ignored, and that pedestrians are too often considered merely as a hindrance to traffic flow in our society. We hope that the results of our study, as well as other related studies, will be helpful in the modification of the minimum pedestrian volume warrant.

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Measurements and Analysis of Degradation of Freight Car Reflectors in Revenue Service

JAMES L. POAGE AND JOHN B. HOPKINS

Accidents at railroad-highway crossings in which a motor vehicle ran into the side of a train during dawn, dusk, and darkness accounted for 13.6 percent of all fatalities and 21 percent of all injuries in crossing accidents during 1980. A possible remedial action for this problem is to mount retroreflective material on the sides of freight cars that, when illuminated by vehicle headlights, may give an indication of the presence of a train in the crossing. Results of measurements conducted on freight-car-mounted reflectors to provide data on the durability of reflectors in revenue service are presented. Reflective intensity measurements were made on engineer-grade retroreflective sheeting on Canadian freight cars; this material has been installed on the side sills of Canadian freight cars since 1959. Reflective intensity measurements were also made over a six-month period on high-intensity reflective sheeting on 19 Boston and Maine Railroad freight cars. The Canadian reflector measurements on engineer-grade reflectors indicated rapid deterioration in the reflective intensity. Data from tests on the Boston and Maine Railroad strongly indicate that high-intensity reflectors deteriorate in the railroad environment at a similar rate, although the limited time for the high-intensity tests precludes absolute conclusions on high-intensity reflector durability. The rapid rate of degradation in reflective intensity has implications for the size of reflectors that might be mounted on freight cars, the useful life of the reflectors, the importance and scheduling of washing of the reflectors, and the cost and cost-effectiveness of reflectorization. Equations that describe the trade-off between reflector size and washing interval are developed.

Accidents at railroad-highway crossings in which a motor vehicle ran into the side of a train during dawn, dusk, and darkness accounted for 13.6 percent of all fatalities and 21 percent of all injuries in crossing accidents during 1980. A possible remedial action for this problem is to mount retroreflective material on the sides of freight cars that, when illuminated by vehicle headlights, may give an indication of the presence of a train in the crossing. Previous research (1) has addressed the issues of potential benefits and required reflector brightness. However, a major remaining uncertainty concerning this safety measure is the rate at which dirt and age affect the reflectors. This paper presents the results of measurements performed on freight-car-mounted reflectors to provide information on the durability of reflectors on cars in revenue service. The rate of degradation in reflective intensity has implications for the size of reflectors that might be mounted on freight cars, for the useful life of the reflectors, for whether washing of the reflectors would be necessary, and thus for the cost-effectiveness and practicality of reflectorization. This paper also investigates the relation between reflector size and frequency of washing.

OVERVIEW OF REFLECTIVE INTENSITY MEASUREMENTS

Several types of tests of freight car reflector durability are described in this paper. In one test, the reflective intensity of reflectors on 208 Canadian freight cars was measured. Since May 1959, the Canadian Transport Commission (CTC) has required that reflective markings be installed on the side sills of Canadian freight cars. Observations of the visibility of reflectors on Canadian trains at night were also made at three railroad-highway crossings. The tests on Canadian freight cars were conducted jointly by the Transportation Systems Center (TSC) and CTC. The reflectors measured on Canadian freight cars are engineer-grade retroreflective sheeting. In another test, high-intensity retroreflective sheeting was placed on 33 Boston and Maine Railroad (B&M) freight cars during spring and summer 1981. Reflective intensity measurements on 19 of these cars were made during a six-month period.

The reflective intensity measurement tests on Canadian freight cars suggest a rapid decline in reflector reflective intensity to an average of 23 percent of initial value after six months, to 14 percent after one year, and to 5 percent after two years. The night-observation tests also indicate a rapid decline in reflector reflectivity. On at least 61 percent of the Canadian cars observed, reflector reflectivity was rated poor. The test period for measuring reflective intensity on the B&M freight cars was not long enough to develop estimates concerning the long-term wear of high-intensity reflective sheeting on railroad cars. However, the results for the first six months indicate deterioration rates that are similar to those obtained from the Canadian measurements.

CANADIAN REFLECTORIZATION PROGRAM

During the late 1950s, the Canadian Board of Transport Commissioners (BTC) studied railroad-highway crossing data that indicated that a large percentage of accidents in which motor vehicles struck a train occurred at night. BTC concluded that the reflectorization of freight cars might reduce this type of accident. BTC recommended to the Canadian federal cabinet that the Railway Act be amended to permit grants to be made from the Railway Grade Crossing Fund toward the cost of the installation of reflectors. The amount of the grants was established at 80 percent of the cost, which was the same percentage granted for other improvements to public crossings. The amount of the grant cannot exceed $8.00/car.

BTC, and later CTC, have issued several orders, beginning in 1959, that have required four reflectors to be applied to each side of cars of 52 ft or less and six reflectors to each side of cars more than 52 ft in length. All reflectors measured in the tests are Scotchlite Brand Reflective Sheeting manufactured by the Minnesota, Mining, and Manufacturing (3-M) Company of Canada. The reflectors are engineer-grade silver 4-in discs used on Canadian National Railway (CN) cars and 4-in squares on Canadian Pacific Railway (CP) cars.

CTC has from time to time attempted to evaluate the effectiveness of the program. The railways are required to report all accidents that occur at public crossings at grade, and the Railway Transport Committee (RTC) investigates those that involve casualties. However, statistics are not maintained that differentiate between those accidents in which the vehicle ran into the side of a train and those in which the train struck the vehicle.

MEASUREMENT OF REFLECTIVE INTENSITY ON CANADIAN FREIGHT CARS

The reflective intensities of reflectors on 208 freight cars were measured in CN and CP yards near Montreal during the week of October 19, 1981. The measurements were made by using a Gamma Scientific, Inc., model 910F retroreflectometer. This instrument consists of (a) an optical head with an optical system, detector, and light source, and (b) a control unit with readout display, operating controls, and rechargeable battery power supply. The instrument is operated by pressing the optical head against the surface to be measured, which activates the device's light source. The instrument is calibrated against a secondary standard and can make measurements during either day or night. Units of reflective intensity are measured in candela per footcandle per square foot. Reflectivity was measured for reflectors on both sides of 120 cars and on one side of 88 cars. Samples of new reflective sheeting of the type installed on Canadian freight cars were measured and showed an average reflective intensity of 94 cd/footcandle/ft^2.

For the data analysis, cabooses and work cars were excluded because the type of service of work cars and the frequent washing of cabooses provide a different environment for the reflectors than that experienced by typical freight cars. The average of reflective intensity measurements for each of the remaining 195 cars is shown in Figure 1. As can be seen from this figure, the reflective intensity of the reflectors decreases rapidly within a year after installation. The reflective intensity continues to decrease into the second year, when it becomes a relatively constant value of less than 10 cd/footcandle/ft^2.

An exponential curve was fitted to the reflectivity data measurements obtained for reflectors that had been in service for less than 2.5 years. The resulting curve (Figure 2) shows a rapid decline in reflective intensity for reflectors in railroad revenue service, with an average reflective intensity that is 23 percent of the original value after six months, 14 percent after one year, and 5 percent after two years. Figure 2 also shows the 95 percent confidence interval for the curve.

A second method was also used to analyze the reflectivity measurement data. The data were averaged over three-month periods and plotted at six-month intervals (Figure 3). As shown, these averages are similar to the exponential regression curve (Figure 2) and imply the same rapid decline in reflective intensity with age.

After the initial reflectivity measurements, reflectors on 24 freight cars were washed and the measurements were repeated. The average reflectivity of the reflectors on each of the 24 cars before and after washing are given in Table 1. The average reflectivity for cars with reflectors that have the same time in service was calculated and expressed as a percentage of the reflective intensity measured for new reflectors (Table 2).

The data suggest that the reflective intensity of the reflector does increase after washing, as expected. The data also indicate that the reflectors deteriorate in the railroad environment at a rate such that, after three years of service, washing of the reflectors restores less than 25 percent of the original reflectivity.

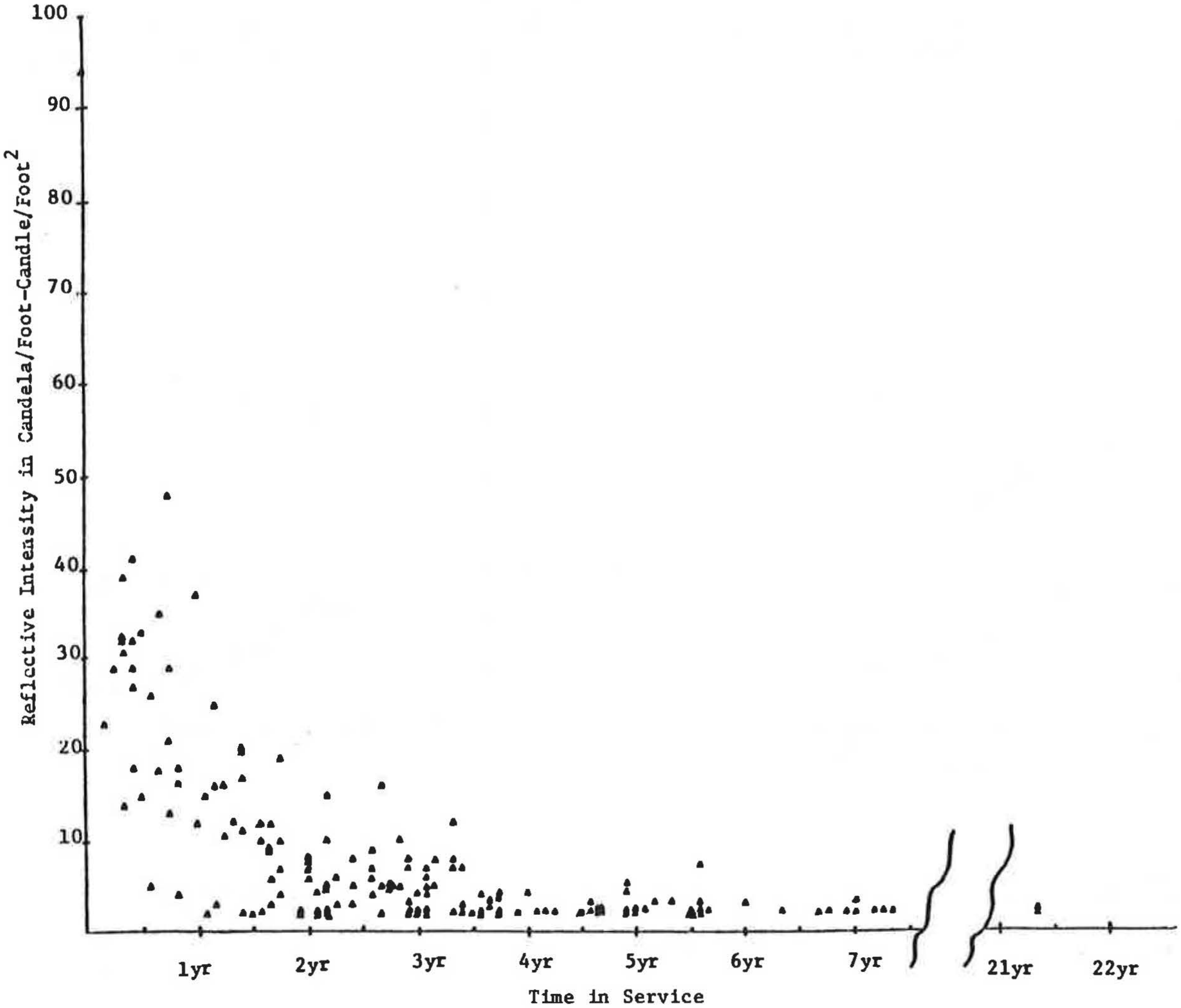
NIGHT OBSERVATION OF REFLECTORS ON CANADIAN FREIGHT CARS

To observe freight car reflector conspicuity under actual railroad operating conditions at railroad-highway crossings, night-observation tests of reflectors mounted on freight cars were made at three Canadian railroad-highway crossings in the vicinity of Montreal during the week of October 19, 1981. The test crossings had minimal automobile traffic, an intersection angle of road and track of 90°, and relatively flat approach grades.

An automobile was parked 300 ft from the crossing such that headlights illuminated the crossing. High beams were used for all tests. An observer sat in the front seat and recorded observations of the visibility of reflectors on each car of the passing trains. A new reflector was posted at the crossing to provide a reference for the observer. An observation of good, fair, or poor was recorded by the observer for each car. A car was rated good if the reflectors were clearly visible, fair if the reflectors were only moderately visible, and poor if barely visible or not visible at all. This test was conducted under the best of conditions, with the observer stationary and anticipating the presence of a train.

The night-observation test results are summarized in Table 3, which gives the percentage of cars with reflectors observed as good, fair, or poor in seven trains with a total of 480 cars. Of the cars ob-

Figure 1. Reflective intensity measurements for each Canadian freight car.



served, 14.2 percent had reflectors with good visibility, 16.7 percent were fair, and 69.1 percent were poor.

Canadian trains typically include freight cars owned by U.S. railroads; these cars usually do not have reflectors. Representatives of CTC, CN, and CP estimated that 20 percent of the cars in Canadian trains are of U.S. ownership. To account for U.S. ownership, results shown in Table 3 were modified to provide values for only Canadian cars. This process results in 17.8 percent of cars having reflectors with good visibility, 20.9 percent with fair visibility, and 61.3 percent with poor visibility.

The second line of data in Table 3 identifies a CN train with 76 cars. The dates on which the cars were built or rebuilt were recorded from markings on the cars after this train entered a nearby classification yard. The reflector visibility rating--good, fair, or poor--is shown in Table 4, along with the built/rebuilt date and car type. Most of the reflectors that were rated as good or fair are less than four years old. These results of the observation of reflectors at night support the measurements of reflective intensity discussed previously in showing a rapid decline in reflective intensity in the first few years.

B&M REFLECTOR TEST

Scotchlite Brand Reflective Sheeting, High-Intensity Grade, was installed on 33 sand-and-gravel hopper cars on the B&M between May through July 1981. Four reflectors, each 4x12 in, were installed on each side of the cars just above the side sill. The material has alternating silver and orange colors, such that each 12-in piece applied to the cars is a composite of both colors. The reflective intensity of the silver portion of the material was measured to be 290 cd/footcandle/ft^2 prior to installation. The B&M sand-and-gravel cars are high-use cars in dedicated service between Boston, and Ossipee, New Hampshire.

During October through December 1981, reflectivity measurements were collected on 19 of the sand-and-gravel hopper cars. The dirt observed on the reflectors was of a sandy, dusty nature, which would be expected from the type of service experienced by the cars. Table 5 gives the average reflector reflective intensity for each car by time in service and the lowest and highest reflector reflective intensity for each car.

The average reflective intensity of reflectors in service for four months was 106 cd/footcandle/ft^2. Reflectors in service for five and six months had average reflective intensities of 55 and 22 cd/footcandle/ft^2, respectively. These data suggest a decline in reflective intensity to 37 percent of the initial reflective intensity after four months in service, to 19 percent after five months, and to 8 percent after six months, as given in the table

Figure 2. Exponential curve fitted to data for reflector reflective intensity measured on Canadian freight cars.

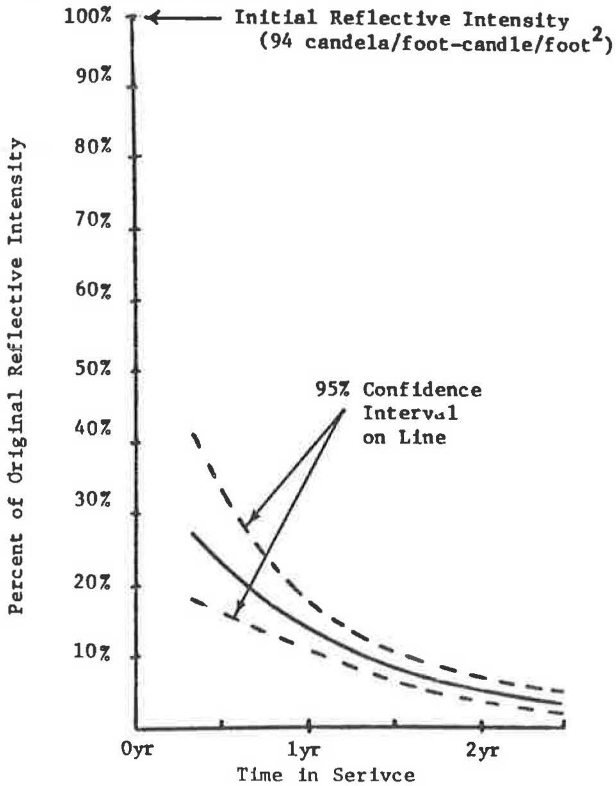


Figure 3. Three-month averages of reflector reflective intensity measured on Canadian freight cars.

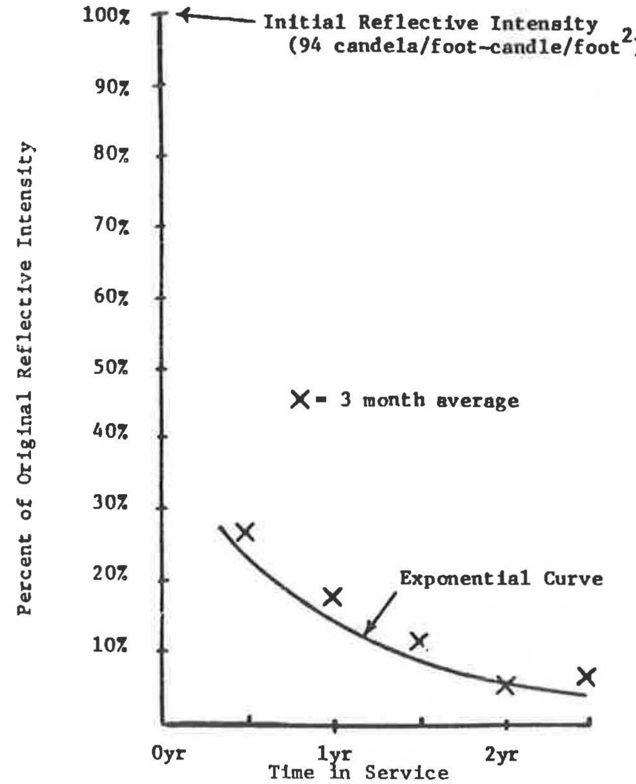


Table 1. Measurement of reflective intensity before and after washing reflectors.

Date Car Built or Rebuilt	Reflectivity (cd/footcandle/ft^2) Before Washing	After Washing	Date Car Built or Rebuilt	Reflectivity (cd/footcandle/ft^2) Before Washing	After Washing
1981	37	67	1979	11	20
	38	67		9	16
	39	64		9	27
	34	63	1978	6	16
	45	72		4	5
	41	73		8	15
	28	82	1977	5	17
	35	67	1975	2	2
	51	85	1972	3	5
1980	18	55	1969	3	10
	8	28		3	5
	3	14			
	43	66			

Note: Measurements listed are averages of the reflective intensity of all reflectors on each freight car.

Table 2. Reflective intensity of reflectors before and after washing as a percentage of original reflective intensity.

Year Car Built or Rebuilt	No. of Cars Washed by Year	Original Reflective Intensity (%) Before Washing[a]	After Washing
1981	9	41.2	76.6
1980	4	19.1	42.7
1979	3	10.3	22.3
1978	3	6.4	22.3
1977	1	5.3	18.1
1976	-[b]	-[b]	-[b]
1975	1	2.1	2.1
1974	-[b]	-[b]	-[b]
1973	-[b]	-[b]	-[b]
1972	1	3.2	5.3
1969	2	3.2	8.0

[a]Percentages listed are averages of all reflectors measured by year car was built or rebuilt.
[b]No data.

Table 3. Night observation of reflectors on freight cars.

Item	Railroad	No. of Cars in Train	Rating of Reflector Visibility by Car (%) Good	Fair	Poor
Test date					
10/19	CN	89	8.9	3.4	87.7
	CN	76	15.8	26.3	57.9
10/20	CP	108	18.5	16.7	64.8
10/21	CP	20	15.0	60.0	25.0
	CP	65	13.8	4.6	81.6
	CP	74	14.9	23.0	62.1
	CP	48	10.4	14.6	75.0
Total for all cars		480	14.2	16.7	69.1
Total modified to show Canadian cars only		384	17.8	20.9	61.3

Table 4. Ratings of reflector visibility by age and type of car.

Item	No. of Cars by Observed Reflector Visibility			No. of Cars by Observed Reflector Visibility by Type of Car								Total No. of Cars by Time
				Good		Fair		Poor				
	Good	Fair	Poor	Box	Tank	Box	Tank	Box	Tank	Hopper	Refrigerator	
Date[a]												
1981	4	2	3	1	3	2	-	1	2	-	-	9
1980	6	-	3	4	2	-	-	1	2	-	-	9
1979	1	2	2	1	-	2	-	-	2	-	-	5
1978	1	11	2	-	1	11	-	2	-	-	-	14
1977	-	-	1	-	-	-	-	1	-	-	-	1
1976	-	1	1	-	-	1	-	1	-	-	-	2
1975	-	2	5	-	-	-	2	1	4	-	-	7
1974	-	-	2	-	-	-	-	-	1	1	-	2
1973	-	-	1	-	-	-	-	-	1	-	-	1
1972	-	2	1	-	-	-	2	-	1	-	-	3
1971	-	-	-	-	-	-	-	-	-	-	-	-
1970	-	-	3	-	-	-	-	-	3	-	-	3
1969	-	-	2	-	-	-	-	-	-	-	2	2
1968	-	-	3	-	-	-	-	-	3	-	-	3
1967	-	-	-	-	-	-	-	-	-	-	-	-
1966	-	-	4	-	-	-	-	-	3	-	1	4
1965	-	-	1	-	-	-	-	1	-	-	-	1
1064	-	-	-	-	-	-	-	-	-	-	-	-
1963	-	-	-	-	-	-	-	-	-	-	-	-
1962	-	-	1	-	-	-	-	1	-	-	-	1
1961	-	-	-	-	-	-	-	-	-	-	-	-
1960	-	-	-	-	-	-	-	-	-	-	-	-
1959	-	-	-	-	-	-	-	-	-	-	-	-
<1959	-	-	3	-	-	-	-	2	1	-	-	3
Total	12	20	38	6	6	16	4	11	23	1	3	70
Non-Canada cars	-	-	6	-	-	-	-	2	2	-	2	6
Total	12	20	44	6	6	16	4	13	25	1	5	76

[a]Date cars built or rebuilt.

Table 5. Reflective intensity of silver reflectors.

Time in Service (months)	Avg Reflective Intensity on Car (cd/footcandle/ft²)	Range of Reflective Intensity on Car (cd/footcandle/ft²)	
		Low	High
4	196	139	232
	15	2	45
	29	13	42
	163	85	202
	103	36	164
	97	64	127
	221	214	227
	70	33	98
	135	67	168
	117	110	123
	58	22	102
	72	55	89
5	28	19	38
	94	78	119
	44	29	56
6	11	5	17
	19	4	25
	2	2	2
	58	33	87

below (note, the initial reflective intensity of the silver portion of reflectors was measured to be 290 cd/footcandle/ft²):

Time in Service (months)	No. of Cars Measured	Avg Reflective Intensity (cd/footcandle/ft²)	Avg Reflective Intensity of Initial Value (%)
4	12	106	37
5	3	55	19
6	4	22	8

For comparison purposes, the reflective intensity, as a percentage of the initial value, is given in the table below for reflectors measured on Canadian cars:

Age (months)	Regressive Analysis: Reflective Intensity of Initial Value (%)	Avg for Cars Measured by Month	
		No.	Reflective Intensity of Initial Value (%)
4	27	5	32
5	25	4	29
6	23	2	26

The decline in the percentage of the initial value with time is given by both the curve developed through a regression analysis (Figure 2) and the average of the reflective intensities measured in each month (Figure 1).

SUMMARY OF FREIGHT CAR REFLECTOR MEASUREMENTS AND OBSERVATIONS

Both the measurement of reflective intensity on Canadian freight cars and the night observation of reflectors on Canadian freight cars suggest a rapid rate of deterioration in the railroad environment. The average reflective intensity measurements made on 208 Canadian freight cars imply that a reflector's reflective intensity is reduced to 23 percent of its initial value after six months in service. After one and two years in service, the reflective intensity is reduced to 14 and 5 percent, respectively, of the initial value. In the night observation of reflectors, 61 percent of the cars were observed to have reflectors that were poor (i.e., barely visible or not visible at all). The reflectors in these tests were engineer-grade reflective sheeting.

An insufficient amount of data and the limited time available for the B&M reflectorization tests prohibit the development of absolute conclusions regarding the durability of high-intensity reflectors in the railroad environment. Also, the measurement of reflectors on B&M gravel cars represents only one type of service environment. However, the data indicate that high-intensity reflectors deteriorate in the railroad environment at a rate similar to that observed of engineer-grade reflectors in use in Canada.

These measurement results have implications for the size of reflectors that would be necessary for freight car reflectorization. A large reflector would compensate for a degradation in reflective intensity in providing a visible warning to motorists. Other ways to compensate for the degradation in reflective intensity are to wash or replace the reflectors periodically. The following analysis investigates some of the relations between reflector size, wash cycles, and replacement cycles.

ANALYTICAL CHARACTERIZATION OF REFLECTOR DEGRADATION

In order to use the measurements described above for the determination of necessary reflector size, it is convenient to express these results in terms of a degradation equation. This is done in a sequence of steps.

First, the reflective intensity deterioration rate for engineer-grade reflectors tested in Canada is examined to separate the deterioration due to dirt alone from that due to age. The dirt deterioration rate obtained for engineer-grade reflectors is then combined with an appropriate aging factor for high-intensity material to determine an overall expected deterioration rate for high-intensity reflectors. In the next section, trade-offs between reflector size, wash interval, and replacement interval for high-intensity reflectors are considered.

The engineer-grade material tested in Canada was found to have an initial reflective intensity of 94 cd/footcandle/ft², which dropped dramatically in the first few months (Figures 1 and 2) and then appeared to diminish exponentially with time. The exponential curve fitted to the data (Figure 2) began with a value of 35.8 cd/footcandle/ft². Letting R(t) stand for reflective intensity and t for time (in years), the reflective intensity at time t, based on a least-squares fit of the Canadian data as shown in Figure 2, is given by the following equation:

$$R(t) = R_o(35.8/94)\exp(-0.9872t) = 0.3809R_o\exp(-0.9872t) \quad (1)$$

where R_o is the initial reflective intensity.

The decay coefficient of -0.9872 combines the effects of dirt accumulation and material aging. In order to determine the effect of dirt alone, the effect of deterioration with age must be quantified. The reflective intensity of engineer-grade material is specified to drop to no less than half its original value in seven years under normal conditions of use, according to a pamphlet from the Traffic Control Materials Division, 3-M Company, St. Paul, Minnesota [pamphlet LH-HIBCB (71.75) MP]. This implies decay at a rate given by

$$R = R_o\exp(-0.099t) \quad \text{(engineer grade; normal conditions)} \quad (2)$$

The specifications are intended for highway traffic-control signs. In this analysis, the assumption is made that the reflectors deteriorate twice as rapidly in a railroad environment. Thus, in railroad use, as in Canada, expected deterioration due to age alone can be described by

$$R = R_o\exp[2 \times (-0.099)]\,t = R_o\exp(-0.198t) \quad \text{(engineer grade; age alone; railroad conditions)} \quad (3)$$

Thus, the Canadian result, which shows a total deterioration time constant of -0.9872, is assumed to be composed of an age effect that contributes -0.198 and a dirt effect of [-0.9872 - (-0.198)] = -0.7892. These results show that, for material with initial reflective intensity of R_o, deterioration due to dirt alone can be represented by the following equation:

$$R(t) = 0.3809\,R_o\exp(-0.7892t) \quad (4)$$

High-intensity reflective material also shows deterioration with age but at a substantially slower rate than engineer grade. High-intensity sheeting is specified to retain 80 percent of its original reflective intensity after 10 years of service (according to the 3-M Company pamphlet). In view of the harshness of the railroad environment, it is again assumed that deterioration with age is twice as fast for reflectors on railcars as it is for reflectors in highway applications. A drop to 80 percent in 10 years implies a decay constant of -0.0223; doubling this value to adjust for the railroad case yields for the aging effect the following equation:

$$R(t) = R_o\exp(-0.0446t) \quad \text{(high intensity; age alone; railroad environment)} \quad (5)$$

Reflectors mounted on freight cars will be subjected to periodic cleaning and replacement. If t_w denotes the time since the last cleaning and t_r the time since the last replacement, the reflective intensity for high-intensity reflectors with an initial intensity of R_o is given by

$$R(t_w,t_r) = 0.3809\,R_o\exp(-0.7892t_w)\exp(-0.0446t_r) \quad (6)$$

Federal Highway Administration (FHWA) specifications and manufacturers' guarantees state that, when new, silver/white high-intensity material will have an R_o of 250 cd/footcandle/ft² (2,3), so that

$$R(t_w,t_r) = 95.23\exp(-0.7892t_w - 0.0446t_r) \quad (7)$$

REFLECTOR BRIGHTNESS

The determination of reflector area requires specification of the brightness assumed to be required to attract the attention of a motorist. For a 90° intersection angle between the roadway and the track, the amount of light received by an observer from a retroreflector is given by the equation below (1):

$$E_e = I_s A B t^{2d} W H/d^4 \quad (8)$$

where

- E_e = illuminance received by the observer (footcandles),
- I_s = intensity of the light beamed toward the reflector (cd),
- A = area of the reflector (ft²),
- B = reflective intensity of the reflector (cd/footcandle/ft²),
- t = transmissivity of the atmosphere (per ft),
- W = windshield transmittance,
- d = distance between observer and reflector (ft), and
- H = headlight efficiency.

According to the Transportation and Traffic Engineering Handbook (4), for a level approach grade, a wet pavement, and a vehicle speed of 50 mph, the desired sight distance so that the motorist can stop before reaching the tracks is approximately 50 ft

(1,4). Based on a previous study, a 30 percent reduction of light by the windshield and a 15 percent reduction of light by dirt on the headlights is assumed (1).

Studies have shown that motorists typically use the low headlight beam even when the high beam would be appropriate (1). Under the assumption of a straight and level road with the reflector mounted on the side sill of the freight car, the beam pattern for typical automobile headlights on low beam will provide a source intensity of 3000 cd incident on the reflector.

The Federal Aviation Administration (FAA) has established criteria for the detection of lights in darkness. Based on these standards, it is assumed that an illumination level of 2.3×10^{-6} footcandles will make the reflector sufficiently visible to virtually all motorists (1). Atmospheric conditions are assumed to be clear, with light attenuated 50 percent due to haze in a distance of 5 miles. (This is the situation normally described as "5 miles visibility".) This implies an atmospheric transmittance (t^d) of 94 percent (one-way) at the assumed range of 500 ft. The parameters for the reflector brightness calculation are summarized below:

Item	Value
Required level of illuminance (footcandle)	2.3×10^{-6}
Required detection distance (ft)	500
Windshield transmittance	0.70
Headlight efficiency	0.85
Headlight intensity (per light) (cd)	3000
Atmospheric transmittance (one-way, 500 ft)	0.94

The required reflector brightness can be determined from the above equation for E_e with the assumed values presented above. The results of applying that equation indicate that, for a straight and level roadway, the reflector must return at least 45 cd/footcandle of incident light in order to attract the attention of virtually all motorists (except those incapacitated by alcohol, drugs, fatigue, etc.) at a distance from the crossing sufficient to permit stopping the vehicle safely.

The reasonableness of this theoretical finding is shown by comparison with two other devices used to warn motorists of obstacles in the highway: the emergency triangle and vehicle marker lights.

1. The emergency triangle "is to be carried in commercial motor vehicles and used to warn approaching traffic of the presence of a stopped vehicle" (5). Triangular in shape, it includes both orange fluorescent material for daytime visibility and red reflective material for night visibility. The basic specification for the reflective portion is that it return 80 cd/footcandle of incident light. If dirt accumulation leads to deterioration of this value in use by as much as a factor 2, the light returned would be 40 cd/footcandle, which is very close to the value of 45 developed above.

2. A variety of white and amber lamps are required on motor vehicles to serve as marker, parking, and clearance lights. All have the basic function of alerting drivers to the presence of a vehicle in or near the road. The minimum intensity required for these lights is 1 cd for white devices and 0.68 cd for amber (6). A reflector that returns 45 cd/footcandle of incident light, determined above to be appropriate for the freight car application, has a brightness of 0.87 cd when illuminated and observed as described in the table above. This brightness is midway between the specified minimum intensity for white and amber vehicle lights.

REFLECTOR AREA AND WASHING INTERVAL

Given the constraint that the reflector must return at least 45 cd/footcandle of incident light, the area (A) of the reflector must be large enough to satisfy the relation: A x (reflective intensity) ⩾ 45. By using the earlier expression for $R(t_w,t_r)$, A x 95.23 exp $(-0.7892t_w - 0.0446t_r)$ ⩾ 45, or A ⩾ 0.4725 exp $(0.7892t_w + 0.0446t_r)$.

In the following analysis, it is assumed that the replacement interval is a multiple of the wash interval. This is not strictly necessary but has practical advantages as well as simplifying the analysis. For specified wash and replacement intervals T_w and T_r, the area is determined from the condition that the above constraint on the area A is met as an equality immediately prior to replacing the reflectors; that is, when $t_w = T_w$ and $t_r = T_r$.

This situation is illustrated by Figure 4, which is a graph of the intensity of a reflector with area A that is replaced after T_r years and washed every T_w years. (In this example, $T_r = 6T_w$.) At time T_r, the intensity has degraded to 45 and the reflector is replaced. The necessary area A is thus determined by the following equations:

$$A \times [95.23 \exp(-0.7892T_w - 0.0446T_r)] = 45 \quad (9)$$

or

$$A = 0.4725 \exp(0.7892T_w + 0.0446T_r) \quad (10)$$

Figure 5 shows the area calculated from this expression, graphed as a function of washing interval T_r, for a 10-year replacement interval. The assumption of a 10-year replacement interval is consistent with manufacturers' specifications for high-intensity material. It can be seen that the required reflector area is quite large--greater than 1 ft² for most washing intervals--and substantially exceeds sizes considered in previous studies.

The choice of the reflector size to be used for a particular situation can be based on minimizing the total lifetime discounted cost of reflector material, installation and replacement, and washing. For material with a given service lifetime (replacement interval), use of larger reflectors increases initial cost, since more reflective sheeting is used, but maintenance expense is lowered because less frequent washing is necessary to prevent reflective intensity from falling below the required 45 cd/footcandle. The least-costly choice of reflector size is that that balances these two effects to attain the lowest total expense. The life-cycle cost to reflectorize a freight car can be written in terms of three components: cost = material cost plus installation labor cost plus maintenance (washing) cost.

This cost is a function of reflector size, the washing interval, and the replacement interval. Once labor and material costs are known, the above equations that relate area, wash interval, and replacement interval could be used to determine the size and maintenance schedule to minimize life-cycle costs. Practical considerations, such as integrating wash and replacement intervals into freight car maintenance schedules and the possible need for stenciling to indicate when a car's reflectors were last washed, would have to be included in a realistic economic analysis.

Figure 4. Reflector brightness versus time for wash period T_w and replacement period T_r.

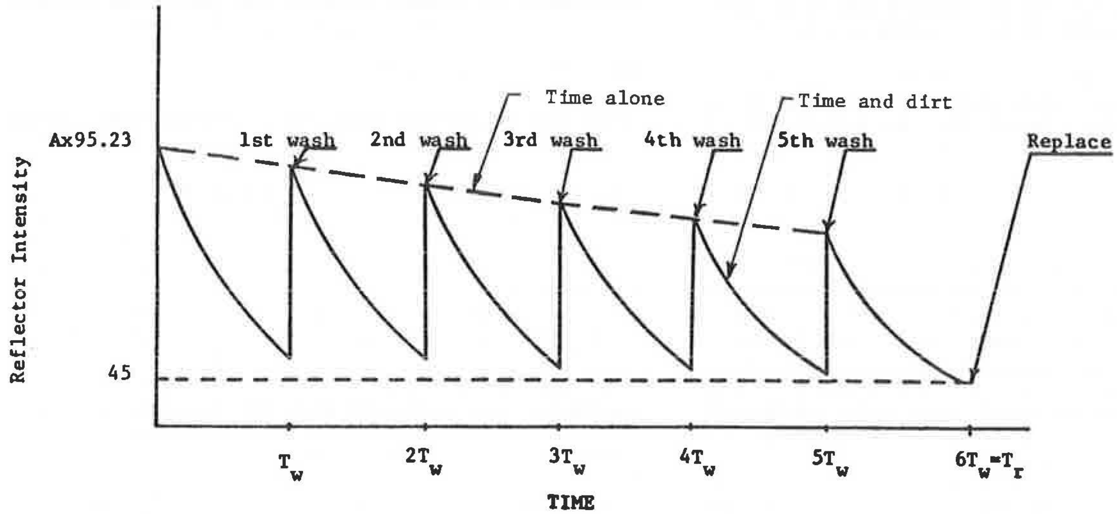
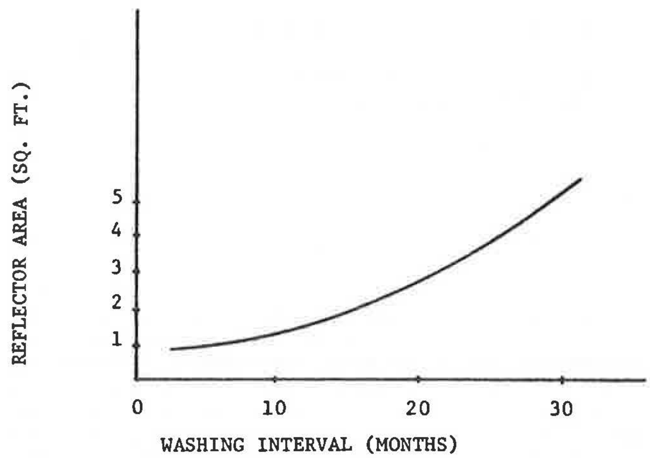


Figure 5. Required reflector area versus washing interval.



CONCLUSIONS

The Canadian reflector measurements on engineer-grade reflectors indicated rapid deterioration in the reflective intensity to 23 percent of original value after six months in revenue service, 14 percent after one year, and 5 percent after two years. Data from tests on the B&M strongly indicate that high-intensity reflectors also deteriorate in the railroad environment and at a rate similar to that observed of engineer-grade reflectors in Canada. However, the limited time for the high-intensity reflector tests precludes absolute conclusions on high-intensity reflector durability.

The decline in reflectivity has important implications for the size, lifetime cost, and cost-effectiveness of reflectors necessary if one is to be confident of attracting a motorist's attention. Reflectors would have to be substantially larger than prior studies have assumed and the expense of reflectorization would be correspondingly greater. For example, as shown in Figure 5, it can be seen that a reflector area of approximately 1.5 ft^2 would be sufficient for a one-year wash interval with replacement after 10 years; a reflector more than 3 ft^2 would be required for a two-year wash interval and 10-year replacement. The choice of a particular combination of size and washing frequency would depend on material, installation and washing costs, and other practical constraints.

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