Reflectorization of Railroad Rolling Stock

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This paper examines the effectiveness of retroreflectors on the sides of railroad rolling stock as a means of reducing highway-railroad grade-crossing accidents, and it estimates the benefits and costs of reflectorizing the U.S. fleet of railroad cars. Factors that affect the amount of reflected light received by a driver (including reflector characteristics, vehicle-reflector positioning, reflector cleanliness, headlight cleanliness and beam usage, windshield transmittance, and atmospheric conditions) were analyzed, and expected reflector illuminance levels were predicted. Under conditions expected in railroad operation, the analysis indicates that 15-cm (6-in) square delineators of high-intensity-grade reflective sheeting will permit detection distances sufficient for safe stopping in most highway situations, even under low-beam headlight illumination. Benefits were estimated from the 1975 Federal Railroad Administration accident data. Accidents were categorized into four groups based on the speeds of the train and motor vehicle and the collision point on the train. Reflector effectiveness for each of these groups was estimated by considering the type of crossing warning device, daylight accident rates, weather conditions, presence of obstructions, human factors associated with nighttime driving, and the train and motor vehicle speeds. The costs of a reflectorization program were estimated and a cost-effectiveness analysis was performed to assess the impact of visibility at grade crossings on annual benefits, since no reliable information is available on this important factor.

Conflicts between trains and automobiles at highway-railroad grade crossings have long been recognized as a major safety problem. Since the 1920s, the railroads and various local, state, and federal government agencies have worked to reduce hazards at the 220 000 public grade crossings in the United States.

Statistics indicate that efforts to improve the safety at grade crossings have been effective: in 1928 there were 2568 fatalities resulting from grade-crossing accidents (1); in 1977, this figure was 63 percent lower, even though vehicle kilometers of travel increased more than 800 percent during the same period (2).

Unfortunately, the problem of grade-crossing accidents has still not been completely solved. There were more than 12 000 grade-crossing accidents reported to the Federal Railroad Administration (FRA) in 1977. Consequently, FRA and the Federal Highway Administration are continuing their programs to reduce the hazards of railroad-highway grade crossings.

Most grade-crossing safety programs have been aimed at improving the warning devices at the grade crossing, but another approach is to improve the conspicuity of the train, so that motorists can actually detect it near a crossing. At some crossings, for example, street lights have been installed to improve nighttime visibility. On-train devices have also been proposed. Recently, interest has been high in the use of strobe lights on locomotives to improve both day and nighttime train visibility. Also, the use of reflectors on the sides of railroad cars has long been advanced by some as an effective way of increasing nighttime train visibility.

The purpose of this study was to examine the effectiveness of reflectors on the sides of railroad cars as a means of reducing grade-crossing accidents. The use of reflectors on railroad cars has been discussed in many documented studies (1, 3-8), but the conclusions reached in these investigations are not consistent and indicate that the effectiveness of reflectors in reducing grade-crossing accidents may be either very considerable or absolutely minimal. This paper provides both an in-depth analysis of reflector effectiveness and an examination of the benefits and costs of reflectorizing the sides of the U.S. railroad car fleet.

REFLECTORIZATION

Reflectorization has its greatest safety potential for accidents that occur at night and involve a motor vehicle striking the side of a train. In many of these accidents, the motorist is apparently unable to see the train in time to stop the vehicle safely. Reflectors on the side of a railcar will reflect light from a motor vehicle's headlights back toward the vehicle and, to the driver, such reflectors will appear as light sources or "bright spots" against a dark background.

The approach taken to analyze the effectiveness of reflectorization was to examine first the factors that affect the amount of reflected light that can be expected at various distances from a grade crossing and then to compare these light levels with visual detection standards to see whether detection (and perception) of a train's presence is likely.

The type of reflector that would be used on railroad cars is called a retroreflector or reflexreflector. Retroreflectors reflect incident light back toward the light source in a narrow beam. Retroreflective materials are used extensively for highway signs, pavement markings, and motor vehicle markings.

The amount of light received by an observer from a retroreflector is affected by six factors: the reflective intensity of the reflector, its size, the intensity of the original light source, atmospheric transmissivity, windshield transmittance, and its distance from the observer. The relationship between these factors and illuminance received by the observer is given by Equation 1:

$$E_e = (I_s \, A \, R \, t^{2d} W)/d^4 \qquad (1)$$

where

- E_e = illuminance received by the observer (lx),
- I_s = intensity of the light beam toward the reflector (cd),
- A = area of the reflector (m^2),
- R = reflective intensity of the reflector [(cd/lx)/m^2],
- t = transmissivity of the atmosphere per meter,
- W = windshield transmittance, and
- d = distance between the observer and the reflector (m).

A FORTRAN computer program was written to compute reflector illuminance received by a driver for various reflector (train) locations. The program used headlamp luminous-intensity distributions and retroreflector properties to determine expected reflector brightness. Values were computed for reflector locations from 30 m (100 ft) to 244 m (800 ft) in front of the motor vehicle and from 122 m (400 ft) to the left to 122 m to the right of the projected path of the motor vehicle. In addition, the program allowed for variation in the size, efficiency, and placement height of reflectors; the conditions of headlights, windshields, and atmosphere; and the intersection angle between the train and the motor vehicle.

Reflective Intensity

The reflective intensity of a reflector depends on the grade of reflective material and on the incidence and divergence angles. The incidence angle is the angle from the light source to a line normal to the reflective surface, and the divergence angle is the angle between the line of sight of the observer and the path of light from the source (Figure 1).

The divergence angle is a function of the distance between the driver's eyes and the light source and the distance between the reflector and the light source. Because the distance between the light source and the driver's eyes is a constant, the divergence angle decreases as the distance between the vehicle and the reflector increases (Figure 1). In the analysis, dimensions for a typical U.S. passenger vehicle were used (9) and produced divergence angles of 2° to 0.14°.

The overall efficiency of a retroreflector is maximized when the divergence and incidence angles are both zero. Furthermore, since both the divergence and incidence angles vary inversely with reflector-vehicle separation, reflector efficiency will increase with separation between train and motor vehicle.

Retroreflective sheeting material is currently available in two grades: engineering grade and high-intensity grade. Analyses in this study are based on the reflective qualities of high-intensity-grade reflective sheeting, since the threefold to fourfold increase in reflectivity that high-intensity grade provides over engineering grade is needed to produce illumination levels that are sufficiently bright at long distances for grade-crossing safety. The low range of divergence angles expected also contributed to the selection of high-intensity grade.

Reflector efficiency is defined as the proportion of the original reflectivity that a reflector maintains under given operating conditions. Reflector efficiency decreases with time because of deterioration of the reflective material and accumulation of dirt and grime. The average efficiency of the reflectors on a fleet of cars would depend on the frequency of reflector replacement, the level of reflector maintenance, the operating environments of the railcars, and the durability and dirt-resistant qualities of the reflective material.

Limited data are available on the decreased reflector efficiency that can be expected from continuous use of retroreflectors on railroad rolling stock. However, a leading manufacturer of reflective materials advertises that silver high-intensity reflective sheeting used on vertical surfaces for highway signs will have a reflective intensity of 200 (80 percent of original specified reflectivity) after 10 years of service and proper cleaning of the material, while the effective performance life is decreased to seven years in areas of abundant sunshine. In general, experience with high-intensity sheeting in highway use indicates an effective performance life of 12-14 years (10). Indications are, however, that the railroad environment is more severe than that experienced by highway signing and that a shorter life may consequently be expected for reflective sheeting used on railroad rolling stock. Nevertheless, the reflector efficiency question cannot be definitively answered before field tests of reflectors on railcars have been performed.

In the absence of reliable data, a reflector efficiency of 0.50 has been used in this study. Since the reflective intensities have been computed conservatively, the actual reflectivities used in the analysis represent approximately 30-40 percent of the reflective intensities of new silver high-intensity sheeting.

Reflector Size

In the analysis, a reflector size of 0.023 m^2 (0.25 ft^2) was used since it is the largest size that can still be viewed as a "point source" under most conditions expected at grade crossings.

Motor Vehicle Headlight Systems

The amount of light beamed on a reflector (and ultimately back to the driver) is a function of the location of the reflector in relation to the headlights, the type of headlight system, the mode of headlight operation (high beam or low beam), and the maintenance level of the headlights (alignment and cleanliness).

In most operational situations, the retroreflectors on the railcars will be located above the horizontal axis of the motor vehicle's headlight system. Under high-beam operation, a substantial amount of light is beamed upward; however, very little light is directed upward in the low-beam operational mode. But the amount of light incident on the reflector surface is enhanced at long distances due to the decreasing vertical angle between the reflectors and the headlight axis. For example, for a vertical separation of 0.3 m (1.0 ft) (see Figure 2) low-beam headlight intensity is 1500 cd at 30 m (100 ft) and 4500 cd at 244 m (800 ft).

The use of high-beam lights was studied by the Southwest Research Institute (11), which found that less than 25 percent of the 23 176 vehicles observed in an open road situation (high beams appropriate) actually used

Figure 1. Divergence and incidence angles of retroreflectors.

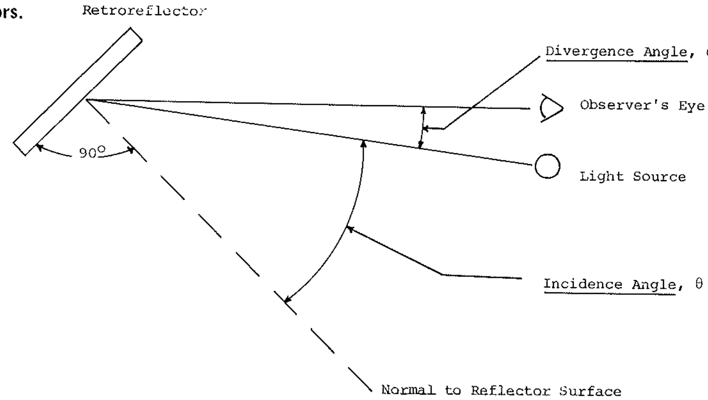
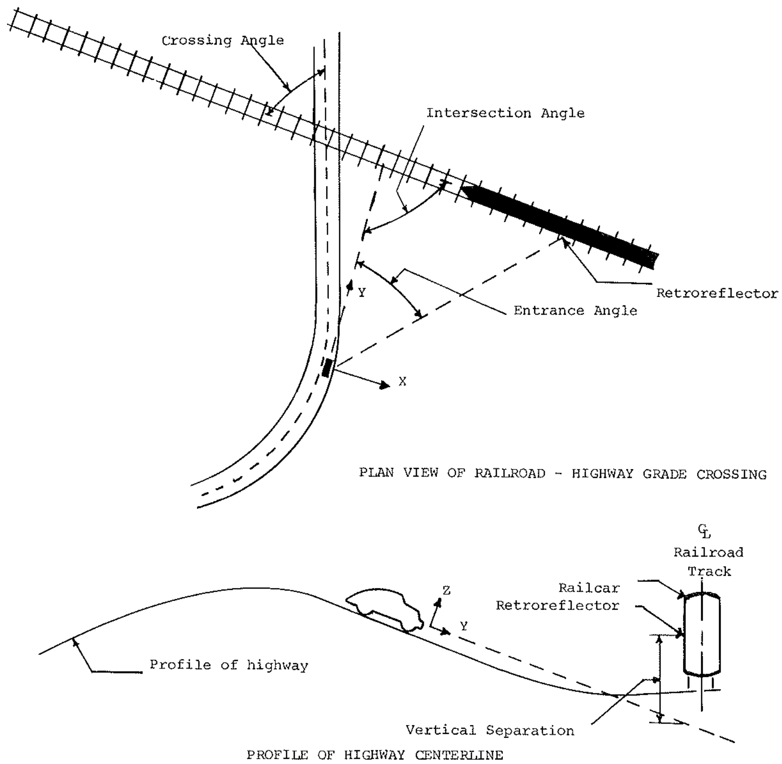


Figure 2. Visibility of retroreflectors at a typical railroad-highway grade crossing.



their high beams. Therefore, if reflectors are to be highly effective, they must be visible under low-beam illumination.

A headlight efficiency of 0.85 was used in all analyses. This figure is consistent with research findings (12, 13) for operation during dry-roadway conditions. During wet-road conditions, light reductions of 50 percent are not uncommon. However, recent research on the visibility of reflectorized overhead highway signs (14) indicates that sign illumination increases by a factor of more than two under wet-road conditions because of the increased amount of light reflected up from the wet pavement. Thus, the 0.85 headlight efficiency used in the analyses should be applicable to most driving conditions. Effects of improper aim of headlights were not included in the analyses because of inadequate data.

Atmospheric Conditions

Atmospheric conditions affect the efficiency of any reflector. Fog and haze, for example, reduce all visibility, including that of light bounced off a retroreflector. In the analyses, a "light haze" condition [8-km (5-mile) daytime visibility] was used.

Windshield Conditions

A windshield transmits only a portion of the total light incident on it. For untinted windshields, the transmittance is about 87.5 percent, but only about 72.5 percent of the light is transmitted through tinted windshields (15). Tinted windshields are known to decrease visibility distances at night; however, these decreases are usually less than 10 percent (16, 17). In the analysis, a windshield transmittance of 70 percent was used.

Detection Level

Detection of reflected light depends primarily on its brightness and the contrast with its surroundings (3). The threshold illumination level for a point source viewed against a background luminance of 0.0034 cd/m^2 (0.001 foot lambert) (overcast, moon) is 24.7×10^{-9} lx (2.3×10^{-9} footcandles) (18). This value represents the illumination level required for 98 percent probability of detection when the observer knows precisely where to look for the light, and it must be increased 5 to 10 times if the light is to be easily found. The Federal Aviation Administration's (FAA) detection level for pilots is 7.8 times this minimum threshold. If the light signal is to attract the attention of an observer who is not actively looking for it, then increases of 100 to 1000 times the threshold level are needed (19).

For the study, a three-region criterion was used to assess the detectability of various reflector illumination levels. It was assumed that the FAA detection level for pilots is the practical minimum illumination that can be expected to be detected by highway users in the vicinity of railroad-highway grade crossings. A driver familiar with the sight of railcar reflectors, approaching a grade crossing that he or she knows has high train volumes, should be able to detect a reflected light source at this level. Most drivers, however, would require an illumination level significantly higher than the FAA threshold for detection.

An illumination level of 1000 times the minimum threshold [24.7×10^{-6} lx (2.3×10^{-6} footcandles)] should be sufficient to make the reflector detectable to all but the few drivers who are completely oblivious to their driving environment. In the region between 100 and 1000 times the minimum threshold (24.7×10^{-7} lx to 24.7×10^{-6} lx), the reflector "probably" would be detected. Between the FAA threshold and the 100-times level, the reflector could "possibly" be detected.

RESULTS

Figure 3 shows the three ranges of reflector visibility

Figure 3. Visibility regions for an intersection angle of 90° for low beams and for high beams.

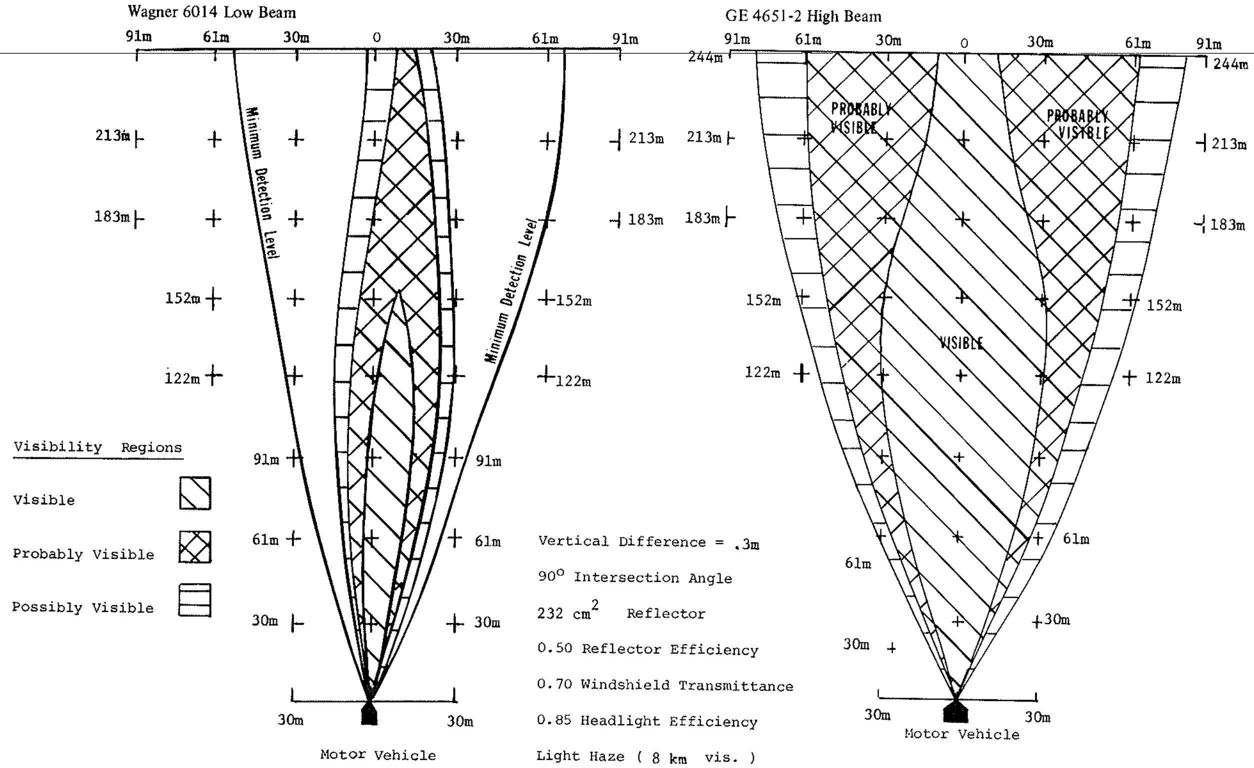
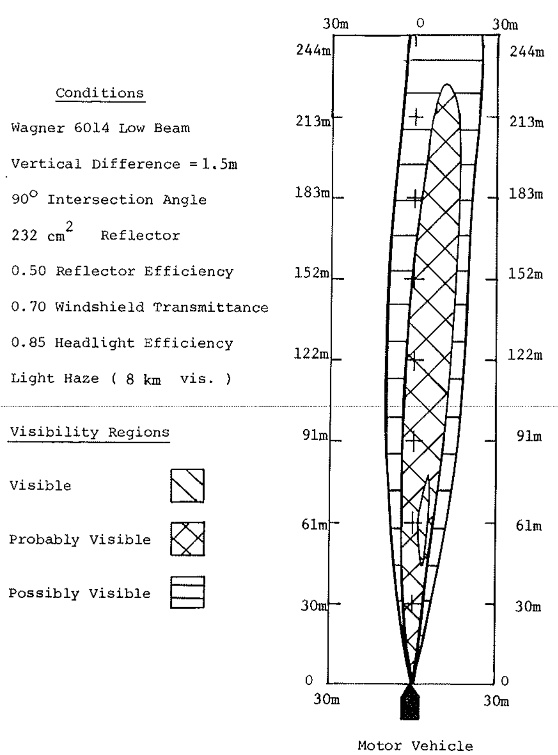


Figure 4. Visibility regions for a 1.5-m vertical difference with low beams.



expected from a two-lamp low-beam system and a four-lamp high-beam system. As expected, the "visible" region is much larger for high-beam illumination than it is for low-beam illumination. Even so, the "visible" region for the low beams extends 152 m (500 ft) from the vehicle and the "probably visible" region beyond 244 m (800 ft). For the crossings represented by these figures, there is little question that reflectors would be visible with high-beam illumination and would most likely also be visible with low-beam illumination. Separate analyses performed indicate that changing the intersection angle to 45° does little to affect the visibility of the reflector.

The effectiveness of the reflectors is greatly influenced by the position of the reflector on the railroad car. Figure 4 shows the visibility regions for a reflector located 1.5 m (5 ft) above the plane of headlights, and a comparison of Figure 4 with Figure 3 for low beams shows that the impact of raising the reflector 1.2 m (4.0 ft) is a reduction of the "visible" region to practically zero, although the "probably visible" region still extends beyond 229 m (750 ft). The impact of a high reflector on visibility is much less when illumination is by high beams.

Reflector Effectiveness

The analytical evaluation of reflector effectiveness indicates that retroreflectors on the sides of railroad cars should be detectable at distances between 152 m (500 ft) and 305 m (1000 ft) if illuminated by low-beam lights and between 274 m (900 ft) and 610 m (2000 ft) if illuminated by high-beam lights. Before any conclusions may be drawn about the effectiveness of the reflectors in eliminating grade-crossing accidents, two questions must be answered: How much sight distance is needed for safe stopping, and how inadequate is the visibility of unreflectorized cars?

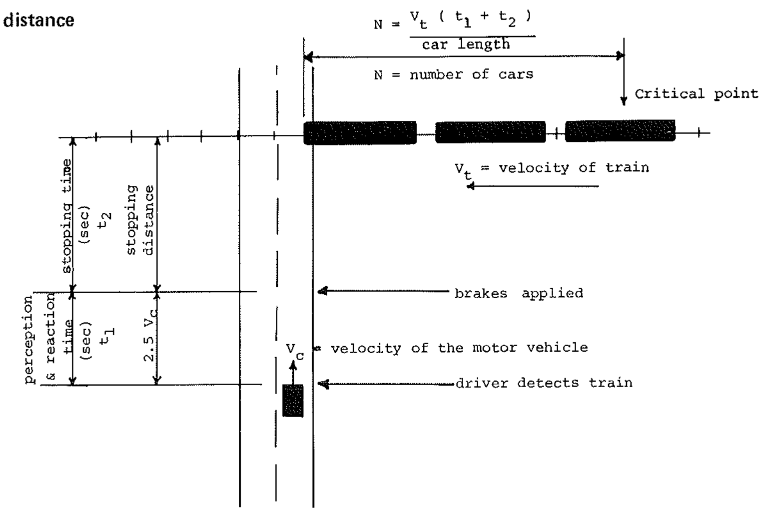
Stopping distance for speeds of 16 km/h (10 mph) to 113 km/h (70 mph) for dry, wet, and icy pavements were computed by using a 2.5-s perception and reaction time. A stopping distance of 152 m (500 ft) should be

Table 1. Nighttime visibility distances for reflectorized and unreflectorized railroad cars.

Type of Rail Car	Approximate Detection Distances[a] (m): Two-Lamp Low-Beam System, Possibly Visible	Probably Visible	Visible	Four-Lamp High-Beam System, Possibly Visible	Probably Visible	Visible
Empty flat car						
Unreflectorized						
Black	<30	<30	<30	91	46	<30
Red	30	<30	<30	137	91	<30
White	91	46	<30	213	152	46
Reflectorized	366	305	152	610	457	274
15-m box car						
Unreflectorized						
Black	30	<30	<30	183	137	46
Red	46	30	<30	244	213	76
White	137	76	30	488	335	137
Reflectorized	366	305	152	610	457	274

Note: 1 m = 3.3 ft.
[a]Based on data reported in the 1947 edition of the IES Lighting Handbook.

Figure 5. Relationship between vehicle stopping distance and critical point on train.



adequate for most highway driving speeds and, since visibility distances of reflectors even when illuminated by low beams exceed 152 m, retroreflectors on the sides of railcars should provide adequate visibility to allow for safe stopping under most conditions experienced at railroad-highway grade crossings.

In order to assess the visibility of existing unreflectorized railcars, visibility ranges comparable to the three used for the reflectors were estimated for a standard 15-m (50-ft) boxcar and for an empty 15-m (50-ft) flatcar (Table 1).

Visibility ranges of unreflectorized railroad cars are significantly shorter when illumination is provided by low-beam headlights rather than by high beam. With the exception of dark-colored empty flatcars, visibility distances for unreflectorized cars illuminated by high-beam headlights seem to be adequate for safe operation at normal highway speeds. On the other hand, illumination by low-beam headlights does not even allow for safe stopping distance at 32 km/h (20 mph).

Given the low visibility of unreflectorized railcars illuminated by low-beam headlights and the fact that most drivers fail to use high-beam lights when they should, it follows that the increased visibility distances provided by reflectorization of railcars should be effective in eliminating certain grade-crossing accidents. The extent of the benefits anticipated from reflectorization is discussed next.

Benefits of Reflectorization

Accidents were classified into four groups. Category 1 consisted of accidents in which the motor vehicle strikes the train at a point that is far enough back along the train to indicate that the driver could have stopped safely if he or she had detected the train's presence just as it started crossing the highway. To determine which accidents met this criterion, a "critical point" (see Figure 5) on the train was computed by using the motor vehicle speed, the train speed, and the condition of the pavement (dry, wet, or icy). If the motor vehicle hit at or behind the critical point, the accident was included in category 1 if the location hit was not the first car or unit and in category 2 if the location hit was the first car or unit. Accidents involving a motor vehicle hitting a train forward of the critical point were included in category 3. Category 4 comprised all accidents in which the train hit the motor vehicle.

Category 1 includes the accidents most likely to be eliminated by reflectorization. Assuming that reflectors are effective, then the only nighttime accidents in this category that would not be eliminated are those that occur at grade crossings where the view of the tracks is obscured, those that occur because of motor vehicle equipment failures, or those that occur because of human factors such as poor eyesight, intoxication, attempted suicide, sleeping at the wheel, or bad judgment.

A smaller proportion of the accidents in category 2 is expected to be rectified by reflectorization. In order for an accident to be included in category 2, it must have had a critical point of less than 15 m (50 ft) (one car length). In some cases the short critical distances were caused by a blank in the data field for either the motor vehicle speed or the train speed.

Categories 3 and 4 contain those accidents least likely to be eliminated by reflectorization. In order for reflectors to be effective in preventing accidents from these categories, the train would have to be visible before it reached the grade crossing. Since the analytical studies of reflector effectiveness (Figure 3) do indicate that trains would be visible at up to 61 m (200 ft) before they reach the grade crossing, it is likely that some of the category 3 and 4 accidents could be prevented by reflectorization.

Calculation of Benefits

A three-step process was used to estimate the number of accidents that would be eliminated by reflectorization. First, the number of accidents that were potentially caused by nighttime visibility problems was estimated from the 1975 FRA computer-file accident data. Next, accidents occurring under circumstances in which reflectors would not be effective (e.g., bad weather, visual obstructions, intoxicated drivers) were eliminated. Finally, the accidents were reduced to reflect the proportion of grade crossings in which highway-railroad geometry does not allow for effective use of reflectors.

A comparison was made of the accident rates at night (and dawn or dusk) with those that occur during daylight. Relative accident rates for each of the four categories of accidents are given in the table below.

	Category			
Item	1	2	3	4
Passive warning				
Dawn or dusk	3.7	3.1	1.4	1.7
Night	9.2	4.0	0.9	1.4
Active warning				
Dawn or dusk	3.2	2.6	1.5	2.1
Night	7.5	3.6	1.8	2.0
All crossings				
Dawn or dusk	3.4	2.9	1.4	1.9
Night	8.6	3.9	1.2	1.6

The accident rates are expressed as ratios and indicate the relative occurrence rate of each accident category in relation to the daylight rate. For example, the value of 9.2 for category 1 accidents occurring at night at crossings that have passive controls indicates that this particular type of accident is 9.2 times more likely to occur at night than it is during daylight. Variations in train traffic volumes by time of day have not been considered in determining these relative accident rates. It is assumed that train volumes at night are equal to or less than daylight volumes and thus do not add to the decreased exposure rate that occurs at night.

Some accident reduction is expected at actively protected crossings. Previous studies of reflectorization have limited the benefits to passively protected crossings on the assumption that actively protected crossings already inform the motorist of the impending presence of a train and that reflectors would add nothing to warn the driver. A study of driver behavior at signalized railroad crossings (20) found a surprisingly high rate of "critical incidents" (vehicles not stopping for the signal or zigzagging around fully descended gates) during signal alarm periods. Furthermore, the fact that the nighttime category 1 accident rate at actively protected crossings is more than seven times the daytime rate indicates that visibility is most likely a contributing factor in these accidents. Since no program of reflectorization could hope to provide visibility levels better than those experienced in daylight conditions, the daylight accident rates were used as the upper limits on effectiveness of reflectorization.

The relative proportions of travel occurring during the day, dawn or dusk, and night periods were used to compute the number of accidents that corresponded to the daylight accident rate. For example, there is 32 percent as much travel at night as there is during daylight; thus, one would expect 32 percent as many accidents to occur at night as occur during the day if visibility and other nighttime-related phenomena are not a problem. The numbers of accidents potentially caused by nighttime visibility problems were obtained by subtracting 32 percent of the daylight accidents from the night accidents and 6.3 percent of the daylight accidents from the dawn or dusk accidents. These values are shown in Table 2.

It is assumed that the daylight accident rates include those accidents caused by motor vehicle equipment failure and human factors. It seems reasonable to assume that accidents resulting from motor vehicle equipment failures, attempted suicide, heart attacks, or bad judgment should be equally likely to occur at night as they are during the day. On the other hand, accidents resulting from human factors such as poor eyesight, intoxication, or sleeping at the wheel are more likely to occur at night than during the day.

Category 1 accidents represent 3.8 percent of all grade-crossing accidents during the day. Since this category of accidents is caused primarily by visibility problems that should not exist during the day, its occurrence rate should represent the nonpreventable accidents discussed above. Accident data from Pennsylvania (22) were available in a form that allowed comparison between grade-crossing accidents and general highway accidents. A total of 3.6 percent of the 274 grade-crossing accidents that occurred in Pennsylvania in 1976 were caused by motor vehicle equipment failure and human factors.

Reflectors are effective only when the driver is able to see them and perceive that the reflectors are on a train. Visibility of the reflectors can be affected by physical obstructions, weather conditions, and human factors such as poor eyesight and intoxication. The ability to perceive and react to the situation is affected by the drivers' attentiveness or degree of intoxication. It was estimated that 65 percent of all drivers were alert.

Table 2 shows the percentages of accidents that occurred under the various conditions that would permit reflectors to be effective. Data on the presence of obstructions and adverse weather (fog, snow, or ice conditions) were obtained from the FRA accident file.

Alcohol and Other Human Factors

Certain causal factors in accidents are more prevalent during the night than during the day. Accidents caused by excessive use of alcohol, drowsiness, and poor eyesight fall into this category.

Limited data are available on the roles of alcohol and other human factors in railroad-highway grade-crossing accidents. Data from Pennsylvania (22); Alameda and Sacramento Counties, California (23); and Dade County, Florida (24) were used in assessing the impact of these factors on reflector effectiveness. On the basis of the results of these studies, it is esti-

Table 2. Factors that affect the effectiveness of reflectors.

Accident Type	Total Accidents	Caused by Daylight Factors	Caused by Nighttime Factors	Percentage With No Obstructions	Percentage Without Adverse Weather	Percentage With Acceptable Speeds	Reflector Effectiveness (%)
Passive warning							
Category 1							
Night	396	43	353	93.3	90.6	100.0	49.0
Dawn or dusk	31	8	23	96.4	75.0	100.0	35.5
Category 2							
Night	375	93	261[a]	90.1	94.9	100.0	38.7
Dawn or dusk	56	18	38	83.0	94.3	100.0	33.9
Category 3							
Night	129	150	0[a]	90.1	83.5	57.8	0.0
Dawn or dusk	41	30	11	79.5	87.1	57.8	7.1
Category 4							
Night	1349	984	365	90.0[b]	93.0[c]	25.0	3.7
Dawn or dusk	336	194	142	80.0[b]	93.0[c]	25.0	5.1
Total	2713	1520	1193	89.0	92.2	50.3	16.1
Active warning							
Category 1							
Night	255	34	221	95.6	94.7	100.0	51.0
Dawn or dusk	21	7	14	94.7	89.5	100.0	38.1
Category 2							
Night	237	65	172	95.2	97.8	100.0	43.9
Dawn or dusk	33	13	20	87.5	96.9	100.0	33.3
Category 3							
Night	145	82	63	90.6	88.5	57.8	20.3
Dawn or dusk	24	16	8	95.7	87.1	57.8	9.7
Category 4							
Night	1157	571	586	90.0[b]	93.0[c]	25.0	6.7
Dawn or dusk	238	112	126	90.0[b]	93.0[c]	25.0	7.2
Total	2110	900	1210	91.4	93.4	46.5	17.9
All crossings	4823	2420	2403	90.0	92.7	48.6	16.9

[a] For category 3 accidents at passive warnings, the nighttime accident rate was less than the daylight rate. The anomaly is probably due to the misclassification of accidents into category 2 because of missing data for train or motor vehicle speed; 21 accidents were subtracted from the category 2 accidents to make up for the deficit in category 3 accidents.
[b] Estimated.
[c] From 1975 FRA Rail-Highway Grade-Crossing Accidents/Incidents Bulletin (21).

mated that 35 percent of the accidents involve drivers who are sufficiently impaired that they would not be expected to detect and perceive the presence of a train from illuminated reflectors.

Effects of Highway-Railroad Geometry

Very little information about the geometry (vertical and horizontal) of railroad-highway grade crossings is available. The Association of American Railroads (AAR)-FRA Grade-Crossing Inventory contains information about the crossing angle of the highway and railroad, but it contains nothing about the vertical or horizontal alignments of the two routes. The grade-crossing geometry, along with natural and manmade obstructions, determines the visiblity at a crossing.

The visibility requirements necessary to eliminate category 1 and category 2 accidents are different from those needed for category 3 and category 4 accidents. In category 1 and 2 accidents, it is only necessary to see the highway-railroad intersection. In order for category 3 and 4 accidents to be eliminated, it is necessary to see the train at some point before it reaches the crossing. The actual distance up the track that the train is required to be visible depends on the train speed and the motor vehicle speed.

The proportion of accidents in which the train speed and motor vehicle speed are both such that the train would be within the range of the motor vehicle's headlights soon enough for the driver to stop is shown in Table 2. For category 1 and 2 accidents, this value is 100 percent, since the train does not have to be seen until it is across the intersection.

The overall effectiveness of reflectorization (assuming adequate crossing geometry for proper visibility) was found by multiplying the percentages for "no obstructions," "without adverse weather," "alert drivers" (65 percent), and "acceptable speeds" by the proportion of total accidents that were caused by nighttime factors. These effectiveness values are shown in Table 2.

Table 3 summarizes the maximum benefits anticipated from reflectorization. These are the benefits that would accrue if all crossings had the proper geometry to allow for adequate nighttime visibility. The numbers of fatalities and injuries and the amounts of property damage were obtained from the FRA 1975 computer-file accident data. Property-damage figures include damage to the motor vehicle, the train equipment, and the track and signal structures.

Costs of Reflectorization

The costs of a reflectorization program were divided into five categories of costs: initial material costs, initial installation costs, annual replacement costs for reflectors destroyed by vandals or train operations, annual maintenance costs for cleaning reflectors, and program implementation costs. Costs are based on the following assumptions:

1. High-intensity, high-tack reflective sheeting is used at a cost of $23.14/m^2$ ($2.15/ft²).
2. Each railroad car is equipped with four (two per side) 15×15-cm (6×6-in) squares of reflective sheeting.
3. Each locomotive is equipped with six (three per side) 15×15-cm squares of reflective sheeting.
4. Five percent wastage of material occurs.
5. The installation rate is 30-60 reflectors/work hour.
6. Labor costs are $20/h.
7. No special handling of cars is required for installation or maintenance (work will be done during required inspections).

Table 3. Maximum annual benefits of reflectorization.

Accident Type	Total Accidents	Reflector Effectiveness (%)	Reduction in Accidents	Reduction in Fatalities	Reduction in Injuries	Reduction in Property Damage ($)
Passive warning						
Category 1						
Night	396	49.0	194	17	92	257 740
Dawn or dusk	31	35.5	11	0	3	5 030
Category 2						
Night	375	38.7	145	5	47	98 510
Dawn or dusk	56	33.9	19	0	7	11 100
Category 3						
Night	129	0.0	0	0	0	0
Dawn or dusk	41	7.1	3	0	1	2 980
Category 4						
Night	1349	3.7	50	3	13	48 124
Dawn or dusk	336	5.1	17	2	4	20 441
Total	2713	16.1	439	27	167	443 925
Active warning						
Category 1						
Night	255	51.0	130	7	64	136 850
Dawn or dusk	21	38.1	8	0	1	10 900
Category 2						
Night	237	43.9	104	4	50	70 370
Dawn or dusk	3	33.3	11	0	6	6 490
Category 3						
Night	145	20.3	29	4	16	39 040
Dawn or dusk	24	9.7	2	0	0	2 160
Category 4						
Night	1157	6.7	77	5	21	77 770
Dawn or dusk	238	7.2	17	1	4	19 820
Total	2110	17.9	378	21	162	363 400
All crossings	4823	16.9	817	48	329	807 325

Table 4. Estimated costs of reflectorizing U.S. railroad rolling stock.

Cost Category	Unit Cost ($)	Estimated Cost Ranges (1977 $) First Cost ($000 000s)	Equivalent Annual Cost[a] ($000 000s)
Material	$23.14/m^2$	4.0	0.8
Installation	0.33-0.67/reflector	2.3-4.6	0.5-0.9
Annual replacement (5 percent/year)	0.90-1.25/reflector	-	0.3-0.4
Maintenance	0.25-0.50/reflector		
Once a year		-	1.7-3.5
Once in two years		-	0.9-1.7
Program implementation			
Research and development	100 000		
Program development	100 000		
Public education	100 000		
Administration (per year)	125 000		0.2
Total		6.3-8.6	2.7-5.8

Note: $1 m^2 = 10.7 ft^2$.
[a]Discount rate = 10 percent.

8. The reflective material has a seven-year economic life.
9. The discount rate is 10 percent.

Table 4 contains a summary of the cost estimates for the reflectorization program. Ranges of costs are given for items that cannot be estimated exactly, due to insufficient documented data. Annual costs are expected to be between $2.7 and $5.8 million. The cost of maintenance is the area that has the highest degree of uncertainty. It is also a major component of the total project cost. Research is needed to answer the questions about the frequency of maintenance required and its associated cost.

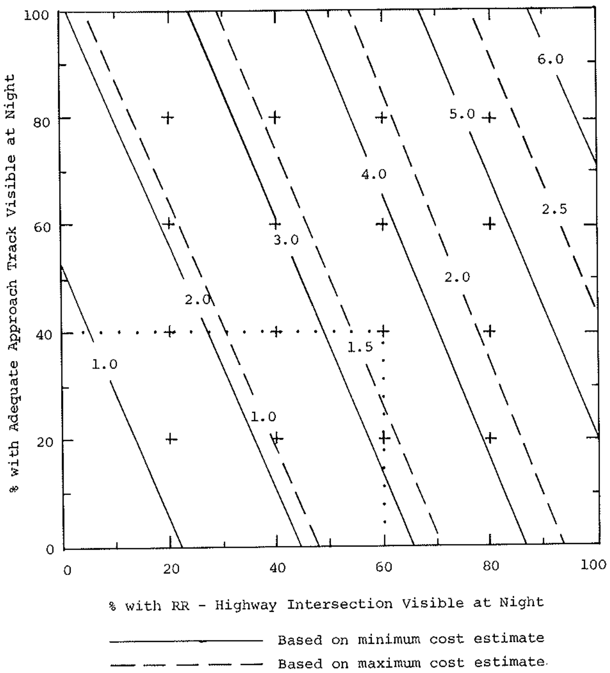
Another unknown that affects the cost of the project is the optimum pattern to be used in placing the reflectors on the railcars. Cost estimates in Table 4 assume that two reflectors are placed on each side of each car. It may be desirable to use additional reflectors on high freight cars to provide a delineating effect that will reduce driver perception time. Again, field research is needed to determine the best pattern to be used. Additional annual costs for extra delineators on high-side cars could run as high as $1.5-3.2 million.

Cost-Effectiveness Analysis

The difficult task of assigning dollar values to the benefits that result from savings in human life and injury was accomplished by using values determined by the National Highway Traffic Safety Administration (NHTSA) (25). NHTSA has made a considerable effort to establish the societal costs of motor vehicle fatalities and injuries. If a reflectorization program is to receive funding, then its cost-effectiveness should be compared with the cost-effectiveness of other proposed safety programs to see whether it merits the spending of scarce dollars. Thus, the absolute values of the benefits assigned to injuries and fatalities is less important than the consistency of values used when comparing the cost-effectiveness of several competing projects.

A value of $318 000 has been used as the average societal cost of a fatality; this is the NHTSA 1975 value updated to 1977 dollars by using a 6 percent annual inflation rate. A value of $5000 has been used as the average societal cost of an injury. This value falls be-

Figure 6. Ranges of benefit/cost ratios for the reflectorization program.



tween the costs established by NHTSA for a moderate injury and that for a severe, but not life-threatening, injury. Property-damage values were obtained from the FRA Grade-Crossing Incident and Rail Equipment Accident files and were updated to 1977 dollars.

The anticipated annual benefits shown in Table 3 were converted into dollars by using the values given above. The actual level of benefits depends on the proportion of grade crossings that have suitable nighttime visibility.

Figure 6 shows the expected benefit/cost ratio for the reflectorization program (based on four reflectors per railcar) as a function of the proportion of grade crossings that have suitable geometry to allow for proper visibility. The solid lines represent the benefit/cost ratio that would result if the project costs were equal to the minimum cost estimate. The broken lines are based on the maximum cost estimate. For example, the dotted lines on Figure 6 show that, if 60 percent of the U.S. grade crossings have geometry such that the railroad-highway intersection is adequately visible and 40 percent of the grade crossings have geometry that allow for adequate visibility of a train as it approaches the intersection, then the expected benefit/cost ratio for a reflectorization program would be between 1.6 (maximum cost estimate) and 3.5 (minimum cost estimate).

Throughout the analysis an attempt has been made to estimate quantities conservatively. The effectiveness analyses were done by assuming low-beam headlight illumination. Much greater visibility is obtained by high-beam lights, and at least 25 percent of the drivers can be expected to use them.

It is important to note that the majority of the benefits are to society and not to the railroads. Other benefits to the railroads may result if liability costs are reduced by the decreased number of accidents. It is possible, however, that liability costs could actually increase if a federal regulation requiring reflectors were passed. With a regulation in force, a dirty or missing reflector could provide the avenue for a negligence suit against the railroad.

FUTURE RESEARCH NEEDS

Research needs to be done to determine the size, pattern, and location of retroreflectors on the sides of railroad rolling stock that will optimize motorist detection and perception of a train's presence.

Research should be conducted to examine the decrease in reflectivity of retroreflectors that is caused by continuous use in railroad environments. This research is needed to determine whether maintenance is required.

Further research investigating driver behavior in the vicinity of railroad-highway grade crossings with both active and passive warning devices should be conducted.

ACKNOWLEDGMENT

The research described in this paper was performed while I was employed by FRA as part of its Summer Professor's Program. Other individuals who contributed to this report are Christa Cudebec, Nancy Ulmer, and Helen Mathias, all of Bucknell University. I wish to express my appreciation to Bruce F. George, Edward S. Lord, and Richard E. Snow of FRA for their advice and assistance in this work. The contents of this paper reflect my views, and I am responsible for the facts and the accuracy of the data reported herein. The contents of this paper do not necessarily reflect the official views or policy of the U.S. Department of Transportation.

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Discussion

Louis T. Cerny, Erie Western Railway Company, Huntington, Indiana

The reflectorization of railroad rolling stock appears to me to be a good idea. Certain factors would make it appear even more favorable than the study shows. In most cases the reflectors would be moving, causing increased probability of detection, and more than one reflector is likely to be in view at all times. I do not believe these additional favorable effects were taken into consideration.

Another favorable aspect is that the cleaning and application of the reflectors is a low-skill job and, because of the national nature of the car fleet, the work could be concentrated at railroad terminals in areas of high unemployment. This project would appear to involve direct federal funding because of the mobile nature of the railroad vehicles, which are not restricted to one state.

It appears, however, that a certain effect that weakens the case for reflectorization was not considered. In a substantial percentage of cases, headlights from highway traffic in the opposing direction can be seen through the spaces between the moving train cars, or under the bodies of the cars between the wheels, thus creating a very eye-catching effect that is more visible than the reflectors, and this is an additional circumstance under which the reflectors would not be effective.

In category 3 and 4 accidents, the locomotive's headlight would normally be visible long before the reflectors, because its visibility does not depend on reflectivity and because it is much higher off the ground than the reflectors. The illumination of objects around the crossing by the locomotive headlights as the train approaches may also attract more attention to the train than the reflectors would, especially since this effect precedes the arrival of the train.

I am skeptical that reflectors on the cars could create a significant increase in attracting a motorist's attention when the crossing is protected by gates (which normally have flashing lights on the gate in addition to those on the mast); I believe, therefore, that accidents occurring at gated crossings are very unlikely to be prevented by reflectors. In some cases, the gate may actually block the view of the reflector. Is there any reason that the distinction between gates and flashers and flashers alone was not made? Perhaps the accidents that occur at gated crossings should be taken as the limit of the effectiveness of reflectors, rather than daylight conditions.

Perhaps a further analysis of category 2 accidents should be made. The paper indicates that in "some cases" accidents fell into this category because of a "blank in the data field." Notes in Table 2 indicate that some adjustment was made, but no justification is given. It would appear that a similar adjustment would be needed in the "active warning" category.

More than four reflectors per car (two per side) would probably be needed on cars more than 18 m (60 ft) long. Common types of cars, such as piggyback, automobile racks, and automobile parts cars are about 26-27 m (85-90 ft) long. It would seem that the maximum distance between reflectors should be about 9 m (30 ft). I feel that answers to these questions, which reflect both positively and negatively on the project, are worth evaluating.

John B. Hopkins, Transportation Systems Center, U.S. Department of Transportation, Cambridge, Massachusetts

McGinnis has carried out a comprehensive and penetrating analysis that appears to achieve as definitive an answer as can reasonably be expected concerning the costs and benefits of railcar reflectorization. His paper brings out many of the uncertainties that are inherent to our basic lack of knowledge concerning accident causation, driver behavior, reflector degradation in the railroad environment, etc. In most cases I find his assumptions and estimates to be quite reasonable. It is my purpose in these brief comments to address only a few aspects in which I feel the ambiguities are so important as to warrant special attention. My aim is not to criticize, for I have no substantive complaints with the study. Rather, I wish to emphasize sources of uncertainty that I consider to be relevant to interpretation of the results, particularly with reference to formulation of policy in this area.

McGinnis has effectively placed an upper bound (the daylight accident rate) on the safety benefits that might be associated with reflectorization. The question then becomes one of estimating appropriate reductions from this value due to various limitations. One could quibble over matters of headlight aim, the assumption of low-beam operation, stopping distances, etc. However, these are minor points, and they tend to balance one another. More complex is the need to assess whether those accidents identified as relevant are truly caused by visibility problems of a type that could be mitigated by reflectors. My subjective view is that reflector effectiveness as shown in Table 2 is somewhat optimistic, or at least represents only a reasonable upper bound, particularly at crossings that have active-warning systems. For example, I find it quite unlikely that 51 percent of the drivers who fail to respond to conventional railroad-crossing flashing lights (some with gates) for night-related reasons will be deterred any more effectively by railcar reflectors. This is a relatively important question, since Table 3 shows that 46 percent of the expected accident reduction is to occur at such crossings.

A factor that affects both cost and effectiveness is reflector maintenance. One can envision many possible maintenance scenarios, each with its own benefit-cost implications. To my mind, the most realistic assumption is that of no maintenance at all. This substantially reduces estimated costs (by 33 percent for the "minimum cost" case and by 60 percent for "maximum cost"), while having a negative but indeterminate effect on safety. (It is appropriate to mention here that other types of reflectors could be used. For example, plastic devices used as highway delineators have somewhat less desirable optical characteristics in this application, but they appear to perform well in a rather dirty environment for many years without cleaning or replacement.)

In the context of policy formulation, another set of factors takes on real significance. These involve the effects of other activities that are expected to improve grade-crossing safety. For example, there are now under way major efforts to improve both passive- and active-warning systems and to achieve more widespread installation of train-activated devices. Reflectorized crossbucks, improved flashing lights, and increased use of gates are of obvious significance to the subject. Serious government and industry consideration is currently being given to widespread installation of locomotive-mounted strobe lights, which should do all that can be done through visibility enhancement to prevent the accidents McGinnis places in categories 3 and 4 (collisions occurring close to the front of the train). These represent 31 percent of the total estimated fatality reduction, which would thus be eliminated as a potential reflector benefit. There could also be a very significant impact on categories 1 and 2. (It is not claimed that strobe lights will necessarily prevent these accidents. However, for potential collisions near the locomotive, if strobes do not help, reflectors are unlikely to succeed either.)

The basic conclusions of the paper, as presented in Figure 6, assume maximum and minimum cost estimates. I suggest that for a more realistic estimate one should use a single no-maintenance cost assumption that still has two curves, based on minimum and maximum estimates of benefits. For the no-maintenance scenario, with full consideration of the limitations on potential safety effectiveness described above, reasonable minimum and maximum benefits might be approximately 25 and 75 percent of the values projected in the paper. The net effect of these modifications, which reduce both costs and benefits, is relatively small; I infer a subjective "most likely" benefit-cost ratio probably in excess of 1.0 but less than 2.0. It should be noted at this point that the benefits accrue primarily to society in general and only to a limited degree to the railroads. Installation at railroad expense would thus almost certainly have a benefit-cost ratio for them well below 1.0. From either the societal or railroad viewpoint, there may well be other investments in crossing safety that can be expected to yield greater benefits. To keep this matter in perspective, note that the above estimates imply a maximum saving of 12 to 36 lives/year, prior to correction for geometric factors that could easily diminish the benefits by another factor of 2 to 4. The net effect on crossing safety would thus be an improvement of approximately 1-2 percent. Thus, while reflectorization may ultimately prove to be a worthwhile step, with significant benefits, it does not appear to be of major importance to crossing safety in general.

I am in full agreement with the research needs McGinnis has identified, and I would only add reflector type and cost to the reflector optimization study. At the same time, the relatively limited promise of reflectorization, and the difficulty of obtaining definitive answers to these questions, seems to warrant only a modest priority for such research.

Otto F. Sonefeld, Atchison, Topeka, and Santa Fe Railway Company, Chicago, Illinois

As McGinnis indicated, the reflectorization of railroad rolling stock has been the subject of debate many times over the past few decades. Arguments favoring reflectorization have generally failed to show significant evidence of the effectiveness of this approach, particularly when compared with substantial argument in favor of other grade-crossing safety activities.

The McGinnis study is perhaps the most comprehensive look at this subject to date, although it leaves many questions unanswered. The problem, in my opinion, is in the attempt to draw fairly firm conclusions from data that do not lend themselves to such detailed analysis. McGinnis has done a commendable job under these circumstances, but it has required making certain assumptions that I feel should be more critically explored.

The part of the study that deals with reflector visibility distances appears to be well documented and reasonable. One of the shortcomings of previous proposals for reflectorization has been the inability of engineering-grade reflective material to function effectively in the severe railroad environment without diligent maintenance. The introduction of high-intensity reflective material would seem to diminish this problem, although it is not clear that even the use of that material would produce the 0.50 rate of efficiency used in the study. The recommended location for the reflective material is the most severe environment on a railcar.

This is not to say that diligent maintenance could not overcome this problem; however, experience in the automatic car identification (ACI) program does not indicate the capability or will of the rail industry to properly maintain the reflective material unless there is a return to the industry far greater than that provided by the ACI program. Such benefits are not apparent. In any event, the long-term effectiveness of the material seems open to question. Certainly, the cost-benefit ratios would be affected by increased maintenance requirements.

In the same vein, although the report acknowledges that a motorist may have a problem perceiving the recommended light source as a railroad train on a crossing, the perception time used in the report appears to assume that a motorist immediately recognizes the light source as a crossing hazard and comes to a prompt halt. I would suggest that a train crossing is unusual enough in the total traffic scheme that a longer perception time would be required to recognize it for what it is.

In developing the "critical point" used as the basis for analysis of the FRA accident reports, apparently vehicle speeds as stated on the reports are used. If so, it appears that vehicle speeds would tend to be consistently understated, inasmuch as the accident reports require speed at the time of impact, not the approach speed at which the decision to stop must be made. If I understand the rationale behind development of the critical point, this would then have the effect of placing that point further back in the train and thus of reducing both the number of accidents shown in categories 1 and 2 and the number of vehicles that would realize any benefits from reflectorization.

Highly important are the assumptions in this study that result in a finding that category 1 accidents at active-warning crossings are 7.5 times more likely to occur at night than during daylight. This further translates to a finding that reflectorization would prevent 51 percent, or 130, of these accidents. Raw data for 1975, however, show a total of 704 nighttime accidents at active-warning crossings of the ran-into-train variety, and 650 during daylight. The exact methodology for derivation of the figures in the study is not known, but my reaction is that the study figures are excessively high, compared with actual figures. This, of course, has a significant effect on the cost-benefit analysis in the report.

Also important to this analysis is the number of accidents used as the base figure, that is, potentially preventable. If 6:00 p.m. to 6:00 a.m. is a reasonable period in which to categorize nighttime accidents, the FRA report for 1975 shows only 1658 ran-into-train accidents in that period, many of which would involve striking the locomotive. The study, on the other hand, appears to be using a base figure of 4823 potentially preventable accidents. I do not understand these differences.

Another problem that is acknowledged but not used in the cost-benefit study is the number of crossings at which vertical and horizontal alignment is such as to eliminate these crossings as candidates for improvement by reflectorizing cars. I would suggest that the number is sizable.

Another category of accidents that is not discussed in the report, but that could possibly be elimin•ted from consideration for treatment by car reflectorization, is those ran-into-train accidents that occurred at illuminated crossings. This involves a minimum of 576 accidents in 1975 (677 in 1977), although the FRA report does not break these into nighttime and daylight accidents.

These comments are not meant to belittle the basic concept of reflectorizing rolling stock. Undoubtedly there are many crossing situations that lend themselves to this treatment. Whether they are of the magnitude suggested in the study is, in my opinion, a matter that requires more rigorous examination.

McGinnis correctly suggests further research into various aspects of this matter. I agree with these suggestions and, as indicated by my comments in this discussion, I would also suggest further refinements or clarifications of some of the critical factors involved in the development of costs and benefits associated with this subject.

Author's Closure

It does not seem that blinking lights from opposing headlights shining through the spaces between moving railcars will affect the results of this study; if what Cerny says is true, and I think it is, then drivers aided by these blinking lights are already seeing the train and are safely stopping. Thus, they are not becoming FRA accident statistics and would not be touched by the potential benefits of reflectorization.

Cerny indicated a concern about the impact of locomotive headlights on potential reductions of category 3 and 4 accidents from reflectorization. There are problems in the use of locomotive headlights as a means of informing motorists about the impending danger of an approaching train. Locomotive headlights are placed close together, giving the impression of a single light, and are aimed in a very narrow beam. First, the lack of space between the two lamps does not allow a motorist to judge distance in the way he or she can with widely spaced automobile lamps. Second, the narrow beam of the locomotive headlight makes detection of these lights difficult for approaching vehicles. In a study conducted on the visual conspicuity of trains at grade crossings (8), Hopkins and Newfell concluded that a beam width of up to 150° would be required if visibility to a great majority of vehicles is to be achieved. Very little light is visible from a locomotive headlight at angles of greater than 15° to 20°; thus, locomotive headlights cannot be assumed to be effective in providing visibility to approaching vehicles.

The missing data responsible for the misclassification of certain category 3 accidents into category 2 do not seem to be too important in regard to the final study results. A sensitivity analysis was conducted to determine the impact of changing perception and reaction time on accident classification. This analysis indicated that the results are very insensitive to reaction and perception time, which also indicates that the results would be fairly insensitive to variations in vehicle and train speeds.

All three discussants expressed concern about the high effectiveness of reflectors shown at actively controlled crossings. I would point out that the analysis indicated that 51 percent of category 1 accidents would be eliminated at active crossings if all crossings had adequate visibility. I suspect that more of the accidents at active-warning crossings than at passive-warning crossings are caused by restricted visibility at grade crossings and would not be eliminated by reflectorization. However, this question cannot be answered until more is known about actual visibility at grade crossings.

Sonefeld questioned the source of several figures and the exact methodology used in determining them. A more detailed description of the methodology is available in an FRA publication (26). The 130 accidents referred to by Sonefeld represent 51 percent of the 255 category 1 accidents that occurred at night at crossings that have active-warning systems (see Table 2). The base figure of 4823 potentially preventable accidents includes accidents in which the motor vehicle was struck by the train, i.e., category 4 accidents.

Without specific regulations to require the cleaning of reflectors, Hopkins' no-maintenance scenario is probably the most realistic. However, it certainly would be nice to have some research on the question of the impact of lack of reflector maintenance on reflector brightness.

Hopkins' suggestion for using a single cost estimate with estimates of minimum and maximum benefits to give a more realistic idea of the program's benefit/cost ratio is impossible until better cost data are available on installation costs and, more importantly, until information on grade-crossing visibility is obtained, so that ranges of benefits can be established. At this point, it is impossible to estimate minimum benefits.

REFERENCE

26. R. G. McGinnis. The Benefits and Costs of a Program to Reflectorize the U.S. Fleet of Railroad Rolling Stock. Federal Railroad Administration, 1979.

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

Accident and Operational Guidelines for Continuous Two-Way Left-Turn Median Lanes

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Thomas Horne, city of Beaumont, Texas
William Fung, Federal Highway Administration

An investigation was begun to provide highway designers and traffic engineers with more definitive information on the installation of left-turn median lanes. Primary emphasis was on documentation of experiences with continuous two-way left-turn median lanes; however, for purposes of comparison, channelized one-way left-turn median lanes (raised and flush markings) were included. This paper presents a summary of the detailed investigation of the literature on left-turn lanes, the results of a survey of current practices and standards in Texas, results of field studies, and guidelines for use. A literature survey and analysis of questionnaires returned by representatives from Texas cities and the Texas State Department of Highways and Public Transportation suggested areas in which definitive guidelines were required. Based on the analysis of these two phases of the study, field studies were conducted that concentrated on operational characteristics, accident experience, and currently accepted practices. The analysis of the data collected on left-turn-lane sites revealed many characteristics, patterns, and relationships of accidents and operational experiences. A brief summary of the conclusions and findings is included, and recommendations are provided to improve current practices. In the operational characteristics phase of the study, emphasis was placed on the lateral placement of vehicles in the left-turn lane and the entering and maneuvering distances of vehicles within the lane. These suggest the characteristics of driver behavior that can be used by traffic engineers and highway designers in determining the optimum design elements for two-way left-turn lanes.

In recent years, there has been increased emphasis on improving the capacity and safety of existing traffic facilities through low-cost improvements or modifications. One concern among highway designers and traffic engineers is the treatment of medians on non-controlled-access highways in urban areas and the development of design and operational standards for median improvements. Although many guidelines have been developed to aid traffic engineers in considering left-turning vehicles, there are still many unanswered questions about how and when special median facilities should be provided.

Basically, three types of left-turn facilities are considered in this study: raised channelized one-way left-turn median lane (raised COWLTML), flush COWLTML, and continuous two-way left-turn median lane (CTWLTML).

A COWLTML (Figure 1) is a median left-turn lane that provides space for speed changes and storage for left-turning vehicles traveling in only one traffic direction to turn at a designated location along a two-direction roadway. A CTWLTML is a left-turn median lane that provides common space for speed changes and storage for left-turning vehicles traveling in either direction and that allows turning movements at any location along a two-way roadway. Raised channelization is generally defined as the use of a curb or other "nontransversible" delineator, while flush channelization generally refers to the use of paint, buttons, tile, or other easily transversible markings.

Although such median lanes have been in operation for some time, very little information has been compiled about their operational differences and about trade-offs between each type of left-turn facility. Therefore, the primary objective of this paper is to present the results of a study that was designed to (a) review previous studies related to traffic operations of left-turn lanes, (b) collect and analyze data for evaluating the operational characteristics of left-turn facilities, (c) identify relationships and characteristics of accidents associated with left-turn-lane facilities, and (d) develop guidelines for design and operational decisions for median treatments. The results presented should enable traffic engineers to better understand the impacts and trade-offs among various types of left-turn facilities in their decision-making process and will facilitate the design of left-turn lanes for individual sites.