

B = Reflective intensity of reflector (*i.e.*, SIA, measured in candela/footcandle/square foot (cd/ft²))

t = Transmissivity of the atmosphere (per foot)

d = Distance between the observer and the reflector (measured in feet)

W = Windshield transmittance (percentage)

H = Headlight efficiency (percentage)

The above relationship assumes that the incident light from the light source is normal to (*i.e.*, perpendicular to) the surface of the retroreflector. At highway-rail crossings, however, light will often strike retroreflectors on rail cars at an angle other than 90 degrees, and as a result, the reflected light received by an approaching motorist will be reduced. This reduction is a function of three factors: the incidence (or entrance) angle, the divergence (or observation) angle, and the properties of the retroreflective material. The incidence angle is the angle formed between a line from the light source (*e.g.*, headlights of approaching motor vehicle) to the reflective surface and a line perpendicular to the reflective surface. The divergence angle is the angle between the line of sight of the observer to the reflective surface and the path of the light from the source to the reflective surface. A retroreflector's effectiveness is affected primarily by the divergence angle and secondarily by the incidence angle. 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. In the scenario of a motor vehicle approaching a highway-rail grade crossing, since the distance between the light source (*i.e.*, vehicle's headlights) and the motorist's eyes is a constant, the divergence angle decreases as the distance between the vehicle and the reflector increases. The retroreflector will produce maximum reflectivity for the motorist when both the incidence and divergence angles equal zero. This maximum reflectivity will not be achieved for highway-rail grade crossings, however, due to the fact that the divergence angle increases as the vehicle approaches the reflective material on the train. In other words, the reflective intensity of retroreflectors on the sides of rail cars will increase with distance since both the observation and entrance angles vary inversely with the distance between the reflector and the vehicle. Similarly, as a vehicle gets closer to a rail car, the entrance and observation angles get larger, and the retroreflective material's performance drops (*i.e.*, the intensity of the reflected light drops). Because illuminance is

inversely proportional to the square of the distance, however, as a motorist gets closer, less performance is needed. In addition, the reduction in the material's reflectivity as a vehicle approaches a train can be partly compensated for by using reflective materials with the highest level of performance (*e.g.*, microprismatic retroreflective material).

In evaluating the performance of reflective materials in the railroad operating environment, the inherent limitations of human eyesight must also be taken into account. In general, an individual's visual attention orients toward areas that contain a great deal of information (such as concentrations of signs, lights, people, *etc.*) and toward objects that differ greatly from their background (such as contrasting color or brightness, or moving objects against a still background). Accordingly, although reflectorization will increase the visibility of trains in normal daytime conditions, it is expected that reflectorization will be most effective in reducing RIT accidents at nighttime or during other times of limited visibility when the reflective material contrasts the most with the background environment.

For human beings to see in darkness and other low-light conditions, sufficient light must illuminate their retinas. Two types of light sources affect a human's ability to see. The primary light source is one that is self-luminous (*e.g.*, a vehicle's headlights or crossing illumination). Secondary light sources (*e.g.*, reflective material) are not self-luminous and can be detected in darkness only if light is reflected from their surface. Non-luminous and non-reflecting objects are also visible under low light conditions based on available contrast with a lighter background against which they stand out. As applied to railroad crossings during periods of darkness or otherwise limited visibility, a motor vehicle's headlights and retroreflection can be used to partially compensate for the daylight that is not present.

The light that illuminates the retina stimulates two types of photoreceptor cells—cones and rods. The cones are sensitive to normal daylight conditions (photopic vision). Photopic vision requires higher levels of illumination and allows color perception and high visual acuity. The rods are sensitive to lower levels of illumination, do not allow color perception, and do not provide as high a level of visual acuity as the cones. This is called scotopic vision. At dusk and dawn both types of receptors are activated (mesopic vision). Mesopic vision is characterized by diminished color vision and reduced

detail discrimination relative to photopic vision.

During normal daylight conditions, the human visual system operates at its highest level of visual acuity and has the greatest capability of distinguishing differences between objects in the visual field (good detail discrimination). At night, and in other conditions of low ambient light, contrast sensitivity is greatly diminished, colors cannot be discriminated, and details are not easily discernible. Thus, in order to be seen at night, objects must be sufficiently brighter (or darker) than their backgrounds. The perceived brightness of an object, including an object with reflective properties, is, at least in part, dependent on its color.

The visible spectrum of light, which lies between the nonvisible ultraviolet and infra-red radiation, contains all colors. Color is the property of an object reflecting the light of a particular wavelength. The colors range from the longest wavelength, red, to the shortest wavelength, violet. The various cones (red, green, and blue) of the human visual system are selectively sensitive to different wavelengths of light, resulting in the perception of color. The unaided human eye is able to detect light (visible radiation) within a narrow band of the electromagnetic spectrum between approximately 400 nanometers (nm) (violet end) and 780 nm (red end). The eye is most sensitive, however, to light in the wavelengths that stimulate both the red and green cones (approximately 500 nm to 650 nm, with peak sensitivity at approximately 550 nm, the wavelength corresponding to the color yellow-green). The eye is least sensitive to red or violet light at either extreme of the spectrum. Wavelengths between 500 nm and 650 nm, and particularly at about 550 nm (yellow-green), contribute most to the perception of color, as well as the definition of visual detail. As such, reflective materials with a color falling within the range of yellow-green peak sensitivity would provide the most visible contrast with the normally dark and dirty background of freight cars.

C. FRA's Studies of Freight Car Reflectorization

FRA's study resulting in the 1999 Volpe Report consisted of a four-phase research program to determine the feasibility of reflectorization as a train conspicuity device. Specifically, the goals of the research were to: (1) Determine whether the new generation of reflective material (microprismatic retroreflective material) would provide adequate brightness in the railroad environment; (2) determine whether the new material could withstand the harsh