behavior. It would be desirable to minimize the number of CL20s at any active crossing in the interest of safety. Figure 7 shows the effects of warning time on CL20 rates, or the number of CL20s per 100 train events. CL20s were lowest for warning times of 20–30 sec, and they increased significantly for longer warning times.

At the Cherry Street crossing, no CL20s were observed for warning times of 20–30 sec. However, the sample size was very small, i.e., only two trains. For warning times of 30–40 sec, the average CL20 rate jumped to 78.8 per 100 trains. Most of these vehicles actually crossed during the gate delay and descent period and not while the gates were down. This fact emphasizes the earlier finding that drivers are not responding as intended to the advance warning provided by the flashing light signals, but are attempting to beat the gates whenever possible. For warning times greater than 40 sec, the CL20 rate remained high, and was highest for warning times of 50–60 sec.

In Figure 7, data for the crossings with flashing light signals are combined, in recognition of the similarities in clearance time characteristics among the crossings, as shown in Figure 6. There were an average of 52.6 CL20s per 100 trains for warning times of 20–30 sec. At higher warning times, the CL20 rate rose significantly. The highest rate (142.1 CL20s per 100 trains) was observed for warning times between 50–60 sec.

CL10s

The research by Heathington et al. (*3*) also defined a CL10, i.e., a clearance time of less than 10 sec, as a measure of a near-miss or potential car-train conflict. Certainly, it would be desirable to minimize (or better yet, totally eliminate) the number of CL10s at active crossings.

Figure 8 shows the effects of warning times on CL10 rates per 100 train events. At the Cherry Street crossing, there were no CL10s for warning times of 20–30 sec. However, the sample size was very small, i.e., two trains. For warning times of 30–40 sec, there was an average of 11.1 CL10s per 100 train events. This rate was computed based on only one CL10 observed in nine train events and thus may be somewhat misleading. The next highest CL10 rate (10.3 CL10s per 100 train events) was observed for warning times of 50–60 sec.

At the crossings with flashing light signals, there were no CL10s for warning times of 20–30 sec. This rate of zero is based on a sample of 19 train events. For warning times of 30–40 sec, there were an average of 6.9 CL10s per 100 trains, and this rate increased to 16.9 CL10s per 100 trains for warning times of 40–50 sec. Clearly, from these data, shorter warning times discouraged CL10s at the two crossings with flashing light signals. These positive effects were statistically significant.

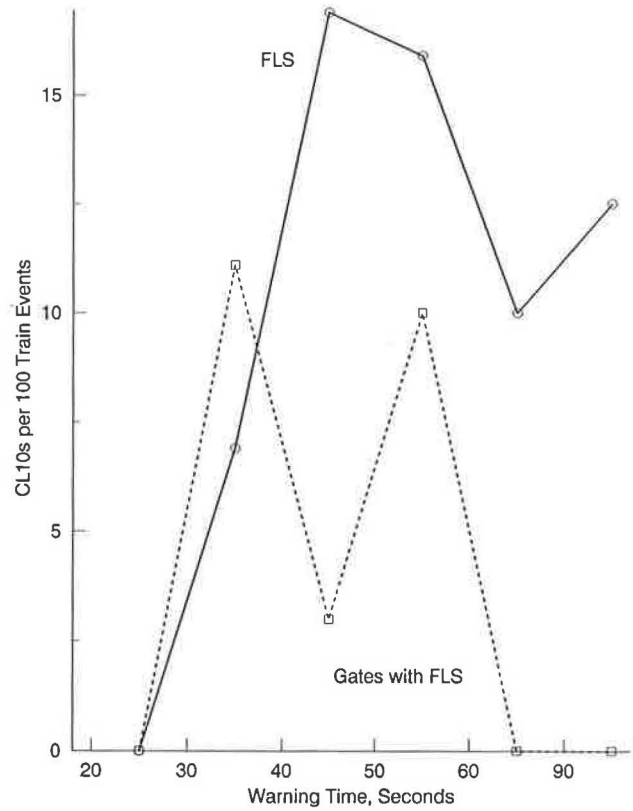


FIGURE 8 Relationship between number of CL10s and warning time.

Warning Time Effects on Exposure Times

Exposure time is the time that a crossing vehicle is on the tracks and directly exposed to a potential car-train accident. Because certain vehicles are required to stop at all crossings, it follows that minimum warning times should be greater than the exposure times of these vehicles. Figure 9 shows the exposure times observed at the study crossings. Exposure time was measured as the time it took a crossing vehicle to travel from the stop line to completely clear the tracks. The data in the figure are for all vehicle types, including large trucks and buses. Unfortunately, the sample included very few trucks and a single bus, thus the results predominantly represent passenger car (including pickups and vans) characteristics.

At the Cherry Street crossing, exposure times ranged from under 2 sec to just over 13 sec. Approximately 50 percent of the exposure times at Cherry Street were less than 4 sec, and about 90 percent were less than 9 sec. A few large trucks drove around the lowered gate arms at the Cherry Street crossing, and these trucks had the longer exposure times. The longest exposure time of 13 sec was experienced by a semi-trailer unit that stopped and then drove around the lowered gate arms.

At the crossings with flashing light signals, exposure times were much shorter and more consistent than at the Cherry Street crossing. Exposure times at the Ebenezer Road and Cedar Drive crossings were 1–11 sec; approximately 80 percent of the times were less than 3 sec. There were very few trucks or buses in the sample; however, a few of these large

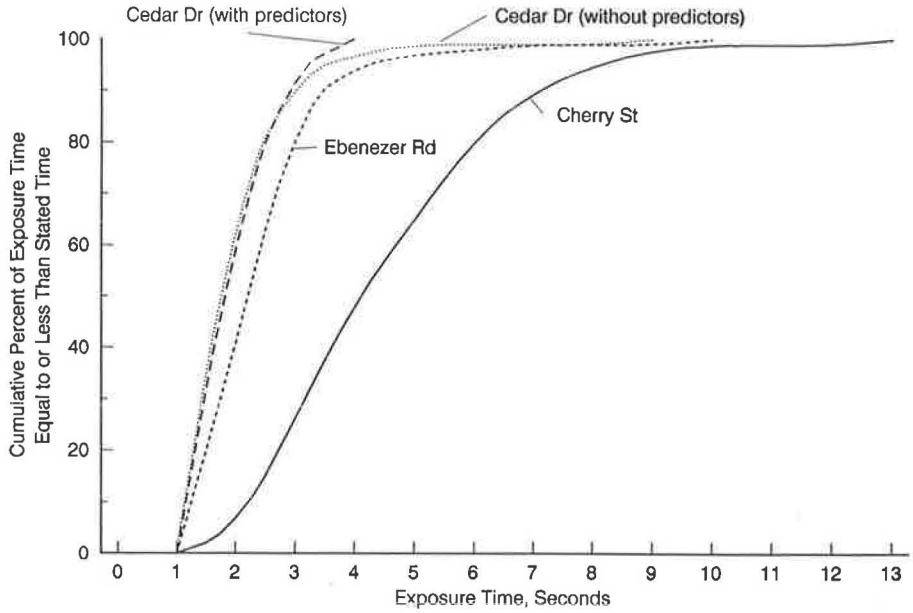


FIGURE 9 Exposure time characteristics.

vehicles did cross and they tended to have the longer exposure times.

Based on the data presented in Figure 9, warning time had no significant effects on exposure time at any of the crossings.

HUMAN FACTORS LABORATORY STUDY

The field study results strongly suggest that drivers have certain expectations and tolerance levels associated with warning times at active grade crossings. These expectations and tolerance levels undoubtedly influence drivers' crossing behavior and thus crossing safety. In order to explore warning time expectations and tolerance levels more fully, a human factors laboratory study was developed and conducted as part of the overall research effort. The specific objectives of the laboratory study were to

1. Determine the extent of variation among drivers with respect to their warning time expectations and tolerance levels;
2. Compare warning time expectations and tolerance levels at crossings with flashing light signals versus crossings with gates and flashing light signals; and
3. Identify general trends in warning time expectations and tolerance levels, and associate these trends to the driver behavior observed in the field studies.

Sixty driver subjects were shown videotapes of staged traffic control device activation events at active grade crossings. While individually viewing an activation event, each subject was asked to indicate: (1) when he or she would expect a train to arrive at the crossing; and (2) when the elapsed time without a train arriving had become too long. One-half of the subjects viewed a videotape that showed the activation sequence at a crossing with flashing light signals. The other half viewed a videotape showing the activation sequence at a crossing with gates and flashing light signals.

Flashing Light Signals

The mean expected time to train arrival for the flashing light signals was 14.5 sec. This mean time is slightly (5.5 sec) less than the 20-sec minimum warning time currently required at crossings with flashing light signals. The fact that drivers, on the average, expect warning times to be less than the minimum time supports the need to keep warning times as short as possible. The relatively short expected train arrival time probably accounts for the high percentages of drivers who cross as the warning times increase above 20–30 sec.

The mean excessive elapsed time was 39.7 sec for the flashing light signals. This time is consistent with driver behavior observed in the field studies, i.e., crossing violations were very frequent when the warning time exceeded 40 sec, whereas violations decreased as the warning time dropped below 40 sec. It is also significant to note that the mean excessive time was approximately 25 sec greater than the mean expected train arrival time, supporting the premise that there is a range of warning times that minimizes unwanted crossings and reinforces the credibility of the warning system.

The range of excessive elapsed times was 26.0–57.8 sec, a spread of 31.8 sec. The low end of this range, i.e., 26.0 sec, is only 6 sec higher than the 20-sec minimum warning time currently required. This supports the conclusion that the majority of drivers would not lose confidence in flashing light signals if warning times were kept at or slightly higher than the current minimum value of 20 sec.

Gates with Flashing Light Signals

The mean expected time to train arrival for the gate with flashing light signals was 30.6 sec, including the gate delay and descent time. This mean time is approximately 10 sec higher than the 20-sec minimum warning time required at active crossings. Thus, warning times at gated crossings at or

only slightly higher than the current minimum allowable warning time of 20 sec should promote driver confidence and respect.

The mean expected train arrival time, including the gate delay and descent time, was significantly longer than the mean time for flashing light signals. However, after the gate descent time is subtracted, the mean expected train arrival for a gated crossing is approximately the same as for a crossing with flashing light signals. The mean expected train arrival time for the gated crossing, excluding gate delay and descent time, was 13.2 sec, compared to 14.5 sec for the crossing with flashing light signals. Thus, it is concluded that drivers generally do not consider the gate delay and descent phase in terms of their warning time expectations at gated crossings. That is, they anchor their expectancies to the end of the gate delay and descent phase rather than the beginning of the phase.

The range in expected times to train arrival for the gated crossing was 20.9–47.4 sec including the gate delay and descent time, and 3.5–30.0 sec excluding the gate delay and descent time. This spread of 26.5 sec is not significantly different than the spread of 26.3 sec for the flashing light signals. However, it is important to note the lower limit (i.e., 3.5 sec) of the range after subtracting out the gate delay and descent time. Apparently, some drivers may grow impatient if the train does not arrive almost immediately after the gates are fully lowered. This is consistent with the field studies that found that some drivers drive around the gates almost immediately upon arriving at the crossing if the train is not imminently close.

The mean excessive elapsed time for the gated crossing was 66.2 sec including the gate delay and descent time, and 48.8 sec excluding the gate delay and descent time. These mean times combined with the expected train arrival times support the premise that there is an optimal range of warning times for gated crossings that minimizes gate violations and maximizes driver confidence and respect for the traffic control system. Based on laboratory study results, this range would be 20–60 sec, including the gate delay and descent time.

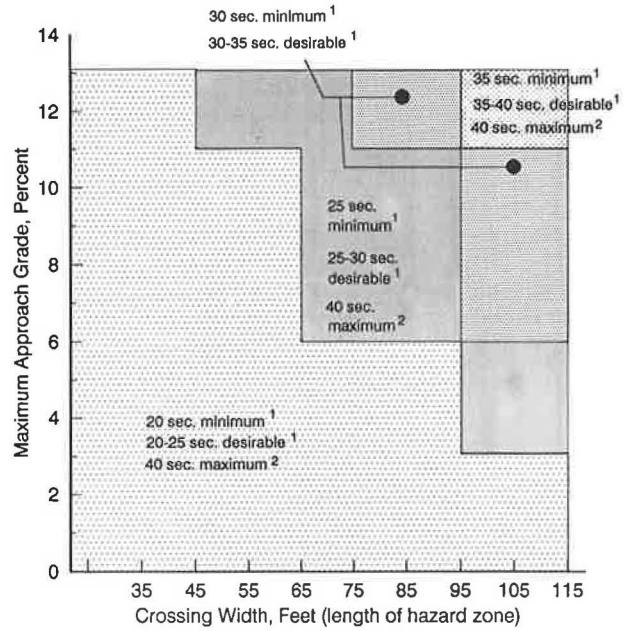
Even excluding the gate delay and descent phase, the mean excessive elapsed time for the gated crossing was significantly higher (at the 99 percent confidence level) than the mean time for the crossing with flashing light signals (i.e., 48.8 sec for gates versus 39.7 sec for flashing light signals). The difference of about 10 sec is consistent with driver behavior observed in the field studies and with the generally more restrictive appearance and legal status of gates. Drivers apparently tolerate longer total warning times at gated crossings before losing confidence in the traffic control.

GUIDELINES FOR WARNING TIMES

On the basis of the results of the field and laboratory studies, guidelines were developed for minimum, maximum, and desirable warning times at grade crossings with active traffic control. Guidelines for gate delay and descent times also were developed.

Flashing Light Signals

Figure 10 shows the suggested guidelines for warning times at crossings with flashing light signals. These values are consistent with the current minimum warning time of 20 sec in



[1] Times shown apply to crossings with no twin or triple tractor-trailer combinations. If twins or triples are expected, times should be increased by 10 percent.

[2] If more than 10 percent of the warning times exceed 40 seconds, installation of motion sensors or train predictors is recommended. If motion sensors or predictors cannot reduce warning times to the desired level, installation of gates should be considered.

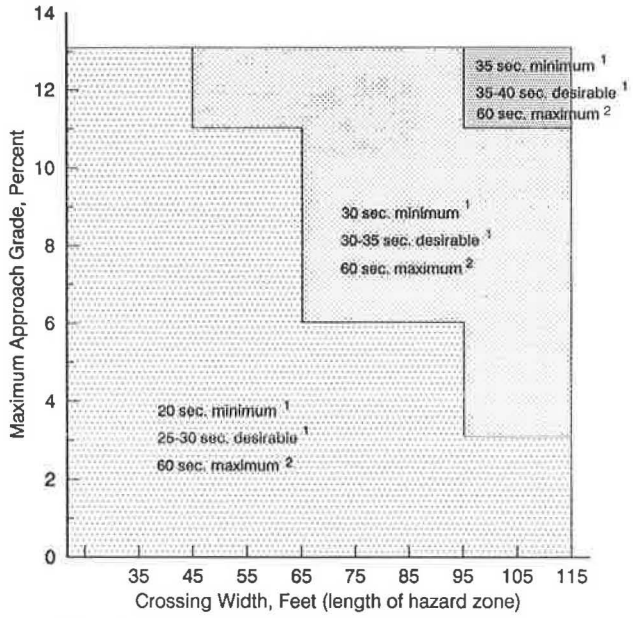
FIGURE 10 Suggested warning time guidelines for crossings with flashing light signals.

this country, and with warning time practices in many foreign countries (*6*). They are designed to (1) provide sufficient time for stopping; (2) minimize vehicles crossing during the warning period; (3) minimize number of CL10s and maintain adequate clearance times; (4) minimize unnecessary driver delay; and (5) promote driver confidence in flashing light signal systems. The values also provide safe clearance time for those vehicles that by law must stop at all crossings. Safe clearance times are reported by Bowman and McCarthy (*7*).

The suggested minimum warning times range from 20 to 35 sec depending on the width and grade of the crossing. These values should be increased by 10 percent if twin or triple tractor-trailer combinations are present. The suggested ranges of warning times are relatively narrow, i.e., 5 sec. These narrow ranges are strongly supported by the research results. Recognizing practical limitations of train operations and train detection hardware, some longer warning times would be allowed. However, if more than 10 percent of the warning times exceed 40 sec, then the installation of motion sensors or train predictors is strongly urged. The 10 percent value is somewhat arbitrary; however, it is intended to define the upper limit of occasional excessive warning times. If motion sensors or predictors are not effective in limiting the warning times to the desired range, then the installation of gates should be considered.

Gates with Flashing Light Signals

Figure 11 shows the suggested guidelines for warning times at crossings with standard gates and flashing light signals.



[1] Times shown apply to crossings with no twin or triple tractor-trailer combinations. If twins or triples are expected, times should be increased by 10 percent.

[2] If more than 10 percent of the warning times exceed 60 seconds, installation of motion sensors or train predictors is recommended. If motion sensors or predictors cannot reduce warning times to the desired level, installation of four-quadrant gates should be considered.

Note: All warning times include gate delay/descent time.

FIGURE 11 Suggested warning time guidelines for crossings with gates and flashing light signals.

These values are consistent with the current minimum warning time of 20 sec in this country, and with warning time practices in many foreign countries (*6*). They are designed to (a) provide sufficient time for stopping; (b) minimize gate violations; (c) minimize CL10s and maintain adequate clearance times; (d) minimize unnecessary driver delay; and (e) promote driver confidence for gates with flashing light signals. The values also provide safe clearance time for those vehicles that by law must stop at all crossings.

The suggested minimum warning times range from 20 to 35 sec depending on the width and grade of the crossing. These values should be increased by 10 percent if twin or triple tractor-trailer combinations are present. The suggested ranges of warning times for gated crossings are relatively narrow, i.e., 5 sec. These narrow ranges are strongly supported by the research results. Recognizing practical limitations of train operations and train detection hardware, some longer warning times would be allowed. However, if more than 10 percent of the warning times exceed 60 sec, then the installation of motion sensors or train predictors is strongly urged. If motion sensors or predictors are not effective in limiting the warning times to the desired range, then the installation of four-quadrant gates would seem appropriate. However, at this time four-quadrant gates are not adopted in the MUTCD.

The gate delay and descent time should not be too long or drivers will try to beat the gate. The following guidelines for gate delay and descent times are suggested:

1. The total gate delay and descent period ideally should be 10–12 sec and should not exceed 15 sec.
2. The gate delay time (i.e., the time that the flashing light signals are activated before the gates are activated) should be approximately 3–4 sec. Slightly longer times may be justified if vehicle approach speeds are above 60 mph. This is consistent with accepted traffic engineering principles for the warning phase at signalized intersections, and would be appropriate at gated crossings (*8*).

ACKNOWLEDGMENTS

The research documented herein was performed as part of an FHWA contract entitled "Evaluation of Warning Times for Active Traffic Control Devices at Railroad-Highway Grade Crossings." The support and guidance provided by Janet Coleman of FHWA are gratefully acknowledged. The authors also would like to acknowledge the assistance and cooperation of the Norfolk Southern Corporation, the City of Knoxville, and many other contributors to the field studies.

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Publication of this paper sponsored by Committee on Railroad-Highway Grade Crossings.