

environmental conditions of railroad operations; (3) establish the minimum intensity level required to attract a motorist's attention; and (4) assess the effectiveness of pattern placement on freight car detectability. After reviewing past and current transportation experiences with the use of reflectors, Volpe conducted a demonstration test to establish the durability of the newly developed microprismatic material, and to create a test pattern. Next, a nationwide in-service test was conducted to measure the microprismatic retroreflectors' performance, accident reduction potential, and costs. Finally, a human factors test was conducted to evaluate the detectability and recognition of several retroreflective designs.

First, Volpe reviewed past and current reflectorization experiences in the railroad environment. Specifically, Volpe surveyed the rail industry and identified several railroads and other industry participants, including the Burlington Northern Santa Fe ("BNSF"), the Soo Line, the Georgia Power Company, and Southern Company, that had already begun using retroreflective markings on at least some portion of their fleets. BNSF reported using a rail car marking system having retroreflective material on each end of freight cars and eleven 5x8 inch rectangular white diamond grade markings along the side sill of each side of its freight cars. Smaller 3x8 inch markings were reportedly used on car sides where surface space is limited, such as under boxcar doors. The Soo Line reported applying retroreflective material to its cars for advertisement purposes and to improve the safety of nighttime yard operations. The Georgia Power Company reported using twelve 3x12 inch yellow prismatic retroreflectors located at 42 inches above the top of the rail ("TOR") on its coal hoppers since 1981, while the Southern Company reported using high intensity yellow retroreflective material on its open top hopper cars. Although none of railroads which responded to Volpe's survey conducted any formal evaluations of their marking systems, the Soo Line reported satisfaction with their program and that some of the retroreflective materials applied to cars in the mid 1960s still performed adequately.

Using information gleaned from previous studies of reflectorization, Volpe next established a minimum threshold for reflector brightness (minimum SIA) to be used as a basis for evaluating reflector performance. For reflectorization to be effective in reducing RIT accidents, reflectors must

be sufficiently bright to attract the attention of approaching motorists early enough in the approach path of the vehicles so that the drivers have time to react to avoid collisions. Accordingly, Volpe defined the minimum threshold of intensity as the lowest luminous value that allows a motorist to detect the presence of a retroreflector (and therefore a freight car equipped with a retroreflector) in a crossing, even if the motorist is not actively looking for a train. In developing this minimum threshold, Volpe took into account the effects of the harsh railroad operating environment, including the inherent dirt and grime that accumulates on rail cars and the effects of often severe weather conditions, as well as the aging of the retroreflective material and the orientation and configuration of rail cars. Utilizing visibility assumptions established by previous reflectorization studies (*i.e.*, a level approach grade, a 2.5 second driver reaction time, wet pavement, and a vehicle speed of 50 miles per hour), Volpe first concluded that a motorist must become aware of a train's presence when the vehicle is 500 feet from the crossing so that the vehicle can be brought to a safe stop.

Next, using the "point source method" upon which many guidelines for reflector intensity are built, Volpe determined that the minimum threshold illuminance level of 2.3×10^{-6} footcandles would be sufficient to make a reflector detectable to most drivers. The "point source method" is based on the fact that astronomical observations have determined that a star producing an luminance of 2.3×10^{-9} footcandles at the eye of an observer against an overcast moon sky illuminance, equal to 9.9×10^{-4} footlamberts, can be detected with a 98% probability when the observer is actively looking for the light and knows precisely where to look for it. This level must be increased five to ten times if the light is to be easily found. (The FAA detection level for pilots is almost eight 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 1,000 times the threshold level are needed—which is equivalent to 2.3×10^{-6} footcandles. Accordingly, Volpe determined that an illumination level of 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.

Finally, using several additional visibility assumptions established by previous research, Volpe used *Allard's Law* to determine the minimum reflector intensity (SIA) required to enable

approaching motorists to detect and recognize a train's presence in a crossing from a distance of 500 feet. These assumptions include:

E_c = Required level of illuminance to be received by an observer sufficient for detectability & recognition— 2.3×10^{-6} fc

W = Windshield Transmittance—0.70

H = Headlight Efficiency—0.85

I_s = Headlight Intensity—3,000 cd (per headlight)

t^{2d} = Atmospheric Transmittance—0.945

Using these known assumptions and rearranging *Allard's Law* to solve for A, the area of the reflector, and B, the reflector's SIA (*i.e.*, $A \cdot B = E_c \cdot d^4 / I_s \cdot t^{2d} \cdot W \cdot H$), a range of values was determined. Specifically, assuming a vehicle is traveling 50 miles per hour on wet pavement, a 4x8 inch reflector (0.22 ft²) must have a minimum reflector brightness (SIA) of 200 cd/fc/ft² for detection to occur in time for motorists to stop before entering the highway-rail grade crossing. A 4x36 inch (one square foot) reflector, however, must have an SIA of only approximately 45 cd/fc/ft² for detection to occur in time for motorists to stop before entering the crossing. These results demonstrate that for the same amount of illumination to attract the driver's attention, the smaller the area of the reflector (*e.g.*, 0.22 ft²) the larger the required SIA of the reflector (*e.g.*, 200 cf/fc/ft²). The same holds true for the opposite scenario, the larger the reflector area (*e.g.*, one square foot), the smaller the required SIA of the reflector (*e.g.*, 45 cd/fc/ft²).

The demonstration test was designed to evaluate the degradation in reflectivity of different reflective materials applied to freight cars under controlled conditions and to develop a test pattern. Three types of reflective materials (enclosed lens, bonded, and microprismatic retroreflective material) were tested. For the tests, nine open top hopper cars were treated with groups of three 4x4 inch diamond shaped markings placed near the side sill (at approximately 42 inches TOR). Each group of markings was comprised of the three types of materials being evaluated. Five more hopper cars had groups of two or three 4x2 inch rectangular markings attached to the wheels at 90, 120, or 180 degrees of separation. Only microprismatic material was used on the wheel application. One car had a 4x96 inch vertical strip applied to the corner post at each end of the car. All of the marking systems evaluated were either all white, all red, or a combination pattern of red and white.

Results of the demonstration test indicated that the white microprismatic