Fallacies and Myths of Retro-Reflectivity Standards
and
Its Implications to High-Visibility Safety Clothing

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Introduction

Just as we wish to provide the very best protection for the people who give the most, and equally important the safety of pedestrian and cyclist who travel on the road way, the prevailing High Visibility Safety Standards including ANSI/ISEA 107, 207, EN471, CAN/CS, AUS/NE and the proposed ISO/DIS 20471 standard (referring as the "Standards" from here on), are not specifying based on the best safety measure nor suitable for those professionals to wear at break-time or when traveling to and from work. Forced by legislation to put on the not so safe but ugly and uncomfortable costume, workers tend to leave the safety vest in their truck before crossing the road to go to lunch or when traveling home, and therefore they are still exposed to the dangers of traffic. In many EU countries, a safety vest is mandated to be put on in the dark road. People normally put the garment in the car-boot/trunk and do not generally wear it. In the event it is needed when the driver gets out of the car to go to the trunk he/she has already been put in danger from passing traffic. Therefore, it is suggested that, because such safety clothing is already being widely used by all people, it shall be properly specified and manufactured to serve the purpose.

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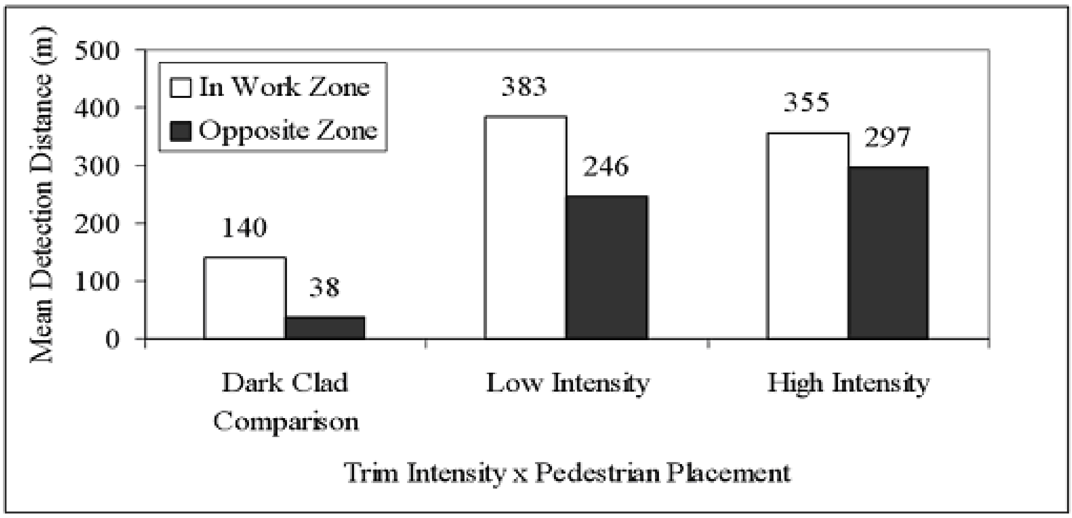
Required Minimum Retro-Reflective Index (R_A):
The R_A as specified in the "Standards" is not the minimum requirement

The minimum required retro-reflective index (R_A) and total area of the reflective material are determined by the critical safe visual detection distance. It is not necessarily true that the farther away a reflective object can be seen the better is the situation. The driver may not pay attention nor act when sighting an object too far away; the "higher the retro-reflective coefficient the better" is not necessarily a true statement**.** Studies actually confirm that garments with the higher retro-reflectivity coefficient (R_A) do not necessarily yield better visibility in real life situations, as shown in University of Michigan's study UMTRI-2003-29 report.

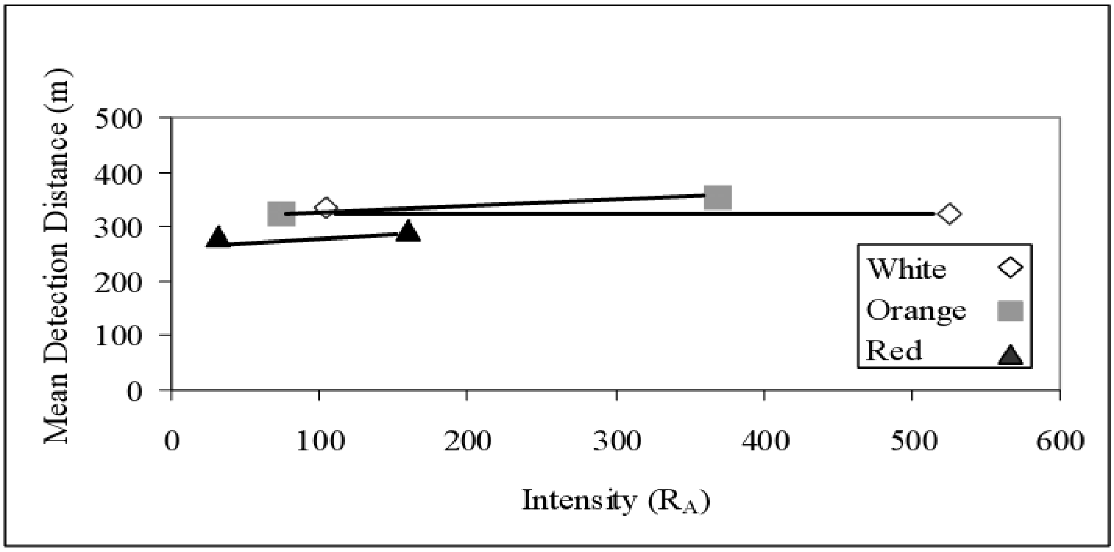
Figure 1 -- The Interaction of Trim Intensity and Pedestrian Placement on Detection Distance



Source: University of Michigan Transportation Research Institute, *UMTRI-2003-29*, Ann Arbor, Michigan, 2003, p.17, Figure 8.

The field tests and statistics showed that the group of vests with the highest mean detection distance did not meet the requirements of the "Standards".

Figure 2 -- Mean Detection Distance by Retro-Reflective Trim and Color



Source: University of Michigan Transportation Research Institute, *UMTRI-2003-29*, Ann Arbor, Michigan, 2003, p.21, Figure 10.

These results clearly show that there is no significant difference in the mean detection distance between the low intensity trim and the high intensity trim. In the above study, the low intensity trim is defined with $R_A > 27$ cd.lx^{-1}m^{-2} and the high intensity trim with $R_A > 315$ cd.lx^{-1}m^{-2}. In the "Standards" the specification of reflective index (R_A), is again being over specified and leads to a vest that is stiff and uncomfortable to wear as shown in Figure 3. Furthermore, this class 2 vest as specified in the "Standards" may not be visible at all in side view. As illustrated in the right-hand-side panel of Figure 3, the retro-reflective function of this safety vest may be totally blocked in the side view if the arm moves back a few inches. In normal highway construction site, this vest is similar to road liners and the person wearing this vest is hard to draw attention of drivers as shown in Figure 4.

Figure 3 – Illustrated Occupational Safety Vest, the “Standards” Class 2

Source: King Tech Industry, San Diego, California, 2010.

Figure 4 illustrates such a vest adjacent to road markers will not draw the driver's attention at all.

Figure 4 -- Worker with Safety Vest among Road Signs and Liners

Source: University of Michigan Transportation Research Institute, *UMTRI-2003-29*, Ann Arbor, Michigan, 2003

A silhouette design of shirt, as shown in Figure 5, with area reflective 50% coverage in the shoulder area, outlines the human body. Luminuous intensity (RI) of this clothing is far above the “Standards” specified for, especially within the critical detective distance. But this t-shirt is not suggested by the “Standards:”.

Figure 5 – High Visibility Safety Clothing, Silhouette Safety T-Shirt

Source: King Tech Industry, San Diego, California, 2010.

The Reflective Index (R_A) as Specified in the “Standards” Shows No Consistency

The minimum R_A requirements as listed in the AZ Standards are not consistent. The purpose of reflective material is to achieve luminance or brightness. When the observation distance is reduced, the required R_A at each entrance angle should reduce in a consistent manner. Assuming the required R_A for an observation angle of 12’ is appropriate the required R_A for 20’ and so on should be reduced at a constant rate. Each observation angle corresponds to an observation distance. When the distance is changed, the required brightness changes at a consistent rate and not randomly. The percentage of reductions in the required levels of R_A, as defined in the AZ Standards, are random as indicated in Table 1 below. The specified levels of the coefficient of retro-reflectivity, R_A, suggested in all of the AZ Standards are the same and are from the same source. It is more like a manufacturer's product specification with biases and do not relate to the minimum requirements.

Table 1 -- Percent reduction in specified coefficient of reflectivity index (R_A) in cd.lx^{-1}m^{-2} based on the "AZ Standards", Table 4

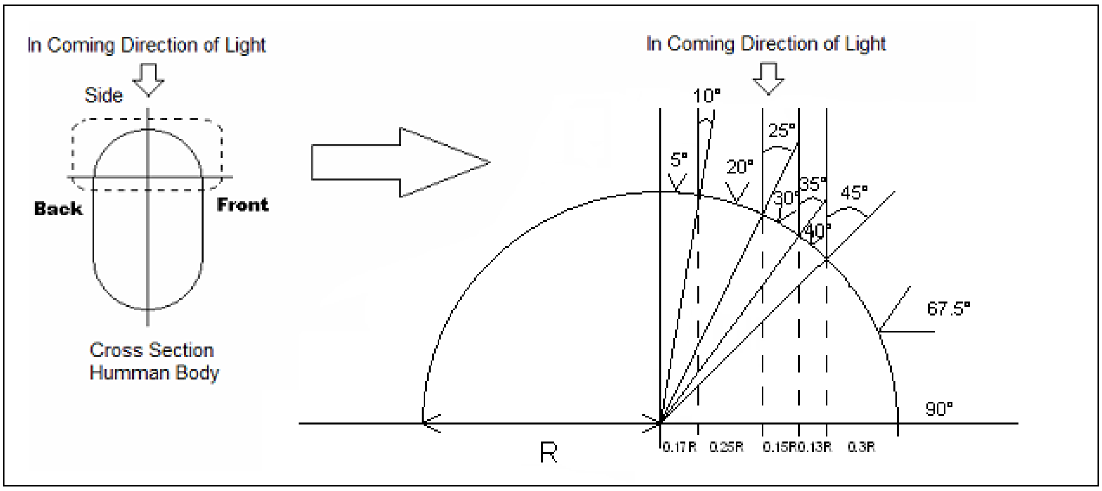
Coefficient of Reflective Index (R_A) (cd.lx^{-1}m^{-2}.)								
Observation Angle	Entrance Angle							
	5°		20°		30°		40°	
	ANSI 107 EN471	Rate of Reduction	ANSI 107 EN471	Rate of Reduction	ANSI 107 EN471	Rate of Reduction	ANSI 107 EN471	Rate of Reduction
12′	330	100%	290	100%	180	100%	65	100%
20′	250	75.76%	200	69.00%	170	94.44%	60	92.31%
1°	25	7.58%	15	5.17%	12	6.67%	10	15.38%
1°30′	10	3.03%	7	2.41%	5	2.78%	4	6.15%

Source: King Tech Industry, San Diego, California, 2010.

The Entrance Angles as Selected in the "Standards" are not Properly Distributed

The entrance angle of a beam of light from a car's headlights varies as it strikes different parts of a human body. The coefficient of retro-reflective index (R_A) reduces as the entrance angle increases. Since the overall brightness is dependent on the total amount of reflected light collected from every part of the reflective fabric, which experiences a range of different entrance angles, the group of entrance angles selected for the laboratory measurements should be chosen that will best represent the behavior of the reflective material in the field. Each entrance angle should represent an equal proportion of the visible area so that each of the measured R_A values has the same relevance and they may all be added together. The most important consideration for the driver is the coefficient of luminous intensity (R_I), i.e. the ratio of the luminous intensity (I) of the retro-reflective garment to the illuminance (E), expressed in candelas per lux (cd.lx^{-1}). The overall R_I is the integrated value of all the values of R_A of the reflective material at all the relevant entrance angles multiplied by the corresponding reflective area. The four test entrance angles, as listed in the ", i.e., 5, 10, 20 and 40, are depicted in Figure 6 showing each of the measured R_A representing a different size of segment of the visible reflective area.

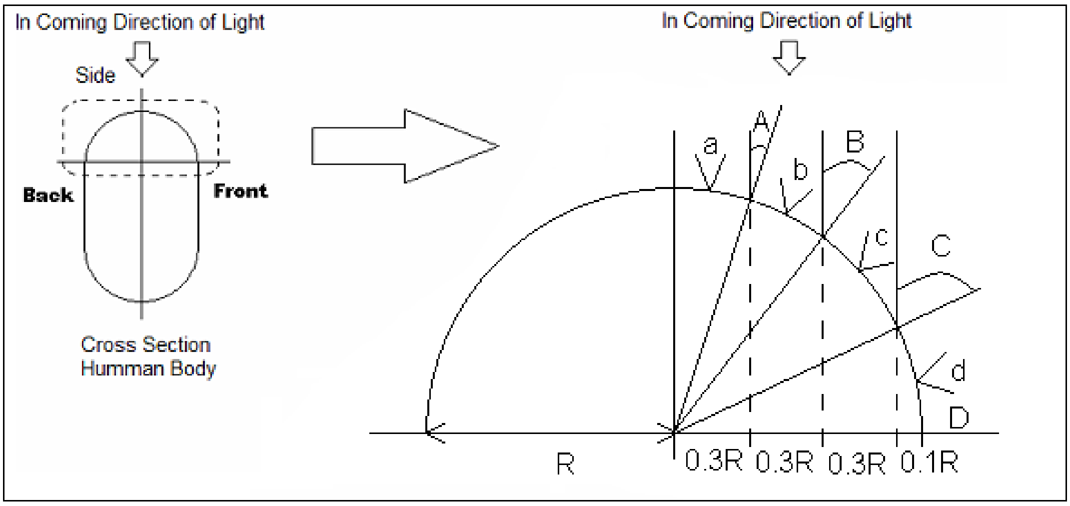
Figure 6 – Entrance Angle as listed in the "Standards" at Side View of Human Body



Source: King Tech Industry, San Diego, California, 2010

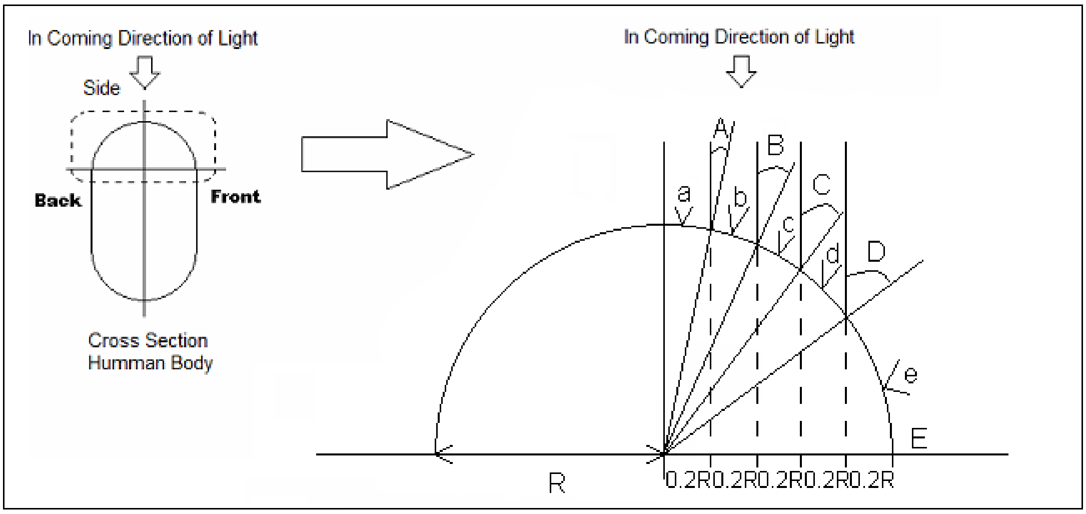
It is suggested that each of the entrance angles measured should represent equal segments of the visual area, as shown in Figure 7. The total visual area is smaller than the actual fabric area because part of the fabric surface is curved. Since workers are just as likely to be presenting the side of their body as they are to be facing an oncoming vehicle, and since the size of the side view is usually smaller than the front view, it is proposed that the side view shall be the governing size of reflective material needed in safety clothing design. The side view of a human body is assumed to be half of a cylinder shape and divided into several equal segments, as shown in Figure 7 and Figure 8. Whereas in Figure 7, the reflective area is divided into four segments, in Figure 8 it is divided into five segments. It has been computed that the end result of these two approaches is about the same.

Figure 7 -- Entrance Angle Divides into 4 Segments



Source: King Tech Industry, San Diego, California, 2010

Figure 8 -- Entrance Angle Divides into 5 Segments



Source: King Tech Industry, San Diego, California, 2010

Therefore, in the following analysis, Figure 7, consisting of 4 segments, is selected for analysis and discussion. Due to each of these entrance angles representing an equal visual size, each unit of the R_A measurement has the same weight and they may be summed together. Also, since what the driver sees is the combination of light reflected from all entrance angles, the minimum R_A requirement shall be the total of the R_A values measured at each observation angle. However, the group of entrance angles specified in the "Standards" different sizes of visual reflective area and the set of R_A values cannot be added together so that the minimum R_A cannot be specified. Each of the entrance angles should represent an equal reflective area, as shown in Figures 7 or 8, so that each of the measured values of R_A has the same weight and same meaning. At the same observation angle, summation of the set of R_A values with different entrance angles is what determines the visibility. It is wrong to specify each R_A to a specific value based on unjustified manufacturer specification.

Testing Observation Angle was Not Properly Selected in the "Standards"

At a certain critical detection distance, the driver of the vehicle can see the reflective material at a certain observation angle. The observation angle (OA) varies depending on the observation distance (OD) and the distance from the driver's eye level to the vehicles head lamps (ED).

$$OA = \tan^{-1} (ED/OD).$$

The distance from driver's eye to vehicle's head lamp, ED, varies. For most passenger cars, the average ED is 0.5 meter, as shown in two vehicles in Figure 9.

Figure 9 -- Group 1, Car and Truck with Eye to Headlamp Distance about 0.5m

The ED increases to about 1.2 meters for full size trucks and buses as show in Figure 10.

Figure 10 -- Group 2, Truck and Bus with Eye to Head Lamp Distance about 1.2m

The head lamp of extreme large-size commercial vehicles could be 2 meters lower from the top driver's seat as shown in Figure 11.

Figure 11 -- Group 3, Truck and Bus with Eye to Headlamp Distance about 2m

The purpose of selecting a group of observation angles for testing reflective materials in the laboratory is to make sure the reflective material may be observable at the critical detectable distance by drivers on most kind of vehicles. At a critical detecting distance of 140 meters, a car driver can see the reflected light with observation angle of 12' only, a regular truck or bus driver can see 30' only and for special truck and bus with the headlight really low, the driver can see that of 49' only. The Observation Angles for each type of vehicle are computed as follows:

For a critical detecting distance of 140 meters,

$$OA1 = \tan^{-1}(0.5/140) = 12'$$

$$OA2 = \tan^{-1}(1.2/140) = 30'$$

$$OA3 = \tan^{-1}(2.0/140) = 49'$$

Observation angles corresponding to distances less than the critical detecting distance are also important for the driver to continue to see the pedestrian. However, as the observation distance is reduced there is a corresponding to the fourth-power reduction in the required R_A for safe detection. All reflective fabrics in present technology have the property that the value of R_A at larger observation angles reduces at a lower rate than the distance effect. Therefore, it is not necessary to specify and measure R_A at observation angles larger than the critical observation angle.

Required Minimum Retro-Reflective Index (R_A)

The required minimum reflective index (R_A) for reflective material shall be set at the performance value after test exposure. Since most safety clothing is not disposable and is used repeatedly, the clothing is subjected to significant abrasion, flexing, folding, and washing during its lifetime, which inevitably will lead to degradation in the reflective performance.[2] Although accepting that the large disparity in the minimum performance requirements for new and worn garments in the "Standards" is no doubt intended to allow for this performance degradation during wear, it is considered to be illogical to have differing requirements for new versus used clothing. The minimum performance requirements for a safety garment must therefore be specified such that the wearer has the best possible protection throughout the life of the garment. Therefore, to be able to best protect the user, it is crucial that the minimum requirement should

[2] High Visibility personal protection garments have a limited lifetime and will wear out depending on their exposure and care. US Federal Highway Administration stated that the useful life of garments that are worn on a daily basis is approximately 6 months.

relate to used rather than new clothing. For used safety clothing, simply specifying that the retro-reflective performance after various test exposures should exceed 100 $cd.lux^{-1}m^{-2}$, at observation angle 12' and entrance angle 5°, as in ANSI/ISEA 107, section 8.2, and ignored all the other crucial observation angles which are impractical. The nighttime visibility or luminance is based on the light returned to the observer. It does not make any difference whether the reflector is a mirror, glass beads, micro prismatic PVC, or combined performance material. Therefore, the minimum coefficient of retro-reflection requirement for all material shall be the same. A separated R_A requirement for combined performance material as Table 6 of the EN471 is not necessary.

Analysis

The luminance intensity (I) is a function of the reflective index (R_A) and the total reflective area. The brightness of a safety garment is dependent on the total of the values of R_A within the reflective fabric for different entrance angles. It is not necessary that the R_A at each entrance angle and observation angle have to be above a minimum specific value, as in the "AZ Standards". The minimum required R_A should be the summation of the values for R_A with the same observation angle. The required reflective area

$$A = R_I / R_A$$

Before attempting to analyze and determine the minimum required reflective fabric properties for general public application, the following definitions are required:

- **Entrance Angle**: The angle between the incoming light and the line perpendicular to the plane of the reflective fabric surface.
- **Observation Angle**: The angle between the line from the light source to reflective fabric and the line from the reflective fabric to the driver's eyes.
- **Candela** (cd): the SI unit of **luminous intensity**, that is, the power emitted by a light source (e.g. from a vehicle's headlamps) in a particular direction.
- **Illuminance** (E), the amount of light striking a surface measured in lux (lx).
- **Luminance:** light retro-reflected back to an observer, seen as "brightness".
- **Luminous Intensity (I):** is the luminance measured in candelas per square meter ($cd.m^{-2}$)
- **Coefficient of luminous intensity (R_I):** is the ratio of the luminous intensity (I) of the reflector in the direction of the observer to the illuminance (E), expressed in candelas per lux ($cd.lx^{-1}$)
- **Coefficient of retro-reflective index (R_A) (**Reflectivity Index or Retro-reflective Photometric Performance): of a planar reflecting surface is the ratio of the coefficient of

luminous intensity (R_I) of a planar reflecting surface to its area (A) expressed in candelas per lux per square meter ($cd.lx^{-1}.m^{-2}$). **$R_A = R_I/A$.**

Since a car headlamp is a source of expansive lighting, as the distance (d) increases the illuminance on an object will decrease in a square power relationship (d^2) whilst at the same time the visual size of the object is decreased in proportion to the square root of the distance ($\sqrt{d}$). Therefore, when the distance is doubled and all the other elements remain constant, assuming all the illuminance (E) on the objective is retro- reflective to the observer, the luminous intensity (I) will be reduced to 1/16. But, due to the eye level of the driver being about 0.5 m above the level of the car headlight beam, as the observation distance is increased the observation angle will be decreased. When the observation angle is decreased, the reflective index (R_A) is increased for most of the retro-reflective material in the market. These two effects resulting from increasing distance tend to offset each other, but the inverse power relationship is usually dominant. Once the object has been observed, the luminance generally increases as the object gets closer.

The minimum required coefficient of retro-reflective index (R_A) in safety specifications shall reasonably match with the required minimum critical observing distance. Based on UMTRI 1998-50, Section 2.2, Driver characteristics:

> ***"****A more realistic preview time for long-range visual guidance appears to be 5* seconds, *with 3* seconds *as an absolute minimum preview time. At a speed of 100 km/h, 5 s would yield a preview distance of 140 m and 3 s would yield 84 m."*

Also, in Morkertrafik Night Traffic Rapport Nr. 5 1982,

> *"A safety distance of 140 m was adopted as the basis of technical requirement. This leads to a corresponding minimum coefficient of luminous intensity (R_I) requirement of about 300 mcd/lux for a safe detection by car drivers on vehicle illuminated road.*

It was thus demonstrated that the shortest safe visibility distance in a low-beam headlight situation, at a speed of 90 kilometer per hours (km/h), is 140 meters, and this visibility distance requires an R_I of 0.3 $cd.lx^{-1}$.

Observation Angle increases as the distance decreases. In average passenger cars, as of Group 1 in Figure 9, the driver's eye level is about 0.5 m above the car headlights. Hence, at a critical distance of 140 meters the observation angle is about 12' (0.2º), while the observation angle becomes 50' (0.8º) at a distance of 35 meters. A fully functional retro-reflective material must exhibit less than perfect retro-reflection. If all of the reflected light returns to the source of the light, in this case the car headlamps, then there is none of the light left for the drivers eyes to see.

In specifying the required levels of retro-reflectivity at a given observation angle allowance must also be made for the inevitable reduction in the coefficient of retro-reflectivity with increase in entrance angle. A reasonable matrix of desirable coefficients of retro-reflective index R_A performance requirements after test exposure is suggested in Table 2.

Table 2. Coefficient of retro-reflection index (R_A) ($cd.lux^{-1}m^{-2}$) after test exposure based on critical detection distance 140 meter. (90 km/h).

Group Observation Angle Type of Vehicle	Entrance Angle				
	9°	27°	50°	Σ	Minimum Area $cm^2/(in^2)$
Group 1, 12' Car and Small Truck	15	12	9	36	880/(136)
Group 2, 30' Bus & Truck	12	10	7	29	1,090/(169)
Group 3, 49' Extreme Size Truck & Bus	7	5	4	16	2,000/(310)

Source: King Tech Industry, San Diego, California, 2010.

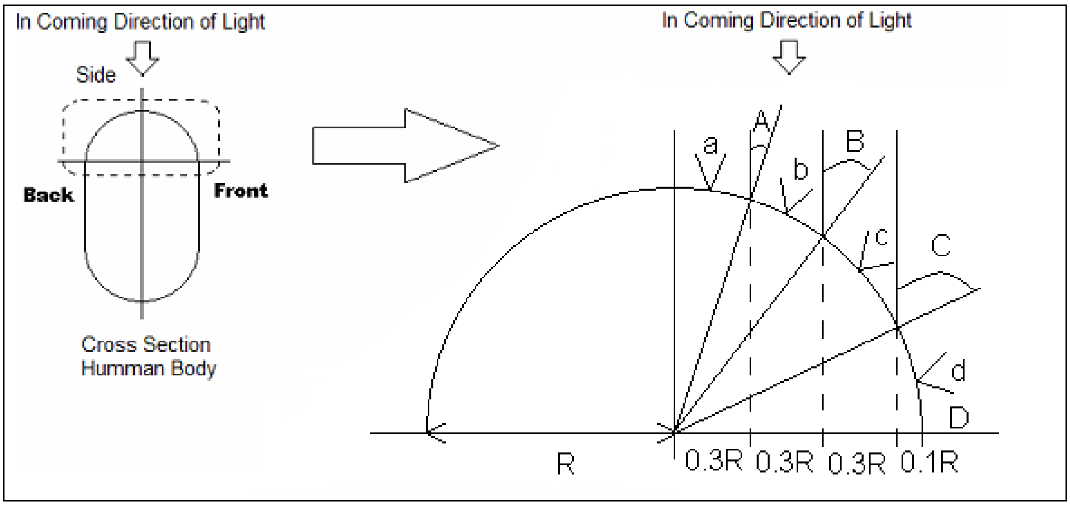
Required Reflective Fabric on High Visibility Safety Clothing

In designing high visibility safety reflective clothing, it is important for the driver to see the pedestrian at the critical distance. With the retro-reflective index values (R_A) of the fabric as in Table 2, the minimum required visible area of the retro-reflective component of the garment in all observing directions, can be computed as follows:

Average Retro-Reflective Index (R_A):

Assuming the side of a human body is in the shape of half of a cylinder, the slope is divided into four sections as show earlier in Figure 7. The average entrance angle is calculated as below:

Figure 7 -- Entrance Angle Divides into 4 Segments



Source: King Tech Industry, San Diego, California, 2010

Entrance Angle is the angle between the incoming light and the perpendicular line of the reflective fabric surface, where:

$$A = \sin^{-1}(0.3)$$
$$B = \sin^{-1}(0.6)$$
$$C = \sin^{-1}(0.9)$$
$$D = \sin^{-1}(1)$$

For example, the average Entrance Angles for the group of vehicles in Figure 9, with a critical detecting distance of 140 meters and the corresponding retro reflective index as in Table 2, are:

$a = A/2 = 9°$, $R_A\ (a) = 15\ cd.lx^{-1}m^{-2}$

$b = (A+B)/2 = 27°$, $R_A\ (b) = 12\ cd.lx^{-1}m^{-2}$

$c = (B+C)/2 = 50°$, $R_A\ (c) = 9\ cd.lx^{-1}m^{-2}$

R_A (d) assume 0 as Safety Factor.

Average $R_A = R_A\ (a)*0.3 + R_A\ (b)*0.3 + R_A\ (c)*0.3 + R_A\ (d)*0.1 = 10.8\ cd.lx^{-1}m^{-2}$

Required Design Reflective Area (Ad)

By definition,

$$R_I = A \times R_A$$

For a critical observation distance of 140 m with a calculated R_A at 10.8 $cd.lx^{-1}m^{-2}$ and with the required R_I = 0.3 $cd.lx^{-1}$, the required visible area will be

$$A = R_I / R_A = 0.028 \text{ m}^2 = 280 \text{ cm}^2.$$

However, since the person's shape is curved, some part of the object is not perpendicular to the observer, and the area view by the observer is actually smaller than the actual fabric area because of this curvature. The actual design reflective fabric area (Ad) should therefore be adjusted as indicated in the following function:

$$Ad = A (\pi R/2R) = 280 \text{ cm}^2 \times 1.57 = 440 \text{ cm}^2$$

Therefore the minimum design reflective fabric area (Ad) shall be not less than 440 cm^2 (or 68 in^2) facing towards any particular visual direction. The total reflective area of the garment, to include all directions of viewing, shall be twice this value, i.e., 880 cm^2.

Area Reflective Fabric and Silhouette Safety Clothing

When specifying safety clothing, other elements, such as comfort and appearance, must also be considered. After all, in order to give protection the clothing must be worn. It is also crucially important that the garment provides good day-time conspicuity, achieved by using a fluorescent-dyed background fabric and by choosing a retro-reflective pattern such that there is minimum interference with the resulting enhanced visibility in daylight.

Area reflective fabric uses a micro glass beads reflective system that covers only a portion of the base fabric so that the fabric has a softer handle and is breathable. Also, the color of base fabric can be revealed and graphic patterns can be designed to enhance the appearance and retain the day-time conspicuity. Since the area reflective fabric is able to preserve the most important characteristics and functions of the base fabric, it can serve as the main body of a garment. Also, since the color of the base fabric is revealed, when the background material conforms to the specified color requirements, the reflective fabric can also provide a credit toward the required area of back ground material, in that it has further enhanced the day time conspicuity. Nighttime conspicuity is currently achieved in traditional protective clothing by sewing or heat-sealing retro-reflective tape to the base fabric. When viewed at night by car headlights, the wearer of such clothing may not be immediately recognized as a human being. However, by using area reflective fabric a garment can be designed to outline the body shape in order to distinguish the human body from road signs or traffic markings. It is suggested that a class of silhouette safety garment to cover group 1 and group 2 vehicles at speed of 90 km/h or 55 mph be included in the standard. It shall have a minimum reflective area of 1,090 cm^2 (or 168 in^2) of reflective fabric, the reflective fabric having a minimum total R_A of 36 $cd.lx^{-1}m^{-2}$ measured at 12' observation angle (at the three entrance angles 9º, 27º and 50º) and total R_A of 29 $cd.lx^{-1}m^{-2}$ measured at 30' observation angle (at the same three entrance angles), as indicated in Table 2, to provide 360 degree visibility of the wearer at all viewing angles in horizontal plan and top view. See Figure 12 as an example.

Figure 12 -- Silhouette Reflective Safety Clothing

Source: King Tech Industry, San Diego, California, 2010.

A class of occupational safety clothing, to cover group 1, 2 and 3 vehicles, at 128 km/h or 80 mph, having a minimum reflective area of 2,000 cm^2 (or 310 in^2) reflective fabric, the reflective fabric having a minimum combined R_A of 150, 122 and 66 $cd.lx^{-1}m^{-2}$, measured at 6', 15' and 25' observation angles (each at the three entrance angles 9º, 27º and 50º) as indicated in Table 3.

Both the shirt as in Figure 5 and the existing class 3 safety clothing as in the “Standards” do meet the above specifications.

Conclusion

High visibility protective clothing must be capable of visually signaling the user’s presence. It is intended to provide conspicuity both during the day under any light conditions and at night under illumination by a vehicle’s dipped head-lights. A safe visibility distance during the daylight has been specified in most highway design standards. For those roadways not illuminated by street light but rely on vehicle head light in the dark, the detective distance is far shorter than that of required. The retro-reflective function shall be specified to cover the majority of night-time occurrences and to serve people traveling after dark. Reflective material can improve nighttime visibility, but in order to have safety effect, a High Visibility Safety Clothing must be designed visible by drivers of vehicles in Critical Detective distance. A minimum luminous intensity index 0.3 $cd.lx^{-1}$ is required for critical detective distance of 140 meter.

It is a wrong perception that the higher the reflective index the better. High reflective index material tend to reflect most of the light back to the source of the light which is a lamp. Considering the source of light a constant, when most of light returns to the lamp there will be less light for driver’s to see. What the driver can see is the part of light not perfectly returned to the source. Because of the driver’s eye level is a distance above head lamp. Therefore, specifying observation distance longer than critical detective distance is counter productive, and detrimental to the safety effect of retroreflective function. Observation angle shall be specified that drivers of most group of vehicle can see the object in critical distance.

In each observation distance or observation angle, what the driver has observed is the returning light from all the “Entrance Angle”. It is wrong and not necessary to specify those of (R_A) to be very high at small entrance angle and very low at large entrance angle as in the “Standards”. To be able to best represent the function of the retroreflective material, each of testing entrance angle shall represent similar size of reflective area. The luminous intensity**,** Coefficient of luminous intensity (R_I), is the summation of each Coefficient of retro-reflective index (R_A) times the correspondence area of the observed retroreflective material.

Over specifying the reflective index (R_A) is further detrimental to the safety because it reduces or eliminates other important functions such as comfort and appearance. On the other hand, reflective clothing that fails to meet the minimum luminous requirement will mislead people into believing they are visible while they are not. Therefore, it is essential for public safety to establish the minimum requirement of reflective index (R_A) and minimum reflective fabric area for high visibility safety clothing. However, the reflective index (R_A) data, as specified in the "Standards", do not relate to the minimum requirements nor does the apparel design configuration fully serve the safety purpose since they fail to take into account the obvious benefits of silhouette reflectivity. A suggested (R_A) requirement is listed in Table 2 of this paper.

The retro-reflective function shall be properly specified to serve occupational use and also a wider spectrum of people. In designing high visibility safety clothing the requirement of the reflective function shall be in balance with the other important elements of clothing such as comfort and fashion. After all, the safety effect prevails only if people are wearing it.

[6]. The containing of Table 4 and Table 5 in all the "Standards" are all the same, taken from the same source.

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