

Field Evaluation of a Four-Quadrant Gate System for Use at Railroad-Highway Grade Crossings

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As part of research to identify and evaluate innovative active warning devices with the potential for improving safety at railroad-highway grade crossings, candidate devices were identified and developed, and the most promising devices were evaluated in detailed laboratory studies. Based on the results of the laboratory evaluation, three devices were evaluated in the field at actual crossings. One of the innovative active warning devices evaluated in the field was a four-quadrant gate and flashing light signal system with skirts. A before-and-after study approach was used to evaluate the four-quadrant gate system. Data were collected on measures of effectiveness (MOEs) at the existing crossing with the standard two-quadrant gate system and then again at the same crossing after the four-quadrant gate system had been installed to allow a direct comparison of the impact on the MOEs. With the installation of the four-quadrant gate system, MOEs such as speeds, perception-brake reaction times, and deceleration levels did not indicate a change in driver behavior. There were no measurable safety disadvantages to the four-quadrant gate system as measured by these MOEs. The four-quadrant gate system had no effect on the level of service at the crossing but had a positive effect on driver behavior at the crossing by eliminating risky and illegal behavior as well as violations at the crossing, thus producing superb improvements in safety MOEs. Such benefits are especially important at crossings with limited sight distance, high-speed trains, and multiple tracks.

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 equipping in 1986 over one in four of the 192,454 public grade crossings with active warning devices. In 1986, 22,066 crossings (11.5 percent) were equipped with automatic gates and 32,778 crossings (17.0 percent) were equipped with flashing light signals (1).

Even with these improvements, over 50 percent of all car-train accidents in 1986 occurred at crossings with active warning devices, which represents only 28.5 percent of the crossings (1). Although this apparently high number of accidents may be a result of higher vehicle and train volumes and 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 (3,4). Therefore, it seems that these active traffic control devices could be improved. Although research to improve safety at railroad-highway grade crossings has been going on for some 50 years, the traffic control devices 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 FHWA 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 developed, and the most promising devices were evaluated in detailed laboratory studies (5,6). Based on the results of the laboratory evaluation, three of the devices were evaluated in the field at actual crossings (7). One of the innovative active warning devices evaluated in the field was a four-quadrant gate and flashing light signal system with skirts. Before field evaluation of the four-quadrant gate and flashing light signal system with skirts, an on-site visit was made to several European installations of similar design. These systems were found to have operated satisfactorily for many years (8).

FIELD EVALUATION PLAN

Study Approach

A before-and-after study approach was used to evaluate the four-quadrant gate system. That is, performance data were collected at the existing crossing with the standard two-quadrant gate system and then again at the same crossing after the four-quadrant gate system had been installed. This approach allowed a direct comparison between the four-quadrant gate system and the two-quadrant gate system currently used at the crossing.

The first set of crossing studies on the two-quadrant gate system was conducted in the spring of 1985. The four-quadrant gate system was then installed in October 1985. After a 1- to 2-month familiarization period, the second set of studies was

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conducted in December 1985 and January 1986. The purpose of this delay was to ensure that the behavioral data being collected did not contain driver responses caused by unfamiliarity with the new device.

Measures of Effectiveness

Realistic field evaluation of the four-quadrant gate system was dependent on selection of suitable measures of effectiveness (MOEs). To avoid influencing drivers and hence influencing their responses, MOEs were selected that 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: (a) speed profiles, (b) perception-brake reaction times (PBRTs), (c) maximum deceleration levels, (d) violations, and (e) vehicles crossing.

The general hypotheses tested in the field studies were that when compared to the two-quadrant gate system, the four-quadrant gate system would result in: (a) quicker driver PBRTs, (b) fewer undesirable and 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 two-quadrant gate system with response to the four-quadrant gate system.

Speed Profiles

Speed profile data were evaluated for the four-quadrant gate system and compared with 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 ($> 8 \text{ ft/sec}^2$) was also used for evaluation purposes. In each of the previously described comparisons, the Kolmogorov-Smirnov goodness of fit test was used to determine whether or not any observed differences in distributions were statistically significant (9).

Perception-Brake Reaction Time

PBRT was defined as the difference in time between activation of the warning device and activation of the vehicle's brake lights. This measure was computed by counting the number of frames on the videotape between these two points in time and dividing by 60 (60 frames per second). Only those vehicles whose brake lights were activated were included in the data set. Since the observations were not necessarily expected to be normally distributed, nonparametric techniques in the Statistical Analysis Systems program were used to ascertain whether or not observed differences were statistically significant (10).

Violations

Violations were compared for the two-quadrant and four-quadrant gate systems. 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. The number of violations that occurred for each train crossing were manually counted from videotapes. The analysis procedure for this measure was exactly the same as that for PBRTs.

Vehicles Crossing

The number of vehicles crossing was the final MOE used to evaluate the relative performance of the four-quadrant gate system. This measure was defined as the total number of vehicles crossing the tracks between activation of the warning device 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 that 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-ft-long vehicle starting from a stop 20 ft away from the crossing, accelerating at a normal rate of 4.8 ft/sec^2 , and clearing a point 20 ft on the far side of the crossing 2.5 seconds before the train's arrival. Vehicles that crossed within 20 seconds of an oncoming train (CL20) were considered an indication of aggressive behavior since this was thought to represent a level of driver performance in which there is some, but not much, room for driver, vehicle, or warning system error. The *Manual on Uniform Traffic Control Devices* (MUTCD) appears to address this point by requiring a minimum warning time of 20 seconds (11).

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 in which the driver must decide to either stop or proceed through the crossing. 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.

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. The recorders were portable and used standard 0.5-in. T120 VHS cassettes and could operate in temperature and relative humidity ranges of approximately 32° to 104°F and 35 to 80 percent, respectively.

The video cameras used with the recorders were black and white closed circuit television cameras that weighed 2 lb each.

They used 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 energized only when the recorders were activated. The cameras would operate from 0° to 140°F and 0 to 95 percent relative humidity.

Detection System

It was necessary to obtain a train presence signal in advance of the railroad's train detection signal to record the events immediately before the activation of the warning device. For this reason, a train detector was used that emitted an infrared light beam and detected its return from a reflector located across the tracks. When a train broke the beam, the detector transmitted an encoded camera activation signal followed by an audio timing signal. Detectors were located on each approach to the crossing such that the activation signal was transmitted at least ten seconds before the train activated the active warning device at the crossing.

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 ft and the lateral distance to about 60 ft; therefore, three 20-ft mounting poles were built. All three video recording systems and mounting poles were used at each field site. The first unit 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 toward the crossing and had overlapping fields of view.

FIELD SITE SELECTION AND STUDY PREPARATION

For a crossing to be considered for evaluating the four-quadrant gate system, it was necessary that it have a relatively high train and traffic volume, have a history of at least some accidents, and have a two-quadrant gate system already in place. Favorable response for use of a crossing with these characteristics in the Knoxville area was received from the Norfolk Southern Railroad.

The crossing (inventory number 730584K) selected for the four-quadrant gate system was located in the eastern part of Knoxville on Cherry Street. It was ranked as the 223rd most dangerous crossing in the state. As shown in Figure 1, the roadway was four lanes wide and straight and level on both approaches to the crossing. There was a building in the southwest quadrant that 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 through-train volume was approximately 20 trains per day. The speed limit on Cherry Street was 30 mph, and train speeds at the crossing ranged from 20 to 40 mph. Although only one car-train accident had occurred at this location in the past 5 years, large numbers of motorists were observed driving around low-

ered gate arms at this site. This type of behavior made the Cherry Street crossing a potentially dangerous crossing.

Implementation of the four-quadrant gate 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-ft gate arm 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. Figure 2 shows the four-quadrant gate system installed at the Cherry Street crossing.

RESULTS FROM FIELD EVALUATION

A large number of motorists disregarded the standard two-quadrant gate system at the Cherry Street crossing by driving around lowered gate arms. This behavior was not only illegal; it was dangerous. The primary change in driver performance that was expected as a result of the installation of the four-quadrant gate system 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 because they provide greater spatio-temporal separation between trains and motor vehicles. The anticipated secondary change in driver



FIGURE 1 Cherry Street crossing: top, looking north; bottom, looking south.



FIGURE 2 Prototype of four-quadrant gate system installed at the Cherry Street Crossing: *top*, gate arms upright; *bottom*, gate arm and skirt assembly.

performance was better response to the new device (i.e., quicker PBRTs and lower deceleration levels) as a result of its 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 gate system was installed at the Cherry Street railroad-highway grade crossing during the week of October 14, 1985. Before this time, the active warning device at the crossing was a standard two-quadrant gate system. 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 gate system) and 64 train movements observed in the after study (four-quadrant gate system). For each observation, the following were recorded and subsequently analyzed: environmental and lighting conditions; train's direction of travel and warning time; and approaching vehicles' clearance times, speed profiles, and brake reaction times.

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 gate system was 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 1, the mean and standard deviation of the warning times from the data sets were numerically slightly less during the after study (four-quadrant gate system); 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 (12). This means that, as expected, installation of the four-quadrant gate system 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 gate or the four-quadrant gate system.

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 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 (7,13). The criteria developed are shown in Table 2 (7). The levels of service are based on the premise that a grade crossing is 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 2, 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 (11,13). 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 1, 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 gate system) and 73.5 percent in the after study (four-quadrant gate sys-

TABLE 1 WARNING TIMES AT THE CHERRY STREET CROSSING¹

Summary Statistics	Two-Quadrant Gates			Four-Quadrant Gates with Skirts		
	Day	Night	Total	Day	Night	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			Four-Quadrant Gates with Skirts		
	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
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		

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

TABLE 2 PROPOSED LEVEL-OF-SERVICE CRITERIA FOR RAILROAD HIGHWAY GRADE CROSSINGS (7)

Level of Service	Warning Time Category	Time Before Train's Arrival ^a (sec)
—	Inadequate ^b	<20
A	Desirable	20-30
B	Marginal	30-40
C	Poor	40-50
D	Maximum	50-60
F	Unacceptable ^c	>60

^aAverage time (in seconds) between activation of the flashing light signals and the train's arrival at the crossing.^b20 seconds is the minimum warning time allowed by the MUTCD.^c60 seconds is the limit of acceptable delay to most motorists as defined by the 1985 *Highway Capacity Manual*.

tem). 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 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. Since the four-quadrant gate system prohibits driving around the gate arms 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 recorded only 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 3, 90 clearance times were observed in the before

TABLE 3 CLEARANCE TIMES AT THE CHERRY STREET CROSSING¹

Summary Statistics	Two-Quadrant Gates			Four-Quadrant Gates with Skirts		
	Day	Night	Total	Day	Night	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			Four-Quadrant Gates with Skirts		
	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	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	100.1	29	100.0	100.0
Total	90			29		

¹Time between last vehicle to cross and the train's arrival at the crossing.²Includes only those observations in which vehicles were present before the train's arrival.

study (two-quadrant gate system) and 29 clearance times were observed in the after study (four-quadrant gate system). 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 (12). This means that installation of the four-quadrant gate system significantly increased the average time between the last vehicle to cross and the train's arrival at the crossing (from 24.5 seconds to 48.9 seconds). In addition to being statistically significant, this change in driver performance was large enough to be considered meaningful from a practical point of view. 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 (12). This

means that there was no evidence that suggested that clearance times were different between day and night operation for either the two-quadrant gate system or four-quadrant gate system.

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; and
- 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 (11). Normal behavior represents a level of driver performance in which most reasonable and prudent drivers fall. Most minor judgmental mistakes and poorly accelerating vehicles will not result in an accident. Cautious behavior represents a level of driver performance in which drivers probably rely totally on the warning device and not on their own judgment of the train's arrival at the crossing.

According to the preceding definitions, 40.0 percent of the clearance times in the before study (see Table 3) 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 gate system 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 judgment about whether 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 judgment. However, to avoid unnecessarily delaying drivers at these crossings and to reduce risky 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 gate system. Hypothetically, the greater conspicuity and more imposing presence of the four-quadrant gate system 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 1 or 2 mph might be statistically significant because of a large sample size; however, from a practical standpoint, such a difference would be meaningless) (14).

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 3. Each data point represents average speeds over 50-ft sections of roadway in advance of the stop bar at the crossing and are plotted at the midpoint of the section. Data in the range of 50 to 200 ft from the stop bar were obtained from

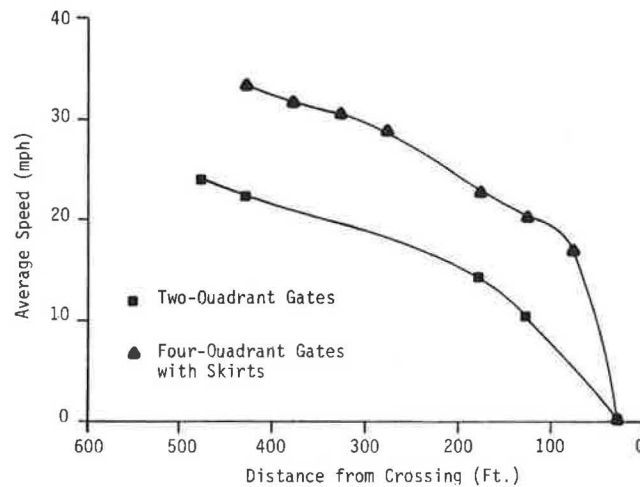


FIGURE 3 Average speed profiles for vehicles in advance of the Cherry Street crossing.

camera 1, in the range of 250 ft to 450 ft from the stop bar from camera 2, and in the range from 500 to 700 ft 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 3.

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 gate system) were about 10 mph faster than they were in the before study (two-quadrant gate system). This figure contradicted the initial premise that drivers slow down or at least maintain their speed in response to the four-quadrant gate system. As a result, an investigation was begun into why drivers speeded up. In the after study, the first vehicle to stop at the crossing did so because the four-quadrant gate system completely blocked the roadway. However, in the before study, visual observation of the videotapes indicated that the first vehicle to stop often followed a queue of slow-moving vehicles that were driving around the gate arms; thus, the first vehicle's 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 4. First, in both studies, the first vehicle to stop began slowing about 450 ft from the stop bar. Second, stopping vehicles did so in a safe, gradual, and consistent manner. Finally, although installation of the four-quadrant gate system 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.

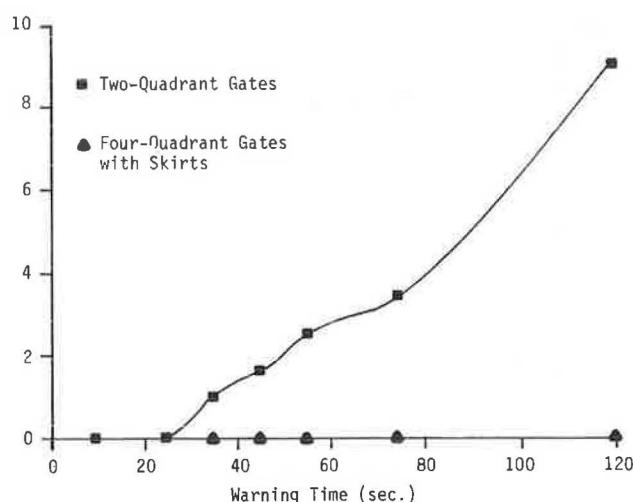


FIGURE 4 Average number of violations as a function of the warning times at the Cherry Street crossing.

PBRT 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 gate system 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 (12). 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 (15):

1. Emergency— $> 20 \text{ ft/sec}^2$;
2. Very uncomfortable—14 to 20 ft/sec^2 ;
3. Uncomfortable—11 to 14 ft/sec^2 ;
4. Undesirable—8 to 11 ft/sec^2 ; and
5. Practical— $< 8 \text{ ft/sec}^2$.

Previous studies have concluded that nearly all drivers approaching an activated flashing light signal decelerate to a

stop at a practical level (16,17). 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 that exist are probably the result of the differences in stimuli for the first vehicle that 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 more slowly 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 normally occur whenever motorists drive around the gate arms in the down position. As stated previously, many motorists drove around the lowered two-quadrant gate system at the Cherry Street crossing even though it was illegal to do so in Tennessee. Installation of the four-quadrant gate system 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 4 shows the number of violations observed at the Cherry Street crossing. As can be seen from Table 4, for those observations in which a motor vehicle was present before the train's arrival at the crossing, the average number of motorists per train arrival who drove around the gate arms went from 2.6 in the before study (two-quadrant gate system) to 0.0 in the after study (four-quadrant gate system). What was not expected was the high number of motorists who drove around the two-quadrant gate system—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 gate system 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 (12).

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 5 and illustrated in Figure 4. Notice that when the warning times were less than 40 seconds (level of service B or better), one or fewer motorists drove around the gate arms; however, when the warning times were between 40 and 60 seconds (levels of service C and D), two to three motorists drove around the gate arms, and when the warning times were longer than 60 seconds (level of service F), three or more motorists drove around the gate arms. 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,

TABLE 4 VIOLATIONS AT THE CHERRY STREET CROSSING¹

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
<hr/>						
Total	93			53		

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

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

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 that will take place.

The four-quadrant gate system simply eliminated all violations, as can be seen in Table 5. 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 6. It should be noted that these numbers include not only the motorists who drove around the gate arms when they were in the down position (i.e., a violation), but also those motorists who drove through the crossing while the gate arms were descending. Installation of the four-quadrant gate system 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 gate system 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 gate system) to 1.13 and 54.7 in the after study (four-quadrant gate system). 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) that indicated that these differences were significant at the 99 percent confidence level (12). These findings support the premise that the four-quadrant gate system improved safety at the Cherry Street crossing by reducing the number of vehicles crossing in front of an oncoming train.

TABLE 5 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	1.64
	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

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

²Includes only those observations in which vehicles were present.

Crossings Less Than 20 Seconds (CL20)

Vehicles crossing within 20 seconds of a train's arrival at a crossing has previously been defined as an indication of aggressive behavior, i.e., there is some, but not much, room for driver or vehicular error. Because motorists had to drive around lowered gate arms 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 gate system was expected to eliminate this type of behavior by completely blocking the roadway at least 20 seconds before the train's arrival at the crossing.

As shown in Table 7, 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 percent confidence level. Thus, as expected, installation of the four-quadrant gate system 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 7. In the before study there were 55 observations with zero CL20s, 27 observations with one CL20, six observations with two CL20s, and five 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 (12).

Crossings Less Than 10 Seconds (CL10)

Although it is illegal in Tennessee 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).

TABLE 6 VEHICLE CROSSINGS AT THE CHERRY STREET CROSSING¹

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)	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			Four-Quadrant Gates with Skirts		
	Observed Train Arrivals	Percent of Total Arrivals	Cumulative Percentage	Observed Train Arrivals	Percent of Total Arrivals	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		

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

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

It was anticipated that installation of the four-quadrant gate system would eliminate this type of behavior by completely blocking the roadway at least 20 seconds before the train's arrival at the crossing.

As shown in Table 8, 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 gate system 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 (12). Thus, it is obvious that installation of the four-quadrant gate system removed the possibility of risk-taking from the driver's set of options.

MAJOR FINDINGS AND CONCLUSIONS

Based on the field test results, the four-quadrant gate system outperformed the standard two-quadrant gate system on sev-

eral key measures and proved to be operationally acceptable under a variety of conditions. Specific findings and conclusions for the four-quadrant gate system are summarized below:

1. Based on evaluation of the MOEs, the four-quadrant gate system substantially increased the safety of the crossing compared with the standard two-quadrant gate system.

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

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

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

5. The four-quadrant gate system did not significantly affect PBRT or maximum deceleration levels at the test crossing.

TABLE 7 CL20S AT THE CHERRY STREET CROSSING¹

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

CL20s (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		

¹Vehicles driving around a lowered gate arm at the crossing.²Includes only those observations in which vehicles were present before the train's arrival.TABLE 8 CL10S AT THE CHERRY STREET CROSSING¹

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

¹Vehicle's crossing within 10 seconds of the train's arrival.²Includes only those observations in which vehicles were present prior to the train's arrival.

6. During the entire time that the four-quadrant gate system was in place at the test crossing, no motorists were trapped on the tracks. The four-quadrant gate system did not appear to increase the risk of a vehicle being trapped on the tracks, provided the lowering of the far-side gate arms was delayed by a few seconds to allow vehicle clearance.

7. The four-quadrant gate system did not interfere in any way with emergency vehicle operations at the test crossing during the field evaluation.

8. The four-quadrant gate system did not create unreasonable delays for motorists during the field evaluation.

9. No significant amount of traffic was diverted to other routes to avoid the four-quadrant gate system.

10. No public complaints were received concerning the use or operation of the four-quadrant gate system.

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

12. Because of 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.

13. A standard two-quadrant gate system can be retrofitted easily to a four-quadrant gate system.

14. Worldwide experience with a four-quadrant gate system has been good and the need to provide for their use in the MUTCD is evident.

15. At a minimum, a four-quadrant gate system can be considered for the following types of crossings:

- Crossings on four-lane undivided roads;
- Multitrack crossings in which the distance between tracks is greater than the length of a motor vehicle;
- Crossings without train predictors in which train warning times are long and variable;
- Crossings that are frequented by trucks carrying hazardous materials, school buses, or high-speed passenger trains; and
- Crossings with consistent gate arm violations or continuing accident occurrences.

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