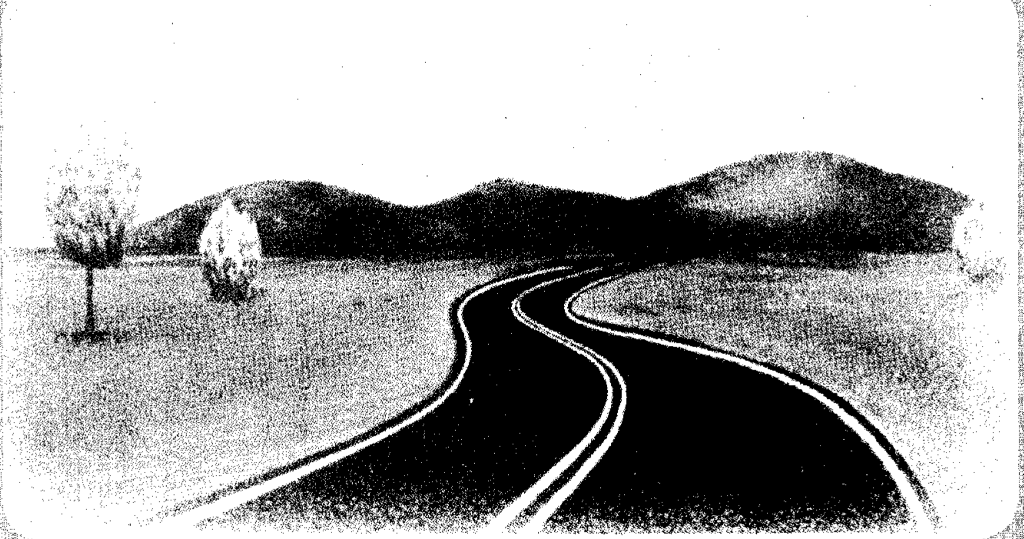
DRIVER'S VISIBILITY REQUIREMENTS FOR ROADWAY DELINEATION

VOL. II. COLOR IDENTIFICATION OF YELLOW HIGHWAY PAINT AS A FUNCTION OF YELLOW/WHITE PIGMENT MIXTURE RATIO



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FINAL REPORT

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FOREWORD

The work reported herein was conducted under Contract DOT-FH-11-8824 to the Federal Highway Administration with Dr. Donald Gordon, of the Traffic Systems Division, Office of Research, serving as Contract Technical Manager. This study was part of the Delineation Task of a much broader FHWA effort, Project 1L, "Improved Traffic Operations During Adverse Environmental Conditions," managed by Mr. Richard N. Schwab of the Environmental Design and Control Division.

Systems Technology, Inc., served as the prime contractor on this study, with a major subcontract handled by Human Factors Research, Inc. R. Wade Allen served as Principal Investigator for STI and James F. O'Hanlon served in the same capacity for HFR.

The research reported herein was conducted during the time period of July 1975 through October 1977 and is documented in two volumes. Volume I covers the simulation and field test work conducted to define optimum and minimum visual roadway delineation treatments. Volume II documents a study to establish the lower saturation limit of yellow/white paint mixture that can still be distinguished from white.

The authors would like to extend their appreciation to the reports groups at both STI and HFR for a fine job in the production of these documents.

Charles F. Scheffey
Charles F. Scheffey
Director, Office of Research

NOTICE

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16. Abstract

The yellow highway paint in current use is often not as visible as white paint under adverse lighting and weather conditions. It has lower initial brightness, darkens more rapidly with exposure, and contains lead pigment ($PbCrO_4$) which is more toxic and more expensive than white pigment (TiO_2). This study showed that up to 50 percent (by weight) of the lead pigment can be replaced by white pigment, without losing yellow color identity under lighting and weather conditions where 100 percent yellow color is normally distinguishable. This maximum dilution which still permits reliable identification of yellow was determined by means of color judgments made by 20 subjects observing a series of paint mixture sample strips (8 ft x 4 in.) from the driver's seat of a parked car at distances of 30, 60, and 90 ft, under both day and night lighting conditions. A cost savings of more than one million dollars could be realized annually in the U.S. by diluting yellow paint with white paint so that a 50:50 pigment weight ratio is obtained. This results in very little color change, providing improved visibility, reduced darkening with age, and reduced toxicity. No change in equipment or procedures is required, and existing stocks of yellow paint can be used by dilution with white paint.

Volume I, Effects of Contrast and Configuration on Driver Performance and Behavior, is report number FHWA-RD-77-165 and is available from NTIS.

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PREFACE

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INTRODUCTION

THE YELLOW PAINT PROBLEM

It is now standard practice in the United States to color code highway lane delineation so that traffic lanes moving in the same direction are separated by white lines, while traffic lanes moving in opposite directions are separated by yellow lines.

The yellow paint presently used has several drawbacks which would be alleviated by a reduction of the yellow lead chromate pigment content. Due to its lower reflectance, yellow paint is less visible than white paint, especially at night and in adverse weather; yellow paint is also more toxic and more expensive than white paint.

The purpose of this research was to determine how much the yellow paint can be diluted with white without causing drivers to misperceive it as white under actual driving conditions. If too much white paint were added to the yellow, it could induce drivers to mistakenly identify the line as white, particularly at night with artificial illumination.

A driver must be able to correctly identify the color of the lane markings in order to make safe use of the color code; misperception of a yellow line as white might lead a driver to cross over into a lane of oncoming traffic, thinking it was a same-way lane. The opposite error, mistakenly perceiving a white line as yellow, is not as dangerous, but can result in the loss of opportunities for passing or of an extra lane for travel; accidents have occurred when a driver mistaking the road as two-way makes a left turn across the adjacent lane looking only for oncoming traffic and is struck by same-way traffic overtaking from behind.

GENERAL EXPERIMENTAL CONSIDERATIONS

This study was designed to produce results directly relevant to the real-world driving situation. If materials other than actual reflectorized highway paint had been used to determine maximum dilution thresholds, field testing would be required to extrapolate the data for development of new Federal guidelines. Although the outdoor testing procedures employed in this research were somewhat unwieldy compared with the usual indoor laboratory method of rapid presentation using small color samples, the field data thus obtained are directly applicable to the problem of determining color identification of various yellow/white mixtures of actual highway paint under realistic conditions of lighting and distance found in the driving environment.

The full diversity of illumination and weather conditions found in the real-world driving situation must be taken into account when considering how much the yellow paint can be desaturated with white to improve its contrast and reduce toxicity and cost. The yellow color code should be identifiable not only in clear daylight but also under the adverse effects of night, rain, fog, headlight glare, various artificial lighting sources, and degradation of paint by traffic, aging, and accumulated oil and dirt.

Lighting

The color of the illuminant can significantly affect judgments of hue and saturation. If yellow light falls on a white line and a yellow line, both will return yellow light to the observer, making a hue discrimination impossible. The tungsten light of some vehicle headlights, fog lights, some fixed luminaires (especially sodium vapor lamps), and various other sources along the roadway may produce enough yellow light to confuse a white color and a light yellow color (although these might be clearly distinguished in the bluer illumination of daylight). The experimental plan thus included some of the range of illumination conditions found in the driving environment.

Subject Selection

Subjects selected for this study were between 40 and 60 years of age, since older drivers in the population would be expected to set the limiting value for maximum permissible white dilution of yellow paint. Night vision and color sensitivity decline with age; thus guidelines based on data from younger subjects might suggest levels of white dilution which could cause color misperception for a significant proportion of older drivers.

Relative Versus Absolute Color Judgment

The driver's task in deciding whether a lane line is either yellow or white is much different from the task of subjects in typical laboratory experiments on color perception. The driver does not have to discriminate two hues, or even the degree of saturation of yellow; the task is simply to determine the presence or absence of yellow in a binary-choice situation. Although subjects in laboratory experiments are good at making side-by-side color discriminations, their ability to make absolute identifications of colors is relatively poor. An observer can make reliable absolute identifications of only about 10 colors.[1] This problem is compounded by the multitude of factors which can affect color perception in the natural environment. The difference between relative and absolute color judgment is illustrated by the difficulty of mixing paint to match within a room, as compared with the inability to detect color differences between rooms.

Unless there is a white line in the field of view (such as an edge line), there will be no white comparison standard and the driver must judge the color of the line delineating the left edge of his lane by making an absolute color identification. Both relative and absolute color judgment tasks were represented in this research by obtaining color identifications of yellow/white mixture samples with and without a 100 percent white sample strip in the field of view.

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[1] Chapanis, A., and R. Halsey, "Absolute Judgments of Spectrum Colors," Journal of Psychology, Vol. 42, 1956, p. 99.

Distance and Angular Size

The angular size of a color sample also affects yellow/white discrimination. Isolated light sources of 20 minutes of arc or less[2] cause confusion between blue and blue-green and between yellow and white when fixated directly. This phenomenon is sometimes referred to as small-angle tritanopia because the color confusions are the same as those made by a type of color-deficient observer known as a tritanope. In this experiment, color judgments were obtained at 30, 60, and 90 ft (9.1, 18.3, and 27.4 m), representing the situation where a driver fixates the road at various distances. At 90 ft (27.4 m), the 8 ft × 4 in. (2.4 m × 10 cm) strip is approximately 12 arc minutes wide by 13 arc minutes high and would thus tend to appear less yellow due to small-angle tritanopic and foveal adaptation. On the highway, other stripes in the lane line would extend from the fixation point down to the left side of the vehicle, but these would fall further into the driver's peripheral field as they approach the vehicle, and thus be less effective color stimuli due to the reduced color sensitivity of the peripheral results.

Color Adaptation

The perception of color is also affected by the process of chromatic adaptation. The effect is a suppression of sensitivity to the adapted hue when viewing a new one, with an increased sensitivity to the opponent color of the adapted hue. Adaptation to yellow would tend to make the next sample appear bluer, and thus less yellow. In the context of this research, exposure to a saturated yellow sample would tend to bias the observer toward a judgment of white for the next sample. This effect was controlled by having the subject fixate an achromatic surface (gray cardboard on the dash) during the interval between judgments.

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[2] Conover, D. W., and C. L. Kraft, The Use of Color in Coding Displays, Wright Air Development Center, WADC TR-55-471, Oct. 1958.

Luminance Cues to Color

Identification of the presence or absence of yellow should be based on color, with no cue from the luminance of the sample strip. To rule out the possibility that subjects in this experiment might wittingly or unwittingly bias their color judgments by the usual systematic relation between brightness and proportion of white in the mixture, the samples were constructed so that brightness varied randomly with yellow/white ratio, and this was made explicitly clear to subjects. They were warned that the brightness and the saturation of the samples were not systematically related; this duplicates the real-world conditions where lighting conditions vary, the contrast background varies, and paint varies in luminous reflectance due to aging, traffic wear, and the accumulation of oil and road dirt.

Vehicular Factors

Four different vehicles were used as the subject's observation point to provide representative variations in visibility due to windshield characteristics, instrument lighting, optical attenuation, and other possible vehicular effects on judgment of color. Use of several vehicles improves the representative generality of the data for the purpose of setting guidelines applying to vehicles in common use in the United States.

Adverse Weather Conditions

Lighting, distance, and reference factors were to be tested in a full factorial experimental design with weather conditions of rain and fog, as they occurred naturally at the test site. As it happened, there was almost no rain during the testing period, but the limited experience obtained with rain showed that under moderate rain conditions color perception was so degraded that even the normal 100 percent yellow strips were not reliably identified. This indicated that carrying out the full factorial experiment would not have provided sufficiently reliable data to justify the effort and expense, even if repeatable rain conditions had occurred. Perception of color varied greatly with the degree of rainfall, which did not stabilize long enough to obtain consistent data. Fog likewise did not occur in sufficient density and stability to allow consistent data to be obtained. Thus only dry weather conditions were available for systematic determination of the effects of lighting, distance, and reference on yellow color identification. The limited rain data that were obtained are presented in Appendix B as individual subject threshold values. No data were obtained in fog.

YELLOW/WHITE COLOR DISCRIMINATION EXPERIMENT

OVERVIEW

Yellow/white color identification thresholds were obtained from 4 subjects in a pilot experiment and from 16 subjects in the main experiment. Data are expressed as the maximum percent white pigment in a yellow/white paint mixture which a subject reliably identified as yellow. These maximum permissible white dilution thresholds were determined: a) with and without a 100 percent white reference sample in the field of view; b) at 30, 60, and 90 ft (9.1, 18.3, and 27.4 m); and c) under seven dry weather lighting conditions (day — high sun, low sun; night — headlights only, headlights plus mercury vapor luminaire, sodium vapor luminaire, tungsten luminaire, and oncoming headlight glare). A limited amount of data was collected under night rain conditions, but due to the light and variable nature of the infrequent rain that was available, these data do not represent threshold values which would be obtained in moderate, steady rain conditions.

Viewing conditions approximated the actual driving situation. Subjects made judgments from the driver's seat of a parked car, identifying as either yellow or white a series of reflectorized highway paint mixtures applied to thin metal strips cut to 8 ft × 4 in. (2.4 m × 10 cm) dimensions, simulating a standard highway stripe. The visual distance and angular size of the samples, the optical effect of the retroreflective glass beads, and the use of actual luminaires in an outdoor setting provided field test validity in the data.

PRELIMINARY EXPERIMENT

Prior to the main experiment with 16 subjects, a pilot study was carried out with 4 initial subjects to explore the range of yellow/white mixture ratios and to standardize the experimental procedures and equipment. Data from this pilot study are presented in Appendix B (subjects arbitrarily numbered 17-20), but were not included in the analysis of the main experiment with the remaining 16 subjects. Exclusion of the data from these initial 4 subjects provided more consistency in the procedures and equipment used to determine maximum allowable white dilution as a function of reference, distance, and lighting conditions.

MAIN EXPERIMENT

Equipment and procedures were standardized in the pilot study with the first 4 subjects and then used in the main experiment with 16 subjects.

Method

Subjects. Five men and 11 women, ages 41 to 57, served as subjects for the main experiment. The average age of this group was 47.5 with a standard deviation of 4.5 and median age of 47 years. All subjects were tested in the 5 dry weather night conditions, with a subset also tested in the 2 daylight conditions and in 4 night rain conditions.

Subjects were recruited through an advertisement in the local newspaper, and paid $3.00 per hour for approximately 8 hours participation in the study.

Normal color perception was verified by the American Optical pseudo-isochromatic color plate test.[3] To ensure that subjects had adequate sensitivity to yellow saturation differences, small (2 × 10 cm) color strips were presented indoors in a test chamber under yellow filtered tungsten illumination with subjects required to arrange them in order of yellow saturation from 100 percent yellow to 100 percent white. The degree of yellow saturation was difficult to see under the yellow lighting; this provided a check for gross deficiency in the ability to make normal yellow/white discriminations. Applicants who could not pass both the pseudo-isochromatic color test and the yellow saturation test were not used as subjects.

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[3] American Optical Corporation, Pseudo-Isochromatic Plates for Testing Color Perception, Philadelphia, Beck Engraving Co., 1965.

Materials and apparatus. The equipment consisted of four automobiles, test strips painted with various yellow/white mixtures, mercury vapor and sodium vapor luminaires, a device for simulating tungsten lighting and oncoming headlight glare, and an isolated test track for testing with no extraneous sources of illumination.

1. Vehicles. The two primary vehicles which served as the subject's observation point were a 1976 Ford Pinto and a 1976 Chevrolet Nova. A 1965 Plymouth Valiant was used for pilot testing and for 18 of 480 night and 10 of 76 day threshold determinations. A 1974 Audi sedan was used for 12 of the 480 night data points. Headlight adjustment was checked according to standard procedure by a certified California headlight inspection station.

2. Paint Samples. Paint samples were prepared by mixing yellow and white highway paint in the desired ratios of pigment by weight. These yellow/white mixtures were applied to thin metal strips 8 ft × 4 in. (2.4 m × 10 cm), simulating the appearance of a standard highway delineation stripe. Painting was done by a California Department of Transportation (Caltrans) paint truck crew using standard equipment (airless spray and compressed air glass bead blower). Two sets of samples were prepared, with percentages of yellow and white pigment by weight as shown in Table 1.* The first set was used in pilot experimentation and for 7 percent of the data points in the main study. The second set of test strips was improved by using aluminum for lighter weight and by eliminating mixtures above 95 percent white. The first set was constructed with 15 strips of 0.016 in (.0004 meters) thick steel, the second set with 12 strips of 0.032 in. (.0008 meters) thick aluminum sheet metal. The pigment percentages by weight indicated in Table 1 were obtained by computing the volume ratios required to give the desired percentage of white pigment, given the pigment weight/gallon of the yellow and white paints used. The formula for this computation is shown at the bottom of Table 1. The second set of samples did not include fine steps above 90 percent white, since experience with the first subjects showed that mixtures above 95 percent white could not be reliably discriminated under night viewing conditions.

   Note: The perception of change in yellow content is much more sensitive toward the white end of the saturation continuum. For example, subjects could readily see the

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*Chromaticity measurements for the second sample set were provided by the National Bureau of Standards, as shown in Appendix C.

TABLE 1. PERCENTAGE OF WHITE PIGMENT IN YELLOW/WHITE TEST STRIPS

FIRST SAMPLE SET 15 STEEL STRIPS 40 DATA POINTS	SECOND SAMPLE SET 12 ALUMINUM STRIPS 516 DATA POINTS
0.0	0.0
31.0	28.0
43.0	38.0
48.0	48.0
78.0	58.0
92.0	68.0
95.0	73.0
96.0	79.0
98.0	84.0
98.4	89.0
98.9	95.0
99.0	100.0
99.5	
100.0	
100.0	

WHITE: CALTRANS PT-361 1 lb TITANIUM DIOXIDE/GAL (.1198 kg/l)	WHITE: CALTRANS PT-225 1 lb TITANIUM DIOXIDE/GAL (.1198kg/l
YELLOW: CALTRANS PT-148 2.2 lb LEAD CHROMATE/GAL (.264 kg/l)	YELLOW: CALTRANS PT-146 2.4 lb LEAD CHROMATE/GAL(.288 kg/l)

FORMULA FOR COMPUTING REQUIRED VOLUME PROPORTIONS OF YELLOW AND WHITE PAINT TO OBTAIN DESIRED PERCENTAGE OF WHITE PIGMENT BY WEIGHT:

$$\text{GALLON VOLUME OF YELLOW TO BE ADDED TO 1 GALLON OF WHITE PAINT} = \frac{(TD/LC)\ (100 - DW\%)}{(DW\%)}$$

TD = POUNDS/GAL OF TITANIUM DIOXIDE

LC = POUNDS/GAL OF LEAD CHROMATE

DW% = DESIRED WHITE PERCENT (PIGMENT WEIGHT) difference between a 5 percent yellow and a 10 percent yellow mixture (in daylight) but could not see the difference between 90 percent yellow and 95 percent yellow. This is perceptually analogous to the easy discrimination between 5 and 10 lb (2.3 and 4.5 kg) weights, as opposed to the difficult discrimination between 90 and 95 lb (38.5 and 40.8 kg) weights. For this reason neither set of test samples included mixtures below 28 percent white (i.e., above 72 percent yellow). It takes a substantial amount of white paint to noticeably lighten yellow; the lower percent dilutions of white were virtually indistinguishable from 100 percent yellow.

3. Lighting Conditions. The two daylight conditions and the five night lighting conditions used in this study were:

   a. High sun (9:00 a.m. to 3:00 p.m.).*

   b. Low sun (30 min before sunset, ending at sunset).*

   c. Vehicle headlights only (beginning 2 hr after sunset).

   d. Headlights plus mercury vapor luminaire at a height of 15 ft (15.5 m) directly over test strip.

   e. Headlights plus sodium vapor luminaire at a height of 30 ft (9.1 m), 10 ft (3 m) to the right of the test strip.

   f. Headlights plus simulated tungsten luminaire (see Fig. 1).

   g. Headlights plus simulated oncoming headlight glare (see Fig. 1).

   Low beam headlights were used for the 30 ft (9.1 m) viewing distance and high beam headlights were used for the 60 and 90 ft (18.3 and 27.4 m) distances. Existing mercury and sodium luminaires at relatively isolated sites were used for Conditions d and e.

   An apparatus to simulate both tungsten luminaire and oncoming glare conditions was constructed as shown in Fig. 1. To simulate tungsten street light illumination, the arm holding two single beam headlights was raised to a height of 6.5 ft (2 m) above the pavement, 5 ft (1.5 m) to the right of the test strip. Four layers of frosted plastic diffuser material were attached to the headlight lenses to spread the beam of light uniformly over the test strip area. This provided a diffused illuminance of 1.4 footcandles (15.1 lux). The mercury vapor lamp was a General

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*Test vehicle was facing east, heading 180 deg (directly away from sun).

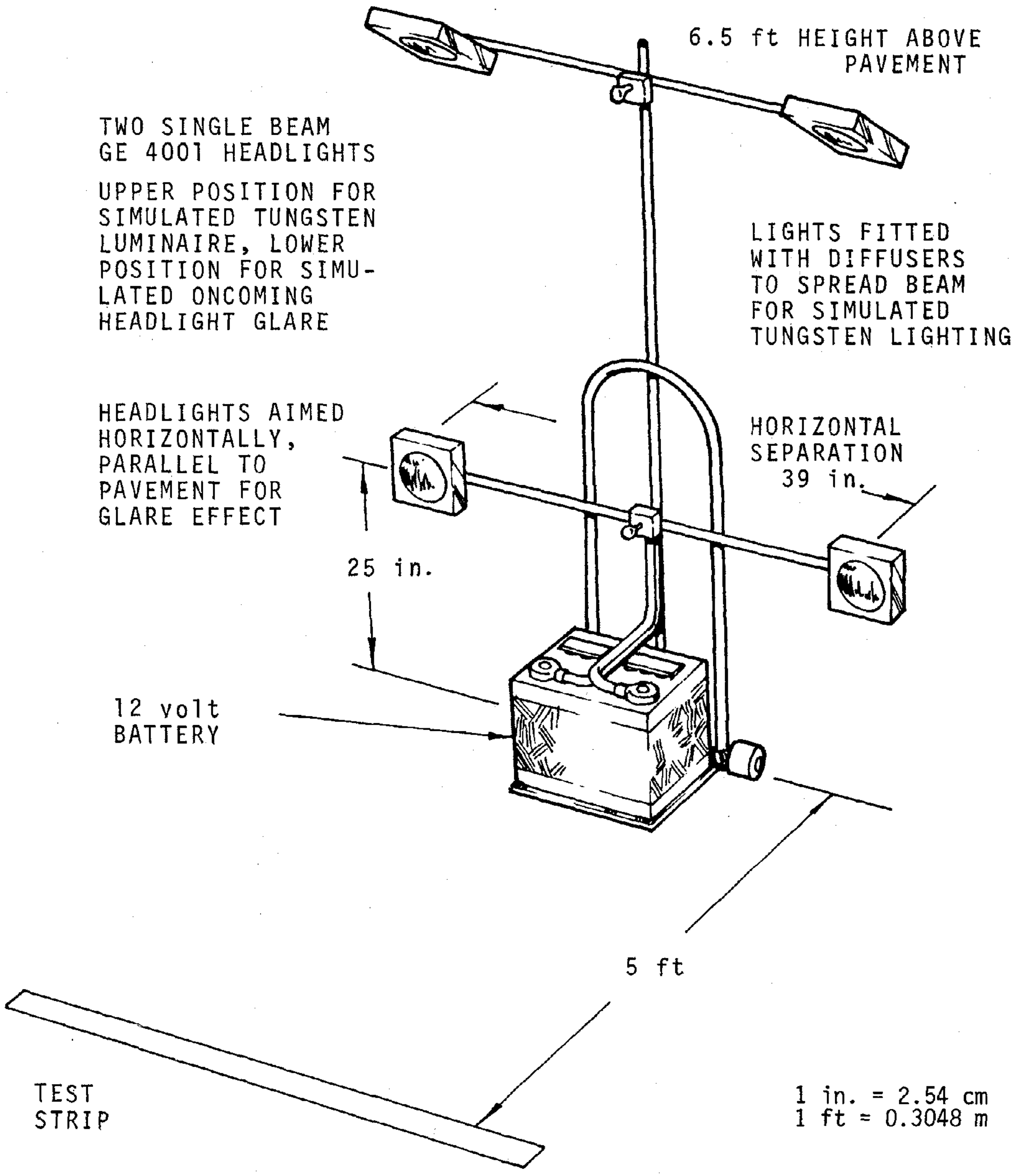


Figure 1. Apparatus for Simulating Oncoming Headlight Glare and Tungsten Luminaire Conditions. (The automobile storage battery was recharged to full capacity between test sessions.)

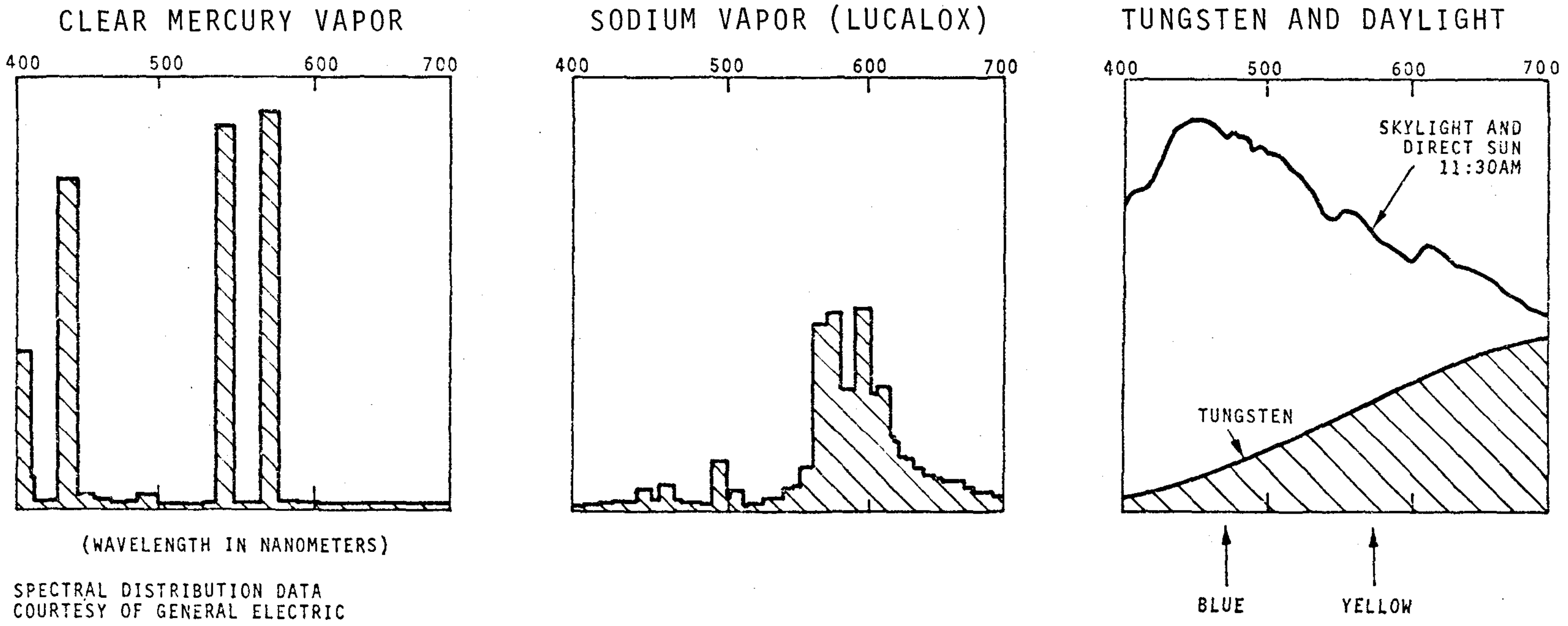
Electric MV GE 175 H175A39-22, providing 2.5 ft-c (26.9 lx) illuminance. The sodium vapor lamp was a GE Lucalox, providing a 4.5 ft-c (49.5 lx).

Note: Clear mercury vapor luminaire illumination is concentrated at 405, 436, 546, and 578 nanometers in the visible spectrum. This provides a higher proportion of light toward the blue end of the spectrum, as shown in Fig. 2, and enhances the discrimination of yellow from white. The sodium vapor Lucalox lamp provides light predominantly in the yellow region of the spectrum, making yellow/white distinctions more difficult. The Lucalox lamp is basically a sodium arc, which ordinarily would be virtually monochromatic at 589 nanometers, but actually provides a broader spectral illumination due to high temperatures in the arc. Tungsten illumination produces a typical black body spectrum, with light energy across the visible region concentrated toward the red end of the spectrum, making yellow/white discrimination difficult.

4. Test Locations. Three test sites were employed: 1) an isolated test track with no unwanted sources of illumination was used for daylight, headlights only, glare, and tungsten luminaire conditions; 2) an existing mercury vapor luminaire located on a seldom-used loop road was used for all mercury vapor lighting conditions; and 3) an isolated sodium vapor luminaire at a nearby shopping center parking lot was used for all sodium vapor conditions. Relative positions of the test vehicle, test strips, and reference strip are shown in Fig. 3. The test strips were placed along a line 2 ft (0.6 m) to the left of the subject, the near edge of the strip being 30, 60, or 90 ft (9.1, 18.3, or 27.4 m) from the subject eye position. For the reference condition a 100 percent white strip was placed 3 ft (0.9 m) to the right of the test strip.

5. Response Apparatus. Subjects indicated their color identification responses by operating the test vehicle turn signals after each test strip presentation. The right turn signal signified that the test strip appeared white (not perceptibly yellow), and the left turn signal indicated that the test strip appeared yellow. This binary forced-choice response was thus visible to the experimenter at the test strip position and was recorded on a tally sheet.

6. Angular Dimensions of Test Strips. The visual size of the test strips as seen from the subject's eye position is shown in Fig. 4 [for comparison, the height of letters on the 20/20 line of a Snellen eye chart at 20 ft (6.1 m) viewing distance is 5 arc minutes (1.5 milliradians)]. The vertical height appearance of a test strip at 60 ft (18.3 m), for example, is 27 arc min (7.8 mrad), calculated by obtaining the difference between the viewing angle to the near end of the



SPECTRAL DISTRIBUTION DATA
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Figure 2. Characteristic Spectral Distributions for Lighting Sources Used in Testing Yellow/White Discrimination. (Note that sodium vapor and tungsten spectra are concentrated toward the yellow end of the color continuum, making yellow/white discrimination more difficult. The blue content of mercury vapor and high sun lighting make yellow/white judgment easier, as is shown in the resulting data. Spectra indicate relative energy as a function of wavelength, not drawn to scale.)

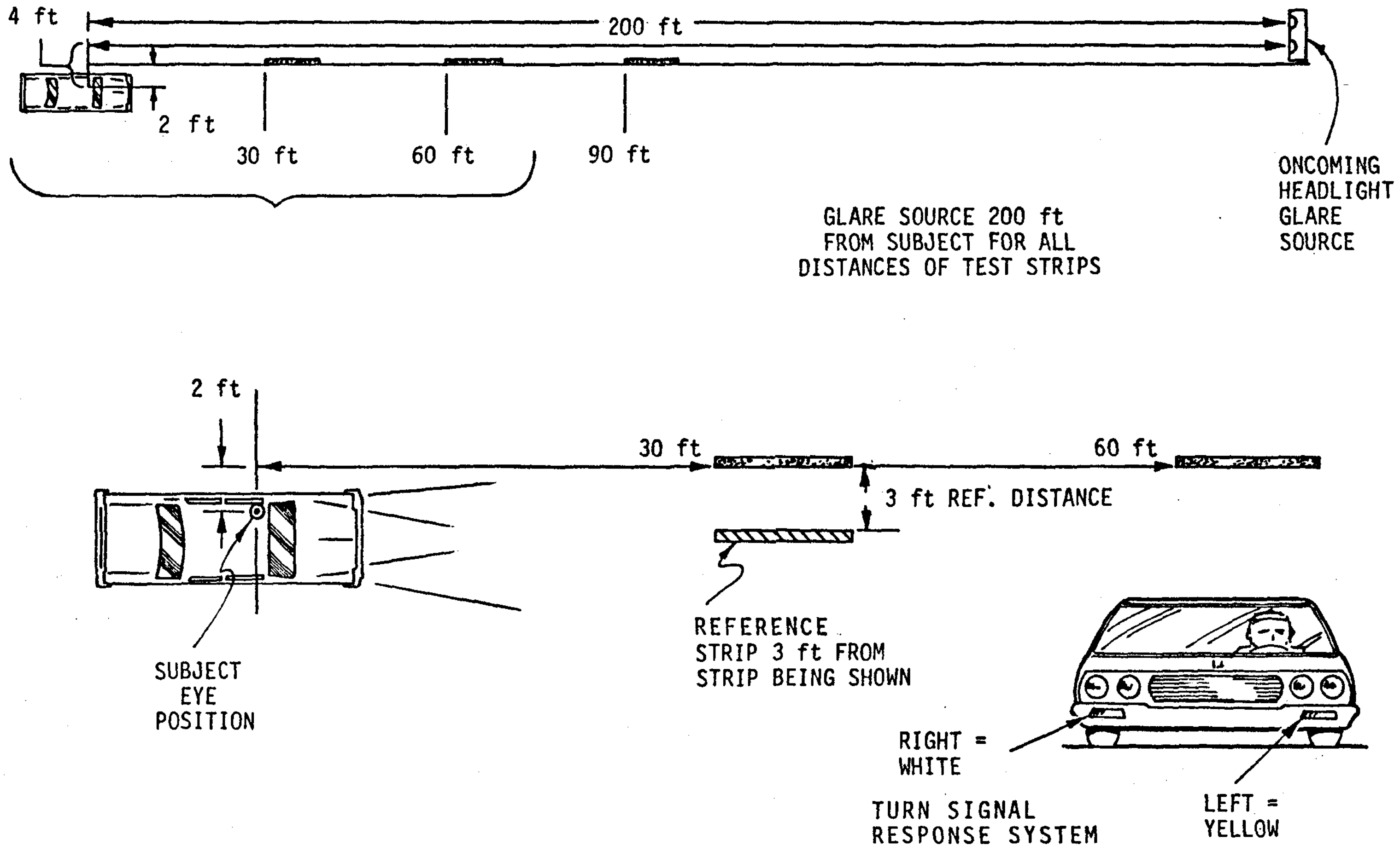


Figure 3. Layout of Test Vehicle, Test Strip, Reference Strip, and Glare Source. Subjects were tested at 30 ft, 60 ft, and 90 ft, with and without a white reference strip near the test strip. (1 ft = 0.3048 m).

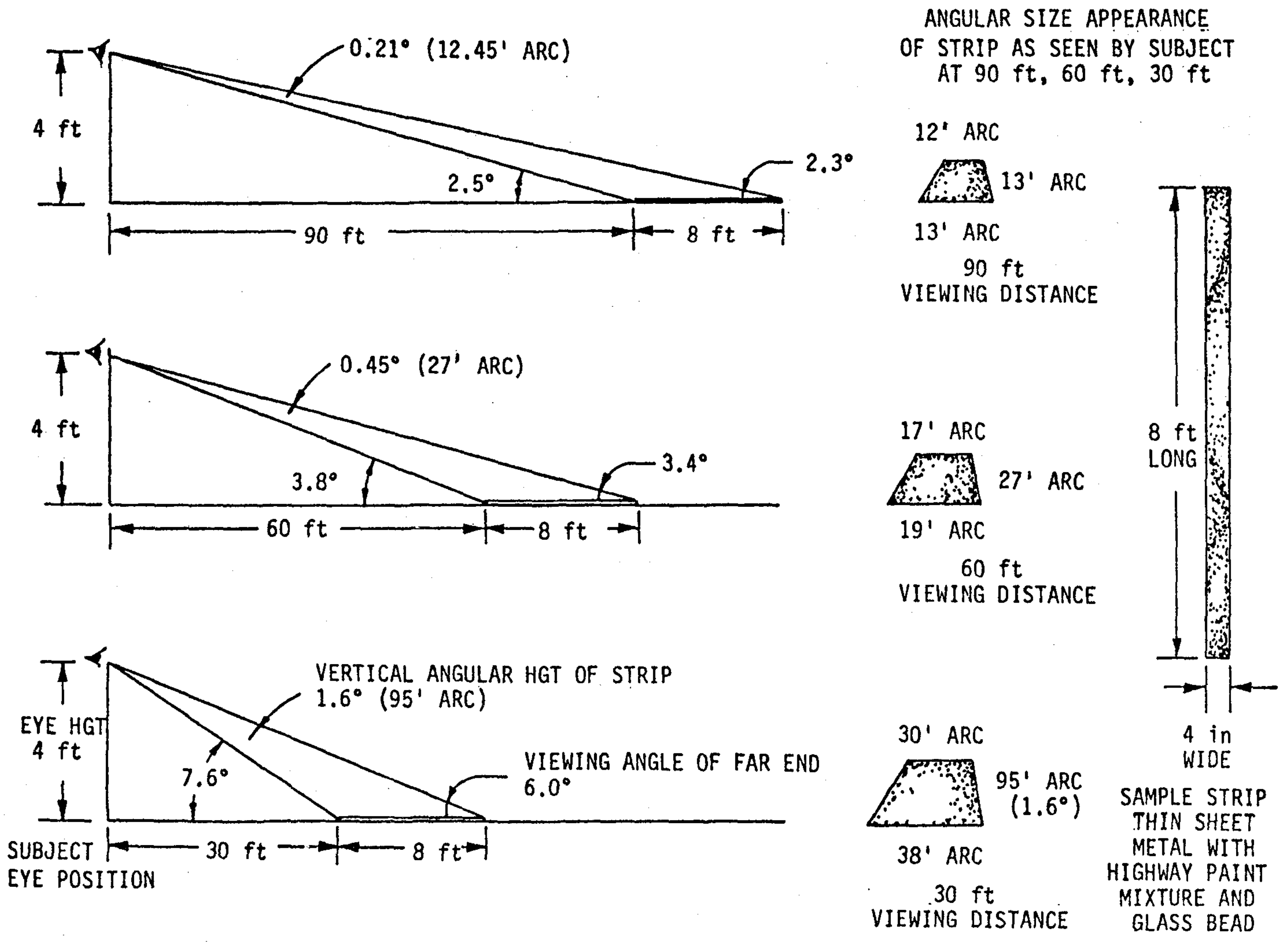


Figure 4. Visual Size of Test Strips Seen From Subject's Eye Position. (Angular size dimensions are given in minutes of arc subtended at subject's eye. Geometric representations not drawn to scale. 1 ft = 0.3048 m. 1 arc min = 0.2909 mrad.)

> strip (3.8 deg) and the angle to the far end (3.4 deg). At the relatively shallow viewing angles indicated in Fig. 4, test strips which looked distinctly yellow when held up perpendicular to the subject's line of sight tended to look white when laid flat on the pavement. This desaturation effect is partly due to the way protruding glass beads obscure the paint surface when viewed obliquely, thus reducing the proportion of light returned directly from the pigmented surface between the beads. This interaction of shallow viewing angle with retroreflective glass beads illustrates the importance of testing with mixtures of actual reflectorized highway paint at angles and distances closely approximating the driving environment.

Procedure. The general procedures and the purpose of the experiment were explained to the subject, as described in Appendix A. After preliminary screening with the pseudo-isochromatic color plate test, each subject was tested indoors with small 2 cm × 10 cm sample strips (cut from the large test strips used in outdoor testing). Subjects practiced making yellow/white judgments in a darkened room with controlled amounts of yellow-filtered tungsten illumination incident on the strips from various angles. The purposes of this indoor testing were: a) to familiarize the subjects with the forced-choice task; b) to demonstrate that samples which looked distinctly yellow under fluorescent room lighting could look completely colorless when viewed at a shallow angle with yellow tungsten light coming from over the subject's shoulder; and c) to check for deficiencies in yellow saturation sensitivity.

Since the objective of the study was to determine the maximum white dilution mixture which subjects could reliably identify as yellow under each experimental condition, an attempt was made to standardize the criterion for color identification. Subjects were instructed to indicate "yellow" when they could actually see some yellow hue in the sample and to indicate "white" when the strip appeared colorless or they were uncertain. Although subjects differed in their criteria for the breakpoint between reporting "yellow" and "white," they were remarkably consistent in their own individual breakpoints for most conditions. Those conditions which made color discrimination extremely difficult resulted in erratic data, which were recorded as a case of "no discrimination" (ND).

Subjects were cautioned that the purpose of the experiment was to determine how the test strips appeared under the various lighting and distance conditions, and were asked to base their responses solely on color appearance and not on what they thought, knew, or suspected the strip's actual color composition to be; they were simply to report the apparent color under those particular viewing conditions. Each subject was given a demonstration at the outdoor test site in which a 100 percent yellow strip appeared to be absolutely white due to the viewing distance and illumination. This was done to overcome the natural tendency to try to guess the actual composition of the sample rather than to report its color appearance.

Subjects were tested individually, each requiring approximately 4 days to complete the series of day and night lighting conditions. The subject was driven to the test site by the experimenter, and the vehicle and test strips were placed in the relative positions shown in Fig. 3. A carrying rack permitted the experimenter to transport the large test strips easily and to select strips to be shown with no indication of the order of presentation.

The experimenter placed one strip at a time on the pavement, then stepped back to indicate that the subject was to judge whether or not the strip looked yellow. The subject responded by turning on the right turn signal for white or the left turn signal for yellow. After each presentation, the experimenter recorded the subject's response and replaced the strip in the carrying rack before selecting the next one. This allowed the same strip to be shown several times in a row without the subject's being aware of the order of presentation. The subject was informed that order of presentation would be random, with the possibility that some test strips would be presented several times in a row.

The experimenter emphasized the point that the apparent brightness of a test strip was not systematically related to its yellow/white mixture ratio, and reminded the subject that the response should be determined only by the apparent color of each sample.

The subject was asked to make color judgments quickly, within 10 seconds or less, and was cautioned that the color of a visually small sample tends to fade with prolonged viewing. The subject looked away from the test strip position between presentations so as to avoid seeing the next strip until it was flat on the pavement, and also to neutralize adaptation effects prior to the next color judgment.

The experimenter wore neutral, dark-colored clothing to avoid providing an unwanted color reference in the vicinity of the test strip, and was careful to remove and replace strips in the carrying rack so that the subject could not obtain a direct view of the painted surface until the strip was flat on the pavement, which had a reflectance of approximately 10 percent at all three test sites.

The simulated glare and tungsten luminaire device shown in Fig. 1 was powered by a high-capacity 12 volt automobile storage battery, which was recharged between test sessions and used for relatively short durations during testing. Headlight lenses and windshield were wiped clean before each test session. At the location used for the sodium vapor lighting condition, several distant non-sodium lights in the field of view were blocked with blackout cloth on the vehicle windows, ensuring that the only sources of light visible to the subject had the characteristics sodium vapor spectrum. Unwanted light sources at the other test sites were similarly blocked. Interference from passing cars was avoided by suspending the test whenever there was traffic in the vicinity.

All subjects were tested under each lighting, distance, and reference condition. The order of lighting conditions was randomized. Half the subjects made judgments for all lighting conditions at 30 ft, 60 ft, then 90 ft (9.1, 18.3, and 27.4 m); the other half of the subjects made judgments for all lighting conditions at 90 ft, 60 ft, then 30 ft. Absolute judgments (without reference) were made prior to comparative judgments (with reference) at each distance.

The instructions to research assistants in Appendix A provide details of the operational procedures used in determining maximum white dilution thresholds.

The experimenter presented samples in an exploratory sequence (detailed in Appendix A) to find the breakpoint at which the subject would switch from a white response to a yellow response. When this threshold or breakpoint was found, it was confirmed by repeated presentation of test strips on either side of the breakpoint. The threshold or breakpoint value recorded for each combination of reference, distance, and lighting was the percent white of the whitest test strip which was reliably identified as yellow.

Individual subjects' thresholds were remarkably consistent for most combinations of reference, distance, and lighting. When no consistent threshold could be established a case of no discrimination occurred; this was arbitrarily assigned a threshold value of —1 percent for computation of means and medians. In the case of "no discrimination," a subject failed to distinguish 100 percent yellow from 100 percent white, either by responding randomly or by identifying all test strips as white.

Each subject was tested for only 2 to 3 hours per day to preclude fatigue effects, and was paid after completing threshold determinations for the complete series of lighting conditions.

Results

Individual subject threshold values for each combination of reference, distance, and lighting are presented in Appendix B. Thresholds are expressed as the maximum percent white dilution mixture which was reliably identified as yellow (i.e., the percent white pigment by weight in the most diluted test strip which a subject reliably identified as yellow).

Instances of no discrimination (ND) were assigned a threshold value of —1, and included in arithmetic means and median values. A numerical value of —2 indicates missing data for the case where a subject was not tested under that particular combination of conditions; these —2 values were not included in the computation of means and medians.

In the main experiment, a total of 556 threshold values were obtained, 480 with night lighting conditions and 76 with daylight conditions. Of the

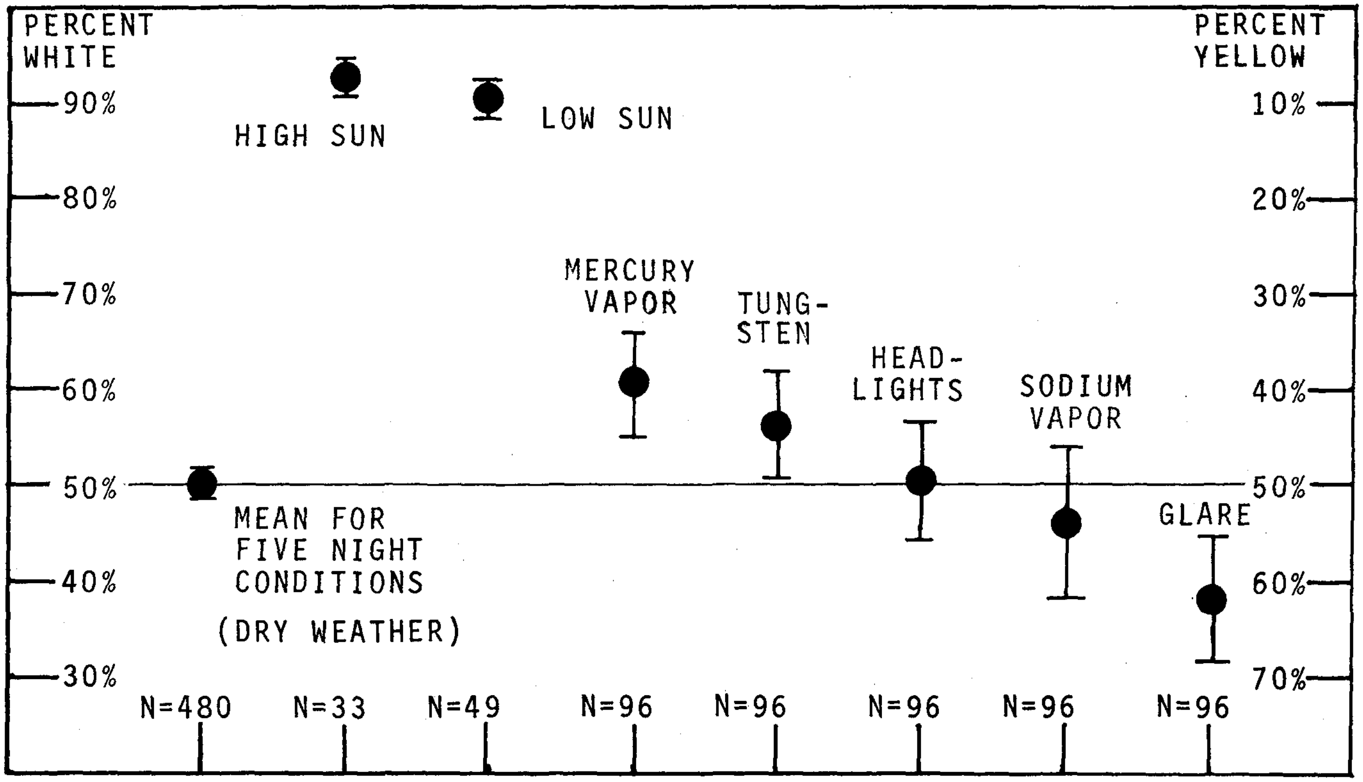
480 night thresholds, 30 were obtained with the first set of test strips, the remaining 450 with the second set (percentages of white pigment in the two sets of test strips are shown in Table 1). Of the 76 daylight thresholds, 10 were obtained with the first set of test strips, 66 with the second set.

The analysis of data for the main experiment does not include thresholds obtained under night lighting conditions in the pilot experiment with four initial subjects (arbitrarily numbered 17-20 in Appendix B).

Arithmetic means for individual subject thresholds under each of seven lighting conditions are presented in Fig. 5, averaged across reference and distance conditions. Mean values for each combination of reference, distance, and lighting are presented in Fig. 6. The 16 subjects provided a total of 96 data points for each night lighting condition.

Figure 5 averages the detailed data presented in Fig. 6 for each lighting condition. Table 2 presents the same detailed data in numerical form and averages data for the six combinations of reference + distance across all five night lighting conditions. For example, the average threshold at 30 ft (9.1 m) without a reference is 58 percent white across all five night lighting conditions, with 80 individual thresholds determining the mean, and 95 percent confidence limits of ±6 percent. The average across all five night conditions at 30 ft with a reference is 68% ± 5%, showing the expected effect of providing a 100 percent white comparison strip near the test strip.

Median values for the five night conditions are also presented in Table 2, as an alternative measure of central tendency. The general agreement between mean and median values indicates basically symmetric distributions of individual threshold measures. Median values are included because of the problem of assigning an arbitrary threshold value to instances of no discrimination, where no actual threshold could be determined. For the purpose of obtaining arithmetic means, instances of no discrimination were assigned a value of −1; the general agreement of means and medians would seem to confirm the adequacy of this approach. An alternative method would



MEAN VALUES FOR EACH LIGHTING CONDITION COMBINING REFERENCE AND DISTANCE THRESHOLDS. THE NUMBER OF THRESHOLD DETERMINATIONS INCLUDED IN EACH MEAN VALUE IS INDICATED ALONG THE X-AXIS. (NINETY-FIVE PERCENT CONFIDENCE LIMITS INDICATED ABOVE AND BELOW EACH MEAN VALUE.)

Figure 5. Summary Data for Each of Seven Dry Weather Lighting Conditions. (Detailed data for the effects of reference and distance are presented in Fig. 6. Overall mean value for each lighting condition: HS = 93 ± 1, LS = 90 ± 2, MV = 61 ± 6, TU = 57 ± 6, HL = 51 ± 6, SV = 46 ± 8, GL = 38 ± 7 percent white dilution.)

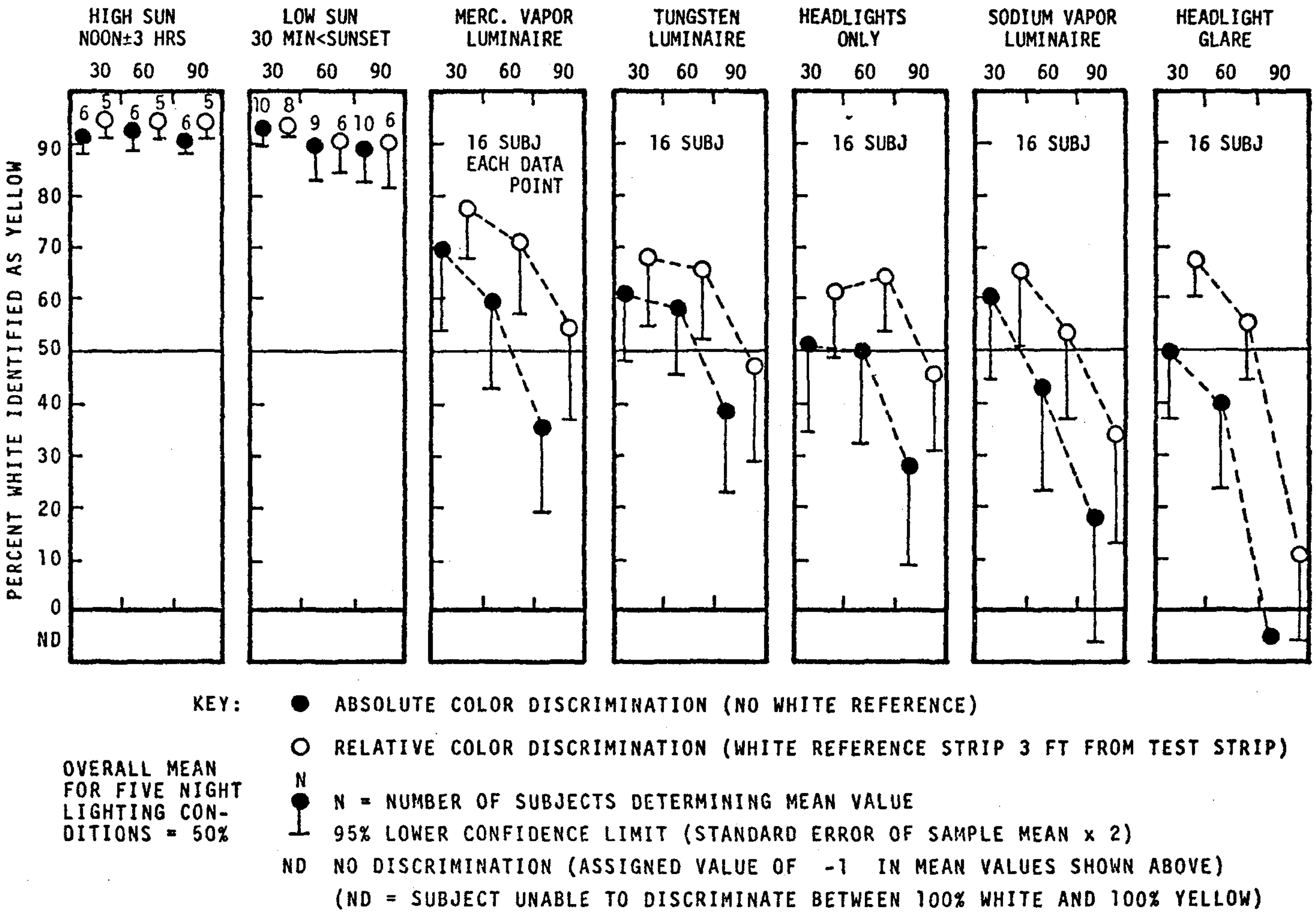


Figure 6. Mean Value of Percent White Pigment Which was Reliably Identified as Yellow for Each Condition of Reference, Distance, and Lighting. (Note that at 30 ft distance, mean values are at least 50 percent, indicating that yellow highway paint may be diluted with white to a pigment ratio of 50:50 by weight without losing color coding information. 1 ft = 0.3048 m)

TABLE 2. AVERAGE WHITE DILUTION THRESHOLDS FOR SEVEN LIGHTING CONDITIONS
(1 ft = 0.3048 m)

DATA EXPRESSED AS % WHITE	30 ft DIST		60 ft DIST		90 ft DIST	
	NO REF	REF	NO REF	REF	NO REF	REF
HIGH SUN (NOON + 3 hrs)	92 ± 3 N = 6	94 ± 3 N = 5	93 ± 3 N = 6	94 ± 3 N = 5	91 ± 3 N = 6	94 ± 3 N = 5
LOW SUN (30 min SUNSET)	93 ± 4 N = 10	93 ± 3 N = 8	89 ± 7 N = 9	90 ± 6 N = 6	87 ± 6 N = 10	89 ± 8 N = 6
MERCURY VAPOR LUMINAIRE (N=16)	69 ± 15 (82)	77 ± 8 (84)	59 ± 16 (71)	71 ± 13 (79)	36 ± 17 (41)	55 ± 18 (71)
TUNGSTEN LUMINAIRE (N=16)	61 ± 12 (68)	68 ± 13 (73)	59 ± 14 (63)	66 ± 14 (68)	39 ± 16 (48)	47 ± 18 (48)
HEADLIGHTS ONLY (N=16)	51 ± 16 (53)	62 ± 13 (66)	50 ± 17 (46)	65 ± 11 (63)	28 ± 19 (0)	47 ± 16 (46)
SODIUM VAPOR LUMINAIRE (N=16)	60 ± 16 (66)	65 ± 16 (73)	43 ± 22 (33)	54 ± 17 (58)	18 ± 19 (-1)	34 ± 20 (14)
GLARE (ONCOMING HEADLIGHTS(N=16)	50 ± 13 (53)	68 ± 8 (68)	40 ± 16 (48)	56 ± 10 (58)	-1 (ND) (-1)	11 ± 12 (-1)
AVERAGES (NIGHT CONDITIONS)	58 ± 6 N = 80	68 ± 5 N = 80	50 ± 7 N = 80	62 ± 6 N = 80	24 ± 7 N = 80	39 ± 9 N = 80

NUMBERS IN PARENTHESES ARE MEDIAN VALUES FOR FIVE NIGHT LIGHTING CONDITIONS, WITH THE MEDIAN OVER ALL FIVE CONDITIONS = 58

MEANS AND MEDIANS FOR NIGHT CONDITIONS FROM SUBJECTS 1-16 ONLY

GRAND MEAN FOR NIGHT CONDITIONS = 50.3% WITH 95% CONFIDENCE LIMITS: 47.5%-52.2% AGREEMENT BETWEEN MEANS AND MEDIANS INDICATES UNSKEWED DISTRIBUTIONS be to average the data only from subjects who were able to provide a threshold within the range of test mixtures used, thus excluding cases of ND from averages. For the purpose of setting maximum dilution guidelines, however, it was considered more appropriate to weight the averages in a conservative direction by including ND as a threshold value of −1 percent.

Instances of no discrimination (ND) provide additional information about the relative difficulty of color perception for the various combinations of reference, distance, and lighting. Figure 7 shows the number of cases of ND occurring under each combination of conditions for Subjects 1-16 (main experiment), with data from Subjects 17-20 (pilot experiment) added for comparison. These data imply that color coding even with 100 percent yellow paint may not be effective under sodium and glare conditions for viewing distances over 90 ft (27.4 m). Failure to discriminate 100 percent yellow from 100 percent white occurred for 13 of 20 subjects (65 percent) under sodium vapor lighting and for 18 of 20 subjects (90 percent) with oncoming glare conditions, viewing a single test strip at 90 ft.

The split-plot factorial design permitted an analysis of reference, distance, and lighting effects within subjects and an analysis of test vehicle effects between subjects. The within-subjects design controlled for individual subject differences in sensitivity and criterion (yellow/white response) across reference, distance, and lighting factors.

In the analysis of variance for night lighting conditions shown in Table 3, the F-ratios provide an estimate of the likelihood that differences among mean values were due simply to chance and subject variability. The effects of reference [Factor R, white strip 3 ft (0.9 m) from test strip], distance (Factor D), and lighting condition (Factor L) are significant at the 0.001 level (i.e., would occur by chance only once in 1000 times). Only one interaction effect was significant: DL indicates that the effect of distance varied with the lighting conditions, and vice versa. This can be seen in Fig. 6, where distance has a more degrading effect on color identification under the more difficult lighting conditions. The lack of significance for the reference/distance (RD) and the

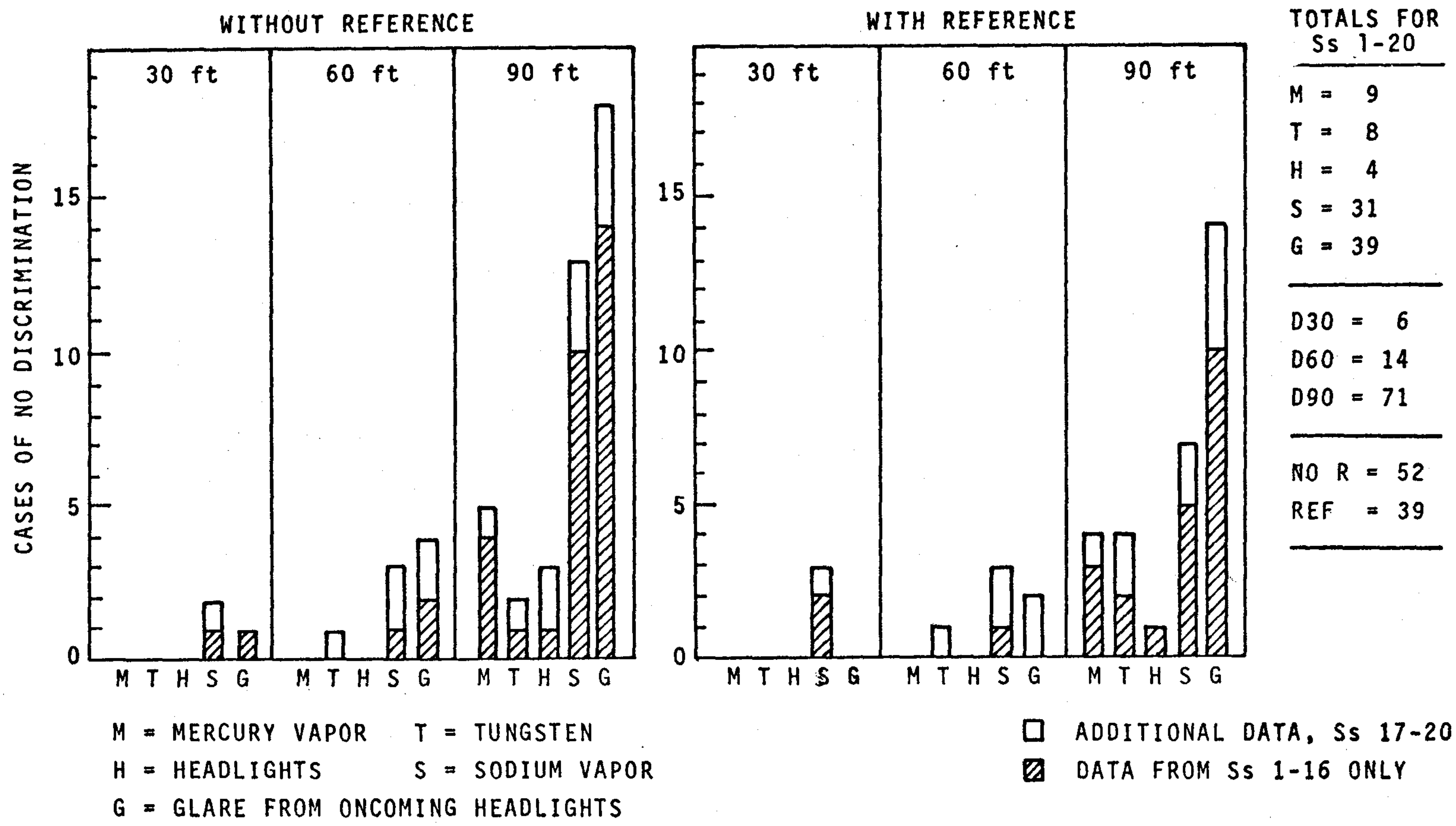


Figure 7. Number of Cases of No Discrimination (ND) for Each Condition of Reference, Distance, and Lighting. (ND means that subjects could not reliably discriminate 100 percent yellow from 100 percent white under each combination of conditions shown above. At 90 ft, 18 of 20 Ss with glare and 13 of 20 Ss with sodium failed to make any color discrimination. Subjects 17-20 (4 initial pilot Ss) were added to show the consistent nature of the effect of lighting, distance, and reference on inability to see color. 1 ft = 0.3048 m)

TABLE 3. ANALYSIS OF VARIANCE

```
(NIGHT LIGHTING ONLY)

DESIGN SPECIFICATION
FACTORIAL WITH REPEATED MEASURES ON FACTORS    R    D    L
REPLICATION FACTOR IS    S

     SOURCE                   SUM OF SQUARES        DF          MEAN SQUARES        F

     BETWEEN SUBJECTS

     A                            17557.0000         1            17557.0000      2.13   NOT SIGNIFICANT
     SUBJ. W. GROUPS             115396.5000        14             8242.6055             (AUTO: NOVA vs PINTO)
     -------------------------  -------------------------
     TOTAL
     WITHIN SUBJECTS

     R                            18044.5000         1            18044.5000     17.08   p < .001 (REFERENCE)
     RA                             632.5000         1              632.5000       .60
     R        * SUBJ. W. GROUPS   14791.5000        14             1056.5356
     -------------------------
     D                            87866.5000         2            43933.2500     41.72   p < .001 (DISTANCE)
     DA                            2559.0000         2             1279.5000      1.22
     D        * SUBJ. W. GROUPS   29482.0000        28             1052.9287
     -------------------------
     RD                             542.0000         2              271.0000      1.13
     RDA                           1526.5000         2              763.2500      3.18
     RD       * SUBJ. W. GROUPS    6717.5000        28              239.9107
     -------------------------
     L                            32461.0000         4             8115.2500      5.86   p < .001 (LIGHTING)
     LA                            7031.5000         4             1757.8750      1.27
     L        * SUBJ. W. GROUPS   77576.5000        56             1385.2944
     -------------------------
     RL                            1034.0000         4              258.5000      1.03
     RLA                            800.0000         4              200.0000       .80
     RL       * SUBJ. W. GROUPS   14034.5000        56              250.6161
     -------------------------
     DL                           14772.5000         8             1846.5625      4.88   p < .001 (DIST/LGHTNG
     DLA                           4580.5000         8              572.5625      1.51             INTERACTION)
     DL       * SUBJ. W. GROUPS   42349.5000       112              378.1205
     -------------------------
     RDL                            850.5000         8              106.3125       .46
     RDLA                          1806.0000         8              225.7500       .97
     RDL      * SUBJ. W. GROUPS   26019.0000       112              232.3125
     ---------------------------------------------------
     TOTAL                       518431.0000       479
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reference/lighting (RL) interactions implies that reference had the same effect regardless of distance and lighting factors.

The 1976 Pinto was used in determining the 240 night lighting thresholds for Subjects 1-8; for Subjects 9-16 the 1976 Nova was used for 210 thresholds and the 1974 Audi for 12 thresholds. The lack of significance for Factor A (vehicle type) implies that the difference between the mean obtained from the Pinto (56 percent) and the mean for the Nova, Valiant, and Audi (44 percent) could have been due to chance and not systematically related to vehicle type.

The analysis of variance included data only from the five night lighting conditions, due to the distinctly different level of thresholds obtained in daylight. For the purpose of setting maximum white dilution guidelines, the more difficult night viewing conditions must be considered as the limiting factor. In daylight conditions, subjects were able to reliably identify yellow diluted by 90 percent white, but this is not relevant to the problem of determining the maximum dilution appropriate for both day and night conditions.

Due to the sparse and intermittent rainfall available during the research project, data were not adequate for a determination of rain effects on color identification. Individual subjects thresholds listed in Table 5, Appendix B, were obtained in light variable rain and thus do not represent dilution thresholds for the moderate steady rainfall conditions which would be relevant to this study.

Discussion

The average threshold values shown in Fig. 6 and Table 2 are estimates of the degree to which yellow highway paint can be diluted by white without losing yellow color identity under each combination of lighting, distance, and reference conditions.

These average values are conservative estimates of maximum permissible white dilution, for the following reasons:

1. Older drivers were used as subjects.

2. The study was conducted under conditions which approximated the actual driving environment, thus taking into account such factors as windshield attenuation, visual distance and geometry, pavement characteristics, glare, etc.

3. Actual highway paint with retroreflective glass bead was used; glass beads tend to desaturate color at night, making yellow identification more difficult.

4. In addition to the relative color judgment task with a white reference in the field of view, the more difficult absolute color judgment task was included to represent the typical driving situation.

5. Median values (Table 2) were generally higher than mean values, indicating that over half the subjects had thresholds above the mean.

6. Rather than excluding cases of no discrimination from mean values, signing an arbitrary value of −1 provided a conservative weighting.

7. The threshold criterion was 75 percent (usually 100 percent) identification as yellow, rather than the typical laboratory threshold criterion of 50 percent.

8. The threshold value for an individual subject was the whitest strip which was reliably identified as yellow. The subject's actual threshold could have been higher, somewhere between the threshold strip and the next whiter strip.

9. Subjects were instructed to identify a strip as yellow only when certain that a yellow hue was visible. In cases of uncertainty or indecision, subjects identified the strip as white. The rationale for these instructions was the fact that currently used white paint may appear off-white, cream colored, or very slightly yellow due to aging, road dirt, and yellow illumination conditions. Subjects were reminded that misperceiving yellow as white could have more serious consequences than misperceiving white as yellow; subjects were thus biased in a conservative direction.

The summary mean values for each night lighting conditions shown in Fig. 5 are conservatively weighted by inclusion of data obtained at the more difficult 60 ft and 90 ft (18.3 and 27.4 m) viewing distances. The 50 percent mean value of 480 thresholds for all five night conditions combined is a conservative general guideline for maximum white dilution since it includes the more difficult sodium vapor and glare data.

It should be noted that the intent of this study was to determine maximum dilutions of yellow/white paint mixtures under a number of viewing conditions representative of the typical driving environment. It was not within the scope of the project to determine color identification as a function of the numerous other factors which can influence perception. For example, the lighting factors along the X-axis in Fig. 5 do not represent spectral content varied systematically as a continuous variable, and the appearance of a straight-line function is due only to ranking the conditions in order of difficulty. The effects of lighting with headlights only, with oncoming glare, and with various luminaires are not directly comparable since the luminance of the test strip varied with each condition. The purpose was simply to determine the maximum white dilution which retained reliable color identification for each of these representative driving conditions; variation in luminance is one of the natural consequences of adding luminaire illumination to the headlights-only condition.

The expected effects of lighting, viewing distance, and reference are evident in Figs. 5, 6, and 7. As anticipated in the background discussion of these factors (pages 2-4), relative color discrimination with a white comparison reference permitted correct identification at higher dilution percentages. Color identification at 90 ft (27.4 m) was considerably worse than at 30 ft (9.1 m), especially for the difficult sodium vapor and glare conditions; the smaller visual size of the distant test strips and the effect of a shallower angle of view on the glass bead surface desaturated the apparent color; the luminance of the distant test strips was lower in relation to the brightly lighted pavement just ahead of the vehicle. Daylight and mercury vapor illumination, with relatively higher proportions of blue light in their spectral distributions, permitted correct identification of yellow/white mixtures at higher dilution percentages than was possible with the predominantly yellow spectral distributions of sodium vapor and tungsten illumination. Color perception in the headlights-only condition was affected by the desaturating effect of retroreflective glass beads on the paint surface. The effects of glare are complex, varying with individuals, primarily producing a reduction in effective luminance of the test strip.

Although the effect of retroreflective glass beads was not specifically studied* as an independent variable, a significant interaction between viewing angle and color saturation was observed. The color of a test strip would appear to be much more saturated when the strip was held up perpendicular to the subject's line of sight. At the shallow viewing angles used for threshold determinations, a test strip would appear much whiter. The likely mechanism of this shallow-angle desaturation effect is suggested in Fig. 8. At a higher angle of view, looking straight at the surface, the relatively large area of paint between the beads can contribute to the color saturation of light returned to the observer. At a shallow angle of view, however, the plain paint surface is obscured by protruding glass beads; the superimposed appearance of protruding beads at a shallow angle of view was confirmed by direct observation with a 30 power stereomicroscope. Glass beads are in effect small convex lenses which focus incoming light at some point behind the front surface, then return the light from this focal point back in the direction of the source.

Although the commonly used highway beads with a 1.5 index of refraction act primarily as convex lenses, returning light selectively absorbed by the pigment at the back of each bead, some of the incident light is returned by total internal reflection without being affected by pigment. This has the effect of desaturating the apparent color of the painted surface. In addition, the light returned by glass beads is significantly brighter, which also has a desaturating effect. At a shallow angle of

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*Since highway delineation is typically reflectorized with glass bead surfacing, all test strips were surfaced with standard Caltrans glass bead, 1.5 index of refraction; it was not relevant to the objectives of this study to test color identification with non-reflectorized paint samples.

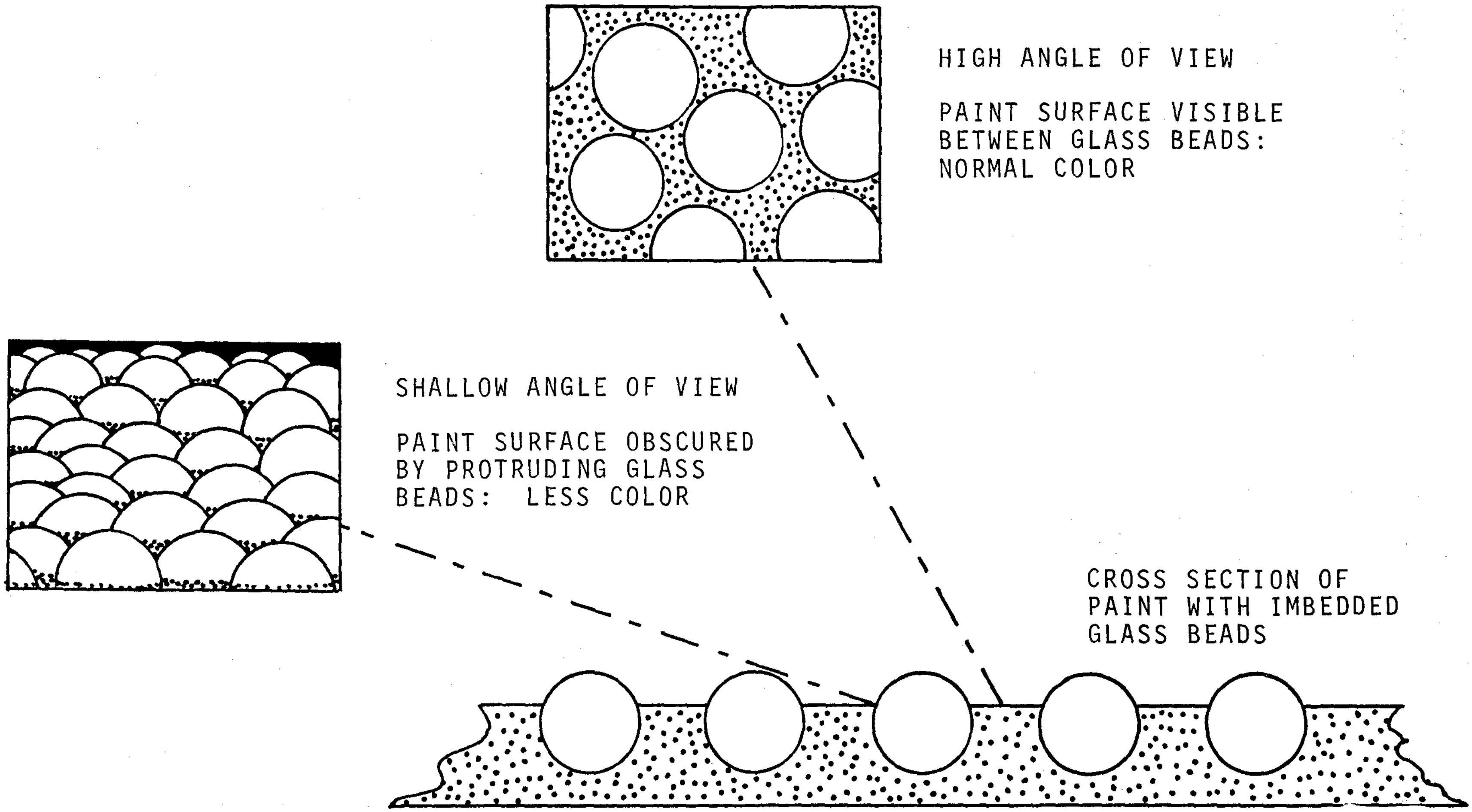

Figure 8. Effect of Glass Beads on Color Saturation at Shallow Angles of View. (At the shallow angles of view from which highway delineation is seen by a driver, glass beads can have a desaturating effect by obscuring the paint surface, in addition to the desaturation caused by returning incident light unaffected by pigment color.)

view, nearly all the light returned to the observer comes from the glass beads; at higher angles of view, much of the light comes from the unbeaded paint surface, producing greater color saturation. It is, therefore, important to use only glass-beaded paint samples at shallow viewing angles in testing color identification of highway paint. Testing at more direct viewing angles, or with unbeaded paint, would tend to underestimate the pigmentation required for reliable color perception.

CONCLUSIONS

Currently used yellow highway paint may be diluted up to 50 percent with white paint without loss of color identity under driving conditions where color is normally visible.

IMPROVED CONTRAST AND VISIBILITY

By replacing some of the yellow pigment with white pigment, several problems inherent in current yellow paint use can be reduced. Yellow delineation is initially less reflective than white, and darkens considerably with exposure after painting. Due to lower brightness contrast with the pavement, yellow markings are typically not as visible as white under adverse driving conditions of night lighting, rain, fog, and windshield degradation due to road film, veiling luminance, icing, interior fogging, glare, and so on. Only in exceptional cases would the additional color contrast of yellow markings improve visibility; under snow conditions or with very light colored pavement, the contrast of color as well as the contrast of brightness may give yellow lines greater visibility than white.

COST SAVINGS

Dilution of yellow paint would also reduce the extra cost of yellow painting, since yellow paint is approximately 15 percent more expensive than white. Table 4 presents a cost savings estimate, assuming 50 percent dilution, 15 percent higher cost for yellow paint, and an annual use of 5 million gallons for yellow delineation. With these assumptions, the current extra cost for yellow delineation (as opposed to all-white delineation) is $2,250,000 annually. By adding 2 gallons (7.57 liters) of white paint (containing 1 lb/gal (.12 kg/l) titanium dioxide pigment) for each gallon of yellow (containing 2 lb/gal (.24 kg/l) lead chromate pigment), the extra cost of yellow delineation would be reduced to $750,000 annually, a 67 percent cost reduction of $1,500,000 annually. The cost reduction for other levels of dilution and other compositions of paint may be estimated in the same fashion.

TABLE 4. ESTIMATED COST SAVINGS

ASSUMPTIONS

yellow paint used annually = 5,000,000 gal
white paint used annually = 10,000,000 gal

yellow paint costs 15% more than white paint
yellow paint (2.0 lb/gal lead chromate) @ $3.45/gal
white paint (1.0 lb/gal titanium dioxide) @ $3.00/gal

ANNUAL COST FOR YELLOW PAINTING (100% yellow)

5,000,000 gal yellow paint @ $3.45/gal = $ 17,250,000
cost for same amount white @ $3.00/gal = $ 15,000,000
15% extra cost of yellow paint = $ 2,250,000

REDUCED ANNUAL COST FOR YELLOW/WHITE MIXTURE (50% yellow)

pigment weight ratio = 50:50
volume mixture ratio = 2 gal white per 1 gal yellow
pigment weight content of mixture: 0.667 lb white/gal
0.667 lb yellow/gal
1.333 lb total/gal

5,000,000 gal yellow/white mixture used annually, containing:

1,666,667 gal yellow @ $3.45/gal = $ 5,750,000
3,333,333 gal white @ $3.00/gal = $ 10,000,000
mixture total = $ 15,750,000
cost for same amount white = $ 15,000,000
extra cost for yellow mixture = $ 750,000

ANNUAL COST SAVINGS

current extra cost for 100% yellow paint = $ 2,250,000
reduced extra cost for 50:50 yellow mixture = $ 750,000
67% cost savings = $ 1,500,000

ADVANTAGES

improved visibility with brighter yellow line
less darkening of line with age and exposure
reduced lead content of yellow paint mixture
existing paint inventory can be used for mixing
no change in equipment or procedures
substantial cost reduction

1 lb/gal = .11983 kg/1

OTHER BENEFITS OF YELLOW/WHITE DILUTION

The toxicity of the yellow delineation paint would be reduced by whatever percent dilution is selected for specific applications.

The use of white-diluted yellow paint would require no change in equipment or procedures, and the current inventory of yellow and white paint can be used to prepare the yellow/white mixture according to the formula given in Table 1. New paint specifications may be prepared for subsequent procurement of paint with the desired yellow and white pigment ratio. The addition of white pigment to replace some of the yellow pigment is preferable to simple reduction of the yellow pigment content, since the white allows yellow reduction while maintaining hiding power and improving reflectance of the paint.

Two other problems inherent in the use of yellow markings in addition to white are: 1) the separate storage and painting equipment required; and 2) the fact that most drivers are unaware that delineation color is intended to signify the direction of traffic movement in the adjacent lane. None of the subjects in this study were aware that use of yellow marking indicates oncoming traffic in the adjacent lane. A recent study by Gordon[4] found that most drivers do not understand the color code specified by the Manual of Uniform Traffic Control Devices (MUTCD). These problems would not be alleviated by use of diluted yellow/white mixtures, but the general lack of color-code use by drivers suggests that misperception of diluted yellow/white mixtures as white under difficult viewing conditions would not adversely affect driving behavior. Only those exceptional drivers who are aware of and rely on the MUTCD color code would be affected by misperception of yellow.

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[4] Gordon, D. A., Studies of the Road Marking Code, FHWA, Office of Research and Development, FHWA-RD-76-59, Apr. 1976.

ALTERNATE APPROACHES

Other alternatives for dealing with the yellow paint problems cited above are use of non-lead organic pigments to provide yellow coloring, or a return to all-white delineation as suggested by Gordon.[4]

BLACK UNDERPAINTING FOR IMPROVED DELINEATION VISIBILITY

Visibility of both yellow and white delineation depends primarily on contrast with the pavement surface. The greater the difference in brightness at the light/dark border between the stripe and the pavement, the better the visibility of the delineation under adverse viewing conditions. This study has explored one way of increasing the brightness of the delineation, but there is an additional means by which contrast can be further improved. The difference in brightness between line and pavement can be made greater by reducing the brightness of the pavement surface adjacent to the line. Either black paint or a line of black asphalt can be laid down prior to painting with yellow or white. This is done routinely in some states (e.g., California), especially when concrete or other light-colored pavement makes standard delineation difficult to see.

Black underpainting provides improved light/dark contrast visibility, better color saturation appearance (e.g., black-matrix screens in color television), seals the pavement surface for more efficient use of delineation paint, covers the previous line to reduce accuracy required in repainting, raises the stripe slightly to improve drainage of surface water (especially true for asphalt underpainting), and in the case of lightly sanded asphalt may provide some audible cues to the driver (as with raised pavement markers).

Underpainting with black paint is more expensive than with asphalt, but has the advantage that one paint truck can lay down the underpainting

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[4] Gordon, Studies of the Road Marking Code.

and the delineation in a single operation. Underpainting with a line of black asphalt coated with fine sand has the advantage of improving paint adhesion on concrete pavement, and the rough textured surface does not reflect light in such a way as to make the black surface appear brighter than the pavement, as sometimes happens with black paint (e.g., with oncoming headlight glare or luminaires ahead of the vehicle). The increase in apparent brightness with a black surround has been extensively studied; Cornsweet[5] provides an excellent review of this lateral inhibition effect. The apparent increase in color saturation, often referred to as the von Bezold spreading effect, is illustrated by Burnham,[6] Fig. 3-12. In laboratory studies of these effects, large changes in apparent brightness and saturation have been produced by the use of black borders.

ALTERNATE CONFIGURATIONS FOR COLOR CODING

Instead of reducing the yellow pigment content of yellow delineation by dilution with white, which disperses the yellow pigment over the entire stripe, a white line could be laid down with a thin 100 percent yellow stripe down the center. This would greatly reduce the amount of yellow pigment used on the roads, would make the yellow color more perceptible under adverse conditions due to the direct superimposition of yellow on white (relative color discrimination), provide a higher luminance contrast at the 100 percent white border of the stripe, and provide color contrast in conditions where brightness contrast is not effective (e.g., in snow conditions or with blowing sand, the yellow color contrast may provide visibility when the white striping was lost in the achromatic surround). This approach to reduction of yellow pigment content would concentrate a small amount of yellow pigment in the center of the stripe, rather than disperse it over the entire stripe; this untested approach may permit even

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[5] Cornsweet, T. N., Visual Perception, New York, Academic Press, 1970,

[6] Burnham, R. W., R. M. Hanes, and C. J. Bartleson, Color: A Guide to Basic Facts and Concepts, New York, Wiley, 1963.

greater reduction in yellow pigment content with full retention of color-code identity. Unlike the dilution approach to the problem, it would require development of a narrow paint spray nozzle behind the standard white striping equipment. Due to the contrast-enhancing mechanisms in the human visual system, the white edges of the stripe would tend to make the entire stripe effectively brighter.[5]

PUBLIC ACCEPTANCE

Only one possible disadvantage is foreseen in use of diluted yellow/white mixtures. Even though diluted yellow markings can be discriminated from white for the purpose of color coding traffic direction, the diluted mixtures may appear to be less acceptable to the driving public in daylight conditions. When the Texas Highway Department painted test sections with various dilutions of yellow/white mixtures, there were some complaints about the "muddy" or "cream-colored" daylight appearance of this delineation.[7] Percentages of less than 30 percent did not produce this unfavorable reaction to dilution of yellow. The appearance of all dilute mixtures was acceptable under night viewing conditions, however.

In preparing the mixtures used in this study, it was noted that substantial amounts of white paint must be added to pure yellow to desaturate the color. In daylight, when the desaturating effect of reflective glass beads is not a factor and the blue content of the spectrum makes yellow/white discrimination relatively easy, even a 70 percent white mixture was distinctly yellow. The 30 percent and 40 percent dilutions were hardly discriminable from pure yellow paint, and appeared to have an aesthetically acceptable vivid yellow saturation. According to the Texas Highway Department tests, however, the yellow color will become less vivid and somewhat muddy in appearance as the yellow component in the mixture darkens with exposure after painting.[7] It was not within the scope of this study to

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[5] Cornsweet, Visual Perception.

[7] Moore, K. K., Texas Highway Department, Austin, Texas. Personal communication, 1976.

determine public acceptance of various white dilutions under daylight conditions, however, and thus this report presents only the data on drivers' ability to discriminate yellow/white mixtures from white.

RATIONALE FOR DILUTION GUIDELINES

Although subjects could readily identify the yellow content of highly diluted text mixtures (over 90 percent white) in daylight, the more difficult night lighting conditions limit maximum permissible dilution, since the color code must be reliably identified under both day and night conditions.

The maximum permissible white dilution need not be limited by a worst-case philosophy in all respects, however. Considering that the lane line is usually visible within 30 ft (9.1 m) of a vehicle, threshold averages for the 30 ft viewing distance (Fig. 6, Table 2) may be taken as appropriate estimates of maximum permissible white dilution for each lighting condition, either with or without a white reference in the field of view. The cases of no discrimination at the difficult 90 ft (27.4 m) viewing distance (Fig. 7) may be regarded as not relevant since only a few subjects failed to make yellow/white discriminations at 30 ft. A driver would be unable to see lane lines just ahead of the vehicle only in exceptional cases, e.g., when a low eye position or high vehicle hood obscure the road surface at near distances.

Only those viewing conditions in which the presently used 100 percent yellow paint can be reliably identified would seem appropriate for consideration in determining dilution guidelines. Drivers may be expected not to rely on color coding under adverse lighting and weather conditions which normally make color identification difficult, or make it difficult even to see the delineation at all. Dilution of yellow paint would not tend to induce unsafe passing behavior in this case, since drivers would be familiar with the difficulty of color perception under such conditions. The benefits of improved delineation visibility with whiter paint would outweigh the remote possibility that a driver might base an unsafe passing maneuver on a misperceived whiter appearance of diluted yellow lane lines.

TAILORING PERCENT DILUTION FOR SPECIFIC LIGHTING CONDITIONS

Average threshold values shown in Fig. 6 indicate the extent to which yellow paint can be diluted by white without losing color identity under each combination of lighting, distance, and reference conditions.

The maximum percent white dilution can be selected for a given type of night lighting and edge-line treatment. Highway engineering staffs can alter the dilution ratio for a given section of delineation according to the averages obtained at the 30 ft (9.1 m) viewing distance. If white striping is at the right edge of the lane, as in a four-lane highway, the averages in Fig. 6 obtained with reference (open circles) may be used for each lighting condition. On a highway without any white delineation (e.g., two-lane road without edge line), then the averages obtained without reference (filled circles) should be used, since an absolute color judgment will be required for identification of yellow hue. For example, the dilution percent which may be used for a section of highway lighted with mercury luminaires would be 77 percent with a white edge line at the right side of the lane and 69 percent without a white edge line. The exact numerical values for maximum permissible dilution are shown in Table 2. Due to the inherently conservative bias of these averages, well over half the driving population would correctly identify the color of yellow/white mixtures, under night viewing conditions where color is normally visible with 100 percent yellow paint.

The higher dilutions specified for mercury vapor lighting may be used for sections with amber retroreflective raised pavement markers, since the brilliant color of the markers will convey the color code at night, and the diluted yellow paint will be clearly identifiable in daylight.

The most conservative guide for each type of night lighting condition would be the average values shown in Fig. 5. The maximum dilutions which can be used with confidence are those for the 30 ft (9.1 m) distance, either with or without reference, as shown in Table 2 and Fig. 6.

SUMMARY

The advantages of using diluted yellow/white paint mixtures for all yellow delineation are:

1. Improved initial brightness of delineation and reduced darkening with exposure, resulting in increased visibility under adverse conditions.

2. Reduced cost.

3. Reduced toxicity.

4. Use of existing paint inventory.

5. No change in equipment or procedures.

6. No significant reduction in driving safety due to alteration of color coding, with an improvement in driving safety due to better delineation visibility.

RECOMMENDATIONS

As a general guideline for dilution of yellow paint with white, use a 50:50 yellow/white pigment weight ratio. To provide at least 1.3 lb/gal (.156 kg/l) total pigment for hiding power and protection of the paint, use 0.65 lb/gal (.08 kg/l) yellow (medium lead chromate) and 0.65 lb/gal (.08 kg/l) white (titanium dioxide). This pigment content can be obtained by mixing 2 gal (7.6 liters) white paint (1 lb/gal (.12 kg/l) pigment) with each 1 gal (3.8 liters) of yellow paint (2 lb/gal (.24 kg/l) pigment), or paint with mixed pigment specifications may be obtained from the manufacturer.

For maximum white dilution, tailor yellow mixture dilutions for each section of highway as a function of the lighting conditions and the presence of other white delineation.

For maximum delineation visibility, increase contrast by underpainting with black paint or black asphalt. If possible, roughen the surface of the underpainting with fine sand to reduce surface sheen and improve adhesion of delineation paint.

Conduct color identification testing of highway delineation materials with fully reflectorized samples at viewing angles which will occur in the actual driving environment. Use of non-reflectorized samples at higher than normal viewing angles may tend to underestimate the pigmentation required for correct color identification in night driving conditions.

APPENDIX A

COLOR NAMING EXPERIMENT PROTOCOL

INSTRUCTIONS TO RESEARCH ASSISTANTS

Objective

To find the point where subjects mistakenly identify a yellow/white paint mixture as white, under varying lighting, distance, and reference conditions.

Background

The Federal Highway Administration has commissioned Human Factors Research, Inc. (HFR) to conduct research to determine how much the yellow highway paint can be diluted with white paint to: a) improve reflectivity and visibility under adverse conditions; and b) reduce the lead pigment in the paint for environmental and cost considerations, without causing drivers to mistake the diluted yellow as white.

Since the yellow/white color is a code for two-way versus same-way traffic in the painted lanes, it is important that drivers correctly identify yellow as such. Perceiving it as white could lead to head-on collisions if drivers assumed that traffic was the same way in the adjacent lane.

Samples of actual highway paint have been mixed and applied to 8 ft × 4 in. (2.4 m × 10 cm) metal strips, which can be placed on the pavement in front of a parked car where the subject sits to make color judgments in the most realistic conditions possible. The fact that fairly yellow sample strips look purely white when viewed from an actual vehicle at normal distances makes it important to gather field-type experimental data, rather than construct an attempted simulation on a small scale indoors. The interactions of the glass beads with color is an important factor.

Absolute color judgment is much more difficult than judgments of one color compared with another. Thus, in some cases a white reference strip will be placed in the field of view, to make the perception of yellow easier. Color perception varies greatly with the type of illumination available. What looks distinctly yellow in one light may look pure white in another, in the presence of glare, etc. Thus, there is the need to test color naming under a variety of lighting conditions.

Observers in a parked car will observe paint samples at 30, 60, and 90 ft (9.1, 18.3, and 27.4 m), under seven lighting conditions: high sun, low sun, headlights only, headlights plus mercury vapor, headlights plus sodium vapor, headlights plus tungsten illumination, headlights plus oncoming headlight glare. The research must explore both favorable and adverse conditions.

Materials and Apparatus

1. Fifteen thin metal strips, 8 ft × 4 in. (2.4 m × 10 cm), painted with various mixtures of yellow and white highway paint.
2. Roof rack for carrying strips, with flip-type holder for selection of strip to be shown.
3. Steel 100 ft (30.5 m) tape measure, chalk for marking road positions at 30, 60, and 90 ft.
4. Score sheets and clipboard, etc.
5. Standard U. S. sedan for subject to sit in.
6. Available locations with: a) no street lighting; b) mercury vapor; and c) sodium vapor lights. Tungsten lighting with headlight glare provided in Location A with portable source.

Procedure

1. Transport test materials and subject to test site.
2. Position car at 30 ft mark (chalk marks on curb).
    a. Test at 30 ft without white reference.
    b. Test again with white reference visible (100 percent of white strip).

3. Position car at 60 ft mark. Test with and without reference (100 percent white strip).

4. Position car at 90 ft mark. Test with and without reference (100 percent white strip).

5. Fill in data on score sheet for each light/weather condition. Note date and time, plus any visual data which may be of interest (e.g., full moon rising, etc.). Note also any comments by subjects, on back of sheet, if necessary.

HFR has permission from Minicars, Inc., for use of the test track at Location A, and the University Plaza headquarters at Location C for this experiment.

TESTING DETAILS

Positioning Car and Strips

See Fig. 1 for graphic showing car/strip/light positions. In the case of street lighting, place the strip centered with respect to light.

The 30 ft, 60 ft, and 90 ft (9.1, 18.3, and 27.4 m) distances are measured from the subject's eye position to the front edge of the strip.

The strip is placed on a line 2 ft (0.6 m) to the left of the subject and parallel to the car.

The glare source light closest to the strip is 2 ft further to the side away from the subject and 200 ft (61 m) from the subject (thus the glare source must be repositioned when the car is moved for each of the three distances).

Use low beams for 30 ft, high beams for 60 ft and 90 ft.

Clean headlight and windshield at beginning of each test session.

Presentation of Test Strips

Begin with the 58 percent strip and, if that is judged yellow, present whiter strips until the breakpoint is found. Go beyond the breakpoint until you have three strips called "white," then come back across the breakpoint toward the yellow end (lower numbers) until you have three strips called "yellow." Use the reverse procedure if the first strip is judged white.

The subject responds by turning on the RIGHT TURN SIGNAL FOR WHITE, LEFT FOR YELLOW (see Fig. 3).

Continue until you have accumulated at least four presentations of the breakpoint strips (i.e., adjacent strips called yellow and white) and then three presentations on either side of these.

You may need to obtain more than this minimum number of presentations if the subject's judgments settle down only after several strips are presented or if the breakpoint is not well-defined initially.

Locations

Location A is the AMF test track northwest of HFR. This is used for the daylight tests, for headlights only, and for glare and tungsten lighting.

Location B is under the mercury vapor streetlight, on the loop road beyind HFR (used for MV only).

Location C is at University Village Plaza, just off Hollister at Pacific Oaks Road.

Other Considerations

Do not wear white or yellow clothing, since you will be in the field of view of the subject. Wear dark colors, preferably dark brown or gray or black.

You will be shown how to adjust the sun visor of the car and blackout cloth to block out unwanted items in the visual field at each location.

Do not present a strip or accept a response if a passing car goes by at that moment.

INSTRUCTIONS TO SUBJECTS

Introduction

The Federal Highway Administration has commissioned Human Factors Research, Inc., to do research aimed at finding ways to improve the visibility of the yellow lane lines painted on the highway. They want to dilute the yellow paint with white to increase its brightness and because the yellow pigment is expensive and toxic.

In this example, you can readily see that yellow paint is darker than white.

If too much white is added to the yellow paint mix, however, it might become such a pale yellow that under poor lighting conditions it would seem white, and not be taken for the yellow line that is intended. Correct identification of the line color is important because yellow means that traffic is two way, while white means that traffic is all in the same direction (as on the freeway). If a driver mistakenly saw a diluted yellow line as white, and thought it was safe to go over into the adjacent lane to pass and continue driving, it could result in a head-on collision with oncoming traffic.

This research project is designed to find out how much the yellow paint can be lightened with white pigment without making it so pale in color that it is confused with white under typical lighting conditions.

The Experiment

We have prepared a series of yellow/white paint mixtures ranging from 100 percent yellow to 100 percent white, with many shades of yellow/white in between. These various mixtures are painted on test strips exactly the size of standard highway paint lines on the road.

You will judge whether the sample strip looks yellow or white under various lighting conditions and distances, viewing the test strips from a parked car. In some cases, a 100 percent white strip will be placed 3 ft from the test strip to provide a color reference which may make the true color of the test strip more evident.

What we want you to do is to say when a line looks yellow, when you are sure it's yellow. If you are not sure, if what you see could be a dirty or faded white line, you should call it white. We are trying to determine the point at which yellow is so diluted with white that it would be confused with pure white under the lighting and distance conditions to be tested.

I will put one test strip at a time on the pavement in front of the parked car and, for each sample, you should indicate whether it looks white or whether you can see some yellow in it. Don't stretch your imagination, but say yellow if you can see the color tint, even if it is pale or faint in comparison to the yellow highway paint you are used to seeing on the road.

In making the color judgment, remember that at least half the samples may be pure white highway paint, and some have been made darker than others so that the brightness of the line is not a cue to its being white or yellow. Instead of thinking about the brightness or dimness of the samples, since in this case it has nothing to do with color, just look for YELLOW COLOR versus WHITE.

Subject's Task

Your task is to distinguish between the pure white (or dull white and gray) samples and the samples that have some yellow pigment in the mixture. You will signal your color judgment by blinking the car's turn signals: RIGHT FOR WHITE, LEFT FOR YELLOW (turn signal lever UP for WHITE = RIGHT, lever DOWN for YELLOW = LEFT).

Notes

1. Don't stare at the sample strip for more than 10 seconds or so. Colors tend to fade or become more pale and white when you stare at them, especially the small patch of color you see when viewing the sample from a far distance.

2. Make your color judgment rather quickly, without thinking it over too much. This is more like the conditions of real driving, where you are just glancing at the lines, not concentrating on them exclusively.

3. So, when the color sample is in place, just look at it briefly and make your WHITE or YELLOW judgment quickly by using the turn signals.

4. Try not to look directly at the sample strips until you are making the judgment; rather, look off to the side or above.

5. Remember not to judge on the basis of brightness, because some of the white samples have been made darker by adding gray, to produce a dull white like that in worn or dirty highway paint.

6. If you are confused or uncertain, call the strip "white." This is very important.

APPENDIX B

PRINTOUT OF RAW DATA FROM YELLOW/WHITE
COLOR DISCRIMINATION RESEARCH

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DATA IN PERCENT WHITE STILL IDENTIFIED AS YELLOW, -1 = NO DISCRIMINATION
                                                  -2 = MISSING DATA, 00 = 0%

  A = AUTO-- 1 = VALIANT, 2 = AUDI, 3 = NOVA , 4 = PINTO.
L = LIGHTING CONDITION     1 = SODIUM, 2 = MERCURY VAPOR, 3 = TUNGSTEN,
                           4 = HEADLIGHTS, 5 = GLARE, 6 = SUNSET, 7 = NOON
D = DISTANCE-- 1 = 30 FT, 2 = 60 FT, 3 = 90 FT      R1 = NO REF, R2 = WITH REF

SUBJ #    A  L        D1/R1       D1/R2       D2/R1       D2/R2       D3/R1       D3/R2

DATA FROM SIXTEEN SUBJECTS USED IN ANALYSIS OF VARIANCE >

AR  01    4  1         95.         89.         84.         79.         89.         84.
AR  01    4  2         89.         89.         84.         89.         73.         89.
AR  01    4  3         73.         73.         79.         89.         84.         84.
AR  01    4  4         68.         79.         79.         84.         84.         84.
AR  01    4  5         58.         73.         58.         73.         -1.         58.

BP  02    4  1         58.         58.         00.         28.         58.         00.
BP  02    4  2         84.         84.         73.         68.         68.         68.
BP  02    4  3         49.         68.         48.         58.         48.         48.
BP  02    4  4         58.         58.         38.         48.         00.         48.
BP  02    4  5         38.         48.         48.         48.         -1.         -1.

EX  03    4  1         84.         89.         84.         79.         -1.         -1.
EX  03    4  2         89.         89.         68.         84.         38.         68.
EX  03    4  3         89.         89.         89.         89.         48.         89.
EX  03    4  4         48.         84.         38.         79.         00.         38.
EX  03    4  5         79.         89.         68.         79.         -1.         00.

EE  04    4  1         00.         48.         00.         00.         -1.         -1.
EE  04    4  2         28.         58.         68.         00.         73.         28.
EE  04    4  3         68.         48.         73.         58.         48.         48.
EE  04    4  4         79.         48.         95.         84.         73.         68.
EE  04    4  5         48.         58.         73.         58.         00.         00.

EN  05    4  1         -1.         -1.         -1.         -1.         -1.         68.
EN  05    4  2         89.         79.         84.         84.         79.         84.
EN  05    4  3         79.         84.         79.         89.         58.         43.
EN  05    4  4         79.         79.         73.         79.         73.         84.
EN  05    4  5         79.         89.         68.         73.         00.         28.

LC  06    4  1         73.         -1.         84.         89.         -1.         79.
LC  06    4  2         73.         84.         84.         95.         68.         84.
LC  06    4  3         68.         89.         84.         95.         58.         84.
LC  06    4  4         79.         84.         89.         95.         00.         73.
LC  06    4  5         38.         84.         48.         73.         -1.         -1.

MT  07    4  1         58.         73.         28.         58.         00.         28.
MT  07    4  2         49.         84.         38.         79.         28.         73.
MT  07    4  3         48.         73.         48.         58.         00.         48.
MT  07    4  4         00.         38.         48.         58.         00.         38.
MT  07    4  5         73.         79.         58.         73.         -1.         48.
```

SJ	08	4	1	79.	84.	79.	79.	-1.	73.
SJ	08	4	2	79.	79.	68.	79.	-1.	-1.
SJ	08	4	3	73.	73.	58.	68.	28.	28.
SJ	08	4	4	58.	58.	58.	58.	-1.	00.
SJ	08	4	5	58.	58.	68.	58.	-1.	-1.
BE	09	3	1	38.	68.	00.	00.	00.	-1.
BE	09	3	2	84.	89.	73.	84.	00.	73.
BE	09	3	3	58.	73.	58.	58.	00.	-1.
BE	09	3	4	48.	48.	28.	48.	00.	00.
BE	09	3	5	38.	58.	-1.	48.	-1.	-1.
FB	10	3	1	89.	89.	89.	84.	79.	84.
FB	10	3	2	89.	84.	73.	79.	48.	84.
FB	10	3	3	73.	48.	48.	48.	58.	-1.
FB	10	3	4	48.	79.	95.	89.	84.	73.
FB	10	3	5	58.	68.	48.	58.	-1.	-1.
RB	11	3	1	73.	58.	28.	48.	-1.	-1.
RB	11	3	2	84.	48.	00.	48.	-1.	28.
RB	11	3	3	48.	48.	00.	28.	-1.	00.
RB	11	3	4	38.	48.	00.	38.	00.	-1.
RB	11	3	5	48.	48.	38.	48.	-1.	-1.
HC	12	3	1	79.	84.	89.	84.	79.	79.
HC	12	3	2	79.	89.	79.	84.	58.	73.
HC	12	3	3	89.	89.	73.	79.	73.	84.
HC	12	3	4	79.	84.	68.	84.	73.	73.
HC	12	3	5	73.	79.	73.	73.	-1.	58.
JA	13	3	1	38.	58.	00.	38.	-1.	00.
JA	13	3	2	00.	68.	00.	68.	-1.	-1.
JA	13	3	3	48.	84.	68.	89.	00.	38.
JA	13	3	4	00.	73.	00.	68.	00.	79.
JA	13	3	5	-1.	58.	00.	48.	-1.	-1.
ZA	14	3	1	58.	79.	38.	58.	-1.	00.
ZA	14	3	2	48.	58.	28.	48.	-1.	-1.
ZA	14	3	3	00.	00.	00.	00.	00.	00.
ZA	14	3	4	00.	00.	00.	38.	00.	28.
ZA	14	3	5	48.	48.	00.	00.	-1.	-1.
RS	15	1	1	95.	96.	92.	78.	-1.	-1.
RS	15	1	2	98.	98.	96.	98.	43.	92.
RS	15	3	3	79.	89.	79.	79.	38.	84.
RS	15	1	4	92.	92.	43.	43.	31.	43.
RS	15	3	5	73.	84.	-1.	38.	-1.	-1.
TH	16	3	1	38.	73.	00.	58.	-1.	58.
TH	16	2	2	43.	48.	31.	43.	00.	43.
TH	16	3	3	28.	58.	58.	68.	84.	79.
TH	16	2	4	43.	43.	43.	43.	31.	31.
TH	16	3	5	00.	68.	00.	48.	-1.	-1.

```
 >>>>> DATA FROM LOW SUN CONDITION (30 MIN < SUNSET)

BE  09  3  6    95.    95.    -2.    -2.    79.    84.
HC  12  4  6    95.    95.    95.    95.    89.    95.
JA  13  3  6    95.    95.    95.    95.    95.    95.
ZA  14  3  6    79.    89.    68.    79.    68.    73.
RS  15  1  6    98.    -2.    95.    -2.    96.    -2.
TH  16  3  6    89.    89.    79.    89.    79.    -2.
VS  17  4  6    89.    89.    89.    89.    89.    89.
CK  18  1  6    92.    -2.    92.    -2.    92.    -2.
AS  19  1  6    99.    98.    96.    -2.    92.    -2.

  >>>>> DATA FROM HIGH SUN CONDITION  (NOON +/- 3 HRS)

BE  09  3  7    95.    95.    95.    95.    89.    95.
FB  10  3  7    89.    89.    89.    89.    89.    89.
HC  12  3  7    95.    95.    95.    95.    95.    95.
ZA  14  3  7    89.    -2.    89.    -2.    89.    -2.
TH  16  3  7    95.    95.    95.    95.    89.    95.
AL  20  3  7    89.    95.    95.    95.    95.    95.



>>>>> DATA FROM  INITIAL (PILOT) SUBJ NOT INCLUDED IN ANALYSIS OF MAIN EXPT


VS  17  3  1    84.    89.    89.    89.    84.    79.
VS  17  3  2    89.    89.    73.    89.    58.    84.
VS  17  3  3    79.    89.    73.    84.    38.    38.
VS  17  4  4    73.    79.    79.    73.    00.    73.
VS  17  4  5    79.    84.    79.    84.    -1.    -1.

CK  18  1  1    92.    95.    92.    92.    -1.    78.
CK  18  1  2    95.    96.    92.    92.    43.    43.
CK  18  3  3    58.    68.    38.    58.    00.    38.
CK  18  1  4    31.    43.    43.    43.    31.    43.
CK  18  3  5    00.    38.    00.    28.    -1.    -1.

AS  19  1  1    -1.    -1.    -1.    -1.    -1.    -1.
AS  19  1  2    92.    92.    31.    31.    -1.    -1.
AS  19  3  3    48.    79.    28.    38.    00.    -1.
AS  19  1  4    31.    92.    00.    43.    -1.    31.
AS  19  3  5    00.    38.    -1.    -1.    -1.    -1.

AL  20  3  1    79.    84.    84.    84.    84.    84.
AL  20  3  2    89.    84.    73.    79.    73.    89.
AL  20  4  3    79.    79.    79.    79.    79.    84.
AL  20  3  4    58.    79.    84.    -2.    89.    89.
AL  20  3  5    79.    89.    73.    73.    -1.    -1.
```

TABLE 5. RAIN DATA

	SUBJ.	30 ft		60 ft		90 ft	
		NO REF	REF	NO REF	REF	NO REF	REF
MERCURY VAPOR	HC	92	92	92	78	96	95
	VS	84	89	0	0	ND	ND
	BP	43	43	31	31	ND	31
HEADLIGHT ONLY	HC	48	92	43	43	43	43
	BP	43	43	43	43	31	43
	AL	58	79	84	**	89	89
SODIUM VAPOR	VS	84	68	38	68	95	84
TUNG-STEN	AL	79	89	89	89	95	95

ND = NO DISCRIMINATION

** = MISSING DATA

NUMERICAL VALUES ARE MAXIMUM PERCENT WHITE WHICH WAS RELIABLY IDENTIFIED AS YELLOW

LIGHTING CONDITION	AVERAGE	±	95% CONFIDENCE LIMIT
MERCURY VAPOR	49	±	18.8
HEADLIGHT ONLY	56.3	±	10.2
SODIUM VAPOR	72	±	16.4
TUNGSTEN	89	±	4.8
OVERALL AVERAGE	60	±	4.5

* Note: rainfall was light, variable, and inconsistent. The data obtained should not be considered representative of color identification in moderate, steady rain conditions.

APPENDIX C

NATIONAL BUREAU OF STANDARDS CHROMATICITY MEASUREMENTS FOR SECOND SAMPLE SET

The National Bureau of Standards provided chromaticity measurements for the second set of yellow/white mixture paint test strips, as listed in Table 1 of the text. Paul G. Campbell, Supervisory Research Chemist of the Materials and Composites Section of the Structures, Materials and Safety Division, noted that these measures are related to daylight illuminant only, and that as the lead chromate content (yellow pigment) is increased, the samples become redder (a+), yellower (b+), and darker (−L).

PERCENT PIGMENT COMPOSED OF WHITE TiO_2	CHROMATICITY MEASURES		
	L	a	b
100 (all white)	84.8	−1.8	7.6
95	78.6	−0.7	23.2
89	77.1	0.7	30.7
84	77.2	2.4	32.8
79	73.9	2.3	35.0
73	73.0	4.1	36.7
68	74.5	4.0	37.3
58	71.5	6.3	38.2
48	67.7	7.6	37.5
38	69.3	8.0	39.9
28	71.0	8.9	41.6
0 (all yellow)	63.0	12.7	38.8

Instrument: Neo Tec Tru-Color

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FEDERALLY COORDINATED PROGRAM OF HIGHWAY RESEARCH AND DEVELOPMENT (FCP)

The Offices of Research and Development of the Federal Highway Administration are responsible for a broad program of research with resources including its own staff, contract programs, and a Federal-Aid program which is conducted by or through the State highway departments and which also finances the National Cooperative Highway Research Program managed by the Transportation Research Board. The Federally Coordinated Program of Highway Research and Development (FCP) is a carefully selected group of projects aimed at urgent, national problems, which concentrates these resources on these problems to obtain timely solutions. Virtually all of the available funds and staff resources are a part of the FCP, together with as much of the Federal-aid research funds of the States and the NCHRP resources as the States agree to devote to these projects.[*]

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements which affect the quality of the human environment. The ultimate goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge of materials properties and technology to fully utilize available naturally occurring materials, to develop extender or substitute materials for materials in short supply, and to devise procedures for converting industrial and other wastes into useful highway products. These activities are all directed toward the common goals of lowering the cost of highway construction and extending the period of maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural designs, fabrication processes, and construction techniques, to provide safe, efficient highways at reasonable cost.

6. Prototype Development and Implementation of Research

This category is concerned with developing and transferring research and technology into practice, or, as it has been commonly identified, "technology transfer."

7. Improved Technology for Highway Maintenance

Maintenance R&D objectives include the development and application of new technology to improve management, to augment the utilization of resources, and to increase operational efficiency and safety in the maintenance of highway facilities.

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[*] The complete 7-volume official statement of the FCP is available from the National Technical Information Service (NTIS), Springfield, Virginia 22161 (Order No. PB 242057, price $45 postpaid). Single copies of the introductory volume are obtainable without charge from Program Analysis (HRD-2), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.

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R&D