Color Effectiveness of Yellow Pavement Marking Materials: Summary

DETAILS

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COLOR EFFECTIVENESS OF YELLOW PAVEMENT MARKING MATERIALS

This digest presents the results of NCHRP Project 5-18, “Color Effectiveness of Yellow Pavement Marking Materials.” The study was conducted by the University of Iowa, with Thomas Schnell as Principal Investigator.

INTRODUCTION

Pavement markings are by far the most widely used traffic control device on the roadways. They convey essential information to the motorists in a continuous fashion, without any need to look away from the roadway. Pavement markings convey information by virtue of configuration (dashed vs. solid) and color (white, yellow). It is essential that both the pavement marking configuration and color be identifiable to the drivers without ambiguities.

Pavement markings may appear yellow during daytime but may not appear yellow at night under automobile headlamp illumination. With the removal of lead from yellow thermoplastic pavement marking pigments, it has been reported that some of the replacement materials appeared to be almost white at night. Since the color of the pavement markings conveys information related to the direction of traffic, it is important that it clearly be distinguished both during day and night. This study provides the scientific and practical basis to ensure that drivers can correctly identify pavement marking color in an operational and demanding environment.

This project included a detailed review of the technical literature, a survey of highway agencies and pavement marking material manufacturers, and a laboratory experiment to determine the range of chromaticity coordinates that observers classify as yellow and white under daytime (D65) and incandescent (Illuminant A) illumination. Color classification performance in the report is expressed in terms of the percentage of observers who classified a color sample (e.g., a painted color chip sample) as either yellow or white. The iso-percentage curves, called iso-chromes, indicate the chromaticity coordinates that ensure a certain percentage of the sample population to identify a color as either yellow or white. A field experiment was conducted to determine pavement marking color classification in the field using actual pavement marking materials. The National Institute of Standards and Technology (NIST) conducted precise characterization of all materials and stimulus presentation devices throughout the study. Detailed pavement marking chromaticity measurements also were conducted in four states to determine the color performance of existing materials. The goal of this project was to provide data that can be used to generate recommendations on day and night color limits for pavement markings.

RESEARCH APPROACH

Pavement marking color perceived by drivers is primarily influenced by the incident light spectrum and intensity, pavement marking spectral and spatial reflectivity, and driver’s light and chromaticity adaptation

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conditions. This means that it is not only the color of the pavement markings, but also the color of the head lights that determine color classification.

The study focused on the color perception and classification by drivers, while controlling the chromaticity and luminance, emulating daytime and nighttime pavement marking viewing conditions. Initial efforts were dedicated to compiling a comprehensive review of the related technical literature. A survey of pavement marking manufacturers and practitioners was conducted to solicit information about the latest practices in pavement marking pigmentation technologies and pavement marking color assessment methodologies in the field, respectively.

Three experiments were designed and conducted to determine how people classify different chromaticities into named color categories. The first experiment investigated the color classification of young and old participants in a color-neutral (gray) booth equipped with a CIE standard D65 and an incandescent (near-Illuminant A) illuminant, through which the daytime and nighttime conditions were simulated, respectively. Participants were sequentially shown a set of Munsell color chips with known spectral reflectances (color). The chips were selected to span a relatively wide range of colors in the CIE 1931 color space. The chips were viewed at an angle of 45 degrees with a light source pointing straight at the chip from above at an angle of 0 degrees. The participants were asked to classify each color chip as yellow, white, or neither, in a forced–choice paradigm. Data were transferred onto the CIE 1931 chromaticity diagram in the form of iso-percentage curves inside where only a certain percentage of yellow or white responses can be expected.

The second experiment also was conducted in the laboratory using a large back–projection screen showing a straight and level two-way rural highway with continuous yellow pavement markings of varying chromaticities. The purpose of this experiment was to obtain color classification ratings for common pavement marking viewing geometries.

The third experiment was conducted in the field using four thermoplastic and one latex paint type pavement markings. Three of the four thermoplastic markings were tailored in their spectral reflectivity only by varying their respective titanium dioxide contents. Pavement marking samples measuring 6 ft (1.83m) were laid out on a straight and level roadway surface, six at a time, in a longitudinal skip-line pattern with a 30 ft (9.14 m) cycle length and 24 ft (7.32 m) gap. The samples were viewed under tungsten-halogen (TH) and high-intensity gas discharge (HID) headlamp illumination. Participants were asked to classify each pavement marking stripe as either yellow or white.

In addition to the experiments, the research team conducted field measurements of existing pavement markings in different climatic conditions in the United States. Each stimulus used in the experiments was meticulously characterized at the Center for High-Accuracy Retroreflection Measurements (CHARRM) facility at NIST, in terms of its spectral and spatial reflectivity.

STATE DOT AND MANUFACTURER SURVEY

Two surveys were conducted to reach out to practitioners in the state DOTs and the pavement marking manufacturers. The DOT survey, to which 29 agencies responded, revealed the following:

- Approximately 7 out of 10 agencies use lead-free markings in their jurisdictions. Of the markings that are lead-free, the majority is waterborne paint, followed by epoxy, thermoplastic, tape, polyurea, and preformed tape. A few polyester and alkyd type markings also are lead-free. In South Carolina, Illinois, and Oregon, thermoplastic markings still contain lead chromate, albeit the rate of thermoplastics with lead is in decline.
- Seven out of 8 complaints received from the driver population regarding misleading appearance of yellow pavement markings were for nighttime conditions. All were about lead-free pavement markings, with roughly an even distribution among paint, epoxy, and thermoplastic type markings.
- Various agencies realized the problem and tried to home in on the issue by various means: South Carolina increased the testing frequency; Virginia, Minnesota, and Ohio have developed, and Delaware is in the process of developing its own color specifications; Iowa shifted the color box towards red spectra and eliminated a portion of the green spectra; Illinois uses a slightly different version of the FHWA color box extending into a more red spectra; Texas tailored an updated formulation for yellow markings and distributed it to the manufacturers; Wisconsin uses more red inorganic pigment in their

yellow pavement markings; and Indiana uses the FHWA chart.

- Approximately 3 out of 4 states perform laboratory and/or field measurements at their expense before a pavement marking is approved for use. Not all states perform quantitative nighttime measurements. Some states verify retroreflectivity in the field and the laboratory, mostly for daytime conditions. Nighttime measurements are less frequent, and consist mostly of retroreflectivity assessments. Numerous states rely heavily on the National Transportation Product Evaluation Program (NTPEP) test decks.
- Only half of respondent states conduct nighttime color measurements upon installation of new pavement markings. Almost no agency conducts such measurements routinely. Most measurements are performed by subjective means for both white and yellow pavement markings during daytime. Three states perform objective measurements of yellow pavement markings only for chromaticity, and two do so for chromaticity and luminance factor (Cap Y). Measurements from NTPEP and other test decks are used in four states. Five agencies use the LTL 2000Y, three agencies use the Hunter Miniscan XE Plus, and two use the Color-Guide Spectrophotometer. About half of the objective measurement results are verified against ASTM D6628, and the other half against agency specifications. Most measurements are carried out by agency field measurement departments, except in Nevada where the University of Las Vegas performs those measurements. In Illinois, manufacturer and state officials perform this function jointly, and in Ohio, the central office team performs these measurements.
- Almost three fourths of the respondent states do not require color measurements in the field during the lifetime of the pavement markings. For those that do require measurements, half are part of an investigation, and the remaining half is either in response to a complaint, or performed for some other unspecified reason.
- Of the agencies that require pavement marking colors to be measured, four perform such measurements at specific locations after complaints, one performs the measurements on a particular type of pavement marking, and one performs the measurements in high traffic areas.
- Most agencies use their resources as well as contractors to apply pavement markings in their jurisdictions in varying capacities. Only in West Virginia do contractors apply all markings. None of the respondent states apply all markings with internal resources. Contractors usually apply durable markings, and where applicable, states stripe their own waterborne pavement markings.
- Contractors supply warranty for the color of pavement markings in only 3 out of 10 states. Some states are considering using warranty specifications in the future.
- Three out of 20 states warrant contingent payment upon satisfactory pavement marking color performance after installation. On a few occasions, states such as Missouri and Oregon asked the contractors to re-stripe as the color did not seem to be satisfactory.
- Traffic volume is the strongest determinant in the type of pavement marking material of choice, where 1 out of 3 states consider traffic volume before installing materials. Traffic volume is followed by snow removal (23%), roadway material (18%), cold (12%), heat (5%), high humidity (4%), and salt exposure, UV exposure, and high humidity (2%). States were free to indicate more than one factor (multiple choice among these options), thus the figures reflect the percentage of states that consider each respective factor among all respondents. Most states apply thermoplastics only on bituminous asphalt surfaces. Paint is used mostly, but not exclusively, on bituminous asphalt surfaces.
- Most states (16 out of 22) do not know how the contractors measure nighttime and daytime chromaticity.
- Approximately 3 out of 10 states conducted research on pavement marking color in the past 5 years.

The pavement marking manufacturer's survey revealed the following:

- Preformed Tapes: For yellow preformed tape materials, zinc chromate is used as inorganic pigment, and PY65 and PY75 are used as organic pigments. Manufacturers of tape materials indicated that they verify chromaticity compliance for both yellow and white against ASTM D6628, Federal Standard 595a, FHWA

Final Rule, state DOT specifications, as well as European standards (CEN). Federal standard color chips (by subjective comparison) and daytime and nighttime color-capable instrument measurements (Hunter Labscan 6000, Hunter Miniscan, and PR650) are used for instrument measurement of yellow and white pavement marking tapes. For white color, titanium dioxide is used as pigment. In determining service life, daytime color, nighttime color, retroreflectivity, and percentage of material remaining are important to the manufacturers of pavement marking tapes.

- Pavement Marking Paints: Manufacturers offer waterborne, alkyd, chlorinated rubber, pre-mix formula, durable, and low VOC type paints. In addition to yellow and white, these paints come in various colors such as black, blue, red, and green. As organic pigments, PY65, PY75, and PY83 are being used. As inorganic pigments, it is the practice to use zinc chromate, lead chromate, barium chromate, synthetic iron oxides, and some other undisclosed pigments. For both yellow and white, only one manufacturer indicated that they observe ASTM D6628 and AASHTO M248, but all manufacturers follow Federal Standard 595a. The FHWA final rule and some state specifications also are followed by two manufacturers. For both yellow and white, one manufacturer conducts daytime and nighttime color measurements at the factory, whereas all manufacturers conduct color measurements in the laboratory, yet only for daytime (i.e., with Gardner Colorimeter). None of the manufacturers use organic white pigments. Instead, the use of inorganic pigments titanium dioxide and zinc oxide are common practice. For the white color, subjective comparisons with Munsell chips and with Federal standard color chips are common. In determining the service life of paint pavement markings, daytime color and retroreflectivity are considered across the board, yet only one manufacturer considers nighttime color as a criterion.
- Thermoplastic Pavement Markings: Companies offer a variety of thermoplastic pavement markings: hydrocarbon, alkyd, preformed (hot-tape), and some polymeric blends. Thermoplastic pavement markings also are marketed in numerous color alternatives such as white, yellow, blue, red, green, black, orange, purple, grey, and yellow-green, to name a few. For yellow, organic pigments PY65, PY75, and PY83 are being used. One manufacturer uses lead-chromate for yellow alongside titanium dioxide. For both yellow and white, ASTM D6628, AASHTO M249, the Federal Standard 595a, the FHWA final rule, and various state DOT specifications are followed. For yellow, two manufacturers use the federal standard color chips for subjective color evaluation, whereas another manufacturer performs daytime and nighttime evaluations at the factory using the Gardner colorimeter and the LTL2000Y. The former two manufacturers also perform laboratory measurements for daytime color only. For white, the only pigment in use is titanium dioxide. For white, the federal standard color chips are used for subjective evaluation by two manufacturers who also perform instrumented daytime measurements in the laboratory. One manufacturer performs daytime and nighttime instrumented color measurements for white pavement markings on the factory floor and in the laboratory using a Gardner colorimeter and an LTL2000Y. In determining service life, manufacturers consider daytime color, nighttime color, durability/abrasion, and percentage of material remaining.
- Two-color component liquids: In this category, epoxy, polyurea, and methyl methacrylate (MMA) based product lines are offered. These markings are exclusively yellow and white, as no other colors are available. For yellow, all manufacturers use organic pigments including PY65, PY75, and PY83. One manufacturer uses the inorganic pigments zinc chromate and synthetic iron oxides, another manufacturer uses lead chromate, and yet another manufacturer does not use any inorganic yellow pigments of any kind. For both yellow and white color, ASTM D6628, AASHTO M249, Federal Standard 595a, FHWA final rule, various state DOT specifications, as well as some European standards (CEN) are followed. One manufacturer performs subjective comparisons with federal standard color chips, whereas two others perform daytime and nighttime measurements on the factory floor (i.e., using a Hunter Miniscan, ColorFlex, and a custom-built instrument). One manufacturer noted

that these materials are essentially manufactured on site by independent contractors with no standard practice of on-site measurements, but the manufacturer's technical support personnel assist the contractor with spot checks. For white color, only inorganic pigments are used: titanium dioxide by all, and zinc dioxide by only one manufacturer.

COLOR BOOTH EXPERIMENT

Forty participants (median age 69.5, average age 69.2, maximum age 83 years) were recruited locally to participate in the color-booth experiment. One female participant was 51 years of age; all other subjects were over the age of 61. Men and women were equally represented in the participant sample. All participants had normal color vision and at least 20/30 visual acuity.

Participants viewed the set of 90 glossy edition Munsell standard color chips, with a diffuse filter (Cotech No. 216) overlaid in front of them to eliminate glossiness. However, during the analysis, this filter turned out to be a problem as it reduced color saturation. An incandescent light source (near illuminant A, at 2521K, to simulate nighttime) and a D65 light source (6500K, to simulate daytime) illuminated the samples diffusely. Each color chip was spectrally characterized at NIST at a diffuse/45 geometry. Both the D65 and Illuminant-A light sources were characterized using a NIST-calibrated PR650 in situ with a standard color plaque. The chromaticity data of the color chips was converted to the CIE L (a,b) color space and a light source adjustment was made to express the chromaticity under standard illuminant A and D65 conditions.

Participants were given sufficient time to adapt to the booth lighting conditions. Each participant viewed each color chip under both illuminants in a pseudorandom design. Chips were located on a table at reasonable height, and participants viewed each color chip at an approximately 45–degree viewing angle from approximately 24 in. (60 cm) placed over an achromatic plate. The subjects were asked to look at a center mark on the table at all times. In the peripheral viewing condition, each chip was placed 6 in. away from the center mark, giving a 15–degree visual angle. This way, the chips were located approximately within the region that corresponds to the near periphery area on the retina. A forced-choice color classification paradigm was used, where the possible responses had to be either yellow, white or neither. An experimenter manually recorded the responses. Under Illuminant A, the overall luminance of the color chips was reduced by using neutral density filters to about 0.11 ftcd (1.2cd/m^2). This luminance level was chosen as it represents the average yellow pavement marking luminance at 30 m (98 ft) illuminated with an average passenger vehicle TH headlamp in nighttime.

The end product of this experiment is a set of curves overlaid on the CIE 1931 chromaticity diagram that delineates the fringes of chromaticity boundaries, within which only a certain percentile of yellow or white responses could be expected. The term iso-chrome was coined for these curves, which are irregular in shape rather than rectilinear color boxes currently used by most agencies. Color perception and naming is a psychophysical process by nature rather than being deterministic, i.e., colors do not by virtue change names beyond a rectangular color box in a step-function fashion, but instead, the probability of being named a certain color shows a gradual transition from one region of the color space to another. Iso-chrome curves resourcefully address such gradual transition, in this case between yellow and white.

By comparing the overlap in the iso-chrome curves with the white and yellow color limits given in the FHWA 2002 final rule (matching those of ASTM D6628-01) overlaid on the CIE 1931 chromaticity diagram, it is evident that with the current color boxes there will be certain confusion between yellow and white color.

Under nighttime foveal (straight on) viewing conditions, it is evident that the highest percentage of yellow responses are centered near the bottom-right corner of the FHWA/ASTM D6628 (nighttime) yellow color box. The nighttime white responses are bi-modal. A large number of the color chips were classified as white, when they were located inside the FHWA/ASTM D6628 (nighttime) white color box. A smaller but still substantial percentage of color chips were classified as white when they contained a hue of green.

Under daytime foveal viewing conditions the majority of the yellow classifications were found to be centered outside and near the upper left corner of the FHWA yellow daytime color box. The daytime foveal white classifications were relatively centered on the daytime white color box.

Peripheral viewing conditions were tested in this experiment because drivers see pavement markings peripherally as well as foveally. The classification percentages were similar to the foveal viewing condition.

These findings corroborate some of the state specifications received in the agency survey. For instance, Iowa indicated that it shifted the FHWA color box towards red and eliminated some of the green region. Illinois indicated that its color box extends into a chroma containing more red, and Wisconsin indicated that it uses red inorganic pigment in yellow markings, which essentially produces yellow-orange hues. Such state initiatives seem to confirm the nighttime findings in the color booth experiment.

DARK ROOM REAR PROJECTION SCREEN EXPERIMENT

This experiment was conducted in a dark hallway with a 4 ft by 7 ft (1.2 m by 2.1 m) calibrated rear-projection screen and projector located at the end. The purpose of the experiment was to determine color classification responses for a common pavement marking viewing geometry. The experiment simulated 4 in. wide (10 cm) continuous yellow pavement marking centerline stripes laid out on a straight and level roadway with 12 ft (3.65 m) lane width, with the markings gradually fading into white along the centerline stripe. Pavement marking luminance, pavement luminance, viewing geometry (gaze direction), and pavement marking chromaticity were controlled in a full-factorial design. For each condition, each participant evaluated the general color appearance of the pavement marking stripe on the rear-projection screen as either yellow or white. During the evaluation, the response time between the onset and the response was measured. Also, each participant indicated the location of the transition point from yellow to white on the continuous centerline stripe with a mouse pointer. The chromaticity of each transition point also was recorded.

Yellow pavement markings were presented on a rear-projection screen using an EIKI (LC-SX1U) LCD projector. The pavement marking stripes were saturated yellow at close distances and desaturated from yellow towards white with increasing simulated viewing distances. The independent variables were as follows:

- Ambient sky luminance [within subject, 2 levels: 0.046 ftcd (0.5 cd/m^2), 0.37 ftcd (4 cd/m^2)]
- Pavement type (within subject, 3 categorical levels: new concrete, old concrete, new asphalt)
- Pavement marking type (within subject, 3 categorical levels: patterned tape, flat tape, alkyd paint)
- Pavement marking chromaticity (within subject, 8 levels)
  - Chromaticity 0: (x, y) = (0.430, 0.507)
  - Chromaticity 1: (x, y) = (0.463, 0.481)
  - Chromaticity 2: (x, y) = (0.495, 0.455)
  - Chromaticity 3: (x, y) = (0.390, 0.460)
  - Chromaticity 4: (x, y) = (0.430, 0.4335)
  - Chromaticity 5: (x, y) = (0.360, 0.415)
  - Chromaticity 6: (x, y) = (0.385, 0.400)
  - Chromaticity 7: (x, y) = (0.340, 0.375)
- Eccentricity (between subject, 3 levels: 0 degree, 10 degree, 20 degree).

The dependent variables were the response (yellow or white), response time (sec) (the time it takes for the subject to respond to a particular pavement marking stimulus from the onset), and the location of the transition point (the point where subjects thought that the color of the pavement marking was no longer yellow).

The experiment was designed to analyze the effects of pavement surface type, pavement marking type, initial chromaticity of the pavement markings, ambient luminance and the eccentricity (the visual peripheral angle while detecting the pavement marking color) on the judgment of pavement marking color (white vs. yellow) and the time it takes to make that judgment. A computer program was developed to measure and record the response time and the transition point.

The dependent variables were investigated to determine the effect of each independent variable and their interactions on these dependent variables. The binary forced-choice responses were analyzed using Generalized Estimating Equations (GEE) as a function of independent variables. GEE features correlated data analysis (repeated measures) methods for binary variables.

The GEE analysis revealed that, among the main factors, initial chromaticity of the pavement markings ($p < 0.01$) and horizon sky luminance ($p = 0.038$) were statistically significant in affecting color judgment at $\alpha = 0.05$ significance level. Eccentricity (between-subjects factor), and the roadway surface type failed to reach statistical significance at $\alpha = 0.05$ significance level. Pavement marking type ($p = 0.077$) was just short of having a statistical significance at $\alpha = 0.05$ significance level. The first order interactions between sky luminance and roadway type (p = 0.003), pavement marking type and roadway type (p = 0.003), chromaticity and roadway type (p ≅ 0.0015), and pavement marking type and chromaticity (p = 0.03) also were statistically significant in affecting subjects' assessment of pavement marking color. Figure 1 shows the selected initial chromaticities and the corresponding percentages of "yellow" responses, and the transition chromaticity curve, overlaid on various color boxes on the CIE 1931 2° standard observer chromaticity diagram.

Notice that only P2 was inside the chromaticity limits for nighttime yellow pavement markings, as outlined in the FHWA final rule and ASTM D6628, yielding the highest yellow response rate at 99.3% among the eight selected points. The transition chromaticity curve was generated by connecting the average transition chromaticities, at which subjects would no longer call the color of the continuous pavement marking line yellow. The rather odd shape of the curve is due to a systematic response pattern of the subjects: For chromaticities 0, 1, and 2, subjects selected transition points closer to the white point (the left wing of the curve). For less saturated yellow hues administered for chromaticities 5 and 6, the transition points retreated to more saturated yellow (right wing of the curve), toward the points themselves. For the chromaticities in between, the transition points were also in between. When the initial chromaticity was a deeper hue, the transition point from yellow to white was closer to white. The collective set of points indicates a general region where the transition from yellow to white occurred.

FIELD EXPERIMENT

A field experiment was conducted to determine the perceptual color correlates of yellow pavement markings at night under TH-halogen and high-intensity gas discharge headlamps. Participants viewed a battery of yellow pavement markings laid out in a skip-line pattern on a straight and level roadway. Four different thermoplastic pavement markings with organic yellow pigments and a waterborne latex paint type pavement marking were used. Three of the four thermoplastic pavement markings were custom tailored for the experiment, differing in their recipes of titanium dioxide (which is white) content to vary

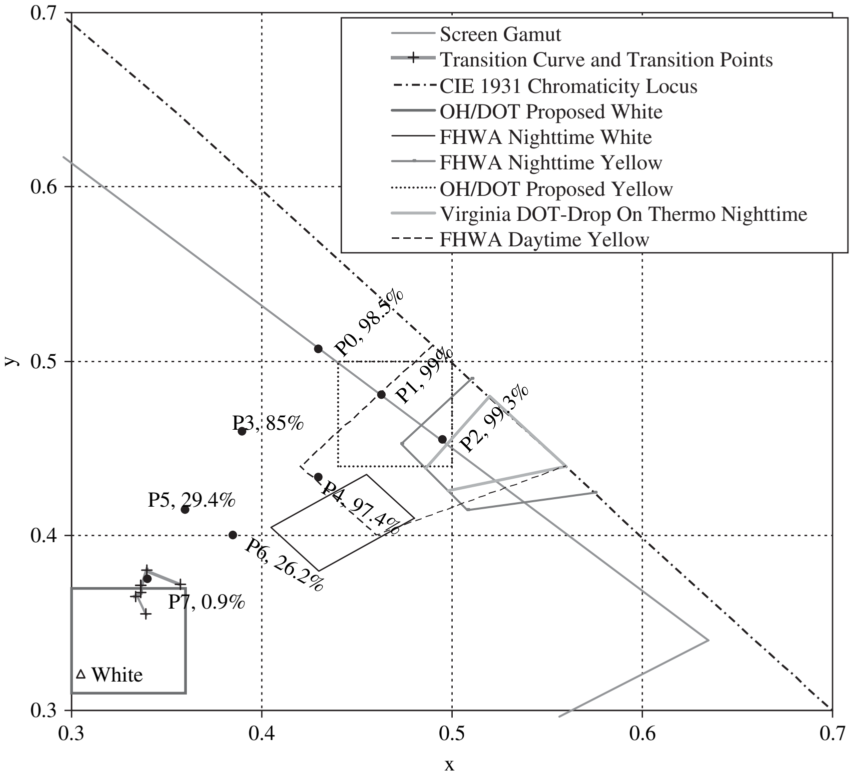

Figure 1 A magnified view of the yellow response percentages overlaid on the CIE 1931 chromaticity diagram.

yellow saturation, while trading-off retroreflectivity. Participants were asked to identify each pavement marking color at different distances as being either yellow or white, presented in a set of six markings in a random design. No white markings were used to prevent relative color assessment. Spectral reflectivities and chromaticities of each pavement marking sample at each distance were measured at the NIST. These measurements were represented on the CIE 1931 chromaticity diagram to correlate chromaticities and perceptual color assessment for different headlamp spectra.

Both the type of pavement marking material and the viewing distance affected the color ratings made by the participants. Also, the percentage of yellow responses did not follow the same pattern for all materials with increasing distance. Thermoplastic materials with low titanium dioxide content suffered a sharp decline in the percentage of yellow responses at long distances, even though these materials exhibit a high yellow saturation at close distances. Less saturated yellow thermoplastics (higher titanium dioxide content) maintained a relatively lower but consistent percentage of yellow responses for distances up to 180 ft (54.9 m). This trend was most likely due to the higher luminances provided by materials with higher titanium dioxide content. The production grade thermoplastic material overall yielded the highest yellow ratings. The latex paint type pavement marking was not affected by distance as much as other materials, yet overall it performed the worst. Generally, chromaticities closer to the spectral locus performed best for yellow recognition at close distances. However, materials with lower coefficients of retroreflected luminance appear to be less capable of rendering saturated yellow colors at long distances. The reason is that cones in the retina require a certain level of luminance for color perception to take place. This range of luminance for color vision is the photopic range. When pavement marking luminances drop into the lower mesopic and even scotopic ranges, the markings will generally be perceived achromatically. In this study, the addition of titanium dioxide in the experimental thermoplastic materials reduced the yellow saturation, but allowed the markings to be brighter at longer distances due to higher coefficients of retroreflected luminance by virtue of the added titanium dioxide. This seems to indicate that the binder material within which retroreflective glass beads are placed is a key component of the true coefficient of retroreflected luminance.

For yellow pavement markings to remain chromatic at longer distances, the bead–material interface must be designed to allow interaction of the incident light with the binder material where the beads reside. In the process of light entering the beads and being retransmitted back to the observer, a certain amount of the light is being retroreflected by total reflection inside the bead, without interaction with the binder material. That portion of the retroreflected light will resemble the chromaticity of the light coming from the headlamps. Another portion of the light leaves the backside of the beads, where the light is allowed to interact with the pigments in the binder. The reflected light reenters the bead and leaves through the front towards the observer. Some light interacts with the binder and is reflected diffusely in the areas between the glass beads. The key for maintaining adequate color recognition in pavement markings at long distances appears to be that enough light is retroreflected to maintain the marking in the photopic region, and that the refractive index of the bead be selected such that a large proportion of the reflected light is allowed to interact with the pigment in the binder.

With regard to color classification performance in the field experiment, there were no statistical or practical differences between HID and TH headlamps. However, HID headlamps seemingly helped render deeper yellow hues at long distances especially for latex paint type pavement markings. If only TH type headlamps were used in the experiment, latex paint samples would suffer greatly at far distances and would be mostly identified as white. It is likely that such poor performance was due to the low coefficient of retroreflected luminance of latex paint type pavement markings, especially at large entrance and small observation angles (typical for long distances). The increasing percentage of yellow responses for latex paint observed at far distances under HID headlamp illumination, as compared with the responses under TH headlamp illumination, is most likely a product of the higher illuminances provided by HID headlamps at almost all distances considered in this study. The analysis of the chromaticities of each pavement marking type as a function of distance and headlamp indicates a gradual shift of chromaticities toward less saturated chromas for all materials. The shape of the chromaticity trajectory as a function of distance seems to be independent of the material type.

HID headlamps shifted the chromaticities for all materials at all distances outside the FHWA nighttime yellow color box, which was not unexpected. HID headlamps have a unique SPD distinguished by sharp spikes. Yet, such a shift in the chromaticities did not significantly affect the color classification responses. It is believed that this is due to chromatic adaptation.

Pavement marking color recognition at long distances on straight sections of roadway may generally be governed by color recognition at short distances. The reason for this is that drivers will most likely assume that continuous pavement markings on a road do not change in their color.

FIELD MEASUREMENTS

A test plan for field measurements was developed and executed. First, portable field instruments capable of color measurements were identified. Then, a protocol was developed for characterizing, calibrating, and validating the field instruments. A climatically diverse set of states with NTPEP test decks were sampled for field measurements, and field measurements were completed at the selected states.

NTPEP pavement marking test decks were measured for chromaticity under daytime (0/45), quasi-diffuse (Q_d) and nighttime (30 m) geometries. By measuring the pavement marking material on the NTPEP test decks, the field tests were conducted in an economical and effective manner because of the available manufacturer and aging information. A total of 177 white lines and 191 yellow lines ranging from 2 weeks to 3 years old were measured on asphalt and concrete surfaces. The uncertainty of the daytime instrument was ± 0.005 ($k = 2$) chromaticity units, the Q_d instrument was ± 0.018 ($k = 2$) chromaticity units, and the nighttime instrument was $\pm$ 0.018 ($k = 2$) chromaticity units. The uncertainty for the Q_d and nighttime instrument is dominated by the display resolution.

The resulting chromaticities for all the white lines measured by the daytime and Q_d instruments were within the ASTM box independent of age, surface material, or geographic location. The only observation is that the Q_d measurements have a larger dispersion due to the larger uncertainty. For the daytime measurement of the yellow pavement lines two possible conclusion are made. One, as the material ages it becomes whiter, and all of the materials had at least one measurement falling out of the ASTM box. Two, the environmental conditions due to the different geographical locations do not make a difference in the chromaticity change over time. The Q_d measurements for the yellow lines are significantly different from the daytime measurements using the 0/45 geometry. The difference is expected because the optical process for each measurement geometry is significantly different. The geometry of the Q_d measurement needs to be standardized based on further research.

No conclusion could be drawn for the nighttime measurements because the uncertainty of the measurements is too large. A few generalizations can be made. Most of the white lines fall within the ASTM box. The spread in the data points is along the red-green axis and is independent of the age or location of the material. The spread in the data points is due to sensitivity in the instrument. For the yellow lines, generally the materials become whiter as the materials age. Surprisingly, two of the yellow line measurements that are less than 3 months old fall within the ASTM white box. These two yellow line measurements that appear white under nighttime conditions fall within the yellow ASTM box for daytime measurements. Both measurements were on yellow paint.

The last analysis was to determine if the pavement marking materials with lead had a significantly different chromaticity than the lead free products. The daytime and Q_d measurements show little chromaticity difference is measured between lead and lead-free pigments. For nighttime measurements, the materials with lead pigment appear to have a shift in the direction of orange-red compared to the lead-free material. However, due to the uncertainty of the nighttime instrument no conclusions can be made. No measurable difference exists for lead-free materials versus materials with pigment.

CONCLUSIONS

Based on the results of this project, changes are recommended to the nighttime yellow and white color boxes. The size and shape adjustment of the existing color boxes is proposed to reduce confusion between yellow and white pavement marking materials. The adjustments are based on robust experimental human response data where selected regions encapsulate 70 percentile response contours for yellow and white. In order to maintain relatively simply shaped regions and to avoid materials that cannot possibly meet both daytime and nighttime limits, only the nighttime limits were reshaped.

Table 1 Recommended nighttime yellow color boundary

x	Y
0.53	0.47
0.49	0.44
0.50	0.42
0.51	0.40
0.57	0.43

The following changes are recommended:

1. Shift the nighttime yellow region slightly towards the red part of the chromaticity chart. This shift will reduce confusion with white. Several states already have changed their requirements to reflect this recommendation.
2. Add a fifth boundary point to allow inclusion of the peak in the yellow response curve. Table 1 contains the resulting coordinates.
3. Move the right side of the nighttime white box towards the white point or Illuminant A chromaticity point. Moving the right side reduces the chances of confusion by widening the gap between the nighttime yellow and nighttime white regions.
4. Add a fifth boundary point on the right side of the nighttime white region (Table 2). By putting this tip on the nighttime white color space the peak of the nighttime white response curves is included and a large gap to the nighttime yellow color limit is maintained. The point was chosen to have the angled edges between the nighttime white and yellow color regions run parallel. Data suggests that the nighttime white box should be smaller with respect to the blue boundary. However, there is no confusion in the blue region, so the white box may be elongated in that direction.

Table 2 Recommended nighttime white color boundary

x	Y
0.45	0.42
0.41	0.40
0.43	0.38
0.47	0.40
0.46	0.42

5. Leave the daytime white and yellow color regions unchanged. The data suggest no changes for the daytime white color region. The data do suggest that the daytime yellow color region ought to be moved toward the green. Moving the daytime yellow color region to the green may cause problems with nighttime qualification. A brief simulation has shown that the average shift in chromaticity in this color region by changing the illuminant from D65 to Illuminant A is roughly −0.13 in x and −0.04 in y. If the daytime yellow color region is shifted to the green, the possibility of materials qualifying under daytime conditions and not at nighttime conditions is likely. At the time of this report few roadway engineers had instruments capable of measuring nighttime 30 m geometry Illuminant A conditions. The roadway engineer is more likely to have a 0/45 D65 Illuminant instrument for measuring the daytime conditions. The nighttime conditions are likely never to be validated. However, agencies should be aware that compliance alone with the daytime color box as part of materials acceptance may not ensure satisfactory nighttime color. At the time of data collection for this report, the nighttime condition instruments had a large uncertainty in chromaticity measurements with respect to the size of the color region. This large uncertainty makes it difficult to statistically qualify material because the uncertainty is almost as large as the accepted color region. The largest source of uncertainty was the number of digits displayed for the three channel measurements. If one more digit was displayed the uncertainty in the chromaticity coordinate measurements, the overall uncertainty would drop from 0.018 ($k = 2$) to 0.006 ($k = 2$). The addition of one more digit put the display resolution to signal at 1:800, typically. This level of uncertainty allows the nighttime material to be statistically qualified. The instruments available at the time of writing this report display an appropriate number of digits.

The measurement protocols for daytime and nighttime field measurements are similar. The 0/45 instrument or 30-m geometry instrument should be calibrated according to the manufacturer's specifications. For a given region of pavement marking material, select three representative spots and measure the chromaticity of the spots using the calibrated instrument. Selection of a representative spot is a subjective decision; a representative spot is free of debris and visually appears to be similar to most of the pavement marking material in the specified region. The average of the three measurements should be reported. For the 0/45 instrument used in this study this procedure is appropriate because the instrument has a smaller measurement uncertainty than the fluctuation of the pavement marking chromaticity. For the 30-m geometry instrument used in this study, the pavement marking material only is required to be sampled once because the instrument had a greater uncertainty than the pavement marking material fluctuation in chromaticity. The newer 30-m geometry instruments have less uncertainty therefore the pavement marking material should be sampled three times. The Q_d geometry instruments still require significant characterization and correlation to human visual perception. Their use is not recommended at this time. Sampling the pavement marking material more than three times does not significantly reduce the uncertainty of the chromaticity measured for a given region. More measurements only add additional time and cost.

An overall conclusion realized from this work is that TH headlamps may lead to possible confusion between yellow and white pavement markings when viewed at night. A good headlight source would have the characteristic of producing a white light chromaticity much closer to daylight. The introduction of HID lights has moved the chromaticity point towards daylight. The closer to daylight the source is, the more separation between the yellow and white space on the chromaticity diagram.

REPORT AVAILABILITY

The complete report for NCHRP Project 5-18 is available on TRB's website as *NCHRP Web-Only Document 125* at http://trb.org/news/blurb_detail.asp?id=8795.

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