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Self-Illuminating Safety Vest

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Supplemental Notes

Abstract
The three models of self-illuminating vests were compared to a standard KDOT safety vest and a low-end off the shelf vest with respect to their nighttime visibility. The vests were mounted at an appropriate height for an average size worker, and a test vehicle was specially equipped to all accurate measurement of the orientation of the headlights relative to the vests. A digital video camera was used to record the vests from the drivers perspective at several vehicle orientations and distances, using both high beams, low beams, and without headlights. Custom software was developed to calculate visibility indices for each of the vests for each of the observed conditions. It was found that when the headlights were oriented directly at the vests, the self-illumination had little, if any, effect. Reflected light drowned out the self-illuminations. At eccentricities of 10 degrees, more than 20% of the vest brightness was due to the self illumination, and at eccentricities greater than 30 degrees, nearly all of the vest brightness was self-generated. The self-illuminating vests were more visible than the purely reflective vests under all conditions. In addition to the greater brightness, the blinking of the LEDs would presumably increase the vest conspicuity over a simply reflective vest, although this test did not measure conspicuity per se. The batter life was tested, and battery replacement costs would be negligible. The vests themselves are durable, but some care should be observed in storage not to damage the wires connecting the LEDs to the battery pack. The weight of the batteries was noticeable, but not egregious.

Midwest Smart Work Zone Deployment Initiative

Self-Illuminating Safety Vests
Final Report

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Self-illuminated Safety Vests

Description

The safety vests evaluated were orange with reflective yellow trim. They meet Kansas DOT requirements for safety vests. For nighttime operations, light emitting diodes (LEDs) within the reflective trim flash, making the vests self-illuminating, thereby increasing their conspicuity and improving the safety of the workers.

(Vendor)
Advanced Supply Company
PO Box 1340
Homewood, IL 60430
708 922 1057
708 922 1067 (fax)
http://www.advancedsupply.com

(Manufacturer)
Illumination Polymer Technologies, Inc.
1751 W Diehl Rd, Suite 110
Naperville, IL 60563
1 800 320 3801
1 630 717 6646 (fax)
http://www.illuminationpolymer.com/

The vests are available in a poncho style and in a split vest style, each costing $31.00 as of July 2002.

Study Site

The vests were tested in a controlled environment for visibility, then field tested for durability during the performance of other evaluations associated with the MwSWZDI.

Data Collection

A video technique was employed to compare the visibility of the vests under evaluation with a standard vest supplied by the Kansas DOT and a low-end vest acquired from retail hardware store. Figure 1 shows the safety vests that were included in the testing under daylight conditions as seen from the reverse. Table 1 provides a brief description of each vest.

Figure 1. Safety Vests Tested; shown in daylight conditions.

Table 1. Vest descriptions.

Vest ID	Description
1	Self-illuminating.
2	Self-illuminating.
3	Self-illuminating.
4	KDOT vest.
5	Low-end safety vest.

The goal of the evaluation was to assess the visibility of the self-illuminating safety vests relative to standard reflective safety vests with respect to their use in nighttime highway maintenance operations. Because the luminance of the self-illuminating vests is dynamic (i.e., the LEDs flash on and off approximately once per second), a measure of their lightness would actually be a conservative measure of effectiveness. Conspicuity is significantly increased when changes in luminance occur, as with the flashing LEDs of the self-illuminating vests, and a static measure of lightness ignores that effect. However, the effect of the flashing LEDs on conspicuity is very difficult to quantify, so this study relied solely on brightness for comparison.

A commercially available digital video camera, Sony TRV-900, was used for the data collection. The charge coupled devices (CCDs) in the camera are the receptors used to convert light energy into quantities eventually expressed as tristimulus components, or RGB coordinate triples, in which three numbers between 0 and 255 represent the red, green, and blue components, respectively, of the composite color of any pixel in the video frame. These numbers can then be retrieved, manipulated, and compared by a computer. Thus, the camera functioned as an array of light meters, each measuring the light at a particular point in the camera's field of view.

The Sony TRV900 was selected for the work because it was one of the least expensive digital video cameras that allowed complete manual control of the aperture, shutter speed, white balance, and focus. If any of these functions were automated, it could compromise the validity of many of the desired comparisons, essentially limiting the analysis to comparing vests shown

simultaneously in a video frame (as opposed to comparing vests at different distances, for example).

The quantities used to facilitate comparison of the vests with one another are referred to as brightness (discussed more fully later), although a word of caution is appropriate. The term brightness is correct, in that it implies a measure of light intensity as perceived by the human eye, which is the measure approximated in the analysis. However, the numbers cannot be assigned any standard units such as lumens or candela because no calibration of the cameras CCDs and associated components was performed. Such a calibration would be toilsome and would subsequently add very little to the evaluation, since the issue of interest is visibility relative to a particular standard reflective vest, that used by KDOT at the time of the study.

Because the distinguishing characteristic of the subject vests was their flashing LEDs, only nighttime visibility was tested. It was assumed that daytime visibility would be comparable to other similarly colored vests (e.g., KDOT vest, 4). To compare the visibility of the vests at night, a regional racetrack was rented. The location of the study site is sufficiently remote that no streetlights, building lights, or other manmade sources of illumination were visible, allowing the light reflected and generated by the vests to be isolated from external sources. Testing was performed during a new moon so that lunar illumination would not interfere with the measurements.

Figure 2 shows a sketch of the setup for the visibility testing. The vests were mounted approximately 4.5 ft above the pavement, emulating the height of a vest worn by a worker when standing. A test vehicle was positioned at various distances from the vests and oriented at various eccentricities relative to the vests. For each condition, a digital video camera was positioned outside the car, just to the left of the driver, mounted on a tripod 3.5 ft above the pavement to represent typical driver eye height. The sole illumination for the vests was the headlights of the car. For each condition, a short video clip was taken. The video clips would be postprocessed to extract the relative brightnesses of each vest. Conditions tested are described in Table 2.

Table 2. Conditions examined.

Distances (ft)	Eccentricities (degrees)	Lights
100, 200, 300, 500, 1000, 1500	0, 5, 10, 15, 20, 25, 30, 35, 40, 50, 60	One "no lights" condition was recorded at each distance. Each distance-eccentricity combination was recorded with both high beams and low beams.

The procedures required 5 workers. One worker drove the car (Driver). A second worker adjusted the lights used for aligning the car to the proper eccentricity (Marker Operator). A third worker operated the video camera (Camera Operator). A fourth worker directed the driver, as will be explained later (Spotter). The fifth worker monitored the vests in case the wind became sufficient to change the orientation of one of the three frames (Vest Monitor).

The vests were hung on racks as shown in Figure 3. The center rectangle of white poster board was intended to serve as a reference for brightness measurements. However, because it is non-reflective, its visibility was insufficient to be used as intended. Vests were simply compared

with the KDOT vest. The vests were mounted by hanging them on clothes hangers, two to a frame (for transportability). Pillows were used to emulate the shape of a human torso. They were covered in black so that the visibility of the vests would be isolated. The black pillowcases were pinned to clothes hangers at the top and fastened to a wooden rail at the bottom. The rail was affixed to the frames. This mounting system held the vests still in the mild wind present during the testing. The setup is shown during the test in Figure 4 with dimensions labeled.
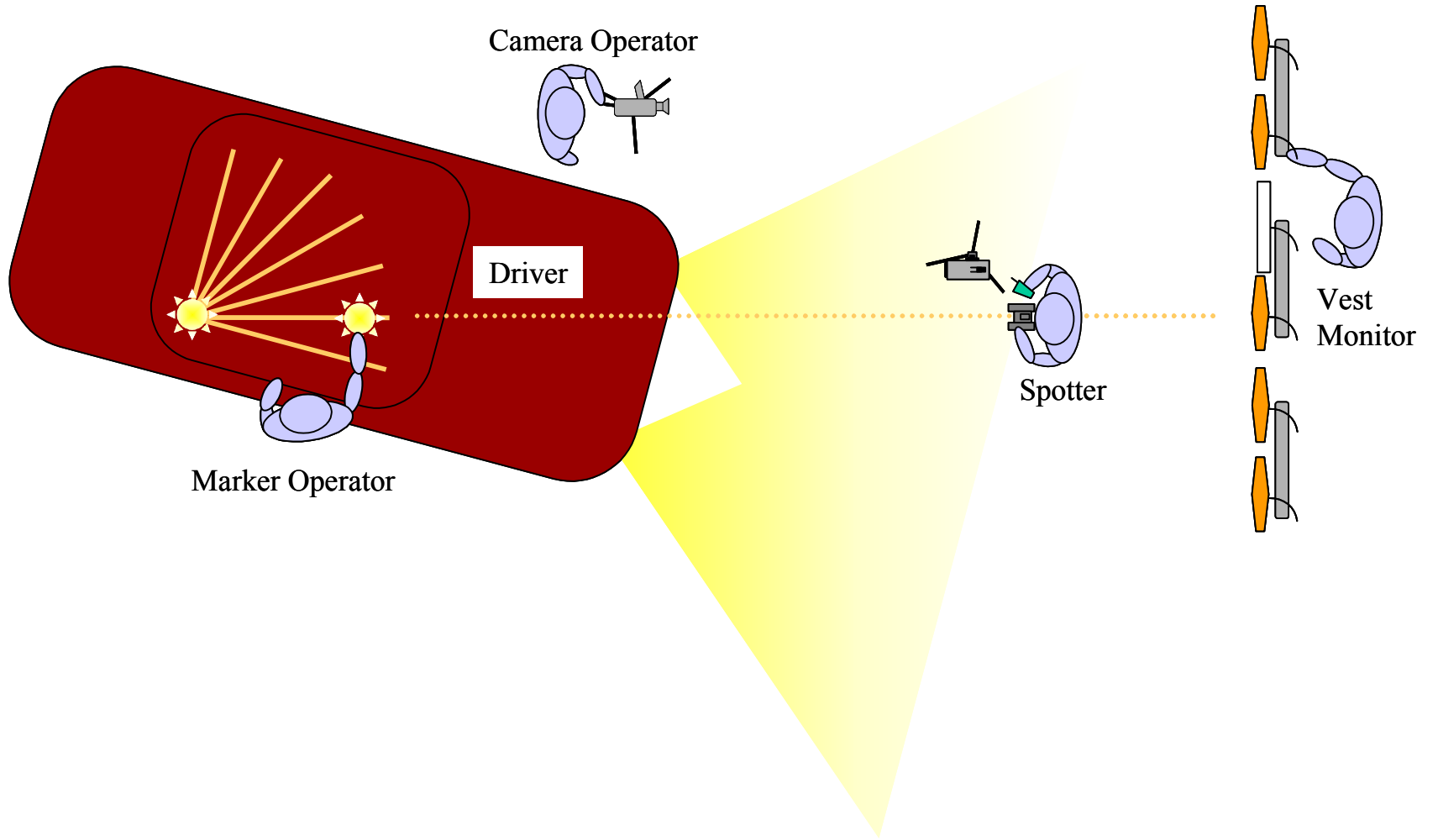
Figure 2. Diagram of test setup.

Camera Operator

Driver

Marker Operator

Spotter

Vest
Monitor

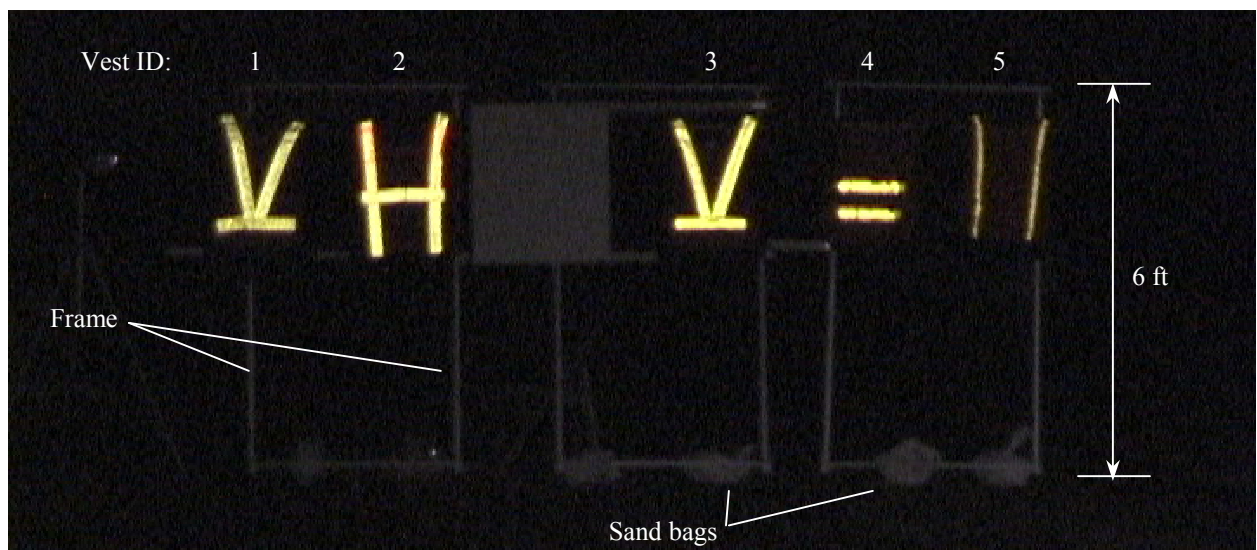**Figure 3. Safety vests as mounted for testing.**

Figure 4. Vests during test (200 ft, 0°, low beams).

The alignment of the vehicle was accomplished by marking off the appropriate eccentricities on the roof of the vehicle using masking tape, as shown in Figure 5. Two lights were used as markers. Both were covered in electrical tape so that only a 1-inch stripe of light was visible. The rear marker was left its original white while the forward marker was colored red, so that the two would be easily distinguishable. Self-adhesive magnetic strips were applied to the underside of each marker so that they could be easily moved, quickly set, and would remain stationary until intentionally moved. The forward marker is shown in Figure 6. The markers were set so that when the vehicle was at the appropriate eccentricity, the markers would line up from the perspective of the worker standing at the vests, as illustrated in Figure 7. So that the rear marker would not be hidden by the forward marker, a block of wood was inserted with a metal plate affixed. The marker was magnetically mounted to the block, and the block was magnetically mounted to the roof of the vehicle.

Figure 5. Eccentricities mapped out on the roof of the test vehicle. (Shown during daylight for illustration purposes.)

Handheld radios were used by the Driver, the Camera Operator, the Marker Operator, and the Spotter, who was positioned at the vests. The Driver initially pulled straight forward and

backward to the appropriate distance, as determined by a laser range finder operated by the Spotter. Once video was taken at 0° eccentricity, the Marker Operator repositioned the markers to indicate the next condition, 5°. The Driver cut the wheels hard right and eased forward until the Spotter, monitoring the marker lights with binoculars, radioed that the lights were properly aligned, indicating that the vehicle was oriented at the designated eccentricity. Another short section of video was recorded, and the process was repeated for the next eccentricity.

   After the data collection process above was completed, the batteries were all replaced with new alkaline batteries, and the vests were left on continuously to test the continuous battery life. Following those tests, the vests were used for the collection of data associated with other MwSWZDI evaluations to test their comfort and durability in field use.

Figure 6. Forward marker set to indicate 15 degrees eccentricity. (Shown during daylight for illustration purposes.)

Figure 7. Spotters perspective of markers when aligned. (Shown during daylight for illustration purposes.)

Data Analysis

In order to determine the visibility of the vests, it was necessary to consider several variables. First of all, the brighter a vest is, then the more visible it will be. However, vest brightness itself depends on both the amount of light it generates and the amount of light it reflects. Reflected light is proportional to incident light, the angle of incidence, and several material properties of the reflective material. Another variable to consider is the size of the lighted area. A vest with a very large lighted area would be more visible than a vest with a very small lighted area. To perform an accurate comparison between these vests, it was necessary to measure the visibility in a way that takes these variables into account.

Vest Lightness

Human vision is like most other senses, in that it does not act linearly. For example, if a human looked at an object that emitted a certain amount of light energy and an object that emitted twice the amount of light energy, the object that emits twice the energy would not be

perceived as being twice as bright. Since the methods used to measure the light energy measure on a linear scale, it is necessary to perform a transformation, so that the scale used to compare the vests, is a scale that represents the human perception of light. The human perceptual response to light is referred to as *lightness*. (CIE 1986) At lower light levels, human perception is approximately linear, and it follows a 1/3 power function at higher levels. The following equations were developed by the Commission Internationale de L'Éclairage (CIE), and are used to turn luminance values on any linear scale into lightness values, ranging from 1-100. The relationship is plotted in Figure 8.

Equation 1 - Lightness Conversion

$$\left\{ \begin{array}{ll} L* = 116 \times \left(\dfrac{Y}{Y_N}\right)^{\frac{1}{3}} - 16 & for\left(\dfrac{Y}{Y_N}\right) > 0.008856 \\ L* = 903.3 \times \left(\dfrac{Y}{Y_N}\right) & for\left(\dfrac{Y}{Y_N}\right) < 0.008856 \end{array} \right\}$$

where:

$L*$ = Lightness, perceived brightness
Y = Luminance, measured amount of light
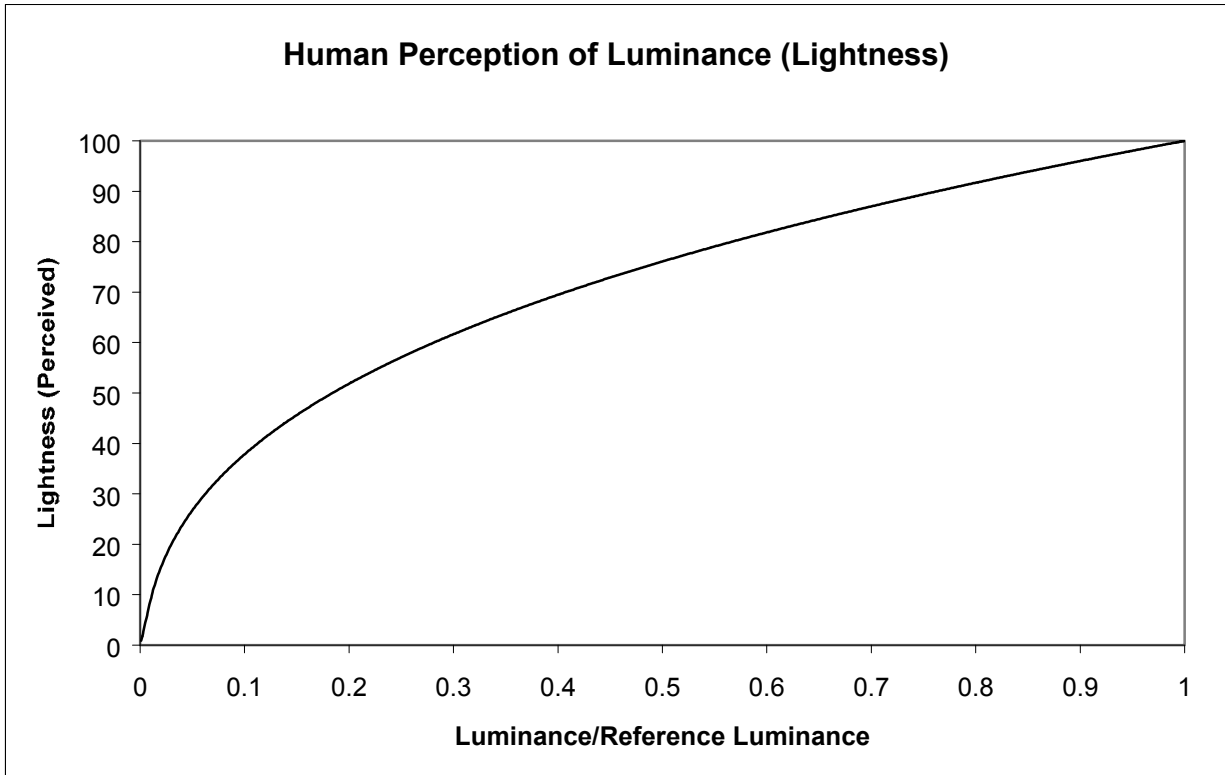Y_N = Luminance of Reference White, maximum light level

Figure 8 - Human Perception of Lightness

Luminance

The luminance values for the safety vests were obtained by videotaping the vests. The video camera captured the light in tristimulus components, or red, green and blue (RGB) values. The camera captured RGB values between 0 and 255 for each pixel in the frame, since the different colors each emit differing amounts of light energy it was necessary to perform a conversion. For example, a completely red pixel with RGB values of (255, 0, 0), red, green, and blue respectively, would be more luminescent than a completely blue pixel with RGB values of (0, 0, 255). The following equation was used to convert the tristimulus components into luminance.

Equation 2 - Luminance from Tristimulus Components

$$Y = 0.2126\ R + 0.7152\ G + 0.0722\ B$$

where
Y = Luminance (0-255)
R = Red component (0-255)
G = Green component (0-255)
B = Blue component (0-255)

Size of Lighted Area

As mentioned previously, the size of the lighted area also affects the visibility of the vests. A larger lighted area (from the perspective of the observer) results in greater visibility. Since the light was measured using a digital video camera with a zoom lens, it was necessary to transform the size of the captured images into an actual size and then into a perceived size based on the viewing distance. This was done by measuring the size of a fixed object on screen in pixels, and then using this area to determine a ratio of the respective scales of the two images as expressed in pixels per sq. inch. Once this was determined a few basic equations could be applied to determine the perceived size of each vest. Figure 9 shows the relationship between viewing distance and perceived size, using two different viewing distances. The amount of light emitted by the vests was recorded at several different distances, and at each distance a different zoom was used. This conversion was necessary in order to compare the vests at different distances.
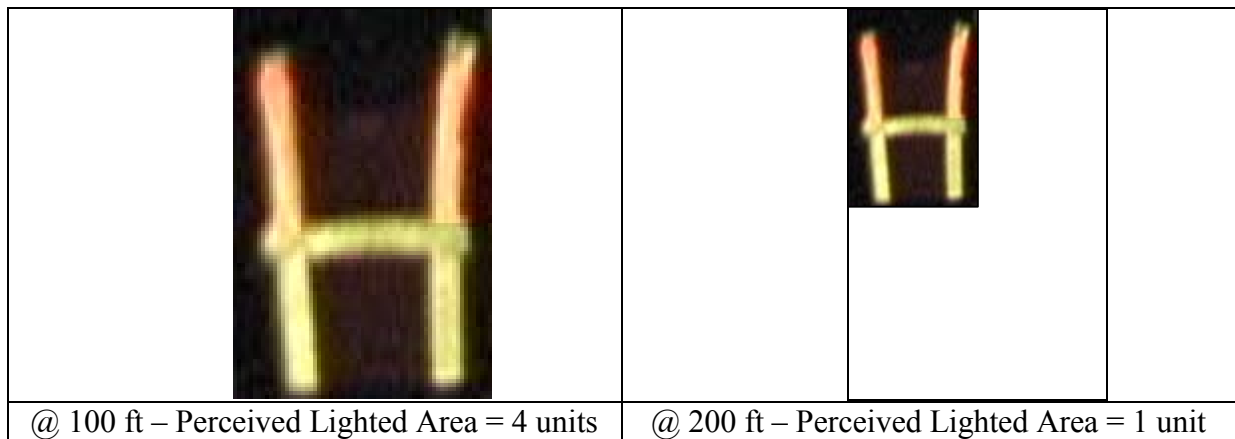

@ 100 ft – Perceived Lighted Area = 4 units	@ 200 ft – Perceived Lighted Area = 1 unit

Figure 9 - Perceived Vest Size

Dynamic Stimuli

While it is known that the blinking lights of the vests do aid in making the vests more visible, the extent of which is hard to quantify. The effects of the blinking lights are also different depending on the brightness of the retroreflective material. When the vests are exposed to the maximum amount of light, the blinking lights were barely distinguishable, and, on the other end of the spectrum, when very little light is incident on the vests, the blinking lights provide nearly the only visual stimuli. When comparing the vests, it was necessary to compare the lightness of the blinking vests with the lights off and with the lights on. The brightness of the vests without the LEDs illuminated can also be used to represent the condition where dead batteries or a broken wire have rendered the self-illumination inoperable. It was important to verify that the modifications made to accommodate the LEDs did not degrade the reflectivity of the vests to the point where such a condition in the field would result in insufficient visibility.

Analysis Program

To aid in the analysis, a computer program was created. The computer program was used to analyze each video frame by frame, calculate the lightness of each vest, and output summary data. This chapter describes the method used to determine which vest was the lightest, and describes the summary data.

Selecting the Vest

For each vest that appeared in the video a virtual box was created. This box is essentially a rectangle drawn on the screen, which encompasses the vest. The box stays in the same location relative to the screen throughout the entire video. The vests location on the screen may move around slightly throughout the video, but never enough to drift outside of its box.

Finding the Lightest/Darkest Frames

For each frame in the video, the computer analyzes the luminance of all of the pixels within each of the boxes on the screen, and sums the lightness values for all non-black pixels. The sum of the lightness of the pixels will be referred to as *total brightness*. The total brightness value for each vest is used to compare every frame of video, so that the frame with the greatest total brightness and the frame with the least total brightness can be determined for each vest. This is done so that the vests with the blinking lights can be evaluated for when the light is on and for when it is off.

Analyzing Vests

Once the lightest and darkest frames for each vest are determined, these frames are then further analyzed in order to create more detailed output data. Table 3 shows descriptions of the data that was output for the lightest and the darkest frame for each vest.

Table 3 - Descriptions of Analysis Output

Total Brightness	Sum of the lightness values of all non-black pixels within a vest's box
Total Pixels	The total number of non-black pixels within a vest's box
Average Brightness	The average lightness value of all non-black pixels within a vest's box *Average Brightness = Total Brightness / Total Pixels*
Max Brightness	The greatest lightness value of all the pixels within a vest's box
Top 10 Brightness	The number of pixels that were in the top 10% of a box's lightness *Number of Pixels with Lightness >= 0.9 * Max Brightness*
Frame Number	Index number of the lightest/darkest frame being analyzed
Distribution [index]	An array that contains the frequency distribution for the lightness values of every pixel in a vest's box

In the data analysis, the Total Brightness parameter proved to be the most useful in examining the differences between the vests. Other parameters were used to identify potential errors in the master data set, but they are not discussed in this document simply because they add very little to the comparisons between vests.

Black Pixels

Many times the description of the analysis states that only *non-black* pixels were analyzed. *Non-black* pixels refers to pixels that have a lightness value greater than 46. This value was determined by analyzing many areas of the black background within the video, and analyzing the distribution of pixels to determine a cutoff value that would eliminate most of the background from the analysis, without removing any of the lighted area. Figure 10 is a histogram of the lightness values obtained from analyzing a large area of the black background, and a vest. Figure 11 contains the still frames of the parts of the video that are analyzed in Figure 10. The lightness histogram shows that the black background does not just have a constant lightness value of zero, but it has quite a range of lightness values that seem to be normally distributed. The lighted vest's box contains mostly black background, but it also contains a lighted area with pixels that have a large range of lightness. From this histogram and many others it became apparent that a lightness value of 46 was the best cutoff value to use.
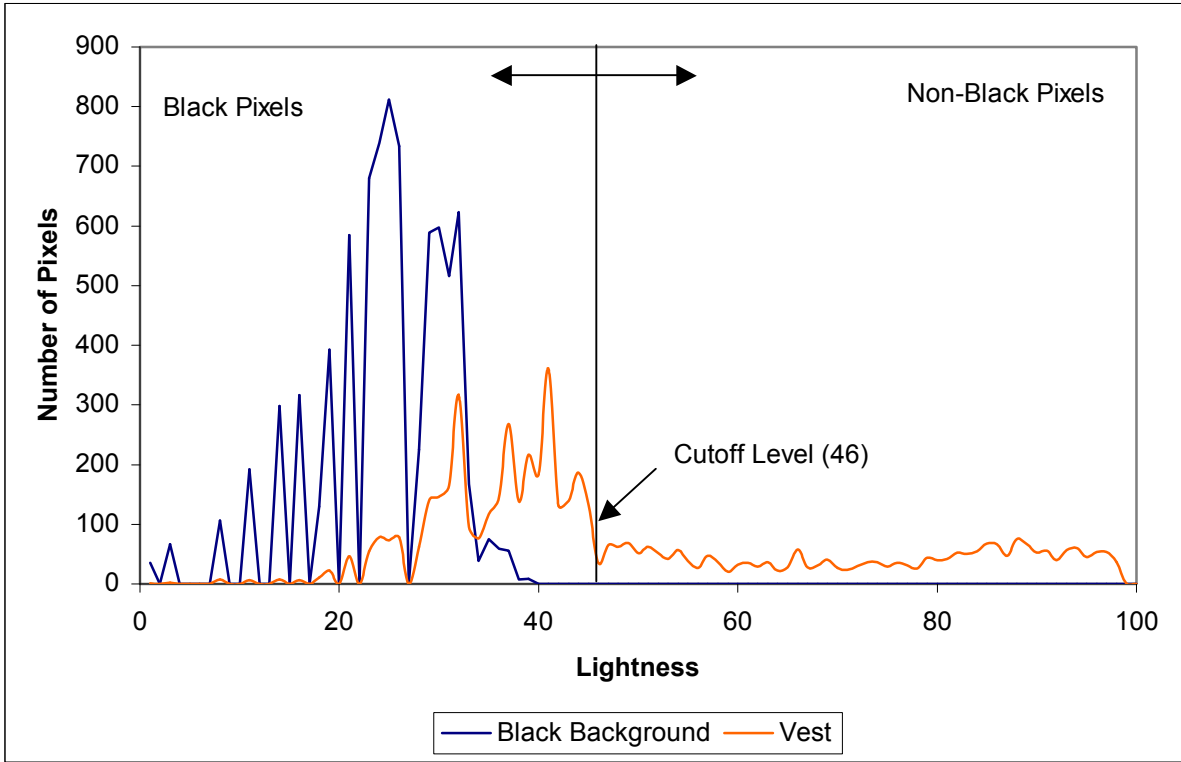
Figure 10 - Lightness Histogram

Figure 11 - Black Background* (Left) and Lighted Vest (Right)
*Note: the variation among the pixels in the left image above is very subtle, and may not be distinguishable on photocopies or with certain printers.

It was necessary to eliminate the effect of the lightness of the black background in the analysis so that the output would not be a function of the size of the box drawn around the vest. Since the box is drawn by hand, each time a video is analyzed, its box must be a slightly different size, and if the black pixels are included in the analysis it's total brightness and other output data will vary each time the video is analyzed. With the black pixels not included in the analysis, the analysis yields nearly identical output from every run regardless of the size of the box drawn around the vest.
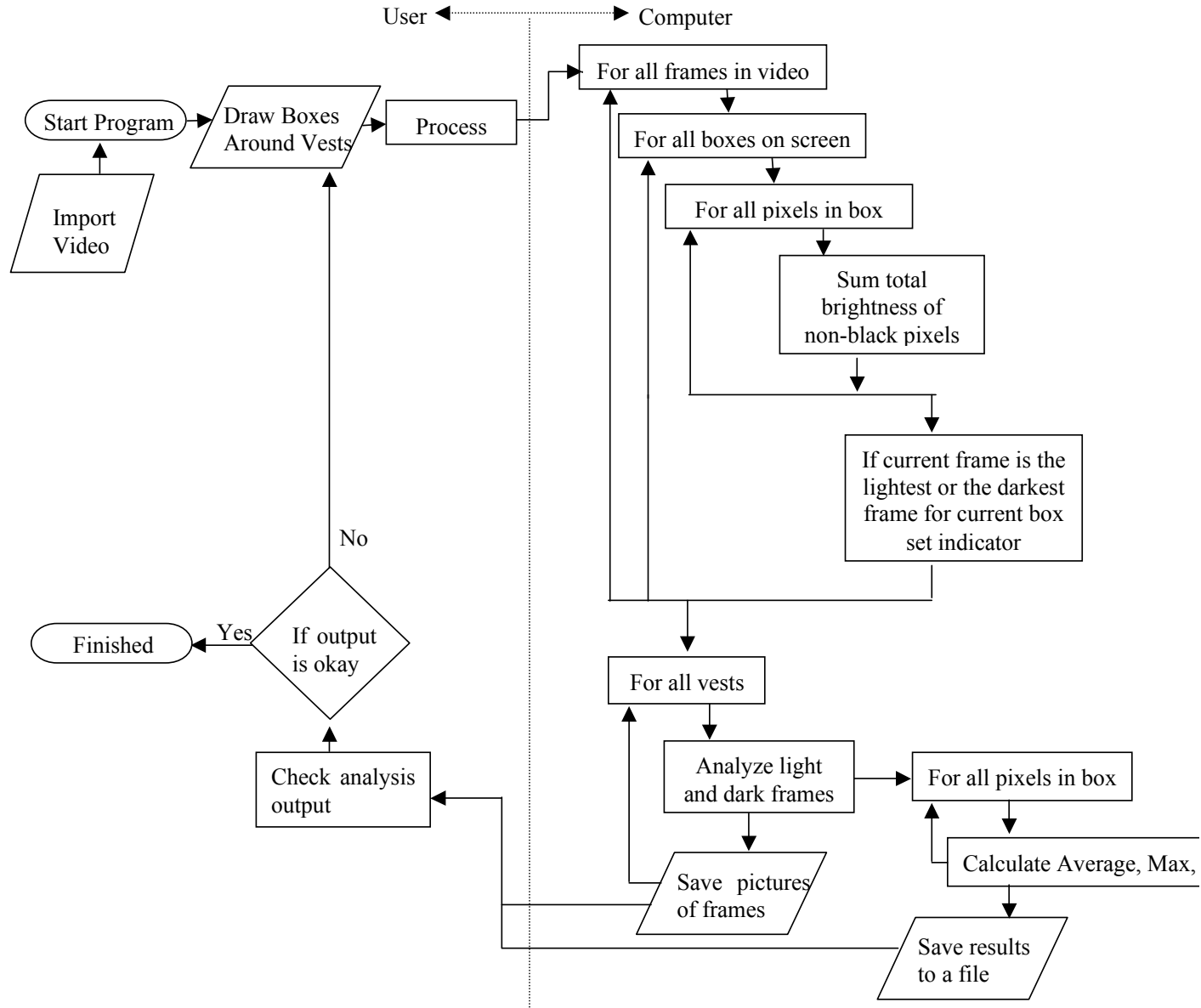
User ◄┄┄┄┄┄┄► Computer

Start Program → Draw Boxes Around Vests → Process

Import Video

For all frames in video

For all boxes on screen

For all pixels in box

Sum total brightness of non-black pixels

If current frame is the lightest or the darkest frame for current box set indicator

No

Finished ◄ Yes ─ If output is okay

Check analysis output

For all vests

Analyze light and dark frames → For all pixels in box

Calculate Average, Max,

Save pictures of frames

Save results to a file

Figure 12. Processing sequence.

Results

ANOVA was applied to the data. Vests 1, 2, and 3 were shown to be different than Vest 4. When dark frames (i.e., when the LEDs were off) were used for the comparisons, the P-values (the probability that the means are identical) were of the order of 0.0001, indicating that the probability of the means being identical was less than one tenth of one percent (VERY small). When the light frames (i.e., when the LEDs were on) were used for the comparisons, the P-values were 4 or more orders of magnitude smaller. Visually, this difference was just as obvious as the numbers would suggest it might be. Vest 5, the low-end vest, was undiscernable or nearly so in almost all conditions.

The numbers used in the analysis ranged from 0 to about 300,000. As mentioned earlier, because no calibration of the camera as a light meter was performed, the numbers cannot be assigned units, and merely express a lightness relative to the other vests. 300,000 represents the lightness of the most reflective vests when the test vehicles headlights were at a distance of 200 ft, an eccentricity of 0 degrees (i.e., head on), and set to high beams. Values below 5,000 require close scrutiny to distinguish the vest from the background, and would be virtually invisible to a driver. Figure 14 and Figure 15 show samples of various values for each of the five vests included in this study. Each vest image is labeled to indicate the conditions under which the image was obtained. The format for the labels is provided in Figure 13.
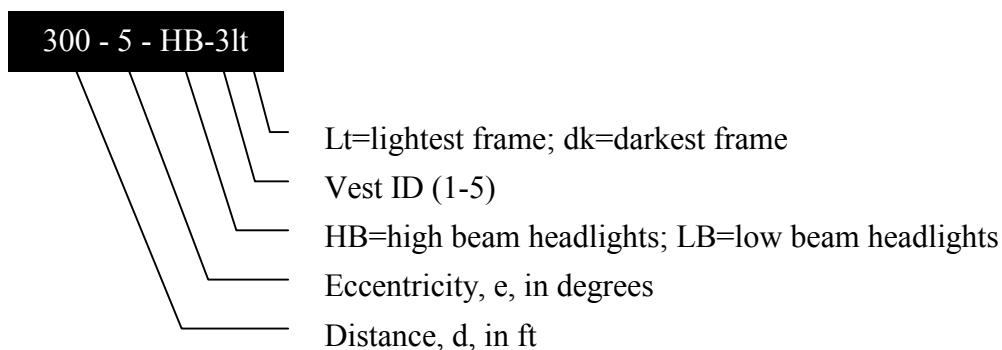

300 - 5 - HB-3lt

- Lt=lightest frame; dk=darkest frame
- Vest ID (1-5)
- HB=high beam headlights; LB=low beam headlights
- Eccentricity, e, in degrees
- Distance, d, in ft

Figure 13. Label format for sample vest images.

Figure 16 and Figure 17 show the brightness values for Vest 2 and Vest 4, respectively. Linear interpolation was employed to estimate values for eccentricities and distances that were not measured directly. The two plots clearly show that Vest 2 is brighter at greater distances and greater eccentricities than Vest 4. For eccentricities greater than 30°, the brightness of Vest 4 is near zero, while that of Vest 2 remains at or above 5,000 for all eccentricities at distances up to 1,000 ft. Vest 1 and Vest 3 are very similar to Vest 2. Vest 5 shows a similar pattern, though less bright in all regards. Vest 5 values are about 20,000 less than Vest 4 at 200 ft, 15,000 less at 300 ft, and 5,000 less at 500 ft.
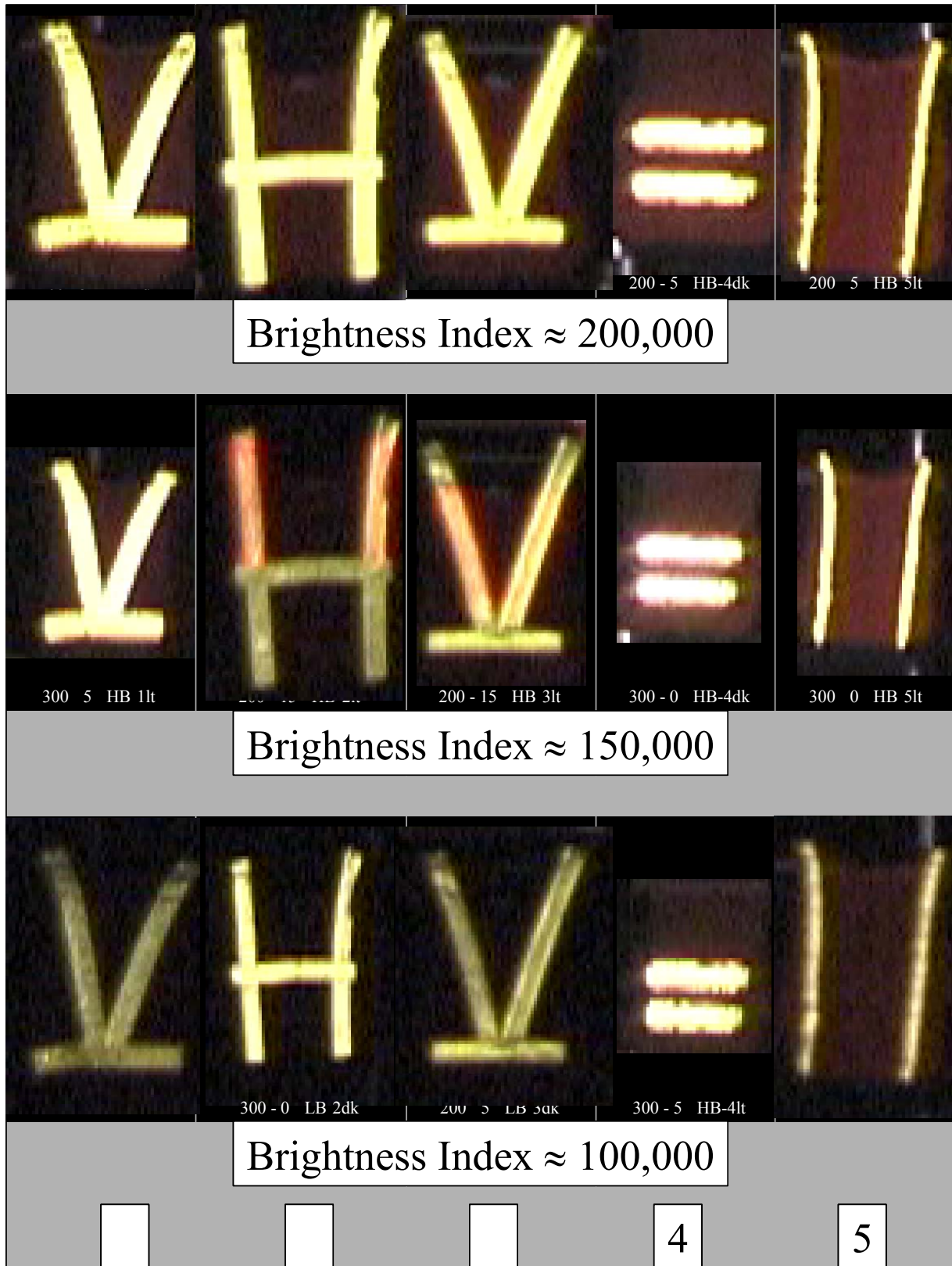
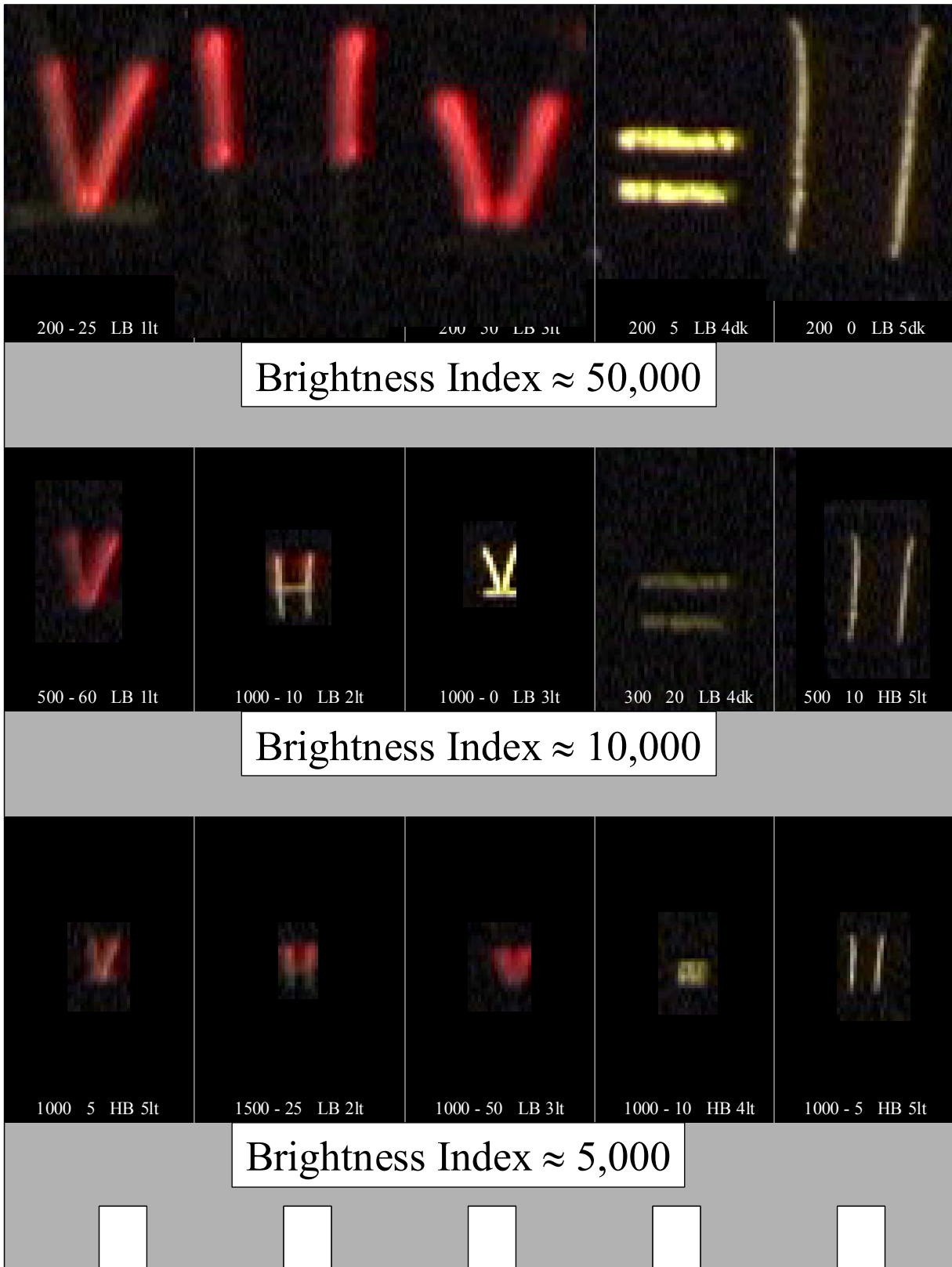**Figure 14. Examples of Brightness Index Values 100,000, 150,000, and 200,000.**

20

Figure 15. Examples of Brightness Index Values 5,000, 10,000, and 50,000.
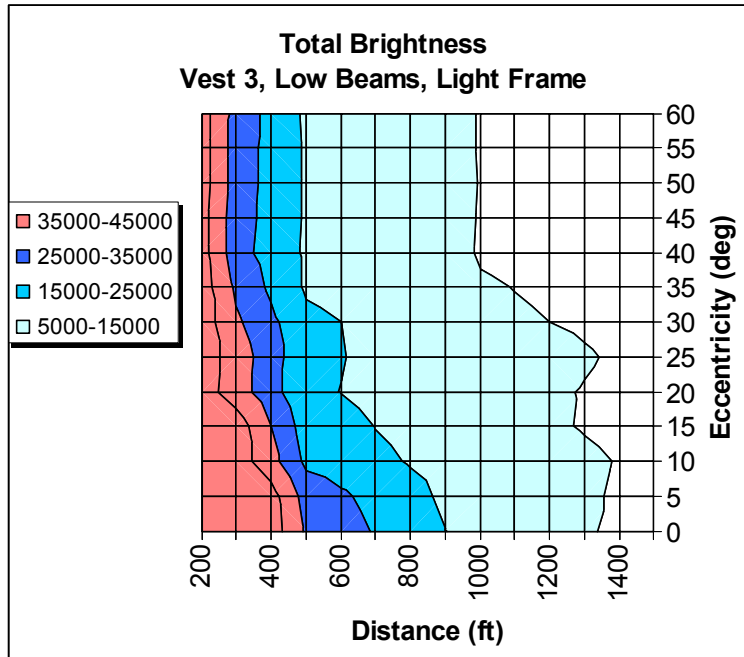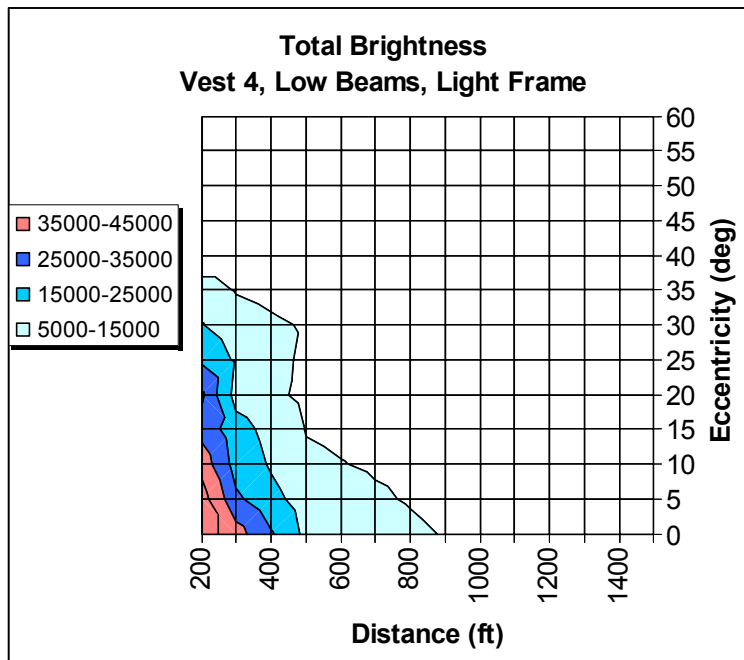
Total Brightness
Vest 3, Low Beams, Light Frame

Legend:
- 35000-45000
- 25000-35000
- 15000-25000
- 5000-15000

Eccentricity (deg): 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60
Distance (ft): 200, 400, 600, 800, 1000, 1200, 1400

Figure 16. Total Brightness for Vest 3.

Total Brightness
Vest 4, Low Beams, Light Frame

Legend:
- 35000-45000
- 25000-35000
- 15000-25000
- 5000-15000

Eccentricity (deg): 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60
Distance (ft): 200, 400, 600, 800, 1000, 1200, 1400

Figure 17. Total Brightness for Vest 4.

The following discussion of the results of the tests include distances ranging from 200 ft to 1500 ft. However, the middle distances of 500 ft and 1000 ft are arguably the most important,

22

based on the presupposition that the speeds of greatest interest are those most commonly encountered on rural highways in the midwest, ranging from about 50 to 70 mph. This range of speeds implies a range of stopping distances that roughly corresponds to the 500 ft and 1000 ft mentioned above. For reference, Figure 18 shows a plot of stopping sight distance versus speed.
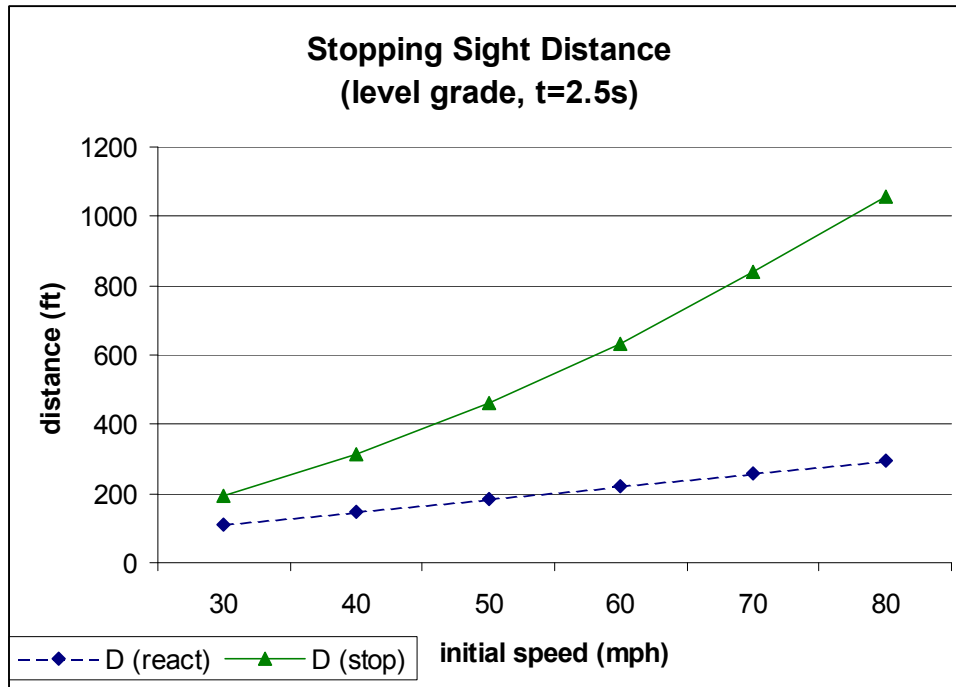

Figure 18. Reaction and stopping distance vs speed.

To isolate the brightness of the internal lights over and above reflected illumination, for each condition and each vest, the respective video footage was processed to identify the frame in which the given vest was the lightest and the frame in which the given vest is the darkest. For vests 4 and 5, without internal lights, the differences are trivial. For vests 1, 2, and 3, though, the lightest frame occurs when the lights are on and the darkest frame occurs when the lights are off. So, by subtracting the brightness index from the darkest frame from that of the lightest frame, the effect of the lights on vest brightness can be determined. Figure 19, Figure 20, and Figure 21 show the difference between the lightest and darkest frames for Vests 1, 2, and 3. For distances up to 500 ft, the internal lights accounts for 25% or more of the vests' brightness at eccentricities of more than 15° or more. For distances over 500 ft and up to 1000 ft, this is true for eccentricities over 10°. For eccentricities greater than 25°, the internal lights account for more than half of the brightness of the vest at all distances. Such eccentricities are commonplace for any classification of highway. For example, a distance of 500 ft and an eccentricity of 10° if occurring on a continuous curve would correspond to degree of curvature of 2°. It could also correspond to a shorter arc of a sharper curve followed by a tangent section. The point is that while direct headlights reflected off the vests at distances of 1000 ft or less essentially drown out

the LEDs, thus negating the advantage of the self-illumination, the circumstances in which this would not occur because of a combination of distance and eccentricity are plentiful, perhaps even in the majority.
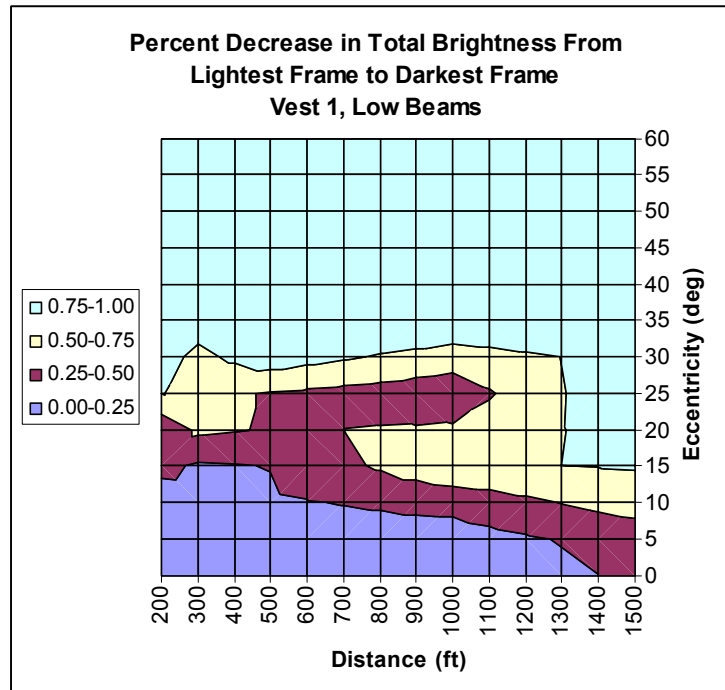

Figure 19. Effect of lights on total brightness, Vest 1.

At eccentricities greater than about 25°, nearly all the brightness of the vest is attributable to the internal lights. The cause is simply that the lens on the test vehicles headlights focuses the light forward, where the light is most useful to the driver. An eccentricity of 25° corresponds to a 500 ft arc of a 5° curve. Figure 22 and Figure 23 also illustrate this phenomena. At 500 ft, when the eccentricity exceeds 30°, all vests without internal lights (including Vests 1, 2, and 3 when the LEDs are off) have a total brightness of zero. They cannot be seen. The vests with internal lights maintain a brightness index of about 12,000 for eccentricities of 35° and above. The eccentricity of the headlights becomes irrelevant because nearly all the brightness is generated by the internal lights.
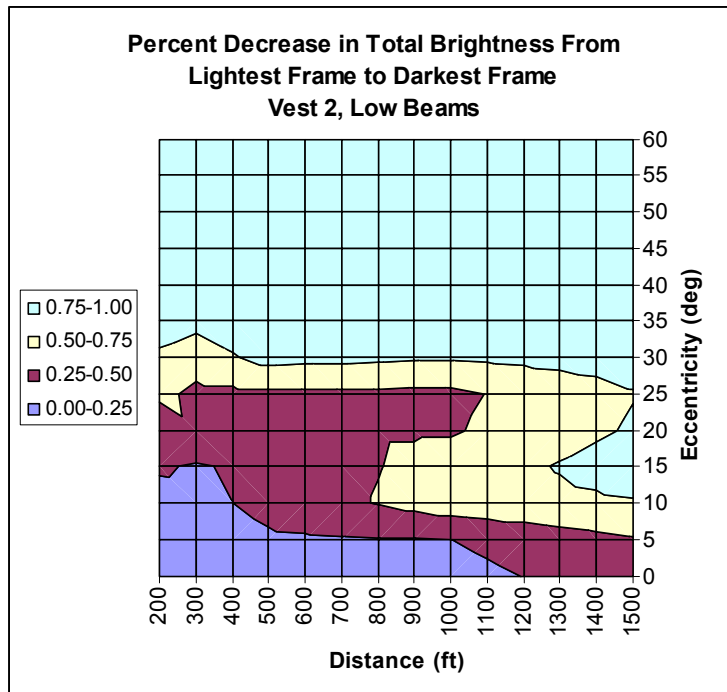
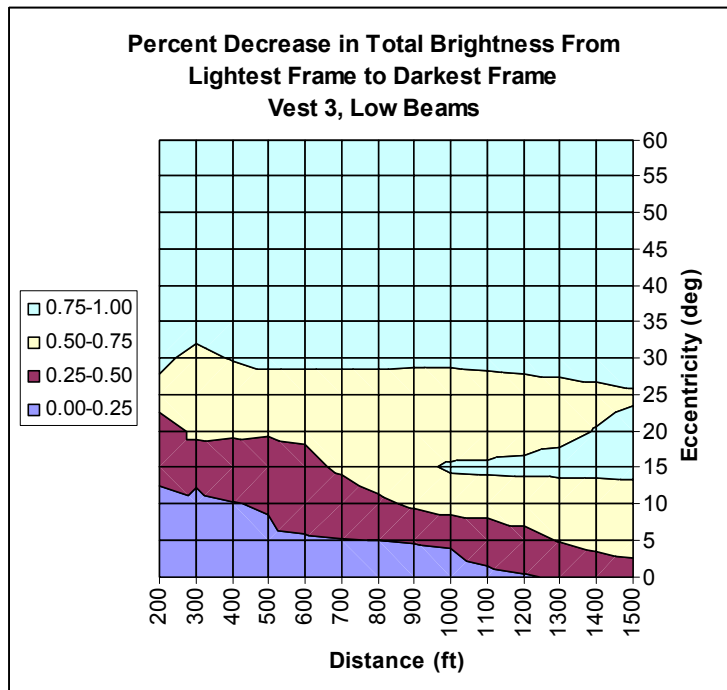**Figure 20. Effect of lights on total brightness, Vest 2.**

Figure 21. Effect of lights on total brightness, Vest 3.

Figure 22 and Figure 23 also show that Vests 1, 2, and 3 are more visible than Vest 4 in all cases, except when neither can be seen at all. This was an expected result because Vests 1, 2, and 3 had significantly more reflective surface area than did Vest 4 or Vest 5. Similarly, Vest 4 is somewhat more visible than Vest 5. Other distances show similar patterns.

In Figure 24, the characteristic inverse exponential curves again show that Vests 1, 2, and 3 are brighter than Vests 4, which is brighter than Vest 5. Incident light is inversely proportional to the square of the distance, so when only distance is varied, the resulting function is inverse exponential. All eccentricities exhibit a similar pattern, except those above 30°. Vests 4 and 5 were not visible at any of the distances from which observations were taken.

Figure 25 shows the vests to relative scale at the distances tested. At every distance, the lighted vest(s) are clearly brighter. Figure 23 depicts the vests at 500 ft for eccentricities up to 30°. At 0° and 5°, the LEDs are barely distinguishable, adding very little to the vests brightness. At 10°, their contribution is significant, and at 15° and higher, the LEDs provide almost all of the vest brightness, as can also be seen from the data shown in Figure 22 and Figure 23. Figure 27 shows the vests with and without the LEDs on.
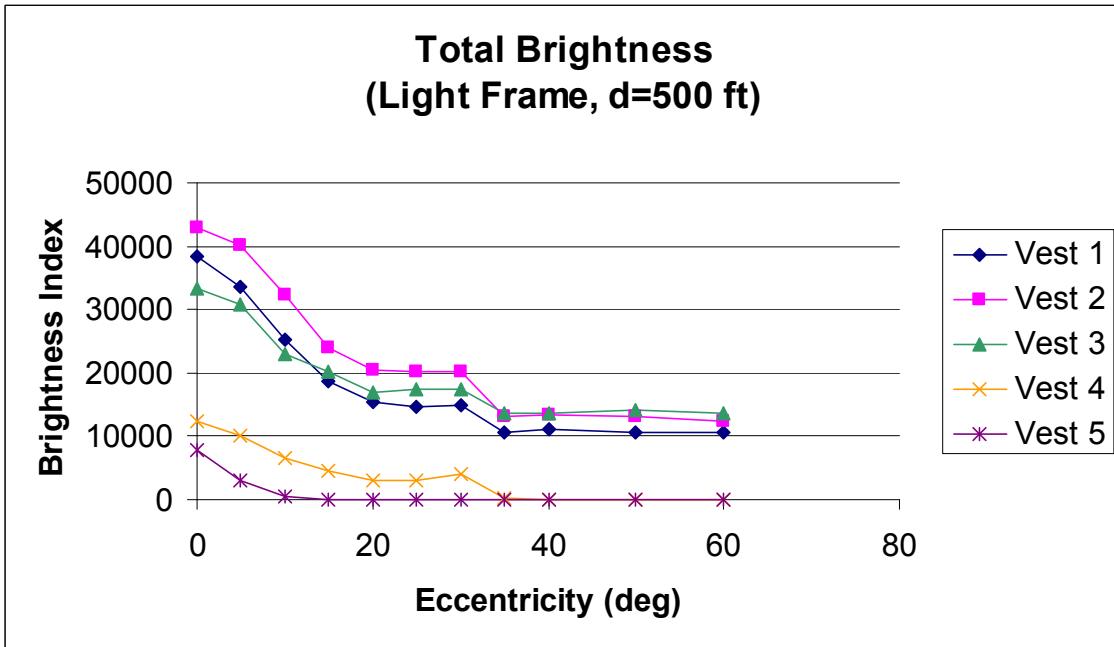
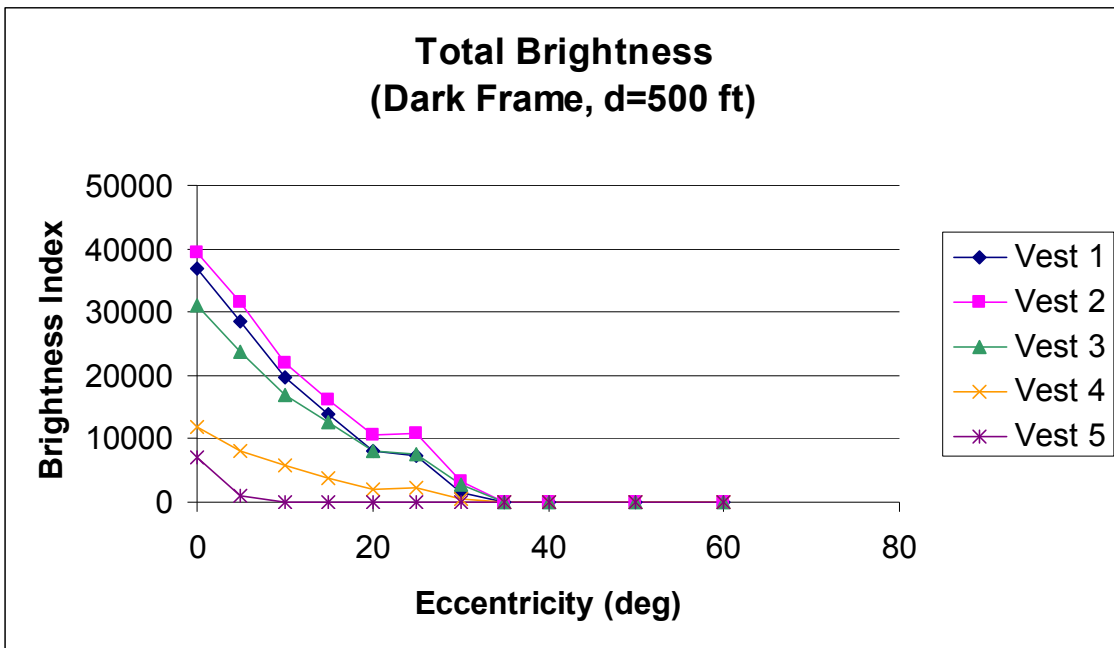**Figure 22. Total Brightness at 500 ft versus eccentricity, Light Frame.**

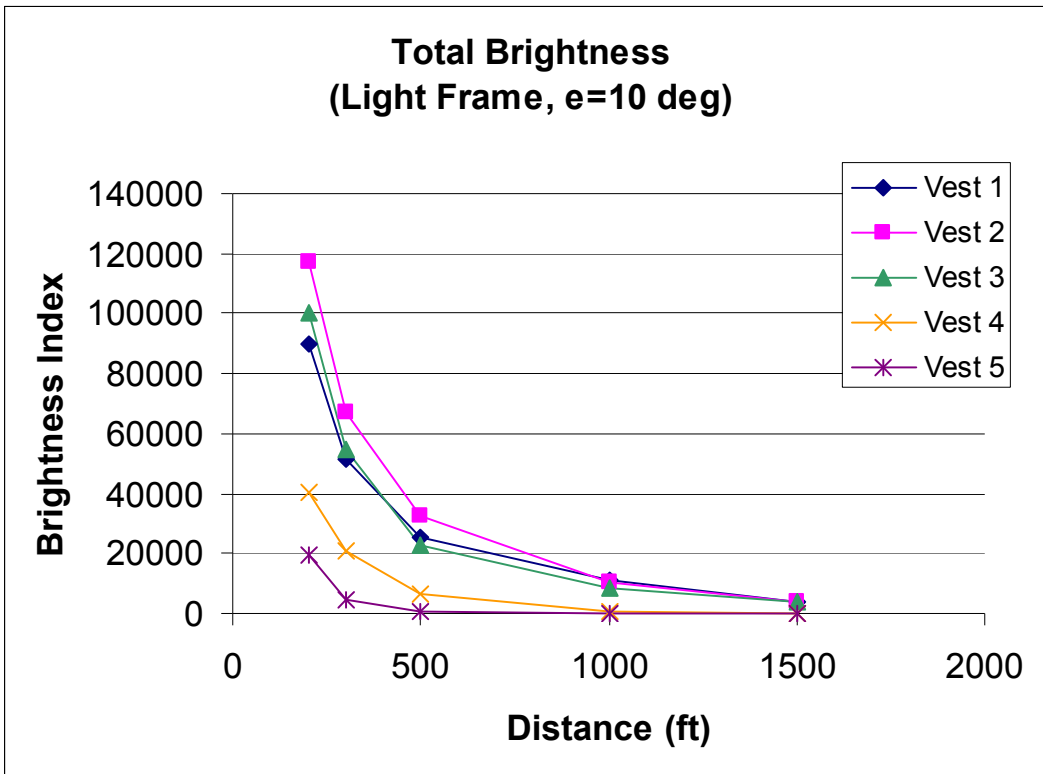**Figure 23. Total Brightness at 500 ft versus eccentricity, Dark Frame.**

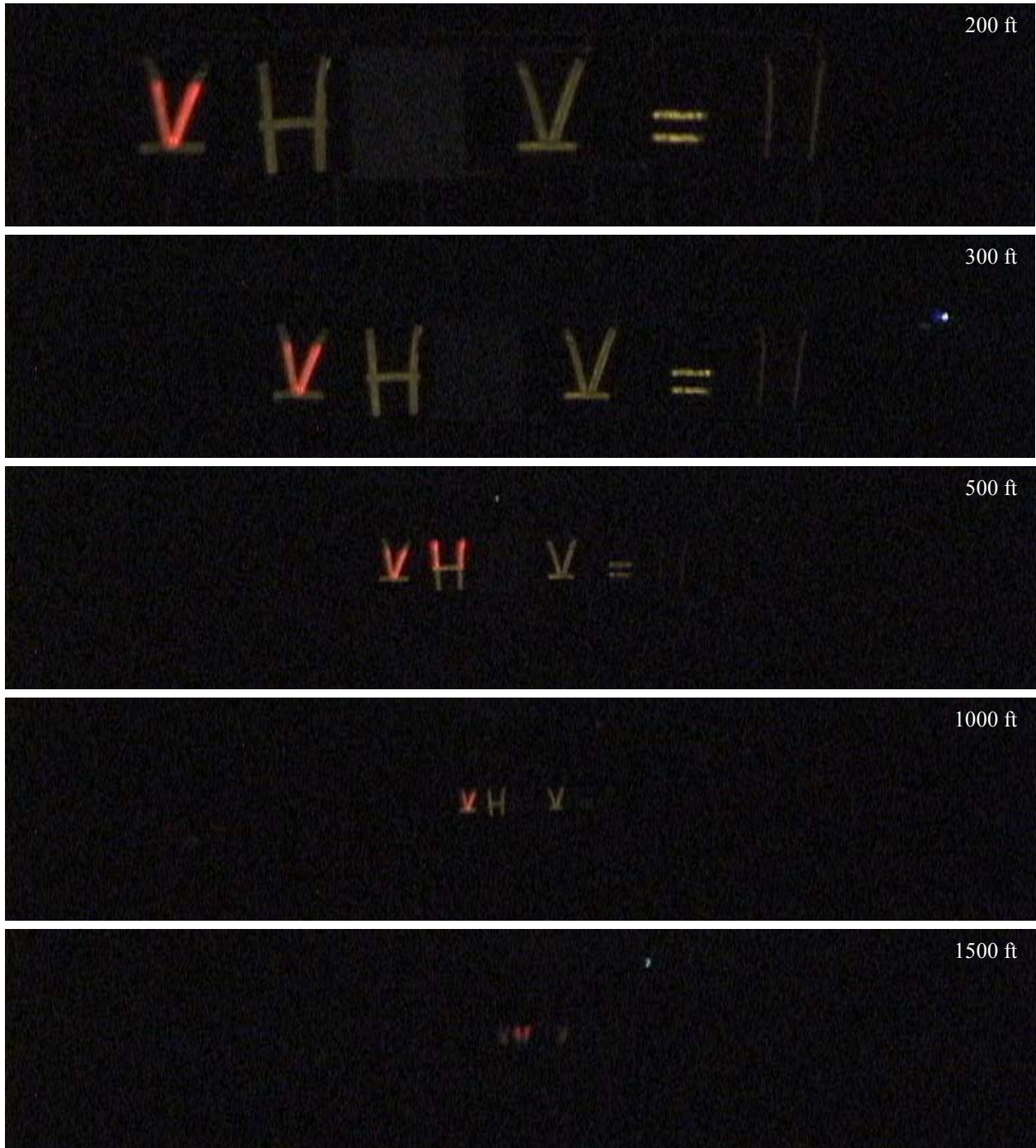**Figure 24. Total brightness at 10 degrees versus distance, light frames.**

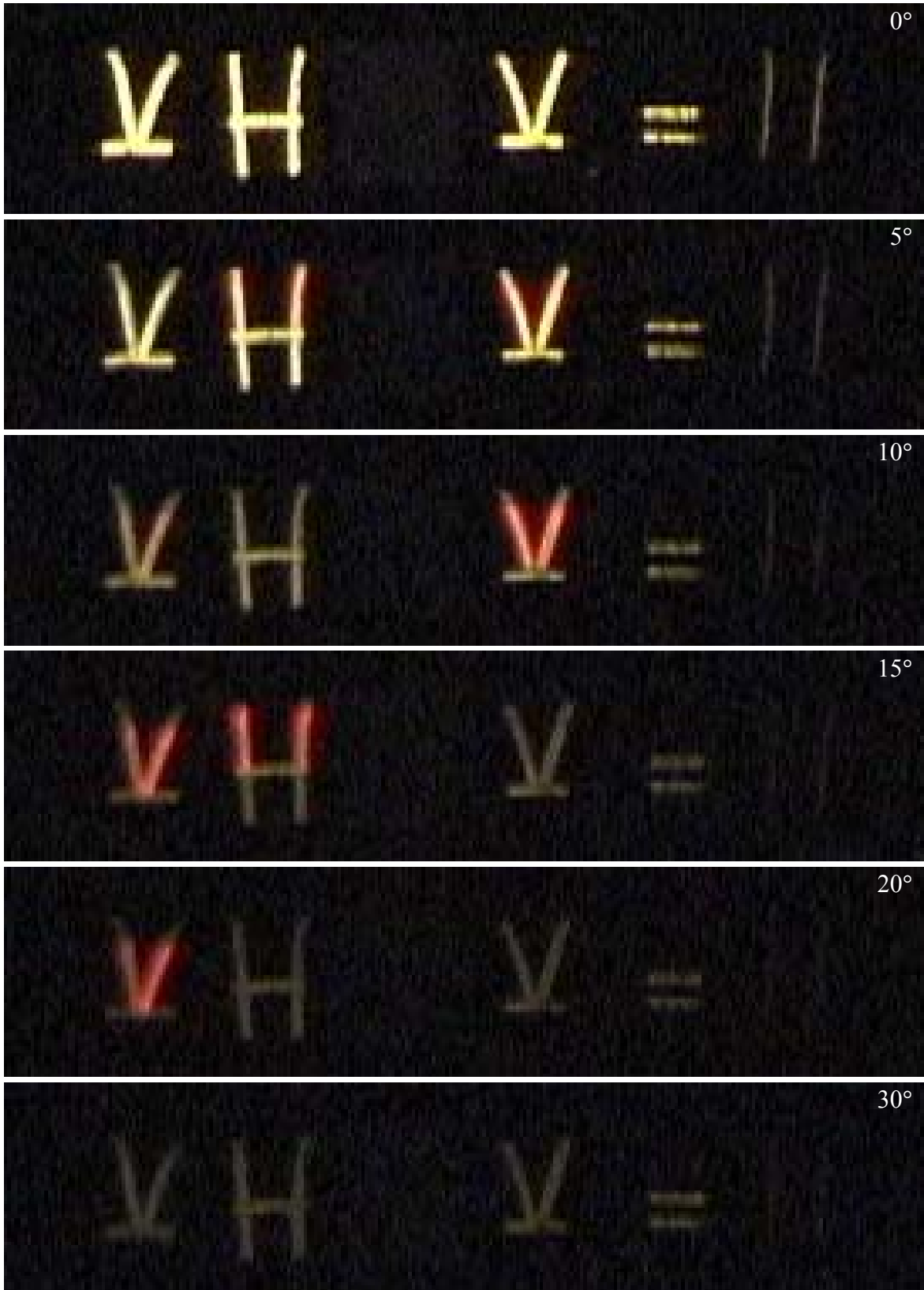**Figure 25. Comparative views of vests at various distances (15°, low beams).**

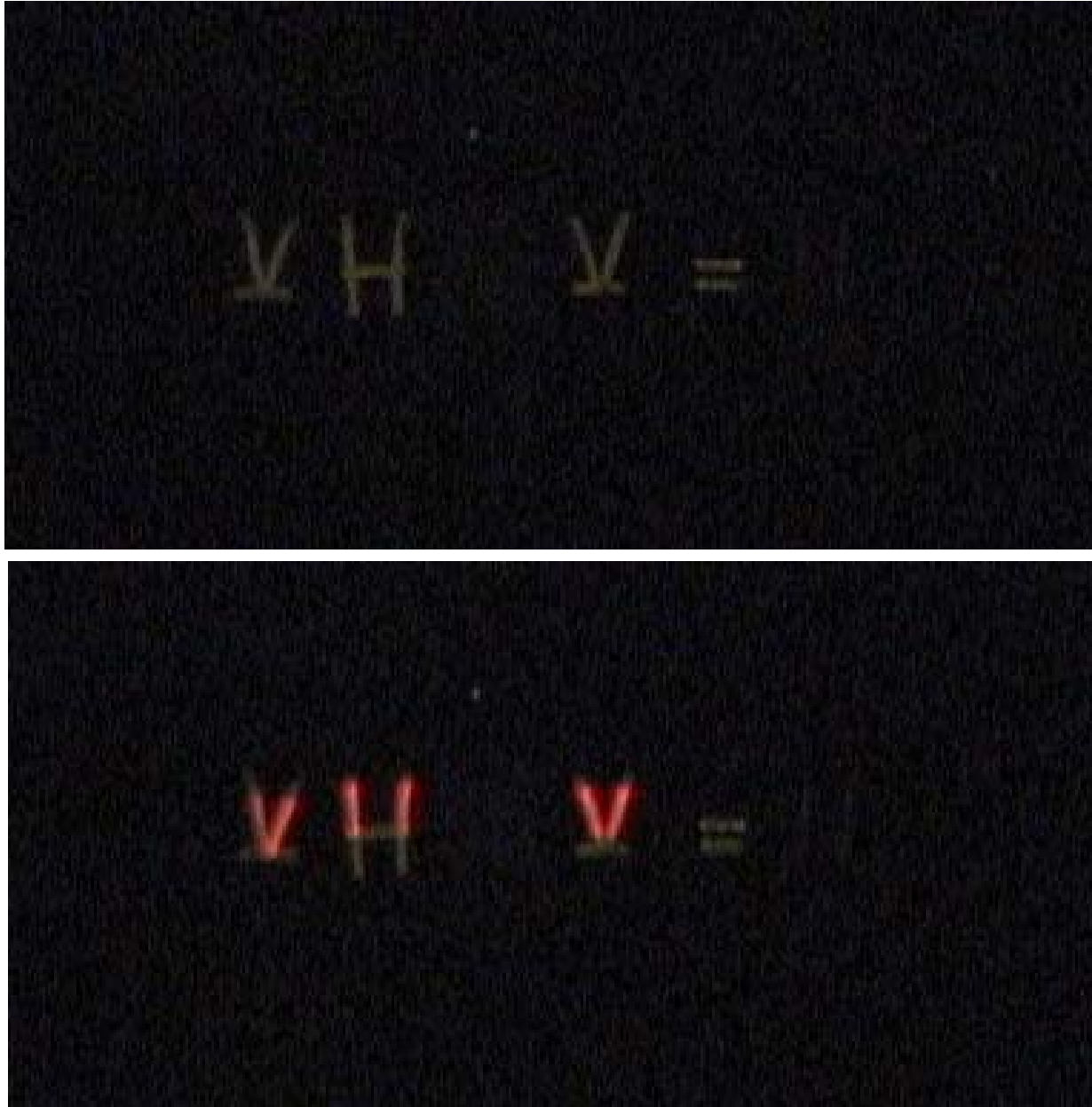**Figure 26. Vests at various eccetricities (500 ft, low beams).**

Figure 27. Vests with and without lights on (500 ft, 30°, low beams).

The vests were installed with new batteries and turned on to test the battery life. In continuous use, no noticeable decrease in brightness of the LEDs occurred for 4 to 5 weeks. At 6 weeks (about 1000 hours), the lights were noticeably less bright. These times are comparable to the manufacturer's claims, and should be conservative since the batteries will recharge slightly when the vests are turned off during the day.

The vests were used for normal field work approximately 1-2 days/week for 6 months. The battery packs were not cumbersome, and the vests were as comfortable as the KDOT vests.

Only two incidents of damage were observed. One of the elastic straps detached and had to be sewn back on, and a wire on one of the vests broke while the vest was being pulled from under some equipment, leaving the LEDs inoperable.

Conclusions

Based on the results of this study, the self-illuminating safety vests are significantly more visible than reflective vests alone. The brightness of reflective material depends on the amount of incident light, and the illumination from a vehicle's headlights decreases significantly with fairly small eccentricities. When the vehicle is oriented directly toward the vests, the reflected light drowns out the internal LEDs. However, with eccentricities as small as 10°, more than 20% of the vests brightness is due to the LEDs, and beyond 30°, nearly all of the brightness is attributable to the LEDs.

These tests measured only the brightness of the vests with and without the LEDs lit in order to compare vests in terms of *visibility*. The *conspicuity* of the vests was not explored explicitly. However, given that conspicuity is a function of visibility, the results of this study do imply that the self-illuminating vests (Vests 1, 2, and 3) would have a greater conspicuity than the standard KDOT vest (Vest 4). Their conspicuity would be further heightened by the blinking action of the LEDs, as local *changes* in luminance are more easily detected by the human eye than a static contrast with surroundings.

These tests were conducted in a semi-controlled environment to isolate the luminance due to the LEDs and the light reflected from the vehicle headlights. In most situations, there will be more ambient light than in our test conditions, and the environment will be more complex. Both factors increase the value of the flashing LEDs for increasing conspicuity.

The power consumption of the vests met expectations (600 hrs), and the operating costs based on battery consumption would be negligible.

The vests did appear to be durable. While a wire did break in one vest, only a small amount of precaution would have prevented it, namely, storing the vests on top of the equipment rather than underneath it.

Recommendations

The self-illuminating safety vests are both more visible and more conspicuous in nighttime conditions than their counterparts without LEDs. The implied safety benefits of greater worker visibility are significant. Therefore, the following are recommended.

1. The vests are *highly recommended* for circumstances where workers must be present on a highway during darkness without substantial workspace illumination. In cases where artificial lighting is being used, the vests may still have safety benefits in that the flashing lights may further increase the conspicuity of individual workers, even though the work zone is readily identifiable.

2. In agencies or areas where such circumstances are somewhat infrequent, the additional cost should be considered before using these vests for all maintenance and

construction activities "just in case" some work must be conducted under nighttime conditions.

3. While the vests are a positive addition to nighttime construction safety measures, they should not be used in lieu of standard workzone lighting practices, but only as a supplemental measure.

4. Some care should be exercised in storing the vests. While the vests are relatively rugged in most respects, tensile stress (such as that caused by pulling a vest out from under a heavy object) should be avoided as it may result in damage to the electrical wiring that connects the LEDs to the battery compartment.

References

CIE No 15.2, Colorimetry, Second Edition. (Vienna, Austria: Central Bureau of the Commission Internationale de L'Éclairage, 1986)