APPLIED RESEARCH ASSOCIATES, INC.

July 8, 2008

Mr. Steve Gillen
Materials Manager
Illinois Tollway
2700 Ogden Avenue
Downers Grove, IL 60515

Subject: **FINAL Report for Pavement Marking Test Section on Ronald Reagan Memorial Tollway (MP 122.7 – 126.5)**
ARA Project No. 17930 – 08C1

Dear Mr. Gillen:

Applied Research Associates, Inc. is pleased to provide the draft report for the 2008 retroreflectivity testing for the pavement marking test section on I-88 from MP 122.7 to 126.5. This draft includes the spectrophotometry testing results as well as the requested changes to the previous draft dated June 27th, 2008. Please review and let us know if you have any comments or questions. We will finalize the report upon your approval of the draft report.

Sincerely,

Carmine E. Dwyer, P.E.
Project Engineer

Michael J. Harrell, P.E.
Senior Engineer

TRANSPORTATION SECTOR
100 TRADE CENTRE DRIVE, SUITE 200 ■ CHAMPAIGN, IL 61820
(217) 356-4500 ■ FAX: (217) 356-3088 ■ WWW.ARA.COM/TRANSPORTATION

BACKGROUND

In May and June of 2007, the Illinois Tollway completed the installation of a pavement marking test section on the Ronald Reagan Memorial Tollway from MP 122.7 to 126.5. The test section includes the mainline markings (edge lines and skip dashes) for all eight lanes and most of the markings on six ramps that fall within the section. All mainline markings are recessed, and the depths of the grooves depend on the thickness of the marking. Nearly all ramp markings, with the exception of the 4-inch edge lines on two of the ramps, are placed on the surface of the pavement. The test section has 13 different pavement marking products from four different manufacturers (3M, Epoplex, IPS, and Poly-Carb). AC Pavement Striping and their sub-contractor, Maintenance Coatings, placed the pavement markings. Applied Research Associates (ARA) performed retroreflectivity testing during the installation to verify that minimum initial retroreflectivity was being met. ARA is currently monitoring the performance of the different markings through continued retroreflectivity testing as well as wet retroreflectivity and spectrophotometry testing.

RETROREFLECTIVITY DEFINED

Retroreflection is the phenomenon of light rays striking a surface and being redirected directly back to the source of light. Figure 1 displays the different types of reflection. Fortunately, retroreflectors are not perfect; the light is not reflected directly back to the source. Instead, there is a scattering of light intensity in directions around that of the source. It is this imperfectly retroreflected light that returns to the driver's eyes and allows retroreflection to be useful for pavement markings.

The most commonly used measure of retroreflectivity for markings is the coefficient of retroreflected luminance, R_L. It is defined by the American Society for Testing and Materials (ASTM) to be the ratio of the luminance of a surface to the normal illuminance on the surface. For a study of the retroreflectivity of pavement markings, this would be the luminance from the pavement marking (seen by the driver) versus the normal illuminance (from head lights) hitting the pavement marking. Figure 2 helps visualize these quantities. R_L is reported in millicandelas (mcd) per square meter per lux. A candela is a basic unit of luminous intensity, and luminous intensity can be thought of as the "amount of brightness". A lux is a unit of illuminance defined as the luminous flux per unit area. Flux is a measure of total light energy emitted per unit time and measured in lumens. Finally, one lumen is defined as the amount of light energy flowing through a solid angle of one steradian from a source having a luminous intensity of one candela. The units of lux are lumens per square meter.

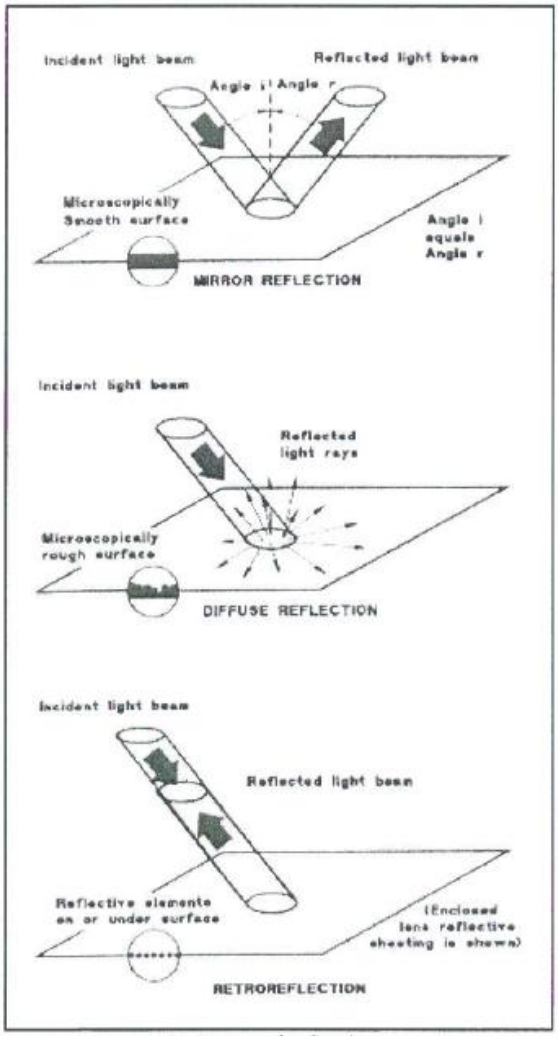


Figure 1. Types of reflection. (From Publication No. FHWA-SA-93-001)

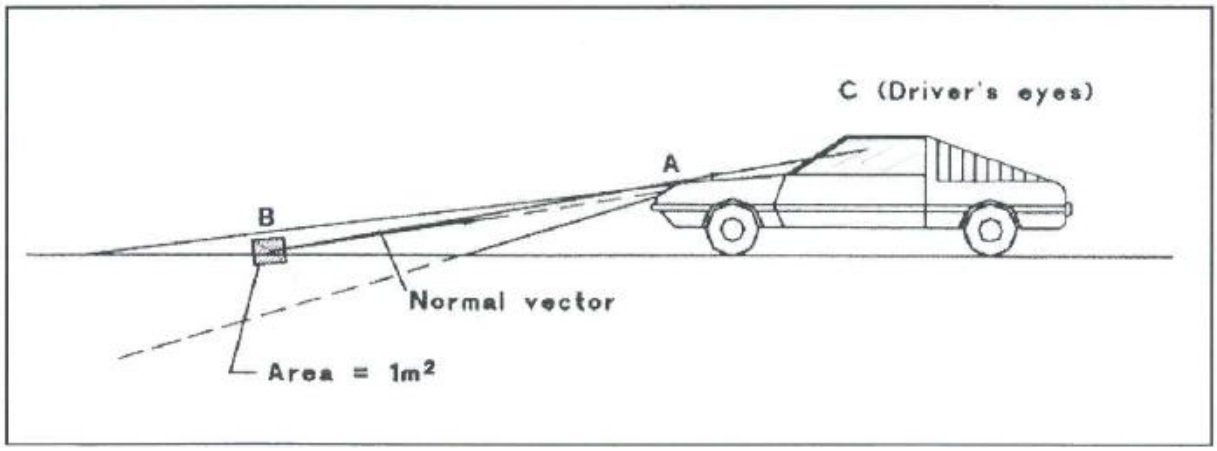


Figure 2. Depiction of roadway retroreflection. (From Publication No. FHWA-SA-93-001)

SPECTROPHOTOMETRY DEFINED

Spectrophotometry is the science of measuring the color of reflecting specimens. There are many methods for expressing colors numerically, in much the same way that we express length or weight. One of the most widely known methods, and the method specified for measuring the color of pavement marking materials, is the Yxy color space. Devised in 1931 by the Commission Internationale de I'Eclairage (CIE), the Yxy color space expresses a specimens color in two parts, lightness (Y) and hue (xy). Lightness is a measure of how light or dark a color is. Hue is the term used for the classification of a color such as red, yellow, blue, etc. The CIE x,y chromaticity diagram is shown in Figure 3.

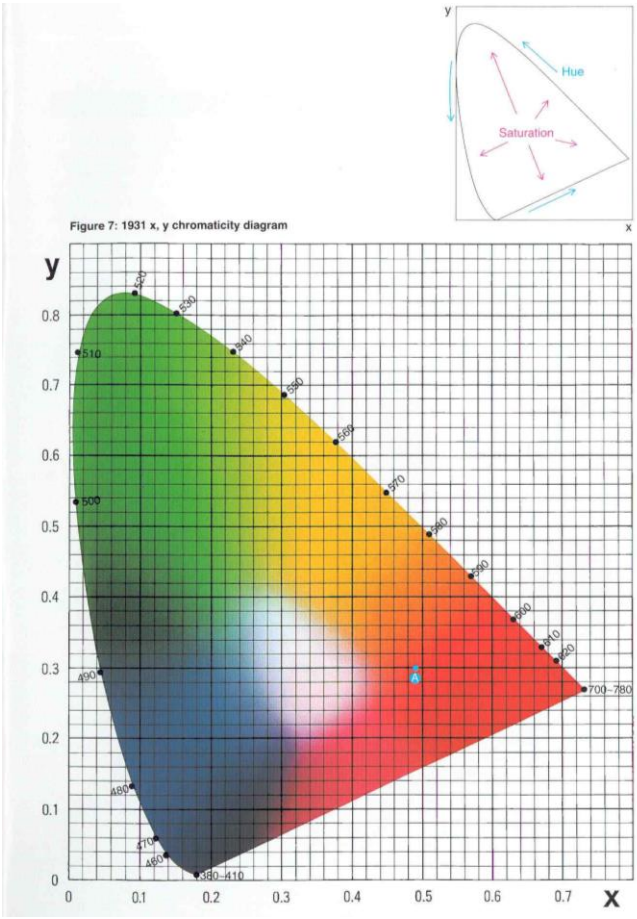


Figure 3. CIE x,y chromaticity diagram.
(From "Precise Color Communication" by Konica Minolta)

Lightness, Y, can be thought of as a value along a third axis perpendicular to the chromaticity diagram. For an example, in Yxy color space point A in Figure 3 has the following color coordinates:

Y = 13.37
x = 0.4832
y = 0.3045

GENERAL INFORMATION

All testing for this study is performed in accordance with the following standards:

- Dry retroreflectivity: ASTM E 1710-05
- Wet retroreflectivity: ASTM E 2177-01
- Spectrophotometry: ASTM E 1349-90 and ASTM D 6628-03

Sampling areas were developed using Section 6 of ASTM D 6359-99, which resulted in approximately 2200 test points for the entire test section. The retroreflectometer being used for this study is a Delta LTL-X, shown in figure 4, and the spectrophotometer is a Konica Minolta CM-2500c, shown in figure 5.

Figure 4. Delta LTL-X Retroreflectometer

Figure 5. CM-2500c Spectrophotometer

Due to the different methods and equipment for placing the pavement markings, the data are separated into three categories. The first group is the Recessed Lines. These are the solid edge lines and skip dashes that were placed in a groove cut into the pavement. The Recessed Lines are expected to give lower wet retroreflectivity since water will be somewhat contained in a groove. Figure 6 is a photo of an edge line after grinding and sweeping.

Figure 6. Edge line groove ready for pavement marking.

The second group is the Surface Lines. These are the lines that were applied directly to surface of the pavement. Data from these two groups should not be averaged together because the optics (beads and elements) placed on the Surface Lines are not protected from snow removal. As seen in Figure 7, Recessed Lines and Surface Lines were placed using a paint truck.

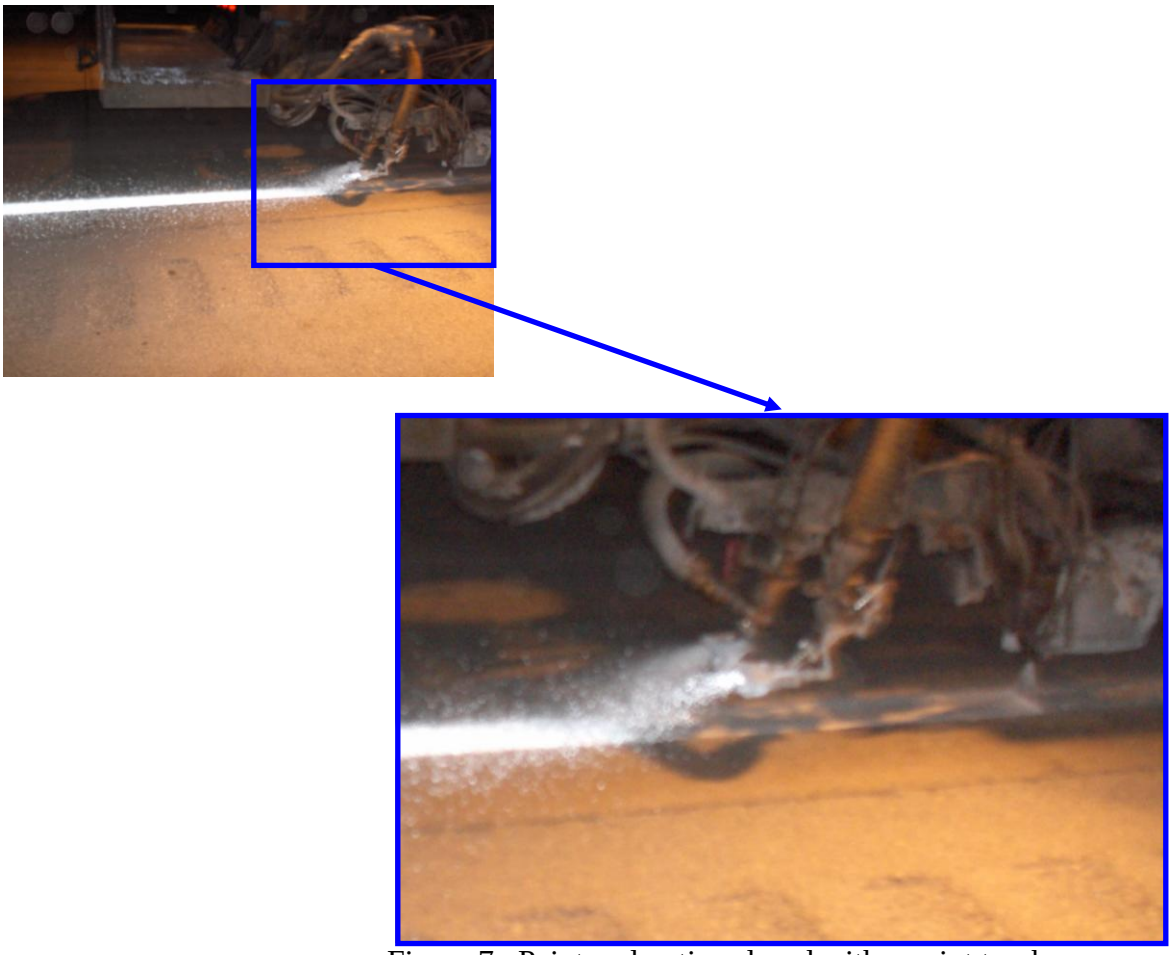


Figure 7. Paint and optics placed with a paint truck.

The truck is maintained at a constant speed which allows the paint to have a constant "wet film thickness" and the optics to have an even distribution. Wet film thickness is important in liquid pavement marking systems because if the film is too thick then the optics will sink and be less visible, but if the film is too thin, then the optics may not be retained as well over time.

Finally, the last group is the Letters & Symbols. Markings in this group were also applied to the surface of the pavement, but the equipment and methods used to place them were different from the Surface Lines.

Letters & Symbols, such as the chevrons in gores and the ONLY's and arrows on ramps, are placed using a paint cart as shown in figure 8. Also, the optics are placed by hand as shown in figure 9.

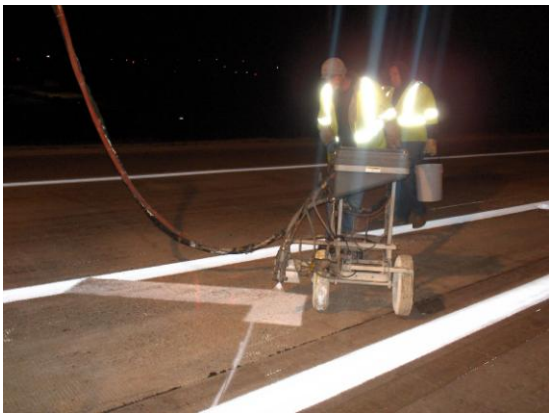


Figure 8. Chevron placed with paint cart.

Figure 9. Optics placed by hand.

For clarity, the tape placed in the test section was placed using different equipment. All tape sections are placed in grooves so they are grouped with the Recessed Lines. Figures 10 and 11 show tape being laid and tamped.

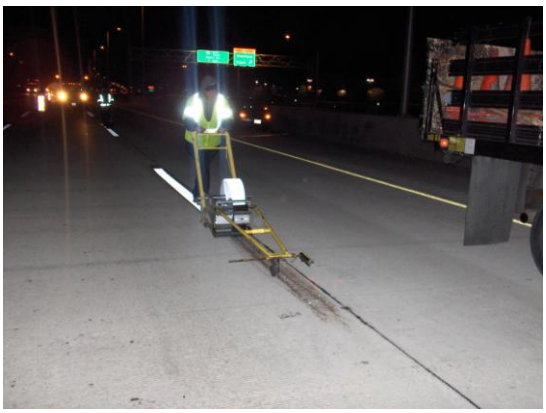


Figure 10. Tape laid and cut with tape cart.

Figure 11. Tape tamped with weights.

Future testing will no longer include the skip dashes between lanes 2 and 3 from MP 126.5 to MP 123.5 (IL Rt 59). Testing those sections requires a 3-lane closure which is difficult to set up, and even when it is set up, some drivers still penetrate the closure, rendering it unsafe to work in. There are four sections of pavement marking located on the lane 2-3 dash. Three of those four are urethane, and unfortunately, those are the only mainline sections with urethane. Therefore, beginning with the May 2008 data collection round, the only urethane that will be tested is the urethane used for Letters and Symbols. One interesting observation: by October of 2007, one of the mainline sections of urethane was already showing poor adhesion, as shown in figure 12.

Figure 12. Examples of urethane exhibiting poor adhesion. Photos taken October 4, 2007.

The remaining section of lane 2-3 dashes has Poly II placed on it, but there are other mainline sections of Poly II so it will still be part of the study.

DRY RETROREFLECTIVITY DATA AND ANALYSIS

To date, four sets of dry retroreflectivity data have been collected. The first set was collected the same night each marking was placed. The second set, referred to as the "Initial" data, was collected as soon as the installation of the entire test section was complete. Excess optics (beads and elements) on liquid marking materials contribute to erroneous readings directly after application and are generally not present a few days after application. Therefore, for many products the highest retroreflectivity occurred during the "Initial" testing. The third set of dry retroreflectivity data, referred to as the "2nd round", was collected in October 2007. The fourth set of dry retroreflectivity data, referred to as the "3rd round", was collected in May and June 2008.

Table 1 presents the dry R_L values of all three pavement marking groups (Recessed Lines, Surface Lines, and Letters & Symbols).

Table 1. Dry Retroreflectivity Readings.

Pavement Marking Material	Application Type	Average R_L (mcd/m^2/lux)			
		Placement	Initial	2nd Round	3rd Round
		May-07	Jun-07	Oct-07	May-08
Epoplex's GLOMARC 90 Wet Reflective Type 1 Polyurea - White	Recessed Lines	853	420	278	276
Epoplex's GLOMARC 90 Wet Reflective Type 1 Polyurea - Yellow	Recessed Lines	496	322	251	175
Polycarb's Mark 55.4 Hybrid Epoxy with 2 Optics – White	Recessed Lines	414	571	636	508
Polycarb's Mark 55.4 Hybrid Epoxy with 3 Optics – White	Recessed Lines	798	564	609	497
Polycarb's Mark 75 Type 1 Polyurea – White	Recessed Lines	683	476	525	390
3M's Stamark 1000 Type 1 Polyurea – White	Recessed Lines	308	544	462	381
3M's Stamark 1000 Type 1 Polyurea – Yellow	Recessed Lines	248	291	299	238
3M's Stamark 1200 Type 2 Polyurea – White	Recessed Lines	949	738	611	384
3M's Stamark 1200 Type 2 Polyurea – Yellow	Recessed Lines	640	514	450	351
3M's Stamark Series 380I ES Preformed Tape – White	Recessed Lines	637	712	728	799
3M's Stamark Series 380 Wet Relective Preformed Tape – White	Recessed Lines	1128	1127	1023	282
IPS's HPS-4 Urethane – White	Recessed Lines	209	377	415	-*
3M's Stamark 1000 WR Type 1 Polyurea – White	Recessed Lines	728	628	567	506
3M's Stamark 1000 Type 1 Polyurea – White	Surface Lines	211	393	377	286
3M's Stamark 1000 Type 1 Polyurea – Yellow	Surface Lines	187	226	215	144
3M's Stamark 1000 Type 1 Polyurea – White	Letters & Symbols	235	452	354	180
3M's Stamark 1200 Type 2 Polyurea – White	Letters & Symbols	590	360	263	173
IPS's HPS-4 Urethane – White	Letters & Symbols	270	401	257	134
3M's Stamark 1000 WR Type 1 Polyurea – White	Letters & Symbols	563	379	224	159

*Not collected after October 2007 round of testing.

Of the 13 recessed products placed on the mainline, 10 were white and 3 were yellow. A comparison of the 10 white products can be seen in Figure 13.

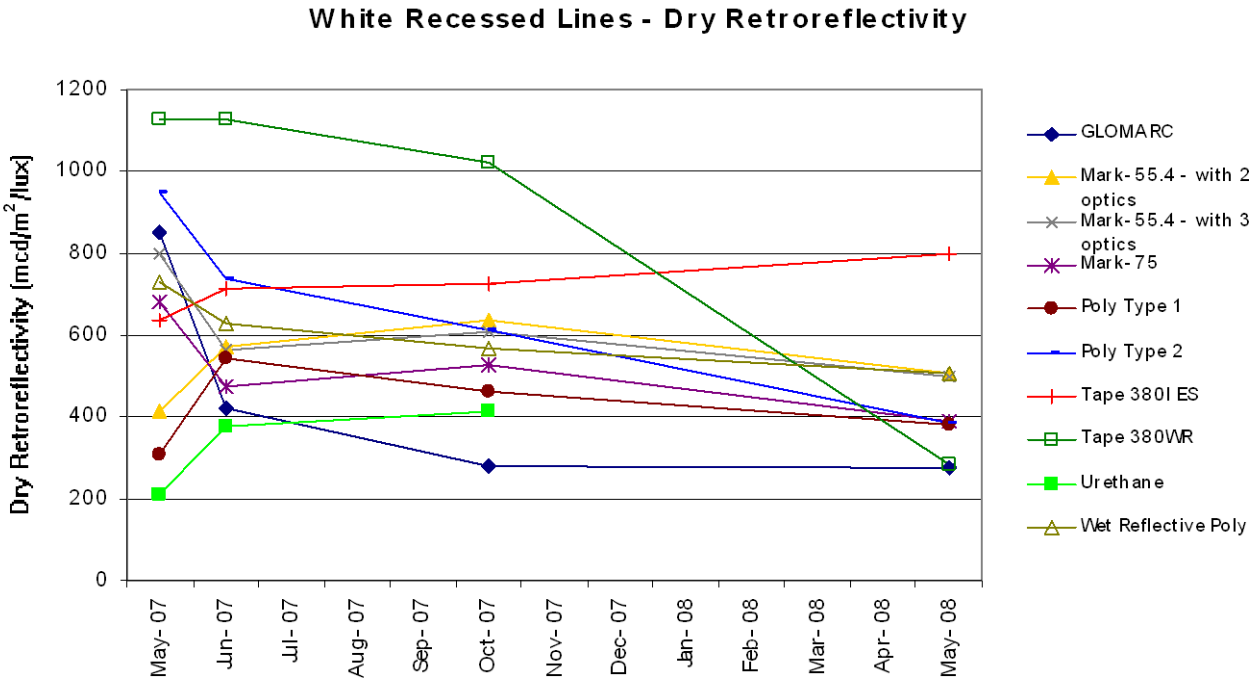


Figure 13. Dry R_L of white recessed lines.
*Please refer to Table 1 for the complete definition of each marking type.

3M's *Stamark 1000 WR Type 1 White Polyurea reflective tape*, which had the highest R_L during the previous measurements, has dropped to the lowest, losing 72% of its R_L since the last round of collection in October 2007. We are aware of this drastic change in the data, and we are researching into this phenomenon. As noted earlier, IPS's *HPS-4 White Urethane* was not be measured because it was only located between lanes 2 and 3, the area that was discontinued from the study because of the challenges of having a three-lane closure for these skip dashes. The only product to show an increase in retroreflectivity during this round of collection was 3M's *Stamark Series 380I ES Preformed White Tape*. Coincidently, this product has shown an increase, though slight, during each subsequent round of testing. This is probably because the thin coating on the surface of the tape that keeps it from sticking to itself while it's rolled up may still be wearing away.

A comparison of the three yellow products and their white counterparts can be seen in Figure 14. All 3 yellow products have a lower R_L than their white counterpart, but all three show similar increases or decreases as their counterpart. 3M's *Stamark 1200 Type 2 Yellow Polyurea* (Poly 2 – yellow) has the highest R_L of the 3 yellow products.

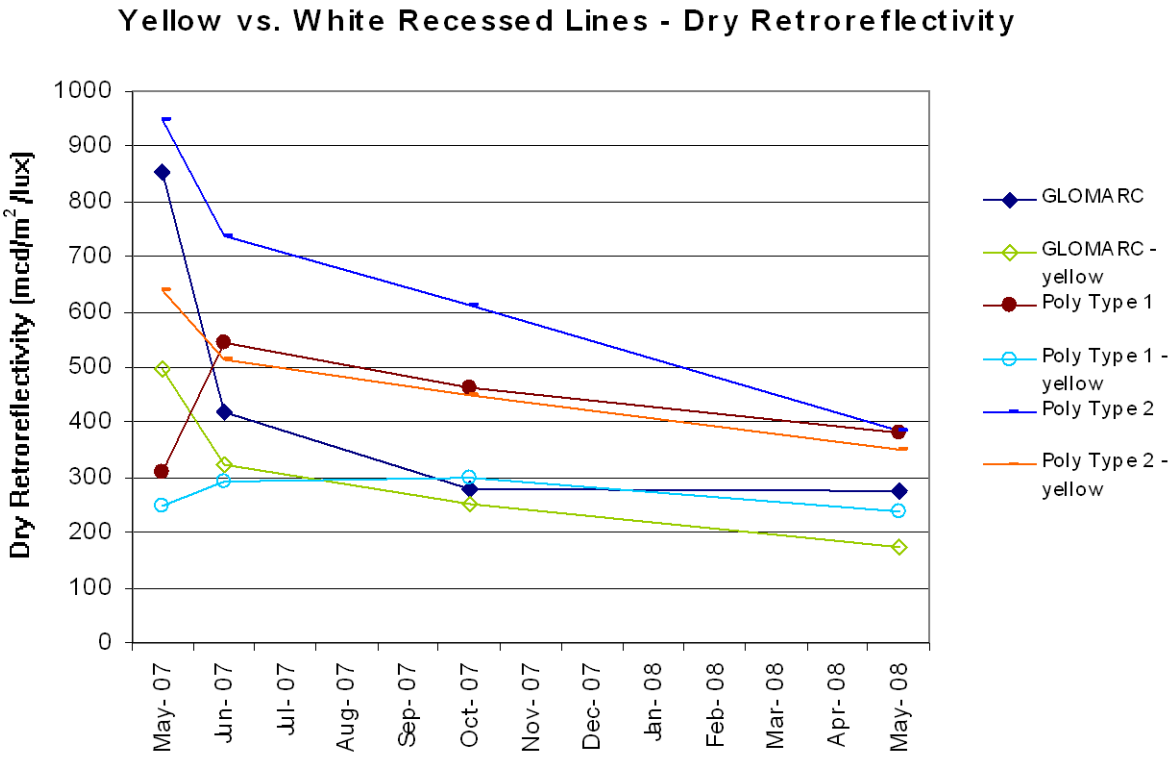


Figure 14. Dry R_L of yellow and white counterpart lines.
*Please refer to Table 1 for the complete definition of each marking type.

The only surface-applied products in the test section are 3M's *Stamark 1000 Type 1 White Polyurea* (Poly I – white) and 3M's *Stamark 1000 Type 1 Yellow Polyurea* (Poly I – yellow). Figure 15 is a comparison of surface-applied Poly I to recessed Poly I. Both recessed lines are showing higher retroreflectivity than their surface counterpart, but both white lines and both yellow lines have very similar trends.

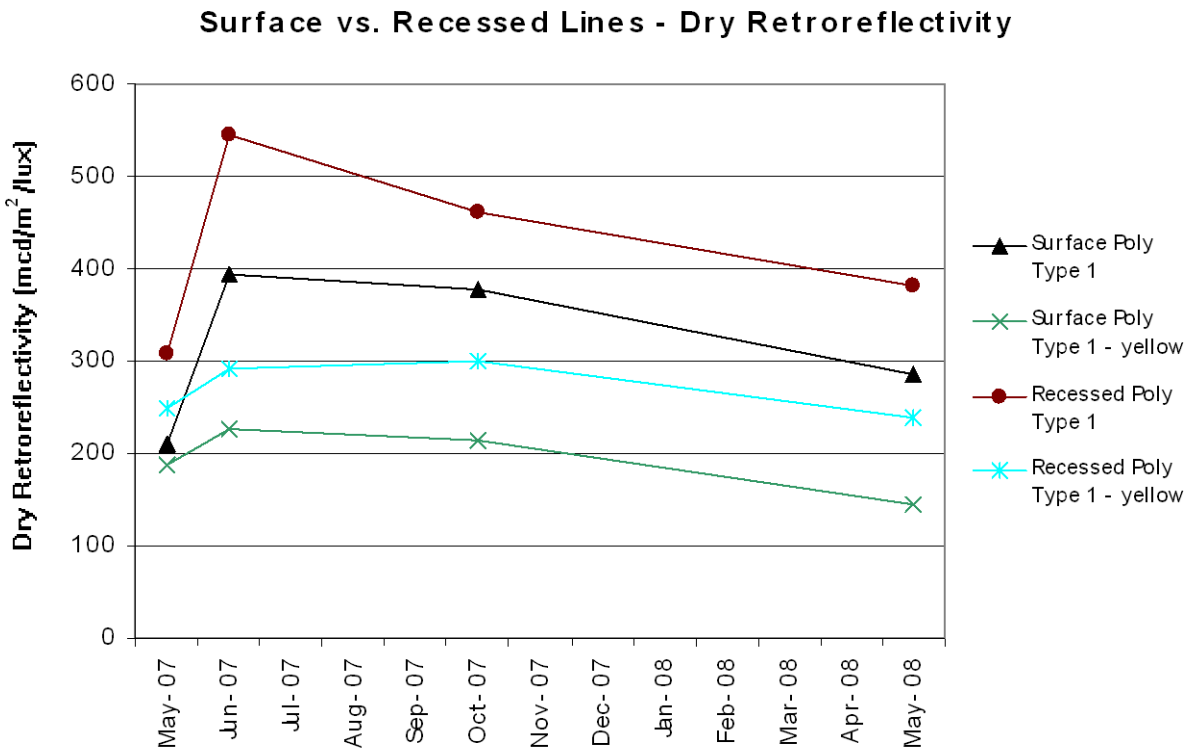


Figure 15. Dry R_L of Poly I surface and recessed lines.
*Please refer to Table 1 for the complete definition of each marking type.

Figure 16 is a comparison of the 4 products used for Letters & Symbols. Poly II is designed to have a much higher retroreflectivity than Poly I, but the fact that it is giving a comparable R_L is most likely due to the optics being hand-mixed and then hand-placed. Optics are not distributed as evenly on Letters & Symbols as they are on lines.

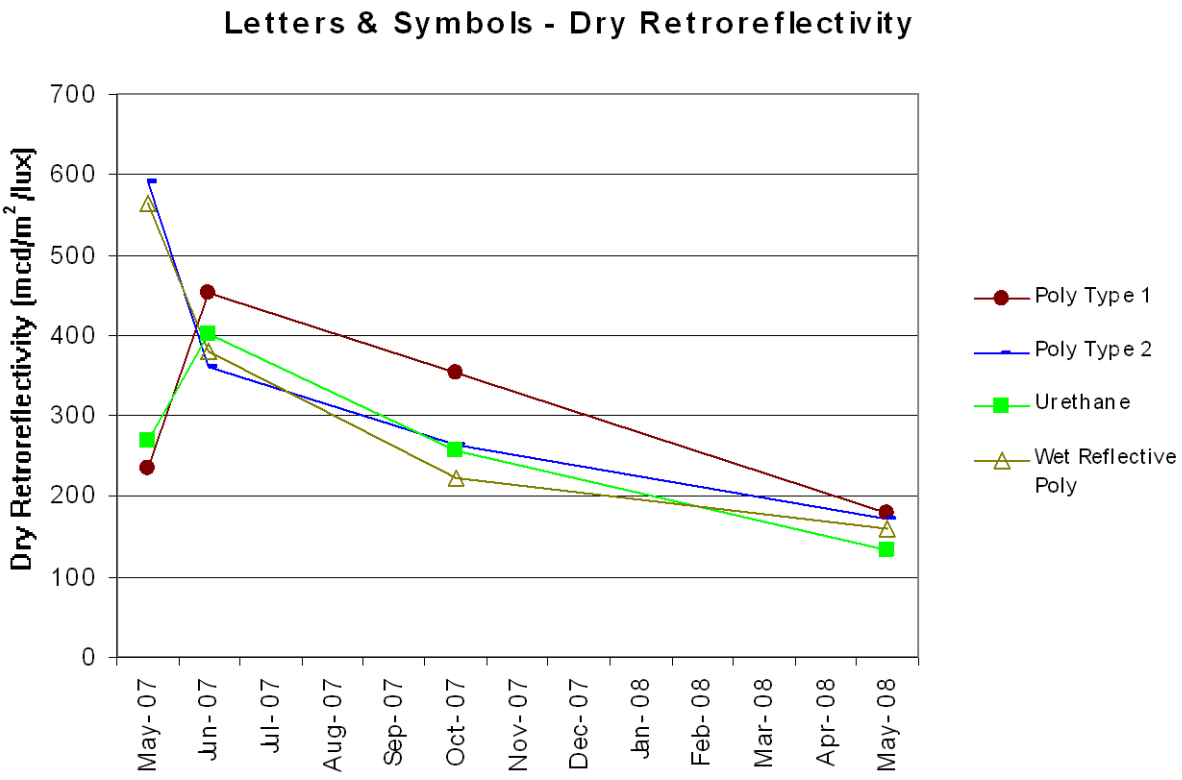


Figure 16. Dry R_L of letters and symbols.
*Please refer to Table 1 for the complete definition of each marking type.

WET RETROREFLECTIVITY DATA AND ANALYSIS

Wet retroreflectivity tests were conducted during the "Initial", "2nd round", and "3rd round" of testing. Table 2 is a summary of those results.

Table 2. Wet Retroreflectivity Readings.

Pavement Marking Material	Application Type	Average R_l (mcd/m^2/lux)		
		Initial	2nd Round	3rd Round
		Jun-07	Oct-07	May-08
Epoplex's GLOMARC 90 Wet Reflective Type 1 Polyurea - White	Recessed Lines	26	38	60
Epoplex's GLOMARC 90 Wet Reflective Type 1 Polyurea - Yellow	Recessed Lines	40	36	71
Polycarb's Mark 55.4 Hybrid Epoxy with 2 Optics - White	Recessed Lines	174	194	157
Polycarb's Mark 55.4 Hybrid Epoxy with 3 Optics - White	Recessed Lines	199	210	141
Polycarb's Mark 75 Type 1 Polyurea - White	Recessed Lines	166	217	84
3M's Stamark 1000 Type 1 Polyurea - White	Recessed Lines	99	43	32
3M's Stamark 1000 Type 1 Polyurea - Yellow	Recessed Lines	98	82	59
3M's Stamark 1200 Type 2 Polyurea - White	Recessed Lines	59	41	18
3M's Stamark 1200 Type 2 Polyurea - Yellow	Recessed Lines	62	49	37
3M's Stamark Series 380I ES Preformed Tape - White	Recessed Lines	64	61	74
3M's Stamark Series 380 Wet Relective Preformed Tape - White	Recessed Lines	422	271	20
IPS's HPS-4 Urethane - White	Recessed Lines	102	92	-*
3M's Stamark 1000 WR Type 1 Polyurea - White	Recessed Lines	312	155	126
3M's Stamark 1000 Type 1 Polyurea - White	Surface Lines	150	123	57
3M's Stamark 1000 Type 1 Polyurea - Yellow	Surface Lines	94	83	41
3M's Stamark 1000 Type 1 Polyurea - White	Letters & Symbols	108	100	37
3M's Stamark 1200 Type 2 Polyurea - White	Letters & Symbols	64	65	55
IPS's HPS-4 Urethane - White	Letters & Symbols	165	96	49
3M's Stamark 1000 WR Type 1 Polyurea - White	Letters & Symbols	150	126**	55

*Not collected after October 2007 round of testing.
**Note this is a correction of the value reported in the 2007 draft report.

As seen in Figure 17, 9 of the 12 recessed lines measured this round only have a wet R_L between 25 and 100. The two wet reflective products, 3M's *Stamark Series 380 Wet Relective Preformed White Tape* (Tape 380WR) and 3M's *Stamark 1000 WR Type 1 White Polyurea*, both gave high initial values, but by the most recent testing the wet R_L value for both have decreased, now giving R_L values that are less than Polycarb's *Mark 55.4 Hybrid White Epoxy with 2 Optics* and Polycarb's *Mark 55.4 Hybrid White Epoxy with 3 Optics*. As noted earlier, it is not yet understood why the R_L values for the Tape 380WR product have decreased so quickly (both dry and wet) but we are researching into this phenomenon.

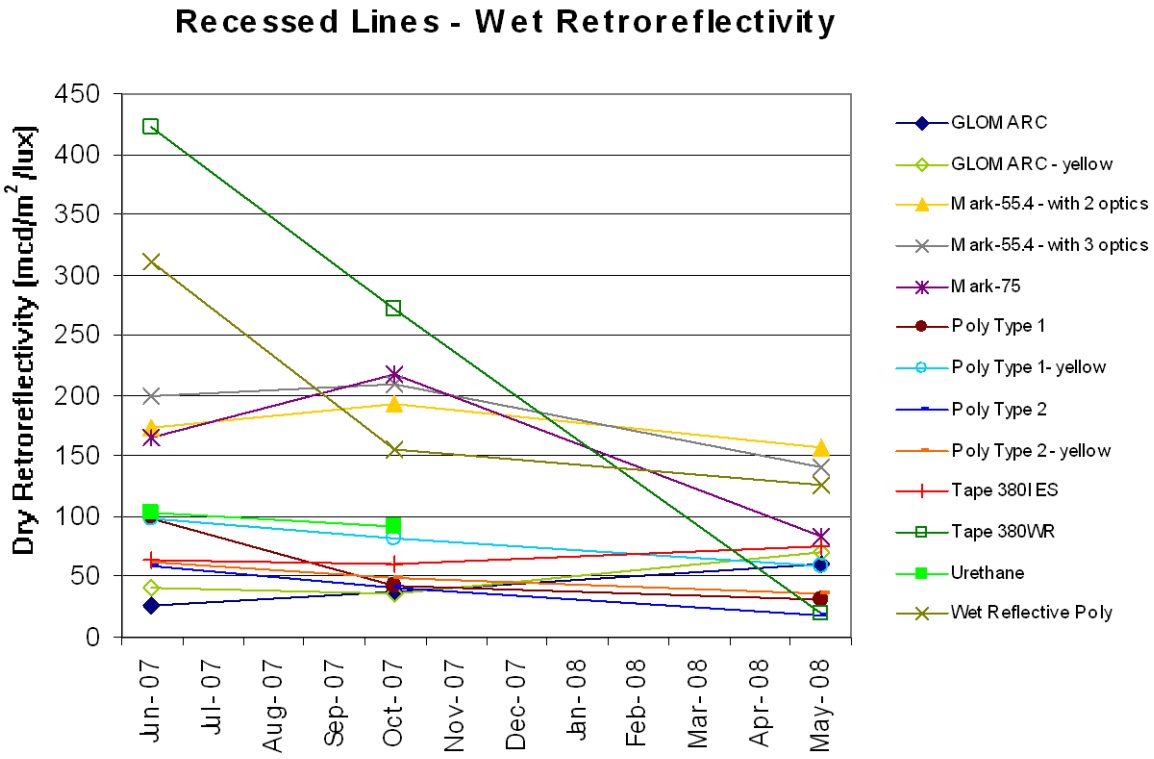


Figure 17. Wet R_L of recessed lines.
*Please refer to Table 2 for the complete definition of each marking type.

As for the Surface Lines (see Figure 18) and for the Letters & Symbols (see Figure 19), some are showing higher wet R_L values than the Recessed Lines. All of the Surface Lines and Letters & Symbols are located on ramps which are sloped allowing water to run off more quickly, therefore improving the wet retroreflectivity. The mainline Poly I has a lower wet R_L value because water ponds on a level recessed line.

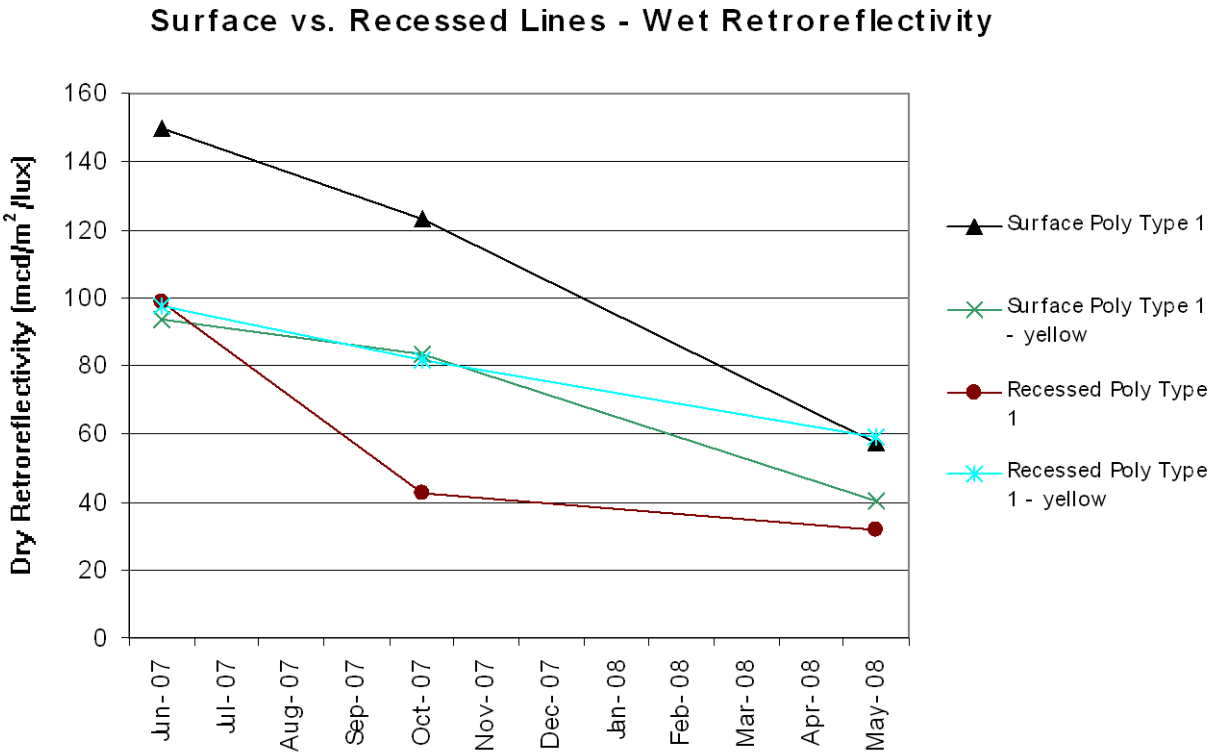
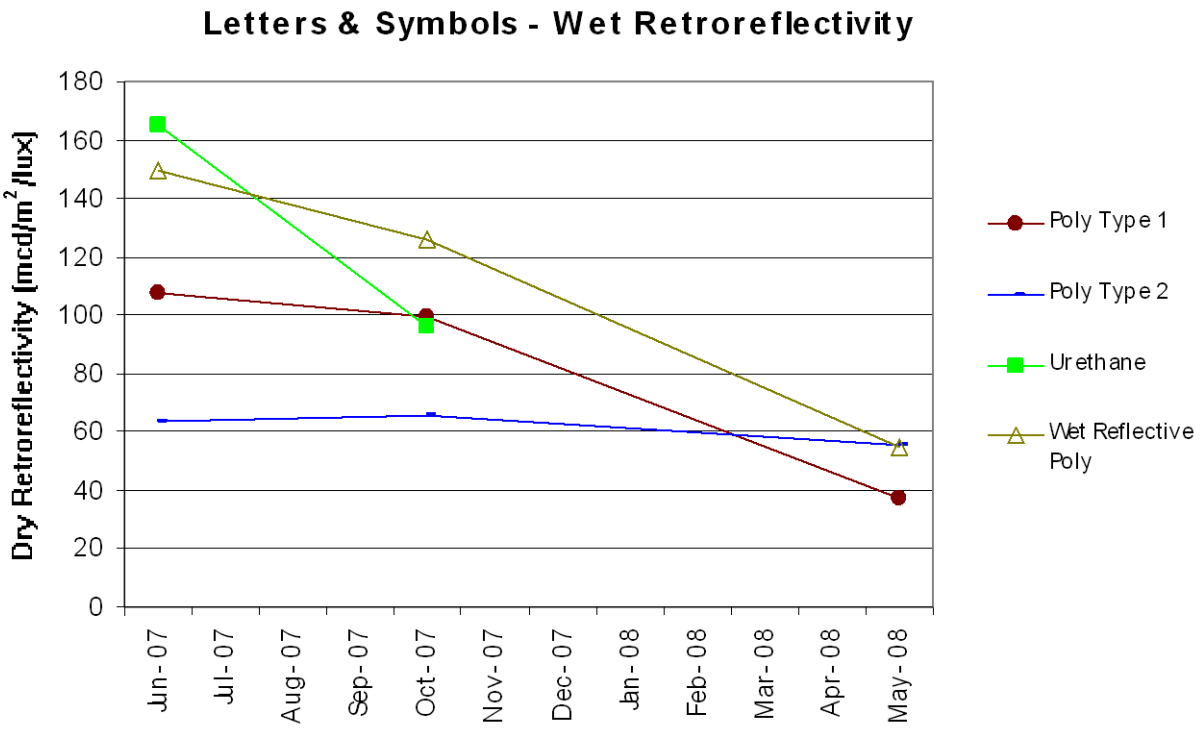


Figure 18. Wet R_L of Poly I surface and recessed lines.
*Please refer to Table 2 for the complete definition of each marking type.



Figue 19. Wet R_L of letters and symbols.
*Please refer to Table 2 for the complete definition of each marking type.

SPECTROPHOTOMETRY DATA AND ANALYSIS

Per ASTM D 6628-03 (Standard Specification for Color of Pavement Marking Materials), a pavement marking material's color coordinates must plot within the chromaticity limits of the polygons in Figure 20 throughout its service life.

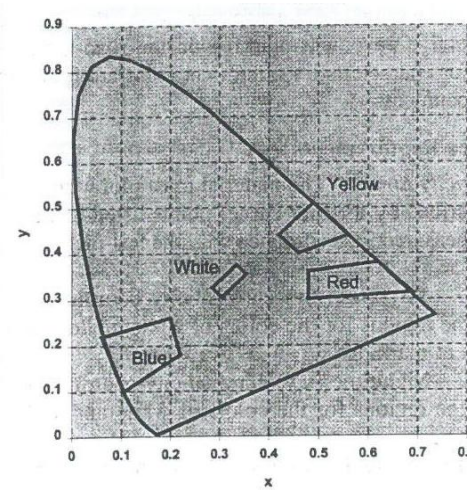


Figure 20. Chromaticity limits of pavement markings. (From ASTM D 6628-03)

The corner points that describe the boundaries of these limits are listed in Table 3.

Table 3. Chromaticity Corner Points of Pavement Markings

Color	Chromaticity Coordinates (Corner Points)							
	1		2		3		4	
	x	y	x	y	x	y	x	y
White	0.355	0.355	0.305	0.305	0.285	0.325	0.335	0.375
Yellow	0.560	0.440	0.490	0.510	0.420	0.440	0.460	0.400

The lightness (Y) limit for white is a minimum of 35 and the limit for yellow is a minimum of 25.

Spectrophotometry tests were conducted during the "Initial", "2nd round", and "3rd round" of testing. Table 4 is a summary of those results.

Table 4. Spectrophotometry Averages

Pavement Marking Material	Application Type	Initial			2nd Round			3rd Round		
		Y	x	y	Y	x	y	Y	x	y
Epoplex's GLOMARC 90 Wet Reflective Type 1 Polyurea - White	Recessed Lines	66	.325	.343	58	.326	.344	59	.334	.352
Polycarb's Mark 55.4 Hybrid Epoxy with 2 Optics - White	Recessed Lines	71	.329	.352	65	.328	.351	61	.330	.352
Polycarb's Mark 75 Type 1 Polyurea - White	Recessed Lines	76	.320	.339	70	.319	.338	65	.324	.343
3M's Stamark 1000 Type 1 Polyurea - White	Recessed Lines	73	.319	.339	69	.321	.340	54	.327	.346
3M's Stamark 1200 Type 2 Polyurea - White	Recessed Lines	73	.320	.340	64	.321	.341	58	.343	.356
3M's Stamark Series 380I ES Preformed Tape - White	Recessed Lines	49	.325	.345	42	.328	.346	56	.367	.373
3M's Stamark Series 380 Wet Relective Preformed Tape - White	Recessed Lines	55	.325	.345	49	.325	.344	52	.327	.347
IPS's HPS-4 Urethane - White	Recessed Lines	65	.328	.350	61	.331	.355	-*	-*	-*
3M's Stamark 1000 WR Type 1 Polyurea - White	Recessed Lines	67	.324	.343	66	.323	.342	64	.322	.342
Epoplex's GLOMARC 90 Wet Reflective Type 1 Polyurea - Yellow	Recessed Lines	38	.463	.414	36	.461	.427	38	.458	.422
3M's Stamark 1000 Type 1 Polyurea - Yellow	Recessed Lines	43	.507	.439	45	.500	.459	40	.457	.428
3M's Stamark 1200 Type 2 Polyurea - Yellow	Recessed Lines	40	.491	.433	35	.490	.452	39	.470	.439
Epoplex's GLOMARC 90 Wet Reflective Type 1 Polyurea - White	Surface Lines	65	.319	.340	55	.323	.344	48	.335	.355
Polycarb's Mark 55.4 Hybrid Epoxy with 2 Optics - White	Surface Lines	39	.493	.434	34	.486	.449	34	.452	.428
Polycarb's Mark 75 Type 1 Polyurea - White	Letters & Symbols	51	.322	.344	36	.326	.346	33	.331	.349
3M's Stamark 1000 Type 1 Polyurea - White	Letters & Symbols	53	.322	.343	40	.324	.344	35	.331	.350
3M's Stamark 1200 Type 2 Polyurea - White	Letters & Symbols	47	.328	.349	36	.333	.355	35	.338	.358
3M's Stamark Series 380I ES Preformed Tape - White	Letters & Symbols	54	.322	.343	45	.325	.345	31	.334	.352

*Not collected after October 2007 round of testing.

As seen from Table 4, after the third round of testing, most materials are still above the required minimum lightness (Y). Most materials experienced some decrease in Y by the third round. Also, most of the Surface Lines and Letters & Symbols have a lower Y than the Recessed Lines.

Figures 21, 22, and 23 show that for all materials except 3M's *Stamark Series 380I ES Preformed Tape*, the xy-coordinates of the white Recessed Lines are still within the chromaticity limits.

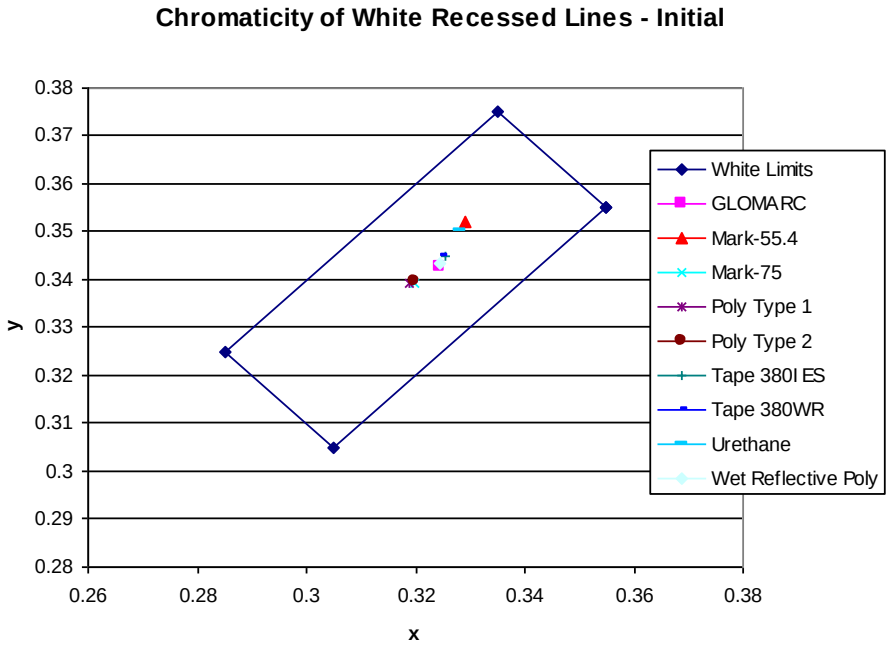


Figure 21. Initial xy of White Recessed Lines

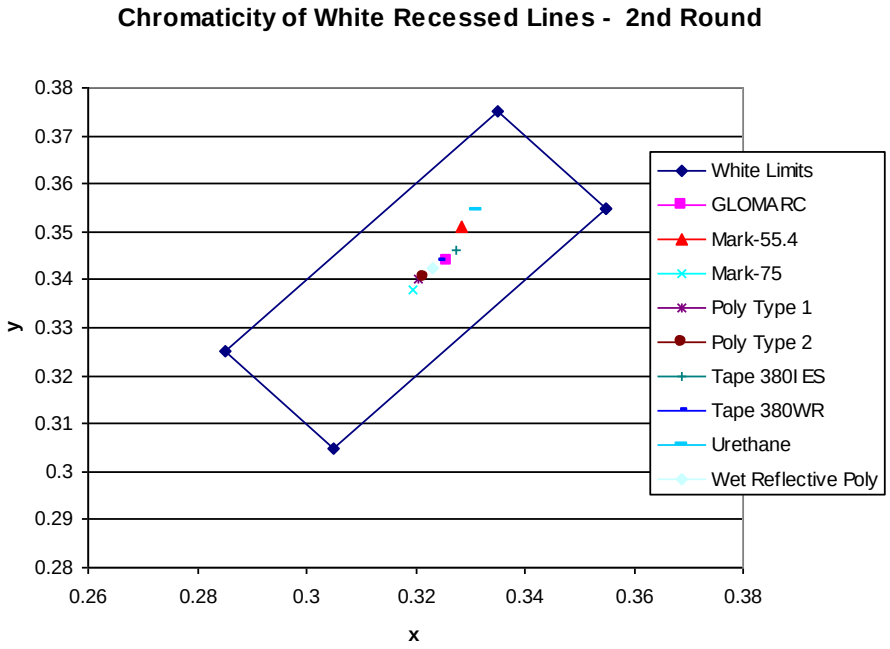


Figure 22. 2nd xy of White Recessed Lines

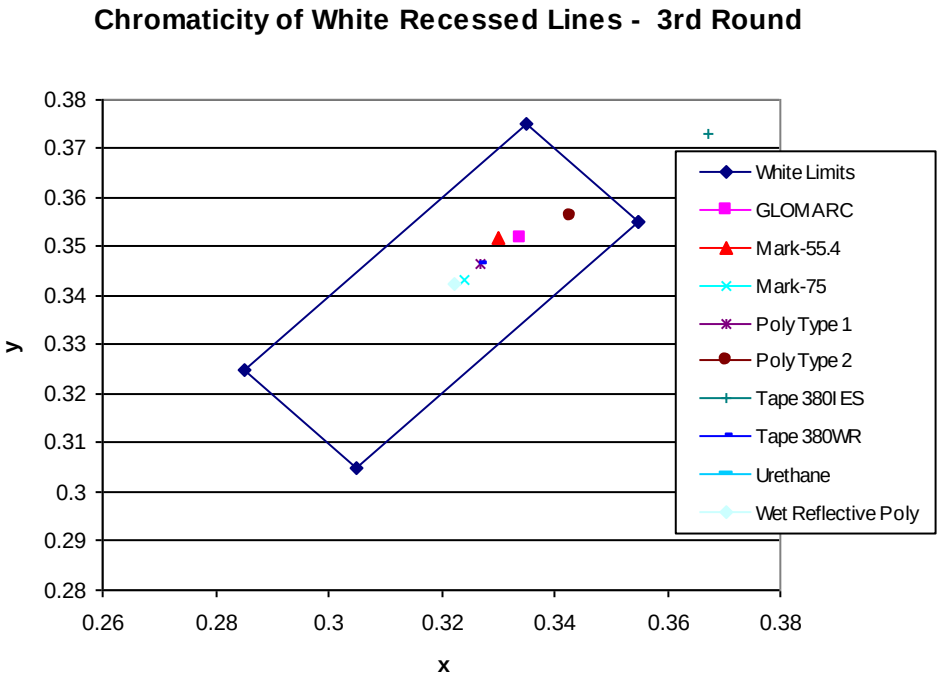


Figure 23. 3rd xy of White Recessed Lines

Figures 24, 25, and 26 show that the yellow Recessed Lines are all well within the limits.

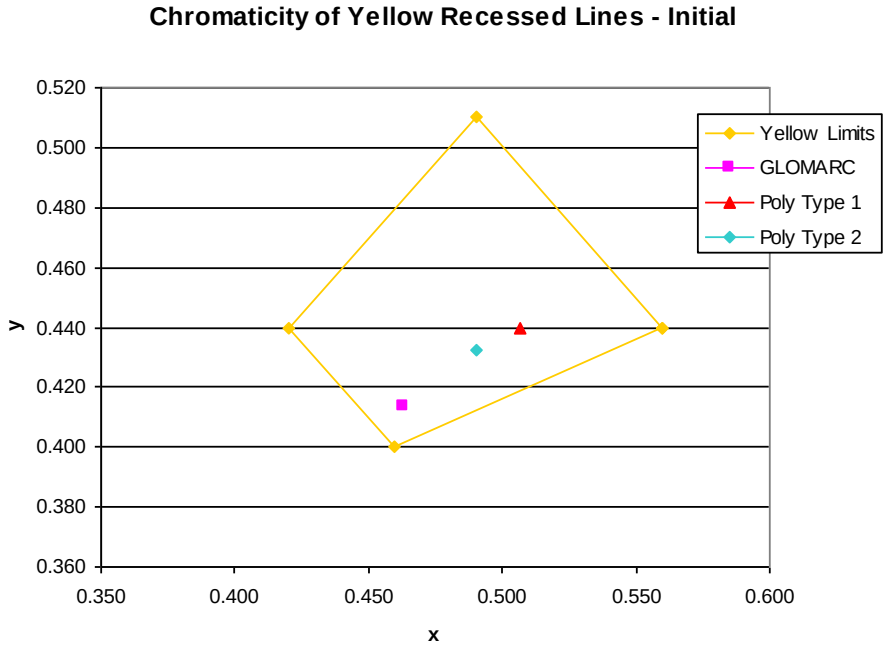


Figure 24. Initial xy of Yellow Recessed Lines

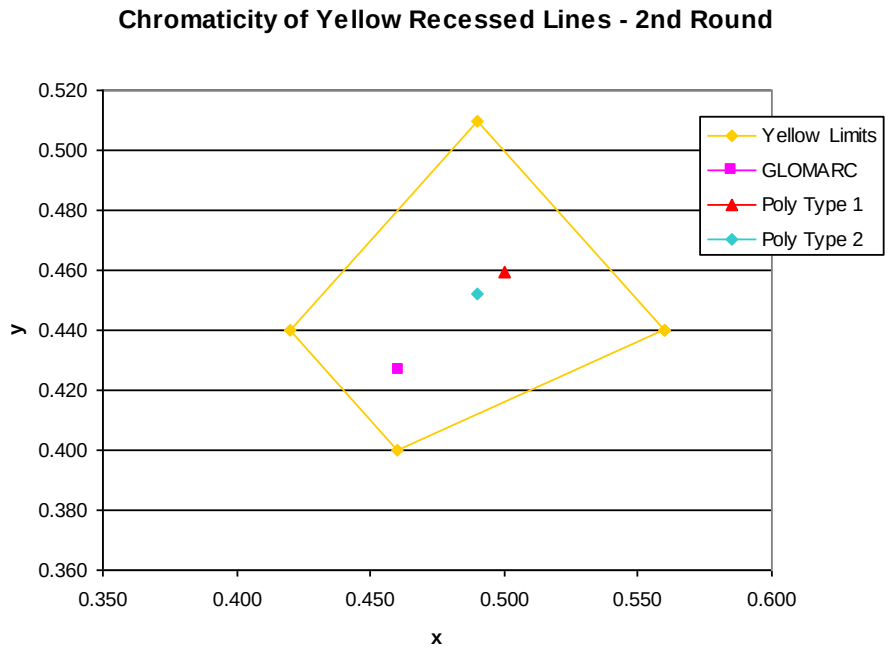


Figure 25. 2nd xy of Yellow Recessed Lines

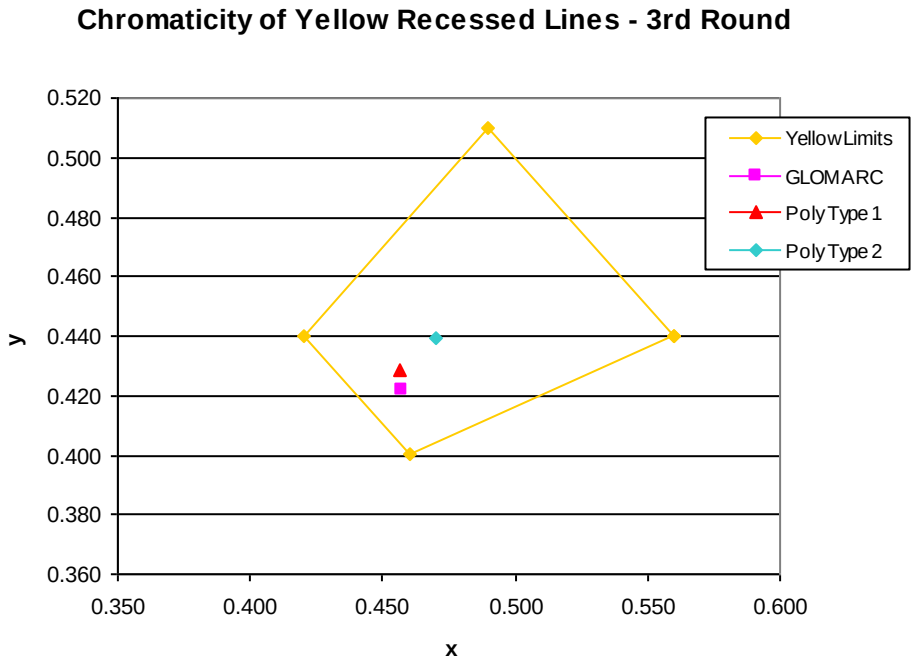


Figure 26. 3rd xy of Yellow Recessed Lines

As seen in figures 27, 28, and 29, the Surface Lines are within the limits.

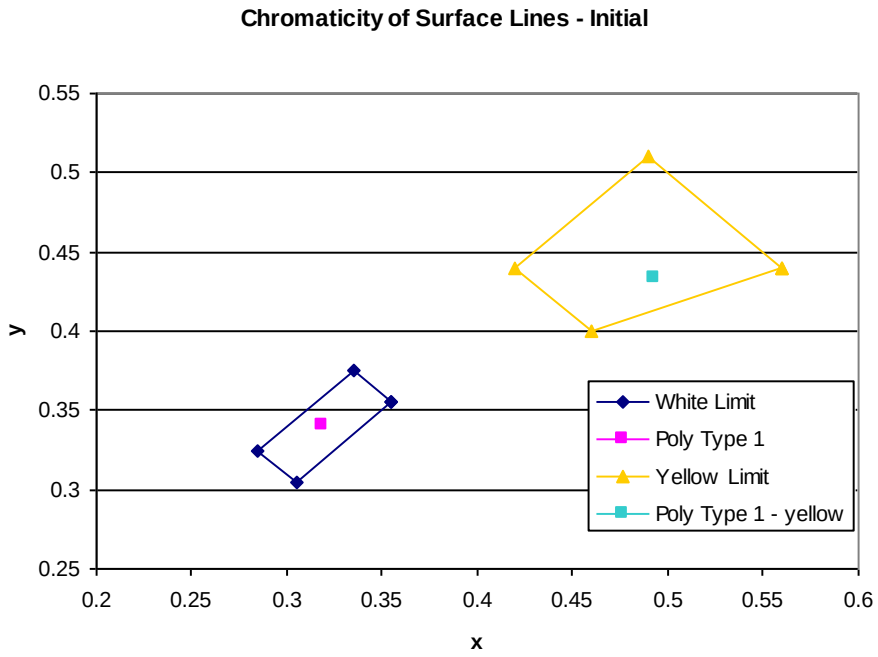


Figure 27. Initial xy of Surface Lines

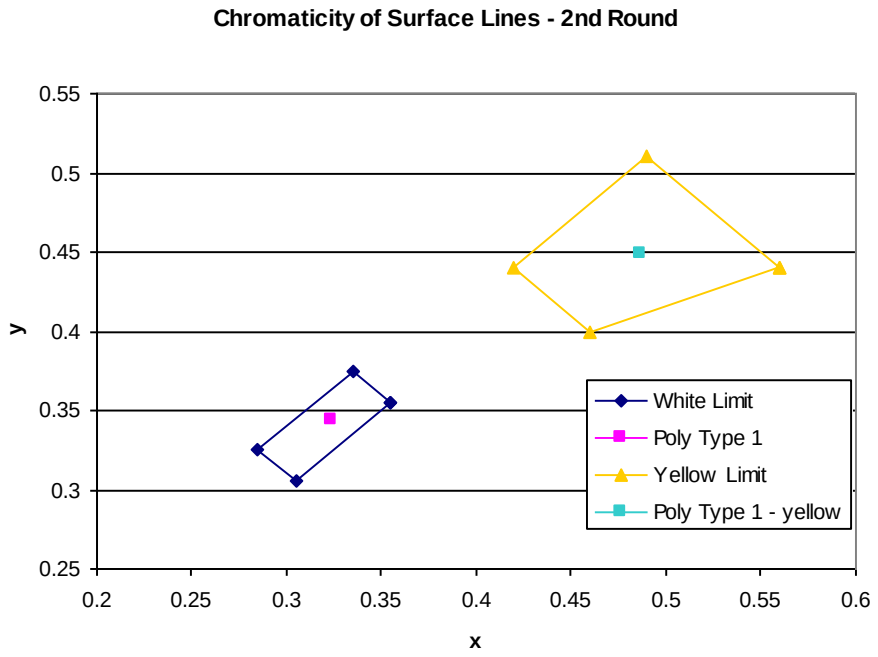


Figure 28. 2nd xy of Surface Lines

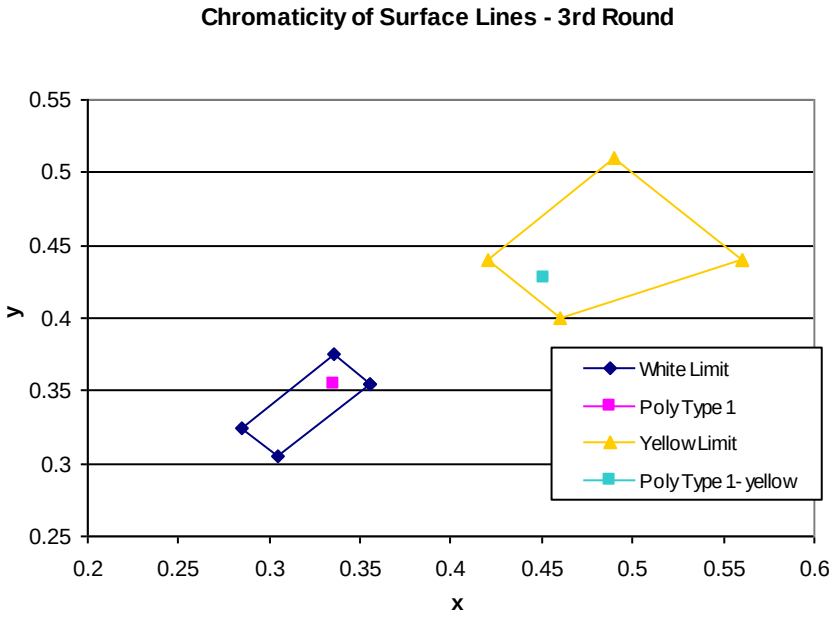


Figure 29. 3rd xy of Surface Lines

Letters & Symbols, which are only in white, are also within chromaticity limits as seen in figures 30, 31, and 32. All the products have experienced both an x and y-coordinated increase since the initial measurements.

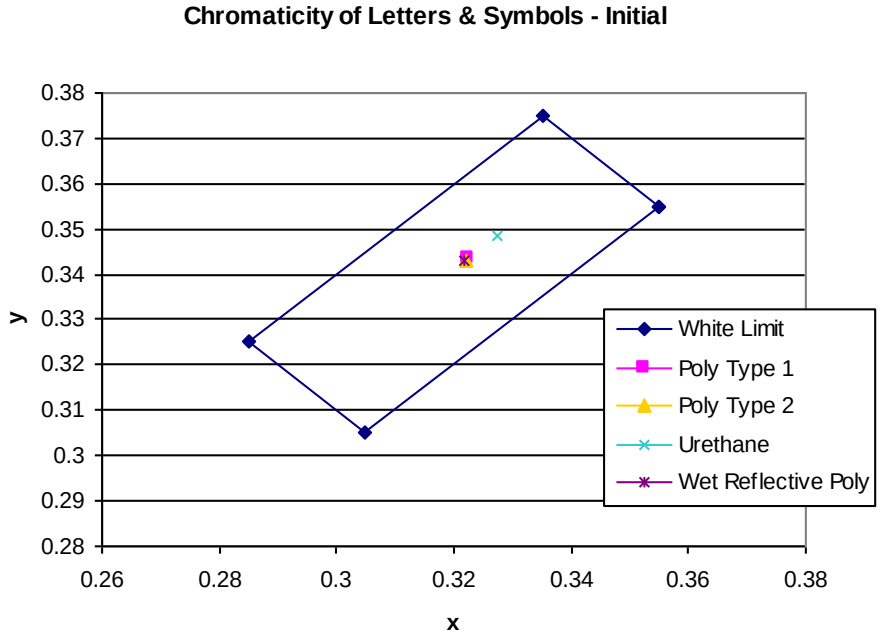


Figure 30. Initial xy of Letters & Symbols

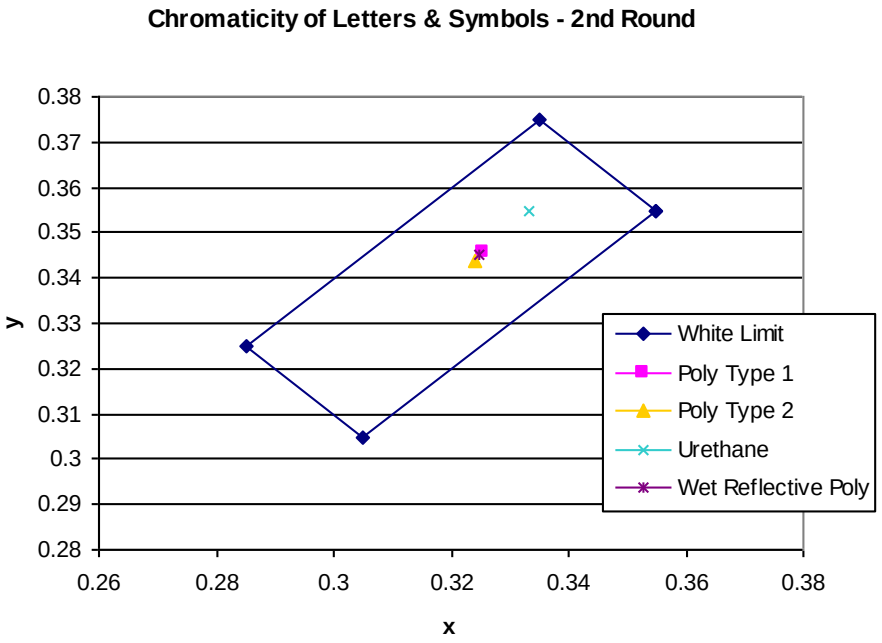


Figure 31. 2nd xy of Letters & Symbols

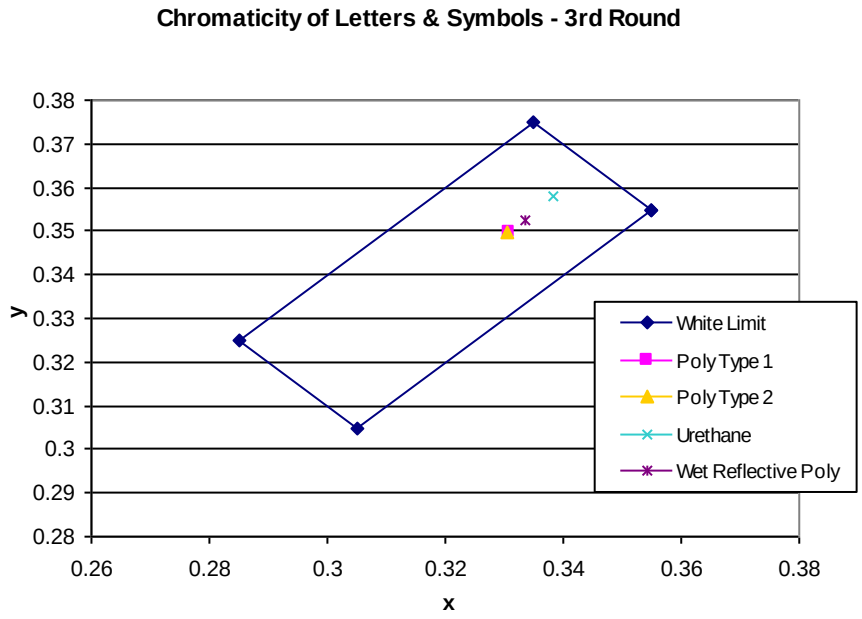


Figure 32. 3rd xy of Letters & Symbols

SUMMARY

Due to the different methods and equipment used to place the pavement marking materials, data was categorized into 3 groups - Recessed Lines, Surface Lines, and Letters & Symbols. Every section of markings received a series of 3 types of tests – dry retroreflectivity, wet retroreflectivity, and spectrophotometry.

Within the materials placed in the Recessed Lines, 3M's *Stamark Series 380I ES Preformed Tape* has the highest dry retroreflectivity, while Epoplex's *GLOMARC 90 Wet Reflective Type 1 Polyurea* has the lowest dry retroreflectivity. 3M's *Stamark Series 380 Wet Relective Preformed Tape* experienced the largest percentage decrease of all Recessed Lines, losing 72% of its R_L since the last round of collection in October, 2007. The only product to show an increase in retroreflectivity during this round of collection was 3M's *Stamark Series 380I ES Preformed White Tape*. Coincidently, this product has shown an increase, though slight, during each subsequent round of testing. This is probably because the thin coating on the surface of the tape that keeps it from sticking to itself while it's rolled up may still be wearing away.

For wet reflectivity, the two wet reflective products, 3M's *Stamark Series 380 Wet Relective Preformed White Tape* and 3M's *Stamark 1000 WR Type 1 White Polyurea*, both gave high initial values. However, by the most recent testing, the wet R_L value for both have decreased, now giving R_l values that are less than Polycarb's *Mark 55.4 Hybrid White Epoxy with 2 Optics* and Polycarb's *Mark 55.4 Hybrid White Epoxy with 3 Optics*.

The spectrophotometry results showed that all materials, with the exception of 3M's *Stamark Series 380I ES Preformed Tape*, exceeded the minimum lightness (Y) requirement, but nearly all showed a decrease in Y by the third round of tests. Most of the Surface Lines and Letters & Symbols have a lower Y than the Recessed Lines. With the exception of 3M's *Stamark Series 380I ES Preformed Tape*, the xy-coordinates of all materials also fell within the xy chromaticity limits.