Identification of Pavement Marking Colors

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April, 2002

Acknowledgments

We would like to express our gratitude to the Ohio Department of Transportation , in particular Mr. Mohammad Khan, P.E., for his continuing support and patience including his participation on my thesis committee and to William Carty for assisting me with the field measurements. I would also like to thank Wright State University, Department of Psychology, particularly Dr. Scott Watamaniuk and Dr. Brian Kruger for their continuing assistance and patience.

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Introduction to Problem

Problem statement – Overview

The Ohio Department of Transportation (ODOT) is charged with selecting and enforcing color specifications for pavement markings. In recent years, changes in materials have affected the physical appearance of these markings. Even though, at application, the colors meet current federal specifications, the specifications themselves are sketchy and, in some cases, given in terms of the physical properties of the materials rather than appearance. This method is particularly troublesome since the markings are viewed under a variety of lighting conditions and against different colored backgrounds (pavement types). Perhaps more of a problem is that current practice requires only a subjective evaluation of whether colors are within specification. Recently, the ODOT has also been put under a legislative mandate to require that a certain percentage of their contracts contain warranties. This mandate makes it necessary to develop appropriate specifications for acceptable changes in the color of pavement markings over time. Research is needed to develop these specifications with regard to the color appearance properties of markings. They need to be more relevant to the needs of the driver than the current specifications, and guidelines for objective evaluation need to be provided. This research includes a review of current literature on color, perception, and measurement as well as a review of current practices with regard to pavement markings. It also includes an investigation of human perception of the color of pavement markings under a variety of conditions and the development of specifications, tolerances for which procedures for enforcement can be easily applied by the ODOT.

Background

The CIE diagram

The Commission Internationale de l'Eclairage (CIE), in 1931, developed a method for specifying colors. This method allows for the specification and replication of any color by associating an x and y coordinate with that color. Figure 1 shows such a diagram, which includes an artist's rendering of the approximate colors in various locations. This diagram is used by both the ODOT and the Federal Highway Administration (FHWA) for specifying the color ranges of proposed pavement color specifications and will be used throughout this research.

Current standards

The current pavement marking color specifications are spread through a number of sources. Few of these sources provide information on supporting research. The earliest specifications for pavement marking materials simply required that they be white or yellow, with yellow being reserved to mark no-passing (AASHTO [The American Association of State Highway and Transportation Officials], 1954). Later, the specifications

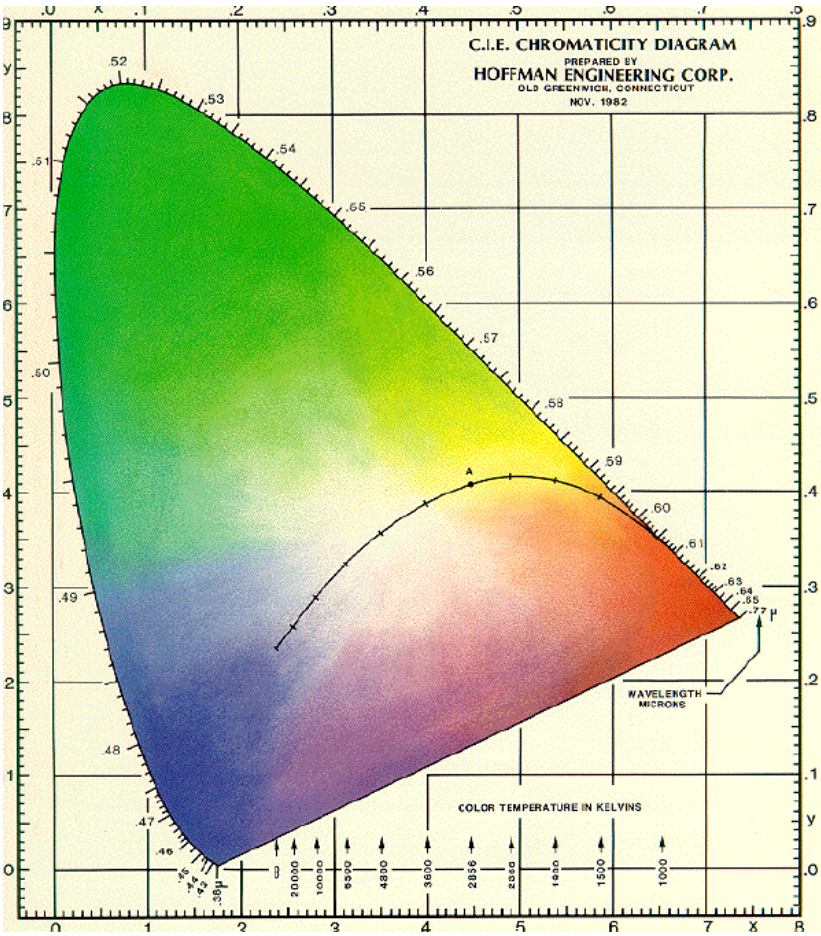

Figure 1: 1931 CIE Chromaticity Diagram with artist's rendering of colors.

were changed to white for edgeline and yellow for all centerline (AASHTO, 1970). The specific colors are not given in the Manual of Uniform Traffic Control Devices (MUTCD). Current Federal standards for pavement marking material are given in Federal Standard 595B. The current standard for yellow for highway use is given by a color number that signifies a sample color (either 13507 or 13538 is acceptable). Color chips, strips, and charts which span a wide range of colors used for a wide variety of federal color standards are available for color matching and quality control inspection purposes (see Figure 2 for sample page). The first digit of the five digit color number refers to the finish (1 refers to gloss), the second digit refers to the predominate color grouping (3 refers to yellow), and the last three digits are assigned in the approximate order of increasing reflectance. Tests for conformity are to be made using official federal test methods. The standards also call for light sources for measurement, referring to ASTM D 1729 as the document in which sources for measurement are listed. The federal guideline ASTM D 1729 provides procedures for visual subjective evaluation of color differences; visual appraisal includes comparing the color with an appropriate color sample as well as checking for inconsistencies. The current methods for measurement of color of thermoplastic and other marking materials call for measuring color under illuminant C at a geometry of 45°(arriving angle)/0°

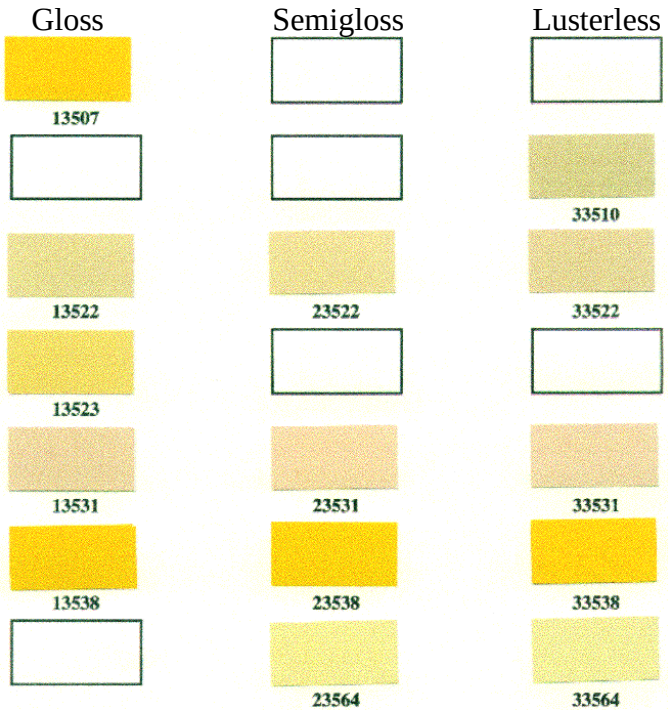

Figure 2: Federal color standards chart (sample).

(refractory angle) with a 2° observer angle or by visual appraisal. If the colors appear to be consistent throughout the marking sample and to match the federal color chip, the marking is acceptable. Instrumentally measured chromaticity coordinates may also be used in accordance with ASTM D 2244. In this case, measurements are to be taken under consistent light sources of both the federal color sample chip (see Fig. 2) and of the marking material and a judgment may then be made as to whether the match is reasonable. Neither of these federal standards include tolerances allowable for highway colors nor do they include any specification of white highway pavement marking color even though the federal color strips include white colors which are referenced in standards written by the Institute of Traffic Engineers (ITE). Again, there is no mention of how or why these particular colors were selected.

Specifications for the precise colors that are the same as those listed in the Federal Standards and mentioned above are also published by AASHTO (1995). These specifications apply to new materials rather than existing markings. Guidelines for when to replace existing markings are left up to the individual user (generally a state or municipality). No color tolerances are currently published at the federal level, although they are currently considering minimum retroreflectivity standards (Khan, personal communication). These standards indicate the minimum amount of light that a marking must reflect direcly back to the driver.

Currently, there is a docket being circulated for comment for proposed Federal standards for pavement marking and sign

colors (Department of Transportation, 1999). Whereas the existing specifications are given in terms of a single color rather than a range into which colors may fall, the proposed specifications indicate four corners of a box in the 1931 CIE Chromaticity diagram into which the colors of pavement markings shall be required to fall (see Table 1, also see Figure 3). These proposed specifications will require that measurements of current colors be taken under illuminant D-65 for daytime color and illuminant A for nighttime color measurements. The current ASTM methods for testing and measurement will still apply.

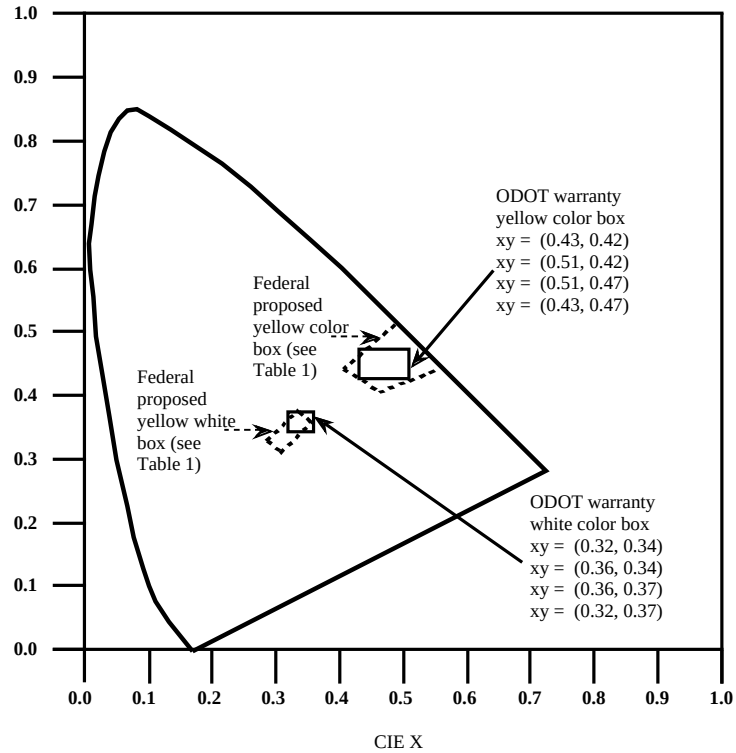

Figure 3: ODOT proposed color warranty specifications (solid boxes) and Federal proposed color specifications (dashed boxes). For coordinates of corner points of federal boxes, see Table 1.

The most problematic thing about the proposed specifications is that it is completely unclear how the colors were chosen. From notes and conversations with ODOT traffic personnel, it appears that the colors were selected based on measurements of samples of currently used materials rather than

Color	Chromaticity Coordinates (corner points)								Y Values %			
	x	y	x	y	x	y	x	y	With glass beads		Without glass beads	
									min	max	min	max
White	.355	.355	.305	.305	.285	.325	.335	.375	60	----	70	----
Yellow	.560	.440	.460	.400	.420	.440	.490	.510	30	----	35	----
Red	.480	.300	.690	.315	.620	.380	.480	.360	6	15	----	----
Blue	.105	.100	.220	.180	.200	.260	.060	.220	5	14	----	----

Table 1: Daytime color specification limits for pavement marking materials with CIE 2 degree standard observer and 45/0 (0/45) geometry and CIE D65 standard illuminant.

being based upon any sort of psychophysical measurements of the appearance of the colors.

As early as 1987, warranties have been attached to pavement marking contracts. The North Carolina Department of Transportation began a four-year performance specification for installation and maintenance of retroreflective pavement marking, and performed an evaluation of that specification in terms of cost effectiveness (Stanley, 1989). Their evaluation of the appearances were made by subjectively rating the markings for reflectance and “overall appearance.” Color was not specifically considered in their analysis.

The Institute of Traffic Engineers (ITE) publishes a guide for performance specifications and testing of traffic-related equipment and materials. Paints, preformed plastic markings, and thermoplastic marking materials are recommended to be evaluated based on appearance, durability, and night visibility. The appearance scale (subjective rating) includes color by way of comparison with the original color. In other words, markings are to be checked for fading, yellowing, etc. Original color is expected to conform to standard highway colors. White paint is to be “no darker than Color Number 37778 of Federal Standard Number 595” and yellow paint “shall conform to Color Number 33538 of Federal Standard Number 595” (ITE, 1994). Color strips can be obtained which illustrate these colors so that subjective judgments may be made. These strips show the color with its number. They are not cross referenced to their CIE coordinates or with Munsell standard color values. There are no references to indicate how or why these particular colors were selected.

The American Association of State Highway Traffic Officials (AASHTO, 1995) specifies procedures to serve as standards for evaluations implemented by or for AASHTO of pavement marking materials. Materials are to be evaluated by retroreflectance, durability, and appearance. For field evaluations, appearance evaluations include color, including “a comparison of the color of the surface . . . with its original color, taking into account changes due to yellowing, bleeding, darkening, fading, dirt collection, mold growth, etc.” Also, yellow paints are to be compared to standard colors provided by the federal government either in the form of standard color chips or in a color chart (PR-1 chart, see Fig. 2) to see if they meet the 13538 “Federal Yellow” and, if not, specified as to whether the color falls “on the white side or yellow side” of it. The evaluation may be made by subjective rating (1 to 10) of color and by using a “colorimeter to measure ‘brightness’ and ‘daytime luminance.’” For field evaluations, nighttime visibility is to be measured with a retroreflectometer. Laboratory evaluations are specified only in regard to materials tests for chemical composition, strength, skid, etc.

Although the Federal Standards specify color for pavement markings, they do little to provide guidelines for tolerances for those particular colors. Also, the specifications are generally for the approval of new materials rather than providing guidance for determining when markings should be replaced. The proposed standards will come somewhat closer to

meeting these goals, but they do not go far enough. Neither the current or proposed standards appear to be based on psychophysical research.

Current standards for pavement marking materials by the ODOT are given in terms of the type of material to be used for different pavement conditions and types. Dry alkyd paint is to be used for new asphalt, thermoplastic or fast dry alkyd paint for good condition asphalt, fast dry alkyd paint for poor condition asphalt or concrete, and thermoplastic for good condition concrete. There is no mention of color in ODOT's application manual.

The ODOT's (1997) Construction and Material Specifications includes pavement marking specifications, calling for "yellow" paint and "white" paint for centerline and edgeline, respectively. No specific descriptions of color are included nor are the federal color numbers or indices specified.

The ODOT has, however, specified CIE coordinates slightly different from the proposed Federal Standards which indicate boxes into which pavement marking colors are expected to fall (see Figure 3). The recommendations for the placement of these boxes in the CIE diagram were provided by pavement marking vendors. No psychophysical research was done to support these choices (M. Khan, personal communication). The ODOT recognizes the need for standards designed to meet the needs of the driving public.

Reflectivity standards and other literature

Much of the research on pavement marking has to do with whether or not the markings can be detected under various conditions (visibility). Many researchers have compared subjective evaluations of markings with reflectivity measurements. While these types of studies test visibility, they do little to test the discriminability of the markings. Color is the most important factor for discriminating between different types of pavement markings, aided in some measure by location. When the location of the markings does not give decisive information about whether the marking is centerline or edgeline (for example, on a multilane road that does not have a median), color is the only factor available for discrimination. However, since locations are standard, drivers do not have to search for pavement markings. Therefore, the marking does not have to draw attention to itself (conspicuity).

There have been a number of studies conducted which recognize the need for adequate reflectivity and appropriate reflectivity standards for pavement markings. Although these studies do not directly deal with the issue of color or color standards, they do provide examples of the investigation of marking appearance and its importance to the driving public. With one exception, none of the literature reviewed related subjective color appearance of pavement markings to instrumental measurements.

In an extensive literature review, no study was found which dealt with color standards in an other than subjective and perfunctory manner. Other studies are cited mainly to provide a

review of procedures rather than results. Results are provided when relevant to the proposed study.

In a 1991 study, Graham and King used subjective evaluations of existing pavement markings to determine minimum luminance and retroreflectivity standards. In their study, they had subjects rate pavement markings as less than adequate, adequate, or more than adequate while being driven through the test sites and in a laboratory light tunnel with a test deck and observation booth. Subjects rated 3-M brand Stamark white and yellow tapes on both gray (concrete on the road) and black (asphalt) backgrounds. The experimenters also took luminance measures in order to establish a relationship between field luminance ratings and lab luminance for future use in predicting field rating values from measurements taken in a laboratory setting. The experimenters noted that older drivers were not used in the study and suggest that the relationship may not hold for them as they are likely to require higher values of luminance for adequate ratings.

Kidd (1986) evaluated waterborne paints applied to two interstate and two state highway locations in Mississippi to determine if those paints would be acceptable substitutes for lead-based paints in use at the time. Markings were compared by measured retroreflectivity and subjectively with control sites which were marked with accepted lead-based markings and were adjacent to the application of the new materials. Interstate locations included white paint on concrete and asphalt and state highway locations included yellow paint on asphalt and double bituminous pavements. For the interstate applications, the lead-based paint had higher reflectivity initially and throughout the life of the marking. On the state routes, the waterborne (new) markings had higher reflectivity initially and throughout the life of the markings. Both paint types showed good durability (as measured by subjective appearance and thickness of the paint after a variety of time periods), and color and appearance (both judged subjectively) were good for both paints.

Attaway and Adeleke-Sheidun (1990)evaluated pavement markings under criteria of ease of installation, appearance, durability, reflectivity and removability. Appearance was rated on an overall impression of the markings at a 10 foot viewing distance (eye height and/or angle were not provided) and included color as part of an overall rating (i.e.. “color okay”). Markings were rated as either acceptable or unacceptable and were tested on both a test deck and in the field.

Glass beads are added to pavement markings to enhance reflectivity. Agent and Pigman (1983) evaluated bead types based on reflectivity measurements, particularly with regard to the size of the beads. The field test was done on a 15-mile stretch of roadway. They compared retroreflectivity measurements to a subjective evaluation under both day and night conditions. No evaluation of color was made.

Anderson (1991) evaluated methods for cutting recessed striping grooves and also materials for placement into them.

All materials tested were found to be durable, but none of the materials tested were acceptable for visibility (as determined by a subjective evaluation of the experimenters) under wet day or night conditions due to a loss of retroreflectivity. Only white materials were tested. The color specification given was that the markings should be “as white as possible.” Anderson noted that one of the materials “became discolored to a creamy white.”

Borg (1986) compared standard thermoplastic traffic marking stripes with 3-M STAMARK‰ tape on new pavement for two years. The markings were evaluated in terms of durability, daytime visibility and nighttime reflectivity. Both yellow and white markings were installed. In color comparisons, Borg noted that the white tape retained its “original white” and the thermoplastic became a “dingy, gray-white” and that both were originally “equally brilliant white.” Reflectivity was measured with a retroreflectometer and compared with a subjective judgment (adequate or not adequate). The tape was found to be inadequate due to reflectivity problems.

Ingerman, Gibson, Ellicott, Wood, Burgett, Baca, Larranaga, Lynch, Murray, and Niessner (1979) conducted a cooperative study to investigate ways to save costs for state striping programs. They recommend performance specifications over chemical composition specifications for paints. Their recommendations were based on team meetings and information exchanges between Florida, Illinois, New Mexico, and North Carolina Departments of Transportation. No specific suggestions for color performance specifications were made.

Pietrucha, Hostetter, Staplin, and Obermeyer (1996) investigated the needs of older drivers regarding pavement markings and other delineation devices and recommended potentially useful treatments. They identified and tested 25 treatments on a simulator and on a closed test track using recognition distance and visual occlusion time (the proportion of viewing time in which the target could be covered and remain recognizable) as measures and conducted cost/benefit analyses for the most promising of the treatments. The treatments focused on increases in materials (i.e. greater width and thickness) rather than material type per se. Color does not appear to have been considered except with regard to its effect on reflectivity – for the yellow markings, the yellows which were more easily distinguished from white were noted to be less reflective. It is worth noting that any attempt to make yellow markings more distinguishable from white will result in a loss of reflectivity since the absorption of some of the incident light is what causes the yellow color appearance.

Kentucky Transportation Center (1997) followed AASHTO testing procedures for 173 materials placed in Kentucky in 1995, consisting of 110 paints (including 10 “durable type” paints), 35 thermoplastics, 8 preformed thermoplastics, 13 nonremovable tapes, and 7 removable tapes. (Appearance data for the materials are given in tables.) Two of the yellow marking materials were subjectively judged by the experimenters to be out of range of the Federal Yellow color (the report only states

that the colors appeared to be out of range – no color measurements were made), but no further information about color was given. Similar studies have been conducted jointly between the Kentucky Transportation Center and the state of Alabama each year since 1993.

Chollar and Appleman (1982) evaluated the effects of alternate pigments and resins on epoxy thermoplastic pavement marking materials in an attempt to find acceptable generic pigments to name in the standards (rather than the proprietary ones that the current standards called for). Their tests measured color by comparing tested colors to the federally accepted colors and making a subjective determination about whether the match was close enough as to indicate conformity to the Federal Highway Administration's recommended colors. No instrumental measurements of chromaticity were taken for this study.

Bryden, Lorini, and Kelly (1985) investigated the durability and reflectivity of both yellow and white epoxy pavement markings on 16 highway projects. They subjectively rated the markings as either good, fair or poor, with discoloration being one of the criteria for the rating of visual effectiveness (part of the durability rating). The reflectivity of the markings was measured, but no chromaticity measurements were made.

Jacoba and Johnson (1999) had observers rate the color appearance of both white and yellow pavement markings at distances of 12, 24, and 36 meters. The observers viewed five white and nineteen yellow markings from a vehicle and rated them on a scale of 1 (whitest) to 5 (yellowest). Materials were placed as centerline, and white edgeline was present for all viewing conditions. The materials were then tested in the laboratory at the same geometries as in the vehicles (comparable angles for each of the distances observed in vehicle). Measurements for brightness were taken by measuring the coefficient of retroreflected luminance as described in ASTM-D-4061. Measurements of nighttime color were made through the use of a telespectroradiometer with the spectral distribution of the incident light being measured at 10 nm intervals. These measurements were made at a distance of 6 m due to the "relatively low level of energy available." The laboratory measurements were then correlated with the visual observations. For all conditions, they found significant differences in color appearance between the materials in the lab vs. in the field and between day and night viewing and the separations appeared greater for larger field distances. The color ratings showed no correlation with the brightness measurements, but were shown to be related to color saturation. Some of the yellow markings appeared white in the nighttime conditions. The authors concluded that, while it was feasible to specify nighttime color by instrumental methods, more effort needed to be made to make the measurement easier (so as to become routine) and to psychophysically define "more precisely acceptable color zones" which relate to the safety needs of the driver.

Adequate reflectivity has certainly been recognized as a

necessary element to traffic control devices such as signs and pavement markings. Researchers have made several attempts to correlate appearance with actual measured values so that standards are appropriate and based on human perception. These attempts stop short of providing the same basis for chromaticity standards.

Maintenance and Testing

Gu and Hubert (1994) examined various techniques and instruments for measuring retroreflectivity, including meters and lasers. Most of the research in the traffic literature evaluated markings using either these sorts of instruments, subjective evaluations, or some combination. Unfortunately, these evaluations (with a few notable exceptions) primarily focused on reflectivity and include very little regarding color. Clark and Sanders (1993) reviewed current literature and made recommendations for guidelines and criteria for testing pavement marking materials. They suggest that criteria for evaluation should include durability, reflectivity, and cost for testing and approving materials. Color was not included in their recommendations. Clark and Sanders based their recommendations on a literature review and surveys of traffic and materials engineers at state DOTs. Specifically, their recommendations are that the traffic engineer should verify that appropriate materials and equipment are used, verify that the surface preparation is appropriate for the material used, check and record the air temperature at the time of application, the alignment and width of the marking, the thickness of application, uniformity of curing, and the percentage of glass bead. They also recommended photographing the markings before opening the road to traffic and measuring the retroreflectivity using a Mirolux 12 portable retroreflectometer. Finally, a schedule for inspection of markings was also recommended.

The Virginia Department of Transportation (VDOT) has developed methodology for testing color of pavement markings under a variety of conditions and has revised specifications to include these procedures. These procedures and revisions were made due to their “observation that cheap non-leaded pigments did not hold up under UV” (James Swisher, personal communication). In addition, after two months, the daytime colors of some thermoplastic materials had faded badly and “even new [yellow] materials look white at night.” They had complaints from their safety office that the contractors had installed the wrong color. (Wendy Ealding, copy of presentation notes, personal communication). The new standards require that materials be placed on an outdoor weathering rack for three months so that nighttime color stability may be tested. They also require that lead free thermoplastic materials be submitted for installation at the 2000 Pennsylvania test deck for “verification of long term performance.” Their test method requires that materials be melted according to AASHTO standards, poured on a sample plate, and have beads added prior to testing. Measurements in terms of chromaticity coordinates are to be taken in a light tunnel using a mounted PR-650 telecolorimeter

using light source A (VDOT, 1999). For liquid materials, color measurements are to be taken initially without beads. Both daytime and nighttime sources and varying limits for new and older (90 day) markings are provided. Measurements, in these cases are to be made on road with a colorimeter (VDOT, 2000). The previously mentioned proposed federal specifications for color of markings in terms of limits on the CIE chromaticity coordinates were resultant from this work (see Table 1, also see Figure 2). Further work is ongoing at VDOT to coordinate and test these techniques (Swisher, personal communication).

There are two basic issues, then, with regard to the effacacy of pavement markings: visibility and discriminability. The visibility issue applies primarily to reflectivity, and standards for minimum reflectivity have been put in place. Discriminibility, on the other hand, has more to do with chromaticity, and no standards for ranges of acceptable chromaticities are in place. Both the Federal Highway Administration (with the assistance of Virginia DOT) and the ODOT have proposed such standards. These proposed standards are based on current engineering practices and judgments and recommendations from marking manufacturers. No current or proposed standards are based on measurements of discriminability.

Color naming literature

Although there are proposals for standards for pavement marking colors, it is not clear whether those choices will be seen as clearly yellow or clearly white by the driver. Since there is some measure of coding involved in marking colors – white is edgeline and yellow is centerline – it is important that drivers recognize those colors as they are intended. Color naming methodology is one way in which one may determine emperically the relationship between a color’s chromaticity and the color label that people will use to describe it. By obtaining and using this type of information, colors may be selected which minimize the probability for confusion between colors and maximize the probability that the colors used will appear to be the color that the designer intends for them to be.

There have been two basic goals of researchers who have used a color-naming paradigm in their studies. The first involves determining the chromaticities of colors that correspond to the basic color names (Boynton and Olson, 1987; Gordon and Abramov, 1988) and the second involves attempting to understand the relationship between color measurements and the names that people give to colors chiefly for the purpose of designing color displays (Post and Green, 1986; Post and Calhoun, 1988 and 1989). Both contribute to the choice of methodology for the current research.

Boynton and Olson (1987) conducted research to test previous notions that there are only eleven basic color names in English commonly used to describe surface colors and to quantitatively define the regions of color space denoted by them. In their study, they displayed the 424 colors represented by the Uniform Color Scales of the Optical Society of America

(OSA colors) to seven subjects, two of whom were the authors and asked them to name the color at varying levels of lightness. One of the authors deliberately restricted his choice of color names to the eleven basic color names which were originally defined by Berlin and Kay (1969, as cited by Boynton and Olson, 1987). All other subjects were free to use any name they wished to describe the color being presented. The eleven basic color names were used by subjects to describe colors 88% of the time. Boynton and Olson classified the colors and names in reference to three indices. One index represented the locations, in a color space defined by OSA, of areas where there was a consensus of subjects on the color name. Consensus was defined as occurring when 100% of "subjects named a color sample consistently using the same . . . color term." Another index represented the locations of focal colors (those which best represented consensus colors as determined by response times) in the color space used by the authors, and the third represented central tendencies for the locations of colors commonly named. Green and blue color samples achieved the most concensus across the range of the 13 lighting levels used. Yellow achieved consensus for two color samples under one lighting condition and three under another. Both of these lighting conditions were at a high lightness level. White achieved consensus for only one color sample and only at one (high) lightness level. Under lower lightess levels, the white sample was named gray and the location in color space of the sample chosen as white shifted toward the yellow region at very high lightness levels. Boynton and Olson conclude from these results that "the link between basic color sensations and their names is congenital and physiologically based" and that "surface colors... fall into eleven basic categories." They also used their data to attempt to represent a color space which is subjectively isotropic, that is, the rate of change of color appearances is the same regardless of the direction in that space from which they are approached.

Post and Green (1986) and Post and Calhoun (1988, 1989) performed a series of color-naming experiments in order to better understand the relationship between colors and their names for the purpose of aiding display design. In each of these studies, subjects were presented colors on a computer display and asked to select from a limited menu of color names. In the initial experiment, viewing conditions were held constant. Post and Green (1986) used the resulting data to establish color naming boundaries for a variety of criteria of likelihoods of colors being described by each of ten color names (see Figure 4). In the second phase of experimentation, Post and Green varied stimulus configuration (solid disk and open line square) and background (black and white) and the menu of color names was increased from ten to twelve. Post and Calhoun (1988) then developed boundaries for the color names used as in the original experiment. They found that the background color influenced the subjects' choices of color names, particularly with the white and light colors. Configuration of stimuli had a less pronounced effect on color naming choices. In comparing

the first and second experiments, the addition of two colors did not seem to affect the boundaries of the ten original colors. In the third experiment, stimuli were presented as in the second with the exception that ambient lighting was added and varied. Although color-naming boundaries shifted somewhat in response to the addition of ambient lighting, the shifts were smaller than anticipated. The boundaries remained fairly stable between all ambient lighting conditions. Post and Calhoun conclude that there are color regions that will be reliably named under varying conditions and that display design would be enhanced by considering these regions.

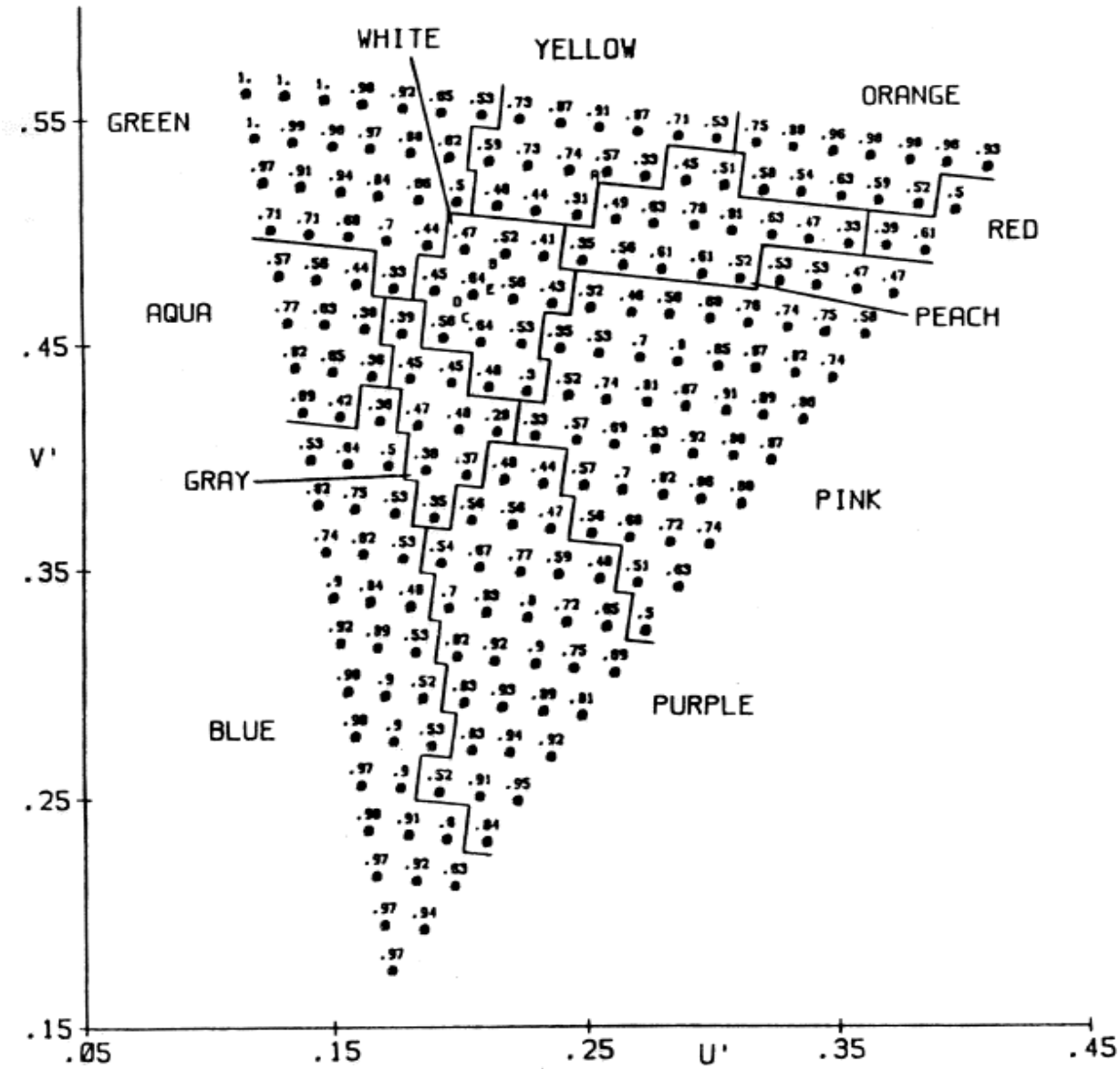

Figure 4: From Post and Calhoun, 1988. The triangle indicates the chromaticities used in their experiment. Boundaries are drawn between color names most likely to be used.

Gordon and Abramov (1988) have developed and tested a methodology of color scaling in order to map the color appearance of a variety of chromaticities onto a color space. Their method uses a scaling procedure wherein subjects describe a chromaticity in terms of the percentage of four basic hues (red [R], green [G], yellow [Y] and blue [B]) combined with the apparent saturation (proportion of hue vs. white) of that chromaticity. In early experiments, subjects rated the percentages of hue and achromatic or white content (lack of hue saturation) simultaneously so the five ratings (R, G, Y, B, and achromaticity) totaled 100%. They reported that subjects found this method to be confusing, so they separated the hue rating from the saturation rating. Essentially, subjects were briefly shown a monochromatic light and asked to report the "percentages in his sensation of R, Y, G, or B," and after doing so to state the "apparent saturation … as a percentage of the sensation elicited by the stimulus." Gordon and Abramov were able to map the results of their scaling experiment onto a color space. They were also able to derive wavelength discrimination functions from that mapping that closely matched well-known experimentally obtained functions. This match indicated that their method was reliable as well as being portable and easy to use by those who wish to design displays in which color appearance is important.

These examples of past color naming experiments indicate that this methodology is useful for establishing regions of color that will be reliably identified as corresponding to a given color name. Yellow and white pavement marking colors are intended to provide information to the driver on the location of both the edge and the center of the road, and, in some cases, the distinction between a lane with same direction traffic and one with oncoming traffic. In order for this color coding to be useful, it is important that marking lines be clearly visible and clearly distinguishable by color. A color scaling methodology seems the most logical choice of experimental paradigm for identifying which colors best serve these needs for discrimination and color recognition.

The Experiment

The basic goal of this research is to determine reasonable tolerances for the chromaticity of pavement markings. Pavement marking color standards should not only state acceptable colors, but should also provide tolerances to indicate when the markings are no longer acceptable. Moreover, those tolerances should be based on the ability of drivers to discriminate between marking colors.

The type of marking, the age of the marking, and the background or pavement color are all expected to affect the color appearance of the marking. For this reason, all of these factors need to be included in the experimental research.

The aim of the study is to compare pavement markings which are currently being used with the proposed standards for marking colors and with data generated by a color scaling experiment. Consistent with that goal, the study will test the hypotheses

that:

1. the chromaticities within the set proposed by the ODOT for yellow and white marking standards will be identified as a yellow and white, respectively, with a high reliability;
2. for markings currently in use, centerline markings fall within the range of colors reliably identified as yellow and edgeline markings fall within the range of colors reliably identified as white; and
3. proposed standards for tolerances are consistent with markings which are currently being used.

Method

Subjects

Twelve female and 3 male undergraduate college students under the age of thirty (range = 19-27, mean = 21.8) along with eight female and seven male subjects over the age of thirty (range = 30-55, mean = 42.4) participated in the color naming experiment. In addition, four male red-green color deficient subjects participated (age range = 23-57, mean age = 38.75). All subjects were checked for normal color vision with the Ishihara color plate test. Individuals diagnosed as color deficient by the Ishihara test were also evaluated using Rayleigh matching.

Apparatus

Field measurements were taken using recommended procedures with a Hunter 3.80 portable spectrophotometer set to D65 as the daytime illuminant and standard illuminant A as the nighttime illuminant.

For color scaling experiments, stimuli were presented on a 17 inch Nanao T2.17 color monitor at a viewing distance of approximately one meter and generated by a Power Mac 8500 computer equipped with a Radius Thunder 30 color card. Subjects’ responses were entered by means of an ordinary computer mouse.

Stimuli

Stimuli consisted of a simulated roadway with a solid line down the center, both of which were shown in perspective. Absolute environmental luminances cannot be replicated on the computer monitor, so contrast ratios were calculated. Past research has indicated that this method is valid for color naming and display procedures (Post and Calhoun, 1988). Contrast ratios between the roadway and markings were set according to measurements made of actual markings and road surfaces with a maximum luminance of 5 candella. Prior to and between presentations of stimuli, the monitor’s screen contained a uniform color representative of either daytime lighting or nighttime (headlamp) viewing conditions in order to maintain adaptation. The luminance for nighttime viewing adaptation was set to zero. For daytime illumination, the adapting luminance was midway between the darkest and lightest luminance. This

setting was based on the “gray world hypothesis,” which assumes that average environmental chromaticity and luminance is a neutral gray approximately midway between the darkest and lightest objects in the environment (Buchsbaum, 1980). During these periods, a small cross was displayed at the center of the screen as a point of fixation. During training, the stimulus display was shown to the subject until he or she clicked the mouse to bring up the response screen. During experimental trials, the stimulus display was briefly (500 ms) flashed on the screen to simulate a single, brief glance at the stimulus. For each trial, the color of the centerline was chosen randomly from a sample of thirty-six colors which span a range extending somewhat beyond both field measurements of white pavement marking colors and current proposed standards for pavement marking colors extending to as far into the yellow as was possible given the limitations of the monitor. Pilot work was done in order to determine the best arrangement of the sample colors in CIE color space (see Figure 5). The chromaticity of the roadway and luminance contrasts between roadway and centerline were consistent with average chromaticies and luminance contrasts of current pavements and markings as determined by field measurements.

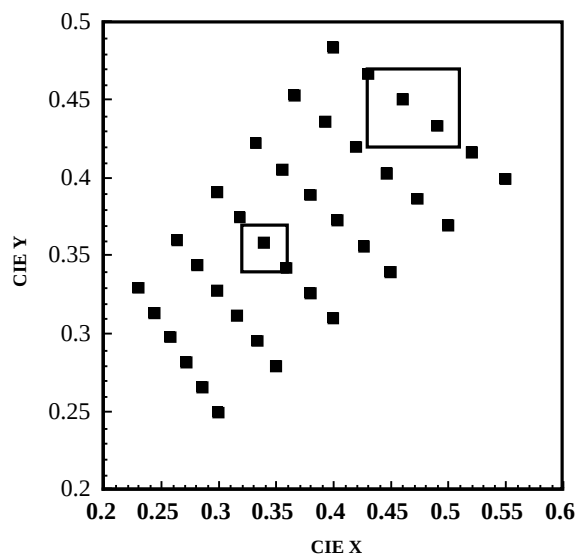

Figure 5 - Small squares represent stimuli colors. Large boxes represent proposed ODOT color specifications. Note: Equal spacing in the CIE color space does not represent equal perceptual spacing.

Procedure

Field measurements

As a guide for the selection of pavement marking colors and background pavement colors for the color naming study and for the purpose of comparison, field measurements were taken of current pavements and current pavement markings. For pavements, measurements were made for both old (> 5 years) and new (< 2 years) pavements for asphalt and concrete surfaces for a total of four background roadway colors. For markings, field measurements were taken by color (yellow and white), age (< 1 year, 2-3 years, and > 3 years), and type (polyester, epoxy, thermoplastic, and paint). The ODOT provided a list of locations for measurements and assisted in the field work.

Color identification study

In the laboratory, subjects were instructed to fixate on a cross at the center of the monitor. During a trial, the fixation cross was removed, and simulated pavement markings varying in color were shown briefly to subjects against one of four roadway background colors chosen on the basis of the field measurements. Stimuli were presented such that the stripe ran vertically through the fixation point, and the subject was asked to enter the percentage of white (achromatic) in the stimulus (center stripe). After making this selection, subjects were presented the four basic hue names (red, green, yellow and blue) and asked to apportion the chromaticity of the stripe such that the sum of the hues was 100%. For example, if the stripe on the center of the road was a light orange-yellow, the subject might have first indicated that there was about 30% white in the stimulus. He was then asked to divide the colorfulness of the stimulus into red, green, yellow and blue so that those four percentages totalled 100. Since the stripe is orange-yellow, the subject might have then responded that the stimulus hue contained 60% yellow and 40% red.

Stimuli were presented to each subject in two blocks of 144 trials, representing daytime and nighttime viewing and allowing each of the thirty-six selected colors to be viewed on each of the four roadway colors in each block. Standard illuminations were shown between the presentation of stimuli for the purpose of maintaining constant adaptation. The area surrounding the simulated road also remained at this adaptation level during stimulus presentation. In one block, screens between the presentation of stimuli were lit to maintain appropriate adaptation for standard daytime lighting conditions. In the other, screens were lit for headlight illumination contrasts. The order of presentation of these blocks was randomly decided for each subject by the toss of a coin. The order of presentation of stimulus color within blocks was randomized by the computer program. Each block of trials is normally took between forty-five and sixty minutes, and subjects were allowed to take breaks whenever they felt that they needed. Blocks were normally completed on different days for each subject. Presentation of the first block was preceded by reading and signing the consent forms and color vision testing along with the completion of a brief training period, so that the first period of participation was normally about an hour and a half. The second period only consisted of presenting the second block of trials and lasted about an hour.

Results

Color scaling

Once the scaling data were collected, average percentages of each of the five color dimensions judged by subjects with normal color vision were calculated across the four pavement types and two lighting conditions. The percentage of white for

each chromaticity tested was simply the percentage white named by each subject and averaged across conditions. For the other hues, the percentage of white was subtracted from one hundred percent, and the result was multiplied by the percentage named for each hue. These results were then also averaged across conditions.

In order to determine colors which were clearly judged to be primarily white, a criterion was set for the area of the standard 1933 CIE color space where chromaticities were reliably judged to be at least two-thirds white (see Figure 6). None of the color dimensions judged except white exceeded 50%. Therefore, in the case of yellow, the criteria were based both on the percentage judged yellow and the ratio of yellow to white. Specifically, the region selected should be perceived to be at least 40% yellow (see Fig. 7) and to contain at least twice as much yellow as white (see Fig. 8). These criteria for yellow were selected because they represent the goal of determining colors that are reliably judged to be more yellow than white and also judged to be more yellow than any other hue. The regions containing the two sets of colors that met each criterion are combined and shown in Figure 9. In this figure, the area inside the bold lines is an approximate average of the areas created by the percentage and the ratio criteria. In Figure 10, the contours for white and yellow are reduced to quadrangles in order that they may be represented by a set of four chromaticity coordinates. The coordinates marking the corners of the white contour are [(0.24, 0.26), (0.27,0.23), (0.32,0.37), (0.39, 0.36)]. The corners of the yellow contour are [(0.42,0.47), (0.46,0.42), (0.45,0.53), (0.55,0.44)]. The yellow contour extends to the spectral locus of the CIE diagram and ends where the diagram also ends. The points toward that

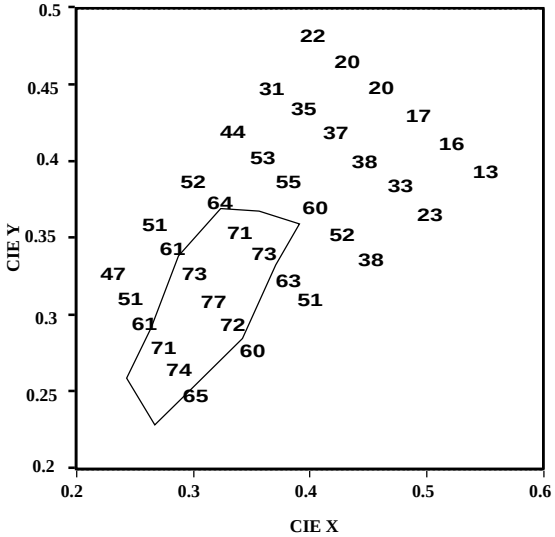

Figure 6: Average percentagesof white across normal subjects for combined day and night viewing across all pavement types.Contour encloses approximated area where percentage is greater than 66%

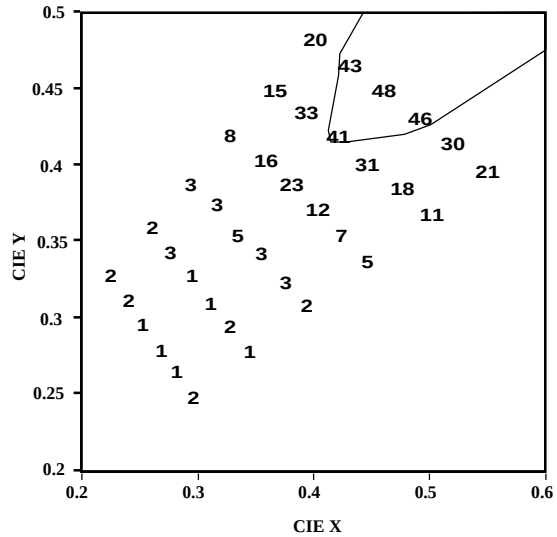

Figure 7: Average percentagesof yellow across normal subjects for combined day and night viewing across all pavement types. Contour encloses approximated area where percentage is greater than 40%

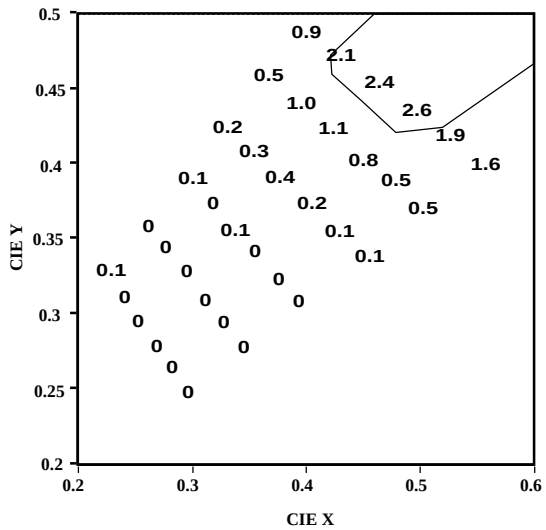

Figure 8: Average ratiosof yellow to white across normal subjects for combined day and night viewing across all pavement types. Contour encloses approximated area where ratio is greater than two

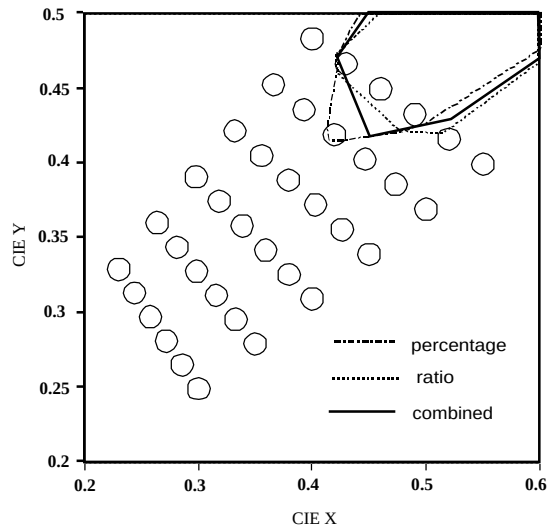

Figure 9: Average percentages of yellow and ratiosof yellow to white across normal subjects for combined day and night viewing across all pavement types. Combined (bold) contour is an appoximate average of the two.

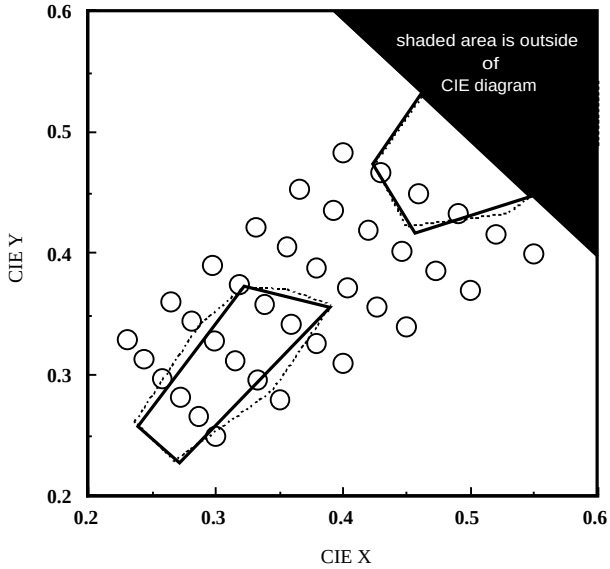

Figure 10: Contours for white and yellow criteria simplified to four-sided figures

side of the contour which contains no tested colors are in an area of the diagram where chromaticities cannot be duplicated on the color monitor, but are a more saturated yellow than those points tested. These quadrangles will be used for all further comparisons.

<u>Day vs. night – combined normal subjects</u>

Normal subjects' responses were graphed for both daytime (see Fig. 11) and nighttime viewing conditions (see Fig. 12). Plotted points indicate test colors meeting criterion for yellow and white. With nighttime viewing, the area of the test colors meeting the criterion for white shifts slightly towards yellow and very slightly toward red. The test colors meeting criteria for yellow shift away from white and somewhat towards red under nighttime viewing. It should be noted that the nighttime viewing condition simulated illumination similar to standard halogen headlights. These lights are more yellow in appearance than daylight. Headlights on newer, more expensive vehicles are more similar in color to daylight, so daytime viewing conditions would apply for them.

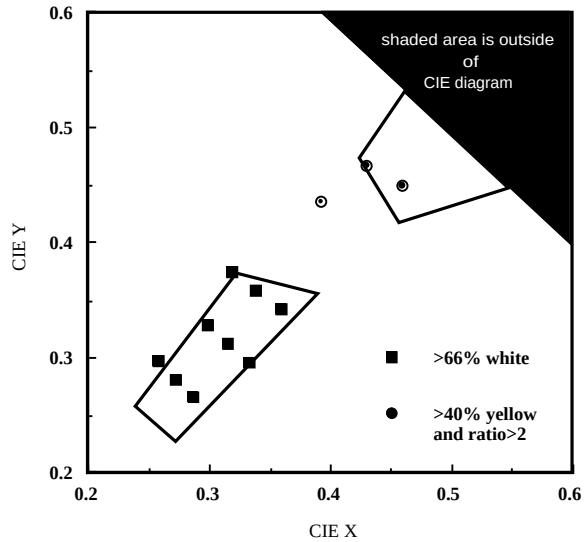

Figure 11: Daytime viewing conditions - quadrangles represent normal viewing contours averaged across conditions.

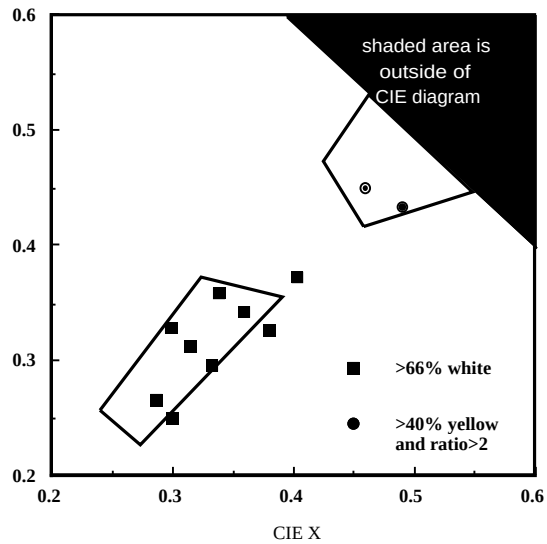

Figure 12: Nighttime viewing conditions - quadrangles represent normal viewing contours averaged across conditions.

Older vs. younger normal subjects

Half of the subjects with normal color vision were over thirty, and half were under thirty. As shown in Fig. 13 & 14, comparing their responses, it is evident that fewer colors reach criterion for younger subjects. For both daytime and nighttime viewing, all test chromaticities meeting the criterion for white among older subjects include, but are not limited to, those meeting the criterion for white among younger subjects. For daytime viewing, test chromaticities meeting the criteria for yellow are shifted slightly to higher x and lower y values (closer to red locus) among older subjects (see Fig. 13) compared to chromaticities meeting criteria for younger ones

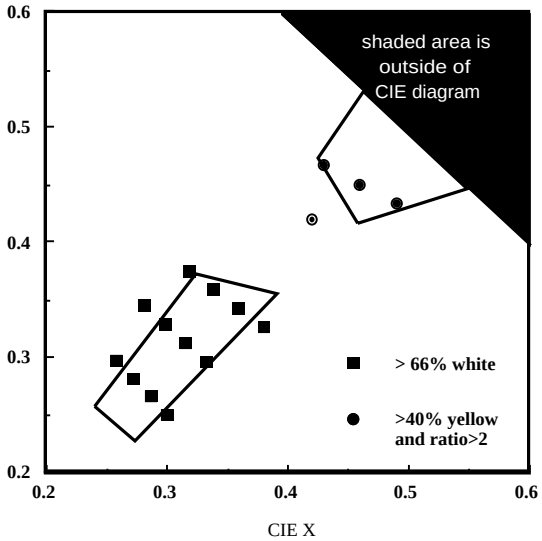

Figure 13: Older subjects under daytime viewing conditions - quadrangles represent normal viewing contours averaged across .

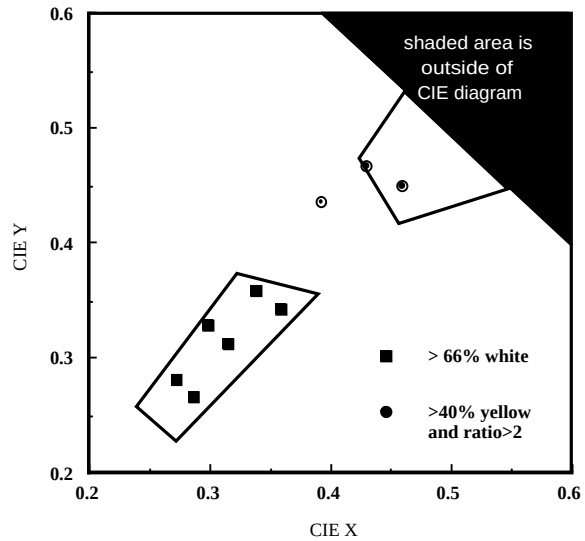

Figure 14: Younger subjects under daytime viewing conditions - quadrangles represent normal viewing contours averaged across conditions.

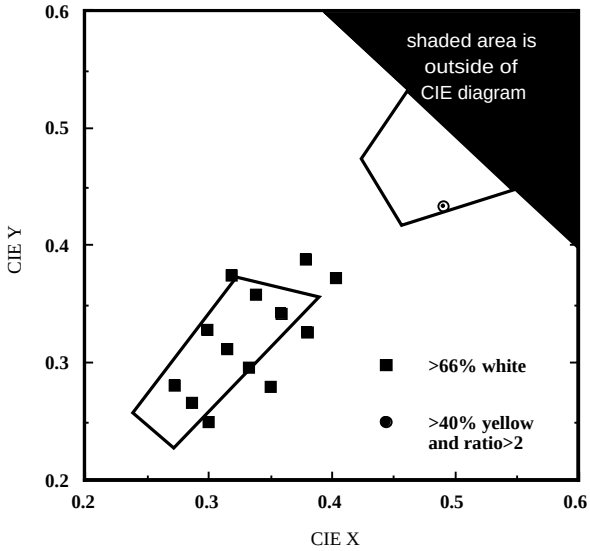

Figure 15: Older subjects under nighttime viewing conditions - quadrangles represent normal viewing contours averaged across conditions.

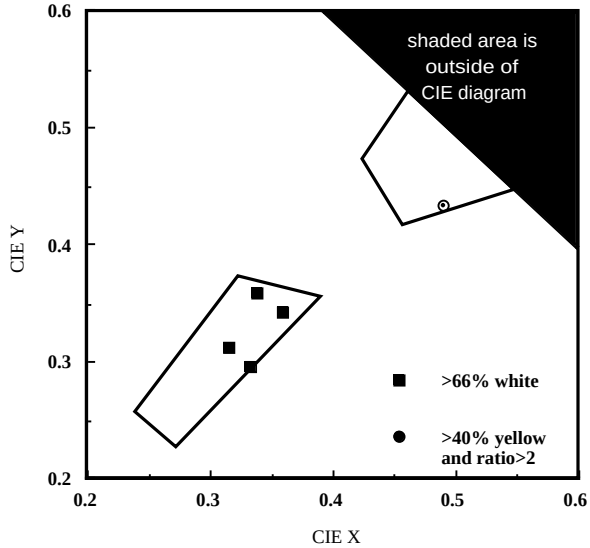

Figure 16: Younger subjects under nighttime viewing conditions - quadrangles represent normal viewing contours averaged across conditions.

(see Fig. 14). For nighttime viewing, only one chromaticity meets the two criteria for yellow, and this chromaticity is the same for both older and younger subjects (see Fig. 15 & 16). Note that when data from older and younger subjects are combined, two chromaticities met the criteria for yellow (see Fig. 12). This additional chromaticity in the combined data failed to meet one criterion in the older group and the other criterion in the younger group; averaging resulted in this chromaticity meeting both criteria. When daytime and nighttime data are combined, test chromaticities meeting criteria for older subjects include and extend beyond those of younger subjects (see Fig. 17 and 18).

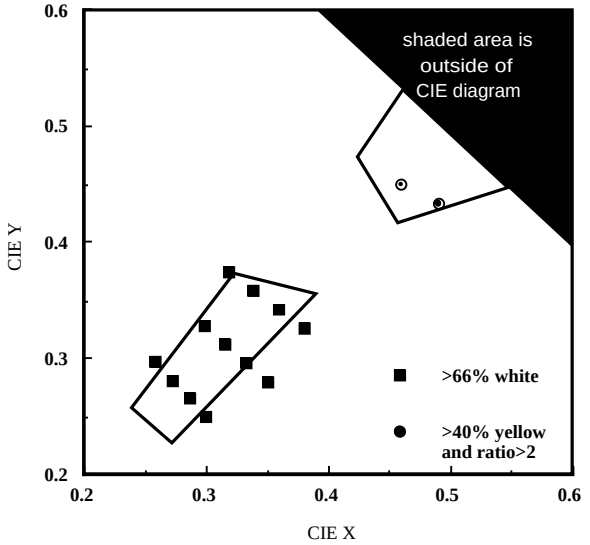

Figure 17: Older subjects under combined viewing conditions - quadrangles represent normal viewing contours averaged across conditions.

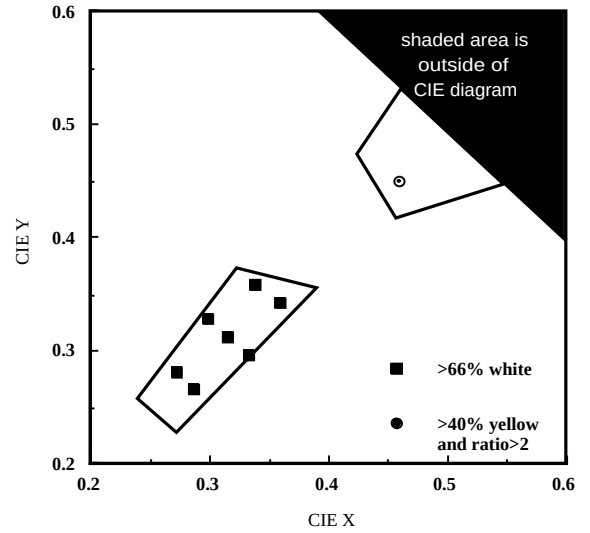

Figure 18: Younger subjects under combined viewing conditions - quadrangles represent normal viewing contours averaged across normal conditions.

Color deficient subjects

Four subjects with red/green color deficiencies were tested in order to compare their responses with those of subjects with normal color vision. Under daytime viewing conditions, color deficients responded similarly to those subjects with normal color vision (see Fig. 11 & 19). The only differences are that color deficient subjects' data include a slightly larger region for which white meets criteria and a slightly smaller region for yellow. These differences are much greater under nighttime viewing conditions (see Fig. 12 & 20). For color deficient subjects, test chromaticities are less apt to be judged yellow and more apt to be judged white at night. Three-fourths of the chromaticities tested meet the criteria for white, and none meet the criteria for yellow. Neither do any chromaticities meet the criteria for yellow when the two conditions are combined (see Fig. 21). For the white, all of the points meeting the criterion for normal subjects are included within the region meeting the criteria for color deficients. For the yellow, the points closest to meeting criteria for colorblind subjects have slightly higher x and lower y values than those meeting criteria for normal subjects. These points are the only ones that were not named as greater

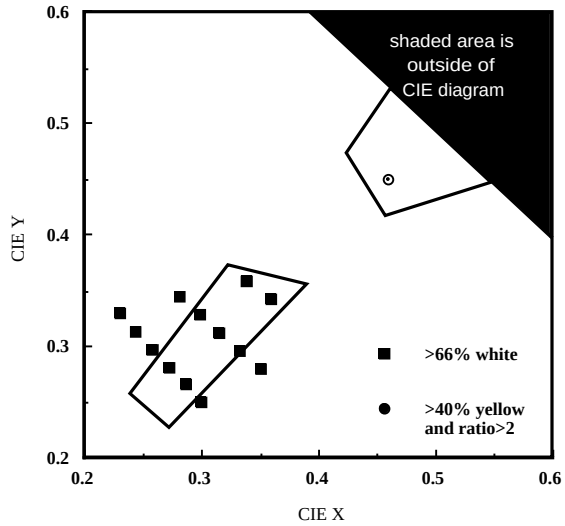

Figure 19: Color deficient subjects under daytime viewing conditions - quadrangles represent normal viewing contours averaged across conditions.

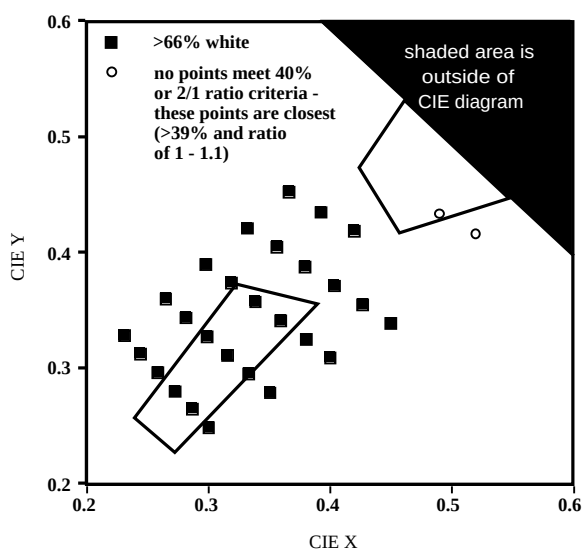

Figure 20: Color deficient subjects under nighttime viewing conditions - quadrangles represent normal viewing contours averaged across conditions.

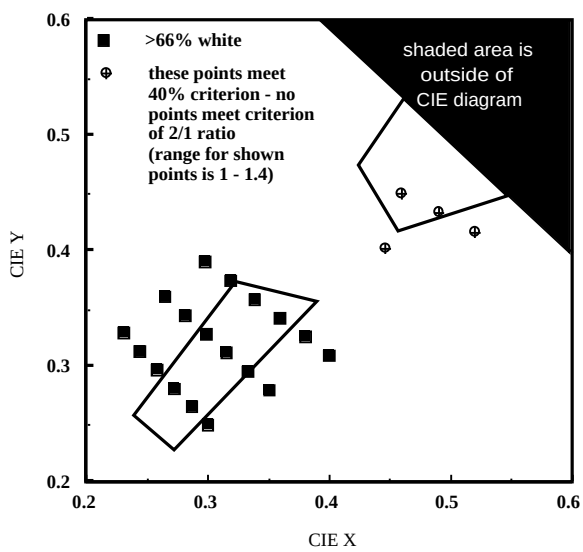

Figure 21: Color deficient subjects under combined viewing conditions - quadrangles represent normal viewing contours averaged across conditions.

than 40% white. For red-green color deficients, then, perhaps the best that can be accomplished with pavement marking is discrimination of white from colorful markings, particularly at night.

Effect of pavement type

Field measurements were taken prior to the color scaling experiment in order to set appropriate contrasts between pavement markings and pavements for different pavement types. Ranging from lightest to darkest in appearance, the pavement types measured were new concrete, old asphalt, old concrete, and new asphalt. For white markings, pavement had little effect on which chromaticities passed criteria (see Fig. 22). Only one chromaticity, which achieved an overall rating of greater than 66% white, did not do so for all pavement types. This chromaticity did not meet the criterion when shown against a background representing old asphalt. Oddly enough, old asphalt was neither the lightest nor the darkest of the pavement types. The chromaticity that did not meet the criterion of 66% was judged to contain about 64% white. It seems reasonable to conclude, then, that the pavement type does not seriously affect the criterion contour for white.

In the case of yellow markings, pavement type did seem to have a small effect upon which chromaticities met the criteria for yellow (see Fig. 23). In this case, chromaticities shown against the darker backgrounds were more likely to meet criteria. For the three chromaticities meeting criteria across all conditions for yellow, only one did so for all backgrounds. A second color met criteria for all but the lightest background, upon which it was judged to contain 33% yellow and met the ratio criterion. The third met criteria for only the two darkest backgrounds. However, this chromaticity almost met the criteria

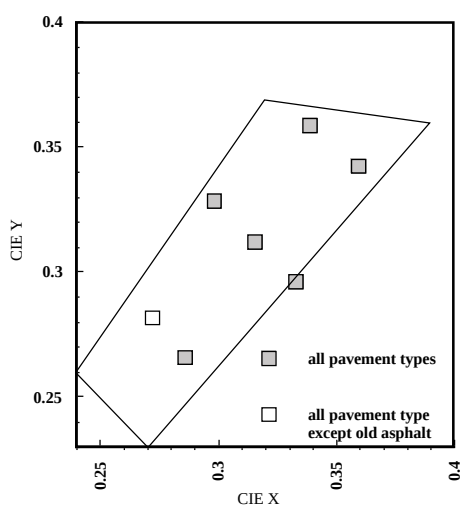

Figure 22: Pavement type and points which were named to contain greater than 66% white. The large diagonal box indicates the contour suggested by color naming data. Pavement types include old and new concrete and old and new asphalt.

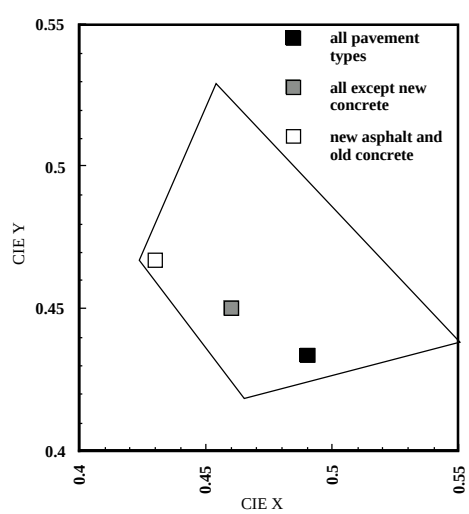

Figure 23: Pavement type and points which were named to contain greater than 40% yellow and had a ratio of yellow to white greater than two. The quadrangle indicates the contour suggested by color naming data.

with a background representing old asphalt; it was judged 39% yellow with a ratio of 1.9. With a background representing new concrete, it also almost met the percentage criterion (judged 37% yellow) and met the ratio criterion. Even for the yellow, then, it seems that background did not have a marked effect on color scaling.

Color Scaling vs. ODOT Proposed

Figure 24 shows the results of color scaling compared with the boxes representing proposed ODOT standards. The points shown indicate the test colors which meet criteria. It is clear from this graph that the ODOT's proposed standards are reasonable, although they could be improved somewhat. In the case of the yellow, colors judged to contain more red than the criteria would allow are included in the standard. Figure 25 shows the yellow scaling contours compared with the ODOT standard. More meaningful is that some of the colors that would meet the standard were judged to appear more white than is desirable. For white markings, the proposed standards could be relaxed somewhat. Figure 26 shows the white scaling contours compared with the ODOT standard. It might also make sense to use chromaticities which are further from the yellow locus (i.e. closer to the bluish corner of the diagram) to improve discriminability.

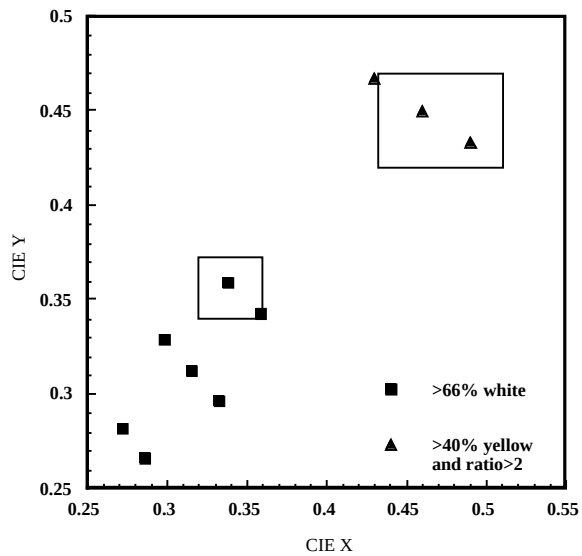

Figure 24: Average of combined daytime and nighttime color-naming data for both younger and older normal color vision subjects

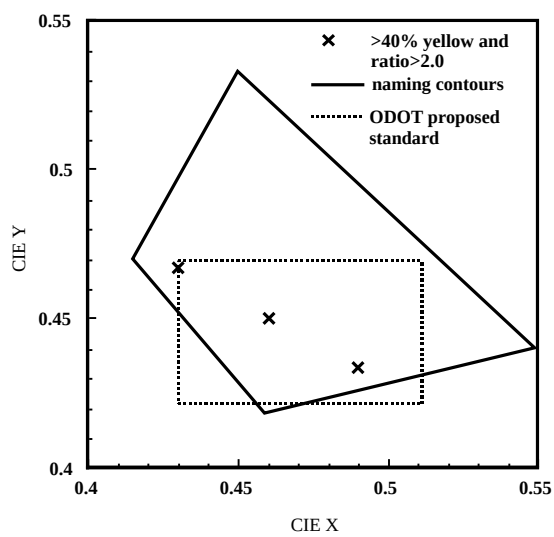

Figure 25: Proposed ODOT standards and color naming contours for yellow markings for normal vision subjects

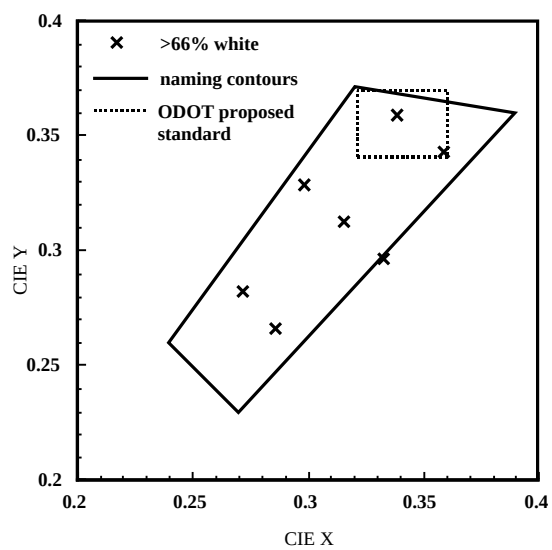

Figure 26: Proposed ODOT standards and color naming contours for white markings for normal vision subjects

Color Scaling and Proposed Standards vs. Measured Marking Colors

Four pavement marking types (paint, epoxy, thermoplastic, and polyester) currently in use were measured in different locations on Ohio roads. For each of these marking types measurements were taken of old, midlife, and new markings. These field measurements were compared to both the color-naming data and the ODOT's proposed standards.

Paint measurements are given in Figure 27. For the most part, those markings measured meet the proposed ODOT standards. They do not, however, all fall within the contours established by the color scaling data. For white measurements, all of the paints measured do fall within the contour based on color scaling, but only the new yellow markings meet color scaling criteria. Most of the old and midlife paint measurements fall just outside of the scaling contour.

Epoxy measurements are given in Figure 28. For both the white and the yellow, all of these measurements are within both proposed standards and contours established by color scaling.

Thermoplastic marking measurements are given in Figure 29. The markings from this pavement type were all in

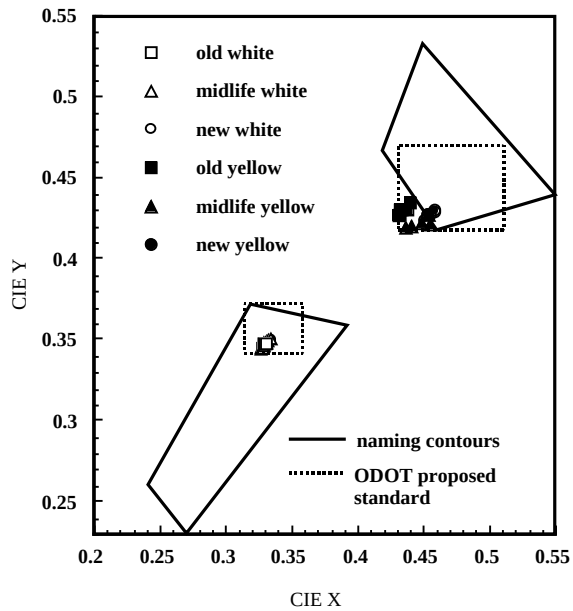

Figure 27: Paint markings as measured on Ohio roads.

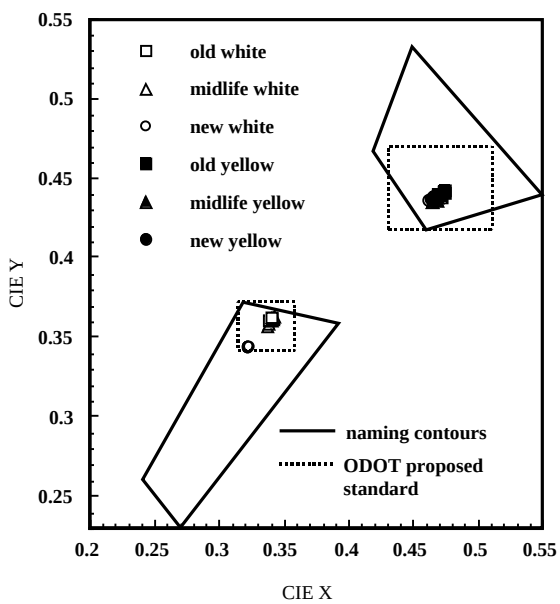

Figure 28: Epoxy markings as measured on Ohio roads.

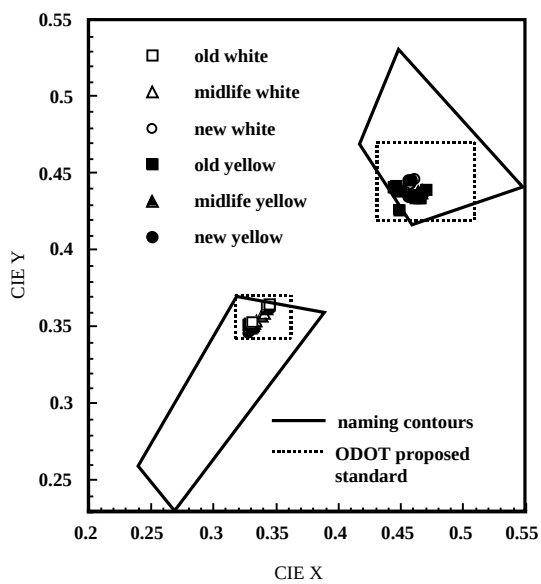

Figure 29: Thermoplastic markings as measured on Ohio roads.

conformance with proposed ODOT standards for both yellow and white markings. In addition, these measurements were quite close to conforming to the contours from color scaling criteria. Only for one case of an older yellow marking is any measurement outside of the color scaling contour.

The polyester marking measurements are the least consistent with color scaling contours and proposed standards (see Fig. 30). The white markings again all conform to the ODOT's proposed standards and all but one to the color scaling criteria. The yellow markings, however, are much less consistent. Measurements from two of the midlife locations indicate chromaticities more reddish than would be allowable by either ODOT proposed standards or contours established by color scaling. More problematic are the measurements of the older markings. It appears that, as these markings age, they fade until they come very close to appearing white. In one case, the measured marking is closer to the white contour than to the yellow. In a few others, the measurements are about equidistant from the white and yellow contours. These results are troublesome, especially since discriminability of white from yellow is of primary importance.

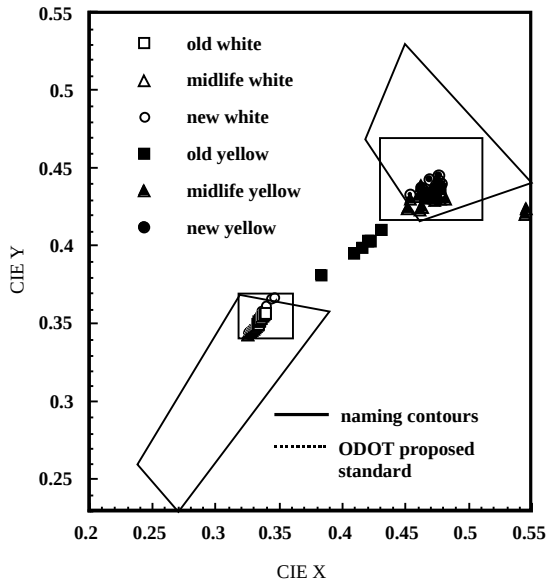

Figure 30: Polyester markings as measured on Ohio roads.

Discussion

The primary goal of this research was to determine whether it is plausible to establish reasonable tolerances for the color of pavement markings and, if so, to make recommendations for those limits. In order to meet this goal, both current practices and proposed color standards were evaluated in light of data obtained through a color-scaling procedure. Three basic hypotheses were tested and are discussed below along with recommendations for changes to those proposed standards.

In order to be included in the region established as white, a chromaticity was required to have been judged to contain at least 66% white. Since none of the chromaticities tested were said to contain even 50% yellow, a set of criteria was established for inclusion in the yellow region. First, in order that it could be established that a particular chromaticity was reliably judged yellow more than any other color, the criterion adopted was that the color must be judged to contain at least 40% yellow. Second, in order that it could be established that the color would not be confused with white, the ratio of yellow to white was required to be at least 2 to 1. Once these criteria were established, color scaling data were evaluated in

terms of ambient lighting, subject age, subject color vision, and background color.

Results from normal observers did not vary appreciably between daytime and nighttime viewing conditions. Lighting condition had only a very slight effect on which test chromaticities were named yellow and which were named white. Under daytime viewing conditions, subjects tended to perceive more yellow in test chromaticities slightly closer to the center of the CIE diagram (the white locus). Conversely, for nighttime viewing, colors slightly closer to the upper right hand corner (yellow spectrum locus) of the CIE diagram were named white. In addition, under nighttime lighting, both the white and yellow regions meeting criteria were shifted slightly toward the corner of the diagram that was judged more red under daytime conditions. All of these changes, however, were very slight. In general, the regions established as being reliably judged yellow and white were similar under both daytime and nighttime lighting contrast conditions.

Age of the subjects made almost no difference in the location of the test colors meeting criteria. Regions meeting criteria for subjects over thirty were slightly larger than for younger subjects for both yellow and white, but the overall locations of the regions did not change.

Color deficient subjects' data were unusual in that those subjects judged quite a large number of chromaticities white. This result was particularly true under nighttime viewing conditions. Color deficient subjects were also less likely to name a chromaticity yellow, but those points that were named yellow most reliably were coincident with the yellow region for normal subjects. The white region established by normal subjects also fit well within the region judged white by colorblind subjects.

Pavement provides a background for pavement marking. In order to test for effects of a variety of pavement types, four background colors were tested which coincide with old and new concrete and old and new asphalt. For white markings, there was almost no effect of pavement type. With one exception, chromaticities meeting the white criterion were the same for all pavements. For that exception, markings on all backgrounds except the one representing old asphalt met the white criteria. Darker pavement types resulted in a larger number of chromaticities being reliably judged yellow. These effects were quite small, however. In general, there is no appreciable effect of pavement type for either yellow or white markings.

Given the fact that none of the variables mentioned had more than a very slight effect on the contours established by combining the data for normal subjects, it seems reasonable that these contours may be used for both further comparison and recommendations for tolerances.

Hypothesis 1: The chromaticities within the set proposed by the ODOT for yellow and white marking standards will be identified as yellow and white, respectively, with a high reliability.

This hypothesis was well supported for the white and for a large portion of the yellow chromaticities included in the ODOT standard. For white, the proposed standard is almost entirely within the color scaling contours. The ODOT's proposed standards box could reasonably be made larger and/or moved farther from the yellow locus and still meet the objective of including chromaticities that would be judged to be primarily white. For yellow, a bit more of the standard box is outside of the contour defined by the color scaling criteria. There are, then, a few chromaticities which would meet the ODOT standard that are not reliably judged yellow. In order to rectify this situation, the ODOT's proposed standards box should be moved a little closer to the yellow locus.

Hypothesis 2: For markings currently in use, centerline markings fall within the range of colors identified as yellow and edgeline markings fall within the range of colors identified as white with high reliability.

This hypothesis was supported only in the case of white markings. For yellow markings, some inconsistencies were found. In the case of new markings, the chromaticities of all of the marking types except paint were within the limits suggested by the color scaling contours. As the markings aged, however, polyester markings seemed to fade much more than the other three marking types. Also, for polyester markings, some mid-life markings that were measured would be likely to be judged to contain quite a large portion of red. It is unclear how much of a problem a reddish appearance would present. On the one hand, standard practice indicates that centerline markings should be yellow rather than orange, which the aging polyester markings are likely to appear. On the other hand, they are clearly not white, and this discriminability between white and yellow markings is probably more important to the driver than whether the marking appears more yellow or more orange. For that reason, it is clear that the older polyester markings which are clearly less discriminable from white are problematic. Care should be taken to prevent the use of yellow markings that will later appear white.

Hypothesis 3: Proposed standards for tolerances are consistent with markings which are currently being used.

It was expected that current markings would comply to the ODOT's proposed standard. Pavement marking measurements did comply fairly well with proposed ODOT standards. All of the white marking colors were consistent with the proposed standards. Some of the yellow marking colors were less consistent, particularly as they aged. In particular, midlife polyester markings in two locations would be likely to appear more red than the current ODOT proposed standards would allow. Additionally, several of the older yellow polyester markings

would be likely to appear quite a bit whiter than ODOT standards would allow.

In light of the variability of older polyester markings, these results suggest that markings of this type should be inspected more frequently than the three other marking types. The Ohio legislature had considered mandating that a certain portion of highway construction projects include warranties for pavement markings. This possibility was one of the reasons that the current research was needed. Given the results, such warranties would be particularly beneficial when polyester markings are used by contractors.

Conclusion

Responses in the color naming experiment were similar for both daytime and nighttime viewing, for older and younger subjects, and for a variety of pavement types. The regions in which test chromaticities met the criteria for color deficient subjects were larger for white and smaller for yellow than for normal vision subjects. These regions were, however, in much the same location. These data indicate that, using color coding, the standards that would be suggested from the color scaling are probably the best that could be established. The only method of improvement would be redundant coding based on some dimension other than color. These results indicate that it is reasonable to establish standards and that these standards can be acceptable across a variety of conditions and for a range of drivers.

Recommended standards

The contours that were derived from the color scaling data could reasonably be used for a new standard. The ODOT, however, would prefer standards that allow a worker to easily and quickly determine if a pavement marking being measure in the field conforms. While the established contours can be represented by their four corner points, a determination of whether a measurement falls within the contour is a bit more complex. The proposed standards, on the other hand, are defined by horizontal and vertical lines only, so that there is a range of both x and y values that a color must fall within to meet the standard. The ODOT has indicated that they would prefer a standard of this type. In keeping with that request, boxes of this sort were established to maximize acceptable colors and stay within the contours suggested by the color scaling data (see Fig. 31). For the

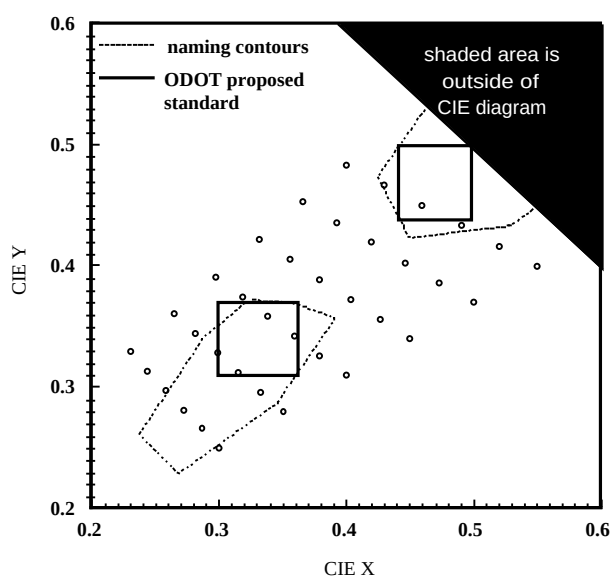

Figure 31: Recommended standard based on color naming contours

white markings, the range of x values is 0.33 ± 0.03, and the range of y values is 0.34 ± 0.03. For the yellow markings, the range of x values is 0.47 ± 0.03 and the range of y values is 0.47 ± 0.03.

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