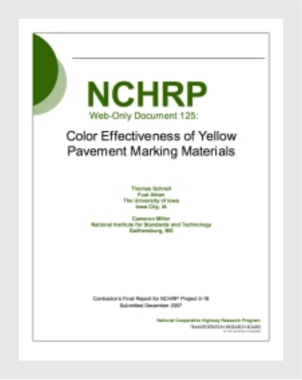

Color Effectiveness of Yellow Pavement Marking Materials: Full Report

DETAILS

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This research project is sponsored by the National Cooperative Highway Research Program (NCHRP) of the Transportation Research Board (TRB) of the National Academy of Science, under the project designation NCHRP 5-18. We would also like to thank to Federal Highway Administration (FHWA) for providing field instruments. The authors would like to thank the NCHRP 5-18 panel members for their support, encouragement, and input in this project.

CHAPTER 1: INTRODUCTION AND RESEARCH APPROACH

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). Thus, it is essential that both the pavement marking configuration and color be identifiable to the drivers without ambiguities. This study provides the scientific and practical basis to ensure that drivers can correctly identify pavement marking color in an operational and demanding environment.

Pavement markings may appear yellow during daytime but may not appear as yellow at night under automobile headlamp illumination. When lead was removed 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 they can be clearly distinguished both during day and night.

Work in this project involved a detailed review of the technical literature, a survey of highway agencies and pavement marking material manufacturers, a laboratory experiment to determine the range of chromaticity coordinates that observers classify as yellow and white under daytime (D_{65}) and incandescent (Illuminant A) illumination. Color classification performance in our 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. We termed the iso-percentage curves as “iso-chromes”, indicating 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 this study. Detailed pavement marking chromaticity measurements were also conducted in four states to determine the color performance of existing materials. The goal of this project is 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 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.

We have focused on the color perception and classification of drivers, while iteratively controlling and measuring stimulus chromaticity and luminance in controlled and calibrated environments, emulating daytime and nighttime pavement marking viewing conditions. Initial efforts were dedicated to compile a comprehensive review of the related technical literature. We conducted a pavement marking manufacturer survey, and a practitioner survey to solicit information about latest practices in pavement marking pigmentation technologies, and pavement marking color assessment methodologies in the field, respectively.

We designed and conducted three experiments to find out 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 so as 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. The data were then transferred onto the CIE 1931 chromaticity diagram in the form of iso-percentage curves inside of which, only a certain percentage of yellow or white responses can be expected.

The second experiment was also 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 6ft (1.83m) were laid out on a straight and level roadway surface, six at a time, in a longitudinal skip-line pattern with a 30ft (9.14m) cycle length and 24ft (7.32m) 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 US. 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.

CHAPTER 2: PAVEMENT MARKING PRACTITIONER AND MANUFACTURER SURVEY

We conducted two surveys to reach out to the practitioner community in state transportation agencies and among pavement marking manufacturers. The agency survey, to which 29 agencies responded, revealed the following:

i. Approximately 7 out of 10 agencies use lead-free markings on their jurisdictions. Of the markings that are lead-free, majority is of type waterborne paint, followed by epoxy, thermoplastic, tape, polyurea, and preformed tape. A few polyester and alkyd type markings are also lead-free. In the states of South Carolina, Illinois, and Oregon, thermoplastic markings still contain lead chromate, albeit the rate of thermoplastics with lead is in decline.

ii. 7 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 pavement markings.

iii. 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 their 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. Indiana uses the FHWA chart.

iv. 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 and in some cases subjective appearance in the field and the laboratory, mostly for daytime. Nighttime measurements are less frequent, and consist mostly of retroreflectivity assessments. Numerous states rely heavily on National Transportation Product Evaluation Program (NTPEP) test decks.

v. Only half of the 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 both chromaticity and luminance factor (Cap Y). 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.

vi. 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 a part of an investigation, and the remaining half is either in response to a complaint, or performed for some other unspecified reason.

vii. 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 markings, and one performs them in high traffic areas.

viii. Most agencies use their resources as well as contractors to apply pavement markings on 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.

ix. Contractors supply warranty for the color of pavement markings only in 3 out of 10 states. Some states consider administering warranty specifications in the future.

x. 3 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.

xi. 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%), 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.

xii. Most states (16 out of 22) do not know how the contractors measure nighttime and daytime chromaticity.

xiii. Approximately 3 out of 10 states conducted research on pavement marking color in the past 5 years.

We did not see an enthusiastic response from the pavement marking manufacturers to our manufacturer survey. Nonetheless, LightGuard systems, Vogel Traffic, Crown Technology, Rohm & Haas, Ennis Paint, 3M, Safety Coatings, Dominion Color Corporation, and Flint Trading responded to our survey. In summary, findings are as follows:

i. Below is an association matrix between manufacturers and their specialties:

	LightGuard Systems, Inc.	**Vogel Traffic Services**	**Crown Technology**	**Rohm and Haas**	**ENNIS PAINT**	**3M**	**Safety Coatings, Inc.**	**Dominion Colour Corporation**	**Flint Trading, Inc.**
Tape:					**X**	**X**			
Paint:		**X**			**X**		**X**		
Thermoplastic:			**X**		**X**				**X**
Two component liquid:		**X**			**X**	**X**			
Other:	Internally Illuminated Raised Pavement Markers			Binders that are used in paint		RPMs		pigments for pavement markings	
Comments:				Rohm and Haas supplies the polymer that is a major portion of the paint formulation and is responsible for much of the paint's performance.				DCC currently manufactures numerous products for the coloration of pavement marking materials including PY34, PY65, PY75, PY83.	PREMARK(R) Preformed Thermoplastic Pavement Markings

ii. 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 and EN). In instrumental measurements, Federal Standard color chips (by subjective comparison), and daytime and nighttime color-capable instrument measurements (Hunter Labscan 6000, Hunter Miniscan, and PR650) on the factory floor are of practice, for both 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 of importance to the manufacturers of pavement marking tapes.

iii. 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, PY 65, PY 75, and PY 83 are being used. As inorganic pigments, it is of 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 are also 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 of common practice. For the white color, subjective comparisons with Munsell chips and with Federal standard color chips are common. In determining service life of paint type pavement markings, daytime color and retroreflectivity are considered across the board, yet only one manufacturer considers nighttime color as a criterion.

iv. Thermoplastic Pavement Markings: Companies offer a variety of thermoplastic pavement markings: hydrocarbon, alkyd, preformed (hot-tape), and some polymeric blends.

Thermoplastic pavement markings are also 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 PY 65, PY 75, and PY 83 are being used. One manufacturer uses lead-chromate for yellow alongside titanium dioxide. For both the colors 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 color, 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.

v. 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 PY 65, PY 75, and PY 83. One manufacturer uses the inorganic pigments zinc chromate and synthetic iron oxides, another manufacturer uses lead chromate, 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 (EN and CEN) are followed. One manufacturer performs subjective comparisons with Federal standard color chips, whereas the 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.

CHAPTER 3: COLOR BOOTH EXPERIMENT

This experiment was conducted in a color-neutral booth with controlled illumination at the Operator Performance Laboratory (OPL) at the University of Iowa.

METHOD

We initially conducted a pilot experiment using 30 subjects (an even mixture of old and young) to aid in the selection of sample color chips for the main color-booth experiment. In this pilot experiment, the subjects classified a total of 180 Munsell color chips that were distributed across a wide range in the CIE 1931 (x,y) color space. The results of the pilot experiment gave us a sense of the region in which people would conceivably call a color either yellow of white.The 180 candidate chips were down-sampled to 90 chips, all of which were called either yellow or white by at least one participant. The final sample of these 90 chips was then used in the main experiment.

A total of 40 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 our 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. The project advisory panel initially recommended the use of such a filter. 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 D-65 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° viewing angle from approximately 24” (60cm), 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 inches away from the center mark, thus, 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 [2]. 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 were reduced by using neutral density filters to about 1.2cd/m^2. This luminance level was chosen as it represents the average yellow pavement marking luminance at 30m (98ft) illuminated with an average passenger vehicle Tungsten-Halogen (TH) headlamp in nighttime.

The end product of this experiment is a set of curves overlaid on the CIE 1931 chromaticity diagram that delineate the fringes of chromaticity boundaries, within which, only a certain percentile of yellow or white responses could be expected. We coined the term "iso-chrome" for these curves, which are of irregular 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.

RESULTS

Figure 2 through Figure 8 show the final form of the iso-chrome curves with the white and yellow color limits given in the FHWA 2002 final rule (matching those of ASTM D6628-01 [3]) are overlaid on the CIE 1931 chromaticity diagram. By comparing the overlap in the iso-percentage response curves for white and yellow classifications, it is evident that with the current color boxes, there will be a certain confusion between yellow and white color.

SUMMARY OF FINDINGS

Under nighttime foveal (straight on) viewing conditions, it is evident that the highest percentage of yellow responses (Figure 1) are centered near the bottom-right corner of the FHWA/ASTM D6628 (night time) yellow color box. We propose a modified nighttime yellow color box that better captures this human performance based response to yellow color stimuli. The coordinates of this recommended nighttime yellow color box are shown in Table 1 and Figure 1. Additional justifications for this recommendation are given in the Discussion and Conclusions section of this report.

Table 1. Recommended 05-18 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 nighttime white responses (Figure 2) are bi-modal. A large number of the color chips were classified as white, when they were located inside the FHWA/ASTM D6628 (night time) white color box. A smaller but still substantial percentage of color chips was classified as white when they contained a hue of green. Thus, we feel justified in our proposal to shift the yellow nighttime color box away from green and more towards red. Also, we recommend changes to the nighttime white color box to better capture the human performance based responses found in this study. The coordinates of our recommended nighttime white color box are shown in Table 3 and Figure 2 and additional justifications for this recommendation are given in the Discussion and Conclusions section of this report.

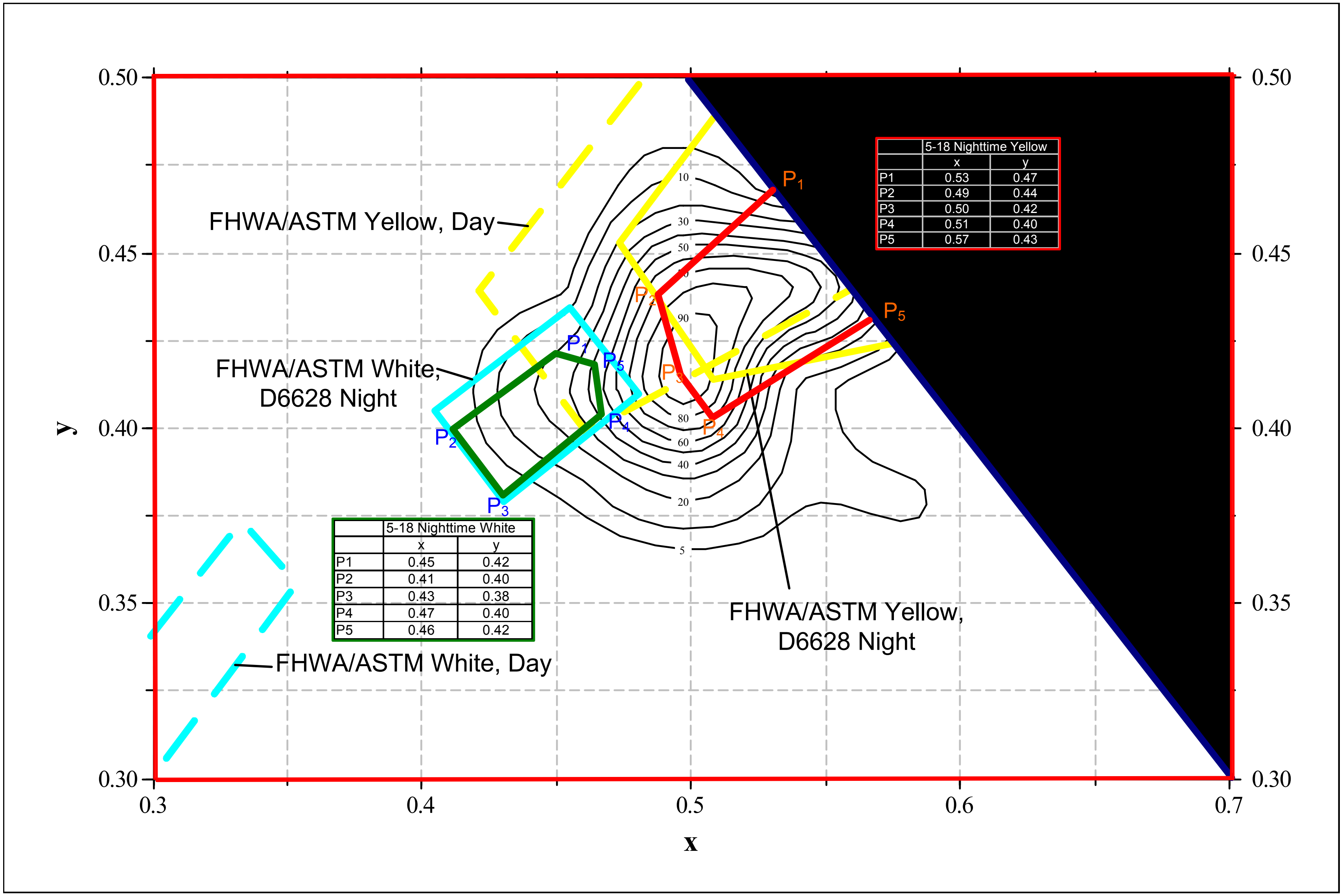
Table 2. Recommended 05-18 Nighttime White Color Boundary

x	*y*
0.45	0.42
0.41	0.40
0.43	0.38
0.47	0.40
0.46	0.42

Under daytime foveal viewing conditions we found the majority of the yellow classifications (Figure 3) to be centered outside and near the upper left corner of the FHWA yellow daytime color box. The daytime foveal white (Figure 4) classifications were relatively nicely centered on the daytime white color box. We do not recommend any changes to the daytime color boxes for reasons given in the Discussion and Conclusions section of this report.

Peripheral viewing conditions were tested in this experiment because drivers see pavement markings peripherally as well as foveally. Figure 5 and Figure 6 show the results for peripheral nighttime viewing conditions for yellow and white, respectively. The classification percentages are similar to the foveal viewing condition. Our proposed new color boxes for nighttime yellow and white result in improved classification under peripheral viewing conditions. Figure 7 and Figure 8 shows the results for the daytime peripheral viewing conditions. These results are close to the results that were obtained under the daytime foveal viewing conditions.

These findings corroborate some of the state specifications received in our agency survey, as mentioned in point iii on page 3. For instance, Iowa indicated that they shifted the FHWA color box towards red and eliminated some of the green region. Illinois indicated that their color box extends into a chroma containing more red, and Wisconsin indicated that they use red inorganic pigment in their yellow markings, which essentially produces yellow-orange hues. Such state initiatives seem to confirm our nighttime findings in the color booth experiment.

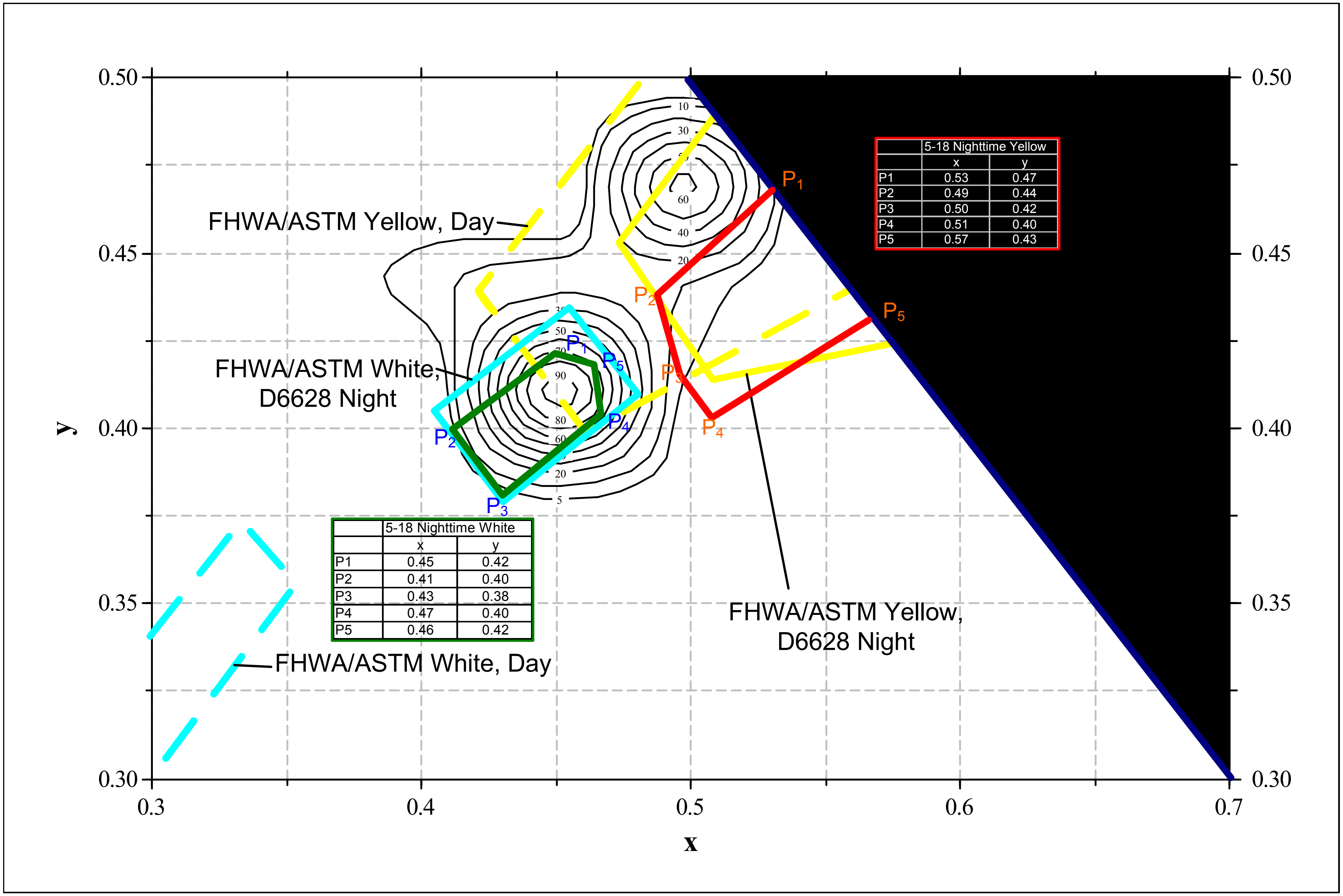


5-18 Nighttime Yellow	x	y
P1	0.53	0.47
P2	0.49	0.44
P3	0.50	0.42
P4	0.51	0.40
P5	0.57	0.43

5-18 Nighttime White	x	y
P1	0.45	0.42
P2	0.41	0.40
P3	0.43	0.38
P4	0.47	0.40
P5	0.46	0.42

Note: Recommended NCHRP 5-18 yellow and white color boxes are shown in above figure. Iso contour lines indicate the percentage of responses that classified a given color coordinate into the corresponding categorical color name. Data is shown in CIE 1931 Color Space

Figure 1. Percentage of Yellow Classification under Nighttime *Foveal* Viewing Conditions adjusted for Illuminant A

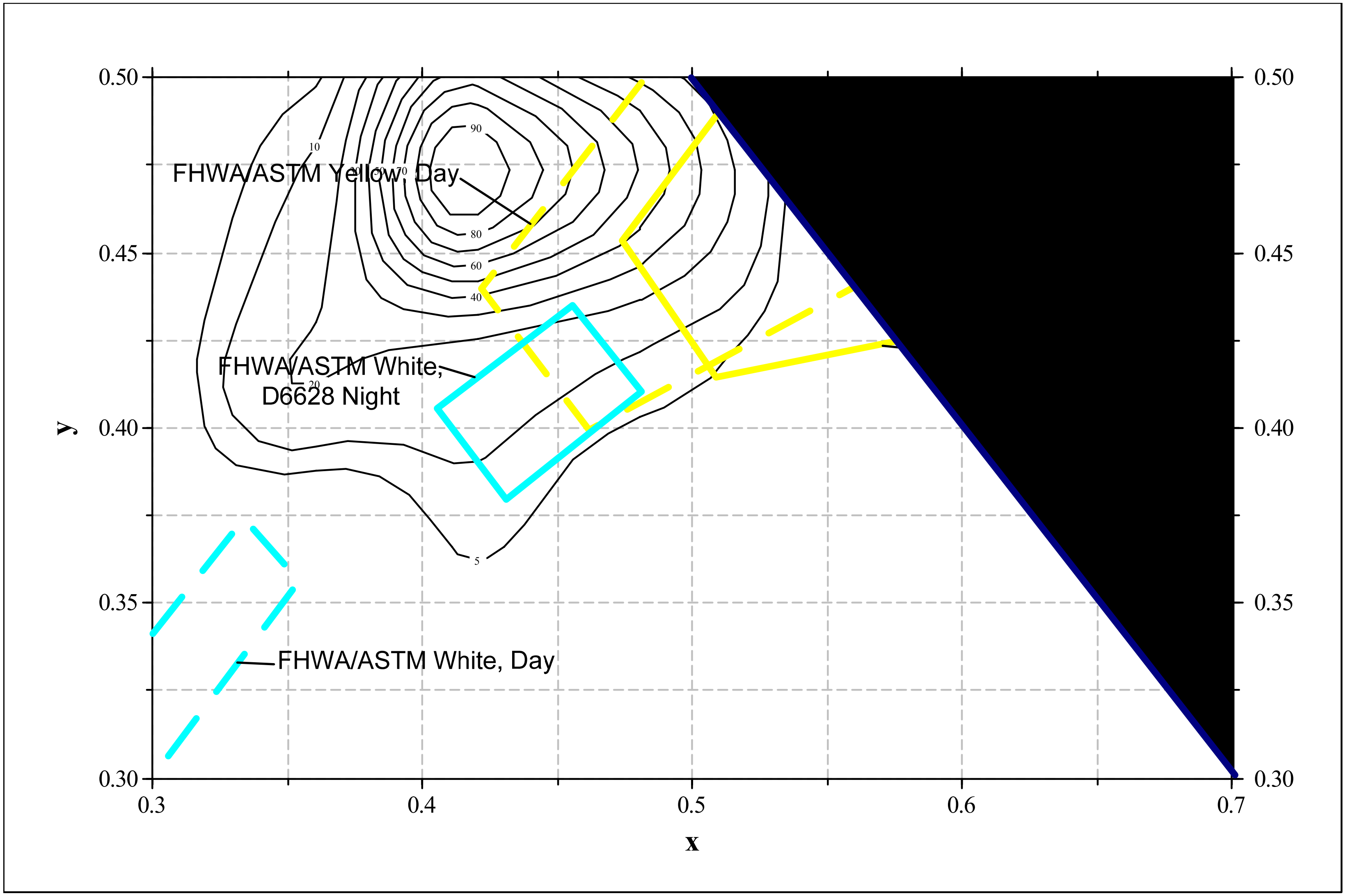


5-18 Nighttime Yellow		
	x	y
P1	0.53	0.47
P2	0.49	0.44
P3	0.50	0.42
P4	0.51	0.40
P5	0.57	0.43

5-18 Nighttime White		
	x	y
P1	0.45	0.42
P2	0.41	0.40
P3	0.43	0.38
P4	0.47	0.40
P5	0.46	0.42

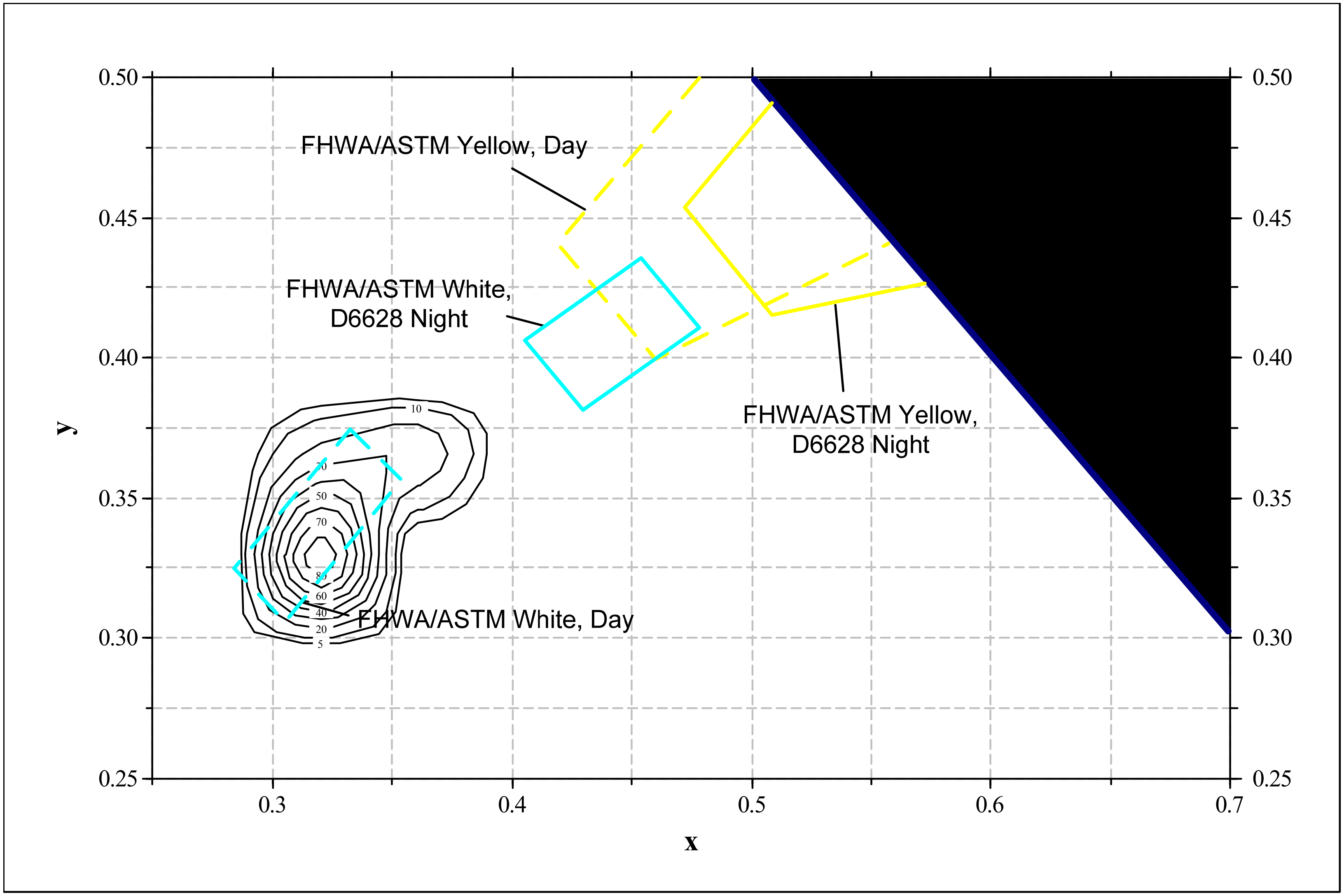
Note: Recommended NCHRP 5-18 yellow and white color boxes are shown in above figure. Iso contour lines indicate the percentage of responses that classified a given color coordinate into the corresponding categorical color name. Data is shown in CIE 1931 Color Space

Figure 2. Percentage of White Classification under Nighttime *Foveal* Viewing Conditions adjusted for Illuminant A



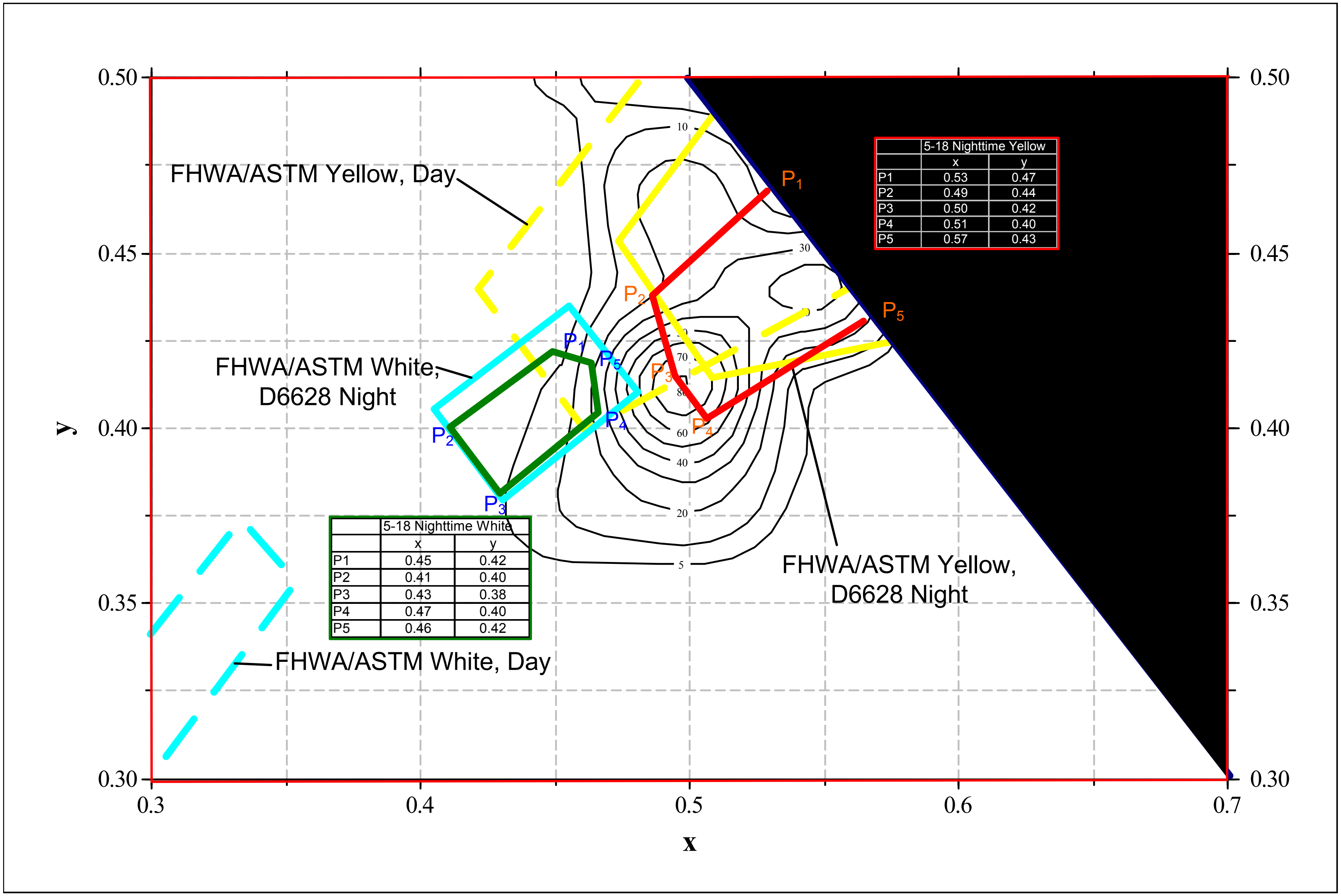
Note: Iso contour lines indicate the percentage of responses that classified a given color coordinate into the corresponding categorical color name. Data is shown in CIE 1931 Color Space.

Figure 3. Percentage Yellow Classification under Daytime *Foveal* Viewing Conditions adjusted for Illuminant D-65



Note: Iso contour lines indicate the percentage of responses that classified a given color coordinate into the corresponding categorical color name. Data is shown in CIE 1931 Color Space.

Figure 4. Percentage White Classification under Daytime *Foveal* Viewing Conditions adjusted for Illuminant D-65

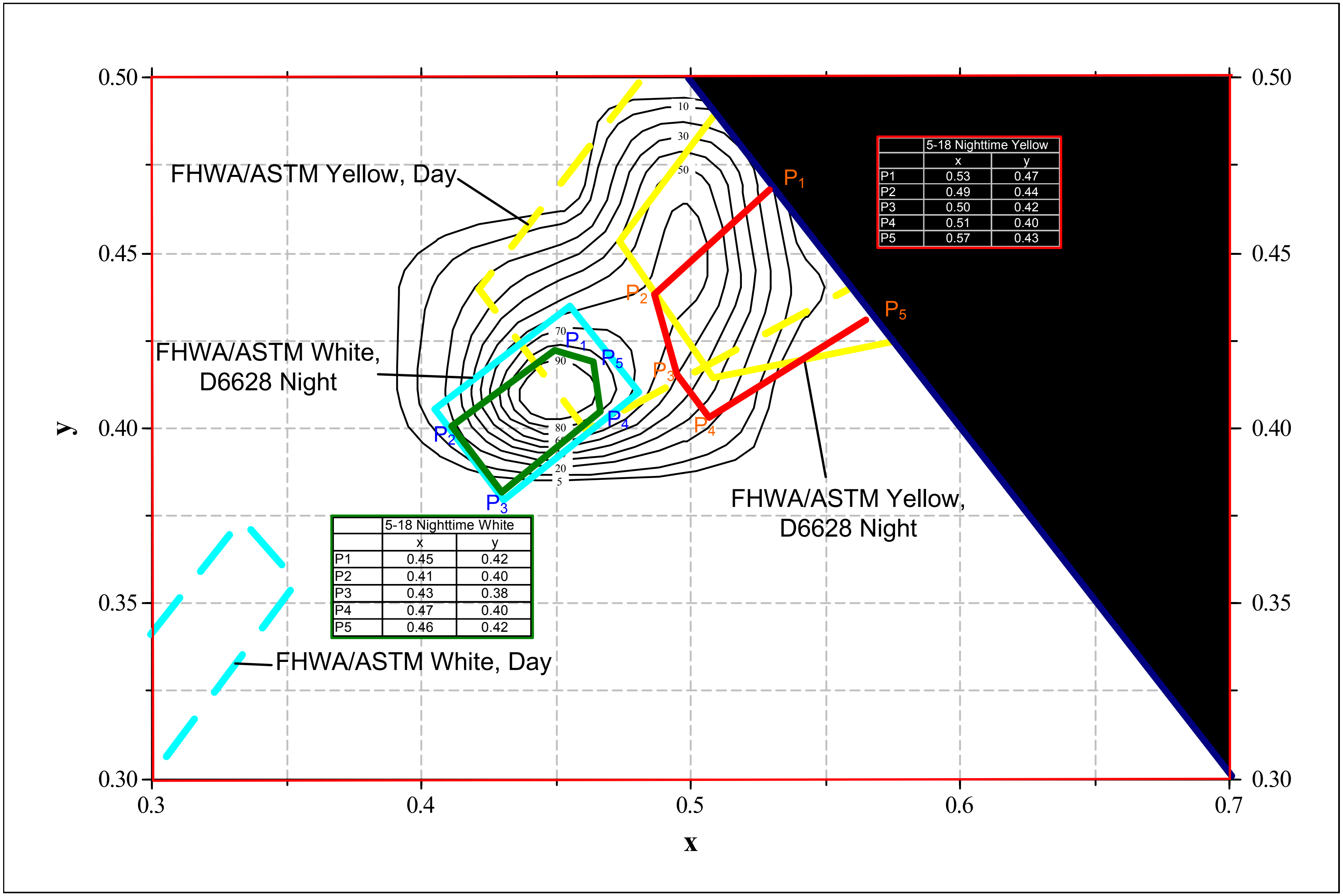


	5-18 Nighttime Yellow	
	x	y
P1	0.53	0.47
P2	0.49	0.44
P3	0.50	0.42
P4	0.51	0.40
P5	0.57	0.43

	5-18 Nighttime White	
	x	y
P1	0.45	0.42
P2	0.41	0.40
P3	0.43	0.38
P4	0.47	0.40
P5	0.46	0.42

Note: Iso contour lines indicate the percentage of responses that classified a given color coordinate into the corresponding categorical color name. Data is shown in CIE 1931 Color Space.

Figure 5. Percentage of Yellow Classification under Nighttime *Peripheral* Viewing Conditions adjusted for Illuminant A



5-18 Nighttime Yellow		
	x	y
P1	0.53	0.47
P2	0.49	0.44
P3	0.50	0.42
P4	0.51	0.40
P5	0.57	0.43

5-18 Nighttime White		
	x	y
P1	0.45	0.42
P2	0.41	0.40
P3	0.43	0.38
P4	0.47	0.40
P5	0.46	0.42

Note: Iso contour lines indicate the percentage of responses that classified a given color coordinate into the corresponding categorical color name. Data is shown in CIE 1931 Color Space.

Figure 6. Percentage of White Classification under Nighttime *Peripheral* Viewing Conditions adjusted for Illuminant A

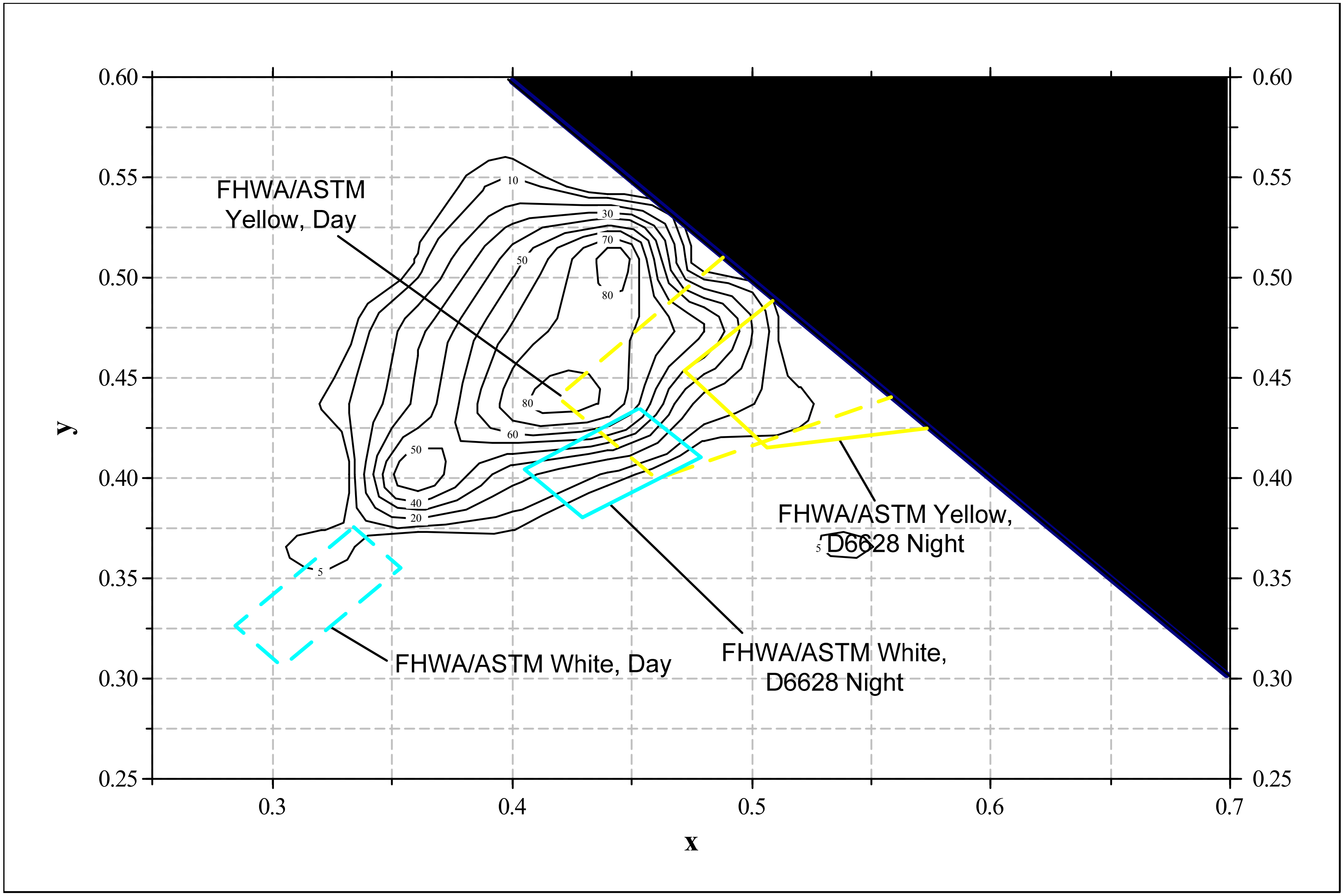
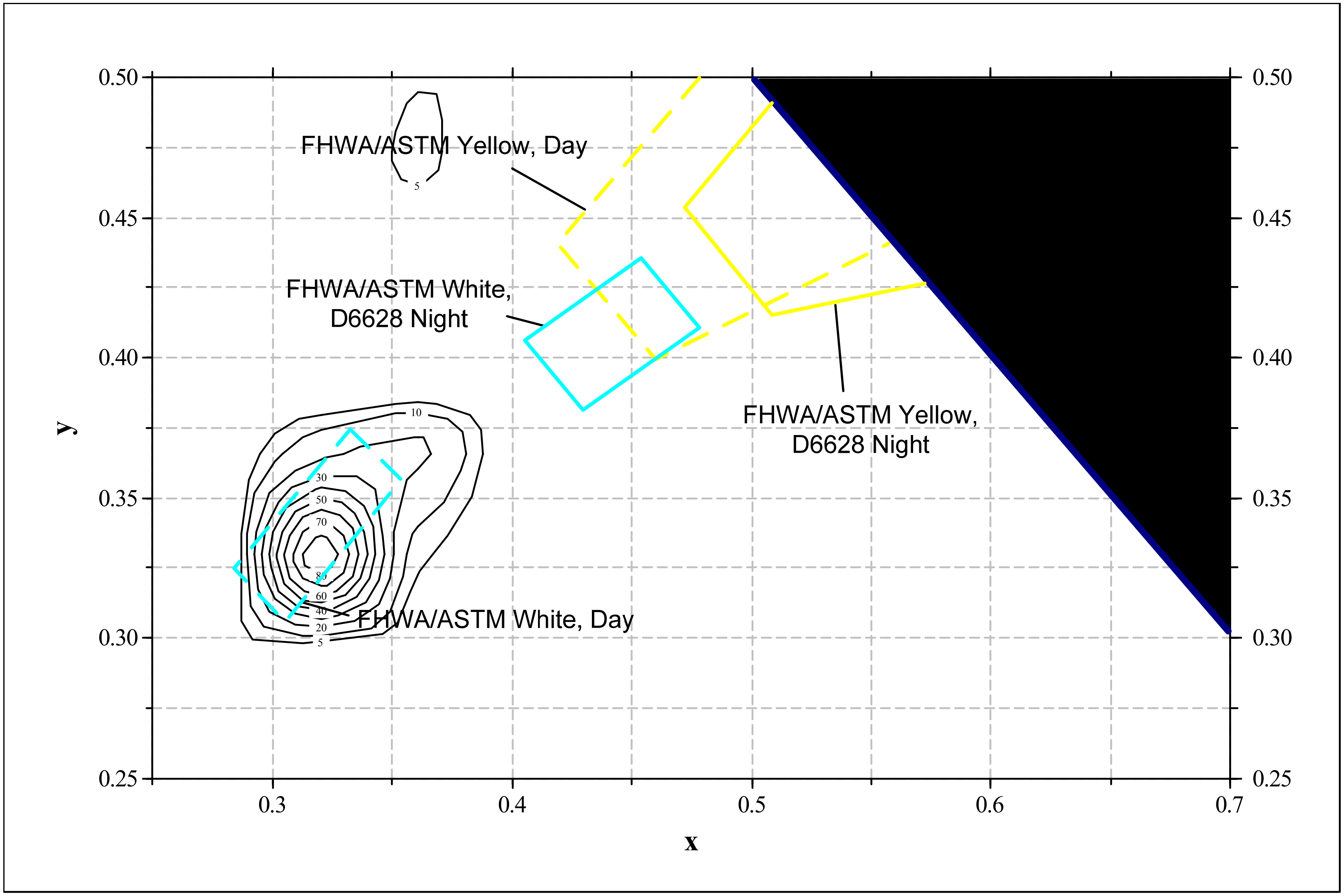


Figure 7. Color Classification under Daytime *Peripheral* Viewing Conditions adjusted for Illuminant D-65.



Note: Iso contour lines indicate the percentage of responses that classified a given color coordinate into the corresponding categorical color name. Data is shown in CIE 1931 Color Space.

Figure 8. Percentage of White Classification under Daytime *Peripheral* Viewing Conditions adjusted for Illuminant D-65.

CHAPTER 4: DARK-ROOM REAR-PROJECTION SCREEN EXPERIMENT

This experiment was conducted in a dark hallway with a 4ft by 7ft 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” wide (10cm) continuous yellow pavement marking centerline stripes laid out on a straight and level roadway with 12ft (3.65m) 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 was also recorded. The results are summarized in the Results section starting on page 22.

METHOD

Yellow pavement markings were presented on a back-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: 0.5 cd/m^2, 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: 0^0, 10^0, 20^0).

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 illuminance as well as 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.

A total of 42 subjects participated in the experiment. All were above the age of 55. All variables except "eccentricity" were within-subject. Eccentricity was manipulated by shifting the gaze direction (by means of a fixation point on the screen). For the between-subjects variable eccentricity, subjects were divided into three groups, each with 14 subjects (7 males, 7 females). The presentation order of the stimuli was completely randomized and each stimulus condition was repeated for each subject in two replications.

Chromaticity in the context of this experiment refers the chromaticity of the closest visible point of the pavement marking at the bottom edge of the viewing screen (see Figure 9). All of the eight initial chromaticity configurations of the presented continuous pavement markings gradually and linearly converged towards the same chromaticity (x, y) = (0.305, 0.321) at the point on the screen that corresponds to 90ft ahead of the vehicle in the real world. Beyond that location, the pavement markings were achromatic. Thus, starting from the closest point (30ft, or 9.14m) up to 90ft (27.4m), the chromaticity of the pavement markings changed at every linear foot, and after 60 iterations at 90ft, the pavement marking was achromatic.

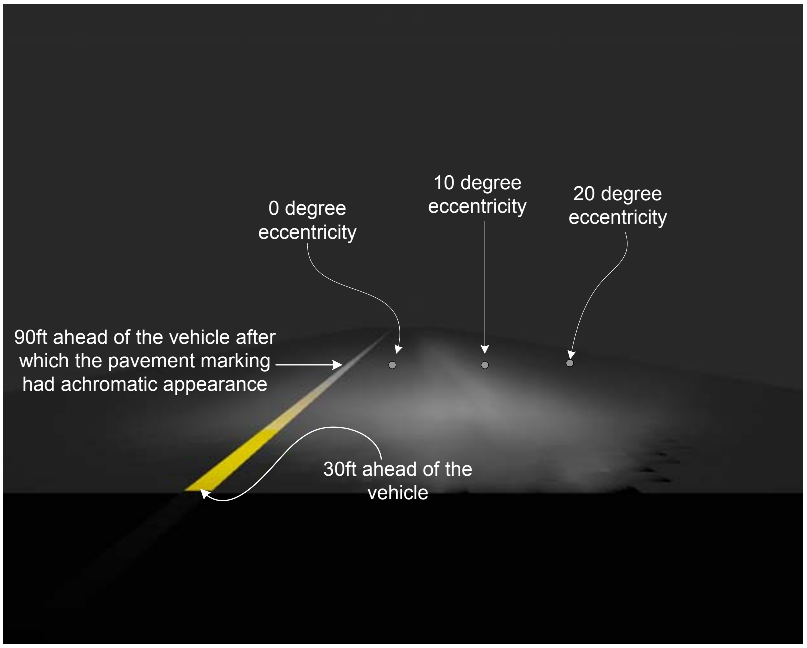


Figure 9. A sample output of POV-Ray with high roadway luminance and high pavement marking luminance at ambient 0.5 cd/m2.

The luminance of the pavement markings and the road surface were obtained using the Tarvip model. Thus, depending on the type of pavement marking material, the luminance at a particular point was determined by the retroreflectivity of a previously characterized and modeled yellow material. The selected three materials were yellow patterned tape, yellow flat tape, and yellow alkyd paint. The headlamps were 2000 year model Ford Taurus VOA headlamps in all cases.

The selected road surfaces were new concrete, old concrete, and new asphalt. The ambient illuminance (and the luminance of the horizon sky) also had two levels: 0.5 cd/m^2 and 4 cd/m^2. The luminance of the horizon sky also assumed to affect the luminance of both the road surface and the pavement markings equally, assuming both were of lambertian surface type for the purposes of ambient lighting.

The stimuli were generated using POV-ray ray tracer software. A sample stimuli generated with POV-ray is illustrated in Figure 9. Three eccentricity points illustrate the points that subjects were fixated at during the color assessment of the pavement markings. The markings were 4” wide, continuous centerlines 6ft left off the vehicle centerline. The idea was to have different saturations to start with and different gradient cut-offs at the transition point where the color changes from yellow to white along the stripe. With this two-dimensional search space for saturation and distance, we were able to determine the effect of saturation and blending distance on percentage of correct color judgments.

The transition of chromaticity from the given eight initial points into the same white point is illustrated in Figure 10. Figure 11 shows a magnified view of the same eight initial chromaticities and their transition path towards white.

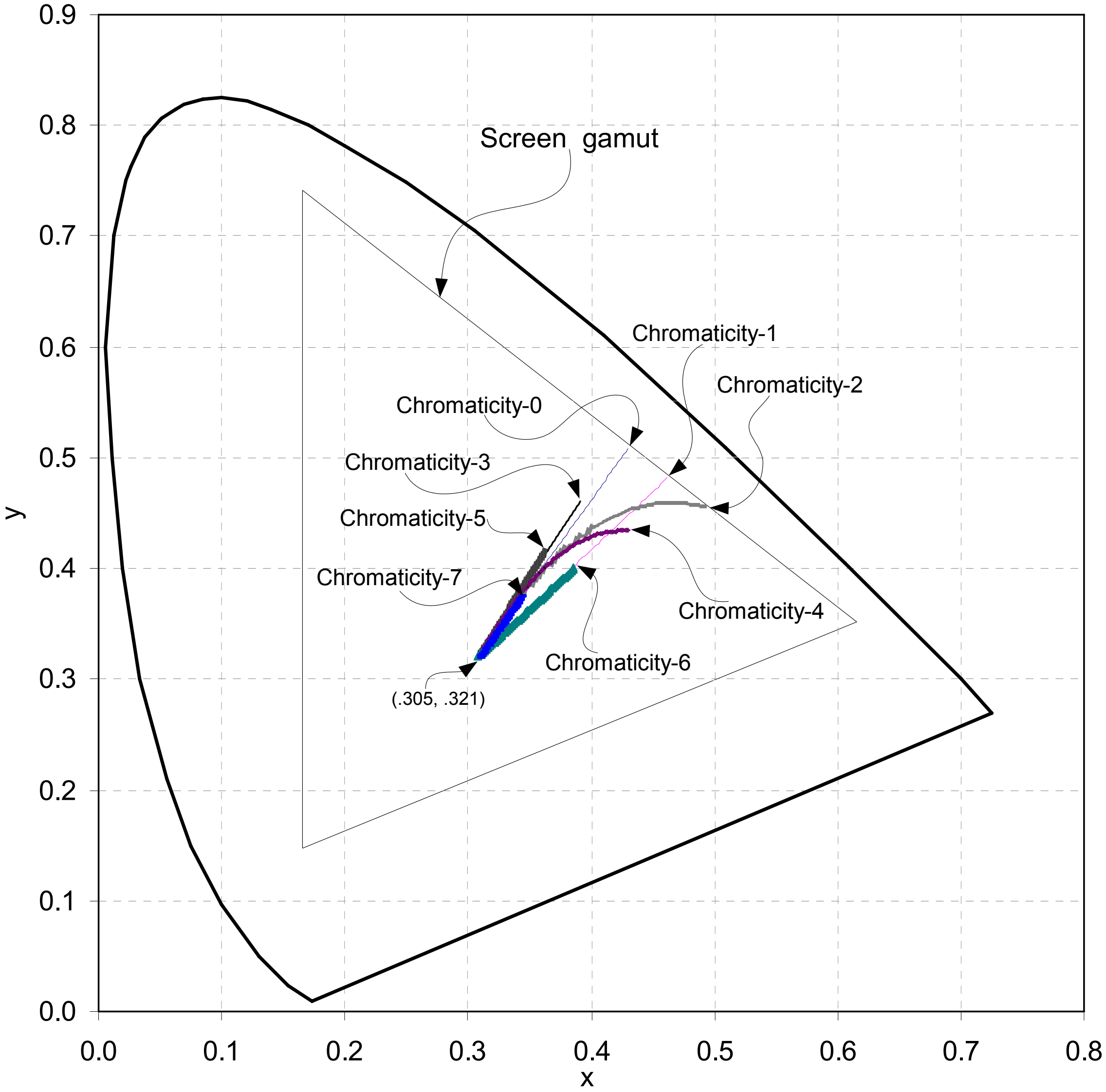


Figure 10. Selected Pavement Marking Color Configurations on CIE 1931 Standard 2^0 Observer Chromaticity Diagram.

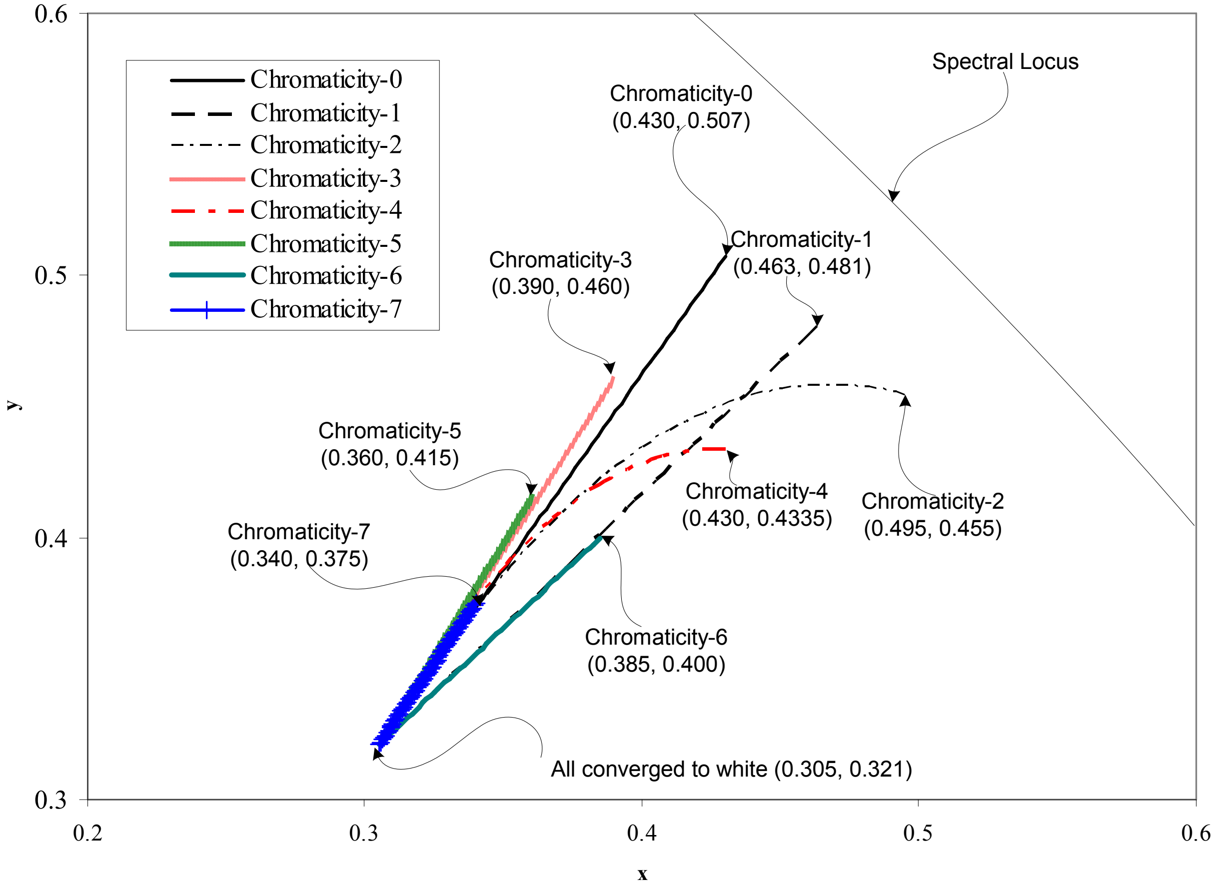


Figure 11. Magnified Illustration of Initial and Final Chromaticities

Notice that the transition from yellow to white was linear on the CIE diagram for all chromaticities but two, and on the screen 90ft ahead of the observer, all pavement marking chromaticities converged to the point (x, y) = (0.305, 0.321) regardless of the initial chromaticity of the pavement markings. Chromaticity-2 and Chromaticity-4 color configurations did not follow a linear transition because the linear path slightly infringed into the magenta area.

RESULTS

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 number and percentage of yellow and white responses are summarized in Table 12 through Table 19 for chromaticity 0 through chromaticity 7 (Located in APPENDIX C). 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 ($p\cong0.0015$), and pavement marking type and chromaticity ($p=0.03$) were also statistically significant in affecting subjects' assessment of pavement marking color. Figure 12 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 of 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. Details of the data are given in APPENDIX C.

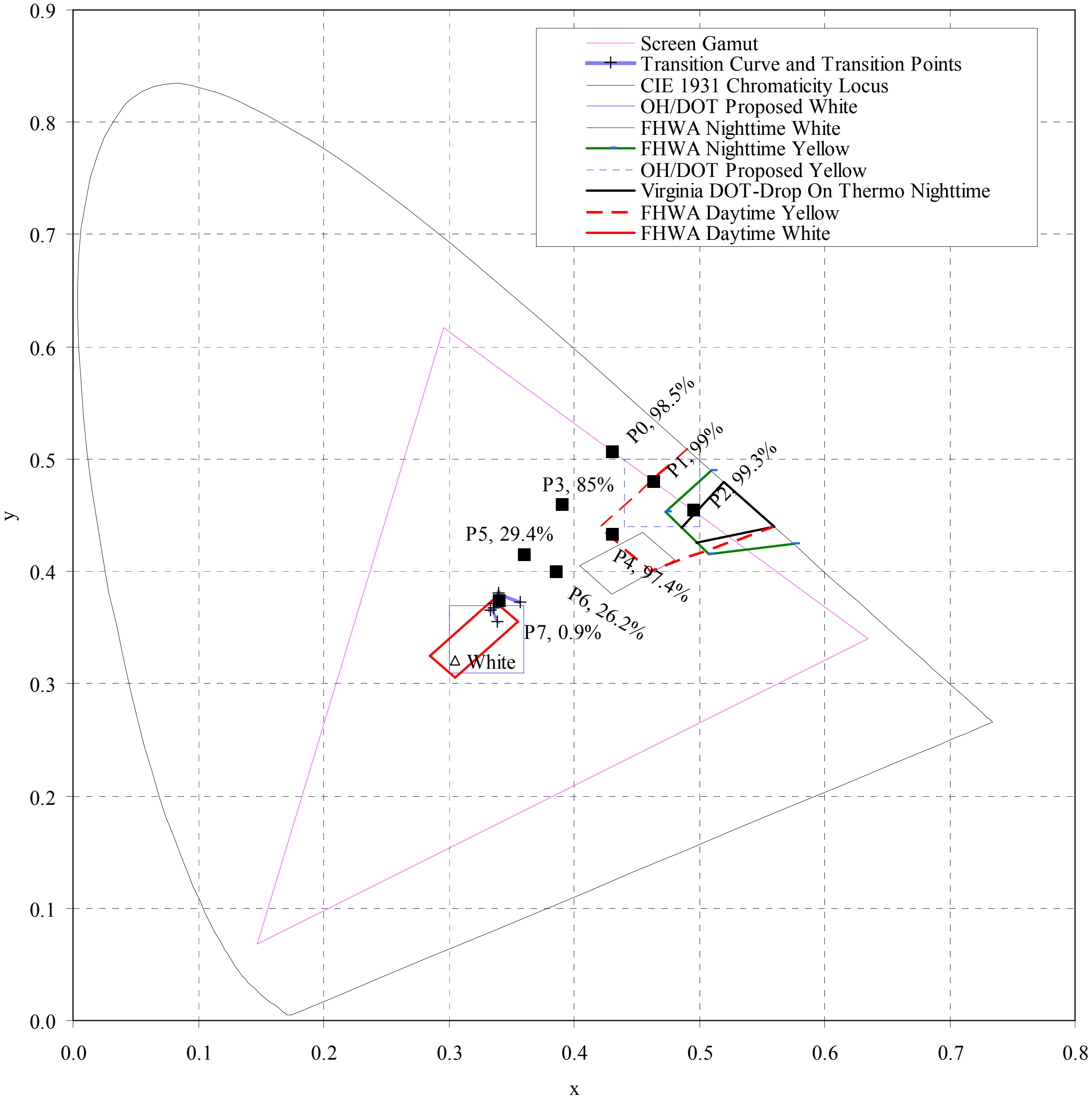


Figure 12. Yellow Response Percentages Overlaid on The CIE 1931 Chromaticity Diagram.

The other statistically significant main factor was the horizon sky luminance. Note that horizon sky luminance was directly passed on to the pavement marking and road surface luminance. Increasing horizon sky luminance, and corresponding increase in both pavement marking and pavement luminance, from 0.5cd/m^2 to 4cd/m^2 increased the overall yellow responses from 64% (3899/6048) to 67% (4064/6048).

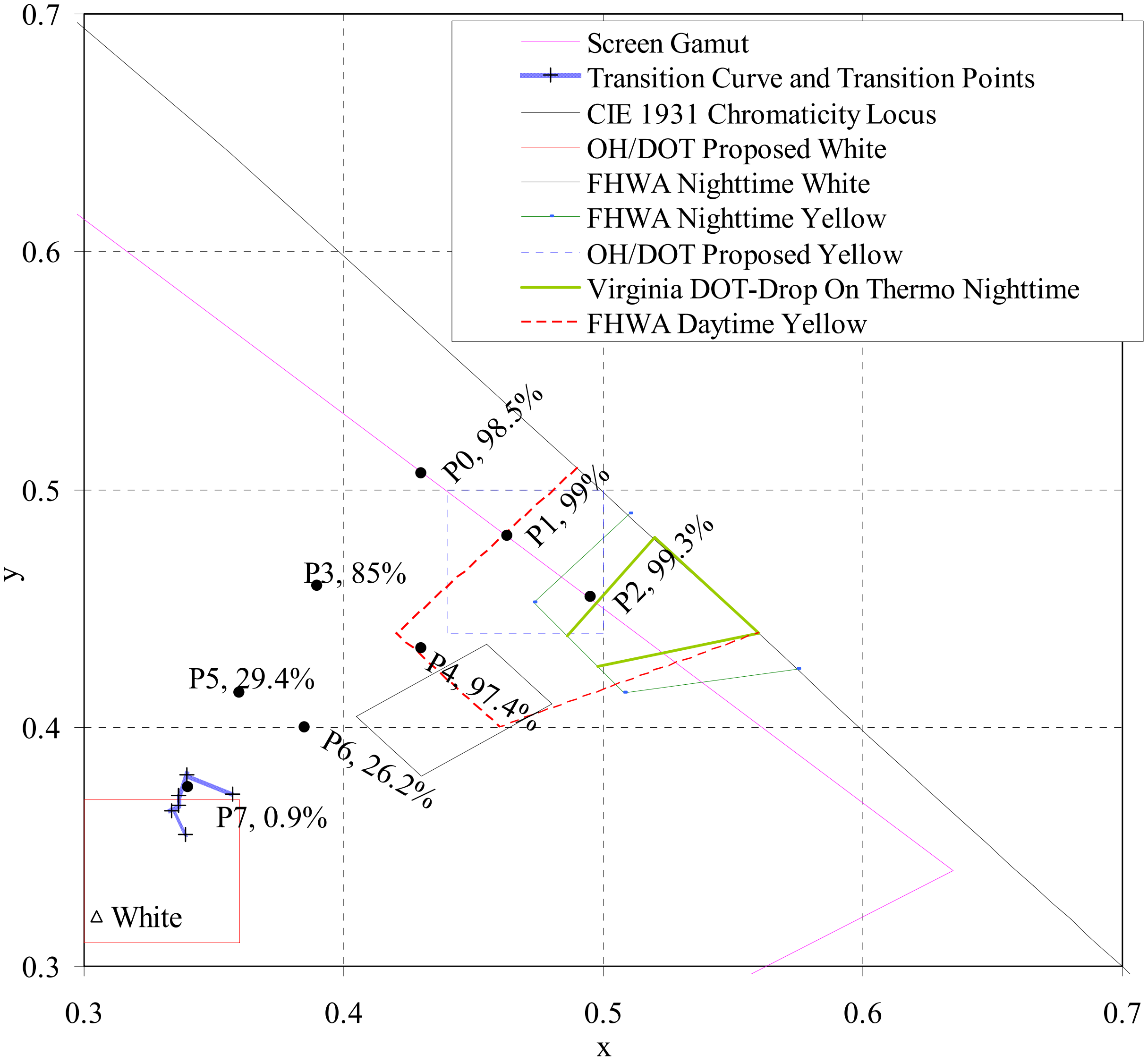


Figure 13. A Magnified View of the Yellow Response Percentages Overlaid on the CIE 1931 Chromaticity Diagram

The between-subject variable "eccentricity" did not seem to generate a strong enough difference between yellow and white responses, and therefore is not a statistically significant factor. Hence, between near-foveal, 10° parafoveal, and 20° parafoveal views, the perception of yellow in our case changed only little. Thus, with 95% confidence, we can say that the probability of a subject assessing the same stimulus as yellow for 0°, 10°, and 20° eccentricity levels is essentially the same. The overall number of responses grouped by the "eccentricity" variable is given in Table 3.

Table 3. Number of “yellow” and “white” responses for the variable “eccentricity”.

		Eccentricity [deg]		
		0	**10**	**20**
Number of responses	Yellow	2706	2628	2629
	White	1326	1404	1403
	Total	**4032**	**4032**	**4032**

The road surface type did not affect subjects’ response for pavement marking color strongly enough to generate a statistical significance at $\alpha=0.05$ significance level. There was a slight increase in overall yellow responses as the roadway surface reflectivity increased (i.e. New concrete), yet again, the difference was not adequately large and consistent to prove statistical significance. Table 4 shows distribution of yellow and white responses grouped by the three road surface types.

Table 4. Number of “yellow” and “white” responses for the variable “Road Surface Type”.

		Road Surface Type		
		New Concrete	**Old Concrete**	**New Asphalt**
Number of responses	Yellow	2751	2628	2584
	White	1281	1404	1448
	Total	**4032**	**4032**	**4032**

Pavement marking type was just shy of proving to be a statistically significant factor (p=0.077). Changing pavement marking type affected only the luminance but not the chromaticity. Therefore, pavement marking type refers only to retroreflectivity in the context of this experiment. The general tendency was that the brighter the pavement marking material, the higher the number of white responses, yet this tendency failed to be statistically significant. Table 5 gives the number of responses for each pavement marking category.

Table 5. Number of “yellow” and “white” responses for the variable “Pavement Marking”.

		Pavement Marking Type		
		Patterned Tape	**Flat Tape**	**Alkyd Paint**
Number of responses	Yellow	2557	2636	2770
	White	1475	1396	1262
	Total	**4032**	**4032**	**4032**

Pairwise comparisons between initial chromaticities showed that the only non-statistically significant differences were found between chromaticity 0, chromaticity 1, and chromaticity 2. All other pairwise combinations of initial chromaticities proved statistically significantly different in affecting the response.

The statistically significant first order interactions are detailed in tables in APPENDIX C.

Response Time Analysis

The response times for all subject responses were measured from the onset of the stimuli to the time that the subjects pressed a mouse button as they made an assessment for the color of the pavement marking stimuli. This was taken as a proxy-measure for the amount of indecision in the subject to choose between yellow or white. Note that the response times were measured regardless of the subject's color classification. The analysis were again conducted using GEE models, but this time the response variable was on a continuous scale (time in seconds), thus the model family was not binomial but rather Gaussian.

The response times were different for different pavement marking initial chromaticities. Road surface type, eccentricity, and horizon sky luminance did not change subjects' response times enough to prove statistical significance at $\alpha=0.05$ significance level. Pavement marking type was just short of having a statistical significance ($p=0.051$) at $\alpha=0.05$ significance level.

Pavement marking chromaticity affected the response time of the subjects. In general, it took longer for the subjects to respond to chromaticities between saturated yellow and white (Chromaticities 3, 4, 5, and 6). For whiter markings (Chromaticity-7), the response time was not as long as those in the confusion area.

SUMMARY OF FINDINGS

Similar to the results in the color-booth experiment, there was an increase in the "yellow" responses for saturated yellow chromaticities closer to yellow-orange spectra. Overall, however, subjects were more likely to classify a color as yellow when compared to the color-booth experiment. The use of a gradual pavement marking color transition from the starting chromaticity to white may have motivated some of the participants to make comparative color assessments. The use of a white reference color at long distances may have allowed the subjects to compare the two ends of the continuous pavement marking stripe, and respond as "yellow" when they perceived even a slight shade of yellow close in. In contrast, this strategy was not available in the chip-by-chip presentation used in the color booth experiment.

As a consequence of this possible relative color judgment strategy, we saw yellow responses for pavement markings with starting chromaticities well into the yellow-green ranges that would have resulted in very low yellow response percentages in the color booth experiment. The reader should also note that in the color booth experiment, "yellow", "white", and "neither" were the acceptable responses, but in this experiment "neither" was not an acceptable response.

CHAPTER 5: FIELD EXPERIMENT

A field experiment was conducted to determine the perceptual color correlates of yellow pavement markings at night under tungsten-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 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 in order to prevent relative color assessment. Spectral reflectivities and chromaticities of each pavement marking sample at each distance were measured at the National Institute for Standards and Technology. These measurements were then represented on the CIE 1931 chromaticity diagram to correlate chromaticities and perceptual color assessment for different headlamp spectra. Pavement marking type and viewing distance affected participants' responses. Headlamp type did not have a statistically significant effect. A first order interaction between pavement marking type and viewing distance was also significant, suggesting that some pavement markings preserved their yellow appearance better at far distances. A second order interaction between pavement marking type, viewing distance, and headlamp type was also statistically significant. This interaction indicates that some materials preserved their yellowness at far distances only under a specific headlamp type. Materials with less retroreflectivity appear to be less capable of rendering saturated yellow colors at long distances. The reason for this 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 referred to as the photopic range. When pavement marking luminances drop into the lower mesopic and even scotopic ranges, the markings will be perceived achromatically.

METHOD

The field experiment was conducted on two consecutive nights at the Coralville Reservoir Beach parking lot on 29th and 30th of November, 2004. One contractor supplied regular thermoplastic pavement markings. Another contractor supplied three types of thermoplastic pavement marking materials identical in all but titanium dioxide (which is white) content by volume. Yet another contractor provided latex paint type pavement markings. The markings were applied on ¼ inch thick concrete fiber board siding panels that were pre-treated with bitumous asphalt. This type of substrate is inexpensive, available at local lumberyards, and has a heat transfer rate similar to that of a normal roadway surface.

A straight section of the parking lot with no existing pavement markings was selected to simulate a 24ft wide two-lane roadway with yellow skip lines. Each pavement marking stripe was aligned with a laser line at pre-marked locations on a 180ft straight section. Each pavement marking sample was 6ft in length (on the concrete fiber board) separated by a 24ft gap from the adjacent pavement marking samples on either end. The first pavement marking sample was 24ft longitudinally in front of the subjects, and with its 6ft length, ended at the 30ft mark. The second marking was at 54ft, ending at 60ft, and so on. A total of 6 pavement marking samples were viewed by the subjects at a time. The farthest one was positioned at 174ft extending to 180ft. No white markings were used, as we only wanted the participants to reference the materials against what they think is yellow or white, not to a nearby reference white pavement marking stripe. The test site and pavement marking configuration are shown in Figure 14.

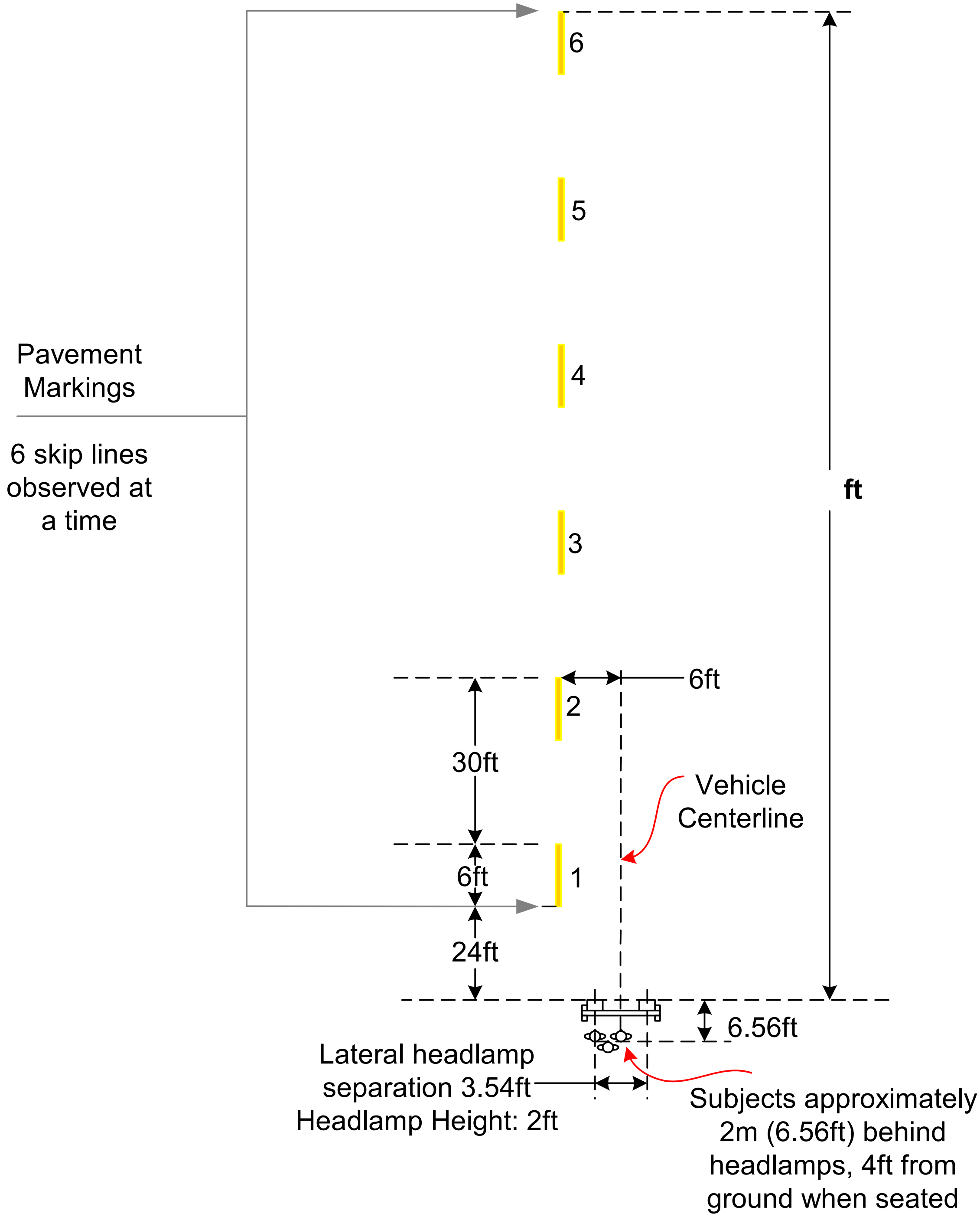


Figure 14 Experimental layout administered in the field experiment.

PAVEMENT MARKING MATERIALS

Five different material types were used: A yellow thermoplastic material with three custom levels of white titanium dioxide concentration, a second (unmodified) thermoplastic material, and latex paint. All three custom thermoplastic materials had 1% organic yellow pigment by volume. The most saturated yellow material included 1.4% titanium dioxide, the intermediate yellow material included 2.3% titanium dioxide, and the pale yellow material included 2.9% titanium dioxide by volume. These materials are denoted as Thermo Y++, Thermo Y+, and Thermo Y, respectively in decreasing order of yellow saturation. The regular thermoplastic material is denoted as Regular Thermo.

There were six samples of each material type, all 6ft in length. Thus, we had a total of 5 materials × 6 samples = 30 individual stripe samples. Each of the 6 identical samples of a material type was shown in one of the six pavement marking locations (distances), as shown in Figure 14 at random. This eliminated the need to carry materials from one location to another. Instead, stacks of 5 samples were presented sequentially at each of the six pavement marking locations. Thermoplastic materials were hot applied by the research team on the 6ft long by 7 ¼ in concrete fiber boards (siding material) that were pre-coated with a bituminous mixture. The latex paint type material was applied on the same type of substrate plates by the contractor.

SUBJECTS

There were 26 subjects, all above the age of 55 years, with the majority over 61 years of age. All subjects had participated in at least one of the earlier laboratory experiments conducted for this project. All subjects had valid Iowa driver license, good vision with at least 20/30 visual acuity (using corrective lenses), and no color deficiencies.

APPARATUS

Two set of headlamps were used: TH headlamps from a 1996 Ford Taurus, and HID headlamps from a 2001 Audi A6. Each pair of headlamps was mounted on a rig designed to replicate the placement and aiming of the headlamps on a vehicle. The headlamps were mounted 0.64m (2.1ft) above the ground and with a lateral spacing of 1.08m (3.54ft). These dimensions represent those of an average passenger vehicle (*4*). After installation in the rig, the headlamps were aimed according to the corresponding shop manual for each vehicle type, using a commercial grade headlamp aiming device. The subjects sat approximately 2m (6.56ft) behind the headlamps while evaluating the colors of the pavement markings. A windshield was not present.

EXPERIMENTAL DESIGN

The experiment used a repeated-measures design, with all of the subjects viewing all markings at all locations under both headlamps. In this manner, each subject constituted his/her own control condition. This design allows correlated statistical data analysis of binary dependent data through Generalized Estimated Equations model (GEE).

The independent variables were subject, headlamp type, pavement marking type, and pavement marking location (or distance). The dependent variable was the perceived color of each marking, white or yellow, a forced choice binary variable. Although the seating positions of the three subjects were slightly different, the effect of position on color perception was not analyzed. We assume that effect to be practically negligible.

EXPERIMENTAL PROCEDURE

In accordance with the within-subjects repeated-measures experimental design, each subject evaluated each material type at each of the six distances (locations). The experiment was conducted on two consecutive nights. Groups were formed such, that any given subject could finish the experiment in one night

Six samples were prepared from each of the five material types. The materials were grouped into six identical batches, each containing one sample from each material type. The order of the materials in each batch was randomized. The six batches were distributed among the six pavement marking locations. The topmost material in each batch was placed on the roadway, so that the materials provided six marking skips. Three subjects at a time viewed the first set of markings. After all of the subjects viewed the first set of markings, the next marking in each batch was placed in the assigned location on the roadway. This process was continued until all five markings in each batch were evaluated by all of the subjects. In this manner, a particular type of pavement marking material was presented once at each of the six locations, while in a single observation the sequence of materials (from the closest to the farthest) was completely randomized

After all subjects evaluated all five materials at each of the six locations, the headlamps were switched. After verifying the headlamp alignment, the materials were presented in the same way, but this time in reverse order. This process was repeated until all materials were presented to all subjects under both types of headlamp illumination. We started with the TH headlamps the first night, and started with HID headlamps the second night for the second group, in an aim to counterbalance any presentation order effect.

Each subject had a datasheet to record his/her answers. Once seated, they evaluated the six 6ft pavement markings laid in front of them starting at 24ft (extending to 30ft), with 30ft gaps up to 174ft, as shown in Figure 14. The data sheet consisted of a set of five visually separated columns in rows, each corresponding to a single set of observation. A set of six evaluations were made by each subject once they were seated, each for one of the markings in front of them starting from the closest to the farthest. They were asked to make their best and honest judgment on whether they would call a particular marking yellow or white. Once they evaluated all six markings, three other participants took their seats. While not on task, participants were allowed to move freely and enjoy the nearby BBQ and warm up next to the heater. Each subject completed the experiment in ten trials. In each trial, they evaluated six materials. Thus, each subject made a total of sixty evaluations: all thirty samples for the two headlamps.

RESULTS

The data was analyzed using Generalized Estimating Equations (GEE), which is the general form of statistical modeling for correlated data, allowing factor variables be the dependent variable. Among the independent variables, material type ($p=0.003$) and pavement marking distance ($p<0.001$) were statistically significant factors in affecting subjects' responses at $\alpha=0.05$ significance level. The summary table for the GEE analysis is given in Table 24.

The interaction between pavement marking distance and pavement marking material type was the only statistically significant second first interaction. The data suggests that different material types seemed to have color appearances that vary between materials as a function of viewing distance. The factor of headlamps proved no main effect, nor a first order interactive effect. Although there was a slight increase in the yellow responses for longer distances with HID headlamps, statistically speaking, TH and HID headlamps were essentially no different when it came to color assessment of the selected pavement markings within the selected distance range. There was, however, a second order statistically significant interaction between headlamp type, material type and distance ($p=0.003$). This suggests that HID headlamps provide a better illumination for recognition of yellow pavement markings at long distances, but only for some of the pavement marking materials (specifically the ones with higher retroreflectivity).

As the distance increased, fewer yellow responses were recorded. This pattern is shown in Figure 15. At 30ft (9.14m), all materials except latex paint were rated as yellow more than 75% of the time. Overall, the yellow ratings decreased with increasing distance. Figure 16 shows the percentage of yellow responses grouped by material type to illustrate the effect of distance within each material. As pointed out by the first order statistically significant interaction between material type and distance, not all materials exhibited a proportional decrease in yellow responses with distance. The effect of distance was more pronounced for the thermoplastic materials with less titanium dioxide content (more saturated yellow), that is Thermo Y++. Thermo Y++, Thermo Y+, and Thermo Y were the three custom tailored materials in the order of decreasing yellow saturation (and increasing titanium dioxide ratio). Titanium dioxide is an inorganic white pigment, which contributes to coefficient of retroreflected luminance of the pavement marking, while reducing the saturation of yellow hues. There is a clear trend for normally less saturated looking yellow thermoplastic markings to be called yellow at far distances. It is believed that this trend is due to higher coefficients of retroreflected luminance of the markings at far distances. Higher coefficients of retroreflected luminance seems to help render the yellow color component, and inversely, markings with low luminance at far distances seem achromatic, thus are identified as "white" at a higher rate.

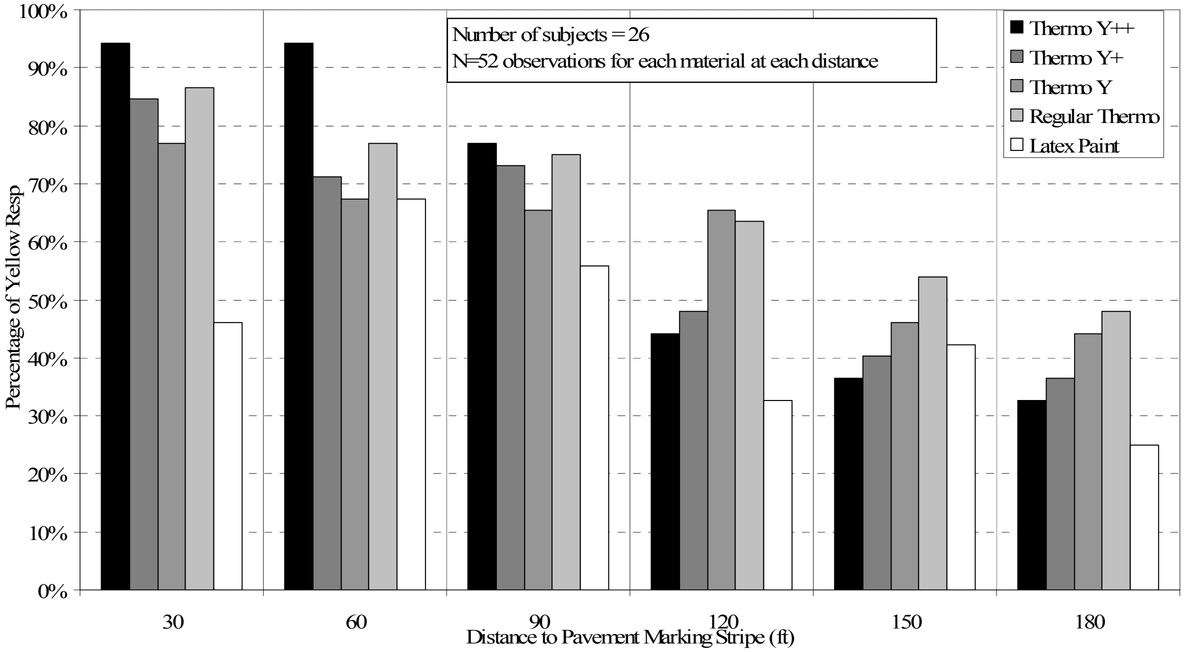
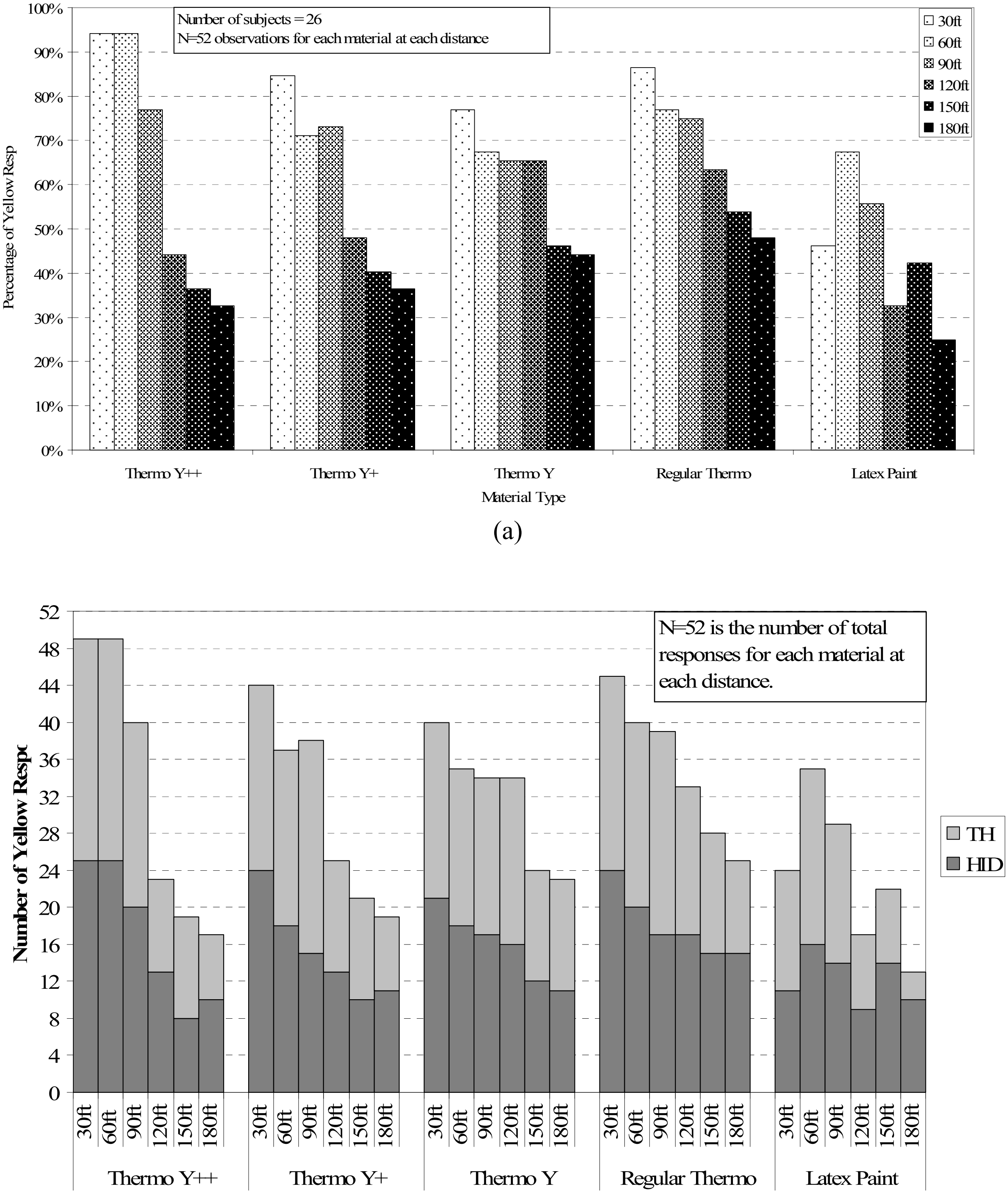


Figure 15. Percentage of yellow responses for each material at each distance, grouped by distance.

The second order statistically significant interaction between material type, distance, and headlamp suggests that some headlamps rendered deeper yellows for long distances for specific materials. Figure 16(b) shows the percentage of yellow responses for each material type partitioned into the headlamp type in a stacked bar chart. For most materials, the percentage of yellow responses under HID headlamp illumination was approximately equal to that under TH headlamps for shorter distances. This even split between the two headlamps for shorter distances was maintained also at far distances for some, but not all, materials. The reader should note that for the latex paint at long distances, most “yellow” responses were obtained under HID illumination.



(a)

(b)

Figure 16 Percentage and number of yellow responses for each material at each distance, grouped by material type.

The normalized percentages for responses classified as yellow for each headlamp are shown in Figure 17. There is a clear gain for HID headlamps over TH headlamps in terms of yellow responses for long distances, especially for latex paint type pavement markings. The reader should notice that latex paint type pavement markings did not elicit a higher number of yellow responses when compared to other materials under HID illumination. Rather, the sharp decline in yellow responses under TH headlamp illumination at long distances leads to a relative increase in yellow responses for HID headlamps. The low luminance of latex paint markings at long distances is, most likely, the cause for a decrease in chromatic perception. Under very low luminance conditions, these markings appeared as achromatic markings, which elicited "white" responses as no particular hue could be perceived by most participants. However, under HID headlamp illumination, the luminances were slightly elevated, affording a hint of yellow hue at 180ft.

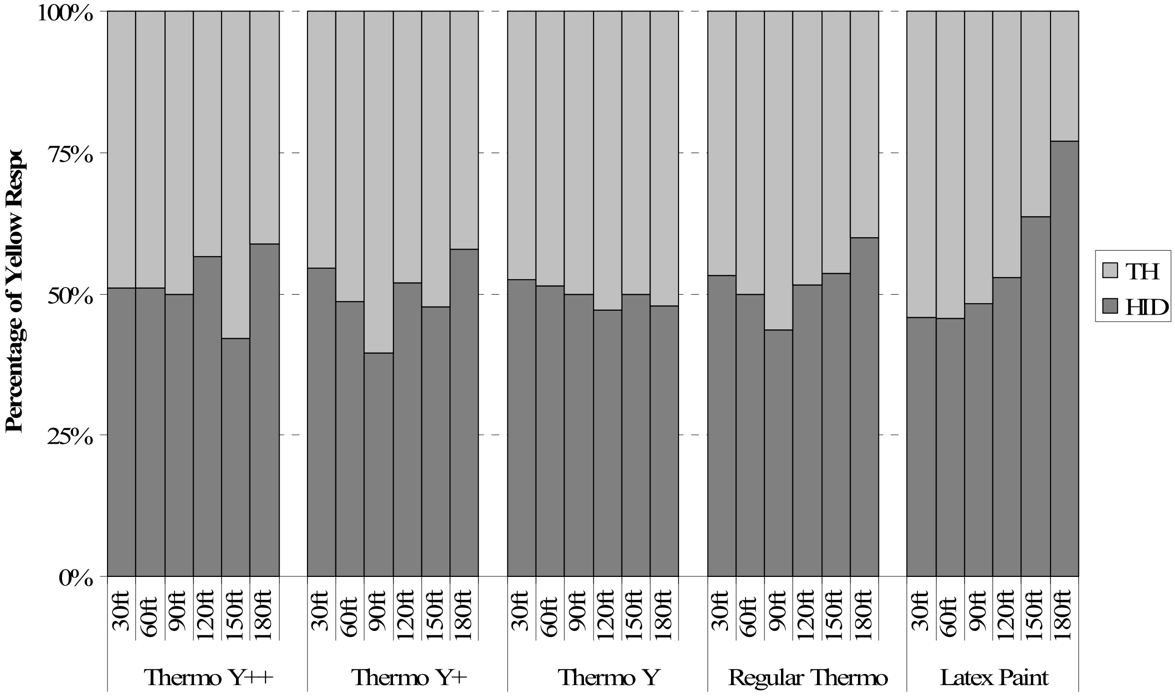


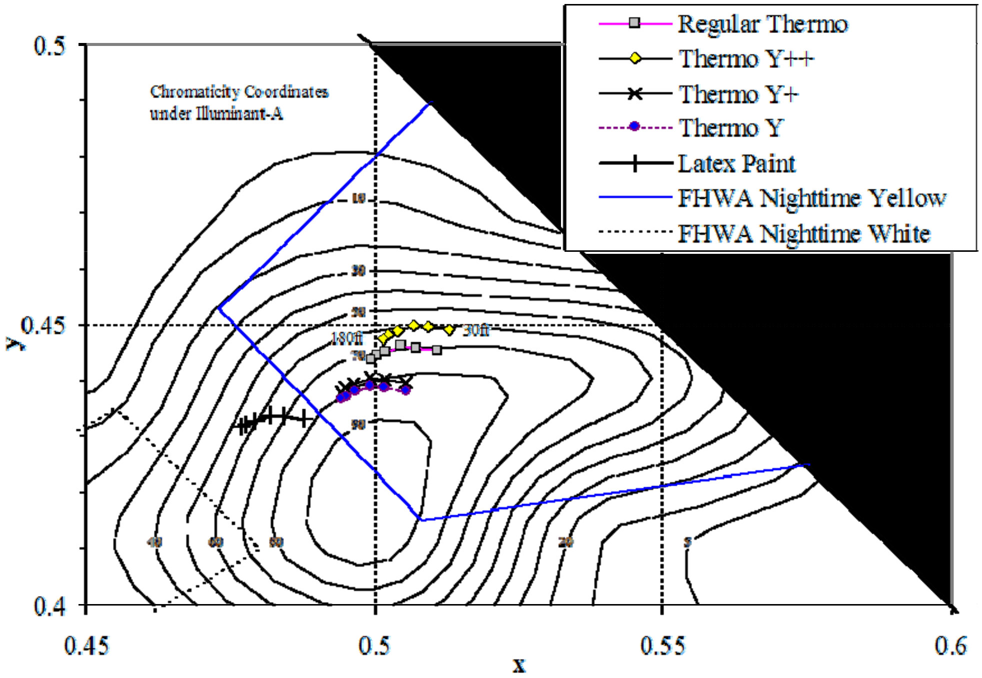
Figure 17. Normalized percentage of yellow responses for HID and TH headlamps for each material at each distance.

The spectral retroreflectivity of each pavement marking type as a function of distance was determined at the Center for High-Accuracy Retroreflectivity Measurements (CHARRM) facility of NIST. The Spectral Power Distribution (SPD) of each headlamp was determined at a Coast Guard facility in Connecticut. By means of the incident spectra and the spectral reflectivity of each pavement marking material, the chromaticity of each pavement marking material was determined mathematically for distances ranging from 30ft up to 180ft for each 30ft interval as administered in the field experiment. The chromaticities for each pavement marking as a function of distance are shown in Figure 18. Regular Latex paint was outside the FHWA nighttime yellow chromaticity limits established for ASTM E1710 30m standard geometry (8) and Illuminant-A type light source. Figure 18(a) illustrates the chromaticity of each pavement marking type with distance under TH headlamp illumination. The color-booth experiment response percentages for the foveal nighttime condition are superimposed to provide a frame of reference between the two experiments. Figure 18(b) illustrates the same under HID headlamp illumination with the color-booth experiment foveal daytime response percentages superimposed.

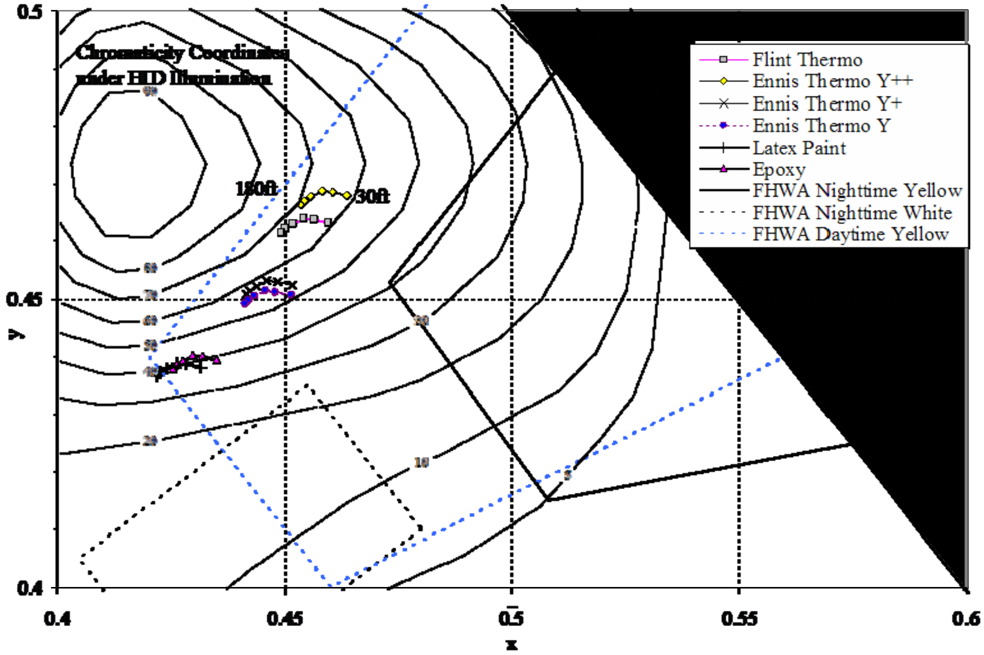
When the magnitude of the effect of distance was compared to the magnitude of the effect of headlamps in terms of chromaticity, the effect of headlamps seemed to be more pronounced, so much as to render all pavement marking chromaticities at all distances outside the FHWA yellow chromaticity limits. This is not unexpected, as the emission spectra of most HID headlamps are substantially different than those of TH headlamps. Strictly in colorimetric terms, the chromaticities under HID illumination would not have been called “yellow” under the guidance of ASTM nighttime color limits. However one should always consider the light source that generated a certain chromaticity when referring to the perceptual color assessment. HID and TH SPD’s are significantly different with dissimilar color temperatures, which triggers chromatic adaptation.

Figure 19 shows the chromaticities for all five pavement markings for both headlamps on the CIE Luv color space. This notation illustrates the differences between the chromaticities, as the CIE 1976 Luv space is uniformly spaced based on perceptive color differences. The effect of headlamp on perceptual color differences seems to be much larger than that of the material type, although the subtle effect of material on the chromaticity (under a single headlamp) notably affected the percentage of yellow responses, whereas headlamp type did not. Headlamps had no statistically or practically significant effect on color naming in the field. Such a large change in chromaticity from TH to HID headlamps without changing the color naming patterns is puzzling, especially in light of the iso-chrome curves for yellow at nighttime. However, when the chromaticities under HID headlamp illumination are overlaid on the daytime CIE 1931 chromaticity limits, the findings correlate well. We believe that such a substantial shift in chromaticities without a shift in color naming patterns indicates a significant effect of the light source SPD alongside chromatic adaptation, and also of luminance. The effect of luminance was also apparent within each material with increasing distance, without changing the illuminant. The chromaticity trace with increasing distance is somewhat minute, yet the percentage of yellow responses changed dramatically with decreasing luminance.

If daytime color naming and chromaticity correlates could be directly applied to HID headlamp illumination condition at nighttime, we would expect higher yellow ratings for the chromaticities obtained under HID illumination than those that were actually realized. Daytime color limits cannot be readily adapted for HID headlamps, but the region with highest yellow rating for HID headlamps in nighttime is most likely somewhere along the gradual shift from TH light source at low luminance levels and daytime conditions. As the luminance of the pavement markings decrease, we also expect the chromaticity region that would yield high yellow response rates to shrink and recede toward the spectral locus. This, quite possibly, is the case for pavement markings at far distances under HID illumination.



(b) Tungsten Halogen (TH) Superimposed on Foveal Nighttime Responses from Color Booth Experiment (Gray Iso-Percentage Lines)



(b) High Intensity Discharge (HID) Superimposed on Foveal Daytime Responses from Color Booth Experiment

Figure 18. Material Chromaticity as a Function of Headlamp Type, Material Type, and Viewing Distance

In colorimetric terms, the chromaticity of a particular type of pavement marking did not change much with increasing distance. No single chromaticity trace followed a path that reached into the FHWA nighttime white color box at far distances.

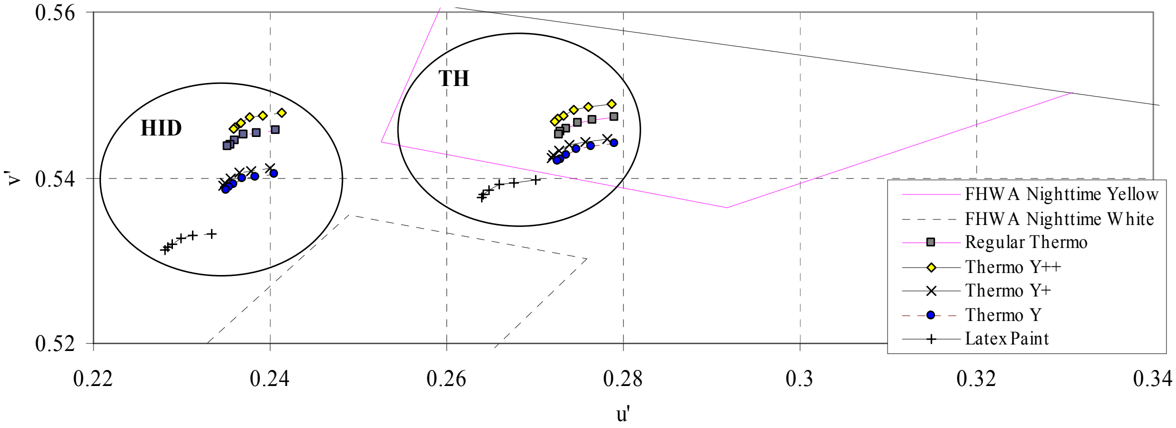


Figure 19 Chromaticity trajectories of each pavement marking material as a function of distance under TH and HID illumination on the CIE 1976 u' v' color space.

CONCLUSIONS

In this experiment, the color perception of various pavement markings were evaluated in the field under two headlamp illumination conditions. 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 180ft (54.9m). 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 for this 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 referred to as the photopic range. When pavement marking luminances drop into the lower mesopic and even scotopic ranges, the markings will generally be perceived achromatically. In our 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 in which 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 very 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.

The reader should note that 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.

CHAPTER 6: 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 set of states.

IDENTIFICATION OF THE INSTRUMENTS CAPABLE OF MAKING FIELD MEASUREMENTS

For the NCHRP Project 5-18, two conditions were to be measured, nighttime and daytime chromaticity. For the nighttime condition the illumination and viewing geometry follows the 30-m geometry. The 30-m geometry is a set of angles that are determined from a condition where the source aperture is 65 cm from the road surface directly over the stripe and the observer aperture is 120 cm from the road surface directly over the stripe and the source. The resulting angles are 88.76° for the entrance angle, 1.05° for the observation angle and 0° for the presentation angle. The illuminating spectrum convolved with the spectral sensitivity of the detectors is equal to the CIE illuminant A multiplied by the CIE color matching functions [5]. At the time of this work only one commercially-available portable instrument was available to make this measurement. The instrument is based on three filters used to approximate the color matching functions. The instrument was provided to the researchers on a loan basis from the Federal Highway Administration.

For the daytime chromaticity measurements, two geometries are used. The 0/45 geometry where the stripe is illuminated normal to the road surface and viewed at an angle of 45°, which is the geometry currently used in standards and thus to qualify a material. The material may also be measured with instruments that measure a 45/0 geometry which is illuminating the strip at 45° and viewing it normal to the road surface. Another distinction for this type of instrument is whether it has a point or annular system. A point system is uniplanar and measures in one direction. An annular system integrates either the illumination or the detection at 45° over the entire 360° possible. Depending on the optics of retroreflective material these two instruments typically produce different results. The illuminating spectrum multiplied with the spectral sensitivity of the detector equals the CIE D65 illuminant multiplied by the CIE color matching functions. Many varieties of these types of instruments are commercially-available. The instrument provided for this research by the Federal Highway Administration was an annular system that illuminated at 45° and viewed at 0°.

The second geometry used for daytime chromaticity measurements is diffuse illumination and a viewing geometry which is based on the 30-m geometry, notated in this report as d/30m. The co-viewing angle for this measurement is 2.29°. The chromaticity coordinates determined using the d/30m geometry are inherently expected to be closer to the white point than the 0/45 geometry. The white point is the chromaticity coordinates of the illuminating source. The reason for this shift is that the 30-m viewing geometry and diffuse illumination allows a specular and retroreflecting component off of the pavement material to be measured, as demonstrated in Figure 20. The intensity of the specular component depends on the gloss of the sample. The illuminating spectrum multiplied with the spectral sensitivity of the detectors equals the CIE D65 illuminant multiplied by the CIE color matching functions. At the time of this work no commercially-available instrument was being produced. A prototype instrument under development was loaned to the research group.

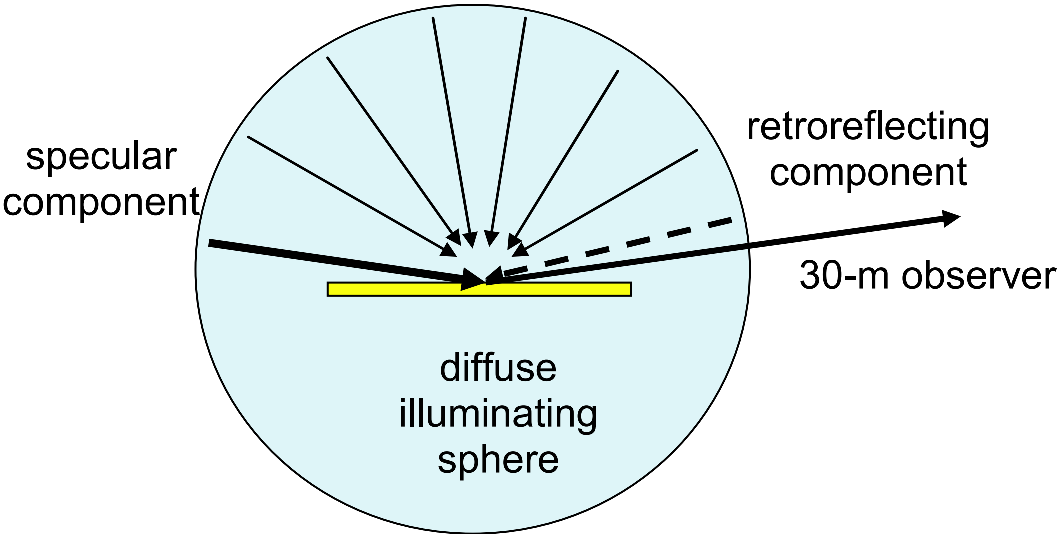


Figure 20. A schematic of the diffuse/30-m viewing geometry shows that a specular (bold line) and retroreflecting (dashed line) component that is collected by the detector.

DEVELOPMENT OF A PROTOCOL FOR CHARACTERIZING AND CALIBRATING THE FIELD INSTRUMENTS

Since the nighttime instrument and the d/30m instruments used in this study have not been tested or the 0/45 instrument was not designed for measuring retroreflective material, the instruments were characterized for their optical properties. The first test performed was the measurement of BCRA ceramic tiles that were calibrated at NIST. The 0/45 instrument was constructed for the purpose of measuring ceramic tiles. The results of the NIST scale minus the instrument value are displayed in Table 6.

Since the instruments were designed for this purpose, the results were quite good. The only deviations were the Black and Deep Blue tiles where the signal is low and the Red and Orange tiles which are difficult to measure because the spectral power distribution changes at the wavelengths where the color matching functions change.

Table 6. The color difference of the NIST scale minus the 0/45 instrument value.

Color	Δx	Δy	Color	Δx	Δy
White	0.0004	0.0000	**Red**	-0.0044	-0.0006
Black	0.0090	-0.0131	**Deep Pink**	-0.0004	-0.0008
Pale Grey	0.0002	0.0002	**Orange**	-0.0086	-0.0025
Mid Grey	-0.0002	-0.0003	**Yellow**	0.0005	0.0004
Diff Grey	0.0000	0.0003	**Green**	0.0002	0.0023
Deep Grey	0.0001	-0.0020	**Diff Green**	0.0001	0.0026
Deep Blue	0.0057	0.0070	**Cyan**	0.0000	0.0005

The nighttime instrument was also characterized using the ceramic tiles. By placing the tiles normal to the light source in the device, as shown in Figure 21, the ceramic tiles can be measured and compared to NIST values. Table 7 presents the results of the NIST scale minus the instrument value.

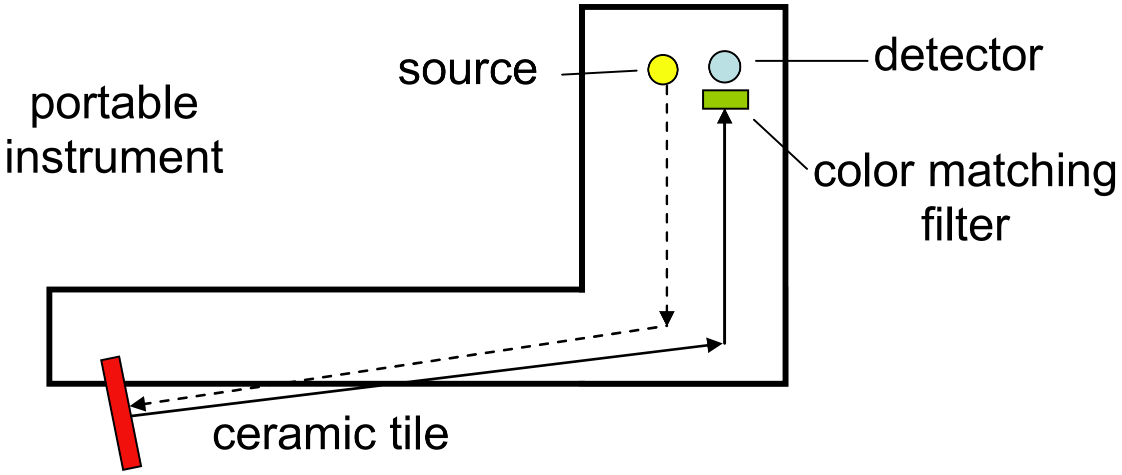


Figure 21. The ceramic tiles were placed in the nighttime instrument approximately normal to the illumination and observation axis.

The differences are significantly larger for the nighttime instrument versus the 0/45 instrument. The Black, Deep Blue and for the most part the Deep Grey have sensitivity issues. The majority of the colors compared to the grey scales have significant differences in the x coordinate. The only reasonable color measurement is the yellow tile.

Table 7. color difference of the NIST scale minus the nighttime instrument value.

Color	Δx	Δy	Color	Δx	Δy
White	-0.004	-0.001	**Red**	-0.030	0.012
Black	-----	-----	**Deep Pink**	-0.046	0.010
Pale Grey	-0.004	-0.003	**Orange**	-0.022	0.001
Mid Grey	-0.019	-0.016	**Yellow**	-0.005	-0.002
Diff Grey	-0.019	-0.011	**Green**	-0.038	0.015
Deep Grey	-0.076	-0.051	**Diff Green**	-0.012	0.000
Deep Blue	-----	-----	**Cyan**	-0.033	0.004

To determine if the nighttime instrument could be improved, further characterization was performed. A true understanding of the instrument required the measurement of the spectral power distribution of the light source and the spectral sensitivity of the three filters and detectors. To measure the spectral power distribution of the nighttime instrument a calibrated diode array spectrometer was used with a diffusing opal glass as the input optic. Figure 22 shows the geometry of the light source measurement. To achieve an acceptable level of signal-to-noise the diode array system was placed in a dark environment, and was set to integrate for 60 sec. Thirty seconds was a total of 22 individual measurements by the nighttime instrument. The spectral power distribution is shown in Figure 23. The spectral power distribution should closely match the CIE illuminant-A distribution, which is reasonably matched except in the red region. The drop-off in the red region is most likely due to a cool mirror used to redirect the light from the halogen light source. A cool mirror is a broadband mirror that reflects visible and transmits heat or infrared. The spectral sensitivity of the three filters and the detector, which is a photomultiplier tube, was measured at the NIST facility for spectral irradiance and radiance responsivity calibrations with uniform sources (SIRRCUS) [6]. SIRRCUS is a laser-based facility that has been developed to provide high-flux, monochromatic, Lambertian radiation over the spectral range 0.2 μm to 18 μm. The facility was designed to reduce the uncertainties in a variety of radiometric applications, including irradiance and radiance responsivity calibrations.

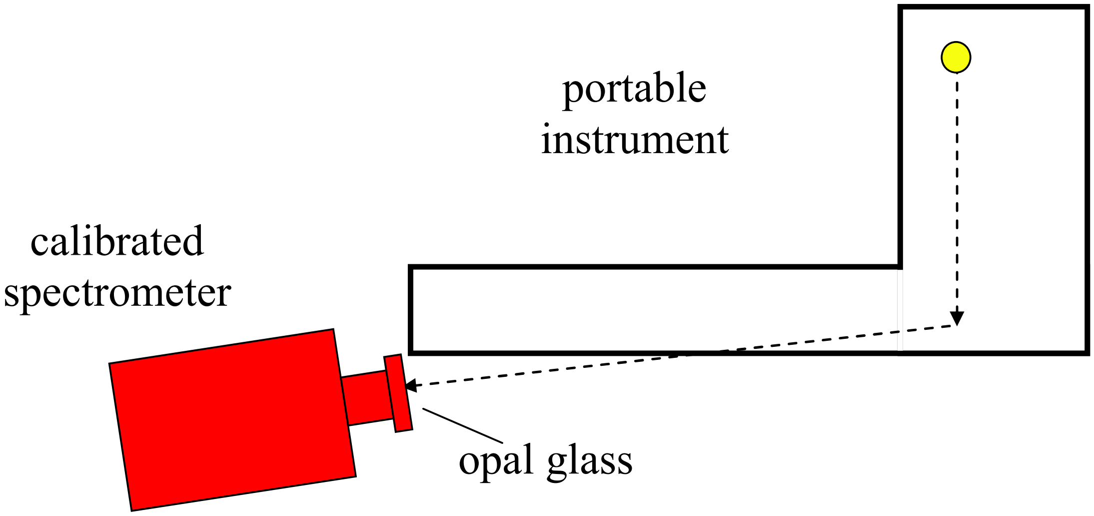


Figure 22. The nighttime instrument source was measured at a normal geometry.

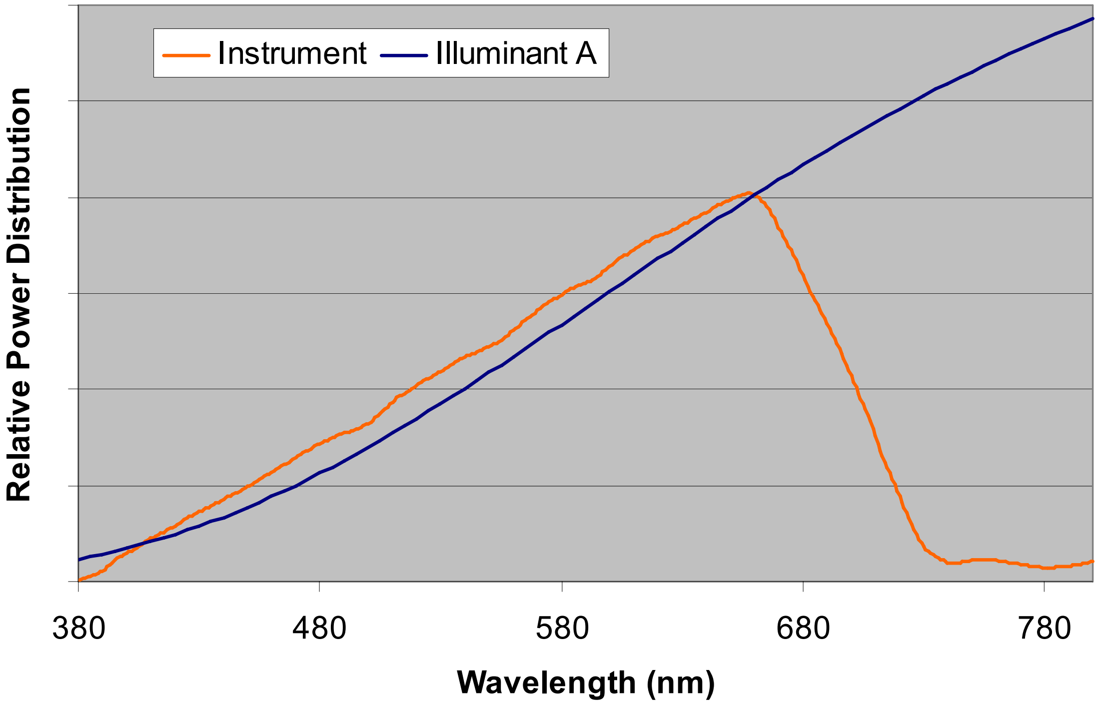


Figure 23. The illumination spectral power distribution of the nighttime instrument compared to CIE illuminant A.

The wavelength uncertainty is on the order of 0.001 nm and the spectral response uncertainty is limited by the resolution of the instruments tested in this study. The measurement geometry is shown in Figure 24. Briefly, when the measure button is pushed on the nighttime instrument, the nighttime instrument measures the dark signal, turns on the light source, and then measures the retroreflected light. A photodetector was used to detect the source illumination. The signal from the photodetector opened the shutter to the tunable laser allowing the sphere to illuminate. The source from the nighttime instrument was blocked and the flux from the sphere source was measured for each color matching filter compared to a calibrated trap detector. The trap detector spectral sensitivity is known; therefore, as the wavelength of light was changed the relative response of the instrument was determined. Figure 25 shows the relative response of the nighttime instrument for the three color matching functions.

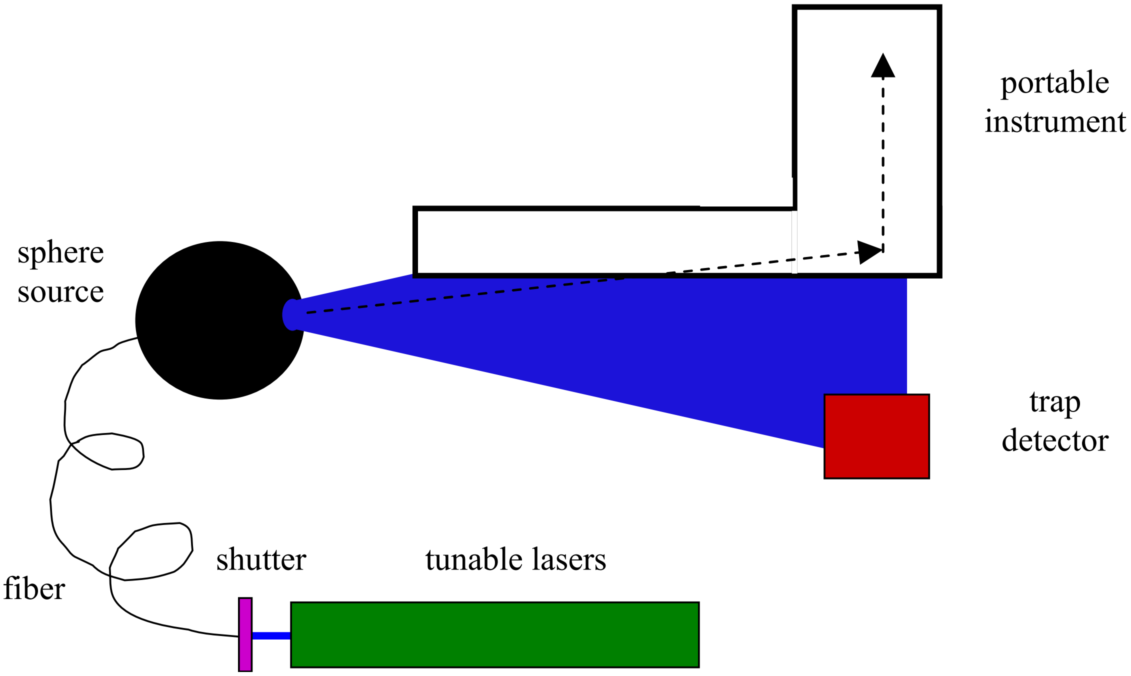


Figure 24. The SIRRCUS facility is composed of lasers and sphere sources used to illuminate the portable instrument.

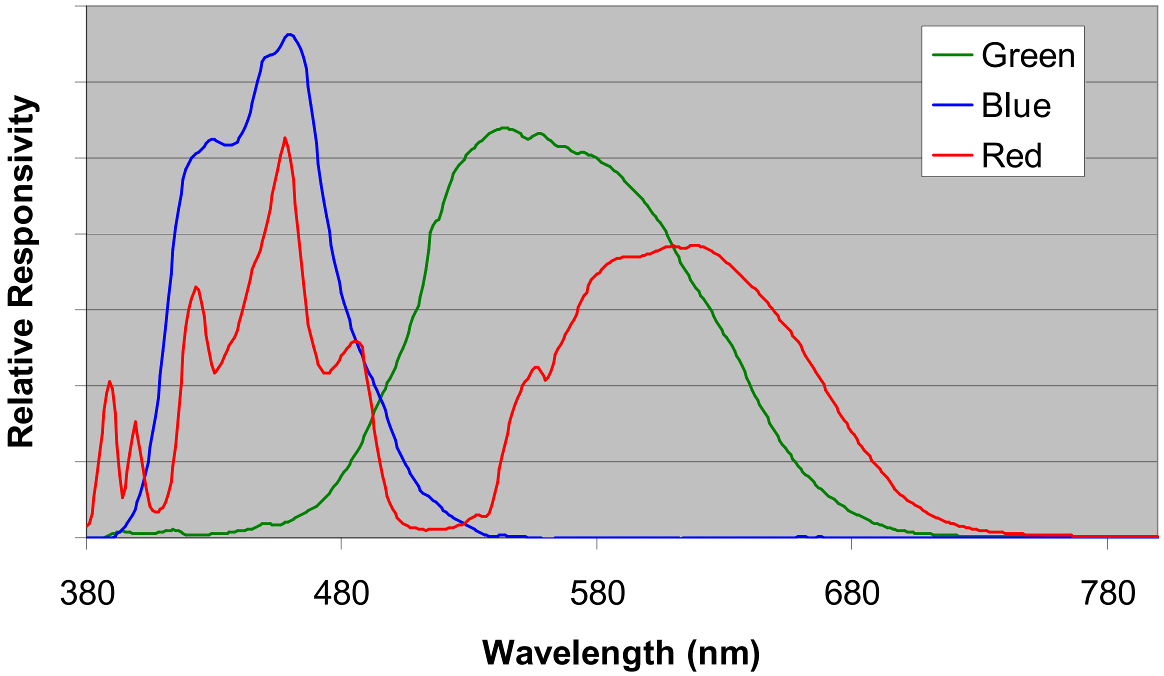


Figure 25. The relative response of the nighttime instrument is plotted versus wavelength.

Assuming that the pavement markings of interest are not fluorescent, the comparison to be made is the relative responsivity multiplied by the illuminant SPD, versus the CIE color matching functions multiplied by the CIE illuminant A. Figure 26 shows this comparison. The match is quite bad. The reason this instrument works is that a correction matrix is constructed from three calibration standards. Three standards, a diffuse white, a pale yellow and amber, are provided with the nighttime instrument. These standards are calibrated by the instrument manufacturer against color standards calibrated at a national laboratory. By measuring these three standards with the three color matching filters in the nighttime instrument, a 3 x 3 matrix is constructed. The three color matching filter measurements multiplied by the correction matrix gives corrected chromaticity coordinates. This correction matrix works quite well on test samples where the chromaticity coordinates fall within the triangle of chromaticity coordinates formed by the three standards. This correction matrix is examined further in the following section on validating the instruments.

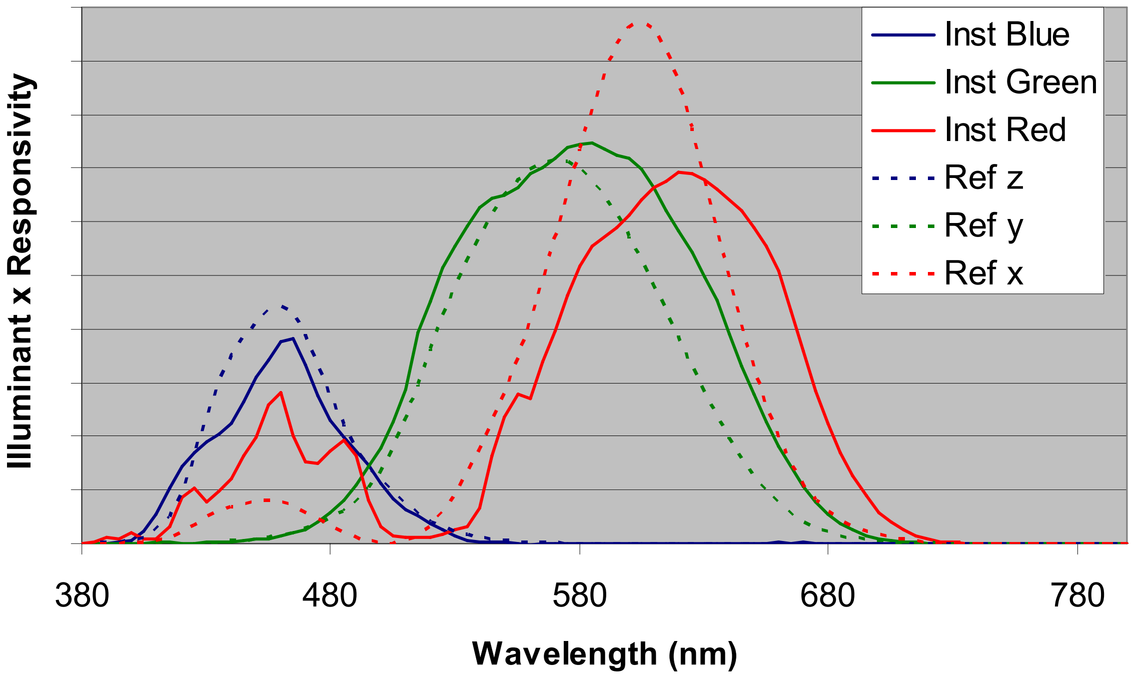


Figure 26. The relative responsivity of the nighttime instrument multiplied by the nighttime instrument illuminant compared to CIE illuminant A multiplied by the CIE color matching functions.

A similar analysis was done to the d/30m instrument. NIST does not currently have the facilities to calibrate the ceramic tiles with the d/30m geometry, so this comparison was not done. The d/30m instrument was characterized for illumination source and spectral sensitivity of the color matching functions. Figure 27 shows the geometry of the light source measurement. To achieve an acceptable level of signal-to-noise the diode array system was placed in a dark environment, and was set to integrate for 0.5 sec. The spectral power distribution of the light source is shown in Figure 28. The spectral power distribution is very similar to CIE illuminant A, but for this measurement the illuminant should approximate CIE D65. This difference can be corrected by shifting the spectral responsivity of the color matching filters. The instrument illuminant multiplied by the spectral responsivity of the instrument is shown in Figure 29. The match is considerably better than the nighttime instrument. The d/30m instrument also uses the three standards to create a correction matrix.

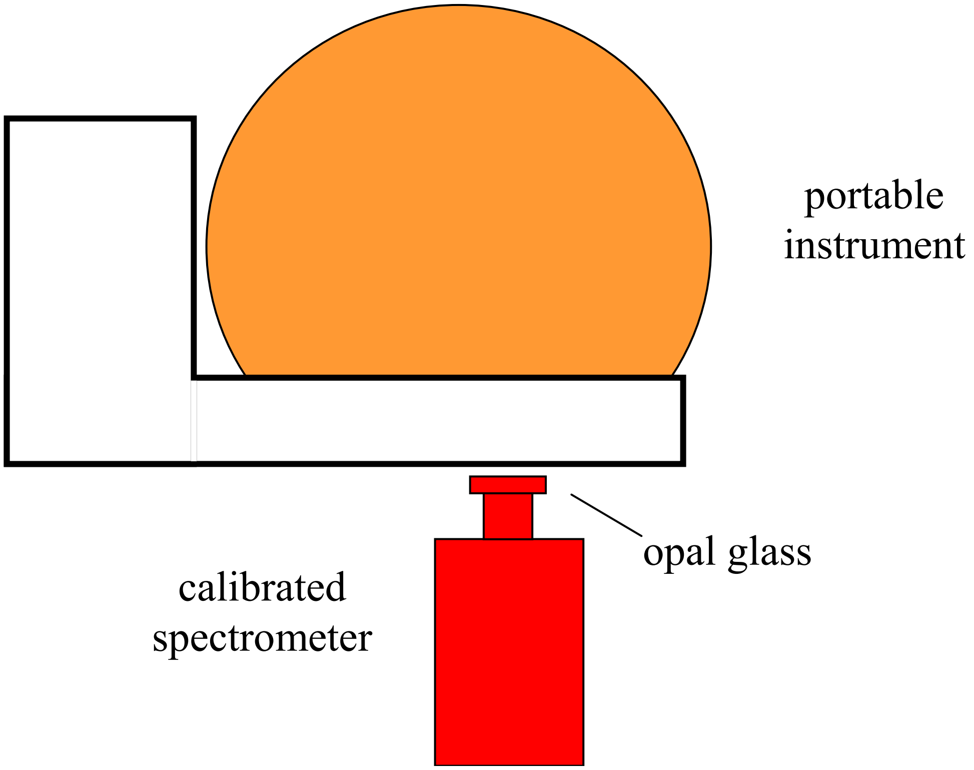


Figure 27. The d/30m instrument source was measured in the sample plane.

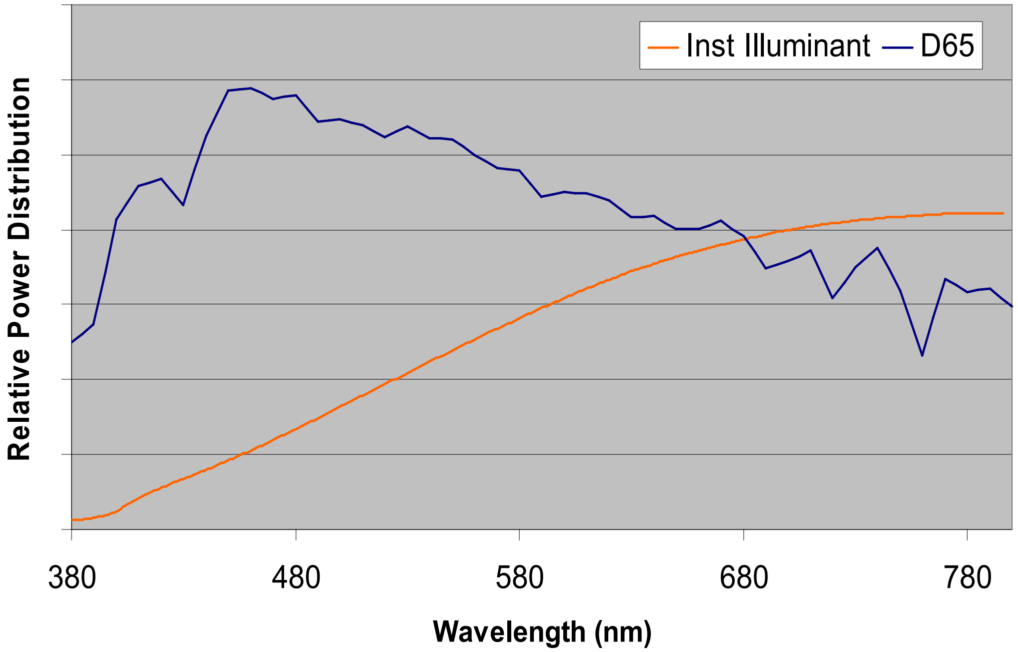


Figure 28. The illumination spectral power distribution of the d/30m instrument compared to CIE D65.

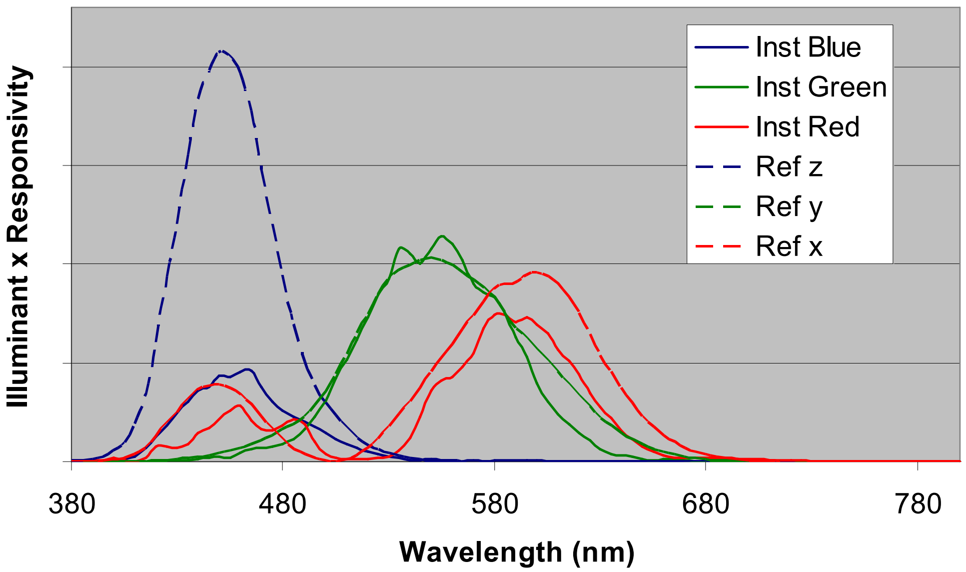


Figure 29. The relative responsivity of the d/30m instrument multiplied by the d/30m instrument illuminant compared to CIE D65 multiplied by the CIE color matching functions.

DEVELOPMENT OF A PROTOCOL FOR VALIDATING THE FIELD INSTRUMENTS

The characterization and calibration protocols show the capabilities of the instruments. Specifically, in some regions of the chromaticity diagram, the user would expect the instrument to produce accurate measurements. The ceramic tile measurements are sufficient to validate the 0/45 instrument because the retroreflective properties of the pavement marking materials to be measured do not significantly affect the 0/45 measurements. A few of the materials that are structured such as some of the tape materials have insignificant changes in the chromaticity but can affect the magnitude of the reflectance factor, which is not under study in this work.

The nighttime instrument was validated by comparing the measured results to measurements made at the Center for High Accuracy Retroreflection Measurements (CHARRM) constructed and developed under NCHRP Project 05-16 and maintained by NIST [7]. The main question is whether the portable instrument, with its compactness, correlate to the laboratory values which represent the road viewing conditions more accurately. One concern is that the portable instrument integrates over a range of observation and entrance angles. As shown in Figure 30, a portable instrument must illuminate a large area of footprint that retroreflects a detectable amount of light. The collection angle from the illuminated area is also an integration over a set of angles.

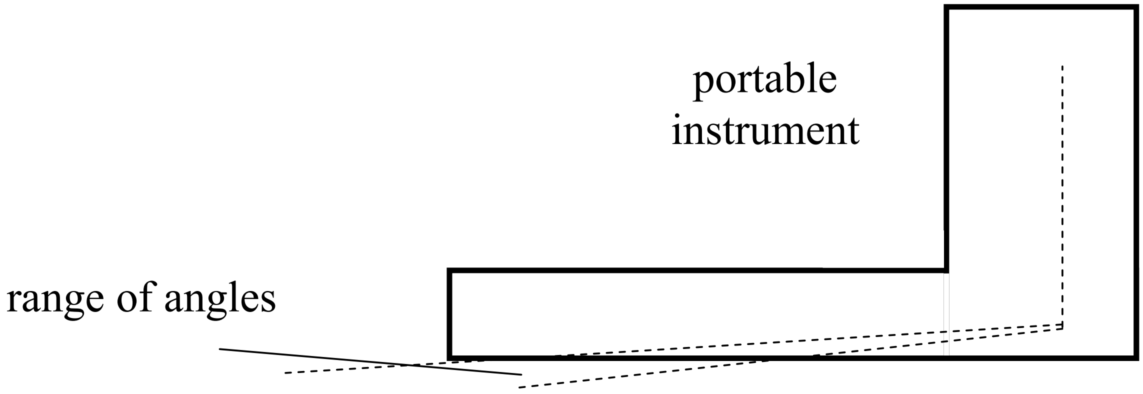


Figure 30. The nighttime instrument averages of a range of entrance and observation angles.

In the road scenario when an observer is viewing a marking material 30 m away, the cone of light about the entrance angle and observation angle is quite small due to the distance. Another concern is the retroreflecting properties of the pavement marking materials at different distances. Figure 31 shows that the light seen by an observer is composed of diffuse scatter and retroreflected light. The diffuse scatter can be approximated by the inverse square law such that when the observer is twice as far away, the flux from diffuse scatter is one fourth. The retroreflected light follows a beam because it is illuminated by a beam of light. The optical properties act much like a mirror. Therefore, at different distances the light that reaches the observer has a different ratio of diffuse scatter and retroreflected light. The portable instrument measures over a distance of approximately 1 m. The road scenario is commonly from 10 m to 90 m. The correlation due to distance needs to be determined.

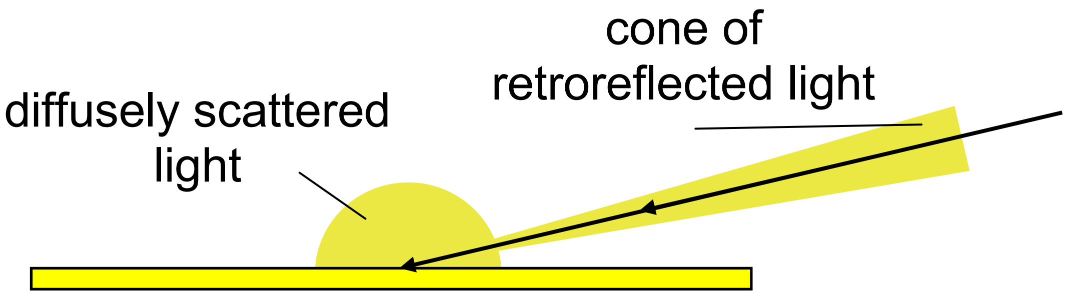


Figure 31. The ratio between the cone of retroreflected light and diffusely scattered light changes with observation distance.

The CHARRM facility at NIST is composed of three components, the source, the goniometer, and the detector. The source composed of a 100 W strip lamp produces an image that under-fills the pavement marking sample. A variable aperture in the projection system is used to control the image such that the light does not hit the edges, most importantly the front edge, of the pavement marking sample. The goniometer of the reference retroreflectometer is mounted on a rail system.

The illumination distance is variable from 3.5 to 33 m. The entrance angle components have an absolute expanded uncertainty of 0.02° ($k=2$) and both axes have a range of ± 95°. The largest retroreflective device the goniometer can accommodate is a device diameter of 95 cm, and it has a clear view to allow almost any length of pavement marking. The sample mounting plate uses vacuum cups to hold the retroreflective devices against a precision register. The precision register is two machined rails that are 150 cm in length. When the vacuum is applied the sample is pulled flat against these rails. The mounting bracket has an adjustable depth to accommodate different sample thicknesses. The detector is supported by the observation angle positioner, which is comprised of a 2 m translation stage, a rotation stage and a 0.2 m translation stage. Each of these motions has an optical encoder to ensure accuracy. The absolute expanded uncertainty of the entrance angle, α, is 0.0002° ($k=2$). The observation distance is maintained equal to the illumination distance to an absolute expanded uncertainty of 0.005 m ($k=2$). The detector is a single grating spectroradiometer with a back-thinned CCD. Researchers at NIST have developed a correction matrix for CCD array spectroradiometers that eliminates the stray light from the signal, therefore, increasing the stray light rejection to at least 10^5. This level of stray light rejection allows measurement of chromaticity coordinates with a standard uncertainty of roughly 0.002. The input optics consists of an observer aperture, a lens, a transmitting diffuser and a fiber optic bundle that directly attaches to the instrument. By spectrally measuring the light returned to the detector, and dividing it by the spectral power distribution of the source measured with the same detector, the spectral coefficient of retroreflected intensity is measured. Using the spectral coefficient of retroreflected intensity and any chosen light source the chromaticity coordinates for the pavement marking samples can be calculated.

The first experiment performed was testing how the chromaticity coordinates change over a range of viewing geometries. The pavement marking samples used in this experiment are the panels described in the field experiments and others submitted by manufacturers, including thermoplastic, paint, epoxy and tape. The panels were positioned on the goniometer at a distance of 10 m. The panels were measured for spectral coefficient of retroreflected intensity at observation and entrance angles that correspond to viewing distances of 10 m, 20 m, 30 m, 60 m, 75 m and 90 m. The chromaticity coordinates were calculated based on CIE illuminant A and are plotted in Figure 32.

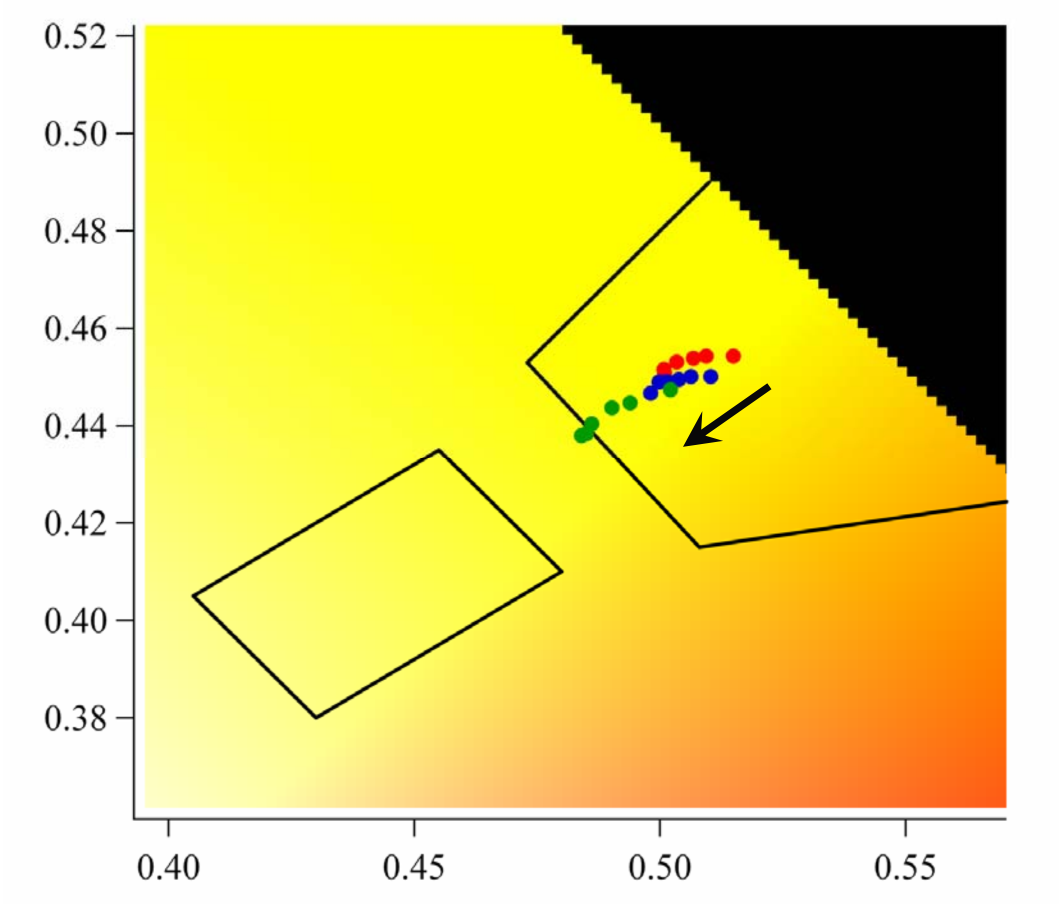


Figure 32. The shift in the chromaticity coordinates for the angles corresponding to viewing distances of 10 m, 20 m, 30 m, 60 m, 75 m and 90 m along with the ASTM nighttime color boxes.

The arrow indicates that as the viewing distance geometry becomes larger, the chromaticity coordinates shift toward the white point, which is (0.45, 0.41) for CIE illuminant A. This shift is expected since at 90 m viewing geometry the entrance angle is very large, the returned light is predominantly from retroreflection and front surface reflection off of the glass beads which spectrally is similar to the illuminant used. The shift was consistent and rather independent of the material. The following polynomial equations are the results of a fit to all the data to determine a correction factor for this set of panels,

$$x_{cf}^{a} = -1.44 \cdot 10^{-7} d^{3} + 2.87 \cdot 10^{-5} d^{2} - 1.99 \cdot 10^{-3} d + 1.038 \qquad (1)$$

$$y_{cf}^{a} = -3.51 \cdot 10^{-8} d^{3} + 6.46 \cdot 10^{-6} d^{2} - 5.39 \cdot 10^{-4} d + 1.012 \qquad (2)$$

where d is the viewing geometry distance. Using this correction factor a material can be measured at the 30m viewing geometry, and corrected for the actual viewing distance used in the field.

The second experiment performed was testing how the chromaticity coordinates change over a range of distances using the same viewing geometry. The panels were positioned on the goniometer at a viewing geometry of 30 m. The panels were measured for spectral coefficient of retroreflected intensity at actual distances of 3.65 m, 5 m, 10 m, 15 m, 20 m and 25 m. Not all of the panels could be measured at the 25 m distance with the current equipment. The chromaticity coordinates were calculated based on the CIE illuminant A and are plotted in Figure 33.

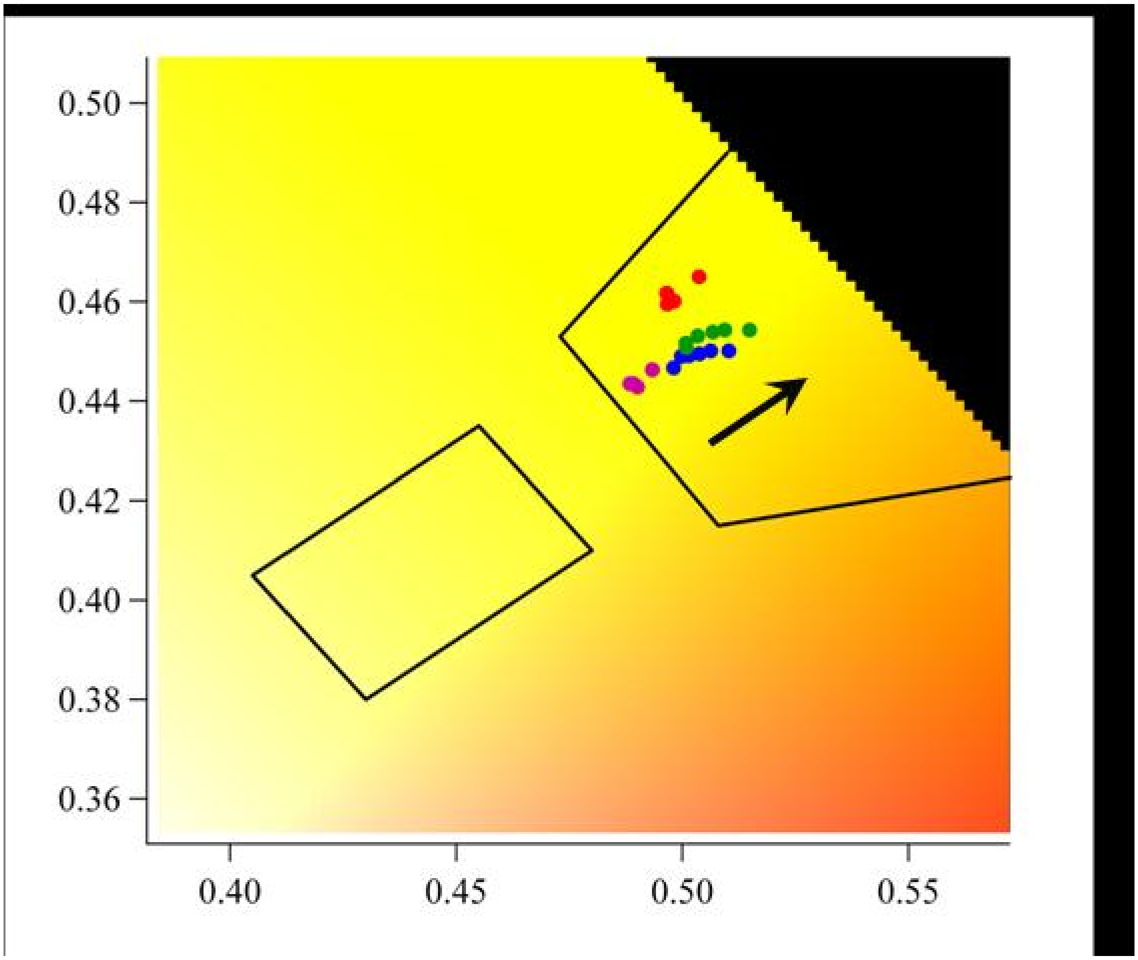


Figure 33. The shift in the chromaticity coordinates for a 30-m viewing geometry with actual distances of 3.65 m, 5 m, 10 m, 15 m, 20 m and 25 m along with the ASTM nighttime color boxes.

The arrow indicates that as the actual distance becomes farther away the chromaticity becomes more saturated that is moves away from the white point. This result was not expected and is currently being investigated at NIST to determine the underlying optical mechanisms that cause this chromatic shift. A possible explanation is that at 30m viewing geometry, the retroreflected light has more saturation than the scattered light by the pavement markings. The shift was consistent and rather independent of the material. The following polynomial equations are the results of a fit to all the data to determine a correction factor for this set of panels,

$$x_{cf}^{d} = 1.24 \cdot 10^{-5} d^{3} - 3.75 \cdot 10^{-4} d^{2} + 3.27 \cdot 10^{-3} d + 0.992 \qquad (3)$$

$$y_{cf}^{d} = 1.40 \cdot 10^{-5} d^3 - 4.32 \cdot 10^{-4} d^2 + 3.95 \cdot 10^{-3} d + 0.989 \tag{4}$$

where d is the actual distance. Using this correction factor a material can be measured at a specific distance, 10 m, and corrected for the actual distance used in the field. NIST is continuing to investigate this correction factor.

The last validation performed was a comparison between the portable nighttime instrument and the laboratory measurement at a 30 m viewing geometry with samples measured at 30 m. Figure 34 shows the comparison. Table 8 presents the CHARRM measurements minus the nighttime portable instrument measurements. The CHARRM measurements were made on samples that were 6 feet long. The nighttime instrument is an average of 4 spots on the sample. The white samples are in good agreement between the two devices. Sample White 6 (the purple circles) is slightly off, but White 6 was highly retroreflective sample and produced readings higher than the nighttime instrument was rated to measure. The yellow samples showed a consistent shift.

Table 8. The CHARRM scale minus the nighttime instrument scale.

Sample	Δx	Δy
White 1	-0.004	-0.001
White 2	-0.002	0.000
White 3	0.001	0.000
White 4	0.001	0.000
White 5	0.000	-0.002
White 6	-0.006	-0.005
Yellow 1	-0.010	0.009
Yellow 2	-0.010	0.008
Yellow 3	-0.010	0.007
Yellow 4	-0.009	0.009
Yellow 5	-0.013	0.012

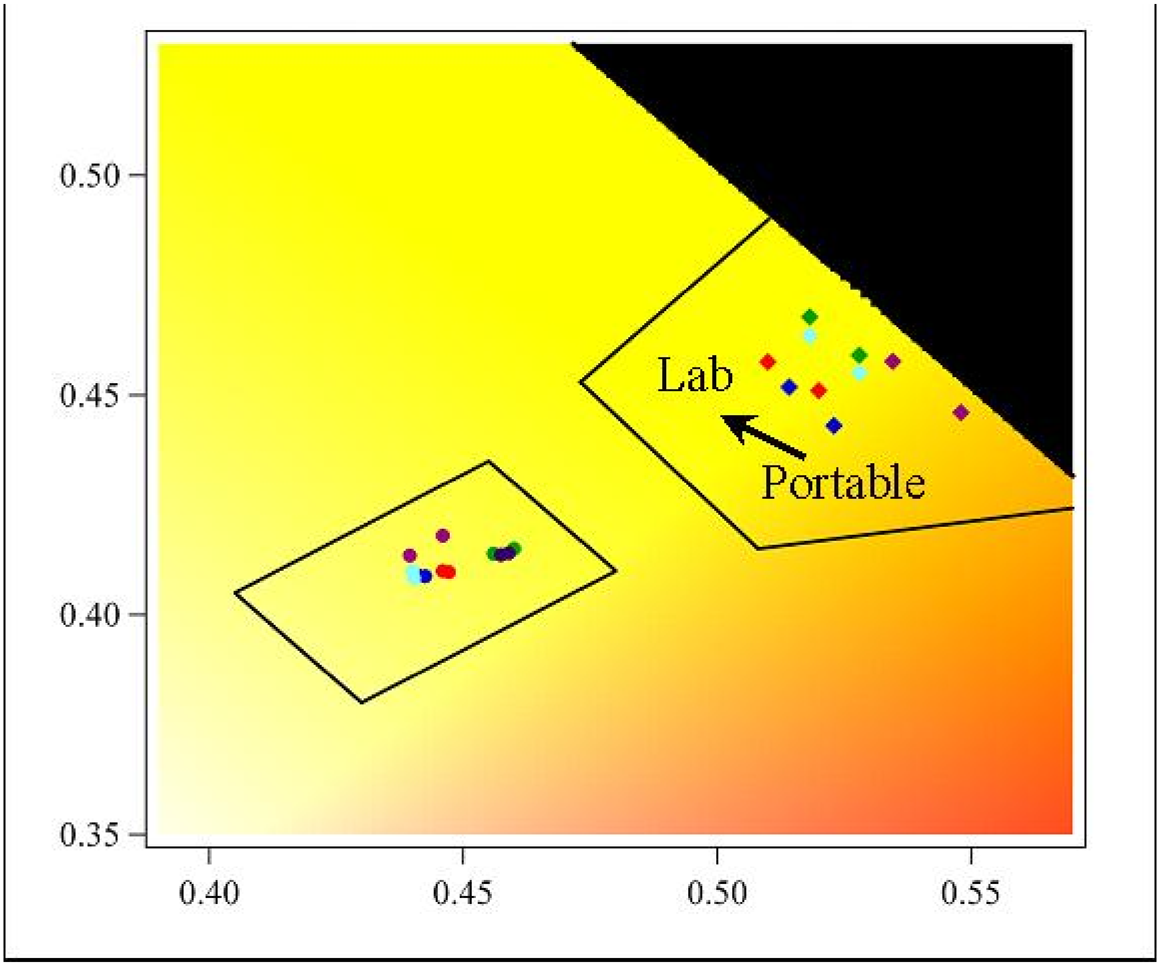


Figure 34. Shown is the comparison of the CHARRM measurements versus the nighttime instrument.

The shift can be corrected by providing new values to the pale yellow and amber calibration standards. The new standard values will be applied to the field measurements.

NIST currently does not have the facilities to validate the d/30m instrument as has been done with the nighttime instrument. We are attempting to obtain a 2-m sphere using funds not from this contract to setup a facility where pavement marking materials and signage material can be calibrated for diffuse illumination and various viewing geometries. Once this sphere is obtain and the source is constructed a complete validation and further research into the d/30m instrument can be completed.

Accounting for all of the uncertainty contributions for the nighttime and the daytime instruments, which includes calibration plaque uncertainty, instrument resolution, transfer from actual 30 m measurements to 1 m portable measurement distance (angle acceptance, chromaticity shifts, distance dependence) among others, the overall expanded uncertainty for the two instruments is 0.018 (k=2) chromaticity units.

SELECTION OF STATES FOR FIELD MEASUREMENTS

To minimize expense and sample a wide range of field material with known background specifications, the research team decided to measure the NTPEP test decks that were currently available.

The first site was outside of Tupelo, Mississippi on state road 78 going west. Pavement markings on concrete and asphalt surfaces were measured on June 24th and 25th of 2004. The data was collected using the three instruments available. The first set of data points was 36 samples that were one week old on a concrete test deck. The second set of data points was 78 samples that were two years old on an asphalt test deck. The second site examined was the test decks in Morgan, Utah on interstate 84 going east. The samples are 3 years old on concrete decks. Unfortunately the asphalt decks had already been removed. The data set includes 149 lines that were measured. There are 95 different materials on the deck so there are a few duplicated materials in this data set. The third site examined was the test decks in Sparta, Wisconsin on interstate 94. The asphalt set are on west bound lanes and the concrete set are on east bound lanes. The material was applied in early July 2004 so it is only a few months old. The data set includes 48 lines on concrete and 65 lines on asphalt. The last site to be examined was in Pennsylvania on Interstate 80 and was measured the end of October 2004.

By measuring the material on the NTPEP test decks, we did the field tests economically and effectively because of the available manufacturer and aging information. A number of the materials are the same products applied in different parts of the country and have been on the road for different periods of time. We will be able to draw some conclusions about changes in chromaticity based on aging and weathering for these overlapping materials.

EXECUTION OF THE TEST PLAN IN NTPEP TEST DECKS

The first site is outside of Tupelo, Mississippi on state road 78 going west. The selection of Mississippi satisfies environmental aging due to the hot, humid, and rainy conditions. In June 2004, the researchers measured lines on concrete and asphalt surfaces. The data was collected using the three instruments available. The first set of data points was 36 samples that were one week old on a concrete test deck. The second set of data points was 78 samples that were two years old on an asphalt test deck.

To establish the required protocol for the sampling of the lines the following procedure was performed. The instruments were fully charged the night before and allowed to come to equilibrium (several hours) with the hot and humid measurement environment. The instruments were calibrated following the manufacturers specifications and the standard blocks results were recorded. Each instrument was placed on the first line such that the active measuring region was the same for each instrument. Three measurements were made without moving the instrument for each filter setting. The instruments were then moved to a new spot on the line and the measurement was repeated. A third spot was chosen and the measurements repeated. This was done for ten lines. The results showed that the repeatability (three measurements without movement) of the instruments was exceptional. The quality of the repeatability was limited by the display resolution of the instruments. The reproducibility of the instrument or the uniformity of the line (three measurements on different parts of the line) revealed that by averaging three spots was no better than measuring one spot. The expanded uncertainty of the nighttime instrument and the Q_d instrument is 0.018 (k=2) chromaticity units. The expanded uncertainty in the daytime instrument is 0.005 (*k*=2) chromaticity units. The typical reproducibity of a pavement line was 0.005 chromaticity units. The researchers when choosing where to measure, selected an area that visually appeared to average for the line – not the cleanest spot and not the most worn spot. The average of three spots did not decrease the uncertainty of the chromaticity coordinates for the line. It only served as a sanity check. Therefore, for further line measurements: a single spot was chosen, the spot was measured once by the instrument, the instrument was moved slightly (re-seated) and the spot was measured again. The average value was recorded. The instruments typically reported the same values. The second measurement is simply a sanity check and does not decrease the uncertainty of the measurements. These repeatability and reproducibility measurements were performed in the laboratory environment (new material) with the same conclusions. After measuring for three hours, the instruments were recalibrated and measurements continued. The instruments were recalibrated at the end of field measurements. For all the field measurements the instrument recalibration showed no differences from the initial calibration or the final calibration.

The overall line statistics are summarized in Table 9. The lines represent the product of over 21 companies. Unfortunately, none of the products are exactly the same from 2001 to 2004; therefore, an aging study on a particular product could not be conducted in this research.

Table 9 – Overall Line Statistics

Year and Location	Surface	Sample Age	Yellow Lines	White Lines
2001 Utah	Concrete	3 years	32	45
2002 Mississippi	Asphalt	2 years	29	21
2002 Pennsylvania	Asphalt	2 years	51	67
2004 Wisconsin	Concrete	3 months	27	21
2004 Wisconsin	Asphalt	3 months	28	32
2004 Mississippi	Concrete	2 weeks	10	5
		Totals	177	191

DAYTIME MEASUREMENTS

Figure 53 shows the daytime measurements of all the white lines on NTPEP test decks using the 0/45 instrument. The individual chromaticity points are plot on an enlarged (*x, y*) 1931 chromaticity diagram. The boxes represent the acceptable white and yellow chromaticities defined in the ASTM standard D6628-01.

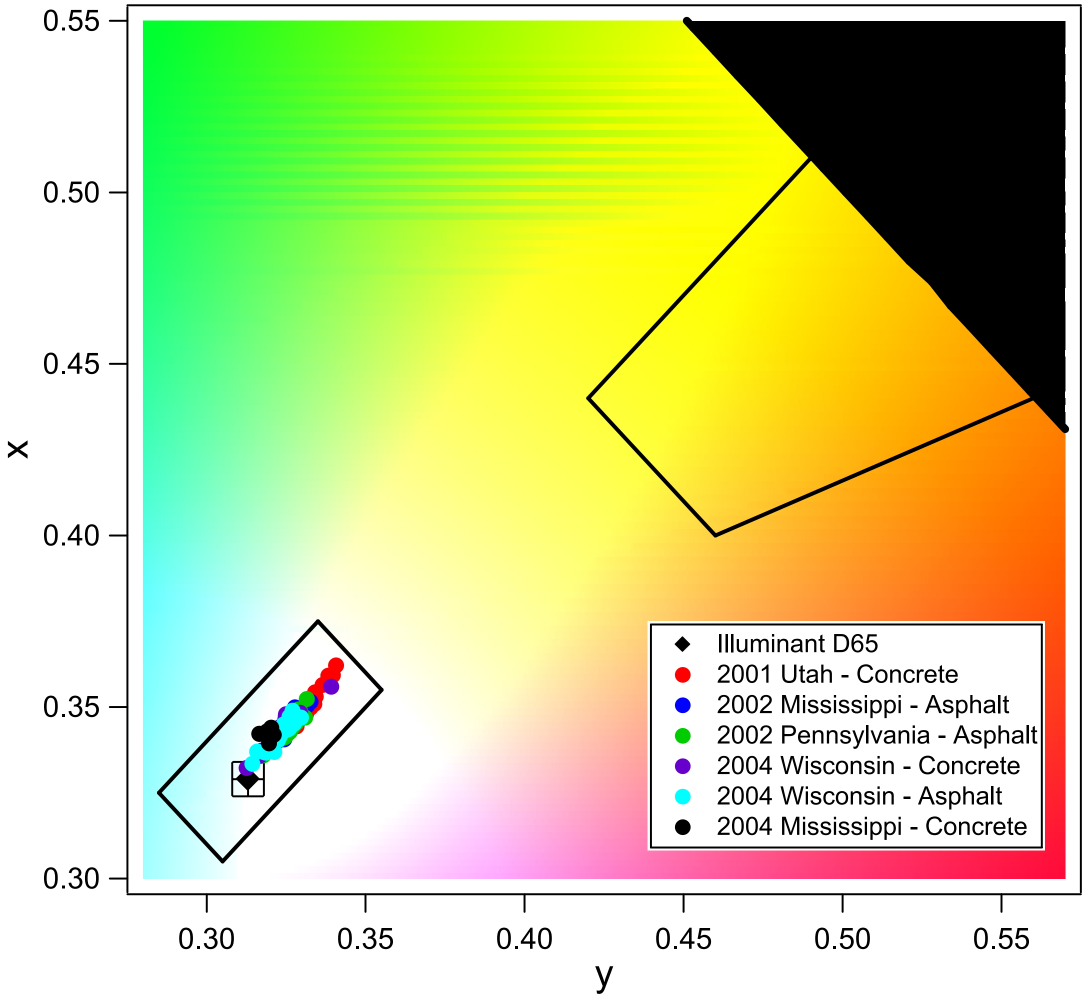


Figure 53 – All daytime measurements of white lines on the NTPEP test decks.

Also shown on the graph is the chromaticity coordinate for CIE Illuminant D65, the reference illuminant for the ASTM D6628-01 standard. The box around the Illuminant D65 mark represents the expanded uncertainty of the measurements. The overall conclusion for these measurements is that all the results, independent of the age or location, are within the acceptable limits. Figure 54 shows the daytime measurements of the white lines on NTPEP decks sorted by the type of material. Within the uncertainty of the measurement no conclusions can be drawn between material types.

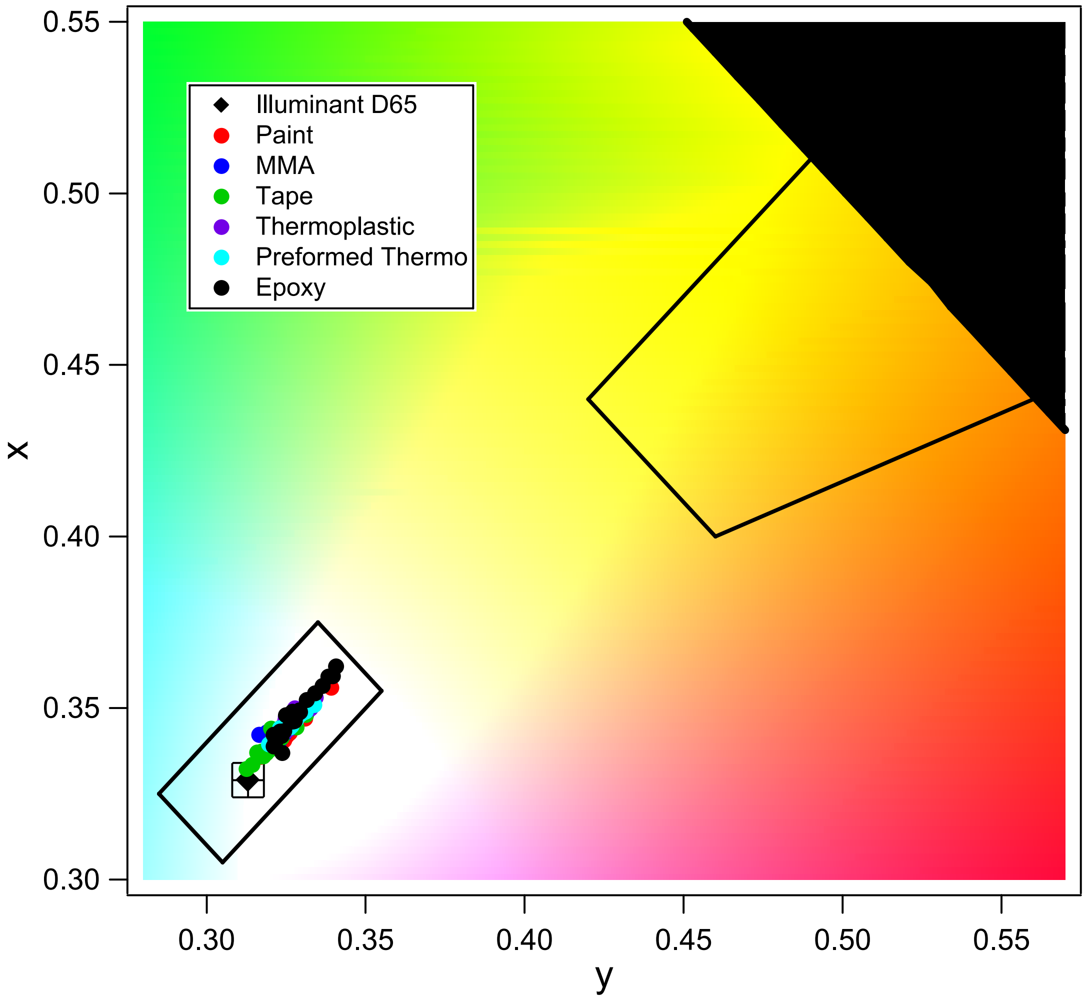


Figure 54 - All daytime measurements of white lines sorted by type.

The daytime specification is based on the 0/45 geometry. A proposed method of measuring the daytime specification of pavement material is using the Q_d geometry. The Q_d geometry diffusely lights the sample and views it at a 30 m geometry, which would appear to represent the real world situation. Figure 55 shows the Q_d measurements of same white lines shown in Fig. 53 sorted by location and Fig. 56 shows the Q_d measurements sorted by type of material. For white material the Q_d measurements show little difference compared to the daytime (0/45) measurements. The spread of Q_d measurements compared to the daytime (0/45) measurements is slightly larger which is due to the larger uncertainty of the Q_d measurements represented by the box around the Illuminant D65 mark.

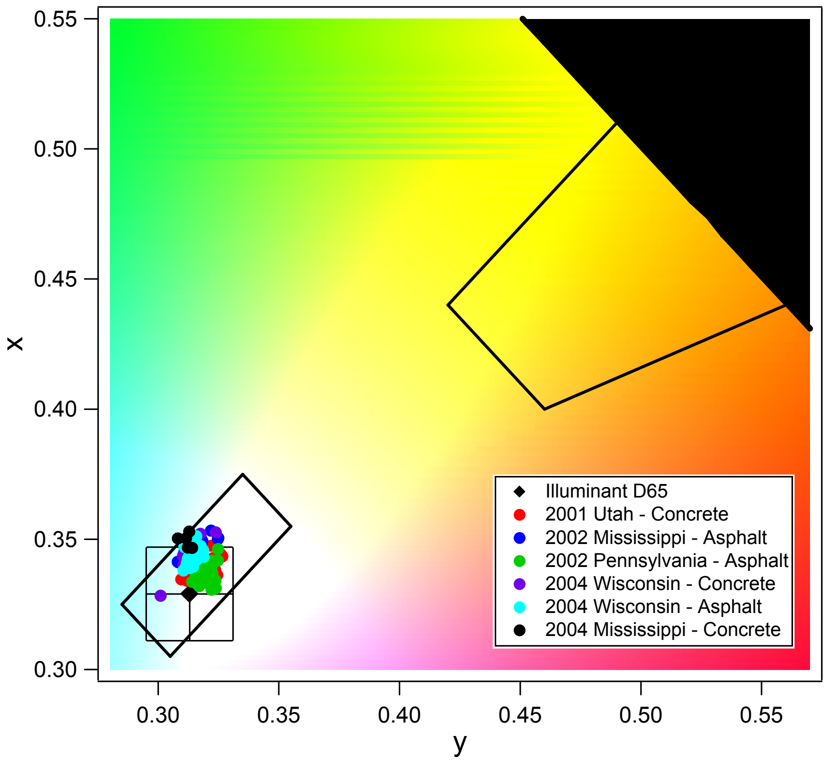


Figure 55 – All Q_d measurements of white lines on the NTPEP test decks.

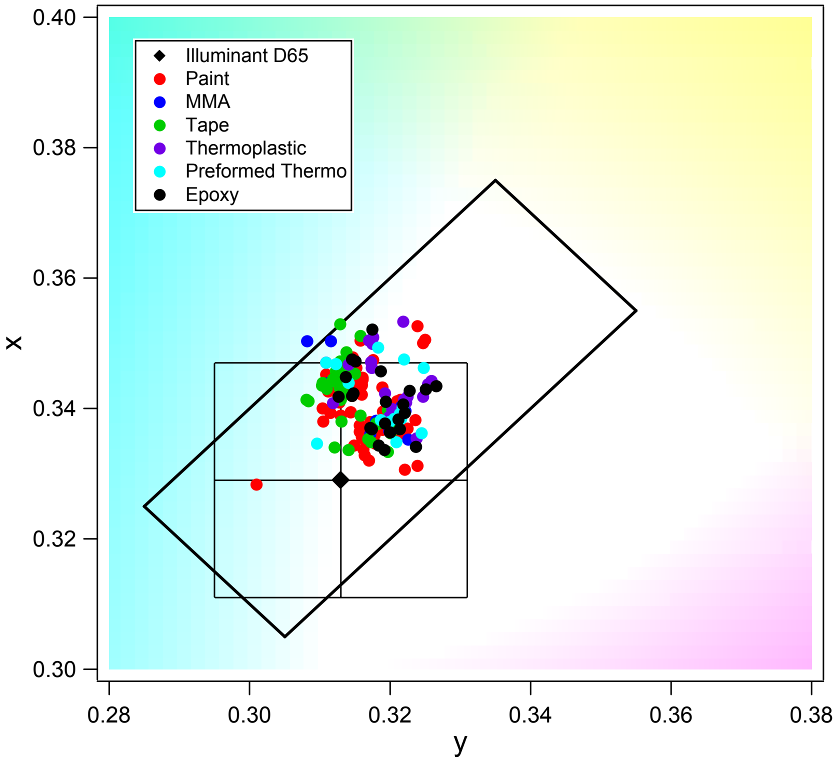


Figure 56 - All Q_d measurements of white lines sorted by type.

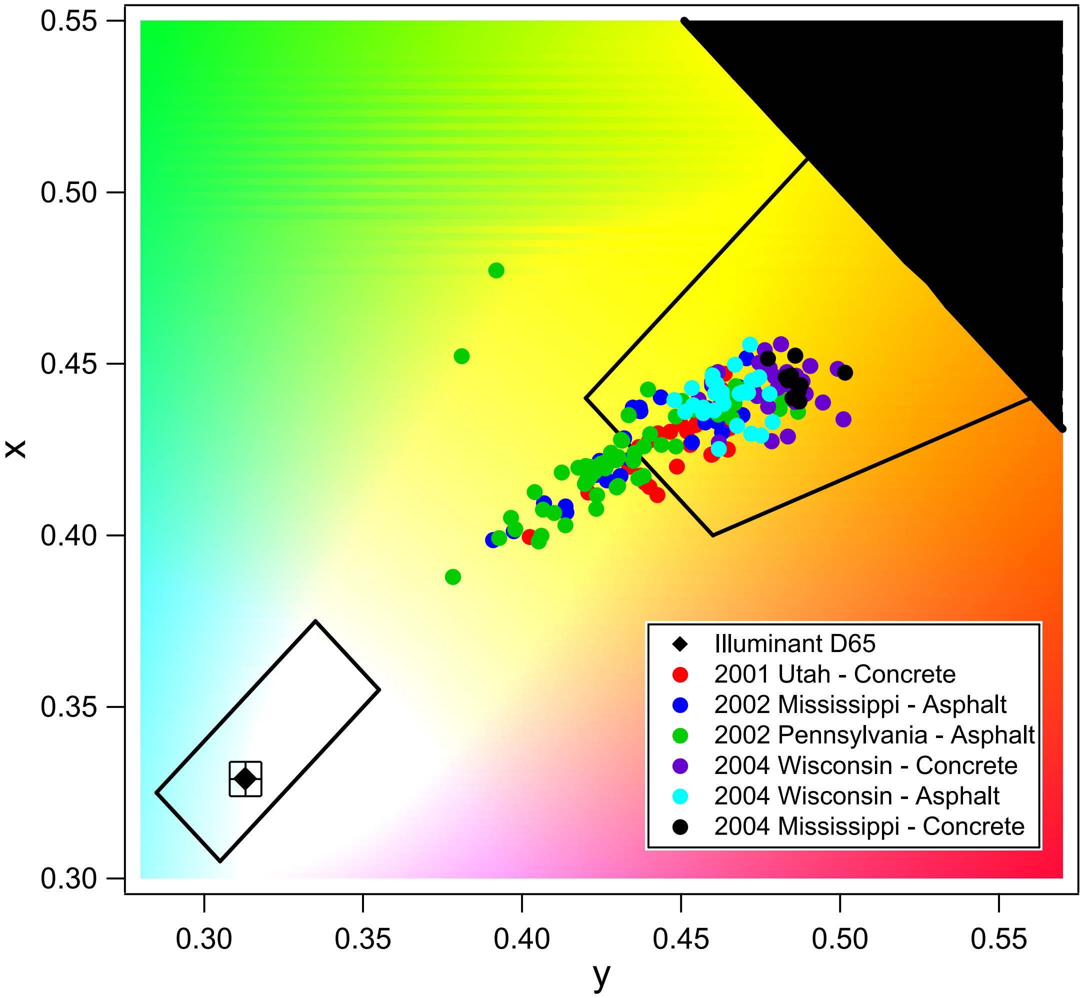


Figure 57 – All daytime measurements of yellow lines on the NTPEP test decks.

Figure 57 shows the daytime measurements of all the yellow lines on NTPEP test decks using the 0/45 instrument. The two points approaching the green part of the chromaticity diagram are intended to be yellow-green pavement marking material. Since none of the lines are the exact same material used at different times, conclusions for an aging study must be general. One conclusion is as the material ages it becomes whiter, falling out of the ASTM box. Another possible conclusion is that the environmental conditions due to the different geographical locations do not make a difference in the chromaticity change over time. Figure 58 shows the daytime measurements of all the yellow lines sorted by the type of material. All of the materials are susceptible to the aging process shown by the fact that all of the materials had at least one measurement fall out of the ASTM box. The thermoplastic material had just one measurement out of 42 fall outside the ASTM box. It was located on a test deck in Pennsylvania applied in 2002. Table 9 shows the statistics for the daytime yellow measurements.

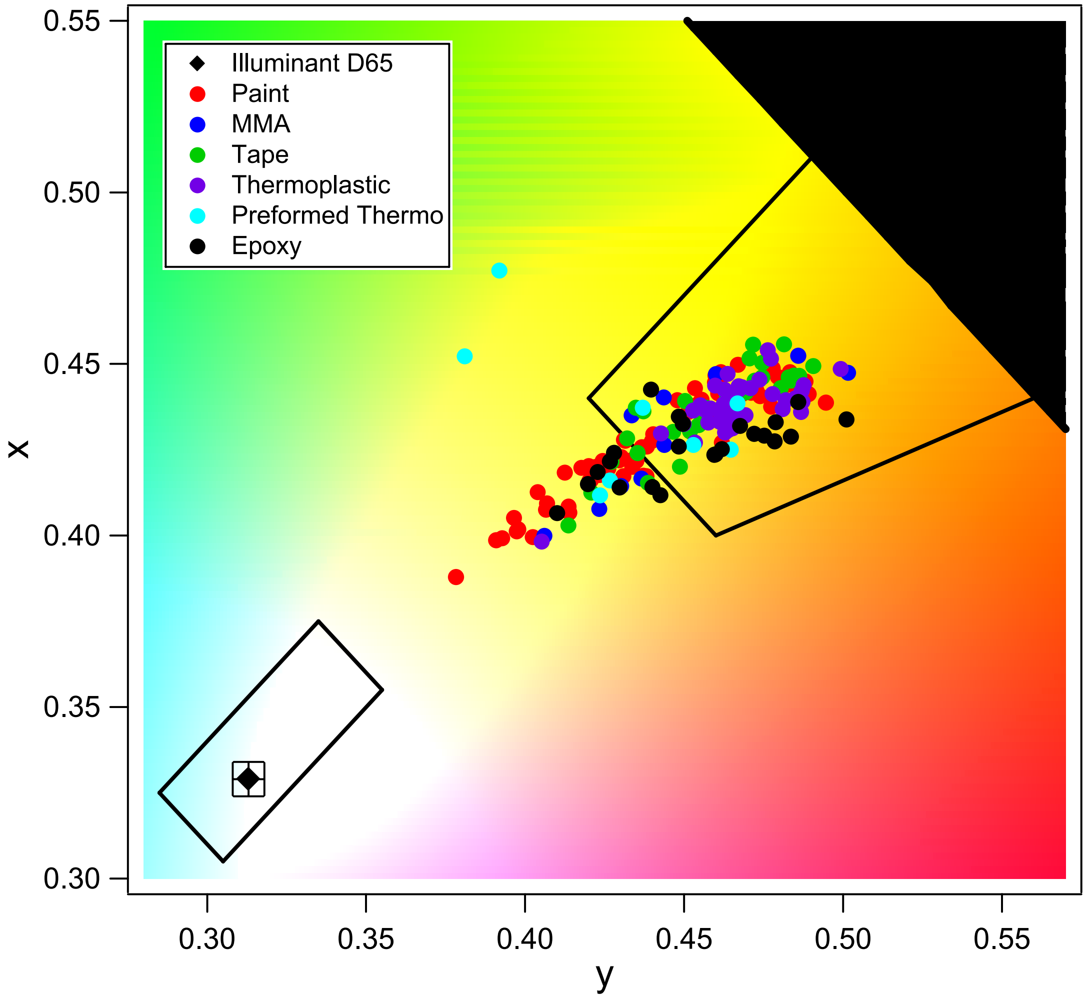


Figure 58 - All daytime measurements of yellow lines sorted by type.

Figure 59 shows the Q_d measurements of the same white lines shown in Fig. 57 sorted by location and Fig. 60 shows the Q_d measurements sorted by type of material. The Q_d measurements for the yellow lines is 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 daytime of 0./45 geometry has light the interacts with the pavement material in one direction. The diffuse scatter is detected in the 45 degree direction. The retroreflective properties of the material have little effect on the chromaticity measured. The Q_d measurement has many more optical process occurring. Figure 61 summarizes the general optical process for the

Table 9 – Daytime yellow line statistics

Year, Location	Surface	Age	Out of ASTM box	Type breakdown
2001 Utah	Concrete	3 years	7 out of 32	4 paint, 1 epoxy, 2 tape
2002 Mississippi	Asphalt	2 years	11 out of 29	9 paint, 1 tape, 1 pre thermo
2002 Pennsylvania	Asphalt	2 years	32 out of 51	20 paint, 2 epoxy, 1 tape, 1 thermo, 2 pre thermo, 3 MMA, 3 urea
2004 Wisconsin	Concrete	3 months	0 out of 27	---
2004 Wisconsin	Asphalt	3 months	0 out of 28	---
2004 Mississippi	Concrete	2 weeks	0 out of 10	---
		Total	50 out of 177	

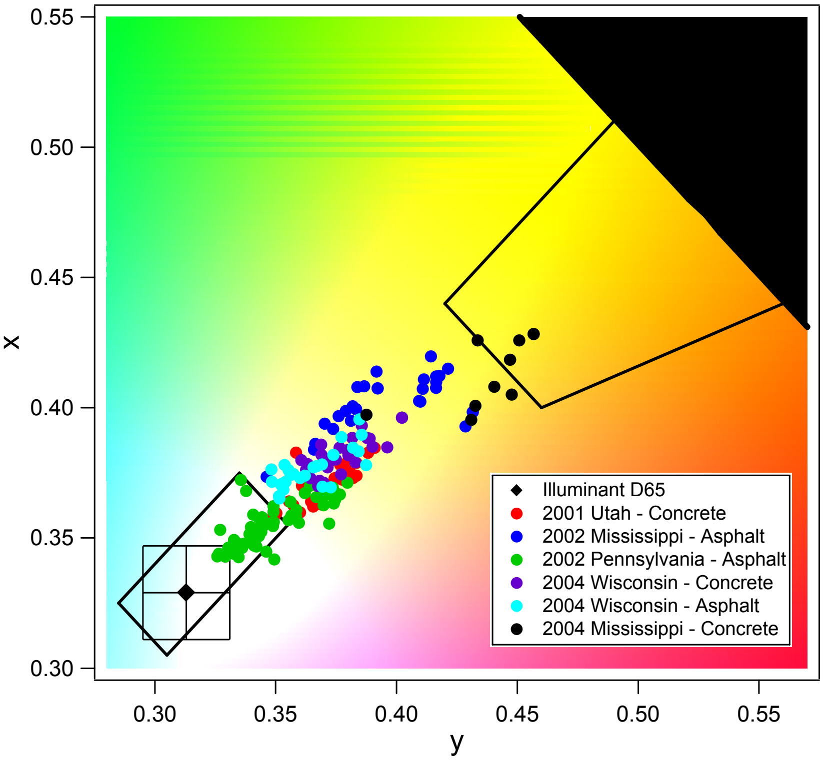


Figure 59 – All Q_d measurements of yellow lines on the NTPEP test decks.

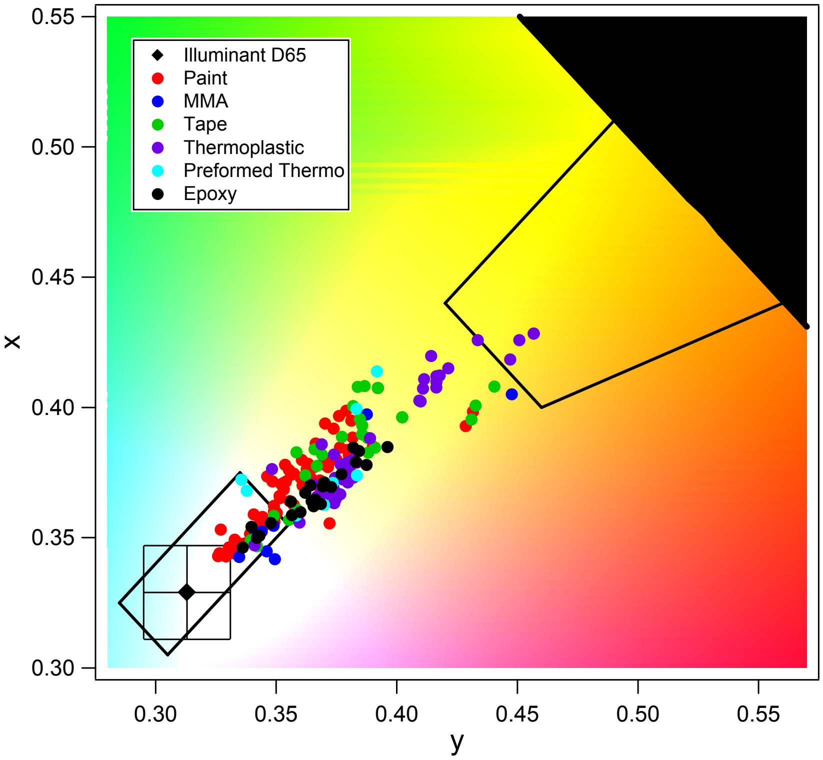


Figure 60 - All Q_d measurements of yellow lines sorted by type.

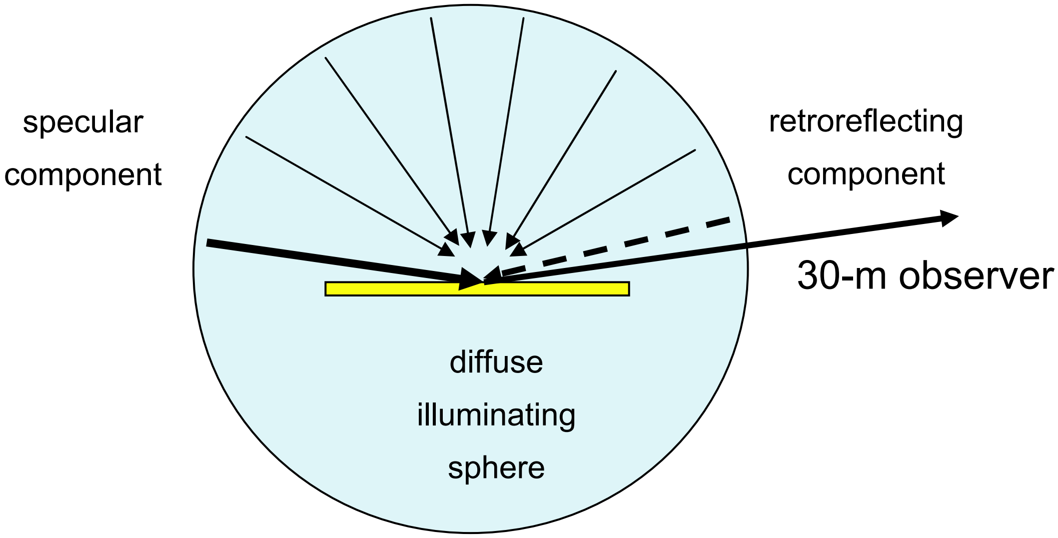


Figure 61 – A schematic of the diffuse/30-m viewing geometry shows that a specular (bold line) and retroreflecting (dashed line) component that is collected by the detector.

Q_d measurements. The primary signal comes from the diffuse illumination causing diffuse scatter that is viewed at the 30 m geometry. Two additional components affect the measurement of the chromaticity of the pavement marking sample. Since the material is designed to be retroreflective, light that emanates from the sphere wall close to the detector aperture is retroreflected. The chromaticity of the retroreflected light may be significantly different than the diffusely scattered light. This component does represent the real world because light does emanate from over the shoulder of the viewer. It critical concern is how the size of the detector aperture affects the signal. A smaller aperture will allow much smaller retroreflection angles and a larger aperture will preclude smaller retroreflection angles; therefore the retroreflected signal will depend on the instrument geometry. Dependence on the instrument geometry is not desired. The second component is the specular component. Light that emanates from the far edge of the sphere follows a specular path into the detector. The chromaticity of the specular light is the same as the source, CIE Illuminant D65. The magnitude of the specular light will depend on the gloss of the sample. The gloss of the pavement material depends on many aspects including how new the sample is, the type of material, and the moisture content on the surface. Once again this is a real world situation. One can image an open mid-west road where the light coming from the horizon is the predominant source of light. However, in a northeast tree lined road, a specular component may not exist because the trees block the specular source. For the portable measurements, the specular component is the reason the samples measure with a whiter chromaticity. Additionally, research is required that establishes correlations between the Q_d measurements and the real world scenario. The geometry of the Q_d measurement needs to be standardized based on the correlation research. The daytime data is graphed by type with respect to year of application. Graph 62 is for yellow paint lines. Graph 63 is for yellow epoxy lines. Graph 64 shows the yellow tape lines and Graph 65 shows the yellow thermoplastic lines.

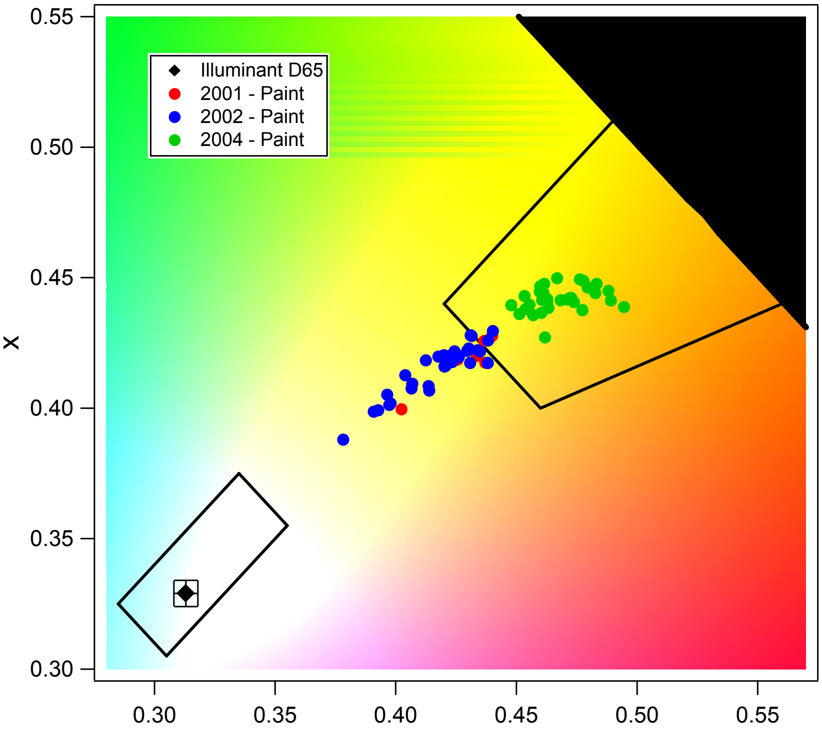


Figure 62 – All daytime measurements of yellow paint lines on the NTPEP test decks.

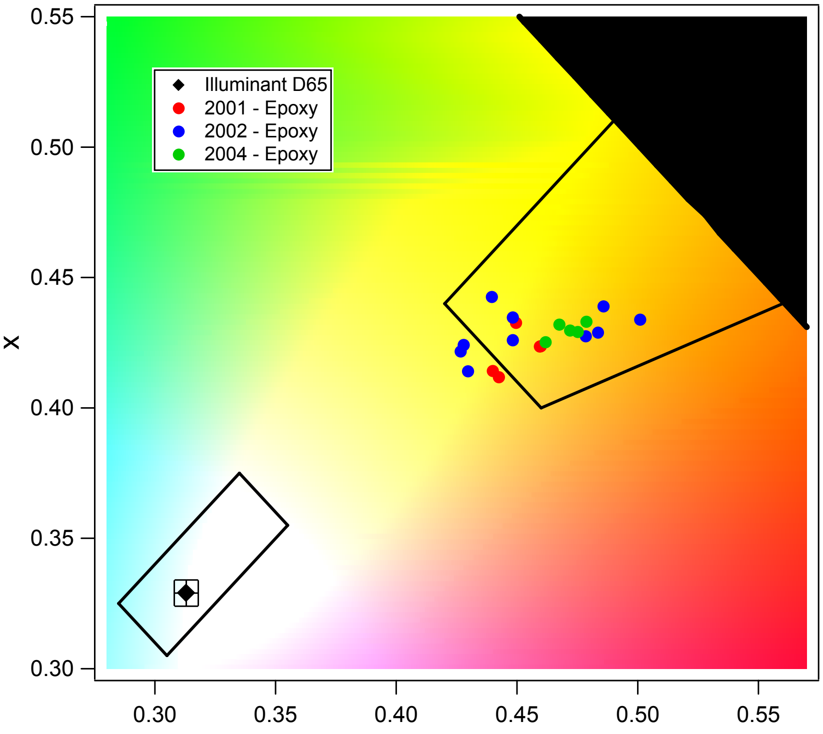


Figure 63 – All daytime measurements of yellow epoxy lines on the NTPEP test decks.

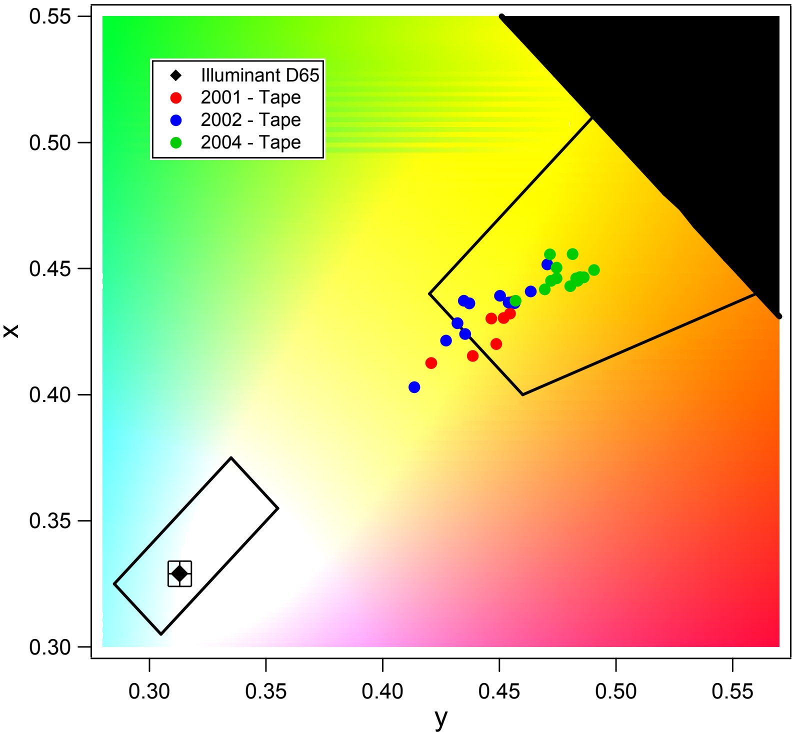


Figure 64 – All daytime measurements of yellow tape lines on the NTPEP test decks.

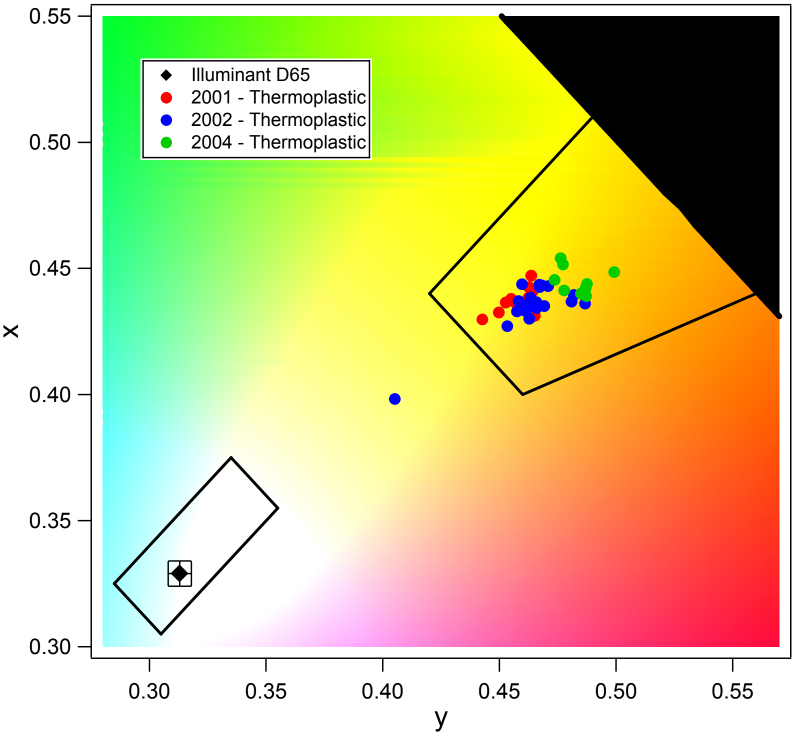


Figure 65 – All daytime measurements of NTPEP test deck yellow thermoplastic lines.

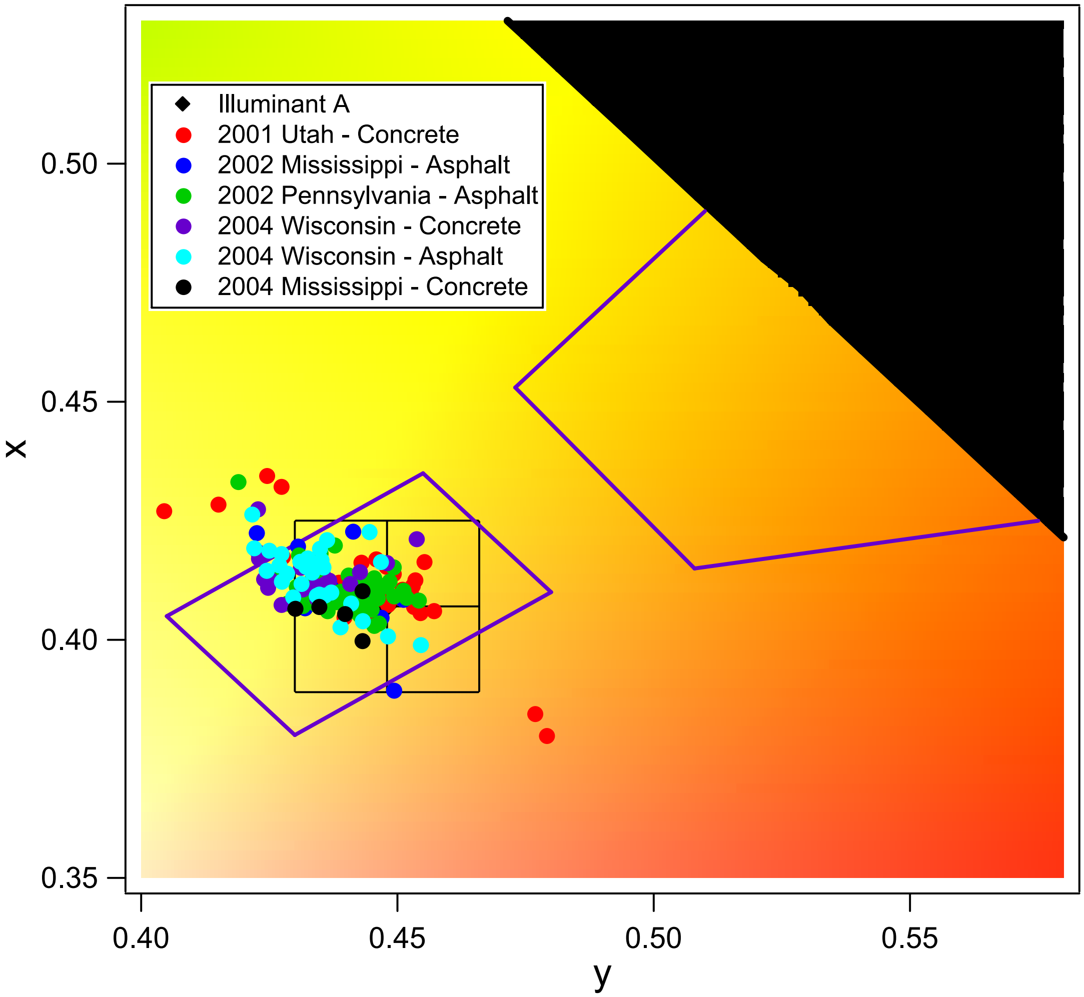


Figure 66 – All nighttime measurements of white lines on the NTPEP test decks.

NIGHTTIME MEASUREMENTS

Figure 66 shows the nighttime measurements of all the white lines on NTPEP test decks using the nighttime 30 m geometry instrument. The individual chromaticity points are plot on an enlarged (*x, y*) 1931 chromaticity diagram. The boxes represent the acceptable white and yellow chromaticities defined in the ASTM standard D6628-01

Also shown on the graph is the chromaticity coordinate for CIE Illuminant A, the reference illuminant for the ASTM D6628-01 standard. The box around the Illuminant A mark represents the expanded uncertainty of the measurements. 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 along the red-green axis is due to the fact that the R_L values measured for the points outside the box have a magnitude less than 30 mcd/m^2/lx.

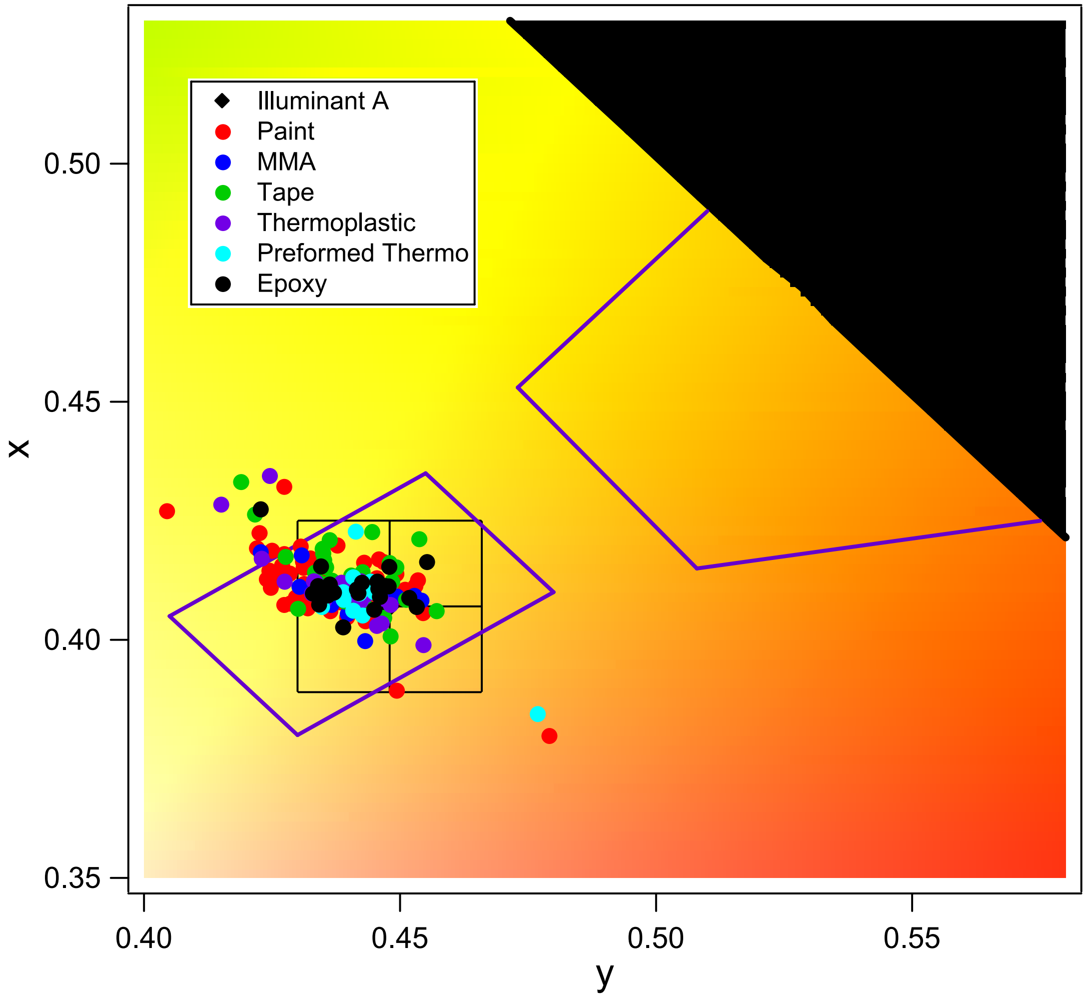


Figure 67 – All nighttime measurements of white lines sorted by type.

Because of the resolution of the instrument read out, the uncertainty of the chromaticity measurement is 0.060 (k=2) for x and y. Figure 67 shows the nighttime measurements of the white lines on NTPEP decks sorted by the type of material. Table 10 presents the number of points outside of the ASTM boxes along with the types of materials that fall outside of the box. Within the uncertainty of the measurement no conclusions can be drawn between material types for the white lines.

Figure 68 shows the nighttime measurements of the yellow lines on the NTPEP decks and Figure 69 shows the nighttime measurements of the yellow lines sorted by type of material.

Unfortunately the instrument does not have a small enough uncertainty to allow a complete analysis or accurate conclusions based on the material type, age and location. Some generalities can be made assuming the uncertainty causes a spread along the red-green axis. The spread along the blue-yellow axis is predominantly due to the fluctuation in the blue or *z*-channel. The blue channel has a typical magnitude of 2 – 6 for the measurement of the yellow lines. A change of one unit in the blue channel changes the chromaticity coordinates by roughly 0.008; therefore, conclusions or generalities can be drawn about the data between the white and yellow boxes. The yellow lines appear to become whiter with age as shown in Figure 68. 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 appears white under nighttime conditions fall within the yellow ASTM box for daytime measurements. The two yellow line measurements are all paint.

Table 10 – Nighttime white line statistics

Year, Location	Surface	Age	Out of ASTM box	Type breakdown
2001 Utah	Concrete	3 years	6 out of 45	3 paint, 2 thermo, 1 pre thermo
2002 Mississippi	Asphalt	2 years	2 out of 21	2 paint
2002 Pennsylvania	Asphalt	2 years	1 out of 67	1 tape
2004 Wisconsin	Concrete	3 months	2 out of 21	1 MMA, 1 epoxy
2004 Wisconsin	Asphalt	3 months	2 out of 32	1 paint, 1 tape
2004 Mississippi	Concrete	2 weeks	0 out of 5	---
		Total	13 out of 191	

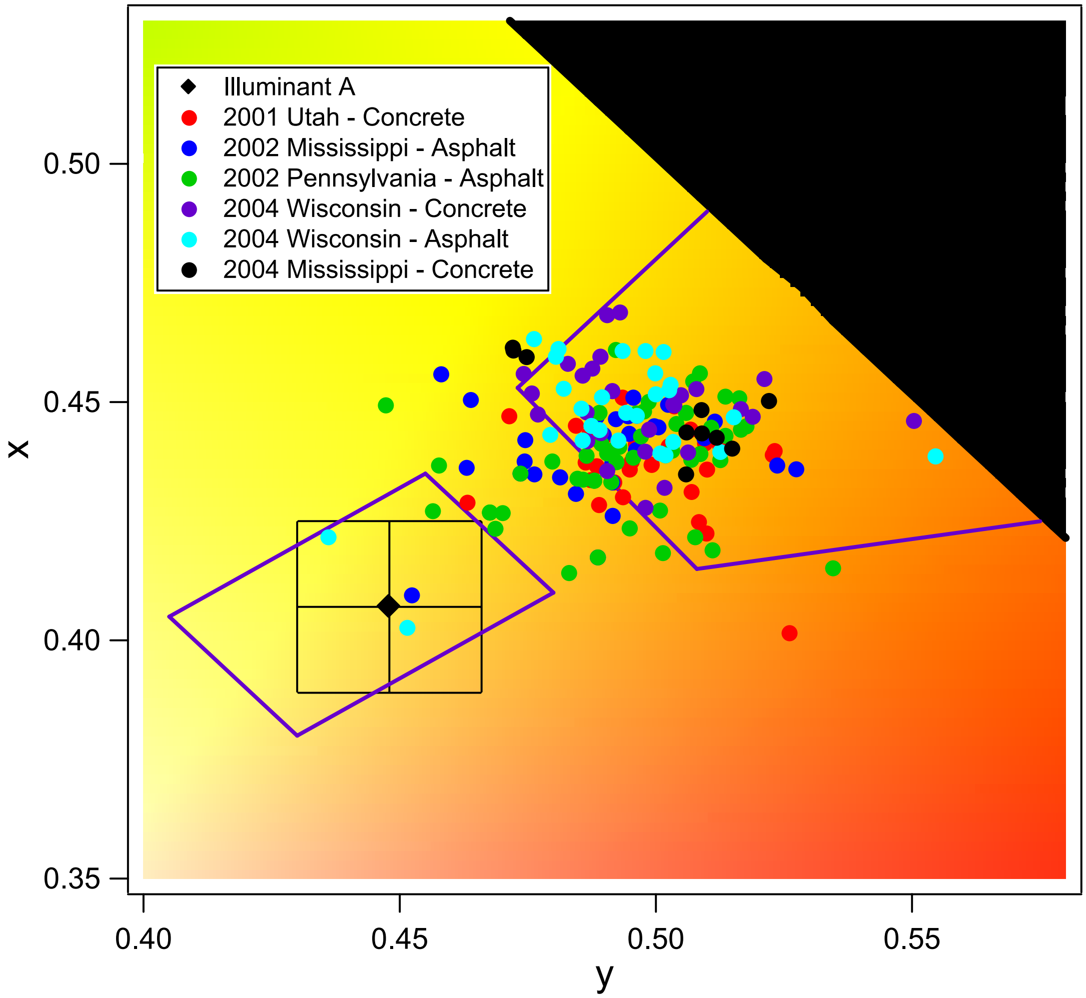


Figure 68 – All nighttime measurements of yellow lines on the NTPEP test decks.

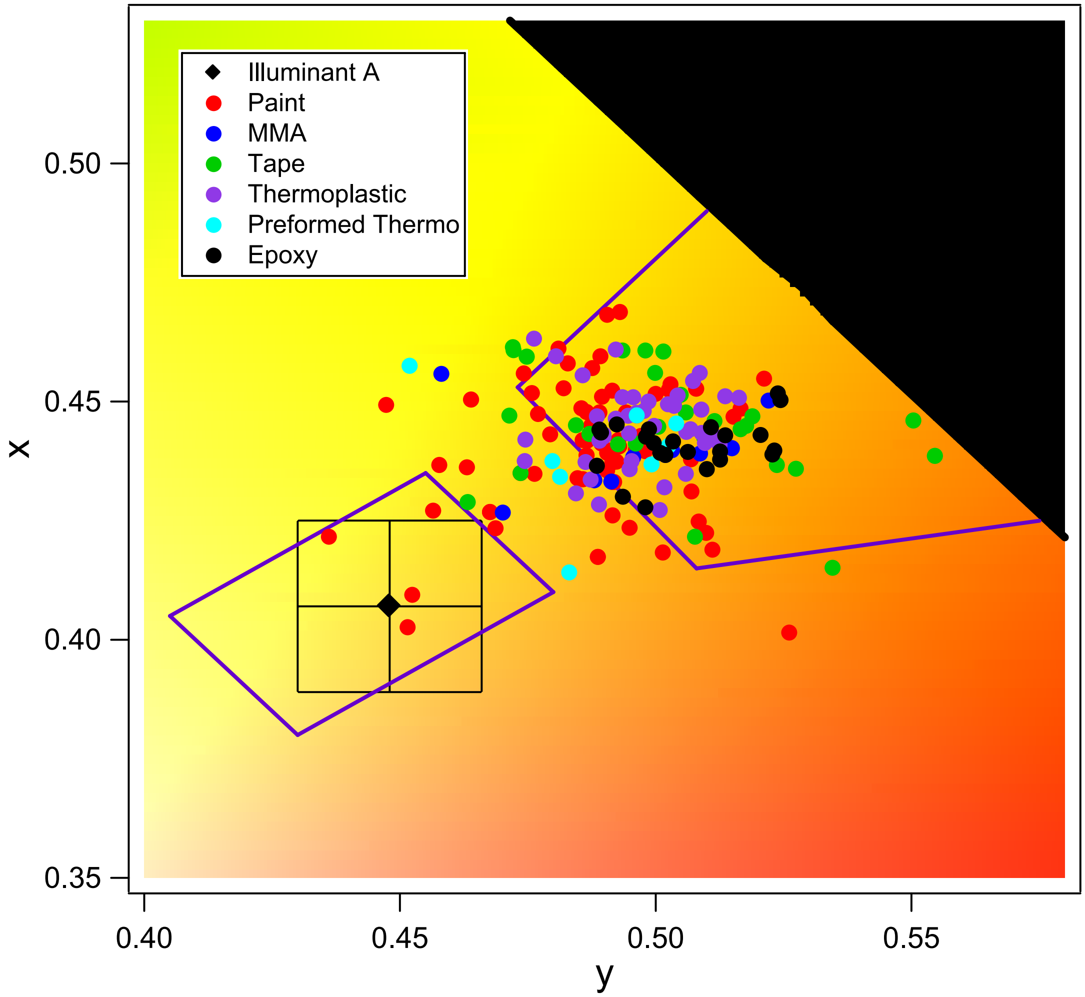


Figure 69 – All nighttime measurements of yellow lines sorted by material type.

The nighttime data is graphed by type with respect to year of application. Graph 70 is for yellow paint lines. Graph 71 is for yellow epoxy lines. Graph 72 shows the yellow tape lines and Graph 73 shows the yellow thermoplastic lines.

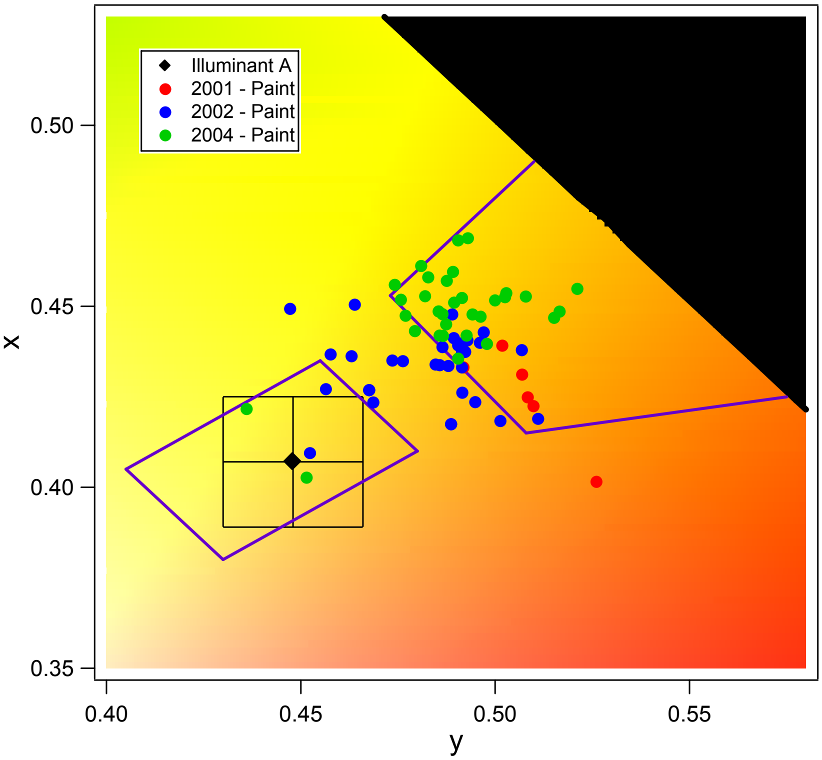


Figure 70 – All nighttime measurements of yellow paint lines on the NTPEP test decks.

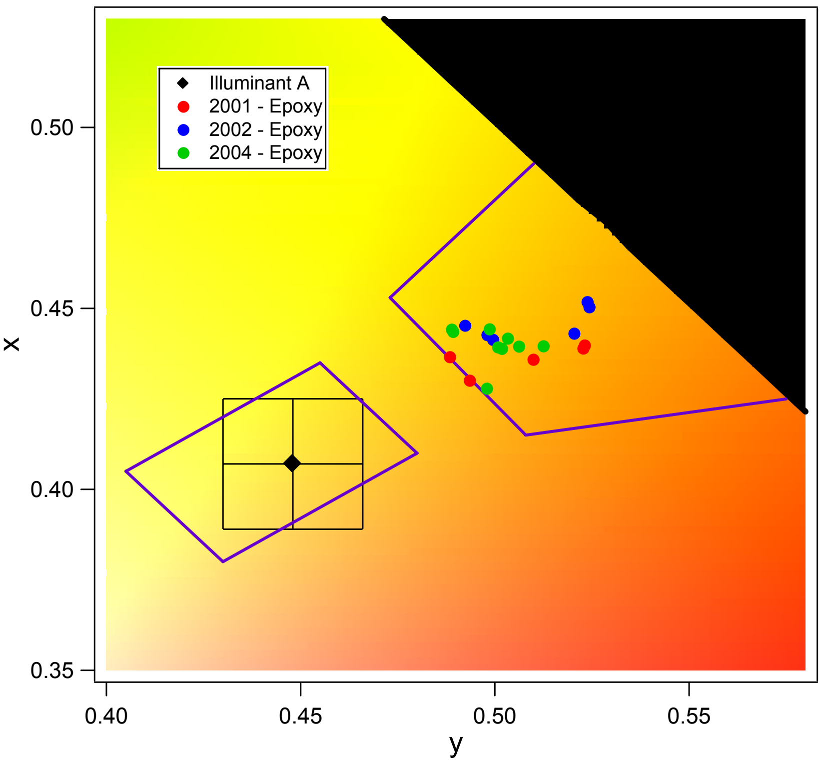


Figure 71 – All nighttime measurements of NTPEP test deck yellow epoxy lines.

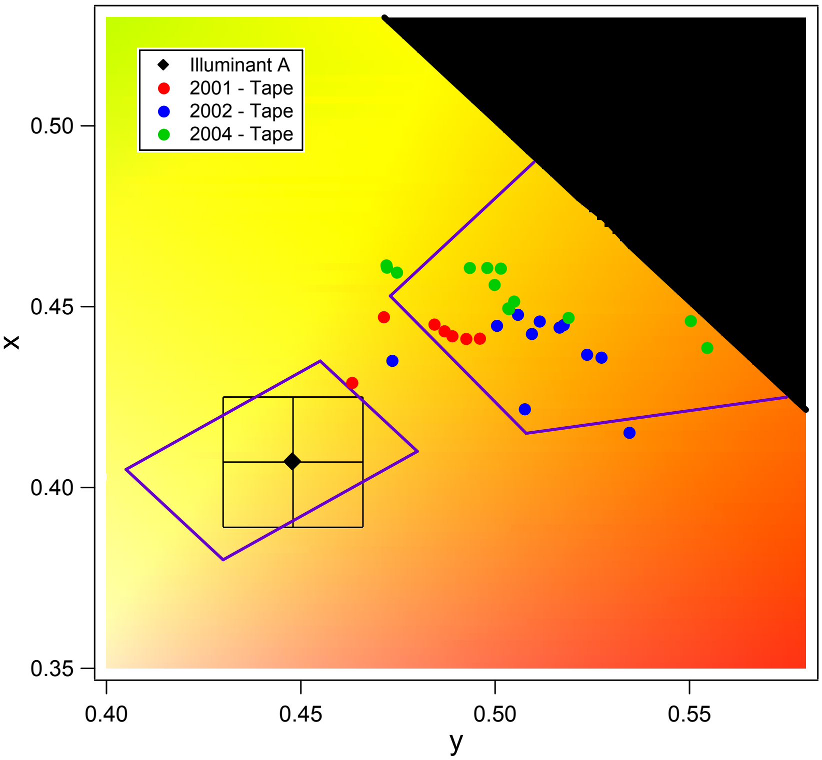


Figure 72 – All nighttime measurements of NTPEP test deck yellow tape lines.

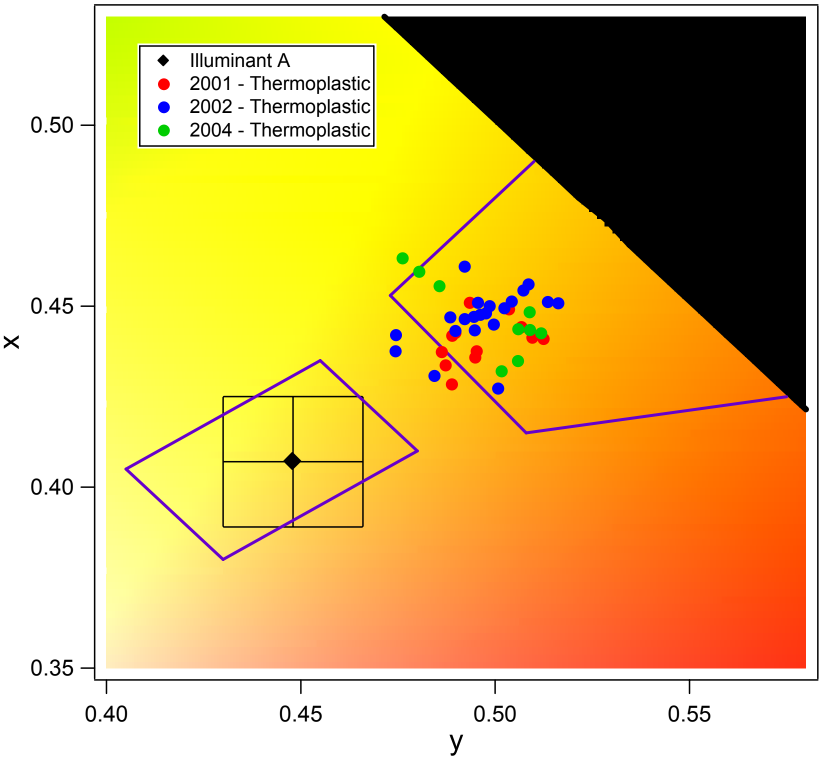


Figure 73 – All nighttime measurements of NTPEP deck yellow thermoplastic lines.

LEAD AND LEAD FREE MEASUREMENTS

Many manufacturers are producing pavement marking material that is lead free reacting to environmental concerns. An analysis was completed to determine if the pavement marking materials with lead had a significantly different chromaticity than the lead free products. Figure 74 shows the daytime measurements (0/45) and the Q_d measurements for the yellow thermoplastic pavement marking lines for all the NTPEP test decks that were known to have lead pigment or known to be lead-free pigments. The daytime and Q_d measurements shows that little chromaticity difference is measured between lead and lead-free pigments. Figure 75 shows the nighttime measurements for the yellow thermoplastic pavement marking lines for all the NTPEP test decks that were known to have lead pigment or known to be lead-free pigments. The materials with lead pigment appear to have a shift in the direction of orange-red compare to the lead-free material. However, due to the uncertainty of the nighttime instrument no conclusions can be made. Therefore, no measurable difference exists for lead-free materials versus materials that have lead pigment.

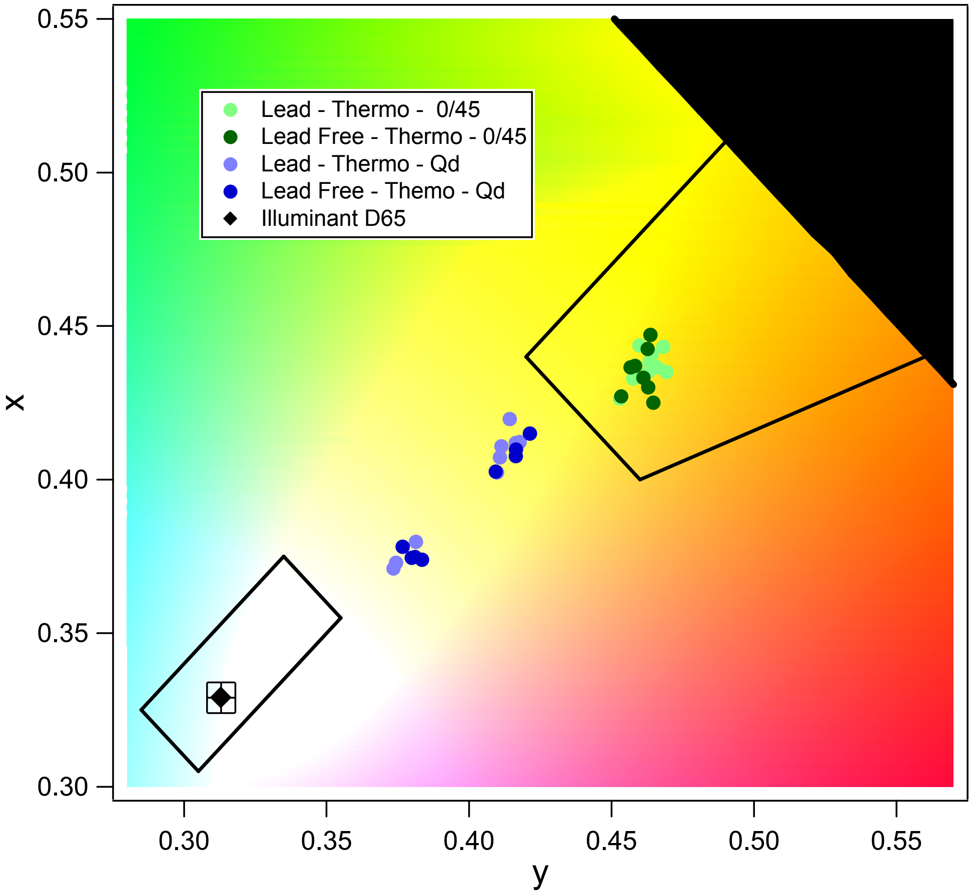


Figure 74 – All daytime measurements of thermoplastic yellow pavement marking lines on the NTPEP test decks that were know to be lead-free or contain lead pigment.

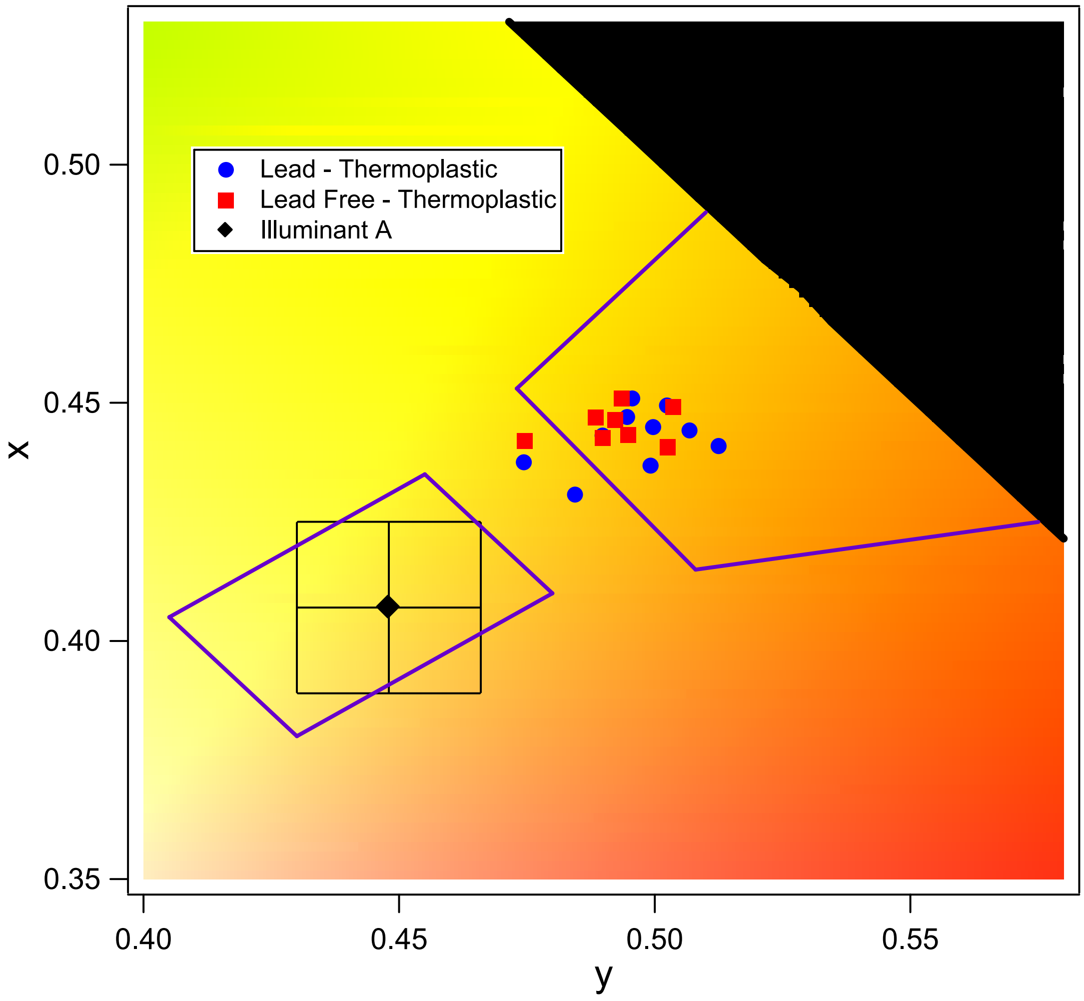


Figure 75 – All nighttime measurements of thermoplastic yellow pavement marking lines on the NTPEP test decks that were know to be lead-free or contain lead pigment.

CHAPTER 7: DISCUSSION AND CONCLUSIONS

Color naming and discrimination, especially when it comes to white and yellow colors, depends heavily on the chromaticity and luminance of the sample, and the spectral power distribution of the light source under which the sample is observed. The correlation between trichromatic properties and perceptional attributes is a stochastic process. For each distinct light source and luminance level, there are distinctive iso-chrome curves that define chromaticities which would be identified as a certain color with a given probability. Chromaticity is determined according to the photoreceptors in the human eye, and can be measured with calibrated instruments. However, chromaticity alone does not determine color in the context of color naming. The SPD of the light source that illuminates the overall scene leads to chromatic adaptation, which causes qualitative adjustments to the perception of a particular chromaticity. This secondary processing occurs deeper in the visual system succeeding the trichromatic photoreceptor level. For instance, the same chromaticity can be called white or yellow by a majority of observers, depending on the SPD of the light source. It is likely that chromaticities closer to that of the illuminating light source be identified as white. This is in fact how ASTM D6628 (and FHWA) specified the color boxes in the first place, i.e. the nighttime white box fences the chromaticity of CIE standard illuminant A, and daytime color box fences the chromaticity of CIE D65 (the chromaticity of the light source is usually referred to as the "white point"). Hence, under illuminant A, which simulates most tungsten halogen headlamps, color rendition of yellow and white pavement markings deserves careful attention, because the chromaticity of Illuminant A is closer to the spectral locus of yellow compared to most standard light sources, which creates more potential for confusion between white and yellow. The color booth experiment clearly supports this argument.

Last, but not least, luminance is a key factor besides chromaticity and illuminant SPD in color identification. Lower luminances, similar to very high luminances, limit hue rendition and promote achromatic perception. With regard to color rendition of pavement markings viewed during the nighttime, very high luminances are usually not the problem. It is the lower end of the luminance scale that may lead to achromatic perception of yellow. Especially under low luminance conditions, it is advantageous to render chromaticities close to the spectral locus and farther away from the white point of the light source. Our findings from the color booth experiment, back-projection screen experiment, and the field experiment strongly support this notion.

Iso-chrome curves, therefore, are functions of the light source and the luminance of the sample. For yellow, as the luminance decreases, the iso-chrome curves shrink and draw near the spectral locus, while the iso-chrome curves for white expands around the light source chromaticity. The center of the innermost yellow iso-chrome curve is always on the spectral locus, yet its location depends on the light source chromaticity. It is our understanding through the experiments that for daytime, the epicenter is located toward the yellow-green locus, and for nighttime (under incandescent source), the center shift downward toward yellow-orange locus. The iso-chrome curves for a particular light source can thereby be envisioned as three-dimensional solids, with luminance being the third dimension.

When the level of most pavement marking luminances in nighttime is considered to be below 5 cd/m^2, it is desirable that measured chromaticities for yellow pavement markings be close to the spectral locus (more saturation). Also, the color booth experiment clearly suggests that the upper half, especially the upper left region of the ASTM D6628 nighttime yellow color box, where the chromaticities are closer to yellow-green than yellow-orange, there is a higher risk of confusion with white. The white iso-chrome curves for low luminance levels extend and encroach well into this upper section of the color box for incandescent light sources. Chromaticities in the yellow-orange region toward the bottom half of the ASTM D6628 nighttime yellow color box are more likely to be identified as yellow in low-luminance conditions, especially when the only other choice is white. Survey findings indicate that some states already are aware of the benefits of using more red hues in yellow pavement markings.

The second laboratory experiment with the rear-projection screen also supports the above argument. We found that the percentage of yellow responses increased in the direction toward yellow-orange, and responses came much faster.

The field experiment also shows the effect of luminance and chromaticity on color perception. The type of pavement marking and the distance of the pavement marking stripes to the observer affected participants color assessment. Also, the percentage of "yellow" responses did not follow the same pattern for all materials with increasing distance. Thermoplastic materials with high yellow saturation (low titanium dioxide content) suffered a sharp decline in the percentage of yellow responses at far distances, whereas less saturated yellow thermoplastics (higher titanium dioxide content) maintained a relatively lower but consistent percentage of yellow responses for distances up to 180ft (54.9m). The production grade thermoplastic material overall yielded the highest yellow ratings. Latex paint type pavement marking was not affected by distance as much as other materials, yet overall it performed worst.

There was a slight but clear chromaticity shift for all pavement markings with increasing distance. All pavement markings exhibited a shift toward the chromaticity of the light source (white point) with increasing distance. However, the shift in the chromaticity was relatively subtle, and even at 180ft distance, most pavement markings were still inside the ASTM D6628 yellow nighttime box for TH headlamps. The sharp decline in the yellow ratings at far distances was most likely due to low luminance levels rather than chromaticity. The path of the gradual shift in chromaticity was almost identical for all materials.

Nonetheless, chromaticity at 180ft (55m) or beyond may not be as important for color assessment purposes, when compared to retroreflectivity at such distances for lane guidance. If drivers can successfully and readily perceive the color of pavement markings close by, they would also know the continuity of the color as far as they can see. The reach of their visibility is directly related with retroreflectivity, which also helps render yellow color. Therefore, ASTM E1710 30m geometry may already be a suitable platform for color evaluation purposes.

The shift in the observed chromaticities from TH headlamps to HID headlamps was notable. Nevertheless, there were no statistical or practical difference between HID and TH headlamps in terms of color identification. Still, HID headlamps helped render deeper yellow hues at far distances especially for latex paint type pavement markings.

None of the pavement markings in the field experiment had a more red hue to render orange-yellow chroma. Based on the findings of the rear-projection screen experiment and the color booth experiment, it is reasonable to assume that such a pavement marking would have yielded the higher rates of yellow responses under both headlamps.

The currently available National Transportation Product Evaluation Program (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 that range 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 ± 0.018 (k=2) chromaticity units. The uncertainty for the Q_d and nighttime instrument is dominated by the display resolution.

For all the white lines measured by the daytime and Q_d instruments the resulting chromaticities 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 on measurement, falling out of the ASTM box. Two, is that 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 is 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 the further research.

For the nighttime measurements no conclusion could be drawn 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 appears white under nighttime conditions fall within the yellow ASTM box for daytime measurements. The two yellow line measurements are all paint.

An overall conclusion realized from this work is that tungsten halogen 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 that has a 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.

The last analysis was completed 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 shows that 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. Therefore, no measurable difference exists for lead-free materials versus materials that have lead pigment.

RECOMMENDATIONS

Based on the results of this work, we recommend changes 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.

The first recommendation is to shift the nighttime yellow region slightly towards the red part of the chromaticity chart. This shift will reduce confusion with white. Several states have already changed their requirements to reflect this recommendation. The second recommendation is to add a single point to allow inclusion of the peak in the yellow response curve. Table 1 contains the resulting coordinates and for convenience, they are reproduced here again in Table 9.

Table 9. Recommended 05-18 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

Figure 1 shows the nighttime yellow boundary graphically along with the nighttime yellow response curves and Figure 2 shows the nighttime yellow boundary graphically along with the nighttime white response curves. The third recommendation is to 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. The fourth recommendation is to add a single point on the right side of the nighttime white region. 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. Table 2 presents the nighttime white boundary and for convenience, those coordinates are again reproduced here in Table 9. 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 left to be elongated in that direction.

Table 10. Recommended 05-18 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

The fifth recommendation is to leave the daytime white and yellow color regions unchanged. The data suggests no changes for the daytime white color region. The data does 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. 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; this is 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 additional 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 protocol for daytime and nighttime field measurements are very similar. The 0/45 instrument or 30-m geometry instrument should be calibrated according to the manufacturers specifications. For a given region of pavement marking material, select three representative spots and measure the chromaticity of the spots using the calibrated instrument. 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 selection of a representative spot is a subjective decision. 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 is only required to be sampled once because the instrument had a larger uncertainty than the pavement marking material fluctuation in chromaticity. The newer 30-m geometry instruments have a smaller 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. There use is not recommended at this time. Sampling the pavement marking material more than three times does not significant reduce the uncertainty of the chromaticity measured for a given region. More measurements only add additional time and cost.

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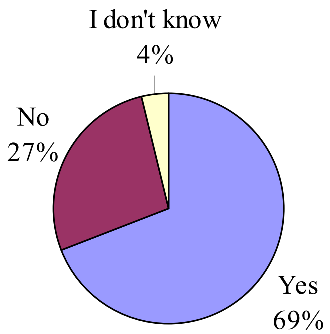
8. ASTM Standard Specification E1710 (Reapproved 2005). Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry Using a Portable Retroreflectometer. ASTM International, West Conshohochen, PA.

APPENDIX A: SURVEY

Table 11. Agency Survey Results

1. Does your agency require lead-free yellow pavement markings on the agency system of roads?



Responses:

Waterborne paint	16
Epoxy	6
Thermoplastic	5
Tape	3
Polyurea	2
Preformed tape	1
Acetone based paint	1
Preformed thermoplastic	1
Polyester	1
Acrylic copolymer paint	2
Alkyd	1
Cold plastic	1

Comments:

- SC: Thermoplastic and other durable striping material still contains lead pigments.
- IL: Thermoplastic, epoxy and chlorinated rubber traffic paint contain lead.
- OR: We use waterborne paint on approximately 60% of our highways. We also use thermoplastic and methyl methacrylate which with some of the versions approved for use in Oregon do contain lead but we are moving toward having these products being lead-free also.

2. Have you received any complaints from drivers about yellow pavement markings looking like white markings?

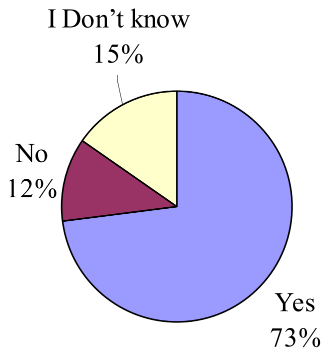
Responses:	
Yes	7
Nighttime	7
Daytime	1
2a. Were the complaints associated with any pigment?	
Lead free pigment	7
Leaded pigment	0
2b. Were the complaints associated with any binder?	
Paint	4
Epoxy	3
Thermoplastic	3

Comments:

- SC: The concerns are generally generated from within our agency.
- IA: This complaint was received several years ago. I have not heard any complaints of this nature in probably the last five years.
- CO: Yellow seems to vastly with our paints from batch to batch. big problem - retroreflectivity lost when using MgCl
- IL: When we tried lead free pigments in thermo...they turned peach and were not visible at night...we then went back to the leaded material.
- VA: Markings looked white at night and daytime color appearance faded soon after application.
- OH: We conducted research to establish color coordinates based upon drivers perseption and differentiation between colors. We use these coordinates to requirements for pavement marking warranty projects.

3. What has your agency done to improve the differentiation between yellow and white materials?
• SC: We have increased the testing frequency of durable markings to ensure that the specified amount of pigment is being provided. • IA: After we switched to lead-free yellow pigments and became aware of the wash-out problem for night-time color, we reduced the size yellow color box. We eliminated some of the green side of the color box and forced the color to fall more in the red side of the color box. • MN: Created Mn/DOT Yellow Color Box • IL: We use a color coordinate box developed from the Federal color box for yellow. We try to make our lines more of a red cast in order to improve nighttime visibility. • VA: Instituted daytime and nighttime color specifications. Require thermoplastic to undergo 3 months outdoor weathering prior to qualifying a formulation. • WV: We have integrated a performance/warranty pavement marking contract and stipulated color scales within this contract for both white and yellow markings. • City of North Las Vegas, NV: RPM'S • DE: We are in the process of creating a color spec for our state! • IN: Our specifications refer to the FHWA's color charts. • TX: We have made changes to our traffic paint formulation to try to improve this. • WI: Using more red in inorganic color helps night vision of yellow color. • MD: We are revising laboratory requirements portion of Color specification. We are also performing some hand held color meter tests in the field to gather data with surface beads. • OH: We did regular field evaluations to select pavement marking materials till 1988. We still do a few field demonstrations of new products. But we now rely primarily on NTPEP testing in Pennsylvania for selection of pavement marking materials. At present we have materials on PQL list from both NTPEP tests and our own filed test in Ohio. • NY: We have noted that the first few lead-free waterbased yellow markings we evaluated did look white at night.

4. Does your agency perform any laboratory or field measurements for material approval to qualify pavement marking materials specific to your agency's requirements before they are implemented?



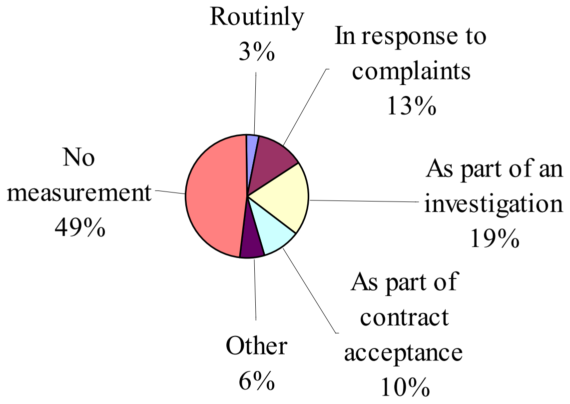
Responses:

Daytime	
Lab	14
Field	13
Other	6
Nighttime	
Lab	4
Field	7
Other	1

Comments:

- IA: We use 2 year NTPEP results for the approval of durable paint markings.
- MN: "Retroreflectivity in field, color in lab"
- IL: We test and approve all materials prior to their use in Illinois. This includes daylight reflectance. We do not perform nighttime color testing. Budget limits the purchase of testing equipment.
- VA: All products are batch tested for daytime color. Thermoplastic is also batch tested for nighttime color. Traffic paint formulations and preformed tape are approved based on their performance on the NTPEP test deck. Daytime color must be retained for a defined period.
- KY: We have attempted to go to a performance based approach. We do lab tests on material then 30-60 day tests for retro. Just starting with field color checks.
- IN: Field tests are for tape only. Lab tests are for waterborne paint only.
- WI: We work with Minnesota DOT on our regional NTPEP and notify the vendors of Wisconsin criteria.
- OR: For all yellow markings we require the material to conform to the PR-1 chart and shall meet 33538 Federal Yellow.
- NY: We did not approve markings which looked too white. We asked the manufacturers to submit new formulations to test.
- NH: We test all paint manufactures batches as well on the contractors samples to make sure they meet our spec.
- OR: We use a \'Qualified Products List\' (QPL), all products submitted will supply us with independent laboratory testing to show conformance to our specification criteria. We then place the material on a test deck of transverse lines that we monitor for presence and retroreflectivity. All products, per category, that perform at least as well as our control are placed on the QPL. The control is the product currently under contract for use on ORDOT highways. The next time we have an open competitive bid the products on the QPL are allowed to bid. We apply waterborne paint, thermoplastic, methyl methacrylate, and preformed tape. These products are applied both in-house and under contract by Contractors.

5. Does your agency require pavement marking colors be measured in the field after markings are newly installed?

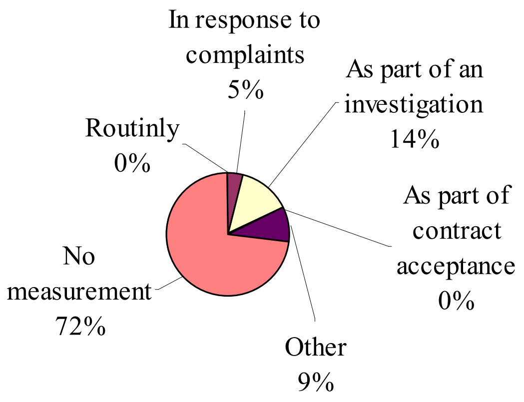


5a. What kinds of measurements?

Responses:		Comments:
Subjective evaluation of the yellow, Day only	3	
Subjective evaluation of the yellow, Night only	0	
Subjective evaluation of the yellow, Both	6	
Subjective evaluation of the white, Day only	3	
Subjective evaluation of the white, Night only	0	
Subjective evaluation of the white, Both	4	
Subjective evaluation of yellow color using a yellow color tolerance chart of standard colors	1	
Objective measurement of the yellow, Cap Y only	0	
Objective measurement of the yellow, Chromaticity only	3	
Objective measurement of the yellow, Both	2	

NTPEP and other test decks	4	
5b. What kinds of instruments do you use?		
LTL2000Y Retroreflectometer	5	
color-guide™ Spectrophotometer	2	
MiniScan XE Plus Spectrophotometer	3	
Other	0	
5c. What are the measured results being compared?		
ASTM D6628	3	• MD: We set ranges with a plus or minus and compare to laboratory and other field test results with surface beads included
FHWA Final Rule	0	
Own specifications	4	
5d. Who performs those measurements?		
The agency field measurement department	3	• IL: Typically the manufacturer of the material and the state officials. • NV: UNLV. • OH: Central Office team at the request of district if they see problem when subjectively evaluating the contract work.
The contractor who applied the pavement marking materials	0	
A specialized contractor	0	
Other	2	
5e. If the pavement marking color failed to pass any specific standard, what will your agency do?		
Replace the deficient pavement markings immediately	1	• NV: Our AC has high oil content. • IL: Our Bureau of Operations is in charge of experimental pavement marking evaluations. They typically work with the manufacturer of the new material to evaluate the work.
Require the contractor to replace the deficient pavement markings immediately	3	
Require the contractor to replace the deficient pavement markings within six months	0	
Don't pay the contractor who installed the pavement markings	0	
Consider the insufficient performance in future contract negotiations	2	
I don’t know	3	

6. Does your agency require pavement marking colors be measured in the field during the life of the markings?



6a. What kinds of measurements?

Responses:	
Subjective evaluation of the yellow, Day only	1
Subjective evaluation of the yellow, Night only	0
Subjective evaluation of the yellow, Both	3
Subjective evaluation of the white, Day only	2
Subjective evaluation of the white, Night only	0
Subjective evaluation of the white, Both	2
Subjective evaluation of yellow color using a yellow color tolerance chart of standard colors	2
Objective measurement of the yellow, Cap Y only	0
Objective measurement of the yellow, Chromaticity only	3
Objective measurement of the yellow, Both	0

Comments:

- OH: Subjective evaluation of yellow day only. Subjective evaluation of white day only. Subjective evaluation of yellow using a chart. Objective Evaluation of pm colors using a color capable instrument. Objective evaluation of yellow using Chromaticity Instrument is only used if subjective evaluation shows color problem.
- GA: Only inspected by eye (day and night).

NTPEP and other test decks	2	
6b. What kinds of instruments do you use?		
LTL2000Y Retroreflectometer	2	
color-guide^{TM} Spectrophotometer	0	
MiniScan XE Plus Spectrophotometer	2	
6c. How frequently does your agency measure pavement marking color?		
Every year during the life of the marker	1	• IA: The NTPEP decks are usually measured every 3 months for the first two years. • MN: Each lot in lab and on selected field samples. • WI: Every two years.
Every 0-6 months during the life of the marking	1	
Every 7-12 months during the life of the marker	1	
6d. What are the sampling procedures?		
Random Sampling	4	• IA: An 18 inch section of unbeaded line on a transverse deck.
6e. What are the measured results being compared to?		
ASTM D6628	1	
FHWA Final Rule	1	
Other	0	
6f. Who performs those measurements?		
The agency field measurement department	1	
The contractor who applied the pavement marking materials	0	
A specialized contractor	0	
Other	0	
I don’t know	2	
6g. If the pavement marking color failed to pass any specific standard, what will your agency do?		
Replace the deficient pavement markings immediately	1	• IA: Color is only measured when approving new materials. So if the color does not comply with our specifications, the new material is not placed on the approved products list. • MN: Reject lot.
Require the contractor to replace the deficient pavement markings immediately	4	

Require the contractor to replace the deficient pavement markings within six months	0	
Don't pay the contractor who installed the pavement markings	1	
Consider the insufficient performance in future contract negotiations	0	

7. If your agency requires pavement marking colors be measured, where are these measurements performed?

Responses:	
Only at specific locations after complaints	4
Only at specific locations based on the pavement marking material used.	1
Only in high traffic areas	1
Only in areas with a high rate of accidents	0
All locations	0

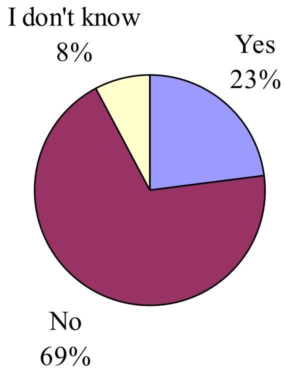
8. Who applies the pavement markings in your agency's jurisdiction?

Responses:	
We apply all of the pavement markings	0
Contractor(s) apply all of the pavement markings	1
We apply some and Contractor(s) apply some	20

Comments:

- SC: Our agency applies only waterborne striping paint and minor amounts of marking tape. All durable materials (tape, epoxy, thermoplastic) are applied by contractors.
- IA: "DOT maintenance applies almost all waterborne paint, contractors would only apply waterborne markings to new pavement surfaces. Durable paint and tape PM are applied by contractors
- IL: We apply the waterborne traffic paint, contractors apply all other pavement markings. I am not sure of the percentages.
- IN: We contract on all new construction, and use in-house forces for all maintenance.
- WI: Our Districts are going out of business but counties are taking over waterborne painting portion. Epoxy is all contractor applied
- GA: On new projects let to contract the contractor does but we maintain them after acceptance and also complete special projects.
- OR: Most of our construction project have contract pavement marking Contractors applying the markings but we have some of our markings that have been in place since 1994. That is why I said we have approximately 60% of our markings in paint but annually the paint approximately 85% of material applied.

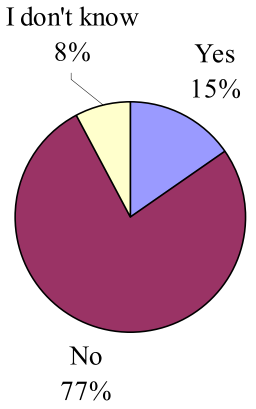
9. If your agency uses contractors to install the pavement markings, do those contractors provide any warranty for pavement marking color (or chromaticity), such that the pavement markings are guaranteed to perform for a period of time and at a satisfactory level in terms of chromaticity?



Comments:

- SC: We require a warranty for durable striping tape, but do not have any requirements for other materials. However, we generally defer subjective evaluation of materials for a period of 120 to 180 days so that workmanship problems have an opportunity to appear.
- TX: We have considered using a warranty specification but have not yet at this time. If we used a warranty specification we would likely include color measurement(s) at some frequency.
- MD: We may in the near future.
- OR: Our durable pavement markings require a Manufacturer warranty, and they provide annual training to certify people authorized to apply their product. The certification is for both State and Contractor employees. The warranty is either a 3 or 4 year warranty depending on product and application.

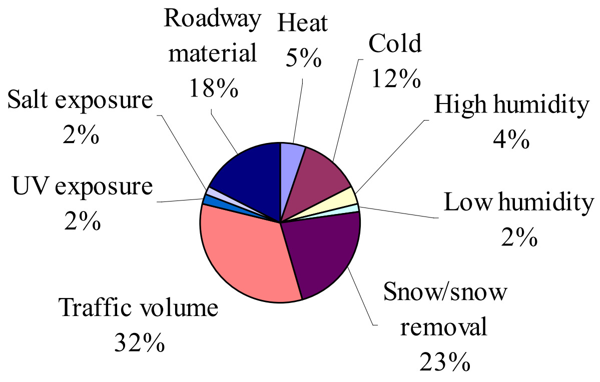
10. Does your highway agency use a performance-based specification, wherein payment for installation of pavement markings depends on satisfactory performance of the product in terms of chromaticity?



Comments:

- MO: We have specifications, the current one is at the above web address. We do not warrant the stripe based on color, although we have had a few instances where unacceptable yellow material has been placed, rejected and corrected by the contractor.
- OR: We do use performance based specifications to have products placed on the QPL and we have application specifications for installation. If the product does not get placed properly it is either removed and replaced correctly or we assess an adjustment to the price paid the Contractor.
- ND: For epoxy resin material - NDDOT Standard Spec 880.B.2. (Color)

11. What factors, if any, affect the choice of pavement marking materials in your area?



Comments:

- SC: Epoxy and tape are used on PCC. Thermoplastic is used on high volume AC. Paint is used for temporary markings and low volume AC.
- AZ: Price & performance
- IL: New concrete and waterborne traffic paint do not work as well in our experiences...probably due to MCC
- HI: Contractor is given option, thermoplastic is almost always chosen
- VA: Hydraulic Cement Concrete and Asphalt Concrete. Distance from the pavement marking shop, budget constraints and policies also affect the type of markings used
- KY: Mostly paint, thermo on some new asphalt, little on concrete. Application may need to wait for weather, if so a temp line is placed.
- MO: Thermoplastic is not allowed on concrete
- IN: Epoxy or cold applied tape on all concrete. Waterborne paint or thermoplastic on all asphalt.
- WI: Raised Pavement Markers on 65mph highways
- OH: Road surface remaining life before repair etc. Type of route (priority vs general)
- OR: We also consider accident rate, safety corridor locations, and what markings are adjacent to the section in question.

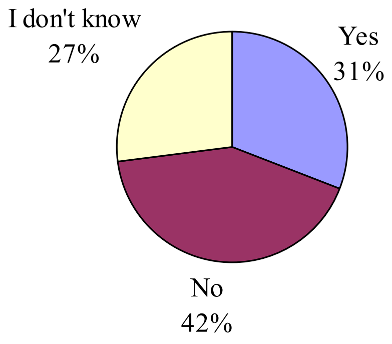
12. To the best of your knowledge, how do the manufacturers of your materials specify, control, and verify (or guarantee) the chromaticity of yellow and white?

Responses:	
Daytime validation	3
Nighttime validation	3
I don't know	16

Comments:

- IL: Accelerated weathering tests are typically done to verify the UV stability of the materials.
- VA: I don't think they do! We seem to be their QC lab.
- ND: We do our own measurement of x,y chromaticity coordinates on our water borne paint before the contractor is given permission to apply the paint to the pavement.
- MO: We require certain white color of the materials, these are verified by testing in our lab.
- IN: Must provide a material certification that the product meets our specs.

13. Has your agency conducted any research on pavement marking colors in the past 5 years?



Comments:

- IL: We have performed QUV weatherometer testing of various materials.
- MO: Ongoing research to determine the best waterborne paint and bead combination for our crews to use.
- TX: We have been doing work in the lab (ongoing) to determine ways to improve our yellow.
- OR: We have tested Epoxy to a limited degree and one of the factor about the product we did not like was the fading of the yellow. But the primary reason for not using more Epoxy is the dry time for the product to cure.

APPENDIX B: COLOR BOOTH EXPERIMENT DATA

Calibration of Light Booth and Color Chips

In this experiment the dependent variables are the percentage of correctly classified colors and the response time needed for identification. The parameter is the color chips. These chips were calibrated by the following procedure. A total of 1200 chips were calibrated.

At NIST, the spectral reflectance of the chips was measured under 0/45 geometrical conditions. Therefore, the chips were illuminated by a tungsten-halogen source operated at 3200 K in a direction normal to the surface of the chip. A spectroradiometer was positioned viewing the chip at an angle of 45° from normal. A sample spectrum is shown in Figure 35. The chips were also illuminated by diffuse light.

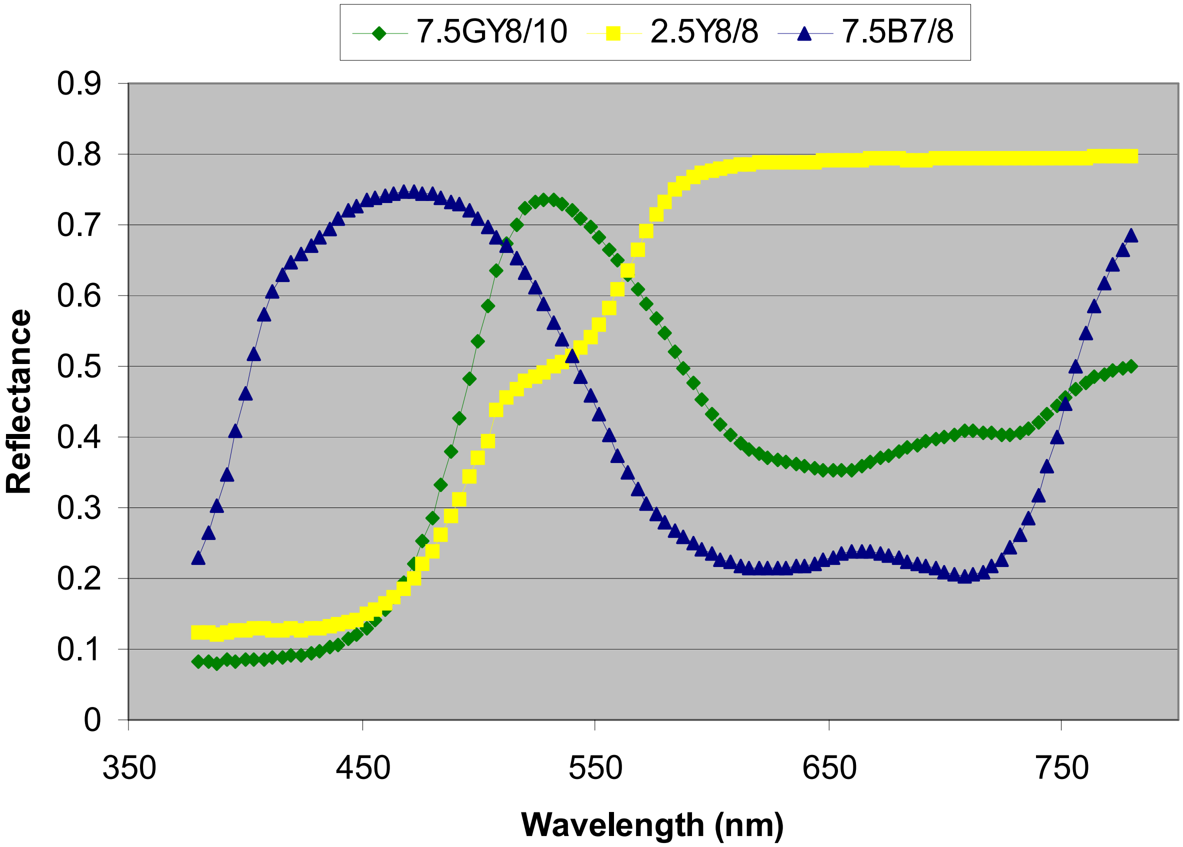


Figure 35. Spectral reflectance curves measured at NIST for three color chips.

The spectral power distribution measured was not different from the 0/45 measurement within the uncertainty of the measurement. Before and after measuring a set of chips, the spectral power distribution of the lamp was measured by placing a calibrated diffuse reflectance plaque in the chip position. By dividing the chip spectral power distribution by the lamp spectral power distribution and multiplying by the spectral reflectance of the calibrated plaque, the spectral reflectance was determined for each chip. It is important to note that the spectroradiometer was previously characterized for wavelength calibration, sample interval with respect to bandwidth, non-linearity in the detector, and scattered light. The procedure followed ASTM E1164-02.

At the OPL, a portable spectrometer and a reference plaque, calibrated at NIST for spectral irradiance (W/nm-m^2), were used to measure the spectral output of the OPL color light booth used for the human factors experiments. The reference plaque, which is a diffuse white material, was placed in the light booth at the same position and angle the observers would view the chips. The spectrometer was positioned to view the reference plaque at 45 degrees, the same angle the observers would view the chips. By having the observers view the chips at quasi-diffuse/45 geometry ensured that no specular reflections reached the observer's eye. The spectral output for the OPL color light booth set in the Illuminant A and D65 mode are shown in Figure 36. The irradiance of Illuminant A is multiplied by a factor of 50 to display on the graph.

The next step is to calculate the chromaticity coordinates and the luminance of the chips. The equations below are taken from CIE Publication 15.2 Colorimetry or ASTM E308-01, which cites the CIE Publications. To calculate the tristimulus values, we used equations 1 – 3,

$$X = k \int_{380}^{780} S_\lambda(\lambda)\rho(\lambda)\bar{x}(\lambda)d\lambda \tag{1}$$

$$Y = k \int_{380}^{780} S_\lambda(\lambda)\rho(\lambda)\bar{y}(\lambda)d\lambda \tag{2}$$

$$Z = k \int_{380}^{780} S_\lambda(\lambda)\rho(\lambda)\bar{z}(\lambda)d\lambda \tag{3}$$

where k = 683 lumen/watt, $S_\lambda(\lambda)$ is the spectral irradiance of the source measured in the OPL color light booth, $\rho(\lambda)$ is the spectral reflectance of the chip measured with the NIST spectroradiometer, and $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the 1931 CIE color matching functions for a 2 degree observer.

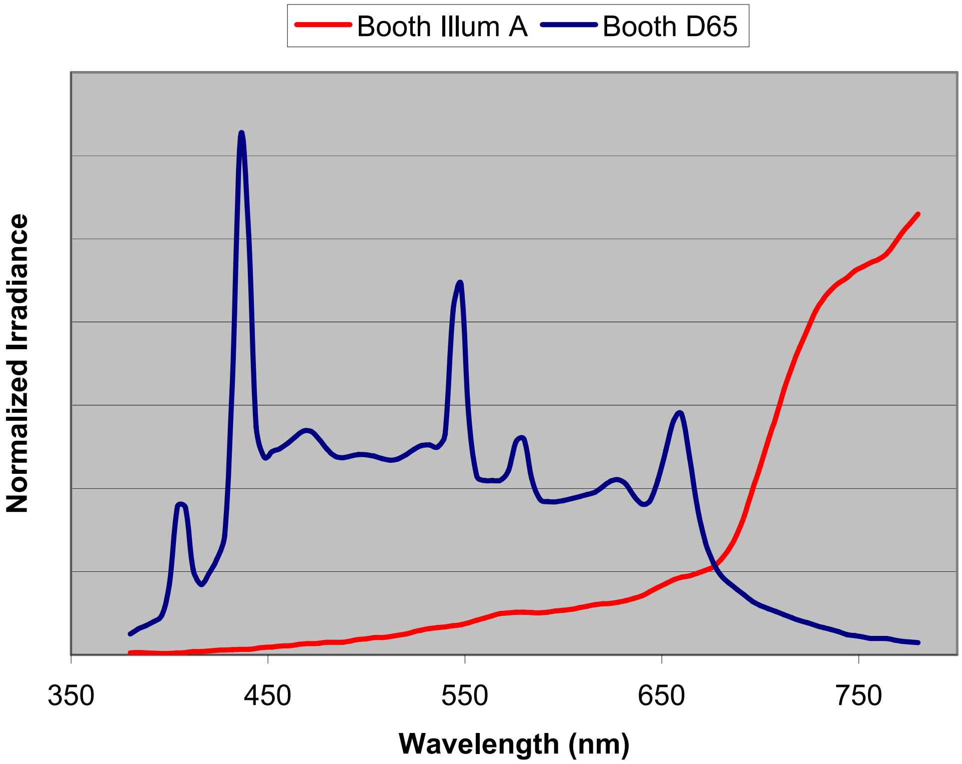


Figure 36. The blue line is the spectral power distribution of the booth in D65 mode and the red line is the booth in Illuminant A mode multiplied by a factor of 50.

The chromaticity coordinates are then calculated by,

$$x = \frac{X}{X+Y+Z} \text{ and } y = \frac{Y}{X+Y+Z}. \tag{4}$$

To determine the chromaticity coordinates in CIE 1976 u' v' color space the following equations were used,

$$u' = \frac{4X}{X+15Y+3Z} \text{ and } v' = \frac{9Y}{X+15Y+3Z}. \tag{5}$$

Several reasons exist why the chips were calibrated with this procedure. The researcher cannot simply use the chromaticity values listed in ASTM D1535-02 because those are viewed under CIE Illuminant C. There is no simple conversion from CIE Illuminant C to A or D65. The reader may notice that the Illuminant A mode of the OPL color light booth does not match CIE

Illuminant A. The OPL Illuminant A mode is about 300 K colder in correlated color temperature than CIE Illuminant A. However, since we used the calibration method described, the specific illuminant is not important because we calculate the x, y and Y using the spectral information.

For analysis purposes the measured x, y and Y values can be shifted to CIE Illuminant A using the chromatic adaptation transformation that is part of the CIELAB space. Chromatic adaptation allows us to interpret color with the context of its surroundings. Under any illuminant that is reasonably white a white piece of paper looks white. CIELAB space performs a chromatic adaptation mathematically by dividing by the X, Y, Z values of the illuminant. Therefore,

$$\begin{aligned} L^* &= 116\left(\frac{Y}{Y_N}\right)^{1/3} - 16 \\ a^* &= 500\left[\left(\frac{X}{X_N}\right)^{1/3} - \left(\frac{Y}{Y_N}\right)^{1/3}\right] \\ b^* &= 200\left[\left(\frac{Y}{Y_N}\right)^{1/3} - \left(\frac{Z}{Z_N}\right)^{1/3}\right] \end{aligned} \tag{6}$$

where X, Y, and Z are the tristimulus values for the sample under the test illuminant and X_N, Y_N, and Z_N are the tristimulus values of the test illuminant. By calculating the L*, a*, and b* chromaticity coordinates under the OPL illuminant and then back converting to X, Y, and Z under CIE Illuminant A using the CIE Illuminant A tristimulus values. This is perfectly acceptable for shift in chromaticity coordinates along the plankian locus. For a larger chromatic shift away from the plankian locus, better transformation exist such as Bradford and Von Kries methods.

The easiest method of measuring the chromaticity of the chips would be to put the chips in the OPL color light booth and use an instrument to measure the chromaticity values. This would be a perfectly acceptable approach if a well-calibrated spectroradiometer was available. The well-calibrated NIST spectroradiometer is not a portable device. Even if we were to crate it and ship it to the OPL, the characteristics will have likely changed. Therefore, we are left using a portable spectroradiometer. Some the inherent problems with small portable devices are wavelength calibration, non-linearity of the irradiance scale, and scattered light. For example, the portable instrument sent to the OPL has a wavelength shift of 1.6 nm, a non-linearity factor that goes logarithmically with the signal and has serious problems with scattered light. The scattered light issue is not with ambient lighting but the scattering of different wavelengths of light inside the spectroradiometer. For example, when measuring the yellow spectrum in Figure 35, 2.5Y8/8, the blue part of the spectrum will be artificially high from yellow and red light scattering onto those detectors.

The question arises, ‘Why can we use the portable device to measure the illuminants?’ The answer is that the portable instrument was calibrated against sources at NIST that are very close in shape to the two modes of the OPL color light booth. This calibration eliminates the systematic errors to reduce the overall uncertainty.

To demonstrate the difference two samples are presented in Figure 37. The first sample 7.5P9/2 is a spectrally smooth light purple virtually white sample. The second sample 10Y 8/10 is a yellow sample that has a very steep change in the spectrum. Measuring the 7.5P9/2 sample with the portable instrument produced values of $x = 0.4969$ and $y = 0.4116$ under booth Illuminant A. The procedure described above determined values of $x = 0.4867$ and $y = 0.4135$. The differences are $\Delta x = -0.0102$ and $\Delta y = 0.0019$. The expected uncertainty from the above procedure should be 0.005 (k=2) for both x and y. Even with this smooth function the x value is out of the uncertainty. For the second sample, instrument values are $x = 0.5107$ and $y = 0.4433$ and the calculation produced values of $x = 0.5168$ and $y = 0.4610$. The difference being $\Delta x = -0.0061$ and $\Delta y = 0.0177$. Both chromaticity coordinates are outside of the acceptable uncertainty. Therefore, the procedure described above will be used to calibrate all of the color chips used in this experiment.

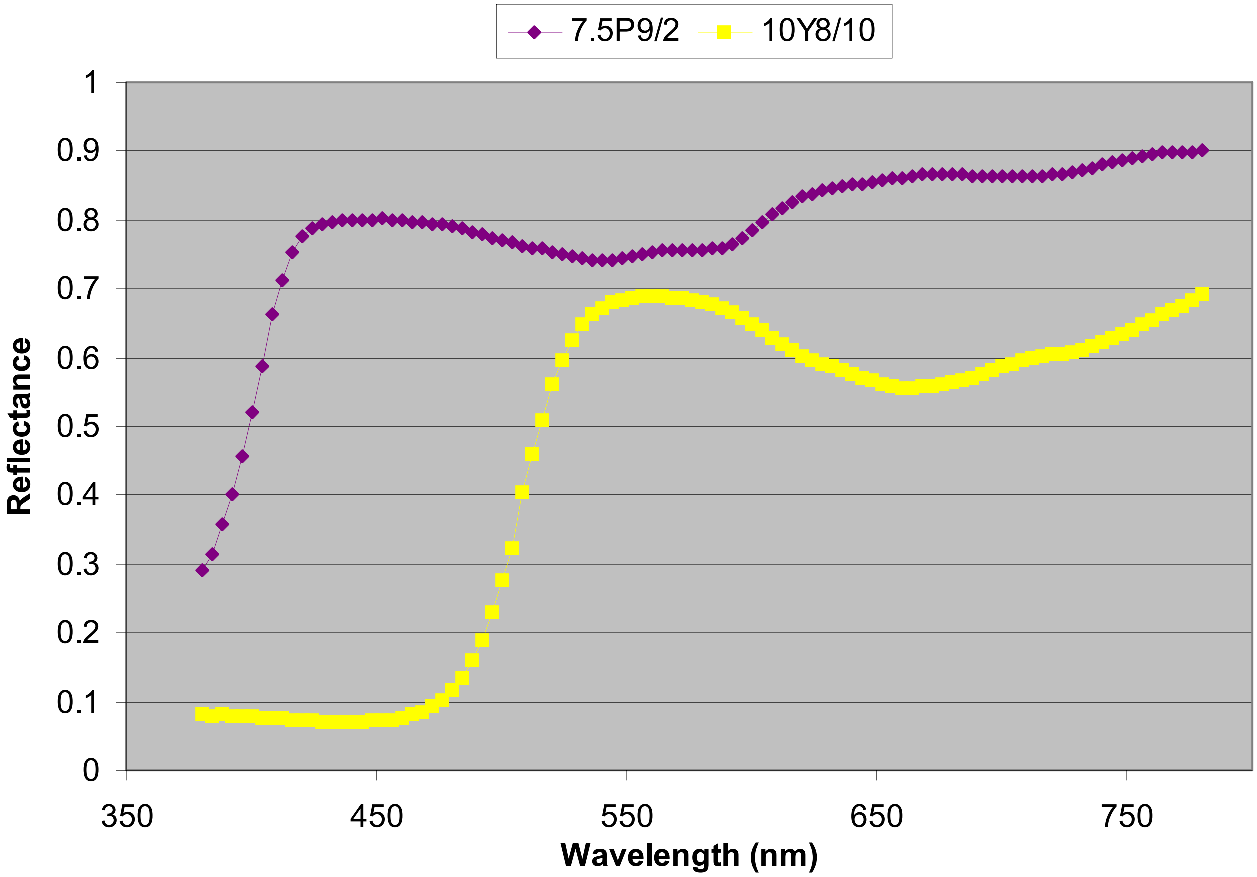


Figure 37. Reflectance curves for 2.5 P9/2 and 10 Y8/10.

Additional information needs to be added to that calibration of the color chips. In the human factor experiments it was suggested that a diffuse material was placed on top of the color chips. Below an additional calculation is described, but the final results are that the chromaticity coordinates for chips that lie on the outside of the curves moved slightly. For example, chips that were more blue or in the green categories of the chromaticity curve saw shifts toward the white and yellow regions.

The diffuse material that was placed on the chips contributes in two aspects. First, is the transmission of light. The light from the booth is transmitted through the diffuser, is reflected from the chip, and is transmitted through the diffuser to the observer. The average transmission curve for many sampled diffusers is displayed in Figure 38. This transmission curve was measured by illuminating a spectralon plaque with a tungsten halogen bulb and measuring the light scattered. Five samples of the diffuser were place in front of the plaque but out of the view of the spectroradiometer. The ratio of these two curves gives the reflectance. The reflectance was also measured by placing the diffusers between the plaque and spectroradiometer at the proper angle as it was viewed in the human factors experiment and not illuminated by the lamp. The curves showed little difference. This transmission curve would typically move the chromaticity curves towards the yellow or red regions, as if the samples were illuminated with a lamp producing a low color temperature.

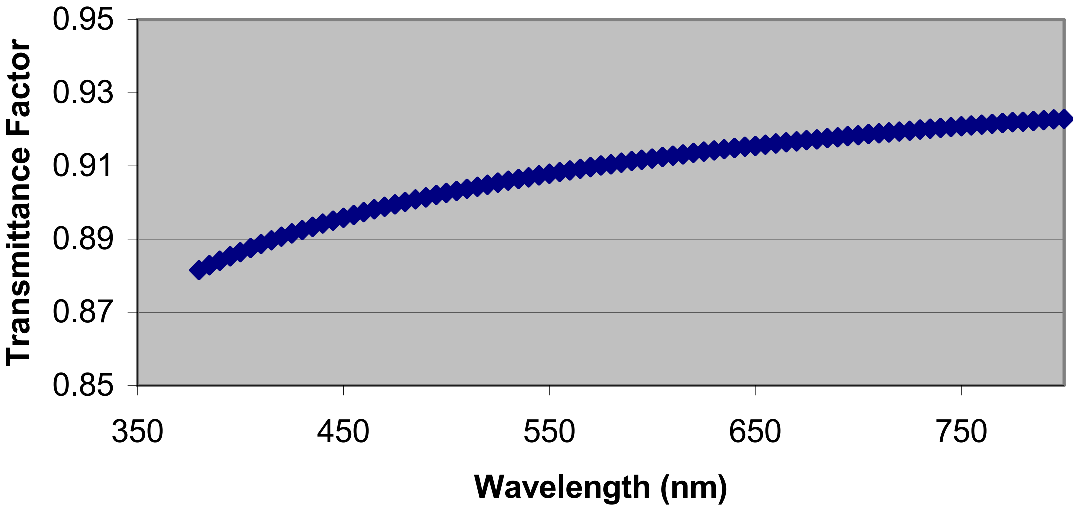


Figure 38. Transmission factor for the diffuser.

The second aspect is the illuminating light from the booth reflected diffusely off of the front surface of the diffuser. To measure this property the diffuser with nothing behind it was measured compared to the reference spectralon plaque. The reflectance curve is shown in Figure 39. The shape of the reflectance curve for the diffuser is going to move the chromaticity of the chips towards the chromaticity of the illuminant source, daytime or nighttime.

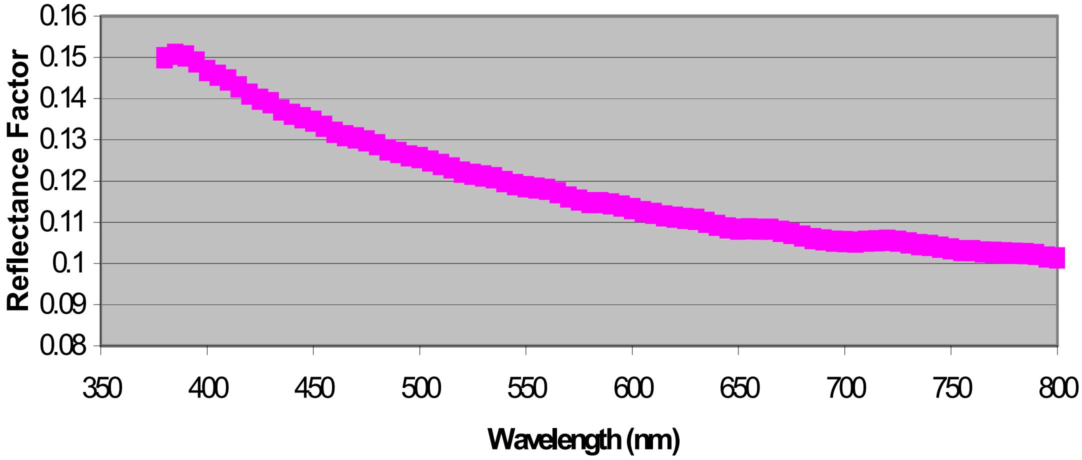


Figure 39. The top surface reflectance of the diffuser is plotted versus wavelength.

To determine the chromaticity and the luminance that the observer was viewing in these experiments the following equations were used,

$$X = k\int_{380}^{780}\left(S_\lambda(\lambda)t_d(\lambda)\rho_c(\lambda)t_d(\lambda) + S_\lambda(\lambda)\rho_d(\lambda)\right)\bar{x}(\lambda)d\lambda \tag{7}$$

$$Y = k\int_{380}^{780}\left(S_\lambda(\lambda)t_d(\lambda)\rho_c(\lambda)t_d(\lambda) + S_\lambda(\lambda)\rho_d(\lambda)\right)\bar{y}(\lambda)d\lambda \tag{8}$$

$$Z = k\int_{380}^{780}\left(S_\lambda(\lambda)t_d(\lambda)\rho_c(\lambda)t_d(\lambda) + S_\lambda(\lambda)\rho_d(\lambda)\right)\bar{z}(\lambda)d\lambda \tag{9}$$

where k = 683 lumen/watt, $S_\lambda(\lambda)$ is the spectral irradiance of the source measured in the OPL color light booth, $t_d(\lambda)$ is the spectral transmission of the diffuser, $\rho_c(\lambda)$ is the spectral reflectance of the chip measured with the NIST spectroradiometer, $\rho_d(\lambda)$ is the spectral front surface reflectance of the diffuser and $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the 1931 CIE color matching functions for a 2 degree observer. From the equations, one can see that the amount of light from the illuminant and the diffuser is constant. However, the amount of light from the chip is variable because is depends on the reflectance factor of the chip. Therefore, one cannot say in general that all chips move toward the white point in chromaticity or that the luminance is consistently going to be higher or lower compared to the previous calculations.

APPENDIX C: REAR-PROJECTION EXPERIMENT DATA

Table 12. Color response data for Chromaticity 0.

Chromaticity 0									
Horizon Sky Luminance	Pavement Marking Type	Eccentricity	Road Surface Type	Number of Responses		Yellow Response Percentage	Average Yellow Response Percentage		
				Y	W				
0.5	Patt. Tape	0	New Conc.	28	0	100%	100%	98%	98.0%
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	98%		
			Old Conc.	26	2	93%			
			New Asph.	28	0	100%			
		20	New Conc.	26	2	93%	95%		
			Old Conc.	27	1	96%			
			New Asph.	27	1	96%			
	Flat Tape	0	New Conc.	28	0	100%	100%	98%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	28	0	100%	95%		
			Old Conc.	26	2	93%			
			New Asph.	26	2	93%			
	Alkyd	0	New Conc.	28	0	100%	100%	98%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	99%		
			Old Conc.	28	0	100%			
			New Asph.	27	1	96%			
		20	New Conc.	26	2	93%	95%		
			Old Conc.	27	1	96%			
			New Asph.	27	1	96%			
4	Patt. Tape	0	New Conc.	28	0	100%	100%	99%	99.1%
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	99%		
			Old Conc.	28	0	100%			
			New Asph.	27	1	96%			
		20	New Conc.	28	0	100%	99%		
			Old Conc.	27	1	96%			
			New Asph.	28	0	100%			
	Flat Tape	0	New Conc.	28	0	100%	100%	98%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	27	1	96%	95%		
			Old Conc.	26	2	93%			
			New Asph.	27	1	96%			
	Alkyd	0	New Conc.	28	0	100%	100%	100%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	28	0	100%	99%		
			Old Conc.	28	0	100%			
			New Asph.	27	1	96%			

Table 13. Color response data for Chromaticity 1.

Chromaticity 1

Horizon Sky Luminance	Pavement Marking Type	Eccentricity	Road Surface Type	Number of Responses		Yellow Response Percentage	Average Yellow Response Percentage		
				Y	W				
0.5	Patt. Tape	0	New Conc.	27	1	96%	99%	98%	98.9%
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	27	1	96%	96%		
			Old Conc.	28	0	100%			
			New Asph.	26	2	93%			
	Flat Tape	0	New Conc.	28	0	100%	100%	99%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	99%		
			Old Conc.	28	0	100%			
			New Asph.	27	1	96%			
		20	New Conc.	28	0	100%	99%		
			Old Conc.	28	0	100%			
			New Asph.	27	1	96%			
	Alkyd	0	New Conc.	28	0	100%	100%	99%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	28	0	100%	98%		
			Old Conc.	27	1	96%			
			New Asph.	27	1	96%			
4	Patt. Tape	0	New Conc.	28	0	100%	100%	99%	99.1%
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	26	2	93%	96%		
			Old Conc.	27	1	96%			
			New Asph.	28	0	100%			
	Flat Tape	0	New Conc.	28	0	100%	100%	100%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	27	1	96%	99%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
	Alkyd	0	New Conc.	28	0	100%	100%	99%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	26	2	93%	96%		
			Old Conc.	28	0	100%			
			New Asph.	27	1	96%			

Table 14. Color response data for Chromaticity 2.

Chromaticity 2									
Horizon Sky Luminance	Pavement Marking Type	Eccentricity	Road Surface Type	Number of Responses		Yellow Response Percentage	Average Yellow Response Percentage		
				Y	W				
0.5	Patt. Tape	0	New Conc.	28	0	100%	100%	100%	99.2%
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	27	1	96%	99%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
	Flat Tape	0	New Conc.	27	1	96%	99%	99%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	99%		
			Old Conc.	28	0	100%			
			New Asph.	27	1	96%			
		20	New Conc.	27	1	96%	99%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
	Alkyd	0	New Conc.	27	1	96%	99%	99%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	28	0	100%	99%		
			Old Conc.	27	1	96%			
			New Asph.	28	0	100%			
4	Patt. Tape	0	New Conc.	28	0	100%	100%	99%	99.3%
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	27	1	96%	96%		
			Old Conc.	27	1	96%			
			New Asph.	27	1	96%			
	Flat Tape	0	New Conc.	28	0	100%	100%	100%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
	Alkyd	0	New Conc.	28	0	100%	100%	99%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	27	1	96%	98%		
			Old Conc.	27	1	96%			
			New Asph.	28	0	100%			

Table 15. Color response data for Chromaticity 3.

Chromaticity 3									
Horizon Sky Luminance	Pavement Marking Type	Eccentricity	Road Surface Type	Number of Responses		Yellow Response Percentage	Average Yellow Response Percentage		
				Y	W				
0.5	Patt. Tape	0	New Conc.	26	2	93%	86%	76%	79.8%
			Old Conc.	25	3	89%			
			New Asph.	21	7	75%			
		10	New Conc.	21	7	75%	69%		
			Old Conc.	20	8	71%			
			New Asph.	17	11	61%			
		20	New Conc.	21	7	75%	74%		
			Old Conc.	19	9	68%			
			New Asph.	22	6	79%			
	Flat Tape	0	New Conc.	26	2	93%	89%	82%	
			Old Conc.	27	1	96%			
			New Asph.	22	6	79%			
		10	New Conc.	26	2	93%	82%		
			Old Conc.	27	1	96%			
			New Asph.	16	12	57%			
		20	New Conc.	25	3	89%	75%		
			Old Conc.	16	12	57%			
			New Asph.	22	6	79%			
	Alkyd	0	New Conc.	28	0	100%	88%	81%	
			Old Conc.	24	4	86%			
			New Asph.	22	6	79%			
		10	New Conc.	27	1	96%	79%		
			Old Conc.	20	8	71%			
			New Asph.	19	9	68%			
		20	New Conc.	24	4	86%	76%		
			Old Conc.	21	7	75%			
			New Asph.	19	9	68%			
4	Patt. Tape	0	New Conc.	26	2	93%	87%	84%	89.9%
			Old Conc.	21	7	75%			
			New Asph.	26	2	93%			
		10	New Conc.	20	8	71%	88%		
			Old Conc.	27	1	96%			
			New Asph.	27	1	96%			
		20	New Conc.	26	2	93%	77%		
			Old Conc.	16	12	57%			
			New Asph.	23	5	82%			
	Flat Tape	0	New Conc.	27	1	96%	92%	89%	
			Old Conc.	26	2	93%			
			New Asph.	24	4	86%			
		10	New Conc.	27	1	96%	89%		
			Old Conc.	25	3	89%			
			New Asph.	23	5	82%			
		20	New Conc.	26	2	93%	86%		
			Old Conc.	24	4	86%			
			New Asph.	22	6	79%			
	Alkyd	0	New Conc.	27	1	96%	98%	97%	
			Old Conc.	27	1	96%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	99%		
			Old Conc.	28	0	100%			
			New Asph.	27	1	96%			
		20	New Conc.	28	0	100%	94%		
			Old Conc.	26	2	93%			
			New Asph.	25	3	89%			

Table 16. Color response data for Chromaticity 4.

Chromaticity 4									
Horizon Sky Luminance	Pavement Marking Type	Eccentricity	Road Surface Type	Number of Responses		Yellow Response Percentage	Average Yellow Response Percentage		
				Y	W				
0.5	Patt. Tape	0	New Conc.	28	0	100%	96%	96%	96.8%
			Old Conc.	26	2	93%			
			New Asph.	27	1	96%			
		10	New Conc.	28	0	100%	99%		
			Old Conc.	27	1	96%			
			New Asph.	28	0	100%			
		20	New Conc.	27	1	96%	93%		
			Old Conc.	25	3	89%			
			New Asph.	26	2	93%			
	Flat Tape	0	New Conc.	28	0	100%	100%	97%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	27	1	96%	92%		
			Old Conc.	26	2	93%			
			New Asph.	24	4	86%			
	Alkyd	0	New Conc.	27	1	96%	99%	97%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	99%		
			Old Conc.	28	0	100%			
			New Asph.	27	1	96%			
		20	New Conc.	27	1	96%	94%		
			Old Conc.	27	1	96%			
			New Asph.	25	3	89%			
4	Patt. Tape	0	New Conc.	27	1	96%	99%	96%	98.0%
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	27	1	96%	99%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	26	2	93%	90%		
			Old Conc.	25	3	89%			
			New Asph.	25	3	89%			
	Flat Tape	0	New Conc.	28	0	100%	100%	99%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	27	1	96%	98%		
			Old Conc.	27	1	96%			
			New Asph.	28	0	100%			
	Alkyd	0	New Conc.	28	0	100%	100%	99%	
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		10	New Conc.	28	0	100%	100%		
			Old Conc.	28	0	100%			
			New Asph.	28	0	100%			
		20	New Conc.	27	1	96%	96%		
			Old Conc.	27	1	96%			
			New Asph.	27	1	96%			

Table 17. Color response data for Chromaticity 5.

Chromaticity 5

Horizon Sky Luminance	Pavement Marking Type	Eccentricity	Road Surface Type	Number of Responses		Yellow Response Percentage	Average Yellow Response Percentage		
				Y	W				
0.5	Patt. Tape	0	New Conc.	3	25	11%	5%	12%	17.6%
			Old Conc.	0	28	0%			
			New Asph.	1	27	4%			
		10	New Conc.	3	25	11%	7%		
			Old Conc.	2	26	7%			
			New Asph.	1	27	4%			
		20	New Conc.	9	19	32%	23%		
			Old Conc.	5	23	18%			
			New Asph.	5	23	18%			
	Flat Tape	0	New Conc.	6	22	21%	11%	16%	
			Old Conc.	0	28	0%			
			New Asph.	3	25	11%			
		10	New Conc.	4	24	14%	8%		
			Old Conc.	1	27	4%			
			New Asph.	2	26	7%			
		20	New Conc.	10	18	36%	30%		
			Old Conc.	7	21	25%			
			New Asph.	8	20	29%			
	Alkyd	0	New Conc.	10	18	36%	25%	25%	
			Old Conc.	7	21	25%			
			New Asph.	4	24	14%			
		10	New Conc.	7	21	25%	20%		
			Old Conc.	7	21	25%			
			New Asph.	3	25	11%			
		20	New Conc.	13	15	46%	30%		
			Old Conc.	6	22	21%			
			New Asph.	6	22	21%			
4	Patt. Tape	0	New Conc.	6	22	21%	21%	17%	23.5%
			Old Conc.	7	21	25%			
			New Asph.	5	23	18%			
		10	New Conc.	4	24	14%	14%		
			Old Conc.	5	23	18%			
			New Asph.	3	25	11%			
		20	New Conc.	5	23	18%	17%		
			Old Conc.	4	24	14%			
			New Asph.	5	23	18%			
	Flat Tape	0	New Conc.	10	18	36%	29%	21%	
			Old Conc.	9	19	32%			
			New Asph.	5	23	18%			
		10	New Conc.	7	21	25%	14%		
			Old Conc.	3	25	11%			
			New Asph.	2	26	7%			
		20	New Conc.	6	22	21%	19%		
			Old Conc.	6	22	21%			
			New Asph.	4	24	14%			
	Alkyd	0	New Conc.	13	15	46%	38%	33%	
			Old Conc.	11	17	39%			
			New Asph.	8	20	29%			
		10	New Conc.	8	20	29%	29%		
			Old Conc.	11	17	39%			
			New Asph.	5	23	18%			
		20	New Conc.	12	16	43%	31%		
			Old Conc.	7	21	25%			
			New Asph.	7	21	25%			

Table 18. Color response data for Chromaticity 6.

Chromaticity 6									
Horizon Sky Luminance	Pavement Marking Type	Eccentricity	Road Surface Type	Number of Responses		Yellow Response Percentage	Average Yellow Response Percentage		
				Y	W				
0.5	Patt. Tape	0	New Conc.	6	22	21%	15%	17%	24.5%
			Old Conc.	2	26	7%			
			New Asph.	5	23	18%			
		10	New Conc.	5	23	18%	12%		
			Old Conc.	0	28	0%			
			New Asph.	5	23	18%			
		20	New Conc.	8	20	29%	25%		
			Old Conc.	7	21	25%			
			New Asph.	6	22	21%			
	Flat Tape	0	New Conc.	5	23	18%	15%	19%	
			Old Conc.	5	23	18%			
			New Asph.	3	25	11%			
		10	New Conc.	6	22	21%	15%		
			Old Conc.	5	23	18%			
			New Asph.	2	26	7%			
		20	New Conc.	11	17	39%	26%		
			Old Conc.	5	23	18%			
			New Asph.	6	22	21%			
	Alkyd	0	New Conc.	16	12	57%	31%	37%	
			Old Conc.	5	23	18%			
			New Asph.	5	23	18%			
		10	New Conc.	13	15	46%	35%		
			Old Conc.	9	19	32%			
			New Asph.	7	21	25%			
		20	New Conc.	15	13	54%	45%		
			Old Conc.	11	17	39%			
			New Asph.	12	16	43%			
4	Patt. Tape	0	New Conc.	10	18	36%	26%	21%	27.8%
			Old Conc.	8	20	29%			
			New Asph.	4	24	14%			
		10	New Conc.	5	23	18%	14%		
			Old Conc.	5	23	18%			
			New Asph.	2	26	7%			
		20	New Conc.	6	22	21%	23%		
			Old Conc.	7	21	25%			
			New Asph.	6	22	21%			
	Flat Tape	0	New Conc.	7	21	25%	31%	27%	
			Old Conc.	11	17	39%			
			New Asph.	8	20	29%			
		10	New Conc.	11	17	39%	26%		
			Old Conc.	6	22	21%			
			New Asph.	5	23	18%			
		20	New Conc.	7	21	25%	25%		
			Old Conc.	6	22	21%			
			New Asph.	8	20	29%			
	Alkyd	0	New Conc.	12	16	43%	40%	35%	
			Old Conc.	9	19	32%			
			New Asph.	13	15	46%			
		10	New Conc.	11	17	39%	37%		
			Old Conc.	11	17	39%			
			New Asph.	9	19	32%			
		20	New Conc.	10	18	36%	27%		
			Old Conc.	7	21	25%			
			New Asph.	6	22	21%			

Table 19. Color response data for Chromaticity 7.

Chromaticity 7

Horizon Sky Luminance	Pavement Marking Type	Eccentricity	Road Surface Type	Number of Responses		Yellow Response Percentage	Average Yellow Response Percentage		
				Y	W				
0.5	Patt. Tape	0	New Conc.	0	28	0%	0%	2%	0.9%
			Old Conc.	0	28	0%			
			New Asph.	0	28	0%			
		10	New Conc.	0	28	0%	1%		
			Old Conc.	0	28	0%			
			New Asph.	1	27	4%			
		20	New Conc.	0	28	0%	4%		
			Old Conc.	1	27	4%			
			New Asph.	2	26	7%			
	Flat Tape	0	New Conc.	0	28	0%	0%	1%	
			Old Conc.	0	28	0%			
			New Asph.	0	28	0%			
		10	New Conc.	0	28	0%	0%		
			Old Conc.	0	28	0%			
			New Asph.	0	28	0%			
		20	New Conc.	1	27	4%	2%		
			Old Conc.	0	28	0%			
			New Asph.	1	27	4%			
	Alkyd	0	New Conc.	0	28	0%	0%	0%	
			Old Conc.	0	28	0%			
			New Asph.	0	28	0%			
		10	New Conc.	0	28	0%	0%		
			Old Conc.	0	28	0%			
			New Asph.	0	28	0%			
		20	New Conc.	0	28	0%	1%		
			Old Conc.	1	27	4%			
			New Asph.	0	28	0%			
4	Patt. Tape	0	New Conc.	0	28	0%	0%	1%	0.8%
			Old Conc.	0	28	0%			
			New Asph.	0	28	0%			
		10	New Conc.	0	28	0%	0%		
			Old Conc.	0	28	0%			
			New Asph.	0	28	0%			
		20	New Conc.	1	27	4%	2%		
			Old Conc.	1	27	4%			
			New Asph.	0	28	0%			
	Flat Tape	0	New Conc.	0	28	0%	0%	0%	
			Old Conc.	0	28	0%			
			New Asph.	0	28	0%			
		10	New Conc.	0	28	0%	0%		
			Old Conc.	0	28	0%			
			New Asph.	0	28	0%			
		20	New Conc.	0	28	0%	0%		
			Old Conc.	0	28	0%			
			New Asph.	0	28	0%			
	Alkyd	0	New Conc.	1	27	4%	4%	2%	
			Old Conc.	1	27	4%			
			New Asph.	1	27	4%			
		10	New Conc.	0	28	0%	0%		
			Old Conc.	0	28	0%			
			New Asph.	0	28	0%			
		20	New Conc.	1	27	4%	1%		
			Old Conc.	0	28	0%			
			New Asph.	0	28	0%			

Pairwise Comparisons

Table 20 shows the number and percentage of yellow responses for each pairwise combination.

Table 20. Number and percentage of "yellow" responses broken down into horizon sky luminance and road surface type categories.

		Horizon Sky Luminance [cd/m^2]	
		0.5	**4**
Road Surface Type	**New Concrete**	1369/2016 (68%)	1382/2016 (69%)
	Old Concrete	1276/2016 (63%)	1352/2016 (67%)
	New Asphalt	1254/2016 (62%)	1330/2016 (66%)

Note: Table shows number of yellow responses out of 2016 trials for each pairwise category.

Notice that for new concrete, changing the horizon sky luminance did not affect the percentage of yellow responses as much as it did in for the other two road surface types.

Table 21 summarizes the number and percentage of yellow responses for each combination of pavement marking type and road surface type. For each combination, a total of 1,344 trials were administered. The general tendency of the subjects was to make more yellow calls with increasing pavement marking retroreflectivity only for brighter road surfaces, hence the first order interaction between road surface and material type. The increase in yellow calls with increasing pavement marking retroreflectivity was not pronounced as the road surface got darker. With the same token, increasing the road surface brightness had less of an effect on yellow responses for brighter pavement markings.

Table 21. Number and percentage of "yellow" responses broken down into pavement marking type and road surface type categories.

		Pavement Marking Type		
		Patterned Tape	**Flat Tape**	**Yellow Alkyd**
Road Surface Type	**New Concrete**	870/1344 (65%)	914/1344 (68%)	967/1344 (72%)
	Old Concrete	839/1344 (62%)	874/1344 (65%)	915/1344 (68%)
	New Asphalt	848/1344 (63%)	848/1344 (63%)	888/1344 (66%)

The second order interaction between road surface type and chromaticity of the pavement marking indicates that for different initial chromaticities, changing the road surface type did not affect subjects' responses the same way. As indicated in Table 22, changing the road surface from a new concrete material to a new asphalt material decreased the percentage of responses for most chromaticities except Chromaticity-1, chromaticity-2, and chromaticity-7. It is nonetheless hard to speculate why that may be.

Table 22. Number and percentage of "yellow" responses, broken down into road surface type and initial chromaticity condition combinations.

		Initial Chromaticity Condition of the Pavement Marking							
		Chr-0	**Chr-1**	**Chr-2**	**Chr-3**	**Chr-4**	**Chr-5**	**Chr-6**	**Chr-7**
Road Surface Type	**New Concrete**	499/504 (99.0%)	497/504 (98.6%)	498/504 (98.8%)	459/504 (91.1%)	494/504 (98.0%)	136/504 (27.0%)	164/504 (32.6%)	4/504 (0.08%)
	Old Concrete	495/504 (98.2%)	502/504 (99.6%)	501/504 (99.4%)	419/504 (83.1%)	490/504 (97.2%)	98/504 (19.4%)	119/504 (23.6%)	4/504 (0.08%)
	New Asphalt	496/504 (98.4%)	498/504 (98.8%)	502/504 (99.6%)	405/504 (80.4%)	489/504 (97.0%)	77/504 (15.3%)	112/504 (22.2%)	5/504 (0.10%)

The final statistically significant second order interaction was between pavement marking type and pavement marking chromaticity. As indicated in Table 23, different pavement markings elicited different response tendencies for different chromaticities. For instance, there were more yellow responses for the flat tape type material than alkyd paint for chromaticities 1, 2 and 4. Yet, for the rest of the chromaticities the situation was the contrary. Overall, flat tape yielded more "yellow" responses than patterned tape in all chromaticities but chromaticity -7. Table 23 gives the number and percentage of "yellow" responses out of 504 trials for each combination of pavement marking chromaticity and pavement marking material type.

Table 23. Number and percentage of "yellow" responses, broken down into pavement marking type and initial chromaticity condition combinations.

		Initial Chromaticity Condition of the Pavement Marking							
		Chr-0	**Chr-1**	**Chr-2**	**Chr-3**	**Chr-4**	**Chr-5**	**Chr-6**	**Chr-7**
Pavement Marking Type	**Patterned Tape**	496/504 (98.4%)	497/504 (98.6%)	500/504 (99.2%)	404/504 (80.2%)	484/504 (96.0%)	73/504 (14.5%)	97/504 (19.2%)	6/504 (1.2%)
	Flat Tape	496/504 (98.4%)	501/504 (99.4%)	501/504 (99.4%)	431/504 (85.5%)	495/504 (98.2%)	93/504 (18.5%)	117/504 (23.2%)	2/504 (0.4%)
	Alkyd Paint	498/504 (98.8%)	500/504 (99.2%)	500/504 (99.2%)	448/504 (88.9%)	494/504 (98.0%)	145/504 (28.8%)	181/504 (35.9%)	5/504 (1.0%)

Response Time Analysis

The analysis of response times as a function of responses showed interesting tendencies. Figure 40 through Figure 47 show the response time error plots as a function of responses for different chromaticity conditions. The response times for chromaticity-0 for yellow and white responses were just short of having a statistically significant difference at α=0.05 significance level (p= 0.051). For chromaticity-1 chromaticity-2, chromaticity-4, chromaticity-5, chromaticity-6, and chromaticity-7, the differences in the response times were statistically significantly different at α=0.05. For chromaticity-3, the differences did not prove a statistically significant difference. Note that for saturated yellow and white chromaticities, the distribution of yellow and white responses is notably unbalanced, which affects the sample size and the size of the confidence intervals.

For chromaticity-1, chromaticity-2, chromaticity-4 (fairly saturated yellow towards red region), the response times for "yellow" responses seemed rather quickly as compared to those for "white" responses. For chromaticity-4, chromaticity-5, chromaticity-6, and chromaticity-7, the situation was contrary: Subjects made a "white" assessment more quickly than they did a "yellow" assessment. This may indicate that for these chromaticities, although subjects still called for more "yellow's", it took more time for them to make that judgment. This may indicate some degree of confusion while making the call. For chromaticity-0 (p= 0.051) and chromaticity-3 (p= 0.09), the difference in the response times was short of having a statistical significance for "yellow" and "white" responses. Note that these two chromaticities are toward the green region rather than the red region while they maintain their yellow hues.

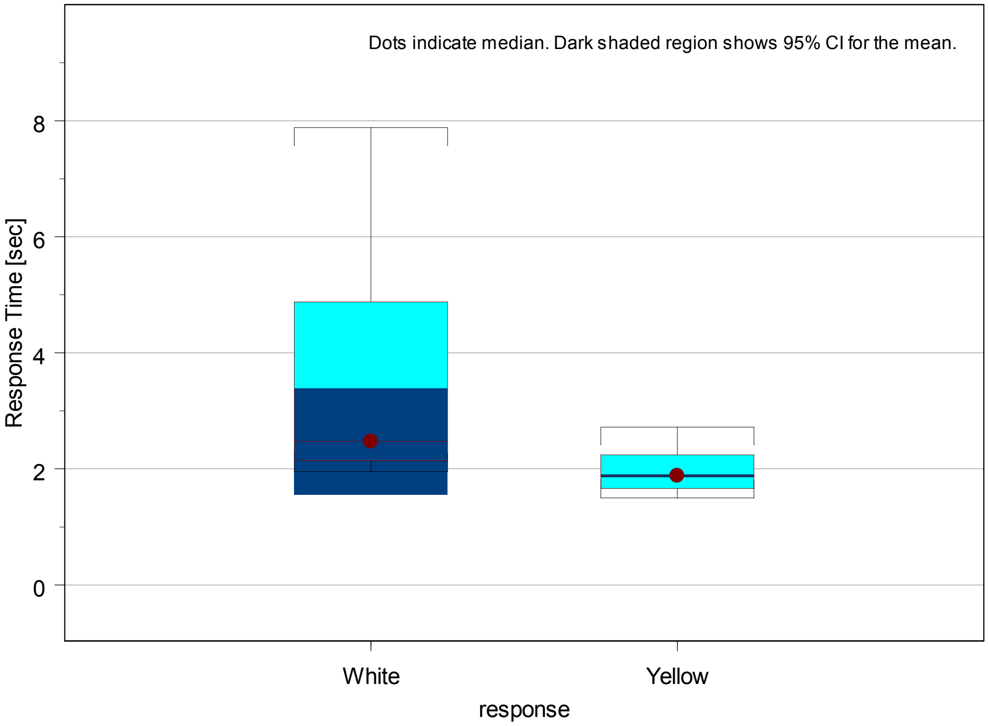


Figure 40. Error plot for the response times as a function of response for chromaticity-0.

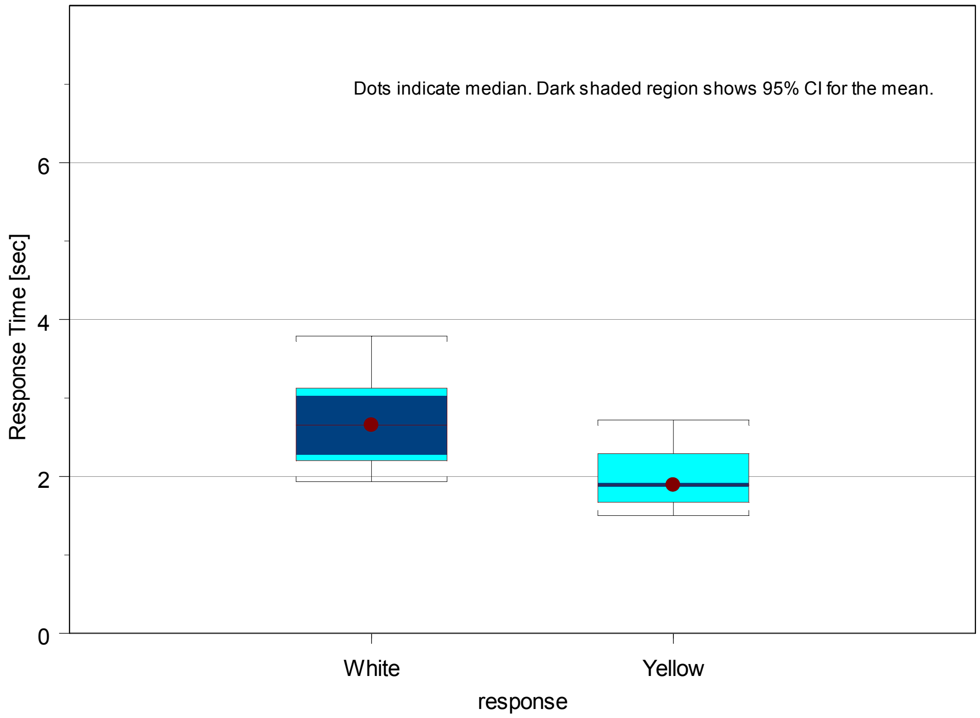


Figure 41. Error plot for the response times as a function of response for chromaticity-1.

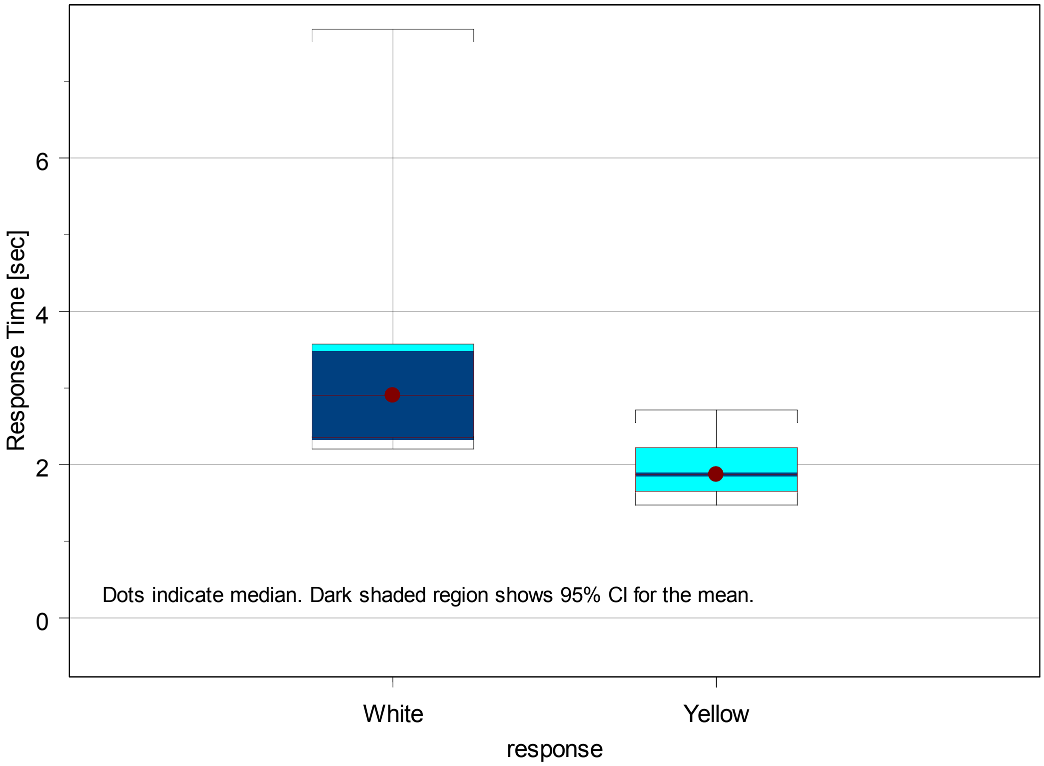


Figure 42. Error plot for the response times as a function of response for chromaticity-2.

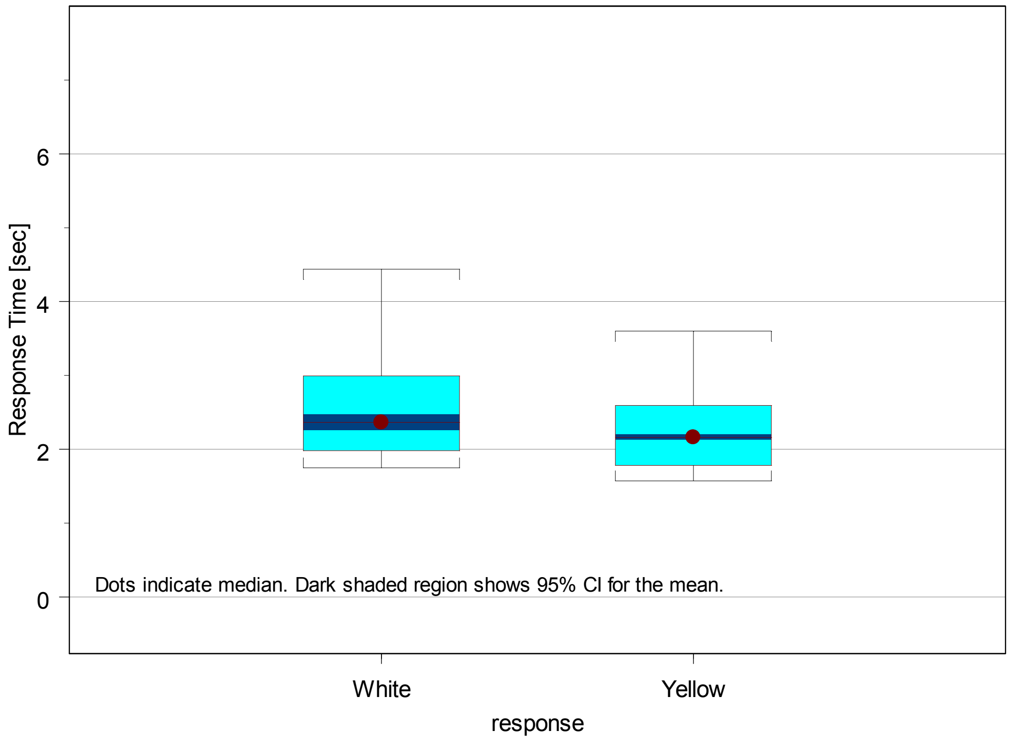


Figure 43. Error plot for the response times as a function of response for chromaticity-3.

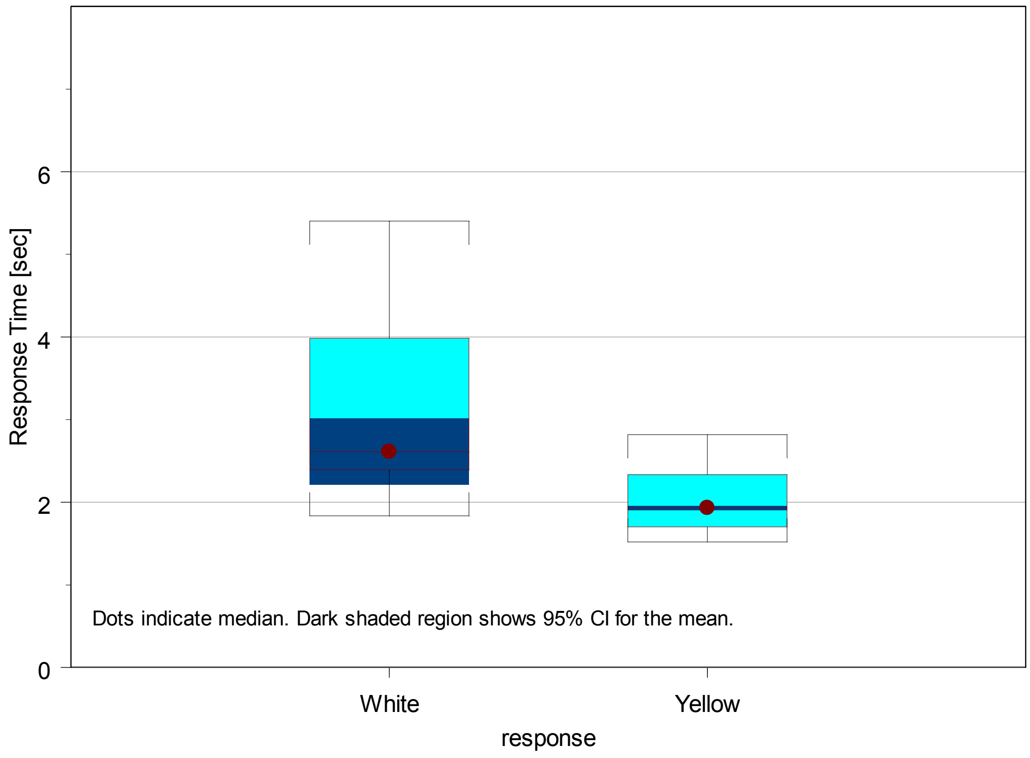


Figure 44. Error plot for the response times as a function of response for chromaticity-4.

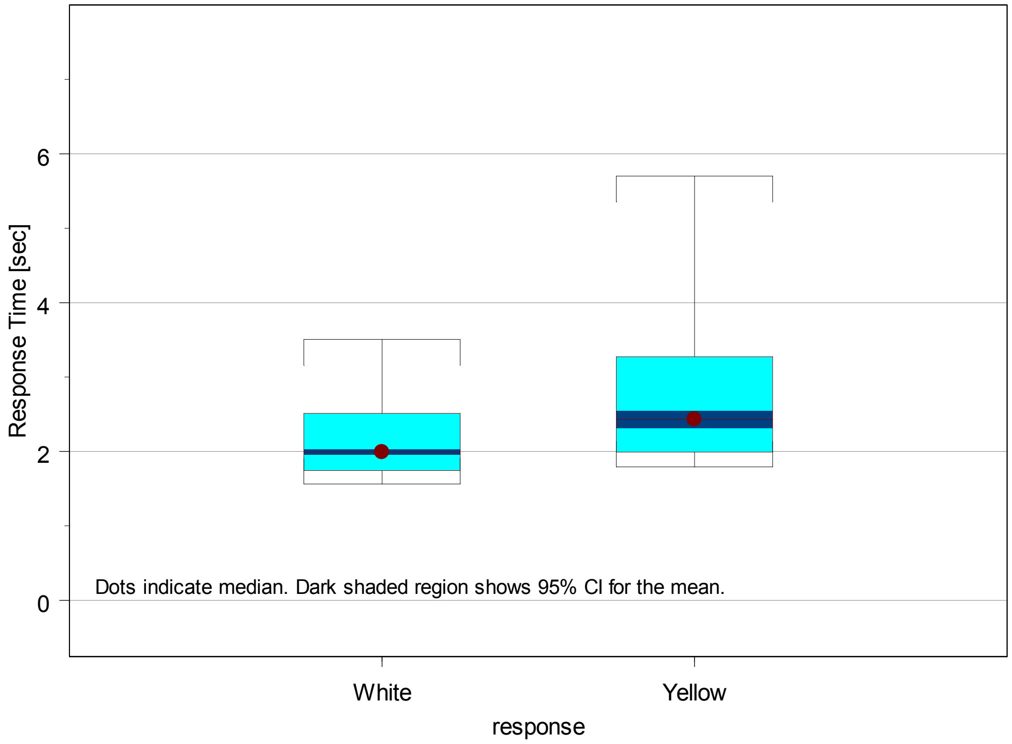


Figure 45. Error plot for the response times as a function of response for chromaticity-5.

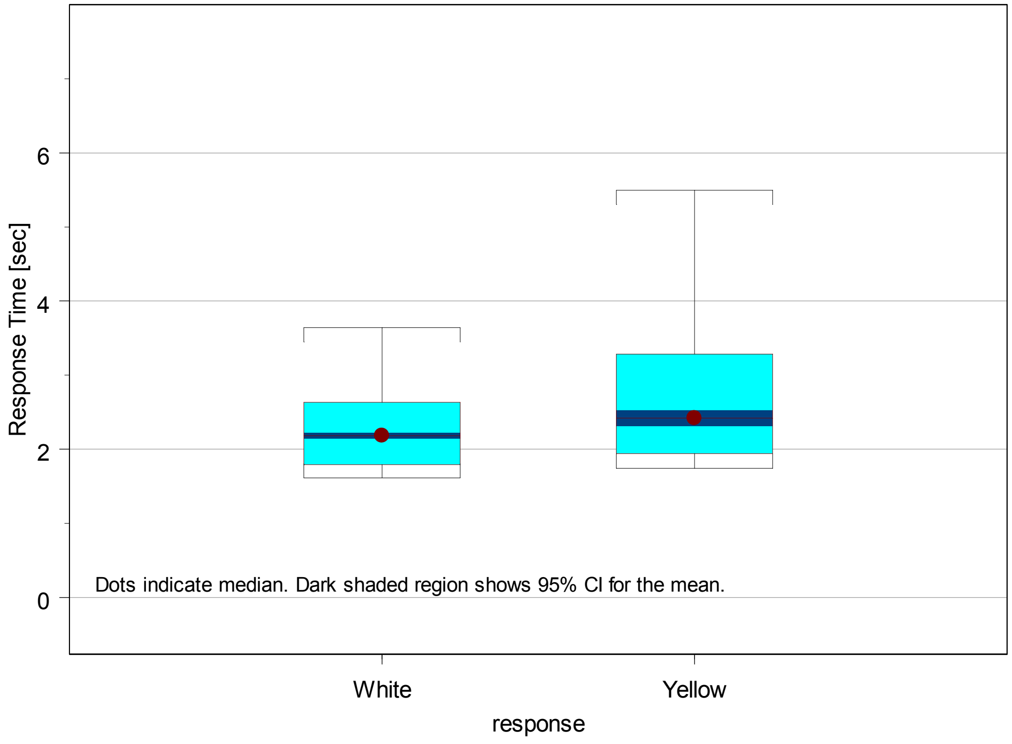


Figure 46. Error plot for the response times as a function of response for chromaticity-6.

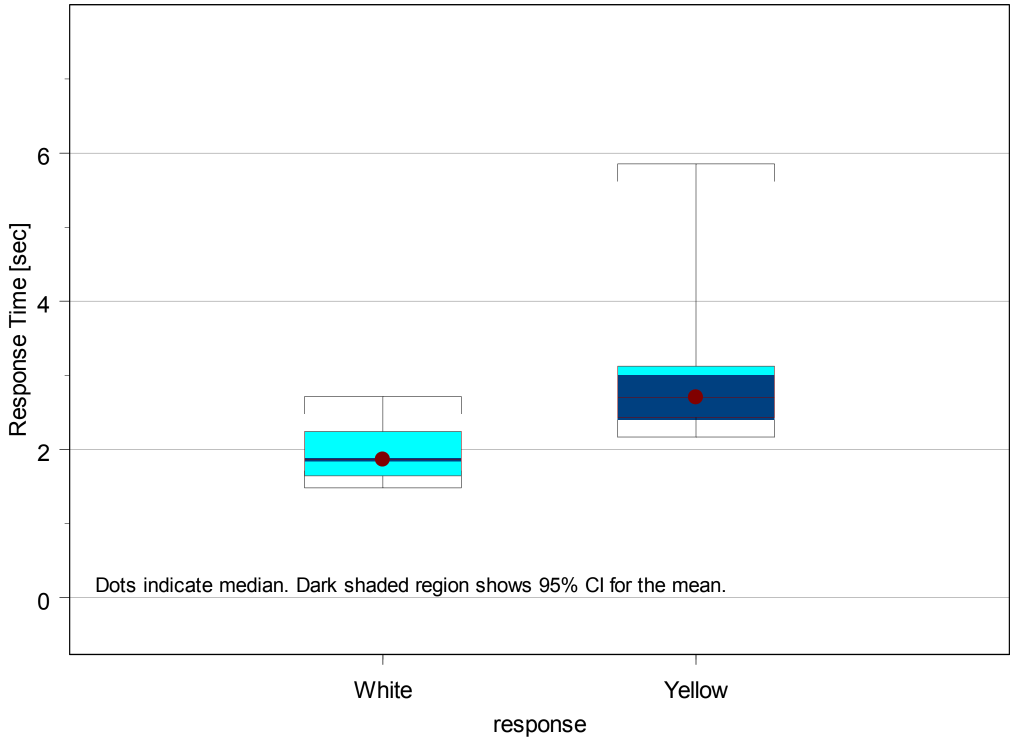


Figure 47. Error plot for the response times as a function of response for chromaticity-7.

APPENDIX D: FIELD EXPERIMENT

Table 24. GEE Analysis Summary for the Binary Data Obtained in the Field Experiment.

```
gee(formula = Response ~ Subject + Headlamp * Skipline + Headlamp *
      Material + Skipline * Material, cluster = Subject, variance =
      "glm.scale", data = NCHRP518Field, family = binomial, link =
      "logit")

Model:
 Family:   binomial
 Link  :   logit

Estimated Parameters:
  Regression Coefficients:
                    Estimate  Std.Err.      Z       Prob
      (Intercept) -2.0543770 0.4678822 -4.39 0.0000113
          Subject  0.0078463 0.0240755  0.33 0.7444962
         Headlamp -0.1080516 0.1398585 -0.77 0.4397724
         Skipline  0.4298452 0.0629424  6.83 0.0000000
        Material1  0.7381654 0.2649007  2.79 0.0053268
        Material2  0.4375480 0.0983541  4.45 0.0000086
        Material3  0.4246154 0.1301054  3.26 0.0011000
        Material4 -0.0409369 0.0421986 -0.97 0.3319963
Headlamp:Skipline  0.0432295 0.0338825  1.28 0.2020038
HeadlampMaterial1 -0.0567028 0.0687353 -0.82 0.4094028
HeadlampMaterial2 -0.0079999 0.0438471 -0.18 0.8552301
HeadlampMaterial3  0.0257604 0.0301984  0.85 0.3936366
HeadlampMaterial4  0.0090844 0.0286120  0.32 0.7508622
SkiplineMaterial1 -0.1626559 0.0668595 -2.43 0.0149825
SkiplineMaterial2 -0.1137373 0.0224581 -5.06 0.0000004
SkiplineMaterial3 -0.0666701 0.0290896 -2.29 0.0219121
SkiplineMaterial4 -0.0132592 0.0148220 -0.89 0.3710217

  Scale Parameter: 1.004171

Number of iterations :  2
Number of observations :  1560
Number of clusters :  26
```

Note: Statistically significant factors are shown in bold typeface. Skipline represents pavement marking location.

Pairwise Material Comparisons

Thermoplastic materials from Ennis Paint are denoted as **EnnisThermoY++**, **EnnisThermoY+**, and **EnnisThermoY**, in decreasing order of yellow saturation. Henceforth in this report, EnnisThermoY++ refers to the most saturated yellow thermoplastic material (with 1% yellow organic pigment and 1.4% Titanium dioxide), EnnisThermoY+ refers to the thermoplastic with intermediate yellow saturation (with 1% yellow organic pigment and 2.3% Titanium dioxide), and finally EnnisPaintY refers to the thermoplastic material with relatively lower yellow saturation (with 1% yellow organic pigment and 2.9% Titanium dioxide).

Ennis Thermoplastic Y++ vs. Ennis Thermoplastic Y+:

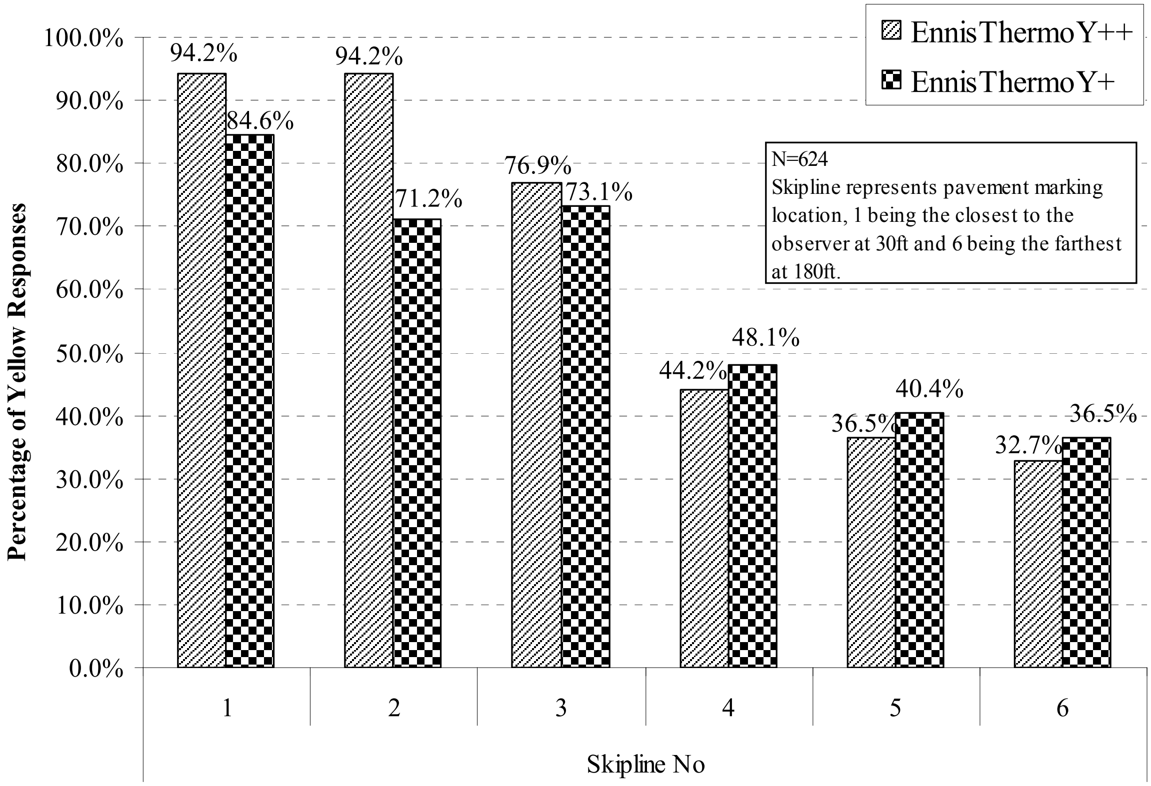
Pavement marking location (shown as skipline in Table 25) and material type were both statistically significant ($p<0.001$ and $p=0.005$, respectively). The further away the samples, the less yellow they appeared. The interaction between material type and location was also significant.

Table 25. GEE Summary Table for the Pairwise Comparison between Ennis ThemoplasticY++ vs. Ennis Thermoplastic Y+.

```
                  Estimate  Std.Err.        Z      Prob
       (Intercept) -2.8547921 0.5714597 -5.00 0.0000006
           Subject  0.0065356 0.0247716  0.26 0.7919086
          Headlamp  0.0273087 0.2209851  0.12 0.9016502
          Skipline  0.6225757 0.0922764  6.75 0.0000000
          Material  0.7410158 0.2645802  2.80 0.0050988
 Headlamp:Skipline  0.0013387 0.0561586  0.02 0.9809826
 Headlamp:Material -0.0626491 0.0687658 -0.91 0.3622693
 Skipline:Material -0.1630064 0.0667931 -2.44 0.0146683
```

The trend in responses with increasing distance (and decreasing observation angle and increasing entrance angle) was not a surprise. For the samples at 180ft, there were more “white” responses than “yellow” responses. For shorter distances, the more saturated yellow markings elicited more “yellow” responses, especially at a distance of 60ft, the difference in yellow response percentages between the two materials were notable. However, with increasing distance, the discrepancy between the percentages diminishes, and even turns in favor of Ennis Thermoplastic Y+ in such far distances. The differences in the trends between the two materials with respect to distance from observers is statistically significant ($p=0.015$) as indicated by the interaction between skipline and material in Table 25.

The more saturated yellow pavement markings seem to be highly efficient at shorter distances in rendering “yellow”, but with increasing distance, this effectiveness becomes less distinct when compared to its less saturated counterpart. Figure 48 shows a bar plot of yellow response percentages for the two materials as a function of distance (location).



Note: Skipline No represents pavement marking location, 1 being the closest to the observers at 30ft and 6 being the farthest at 180ft.

Figure 48. Percentage of "yellow" responses for Ennis ThermoplasticY++ vs. Ennis Thermoplastic Y+ as a function of pavement marking location.

Ennis Thermoplastic Y++ vs. Ennis Thermoplastic Y:

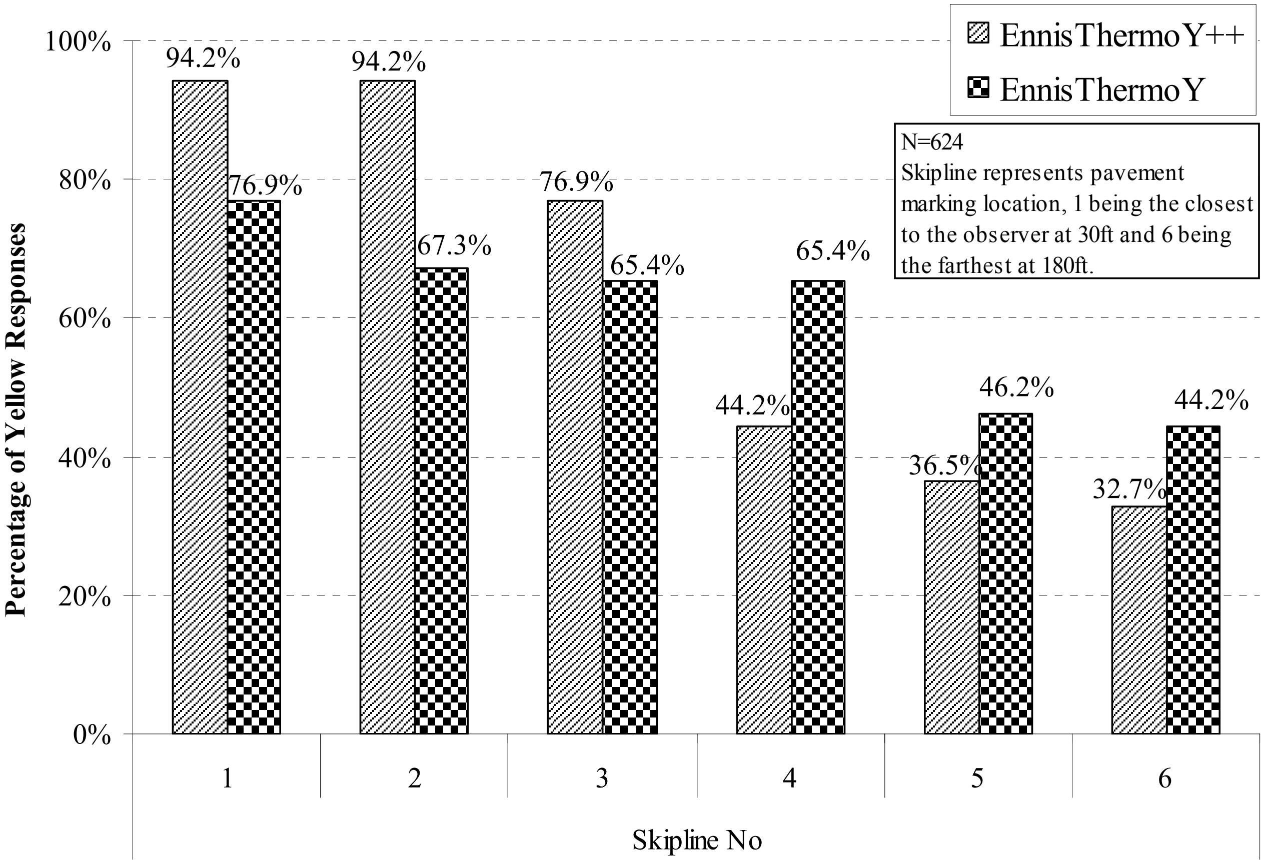
Pavement marking location (shown as skipline in Table 26) and material type were both statistically significant ($p<0.001$ for both). Results were similar to those given in the previous section for the comparison of Ennis Thermoplastic Y++ and Ennis Thermoplastic Y+. GEE summary table is given in Table 26.

Table 26. GEE Summary Table for the Pairwise Comparison between Ennis ThemoplasticY++ vs. Ennis Thermoplastic Y.

```
  Regression Coefficients:
                   Estimate  Std.Err.      Z      Prob
      (Intercept) -2.6372694 0.6062992 -4.35 0.0000136
          Subject  0.0109395 0.0302159  0.36 0.7173194
         Headlamp  0.2006379 0.1940610  1.03 0.3011872
         Skipline  0.5353335 0.0904947  5.92 0.0000000
         Material  1.0319068 0.2327207  4.43 0.0000092
Headlamp:Skipline -0.0397396 0.0515937 -0.77 0.4411567
Headlamp:Material -0.0545756 0.0709002 -0.77 0.4414463
Skipline:Material -0.2529212 0.0490627 -5.16 0.0000003

Scale Parameter: 0.9944718
```

For the samples at 180ft, there were more “white” responses than “yellow” responses. For shorter distances, the more saturated yellow markings elicited more “yellow” responses, especially at a distance of 60ft, the difference in yellow response percentages between the two materials were notable. The reverse trend in responses as the distance increases was more noteworthy between these two materials. Interestingly enough, unlike shorter distances, the less saturated yellow elicited more yellow responses at far distances. Hence, the interaction between the location and the material type was statistically significant ($p<0.001$). Figure 49 shows a bar plot of yellow response percentages for the two materials as a function of distance (location).



Note: Skipline No represents pavement marking location, 1 being the closest to the observers at 30ft and 6 being the farthest at 180ft.

Figure 49. Percentage of "yellow" responses for Ennis ThermoplasticY++ vs. Ennis Thermoplastic Y as a function of pavement marking location.

Ennis Thermoplastic Y++ vs. Flint Trading Thermoplastic:

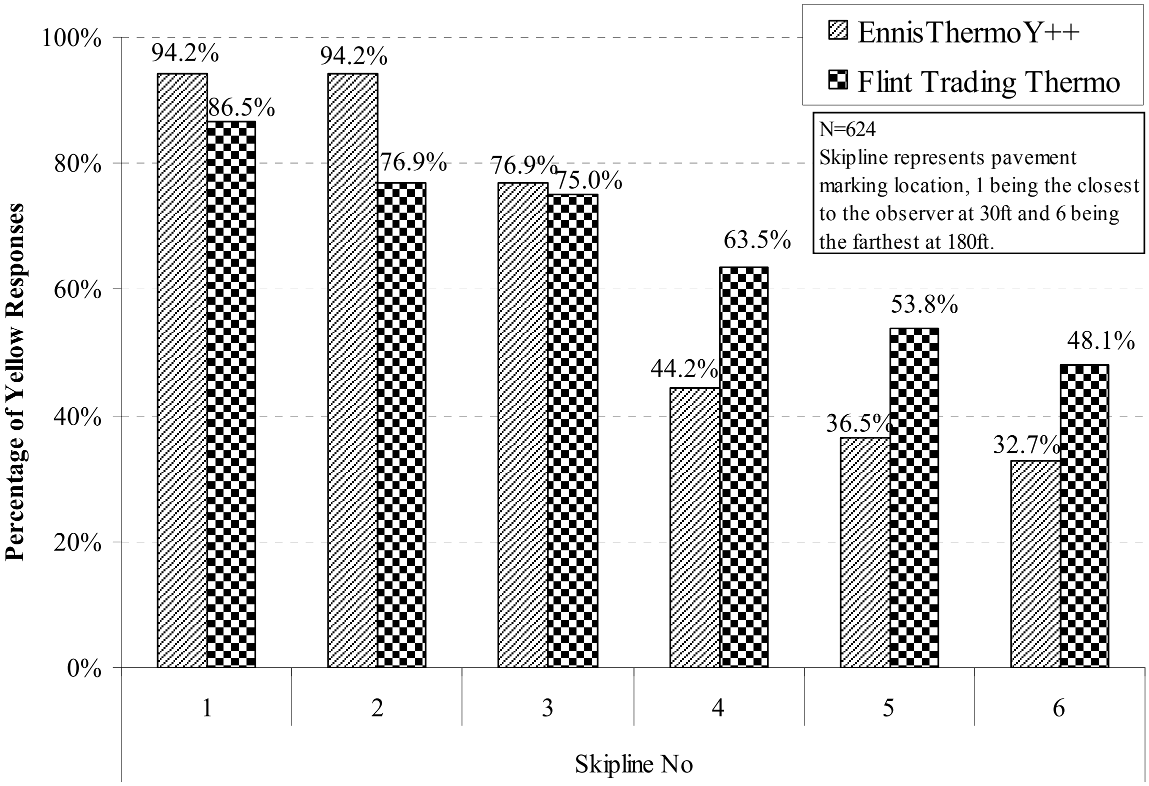
Pavement marking location (shown as skipline in Table 27) and material type were both statistically significant ($p<0.001$ for both). Results were similar to those given in the previous pairwise comparisons. The GEE summary table for the comparison between Ennis Thermoplastic Y++ and Flint Trading thermoplastic materials is given in Table 27.

Table 27. GEE Summary Table for the Pairwise Comparison between Ennis ThemoplasticY++ vs. Flint Trading Thermoplastic.

```
  Regression Coefficients:
                    Estimate  Std.Err.      Z       Prob
      (Intercept) -3.0680132 0.6115840 -5.02 0.0000005
          Subject  0.0184761 0.0274823  0.67 0.5013981
         Headlamp -0.0009058 0.1490214 -0.01 0.9951502
         Skipline  0.5831072 0.0860656  6.78 0.0000000
         Material  0.6989758 0.2000400  3.49 0.0004755
Headlamp:Skipline  0.0245047 0.0446972  0.55 0.5835279
Headlamp:Material  0.0018457 0.0883248  0.02 0.9833279
Skipline:Material -0.2050196 0.0529928 -3.87 0.0001094

  Scale Parameter: 0.9950483
```

The general trend for both materials was to be identified as more “white” as the distance increased. Yet, the situation was more dramatic for Ennis Thermoplastic Y++. Again, similar to the earlier pairwise comparisons, the highly saturated yellow thermoplastic (Ennis Thermoplastic Y++) educed higher yellow responses for distances up to 90ft, but beyond 90ft, the trend was reversed. For the samples at 180ft, there were more “white” responses than “yellow” responses. Hence, the interaction between the location and the material type was statistically significant ($p<0.001$). Figure 50 shows a bar plot of yellow response percentages for the two materials as a function of distance (location). In general, the two materials behaved differently in terms of color rendition with distance. The less-saturated material (Flint Trading Thermoplastic) was more uniformly identified as yellow as compared to the highly saturated thermoplastic material.



Note: Skipline No represents pavement marking location, 1 being the closest to the observers at 30ft and 6 being the farthest at 180ft.

Figure 50. Percentage of "yellow" responses for Ennis ThermoplasticY++ vs. Flint Trading Thermoplastic as a function of pavement marking location.

Ennis Thermoplastic Y++ vs. Latex Paint:

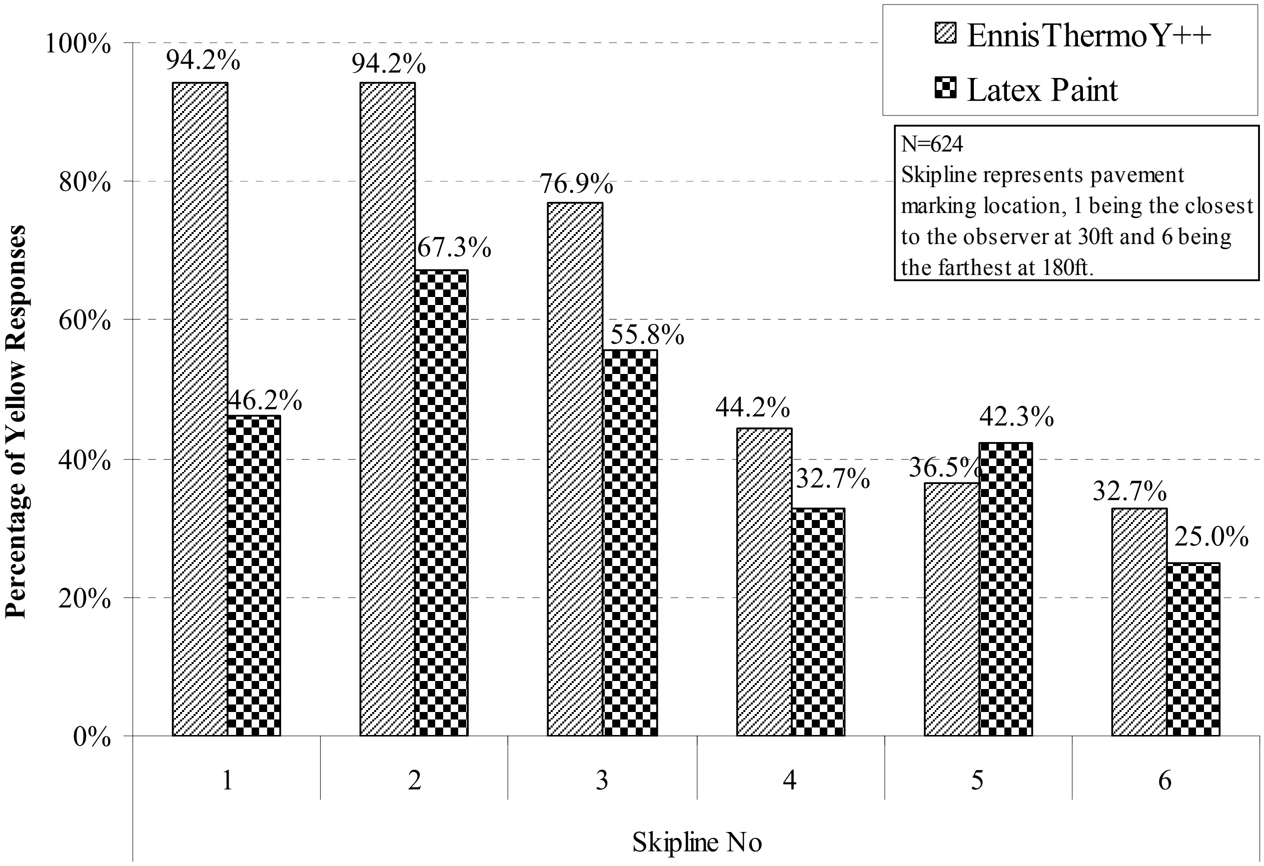
Pavement marking location (shown as skipline in Table 28) and material type were both statistically significant ($p<0.001$ for both). The GEE summary table for the comparison between Ennis Thermoplastic Y++ and Latex Paint materials is given in Table 28.

Table 28. GEE Summary Table for the Pairwise Comparison between Ennis ThemoplasticY++ vs. Latex Paint.

```
                           Estimate  Std.Err.      Z       Prob
             (Intercept) -1.9430579 0.4721223 -4.12 0.0000386
                 Subject -0.0107647 0.0253230 -0.43 0.6707662
                Headlamp -0.1725517 0.1729792 -1.00 0.3185079
                Skipline  0.5206151 0.0698420  7.45 0.0000000
                Material  1.4262039 0.3130920  4.56 0.0000052
       Headlamp:Skipline  0.0821678 0.0467265  1.76 0.0786653
       Headlamp:Material -0.3450977 0.1936340 -1.78 0.0747140
       Skipline:Material -0.2663101 0.0747388 -3.56 0.0003663
Headlamp:Skipline:Material  0.1013593 0.0490711  2.07 0.0388702
```

The second order interaction between material and location was also statistically significant similar to the previous cases ($p<0.001$). Yet, unlike the previous cases, the third order interaction between material, location, and headlamp was also statistically significant ($p\cong 0.04$). That is, the trends for the interaction between location and material were also headlamp dependent.

The general trend for both materials was to be identified as more “white” as the distance increased. Overall, the highly saturated yellow thermoplastic (Ennis Thermoplastic Y++) educed higher yellow responses at all distances but at 5th location (150ft). Nonetheless, the difference in the number of yellow responses was not as pronounced at longer distances as it was for shorter distances. Figure 51 shows a bar plot of yellow response percentages for the two materials as a function of distance (location). Figure 52 shows the percentage of yellow responses partitioned into headlamp types. The significant third order interaction between location, material and headlamp can be seen in Figure 52. Note the responses for each material type at different distances for the two headlamps: For the thermoplastic material (Ennis Thermo Y++), HID illumination elicited more yellow responses than did the TH headlamps in general regardless of the distance. Yet, for the latex paint material, HID headlamp illumination causes fewer yellow responses in shorter distances, whereas for longer distances the trend was reversed. HID headlamps elicited more yellow responses in longer distances regardless of the headlamp type.



Note: Skipline No represents pavement marking location, 1 being the closest to the observers at 30ft and 6 being the farthest at 180ft.

Figure 51. Percentage of "yellow" responses for Ennis ThermoplasticY++ vs. Latex Paint as a function of pavement marking location.

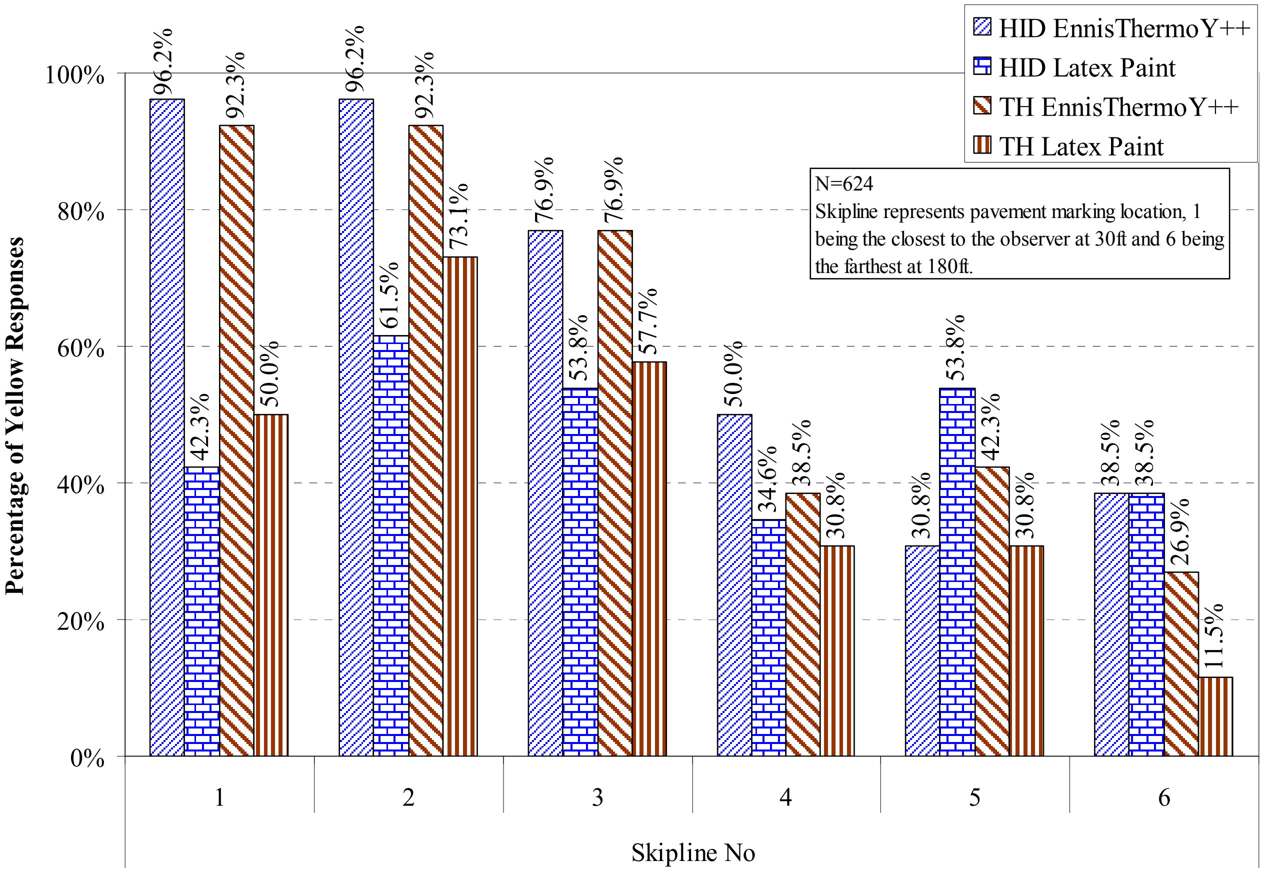


Figure 52. Percentage of "yellow" responses for Ennis ThermoplasticY++ vs. Latex Paint as a function of pavement marking location and headlamp type.

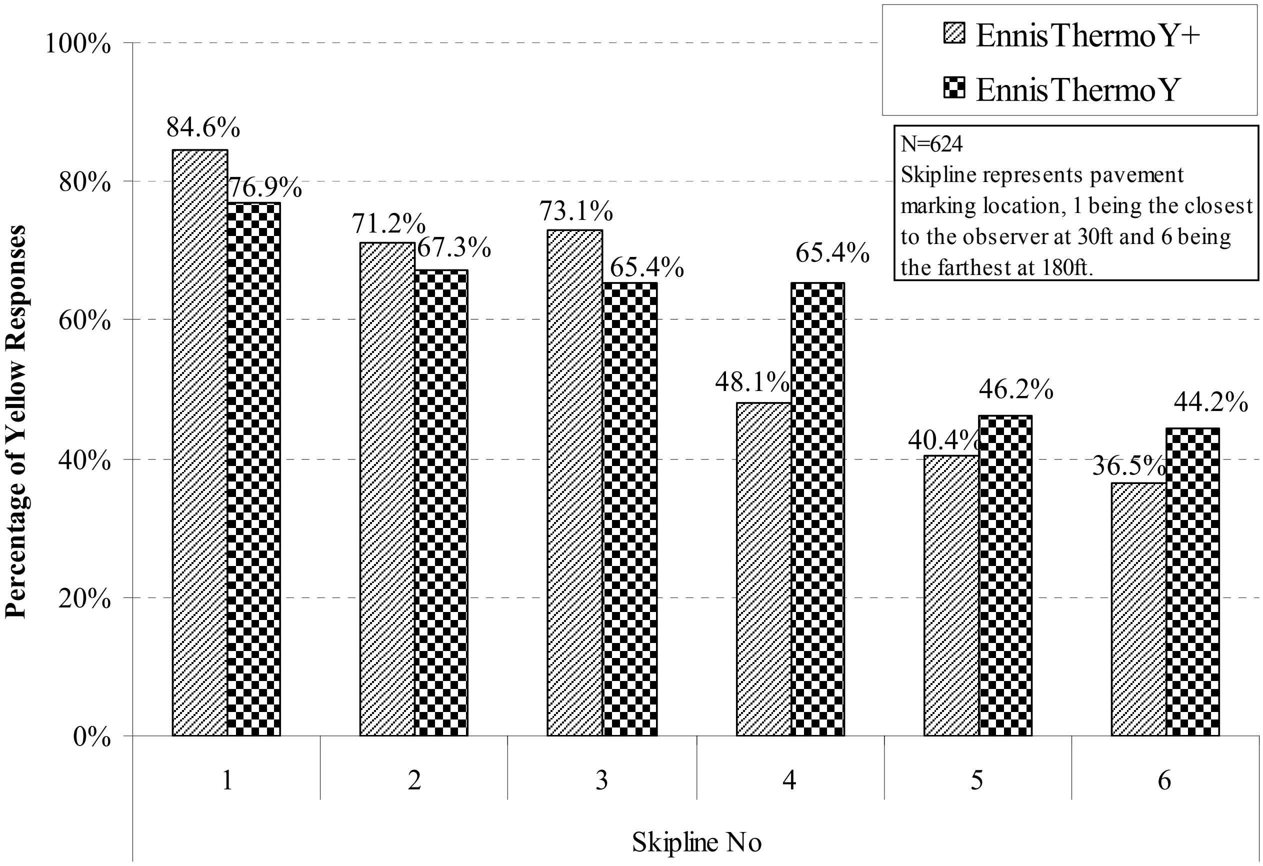
Ennis Thermoplastic Y+ vs. Ennis Thermoplastic Y:

For these two materials, the only statistically significant factor was pavement marking location ($p<0.001$). Statistically speaking, these two materials performed equally well. The GEE summary table for the comparison between Ennis Thermoplastic Y+ and Ennis Thermoplastic Y materials is given in Table 29. Material type and the interaction between the material type and location was just short of having statistical significance at $\alpha=0.05$ confidence level ($p=0.067$ and $p=0.052$, respectively). Although there was a slight trend similar to the earlier pairwise comparisons for material type and location, the difference was short of having a statistical significance. No other main factor or interaction was found to be statistically significant.

Figure 53 shows the percentage of yellow responses for these two material types as a function of pavement marking location.

Table 29. GEE Summary Table for the Pairwise Comparison between Ennis Themoplastic Y+ vs. Ennis Thermoplastic Y.

```
  Regression Coefficients:
                             Estimate  Std.Err.     Z      Prob
              (Intercept) -1.9324491 0.5390669 -3.58 0.0003373
                  Subject  0.0138516 0.0267355  0.52 0.6043913
                 Headlamp  0.0519879 0.1720962  0.30 0.7625862
                 Skipline  0.3718200 0.0877815  4.24 0.0000228
                 Material  0.2847902 0.1554002  1.83 0.0668584
        Headlamp:Skipline -0.0183845 0.0393280 -0.47 0.6401658
        Headlamp:Material  0.1360718 0.1571672  0.87 0.3866120
        Skipline:Material -0.0887882 0.0455997 -1.95 0.0515199
Headlamp:Skipline:Material -0.0327811 0.0411028 -0.80 0.4251376
```



Note: Skipline No represents pavement marking location, 1 being the closest to the observers at 30ft and 6 being the farthest at 180ft.

Figure 53. Percentage of “yellow” responses for Ennis ThermoplasticY+ vs. Ennis Thermoplastic Y as a function of pavement marking location.

Ennis Thermoplastic Y+ vs. Flint Trading Thermoplastic:

For these two materials, the only statistically significant factor was again pavement marking location ($p<0.001$). These two materials were very similar in nature. The GEE summary table for the comparison between Ennis Thermoplastic Y+ and Ennis Thermoplastic Y materials is given in Table 30. No other main factor or interaction was found to be statistically significant. Figure 54 shows the percentage of yellow responses for these two material types as a function of pavement marking location.

Table 30. GEE Summary Table for the Pairwise Comparison between Ennis ThemoplasticY+ vs. Flint Trading Thermoplastic.

```
     Regression Coefficients:
                              Estimate  Std.Err.      Z       Prob
                 (Intercept) -2.3599131 0.5120934 -4.61 0.0000041
                     Subject  0.0207929 0.0243483  0.85 0.3931191
                    Headlamp -0.0967779 0.1692611 -0.57 0.5674799
                    Skipline  0.4202872 0.0754286  5.57 0.0000000
                    Material -0.0428596 0.1897291 -0.23 0.8212802
           Headlamp:Skipline  0.0337560 0.0446545  0.76 0.4496869
           Headlamp:Material -0.0124906 0.1751556 -0.07 0.9431500
           Skipline:Material -0.0417148 0.0599002 -0.70 0.4861758
  Headlamp:Skipline:Material  0.0193270 0.0403596  0.48 0.6320323
```

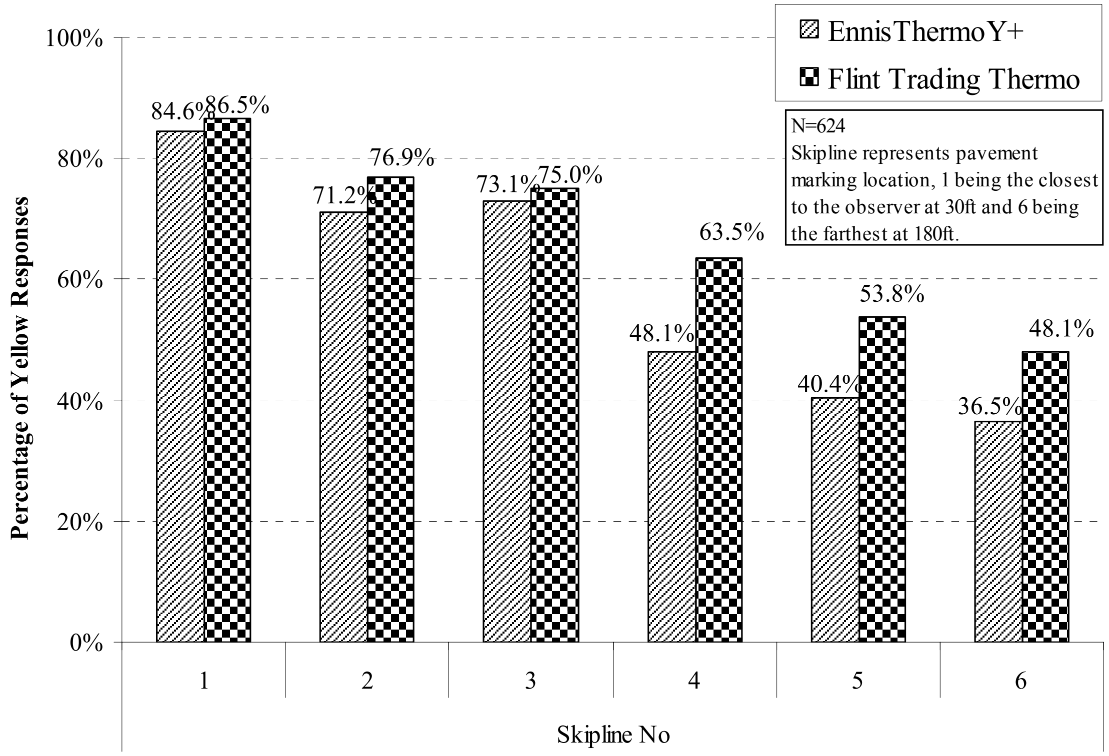


Figure 54. Percentage of "yellow" responses for Ennis Thermoplastic Y+ vs. Flint Trading Thermoplastic material as a function of pavement marking location.

<u>Ennis Thermoplastic Y+ vs. Latex Paint:</u>

Pavement marking location (shown as skipline in Table 31) and material type were both statistically significant ($p<0.001$ and $p=0.021$, respectively). The GEE summary table for the comparison between Ennis Thermoplastic Y+ and Latex Paint materials is given in Table 31.

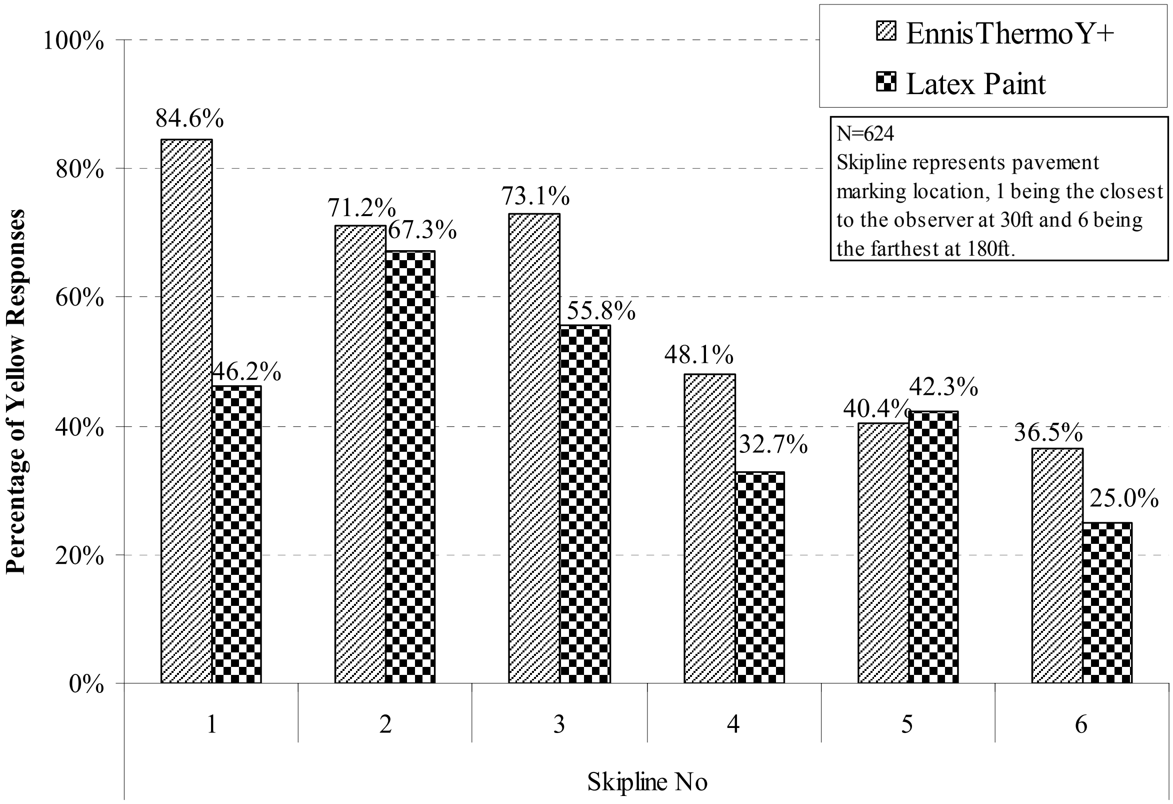
Table 31. GEE Summary Table for the Pairwise Comparison between Ennis Themoplastic Y+ vs. Latex Paint.

```
      Regression Coefficients:
                             Estimate  Std.Err.     Z      Prob
               (Intercept) -1.2657229 0.4213129 -3.00 0.0026625
                   Subject -0.0057865 0.0234129 -0.25 0.8047914
                  Headlamp -0.3005275 0.1801009 -1.67 0.0951845
                  Skipline  0.3568612 0.0704066  5.07 0.0000004
                  Material  0.6823739 0.2964756  2.30 0.0213567
         Headlamp:Skipline  0.0988561 0.0386098  2.56 0.0104556
         Headlamp:Material -0.2165778 0.1512392 -1.43 0.1521377
         Skipline:Material -0.1028277 0.0671888 -1.53 0.1259105
Headlamp:Skipline:Material  0.0844810 0.0402295  2.10 0.0357311
```

The second order interaction between headlamp and pavement marking location was also statistically significant (p≅0.01). Furthermore, the third order interaction between material, location, and headlamp was also statistically significant (p≅0.04). That is, the trends for the interaction between location and material were also headlamp dependent. The interaction between material and pavement marking location was not statistically significant. Figure 55 illustrates the percentage of yellow responses as a function of location and material type.

The interaction between headlamp type and location is apparent in Figure 56. HID headlamp illumination elicited more “white” responses for distances up to 90ft, beyond which the trend was the contrary. Such shift in the response trend may be attributed to higher illumination at longer distances provided by the HID headlamps rather than solely on spectral content. However, as yet, the reason is unknown.

Figure 57 shows the percentage of yellow responses categorized into headlamp types. The significant third order interaction between location, material and headlamp can be seen in Figure 57. Note the responses for each headlamp type at different distances for the two materials: under HID headlamp illumination, more subjects voted for yellow for Ennis Thermoplastic Y+ type material only for closer distances. For distances beyond 60ft, the “yellow” responses were similar for both materials under HID illumination. Yet, under TH headlamp illumination, Ennis Thermoplastic Y+ type material had more “yellow” votes that did the Latex paint regardless of the distance. In a sense, HID headlamps pronounce the yellow in latex paint more successfully than did the TH headlamps at longer distances.



Note: Skipline No represents pavement marking location, 1 being the closest to the observers at 30ft and 6 being the farthest at 180ft.

Figure 55. Percentage of “yellow” responses for Ennis ThermoplasticY+ vs. Latex Paint as a function of pavement marking location.

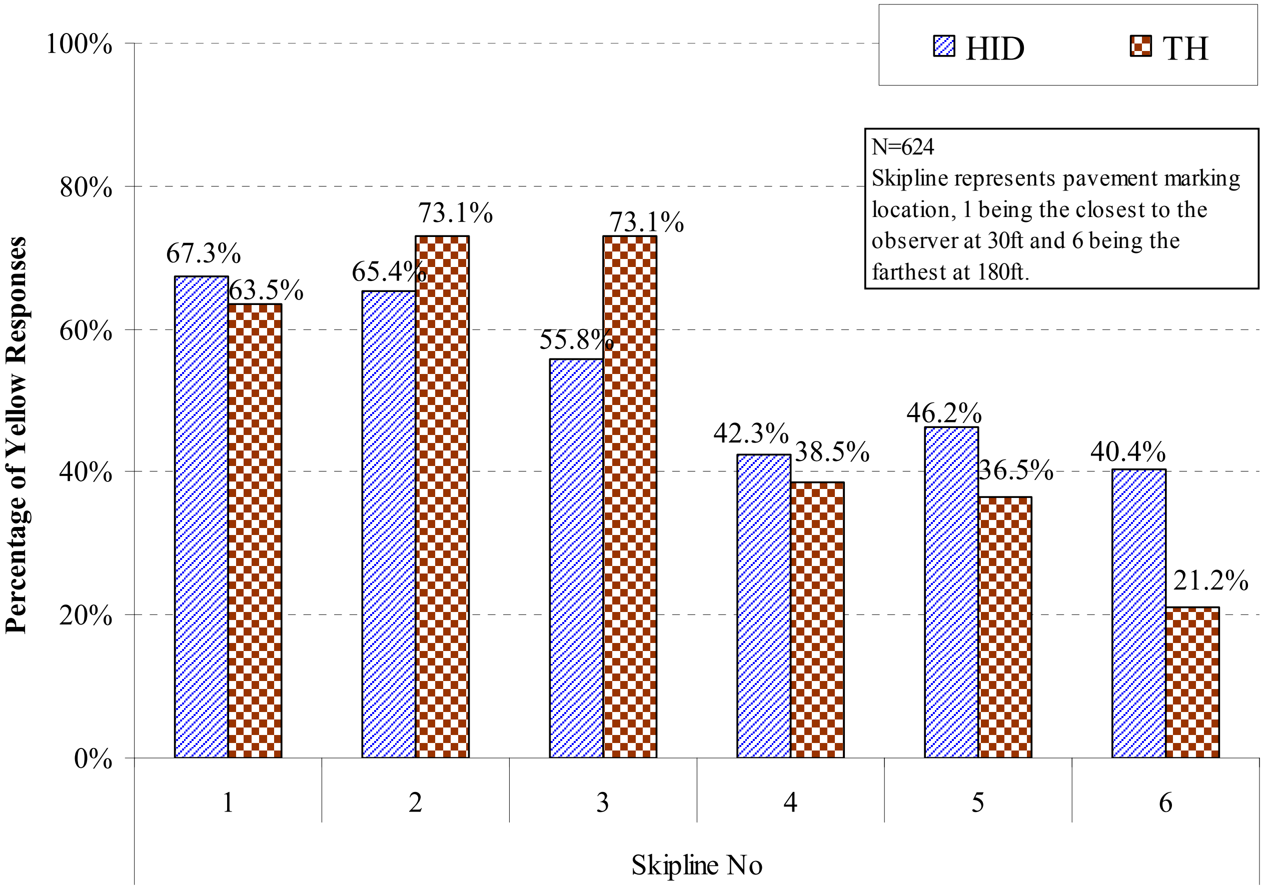


Figure 56. Percentage of combined "yellow" responses under HID and TH headlamp illumination for the combined data of the two materials Ennis Thermoplastic Y+ and Latex Paint as a function of pavement marking location.

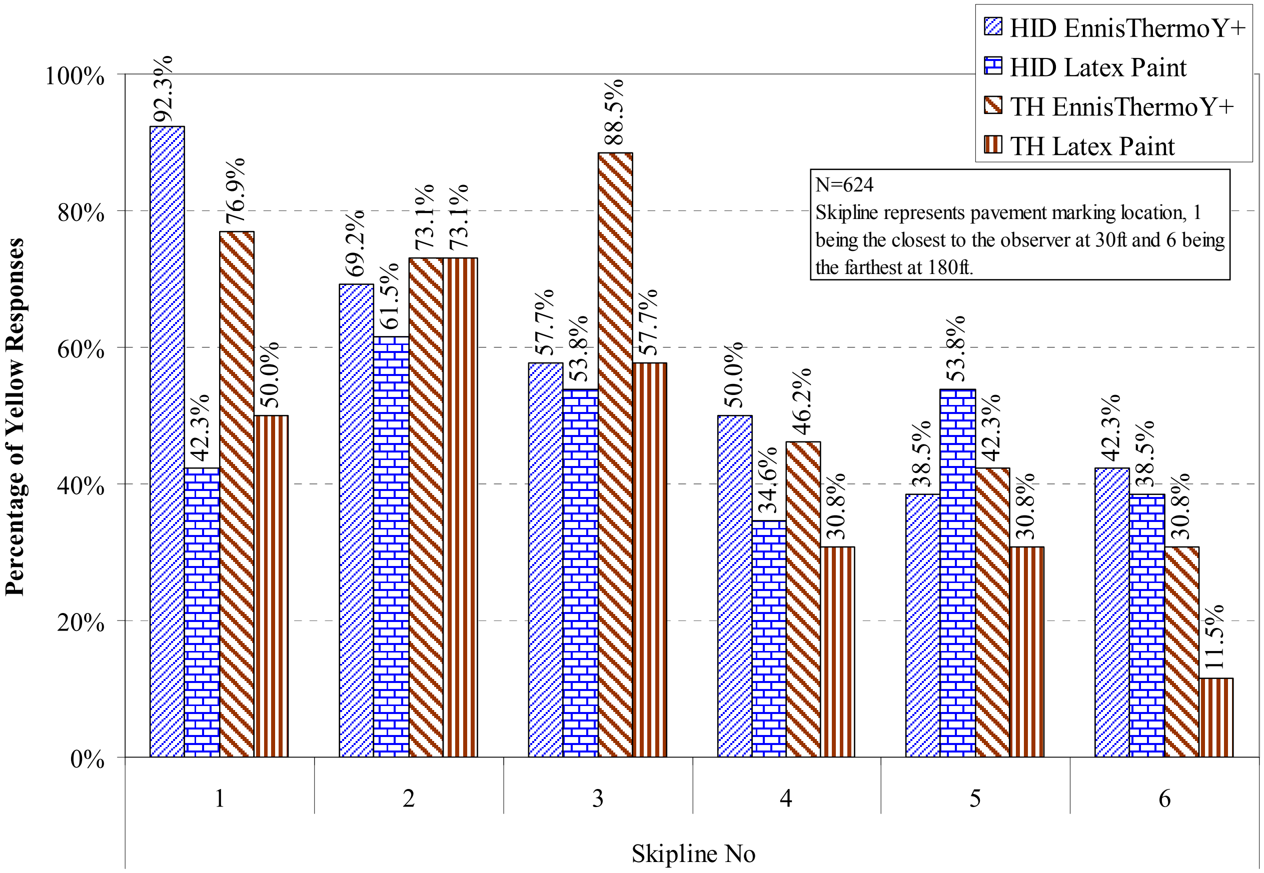


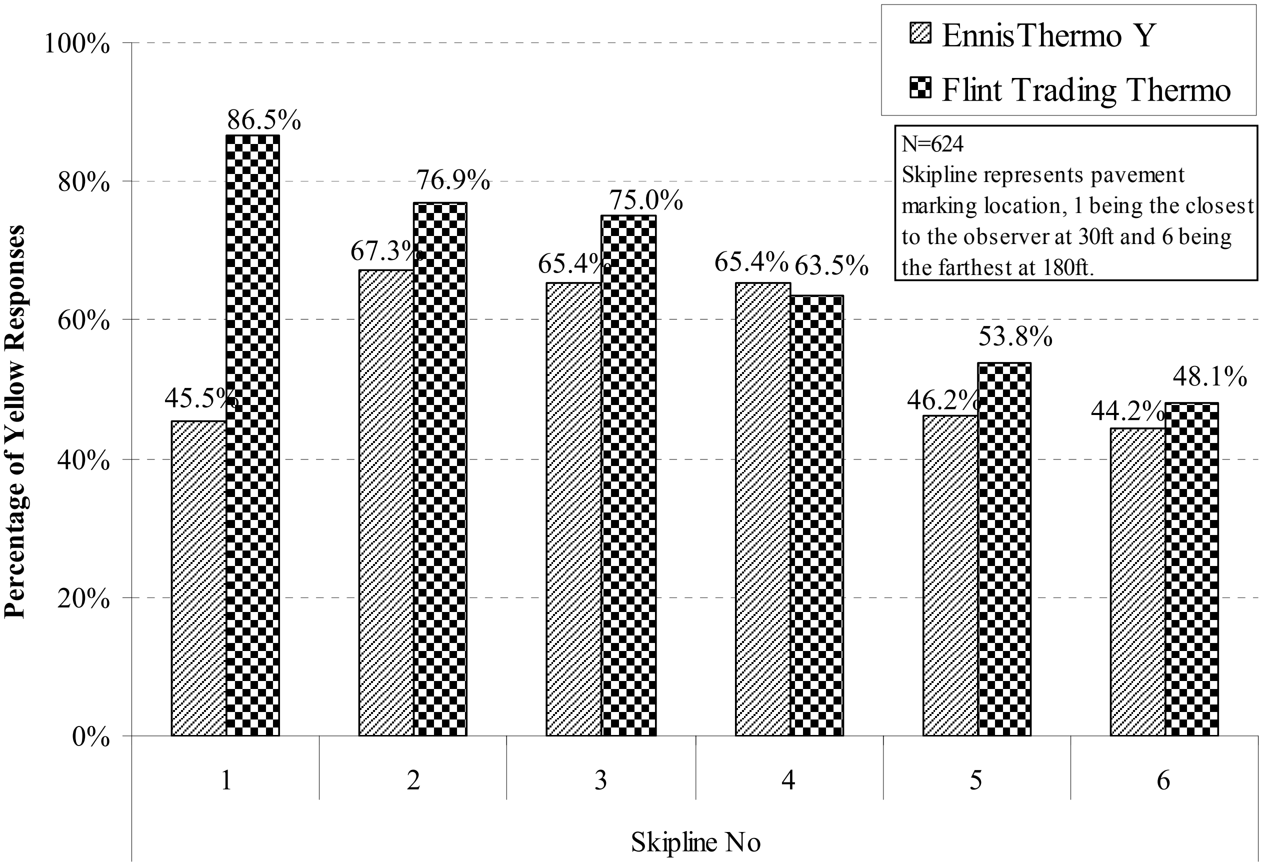
Figure 57. Percentage of “yellow” responses for Ennis ThermoplasticY+ vs. Latex Paint as a function of pavement marking location and headlamp type.

Ennis Thermoplastic Y vs. Flint Trading Thermoplastic:

For these two materials, both location and material type were statistically significant factors ($p<0.001$ and $p\cong0.007$, respectively). The GEE summary table for the comparison between Ennis Thermoplastic Y and Flint Trading Thermoplastic materials is given in Table 32. No interactions were found to be statistically significant. Figure 58 shows the percentage of yellow responses for these two material types as a function of pavement marking location.

Table 32. GEE Summary Table for the Pairwise Comparison between Ennis Themoplastic Y vs. Flint Trading Thermoplastic

```
        Regression Coefficients:
                              Estimate  Std.Err.      Z      Prob
                 (Intercept) -2.1270022 0.5434218 -3.91 0.0000907
                     Subject  0.0244241 0.0291967  0.84 0.4028527
                    Headlamp  0.0397262 0.1907855  0.21 0.8350536
                    Skipline  0.3319076 0.0729135  4.55 0.0000053
                    Material -0.3289563 0.1229233 -2.68 0.0074482
           Headlamp:Skipline  0.0008894 0.0437665  0.02 0.9837870
           Headlamp:Material -0.1492236 0.1349175 -1.11 0.2687112
           Skipline:Material  0.0473965 0.0402237  1.18 0.2386688
  Headlamp:Skipline:Material  0.0523082 0.0358740  1.46 0.1448098
```



Note: Skipline No represents pavement marking location, 1 being the closest to the observers at 30ft and 6 being the farthest at 180ft.

Figure 58. Percentage of "yellow" responses for Ennis Thermoplastic Y vs. Flint Trading Thermoplastic material as a function of pavement marking location.

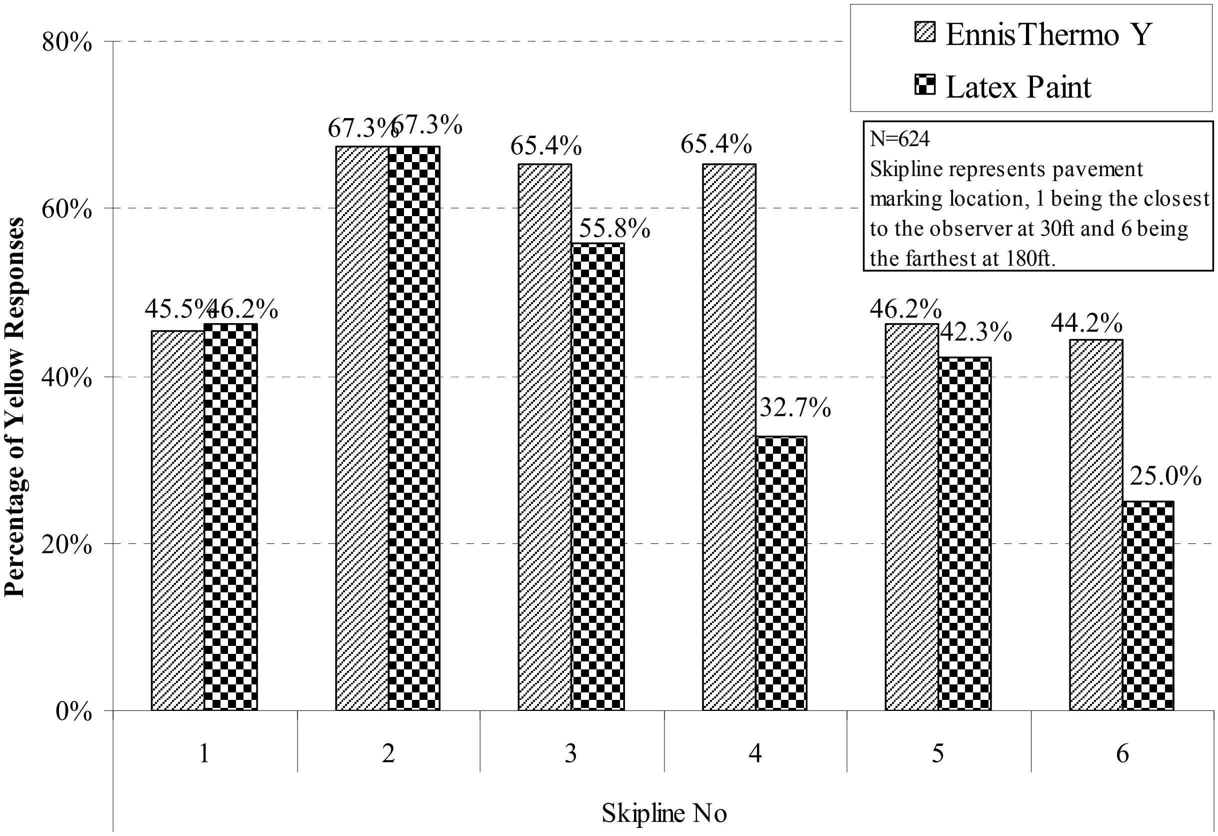
Ennis Thermoplastic Y vs. Latex Paint:

Among the main factors, only the pavement marking location was statistically significant ($p<0.001$). Among the second order interactions, only the interaction between headlamp and material type was significant ($p\cong0.019$). Furthermore, the third order interaction between material, headlamp, and pavement marking location was also statistically significant ($p<0.001$). The GEE summary table for the comparison between Ennis Thermoplastic Y and Latex paint type materials is given in Table 33.

Table 33. GEE Summary Table for the Pairwise Comparison between Ennis Themoplastic Y vs. Latex Paint.

```
         Regression Coefficients:
                                 Estimate  Std.Err.      Z       Prob
                (Intercept) -1.0372759 0.4579796 -2.26 0.0235191
                    Subject -0.0016194 0.0262698 -0.06 0.9508462
                   Headlamp -0.1646294 0.1662279 -0.99 0.3219866
                   Skipline  0.2681352 0.0624103  4.30 0.0000174
                   Material  0.3979365 0.2545302  1.56 0.1179549
          Headlamp:Skipline  0.0661094 0.0391573  1.69 0.0913529
          Headlamp:Material -0.3522719 0.1495834 -2.36 0.0185217
          Skipline:Material -0.0142034 0.0575952 -0.25 0.8052117
 Headlamp:Skipline:Material  0.1171564 0.0336624  3.48 0.0005008
```

Figure 58 shows the percentage of yellow responses for these two material types as a function of pavement marking location.



N=624
Skipline represents pavement marking location, 1 being the closest to the observer at 30ft and 6 being the farthest at 180ft.

Note: Skipline No represents pavement marking location, 1 being the closest to the observers at 30ft and 6 being the farthest at 180ft.

Figure 59. Percentage of “yellow” responses for Ennis Thermoplastic Y vs. Latex Paint type material as a function of pavement marking location.

HID headlamp illumination yielded more “yellow” responses only for the latex paint type pavement marking. This interaction can be seen in Figure 60.

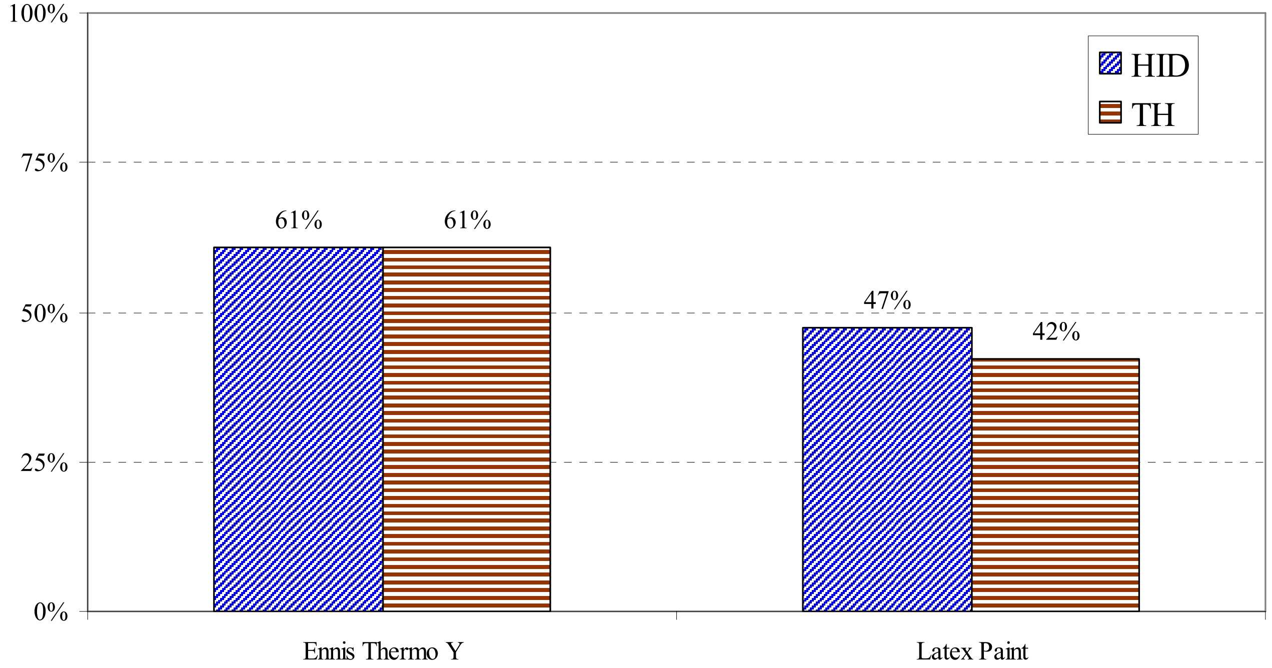


Figure 60. The percentage of yellow responses for the two headlamps as a function of pavement marking type.

The trends for the interaction between headlamp and material were location-dependent. The higher number of "yellow" responses under HID illumination was especially pronounced at far distances similar to the cases in earlier pairwise comparisons.

Figure 61 shows the percentage of yellow responses categorized into headlamp types. The significant third order interaction between location, material and headlamp can be seen in Figure 61. Note the responses for each headlamp type at different distances for the two materials: there was no significant difference in the number of yellow responses between HID and TH headlamps for Ennis Thermoplastic Y type material regardless of the distance. However, the same was not true for Latex Paint type material. The further away the material, the more yellow responses under HID illumination only. The yellow responses suffered under TH headlamp illumination for distances beyond 60ft.

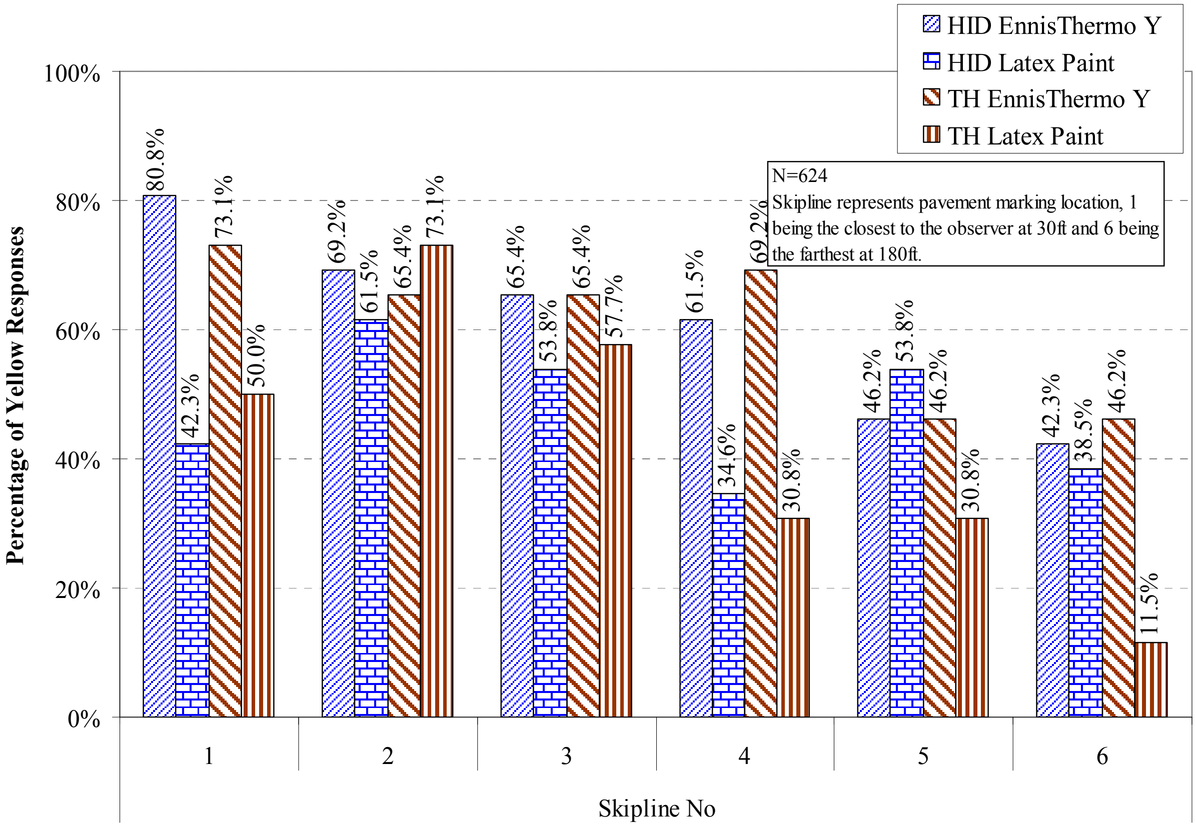


Figure 61. Percentage of "yellow" responses for Ennis Thermoplastic Y vs. Latex Paint as a function of pavement marking location and headlamp type.

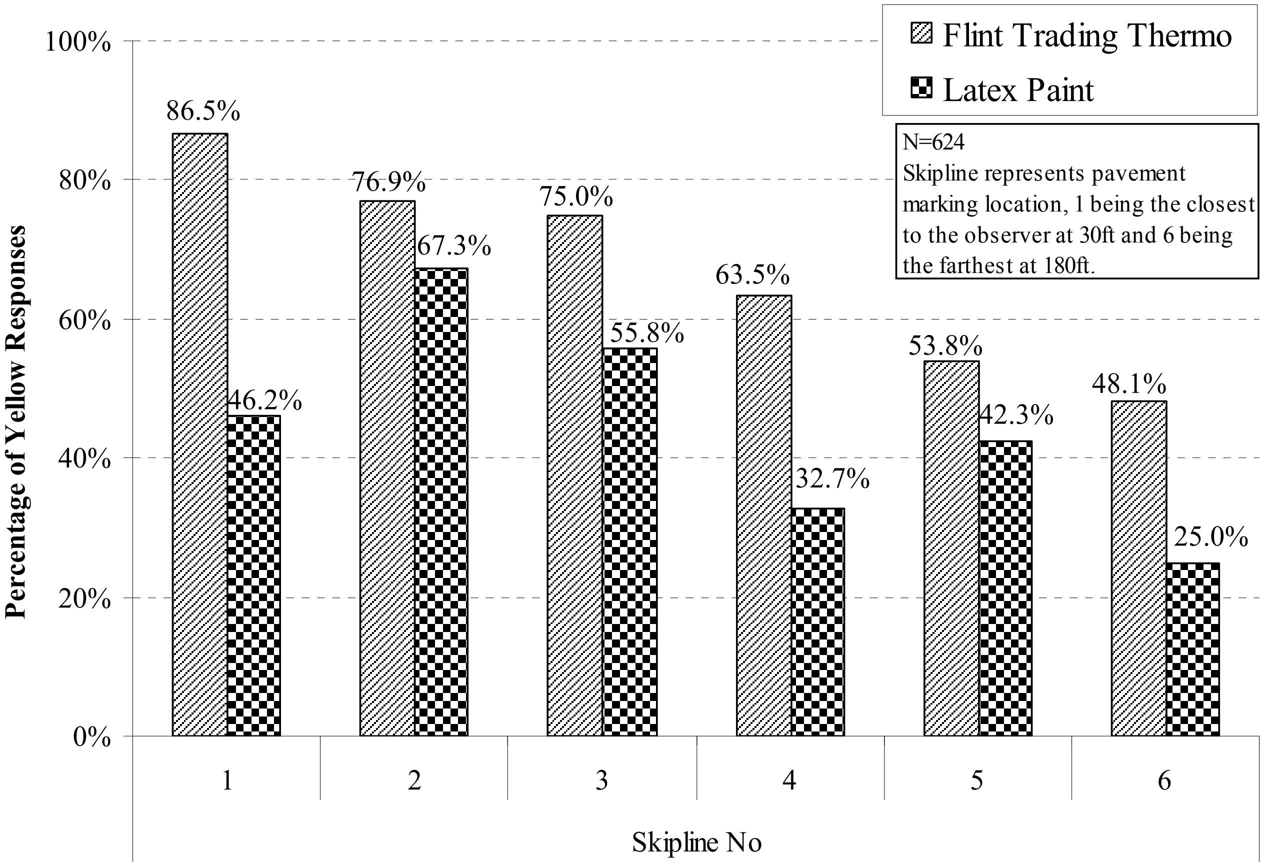
<u>Flint Trading Thermoplastic vs. Latex Paint:</u>

Among the main factors, both pavement marking location and material type were statistically significant ($p<0.001$ and $p\cong0.002$, respectively). Among the second order interactions, only the interaction between headlamp and pavement marking location was statistically significant ($p\cong0.015$). Furthermore, the third order interaction between material, headlamp, and pavement marking location was also statistically significant ($p<0.001$). The GEE summary table for the comparison between Ennis Thermoplastic Y and Latex paint type materials is given in Table 34.

Table 34. GEE Summary Table for the Pairwise Comparison between Flint Trading Thermoplastic vs. Latex Paint.

```
                            Estimate  Std.Err.      Z       Prob
               (Intercept) -1.4414560 0.4167374 -3.46 0.0005424
                   Subject  0.0040774 0.0236297  0.17 0.8630036
                  Headlamp -0.3128407 0.2035606 -1.54 0.1243317
                  Skipline  0.3153469 0.0585939  5.38 0.0000001
                  Material -0.7250900 0.2357943 -3.08 0.0021044
         Headlamp:Skipline  0.1180451 0.0485663  2.43 0.0150740
         Headlamp:Material  0.2041531 0.1165149  1.75 0.0797457
         Skipline:Material  0.0613690 0.0570298  1.08 0.2818882
Headlamp:Skipline:Material -0.0652531 0.0262752 -2.48 0.0130117
```

Figure 62 shows the percentage of yellow responses for these two material types as a function of pavement marking location.



N=624
Skipline represents pavement marking location, 1 being the closest to the observer at 30ft and 6 being the farthest at 180ft.

Note: Skipline No represents pavement marking location, 1 being the closest to the observers at 30ft and 6 being the farthest at 180ft.

Figure 62. Percentage of "yellow" responses for Flint Trading Thermoplastic vs. Latex Paint type material as a function of pavement marking location.

The second order interaction between headlamp and material type was just short of having statistical significance at $\alpha=0.05$ significance level.

As the second order interaction between the headlamp type and pavement marking location suggests, there was a discrepancy between the percentages of yellow responses from one headlamp to the other as the pavement marking location changed. Although there was not much of a difference in yellow responses for closer distances, for pavement markings beyond 90ft, HID headlamps elicited more yellow responses. This second order interaction can be seen in Figure 63.

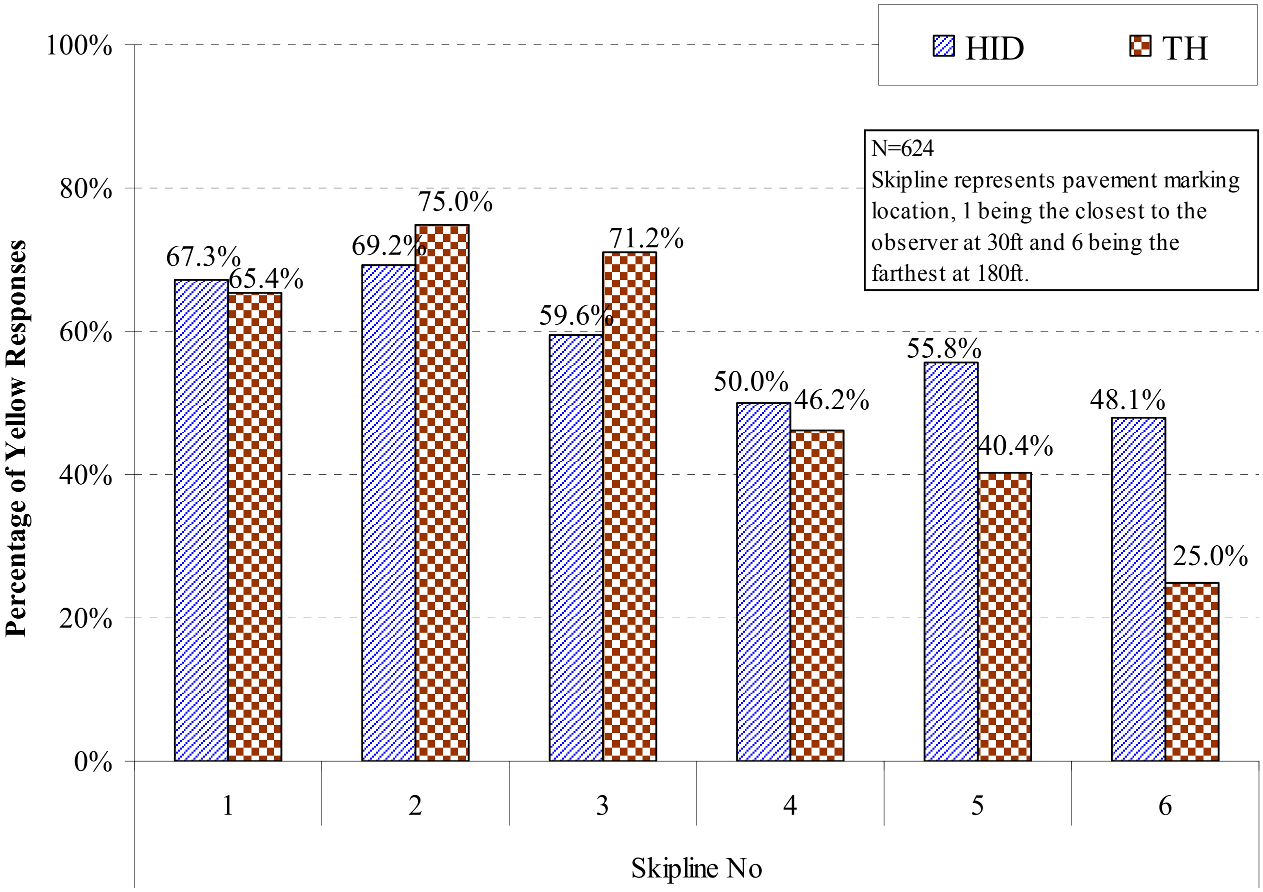


Figure 63. The percentage of yellow responses for the two headlamps as a function of pavement marking location for the combined data of the two materials Flint Trading Thermoplastic and Latex Paint.