ft-candle in order to have the same assurance of seeing the reflector. It would have to be four times brighter. An engineer need only substitute into Equation 5 the required sight distance needed at a particular location on a highway, a nominal value of headlamp intensity (20,000 might be a good number, based on SAE J579) and the age/color equivalent intensity of an RPM tabled above to determine the SI of an RPM that would yield the 100 per cent detection threshold. A set of such calculations for various sight distances is provided in the Table 4-4 for a nominal headlamp intensity of 20,000 candela. These values would not hold for the "urban" condition in which the driver's eyes are much more light adapted and not as sensitive. The single condition simulated in this study cannot be generalized to all urban circumstances. Under the urban condition set up in this study, the 80-year-old amber threshold illuminance by an RPM becomes 0.000000349 ft-candles (using Eq.4), which represents an increase in brightness of almost an order of magnitude (10 times)!

These thresholds are "achromatic," that is to say, the drivers were reporting detection of an object as a point of light. They often were unsure as to the color of the RPM that they were seeing, particularly amber vs white or crystal. Red was almost always correctly identified.

Table 4-4. Predicted specific intensity thresholds for 80-year-old drivers, RPMs illuminated by 20,000 candela headlamps.

Distance(ft)	Red RPM SI	Amber RPM SI	Crystal RPM SI
50	.0000	.0000	.0000
100	.0002	.0002	.0002
150	.0010	.0009	.0012
200	.0033	.0027	.0039
250	.0080	.0065	.0095
300	.0166	.0135	.0197
350	.0308	.0250	.0365
400	.0525	.0426	.0623
450	.0841	.0682	.0998
500	.1281	.1040	.1522
550	.1876	.1523	.2228
600	.2657	.2156	.3155
650	.3659	.2970	.4346
700	.4922	.3995	.5845
750	.6486	.5265	.7703
800	.8397	.6816	.9972

These results are comparable to those found by other researchers dating back to 1946 and before. They represent the lowest practicable bounds for degradation of RPMs installed on the highways. The seeing conditions in the "rural" situation were ideal for detecting these objects: no distractions, not driving, good visibility, very dark environment, and knowledge that an object was present. Hence it can be said with some confidence that RPMs that have degraded to such an extent that they can no longer deliver the threshold amount of light to the eye at the needed sight distance with the dimmest legal headlamps definitely need to be replaced. This study sets the lower limit of usability.

Discrimination Between Degraded and Masked Test Specimens

No significant differences were noted in sight distances between equivalent SI RPMs which were abraded on the reflective surface, vs those taped to occlude part of the reflective surface. The two observers were unable to discriminate between the two types of devices. This demonstration confirms the assertion that at the operating distances used to illuminate and view RPMs, they are point sources of light.

Threshold Study 2: An Analysis of Threshold Specific Intensities to Account for Rain Diffusion

The results of Study 1 document the threshold specific intensities for observers under two different lighting conditions. In the discussion of those results, a rationale was presented for predicting the lowest illuminance from a point source of light, such as an RPM lit by headlamps, that a driver might be able to discern with high certainty. These values, repeated below, are valid for reasonably dark, clear seeing conditions (all values in ft-candles x 10^{-8}):

	Age		
Color	54.5 yrs	67 yrs	80 yrs
Red	1.025	2.050	4.100
Amber	0.832	1.664	3.328
Crystal	1.217	2.434	4.869

As would be expected, the elderly driver (80 years of age) needs considerably more illumination from an RPM to see it, thus providing a "worst case" for design purposes. Study 2 provides an analysis and discussion of the influence of rain on the predicted RPM intensity requirements for these drivers.

In order for a driver to see a light source, the specified amount of illumination to the eye must be provided regardless of what the light has to traverse before impinging on the eye. In the case of an RPM on a rainy night, the attenuation introduced by the environment can be a very significant factor.

To assess the extent of light attenuation due to rain, the values in Table 4-4 (from Study 1) can be corrected to account for various rainfall rates. It will be recalled that Table 4-4 provides predicted SI (in the usual candela per incident foot-candles) for all three colors of roadway RPMs as a function of sight distance, ranging from 50 feet to 800 feet. This table assumes clear seeing conditions: dry, dark road, no opposing traffic, no rain or mist in the air. The headlamps illuminating the RPM are assumed to be at nominal high-beam level of 20,000 candela, again a conservative assumption.

If we now assume that the driver is looking at the RPM through a downpour, the light from the headlamps is scattered and absorbed as it travels to the RPM. The light returning from that RPM is likewise scattered and attenuated by the rain. Ivey, Lehtipuu, and Button (1975) studied visibility through rainfall. They found that rainfalls exceeding 1 inch per hour, even in areas of Texas where heavy rainfall is common, were rarely encountered (less than 5 hours per year). Ivey et al recommended a "design rainfall" of 1 inch per hour for further analysis. In order to bracket the situation, we shall use this level of rainfall, plus values of 0.5

inch per hour and 2 inches per hour. In a relatively qualitative estimate of daylight visibility, Ivey et al associated a 1-inch-per-hour rainfall with a 30 percent loss in visibility in a car travelling 50 MPH. A 2-inch-per-hour rainfall intensity reduces visibility to less than 50 percent of clear conditions.

Atlas (1953) developed an analysis of optical extinction by rainfall in which he derived a coefficient of atmospheric extinction:

(6) $$s = 5.85R^{0.63} \times 10^{-4}$$

Where R = rainfall, in/hr

The extent to which the medium through which light is travelling absorbs or scatters that light is expressed by "s". There is a straightforward relationship between s and "t" which is transmissivity, a term encountered in meteorology, aviation, and many other places. The conversion (Middleton, 1952) is as follows:

(7) $$t = e^{-s}$$

Where e = natural log base

Allard's Law (IES, 1966) relates illuminance provided by a source shining through a medium for which the transmissivity is known by the simple relationship:

(8) $$E = I\ t^d/d^2$$

Where E = Illuminance
I = Intensity of the source
d = distance

Using these relationships, a table of predicted threshold SI for red, amber and crystal RPMs was generated and is given as Table 4-5. As a function of distance in feet, equations 7 and 8 are used to compute transmissivity over the distance (t^d) under the three conditions of rainfall, 0.5, 1, and 2 inches per hour. "Clear" visibility SI is reproduced from Table 4-4. For example, at 50 feet, the transmissivity factor is 0.9712 for 1 inch per hour rain, a loss of 3 percent. For the same condition, equation 8 is used to compute an illuminance provided by the 20,000 candela headlamps assumed in this table. For this same example, the illuminance would be 7.7693 ft-candles impinging on an RPM in the road. Equation 8 is also used to compute the intensity required of an RPM to permit it to be seen by an 80-year-old observer. For this calculation, the illuminance values provided by Study 1 are used. For a red RPM, the illuminance that must be delivered to the eyes is 0.000000041 ft-candle. In order for the RPM to be seen at 50 feet through a rainfall of 1 inch per hour, Equation 8 is solved for I, intensity. The intensity need be only 0.0001. This means that even a "dead" RPM could be seen easily. The ratio of required I (Intensity) for the RPM to the incident illuminance of the

headlamps yields the estimate of the SI required for visibility, in this case, zero.

The picture radically changes with distance, however. Take the case of an amber RPM. At 400 feet, under clear seeing conditions, the device needs to have an SI of 0.0426 or 0.04 to be seen by an 80-year-old. If the rainfall through which our elderly driver is peering is 1 inch per hour, the SI needed jumps up to 0.068. At 800 feet, the difference is from 0.68 to 1.7. This means that only a brand-new RPM could be seen through this rain by an older driver! SI's greater than 2 are rarely attainable with amber RPMs; therefore even a brand new amber RPM could not be discerned by a typical 80-year- old driver in a 2-inch-per-hour rainstorm at 750 or more feet.

Table 4-5 suggests that for a heavy downpour of 2 inches/hour, a red RPM could be glimpsed at 250 feet if it were degraded to 0.01 SI (a level commonly found after an RPM has been in place for a year or more). An amber RPM degraded to the same level could only be seen 150 feet distant. A crystal or white RPM could be seen about as far away as a red RPM.

The values given in Table 4-5 represent an estimate of RPM visibility under dark, rainy conditions. These represent the very best that could be expected, since several very significant factors are not taken into account,including:

1. Windshield smearing and water scatter from motion of the car,
2. Moisture on the face of the RPM, and
3. Reflections from the wet roadway.

These estimates are refined on the basis of data collected in Study 3.

Table 4-5. Predicted specific intensity thresholds for 80-year-old drivers under clear and rainy conditions, RPMs illuminated by 20,000 candela headlamps.

RPM COLOR: RED

Feet	Threshold SI (Clear)	Transmissivity of Rainfall 0.5*	1.0*	2.0*	Illuminance of Headlamps 0.5*	1.0*	2.0*	Luminance of RPM Req'd to See 0.5*	1.0*	2.0*	Threshold RPM SI in Rain 0.5*	1.0*	2.0*
50	.0000	.9813	.9712	.9557	7.8502	7.7693	7.6459	.0001	.0001	.0001	.0000	.0000	.0000
100	.0002	.9629	.9432	.9134	1.9258	1.8863	1.8269	.0004	.0004	.0004	.0002	.0002	.0002
150	.0010	.9449	.9160	.8730	.8399	.8142	.7760	.0010	.0010	.0011	.0012	.0012	.0014
200	.0033	.9272	.8896	.8344	.4636	.4448	.4172	.0018	.0018	.0020	.0038	.0041	.0047
250	.0080	.9098	.8639	.7975	.2911	.2764	.2552	.0028	.0030	.0032	.0097	.0107	.0126
300	.0166	.8928	.8390	.7622	.1984	.1864	.1694	.0041	.0044	.0048	.0208	.0236	.0286
350	.0308	.8761	.8148	.7284	.1430	.1330	.1189	.0057	.0062	.0069	.0401	.0463	.0580
400	.0525	.8597	.7913	.6962	.1075	.0989	.0870	.0076	.0083	.0094	.0710	.0838	.1083
450	.0841	.8436	.7685	.6654	.0833	.0759	.0657	.0098	.0108	.0125	.1181	.1423	.1899
500	.1281	.8278	.7463	.6359	.0662	.0597	.0509	.0124	.0137	.0161	.1870	.2300	.3168
550	.1876	.8123	.7248	.6078	.0537	.0479	.0402	.0153	.0171	.0204	.2843	.3571	.5078
600	.2657	.7970	.7039	.5809	.0443	.0391	.0323	.0185	.0210	.0254	.4182	.5362	.7873
650	.3659	.7821	.6836	.5552	.0370	.0324	.0263	.0221	.0253	.0312	.5982	.7830	1.1872
700	.4922	.7675	.6639	.5306	.0313	.0271	.0217	.0262	.0303	.0379	.8356	1.1167	1.7482
750	.6486	.7531	.6448	.5071	.0268	.0229	.0180	.0306	.0358	.0455	1.1436	1.5603	2.5221
800	.8397	.7390	.6262	.4847	.0231	.0196	.0151	.0355	.0419	.0541	1.5375	2.1416	3.5743

RPM COLOR: AMBER

Feet	Threshold SI (Clear)	Transmissivity of Rainfall 0.5*	1.0*	2.0*	Illuminance of Headlamps 0.5*	1.0*	2.0*	Luminance of RPM Req'd to See 0.5*	1.0*	2.0*	Threshold RPM SI in Rain 0.5*	1.0*	2.0*
50	.0000	.9813	.9712	.9557	7.8502	7.7693	7.6459	.0001	.0001	.0001	.0000	.0000	.0000
100	.0002	.9629	.9432	.9134	1.9258	1.8863	1.8269	.0003	.0004	.0004	.0002	.0002	.0002
150	.0008	.9449	.9160	.8730	.8399	.8142	.7760	.0008	.0008	.0009	.0009	.0010	.0011
200	.0027	.9272	.8896	.8344	.4636	.4448	.4172	.0014	.0015	.0016	.0031	.0034	.0038
250	.0065	.9098	.8639	.7975	.2911	.2764	.2552	.0023	.0024	.0026	.0079	.0087	.0102
300	.0135	.8928	.8390	.7622	.1984	.1864	.1694	.0034	.0036	.0039	.0169	.0191	.0232

* Rainfall in inches per hour

Table 4-5 (Cont'd)

Feet	Threshold SI (Clear)	Transmissivity of Rainfall 0.5*	1.0*	2.0*	Illuminance of Headlamps 0.5*	1.0*	2.0*	Luminance of RPM Req'd to See 0.5*	1.0*	2.0*	Threshold RPM SI in Rain 0.5*	1.0*	2.0*
350	.0250	.8761	.8148	.7284	.1430	.1330	.1189	.0047	.0050	.0056	.0325	.0376	.0471
400	.0426	.8597	.7913	.6962	.1075	.0989	.0870	.0062	.0067	.0076	.0576	.0680	.0879
450	.0682	.8436	.7685	.6654	.0833	.0759	.0657	.0080	.0088	.0101	.0959	.1155	.1541
500	.1040	.8278	.7463	.6359	.0662	.0597	.0509	.0101	.0111	.0131	.1518	.1867	.2572
550	.1523	.8123	.7248	.6078	.0537	.0479	.0402	.0124	.0139	.0166	.2308	.2898	.4122
600	.2157	.7970	.7039	.5809	.0443	.0391	.0323	.0150	.0170	.0206	.3395	.4352	.6391
650	.2970	.7821	.6836	.5552	.0370	.0324	.0263	.0180	.0206	.0253	.4856	.6356	.9637
700	.3995	.7675	.6639	.5306	.0313	.0271	.0217	.0212	.0246	.0307	.6783	.9064	1.4190
750	.5265	.7531	.6448	.5071	.0268	.0229	.0180	.0249	.0290	.0369	.9283	1.2665	2.0472
800	.6816	.7390	.6262	.4847	.0231	.0196	.0151	.0288	.0340	.0439	1.2480	1.7383	2.9013

RPM COLOR: CRYSTAL

Feet	Threshold SI (Clear)	Transmissivity of Rainfall 0.5*	1.0*	2.0*	Illuminance of Headlamps 0.5*	1.0*	2.0*	Luminance of RPM Req'd to See 0.5*	1.0*	2.0*	Threshold RPM SI in Rain 0.5*	1.0*	2.0*
50	.0000	.9813	.9712	.9557	7.8502	7.7693	7.6459	.0001	.0001	.0001	.0000	.0000	.0000
100	.0002	.9629	.9432	.9134	1.9258	1.8863	1.8269	.0005	.0005	.0005	.0003	.0003	.0003
150	.0012	.9449	.9160	.8730	.8399	.8142	.7760	.0012	.0012	.0013	.0014	.0015	.0016
200	.0039	.9272	.8896	.8344	.4636	.4448	.4172	.0021	.0022	.0023	.0045	.0049	.0056
250	.0095	.9098	.8639	.7975	.2911	.2764	.2552	.0033	.0035	.0038	.0115	.0127	.0150
300	.0197	.8928	.8390	.7622	.1984	.1864	.1694	.0049	.0052	.0057	.0247	.0280	.0339
350	.0365	.8761	.8148	.7284	.1430	.1330	.1189	.0068	.0073	.0082	.0476	.0550	.0688
400	.0623	.8597	.7913	.6962	.1075	.0989	.0870	.0091	.0098	.0112	.0843	.0995	.1286
450	.0998	.8436	.7685	.6654	.0833	.0759	.0657	.0117	.0128	.0148	.1403	.1690	.2255
500	.1522	.8278	.7463	.6359	.0662	.0597	.0509	.0147	.0163	.0191	.2221	.2732	.3762
550	.2228	.8123	.7248	.6078	.0537	.0479	.0402	.0181	.0203	.0242	.3377	.4240	.6030
600	.3155	.7970	.7039	.5809	.0443	.0391	.0323	.0220	.0249	.0302	.4966	.6368	.9350
650	.4346	.7821	.6836	.5552	.0370	.0324	.0263	.0263	.0301	.0371	.7104	.9299	1.4099
700	.5845	.7675	.6639	.5306	.0313	.0271	.0217	.0311	.0359	.0450	.9924	1.3262	2.0761
750	.7703	.7531	.6448	.5071	.0268	.0229	.0180	.0364	.0425	.0540	1.3581	1.8529	2.9951
800	.9972	.7390	.6262	.4847	.0231	.0196	.0151	.0422	.0498	.0643	1.8259	2.5432	4.2447

Threshold Study 3: Thresholds for Detection of Retroreflective Raised Pavement Markers under Simulated Wet Weather Conditions

Introduction

This experiment was designed to extend the findings of the first study in detection thresholds for retroreflective raised pavement markers (RPM) under good seeing conditions to the situation in which the pavement is flooded and opposing traffic headlamps are both causing specular reflections from the flooded pavement and reducing the dark adaptation of the observer. Under these conditions of seeing, the minimum specific intensities that would be expected to be at near 100 percent threshold will be far higher than found in the first study. Data derived from this experiment was then corrected using factors developed and discussed in Study 2: An Analysis of Threshold Intensities to Account for Rain Diffusion.

Method

Equipment

1. 1979 Pontiac Grand Am used in Study 1. This car is equipped with quartz iodide headlamps that produce a nominal 26,240 candela (high beam), and 33,600 candela (low beam) at 200 feet directly in front of the vehicle. (Figure 4-3)

2. Water distribution system. The water distribution system used for TTI truck splash and spray investigations was used to provide water on the test pad sufficient to produce a flooded, specular condition between the observer and the test apparatus (approximately 0.05 inch).

3. Rotating shutter apparatus for exposing a test RPM to the observer. This device consists of a 5-inch radius disk with a slot cut in its outer periphery. The disk is mounted vertically on a 1 rpm motor driven shaft such that an RPM behind the disk is gradually revealed and then concealed. The effect of this device, when illuminated by headlamps and viewed at a distance, is to make the point source of light produced by an RPM seem to grow brighter and brighter until it is fully exposed, then diminish in brightness until it can no longer be seen. By pressing a switch wired to break a latch circuit, an observer can stop the shutter at any point. The shutter disk is equipped with a vernier scale to permit its position with respect to the test RPM to be measured. The scale measurement is calibrated to provide conversion of the angular data to specific intensity of the exposed RPMs. This apparatus is depicted in Figures 4-4 and 4-5.



Figure 4-3. Test observer vehicle.



Figure 4-4. Shutter apparatus for presenting RPMs

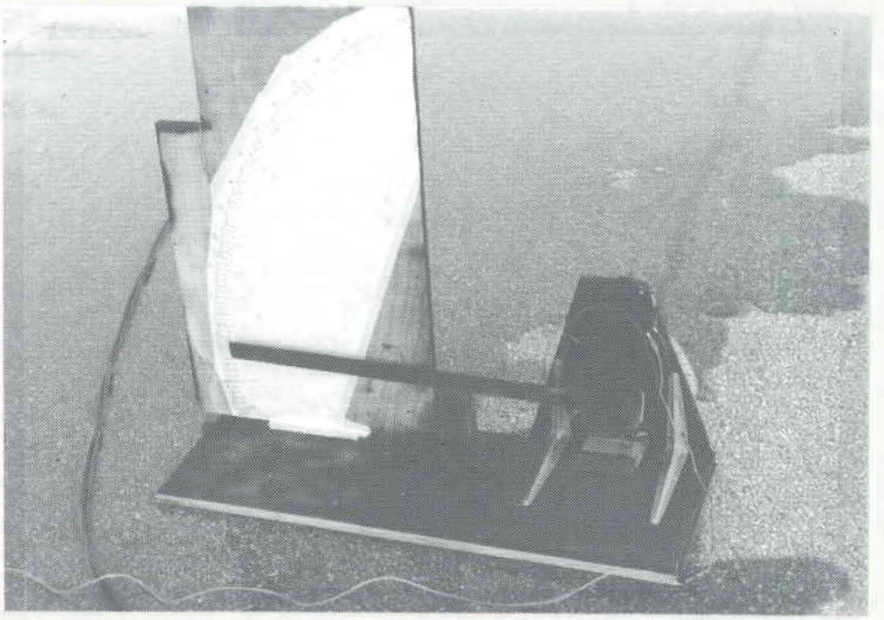


Figure 4-5. Rear view of shutter apparatus



Figure 4-6. "Opposing traffic" vehicle.

4. RPM specimens prepared for this study were Stimsonite Type 88, in red, amber and white. They were reduced by area adjustmentto 50 per cent of their nominal full SI value.

5. An opposing vehicle which was stationed just off the test pad as though it were in an opposing traffic lane on a two lane highway. This vehicle had its low beam headlamps on. The vehicle, a 1981 Cadillac Coupe DeVille depicted in Figure 4-6, was positioned 200 feet north of the test RPM. The car's headlamps delivered 0.156 ft-candles of illuminance to the observer, 400 feet away. The headlamp's equivalent candlepower was, accordingly, 25,960 candela.

Research Participants

Fourteen research participants were recruited to work in this study. Age, gender and corrected acuity data for these individuals are summarized in Table 4-6. Of this group, participants 11 and 12 were eliminated, because they were unable to discern any objects at any brightness in the glare from the headlamps of the opposing vehicle. They were very sensitive to glare at night, and neither drove at night.

Procedure

The method was the classic psychophysical Method of Adjustment. Each observer was driven to the test site and then stationed behind the wheel of the test vehicle already positioned on the test surface. Low beam headlamps were used. The test location for this vehicle was 200 feet south of the test RPM in its

Table 4-6. Study 3 research participants.

Participant No.	Gender	Age	Visual Acuity
1	F	52	20/29
2	M	53	20/40
3	M	54	20/20
4	M	67	20/40
5	M	68	20/29
6	F	66	20/29
7	F	73	20/20
8	M	60	20/20
9	M	69	20/18
10	M	69	20/25
11	F	77	20/40, 20/50
12	F	71	20/40
13	F	60	20/20
14	F	57	20/20

rotating shutter device. The RPM in its shutter was positioned on the flooded road surface, in the water. Figure 4-7 shows the scene from the observer's viewpoint in daylight, and Figure 4-8 shows it at night. The line of RPMs on the left are for a durability study and were not involved in this experiment.

At the beginning of a test sequence, the observer was told to observe the RPM and watch for its disappearance. The experimenter at the site then started the shutter rotating. As the shutter covered the RPM, the observer attended the visual scene, and when he or she lost sight of the RPM, the observer depressed a stop button. This broke the circuit to the rotating shutter motor. The test site experimenter then read the shutter position scale. The position scale corresponded to the amount of RPM reflective area exposed, which, in turn, was indicative of the SI of the exposed RPM. The shutter was activated again and the observer was now instructed to watch for the reappearance of the RPM. The observer was instructed to press the button again when the RPM just appeared. The shutter position was then again read. The mean of these two readings was taken as the threshold value. The procedure was followed for all three colors, with twelve replications per color.

Results

Table 4-7 presents a summary of test results for the 12 participants that were able to see through the glare. Values for the raised pavement markers are in terms of specific intensity (SI), candela per incident ft-candles. Mean (average) SI for red markers was 0.104, 0.240 for amber, and 0.229 for clear or crystal RPMs. By using the sample standard deviation or RMS error also reported in Table 4-7, and data reported from Study 1 in this series, some conclusions can be drawn concerning minimum values of SI for various sight distances and weather conditions.

Estimate of Minimum Acceptable Illuminance at Eye from RPM

By using the standard deviation computed from the data on the 12 participants, a 95 percent confidence interval can be estimated. If the sample taken in this study approximates the parameters of the population of older middle-age drivers from which it was drawn, 95 percent of the thresholds measured under the seeing conditions of this study should fall within plus or minus 2 standard deviations from the mean. If only about half of the population could reliably see an amber RPM under these conditions with an SI of 0.24, then 95 percent should be able to see an RPM with an SI = 0.24 + (2 x 0.187) = 0.614.



Figure 4-7. Test setup from observer vehicle (daylight).



Figure 4-8. Test setup from observer vehicle (night).

Table 4-7. Threshold specific intensities, Threshold Study 3.

Test Conditions: Observer vehicle 200 ft from RPM.
Low beam headlamps.
Low beam opposing vehicle, 200 ft beyond RPM.
Wet pavement.

	RPM Color		
Subject	Amber	Red	Crystal
1	.045	.045	.082
2	.239	.052	.244
3	.158	.095	.185
4	.205	.185	.139
5	.757	-	.475
6	-	-	-
7	.248	.164	.377
8	.321	.147	.313
9	.168	.088	.196
10	.164	.085	.175
13	.110	.104	.115
14	.222	.071	.213
Mean	.240	.104	.229
Std. Dev.	.187	.047	.118

Calculations like this lead to the following results:

Amber RPM	SI = 0.614	Candela = 0.516
Red RPM	SI = 0.198	Candela = 0.166
Crystal RPM	SI = 0.465	Candela = 0.391

The equivalent candlepower of the RPM as reflected in this table is computed by multiplying the SI by the illuminance from the vehicle's headlamps, which was measured to be 0.84 ft-candle. These values lead directly to an estimate of how much light must fall on the observer's eyes in order for 95 per cent of a sample of people ranging in age in from their late 50's to early 60's to say that they see an RPM. Invoking Lambert's Inverse Square Law, the equivalent candlepower of each RPM above is divided by the square of the distance between the RPM and the observer (200 ft x 200 ft) to yield the following values:

Amber RPM	Illuminance at eyes = 0.0000129 ft-candle
Red RPM	Illuminance at eyes = 0.00000415 ft-candle
Crystal RPM	Illuminance at eyes = 0.00000977 ft-candle

These three numbers represent the best conservative estimate of the amount of light that must fall on an observer's eyes from an RPM when he or she is looking at oncoming traffic on a dark and wet road and trying to see the marker. From a target detection standpoint, this is "worst case" for design purposes.

Comparison with Theoretical Estimate for Elderly Driver

In Study 1 of this series, "Threshold Specific Intensities of Retroreflective Raised Pavement Markers," an extrapolation was made to the vision of an 80-year-old person. Using the rule that the amount of light needed for threshold detection doubles every 13 years, a correction factor of 3.1 could be applied to the above data to derive an equivalent 80-year-old threshold from the 60-year-old threshold data. The multiplier applied to the mean thresholds would yield these results:

Amber RPM	Illuminance at eyes = 0.0000157 ft-candle
Red RPM	Illuminance at eyes = 0.00000677 ft-candle
Crystal RPM	Illuminance at eyes = 0.0000162 ft-candle

Illuminances of this level would permit at least half of those 80 years old to discern an RPM. They are not very much different than the 95 percent confidence level 60-year-old thresholds described in the last section. If those thresholds are multiplied by 3.1, then everyone 80 years or younger with normal or correctable vision should be able to see the RPMs, if the deleterious effects of glare were not a problem to elderly observers.

Observers much over 70 tend to have a great deal of problem with nighttime glare, as evidenced by two of the 14 participants in this study. Hence these theoretical thresholds are probably suspect, because in fact many 80-year-olds would be unable to make out the RPM in the veiling glare. Thus further analysis of the data in this experiment will use the 95 percent 60-year-old average age observer thresholds, with a caveat that some very elderly drivers (perhaps half of those averaging 80 years of age) would probably be able to discern RPMs delivering that amount of light, but many would have problems.

Prediction of RPM Visibility as a Function of Distance and Rainfall

The rationale for computing threshold RPM specific intensity as a function of seeing distance and rainfall is explained in Study 2. Generation of the tables and graphs for this analysis assumes a nominal value of 20,000 candela for the equivalent candlepower of the observer's vehicle headlamps. This value is picked from the range of 18,000 to 30,000 candela for low beam lamps reported in Perel, et al (1983).

The "Clear" column in Table 4-8 provides the threshold SI for red, amber, and crystal RPMs on wet pavement, with opposing traffic but no rain as a function of sight distance in increments of 50 feet. In the case of amber RPM's, perhaps the most critical color of marker, sight distances of over 250 feet are not attainable, since a brand new marker does well to yield an SI of 2. Under conditions in which light is attenuated by rainfall, not much more than 200 feet can be attained with a new marker. The typical marker which has been in place for a year or so, and has an SI of 0.1 or less would not be usable at distances much beyond 100 ft. Similar results are shown in Table 4-8 for red and crystal markers.

For comparison, two other cases previously investigated (and reported in Study 1) are analyzed in the same fashion and shown in Tables 4-9 and 4-10, for the perfect-seeing dark road condition, and for a nominal "urban" condition which does not involve opposing traffic. In Table 4-9, it can be seen that a somewhat degraded amber RPM with an SI of 0.36 can be seen at 800 feet and can be picked up at 600 feet even in a driving rainstorm of 2 inches per hour. An RPM with the "typical" SI of 0.1 could be seen at 600 feet and at a little less than 500 feet in the rainstorm. In the nominal "urban" circumstance, such a marker could be seen at 300 feet in the clear and somewhat over 250 feet in the 2-inch-per-hour downpour.

Figures 4-9, 4-10 and 4-11 are plots of threshold SI for amber RPMs for the three scenarios that were discussed, based on the tabled data. Figure 4-9 presents the findings for the opposing traffic, wet pavement condition, Figure 4-10 shows thresholds for the clear but wet pavement seeing condition, and Figure 4-11 depicts the nominal "urban" situation.

Summary of Findings

The geometrics of a particular highway setting dictate how far away an RPM needs to be seen in order to provide proper guidance to the driver. Many jurisdictions use a "rule of three" to set guidelines for RPM visibility: at any given point on the highway, at least three RPMs must be above threshold to provide path information. Add to this a rule of thumb which is widely endorsed in traffic engineering circles: 2.5 seconds decision-response time. (ITE, 1976) If a driver is travelling at 55 MPH (80.7 feet/sec), he or she needs to see the farthest of three RPMs at a distance of 2.5 x 80.7 = 201.8 or 200 feet. In curved sections at reduced speeds, or under wet weather conditions in which average speeds would be lower, this decision sight distance decreases proportionately.

If the traffic engineer assumes a "worst case" situation with a wet, shiny pavement, glaring headlamps in the opposing lane, and rain falling (but assuming good visibility through the windshield - a perhaps dubious assumption) then reference to Table 4-8 gives the minimum level of SI at which replacement should be considered. For

example, in areas subject to downpours of up to 2 inches per hour, assuming a 200 foot sight distance requirement and traffic at 55 MPH, amber RPMs should exhibit SIs no less than 1.5. Similarly, crystal and red RPMs can be expected to function at SIs of 1.1 and 0.5, respectively. For sites at which little rainfall occurs, the "Clear" column could be used, indicating SIs of 1 for amber, 0.8 for crystal, and 0.3 for red RPMs.

Suppose that opposing traffic glare is not a problem, but the other assumptions hold: 55 MPH, 2.5 second decision-sight distance, and "urban" lighting conditions similar to that in a strip business district. Then Table 4-10 would give some values for minimum SI. Under heavy rain (2 inches per hour) amber RPMs would be replaced when their SI fell below 0.03, crystal at an SI of 0.04, and red units under 0.03.

Table 4-9 yields equivalent figures for very dark situations which might occur in farm-to-market or other rural roads.

Thus these findings strikingly emphasize the importance of operational, geometric, and weather considerations in deciding when an RPM is no longer effective in its place.

Table 4-8. Predicted threshold SI as a function of distance and rainfall. Adapting condition for observer:

Opposing traffic
Wet pavement
Headlamp illuminance = 20,000 candela.

Detection Distance (ft)	Rainfall Rate: Clear	0.5 In/Hr	1 In/hr	2 In/hr
RPM COLOR: AMBER				
50	0.004	0.004	0.004	0.004
100	0.06	0.07	0.07	0.08
150	0.33	0.37	0.39	0.43
200	1.03	1.20	1.30	1.48
250	2.52	3.04	3.38	3.96
RPM COLOR: CRYSTAL				
50	0.003	0.003	0.003	0.003
100	0.05	0.05	0.06	0.06
150	0.25	0.28	0.30	0.32
200	0.78	0.91	0.99	1.12
250	1.91	2.30	2.56	3.00
RPM COLOR: RED				
50	0.001	0.001	0.001	0.001
100	0.02	0.02	0.02	0.03
150	0.11	0.12	0.13	0.14
200	0.33	0.39	0.42	0.48
250	0.81	0.98	1.09	1.28
300	1.68	2.11	2.39	2.89

Table 4-9. Predicted threshold SI as a function of distance and rainfall. Adapting condition for observer:

Dark highway, no ambient lighting
Headlamp Illuminance: 20,000 candela

Detection Distance (ft)	Rainfall Rate: Clear	0.5 In/Hr	1 In/hr	2 In/hr
RPM COLOR: AMBER				
50	0.000	0.000	0.000	0.000
100	0.000	0.000	0.000	0.000
150	0.000	0.000	0.000	0.000
200	0.001	0.002	0.002	0.002
250	0.003	0.004	0.01	0.01
300	0.01	0.01	0.01	0.01
350	0.01	0.02	0.02	0.03
400	0.02	0.03	0.04	0.05
450	0.04	0.05	0.06	0.08
500	0.05	0.08	0.10	0.13
550	0.08	0.12	0.15	0.22
600	0.11	0.18	0.23	0.33
650	0.16	0.25	0.33	0.50
700	0.21	0.35	0.47	0.74
750	0.27	0.48	0.66	1.07
800	0.36	0.65	0.91	1.51
RPM COLOR: CRYSTAL				
50	0.000	0.000	0.000	0.000
100	0.000	0.000	0.000	0.000
150	0.001	0.002	0.001	0.001
200	0.002	0.002	0.002	0.003
250	0.005	0.005	0.006	0.007
300	0.009	0.01	0.01	0.02
350	0.02	0.02	0.03	0.03
400	0.03	0.04	0.05	0.06
450	0.05	0.07	0.08	0.11
500	0.07	0.10	0.13	0.18
550	0.10	0.16	0.20	0.28
600	0.15	0.23	0.30	0.44
650	0.20	0.33	0.44	0.66
700	0.27	0.46	0.62	0.97
750	0.36	0.64	0.87	1.40
RPM COLOR: RED				
50	0.000	0.000	0.000	0.000
100	0.000	0.000	0.000	0.000
150	0.000	0.000	0.000	0.001
200	0.001	0.001	0.001	0.002
250	0.003	0.003	0.004	0.004
300	0.006	0.007	0.008	0.01
350	0.01	0.01	0.02	0.02
400	0.02	0.02	0.03	0.04
450	0.03	0.04	0.05	0.06
500	0.04	0.06	0.08	0.11
550	0.06	0.09	0.12	0.17
600	0.09	0.14	0.18	0.26
650	0.12	0.20	0.26	0.39
700	0.16	0.28	0.37	0.58
750	0.21	0.38	0.52	0.84
800	0.28	0.51	0.71	1.18

Table 4-10. Predicted threshold SI as a function of distance and rainfall. Adapting condition for observer:

Urban Corridor, no opposing traffic
Headlamp Illuminance = 20,000 candela

Detection Distance (ft)	Rainfall Rate: Clear	0.5 In/Hr	1 In/hr	2 In/hr
RPM COLOR: AMBER				
50	.00	.00	.00	.00
100	.00	.00	.00	.00
150	.01	.01	.01	.01
200	.02	.03	.03	.03
250	.05	.06	.07	.08
300	.11	.14	.16	.19
350	.20	.26	.31	.38
400	.35	.47	.55	.71
450	.55	.78	.94	1.25
500	.85	1.23	1.52	2.09
550	1.24	1.88	2.36	
600	1.75			
650	2.42			
RPM COLOR: CRYSTAL				
50	.00	.00	.00	.00
100	.00	.00	.00	.00
150	.01	.01	.01	.01
200	.03	.03	.03	.04
250	.07	.08	.09	.10
300	.14	.17	.19	.23
350	.25	.33	.38	.47
400	.43	.58	.68	.88
450	.69	.96	1.16	1.55
500	1.04	1.52	1.87	2.58
550	1.53	2.32	2.91	4.14
600	2.17	3.41	4.37	
650	2.98	4.88		
700	4.01			
RPM COLOR: RED				
50	.00	.00	.00	.00
100	.00	.00	.00	.00
150	.01	.01	.01	.01
200	.02	.02	.02	.03
250	.05	.06	.06	.07
300	.09	.12	.13	.16
350	.18	.23	.26	.33
400	.30	.40	.48	.62
450	.48	.67	.81	1.08
500	.73	1.07	1.31	1.81
550	1.07	1.62	2.04	2.90
600	1.52			
650	2.09			

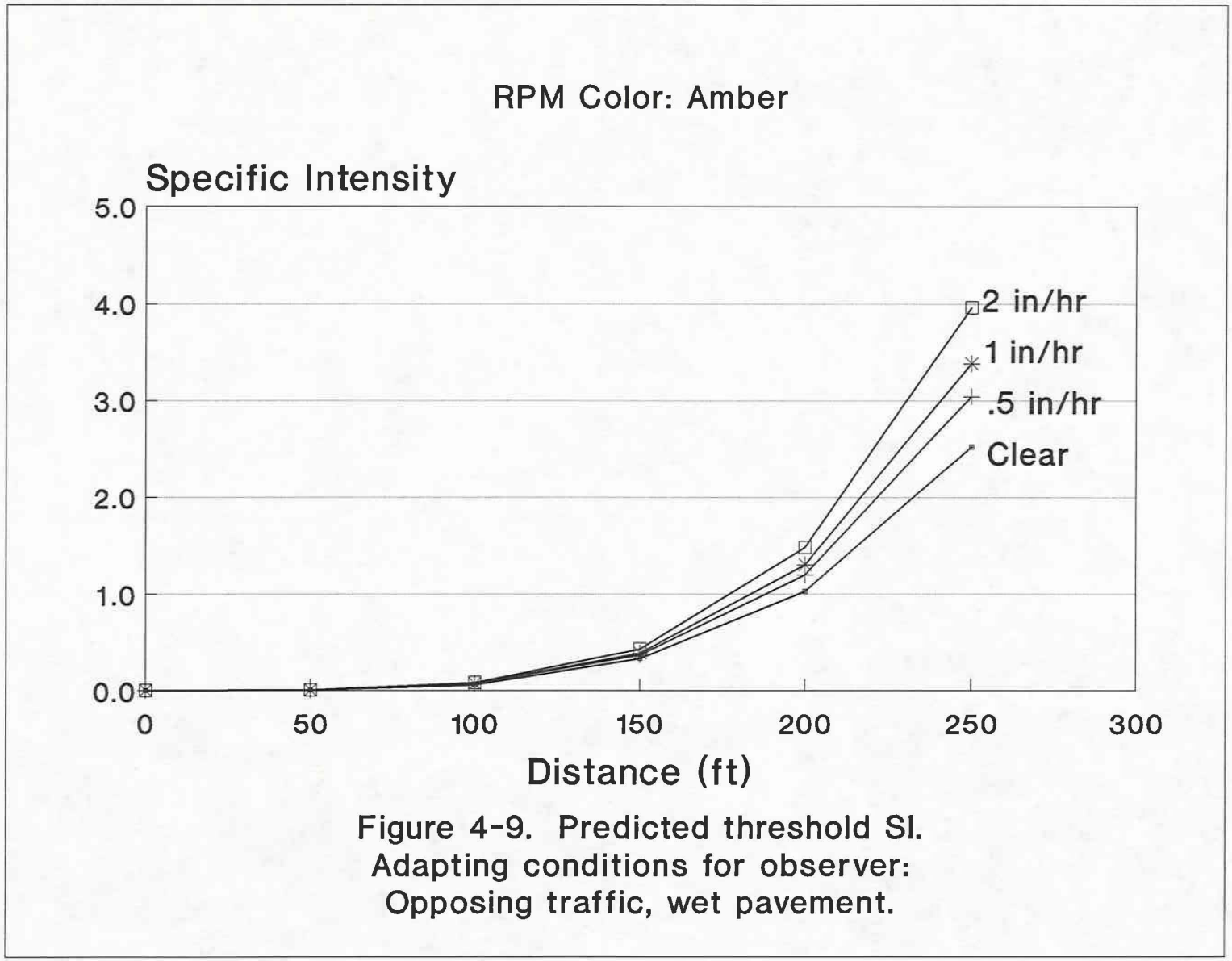


Figure 4-9. Predicted threshold SI.
Adapting conditions for observer:
Opposing traffic, wet pavement.

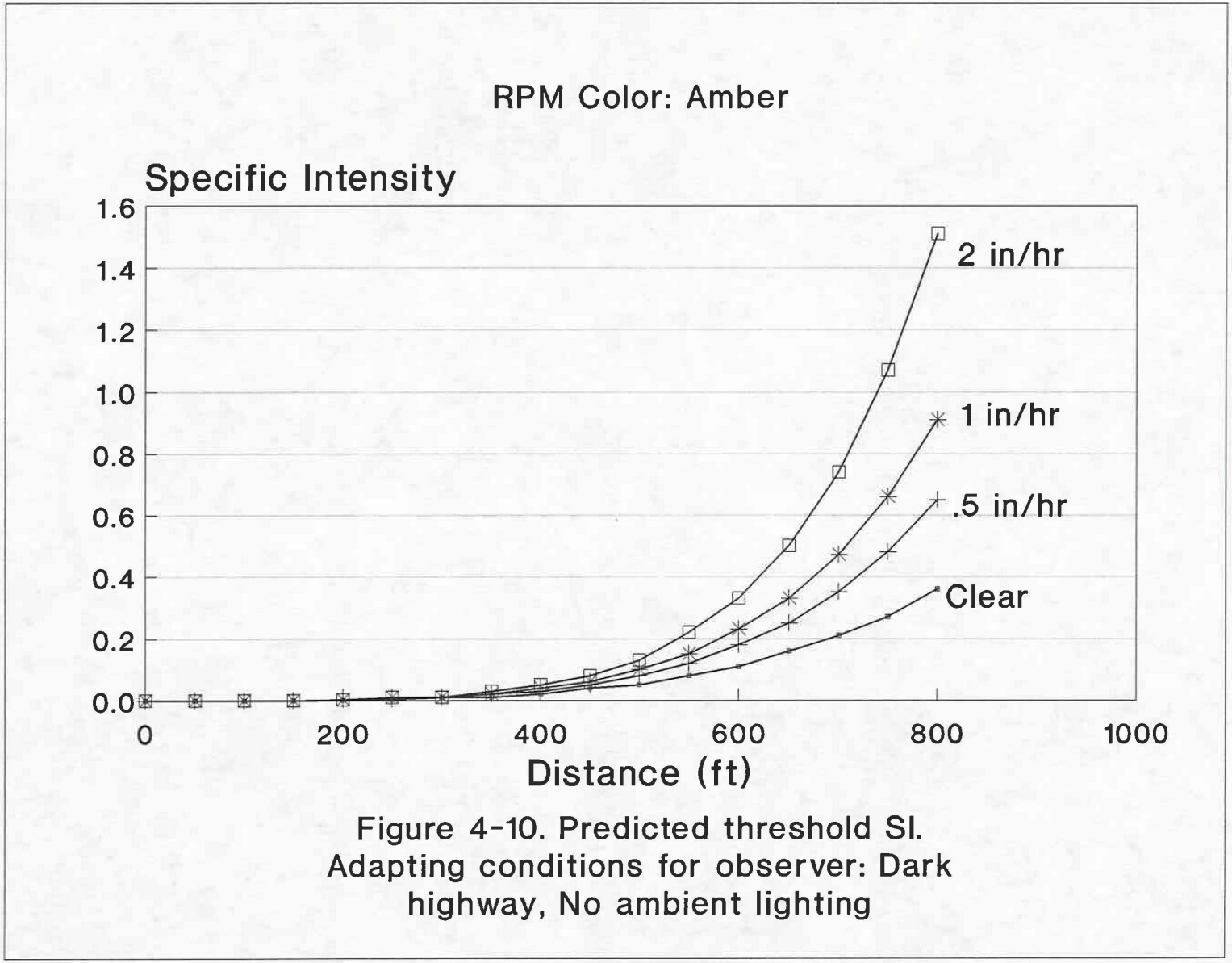


Figure 4-10. Predicted threshold SI. Adapting conditions for observer: Dark highway, No ambient lighting

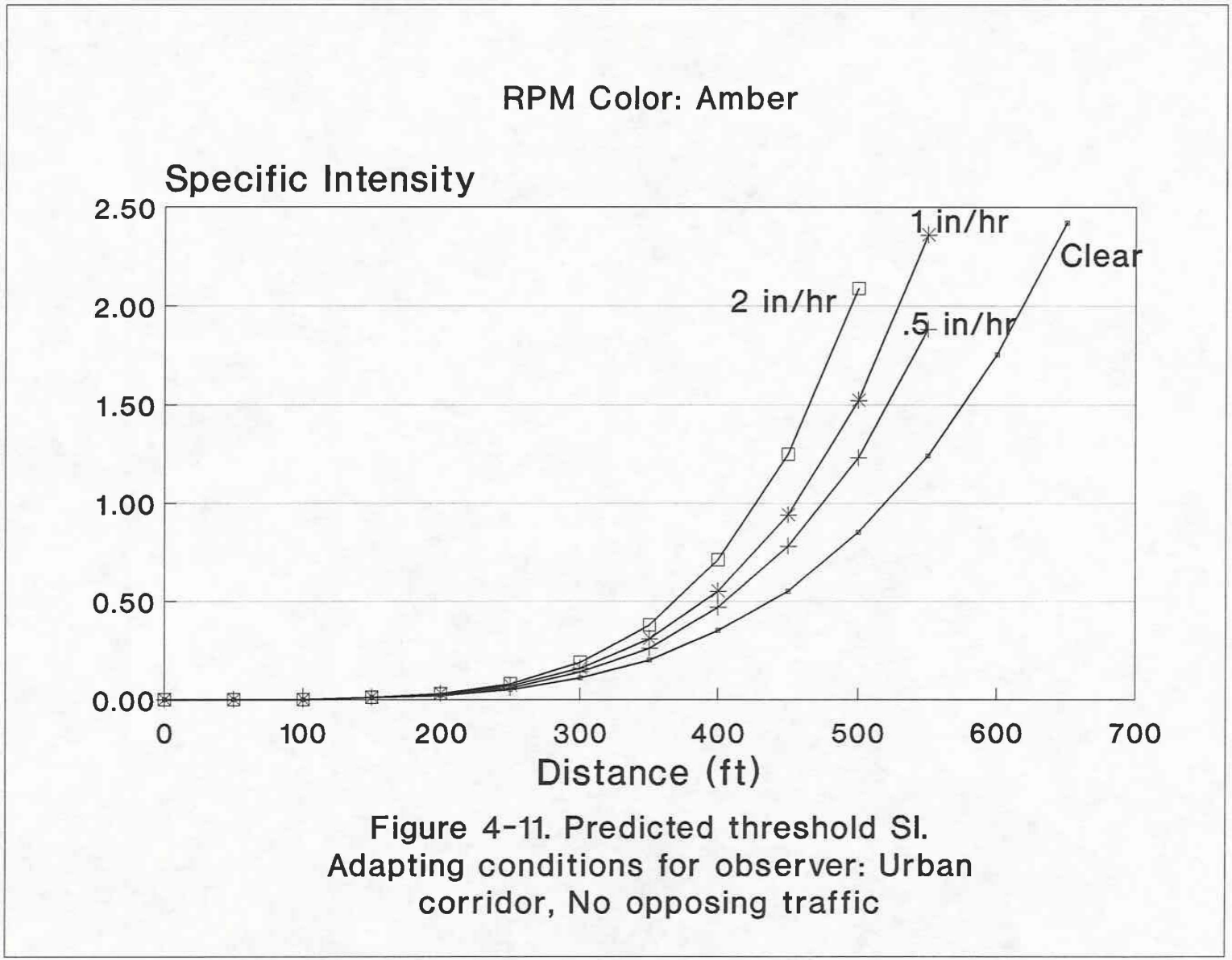


Figure 4-11. Predicted threshold SI. Adapting conditions for observer: Urban corridor, No opposing traffic

5. RAISED PAVEMENT MARKER DURABILITY

In order to provide effective path delineation over extended time periods, raised pavement markers installed on Texas highways must maintain a minimum level of retroreflectivity. The minimum specific intensities necessary for RPMs to effectively perform their function were discussed in Section 4. This section provides a brief discussion of the types of RPMs used on Texas highways and the materials used in fabricating these markers and reports the findings of a series of studies of some of the conditions that may mitigate against long term retention of sufficient retro-reflectivity. Among the abuses to which in-service RPMs are subjected are extremes of ambient temperature and repeated impacts from vehicular traffic. Three separate sets of studies are addressed in this section. The first is an assessment of the specific intensity of RPMs in several SDHPT districts after different periods of time in-service. Second, an account of two studies of the effect of thermal stress on RPM reflectivity is provided. Finally, the results of durability tests of RPMs when exposed to a laboratory abrasion test and to repeated tire impacts are reported.

Types of Pavement Markers Used in Texas

The vast majority of retroreflective raised pavement marker products used in Texas (by both the Highway Department and its contractors) are marketed under two trade names, Stimsonite, manufactured by a division of the Amerace Corporation and Ray-O-Lite, a division of Pac-Tec, Inc.

Both manufacturers make standard and low profile RPMs with reflective surfaces on one or both sides. Markers are available in a variety of reflective colors and color combinations, including amber(or yellow) clear ("crystal") and red. All of the markers are designed to reflect light back in the direction of the light source. This reflex- or retro-reflective property is accomplished by the incorporation of many small molded cube-corner (or prismatic) elements. In addition to size and color, the primary difference among RPMs lies in the treatment of the surface of the reflective element. The base surface of all markers is Methyl Methacrylate. On some Stimsonite markers, a thin layer of untempered glass is added to the RPM face. Table 5-1 provides a description of the primary RPMs used on Texas highways and employed in the empirical studies conducted under this project.

A preliminary comparative study of alternative materials for RPMs was conducted early in the research. This study consisted of library research plus interviews with cognizant individuals in the SDHPT, two major manufacturers of these devices (Amerace and FERRO), and Dow Chemicals in Freeport, Texas. As was mentioned in the preceding paragraph, the state-of-the-art in the manufacture of RPMs is the use of methyl methacrylate for the shell, which

Table 5-1. RPMs used on Texas highways.

Manufacturer	Model	Dimensions (in)	Reflective Area per side (in^2)	Surface Material
Ray-O-Lite	28	4.0x4.0x.70	≈ 3.25	Methyl Methacrylate
Ray-O-Lite	Mini	2.0x4.0x.45	≈ 1.87	Methyl Methacrylate
Stimsonite	88	4.0x4.0x.75	≈ 3.25	Methyl Methacrylate
Stimsonite	911	4.0x4.0x.75	≈ 3.25	Untempered Glass
Stimsonite	948	2.3x4.7x.52	≈ 1.87	Untempered Glass, recessed.
Stimsonite	947	2.3x4.7x.52	≈ 1.87	Untempered Glass
Stimsonite	74	2.3x4.7x.52	≈ 1.87	Methyl Methacrylate

includes the cube corner prism array. The interior of the shell in the area of the prism array is given a thin coating of aluminum as a reflective surface. Then the shell is filled with epoxy filler to produce the finished RPM. Stimsonite-made glass-faced RPMs are exactly the same as all-plastic RPMs, except a very thin glass surface is bonded by a patented process to the face of the prism array. The only way that water or any other contaminant can penetrate to the aluminum reflective layer to destroy the optical qualities of the device is outright cracking or breakage of the shell itself, provided the bond between the shell and filler is tight to begin with, a quality control problem in the past, but reportedly not a major problem now.

The major reason that methyl methacrylate thermoplastics are used to fabricate RPMs is their low cost and excellent performance under the wide extremes of heat and sun exposure to which these devices are subjected. In outdoor exposures, clear acrylics (the usual generic name for methyl methacrylate, since "Plexiglas" is a trade name) have experienced losses of less than 1 percent of their light transmission in 5 years. These plastics are universally used in aircraft windows. (Modern Plastics Encyclopedia, 1972-73). The only plastic that compares to acrylics in performance and durability for RPM use is the polycarbonate family. Polycarbonates, used very extensively for shells of power tools, sport helmets, space helmets and visors, and similar applications, have optical performance characteristics comparable (but not superior) to acrylics, but greater impact strength. The cost is roughly double that of acrylics. None of the persons contacted indicated that any plans exist among RPM manufacturers for substituting polycarbonate plastic for acrylics.

As the project progressed, it became apparent that the major problem with the optical qualities of RPMs with exposure was

associated with abrasion of the surface of the optical array, as will be described in the paragraphs that follow. Hence the investigators decided to pursue this line of inquiry, and not further consider alternative materials for RPMs.

Assessment of In-Service RPMs

Among the first tasks undertaken for this project was an informal investigation of RPM experience and practices in several SDHPT Districts. Discussions with District Engineers and Maintenance Engineers in several of the Districts led to the collection of a small sample of in-service RPMs that were subsequently subjected to laboratory photometric analyses. The purpose of the measurements made on these RPMs was to provide a bench mark for the condition of RPMs that had been subjected to real-life operating conditions for known periods of time and to provide information pertinent to the life cycle of RPMs. Although several Districts provided RPM samples, the data presented here are based on RPMs provided by Districts 20 and 6, since those Districts provided specimens on the most regular basis.

Sets of seven amber Stimsonite Model 88 RPMs were removed from service on US Highway 89 in District 20 after 6, 9, and 12 months of service. The markers were selected randomly from areas with similar roadway geometry. The mean specific intensity of each set, measured after the markers were cleaned with a mild soap and water solution, and the nominal new SI of these markers are shown in Figure 5-1. This figure can be viewed as providing a "typical" life cycle for this model of marker on a rural, east Texas two-lane highway. Clearly evident in the figure is the dramatic drop in SI after only 6 months of service. Following 6 months of use, these RPMs retained an average of only 18% of their original specific intensity. The differences among the mean SIs after 6, 9 and 12 months are not statistically significant, suggesting that most of the performance decrements among these RPMs occur in a relatively short period of time, followed by a leveling off at a low SI level.

The specific intensity of the RPMs received from District 20 were measured under four conditions. In addition to determination of SI after the RPMs were cleaned and dried, as shown in Figure 5-1, each RPM was also evaluated:

As received, i.e. dry, but contaminated with dirt,
As received, but wet, and
After cleaning, wet.

Useful information is provided from the determination of SI under each of these conditions. The "as received - dry" measurement is consistent with the conditions under which RPMs are most often viewed on the road. This state, however, is not congruent with the

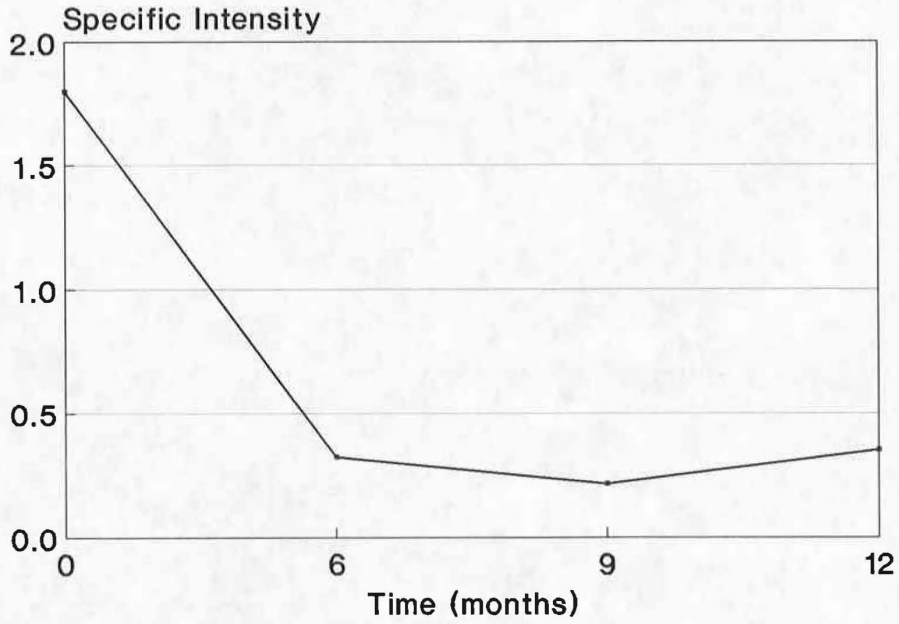


Figure 5-1. Typical RPM life cycle, plastic-faced Model 88.

conditions under which RPMs may be most useful for drivers, i.e., when visibility conditions are degraded. A critical need for RPMs is most likely to occur when it is raining, hence measurement of the markers "as received - wet." The "cleaned - dry" and "cleaned - wet" measures provide a means of evaluating changes in the physical status of RPMs without the confounding introduced by variable amounts of dirt buildup. Figure 5-2 illustrates the individual and average SI exhibited under each of these conditions for the seven 9-month-old Model 88 RPMs. The photometric performance of these RPMs, while variable, is quite poor under all measurement conditions except "cleaned - wet." It has often been observed that wet plastic-faced RPMs perform considerably better than the same RPMs dry. Inspection of Figure 5-2 shows this to be the case for this sample. The improvement, however, is striking only if the RPMs are relatively free of accumulated road dirt (i.e. "cleaned - wet"). RPMs measured wet, but not cleaned perform very similarly to the same RPMs that have been cleaned and dried (mean "cleaned-dry" SI = .217, mean "as received-wet" SI = .210). It has been suggested that although acrylic-faced RPMs are subject to abrasion from tire impacts, the reflectivity they lose from such abrasion is evident only under dry conditions where high levels are not critical. Based on this very small sample, it appears that the recovery of SI, presumably due to water filling the surface scratches, may be limited if the markers are not clean. Thus, while some improvement in the performance of plastic-faced markers may be

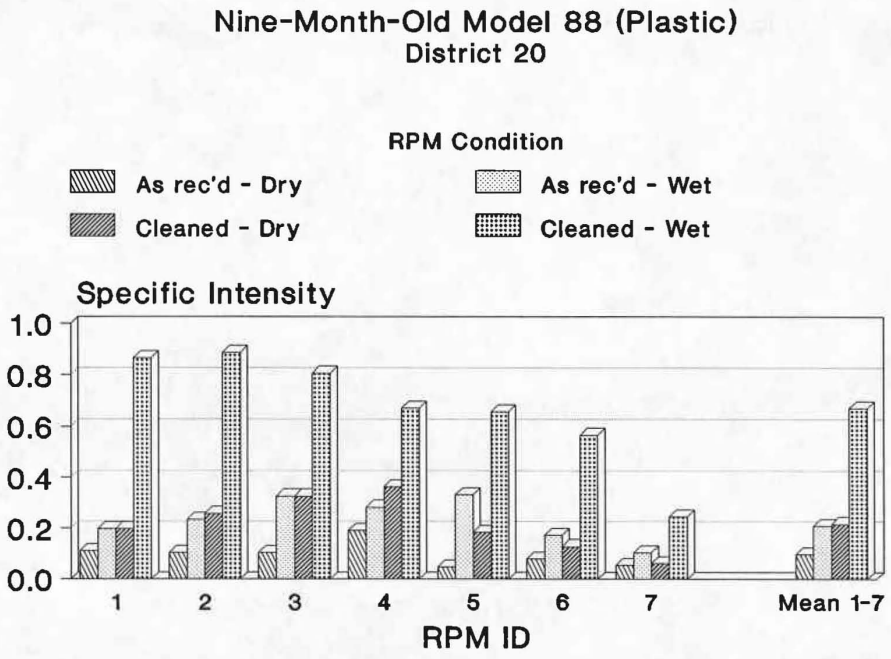


Figure 5-2. Dry and wet measurements of Model 88 RPMs.

anticipated under wet weather conditions, such improvement is likely to be minimal in areas where considerable environmental dirt is present.

A set of 11 glass-faced Model 911 RPMs removed from service in District 6 two years after installation showed much less evidence of degradation than the 9-month-old Model 88s (see Figure 5-3). Comparison of Figures 5-2 and 5-3 suggest that glass-faced markers may retain higher levels of SI under both wet and dry ambient conditions. The conditions to which these two sets of RPMs were exposed; including ambient temperatures, traffic volumes, and rainfall, are not known. It is important, therefore, to recognize that the superior SI retention of the glass-faced markers could be the result of exposure to less hostile conditions rather than an inherent superiority of those markers. These data are sufficiently suggestive, however, that empirical efforts, under controlled conditions, were carried out to determine if RPM surface material has a significant influence on the durability and SI retention of RPMs. The remainder of this section reports the methodology and results of those studies.

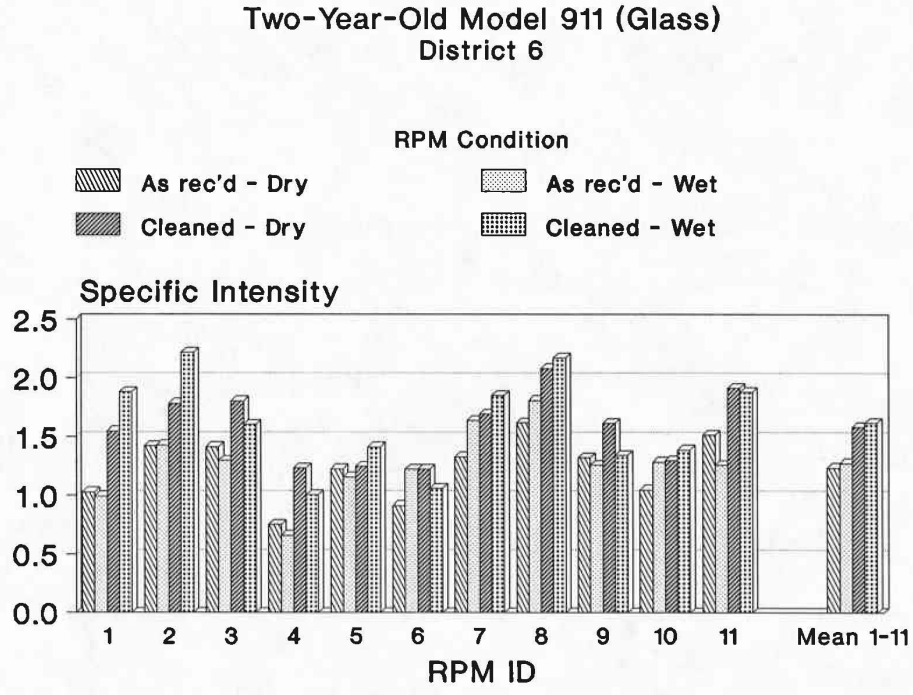


Figure 5-3. Dry and wet measurements of Model 911 RPMs.

Thermal Stress Study 1: The Effect of Thermal Stress on the Photometric Performance of Retroreflective Raised Pavement Markers

Introduction

Retroreflective raised pavement markers (RPMs) installed on Texas highways are subjected to a wide range of environmental conditions including large differences in ambient temperature in different geographical locations in the state, as well as substantial seasonal and day-night fluctuations. These ambient temperature differentials are magnified by the heat retaining characteristics of the asphaltic cement road surfaces to which RPMs are adhered.

Test Method Tex-846-B, "Method of Testing the Heat Resistance of Reflector Units", is implemented as part of the RPM acceptance testing conducted by D-9 of the State Department of Highways and Public Transportation. This test method calls for test specimens to be subjected to 140 degrees F for four hours. Test specimens whose photometric performance after heat treating, as measured by specific intensity, is less than 80% of the minimum specified performance prior to heating are considered to have experienced a substantial change in prismatic configuration.

Because the heat stresses to which installed RPMs are subjected are cyclical, a single test of heat resistance may not be adequate to characterize the effect of heat on RPM performance. In addition to being subjected to elevated temperatures, installed RPMs in some highway districts are exposed to low ambient temperatures. Therefore, a test of the effect of thermal stress arising from both high and low temperatures was conducted. One set of RPMs was subjected to repeated testing under the heat stress conditions specified in Test Method Tex-846-B. A second set of test specimens was exposed to an analogous procedure for low temperature in which RPMs were placed in a controlled cold environment. This set of RPMs was exposed to repeated cycles of 0 degrees F for four hours.

Method

Test Specimens

A total of 40 RPMs were tested, 20 in the "heat" test and 20 in the "cold" test. In each case, five new RPMs of each of four models were tested. The test sample comprised Stimsonite models 88, 911, and 948 and Ray-O-Lite Mini-markers. All test markers were reflective on two sides, thus providing 10 test surfaces of each type. The Stimsonite model 88 and Ray-O-Lite Mini-markers have plastic (methyl methacrylate) faces. Stimsonite models 911 and 948 have untempered glass covered faces. All RPMs used for this test are amber (yellow). Model 88 and 911 RPMs are standard

4 x 4 inch markers. Model 948 and Mini-markers are 2 x 4 inch "low profile" RPMs.

Test Procedure

The specific intensity (SI) of each test RPM was determined at the photometric laboratory at the Texas A&M Riverside Campus before heat treating. The entrance and observation angles for this and all subsequent SI measurements were 0 and 0.2 degrees, respectively.

The test markers in the "heat" set were subjected to eight cycles of heat treatment. In each cycle, the test specimens were exposed to 140 degrees F for four hours in a temperature controlled Precision Scientific convection oven. The SI of each reflective surface was determined after each heat cycle. In all cases, the RPMs were allowed to return to room temperature and were cleaned and dried before remeasurement. Markers in the "cold" set were tested in the same manner, except that they were exposed to only three cycles of cold treatment in a 0 degrees F cold vault for four hours.

Results

The influence of the hot and cold environments on RPM photometric performance are reported separately.

Heat Stress

The percent change (% Delta SI) from the pre-heat SI after each heat cycle was computed for each test RPM following each of the eight heat cycles. These data were subjected to a 4 (RPM type) x 8 (heat cycle) repeated measures analysis of variance, using the General Linear Models Procedure of SAS (SAS Institute Inc., 1988) to assess the influence of cyclical heat exposure on RPM photometric performance. The "percent change" data were used in the analysis, rather than absolute SI, to allow direct comparisons among the different RPM models. Substantial differences in initial photometric performance are observed among the various models due, in large part, to the inherent differences in the size of the retroreflective area.

The results of the analysis reveal a statistically significant effect on the amount of change in SI after heat-treating as a function of both RPM type, $F(3,36) = 114.9$, $p<.0001$, and heat cycle, $F(7,252) = 134.7$, $p<.0001$. Importantly, the interaction between RPM type and heat cycle is also significant, $F(21,252) = 37$, $p<.0001$.

This analysis clearly indicates that the effect of cyclical exposure to heat on RPMs is dependent on both the type of marker and the number of heat cycles. Table 5-2 shows the average percent

Table 5-2. Mean percent change in SI after heat-treating as a function of RPM type.

RPM Type	948	911	88	Mini
Mean % Change*	33.5	14.4	-10.7	-18.3

* All means differ significantly from each other, $p<.05$.

change in SI for each RPM type tested, collapsed over all heat cycles. Both of the glass-faced RPM models (models 948 and 911) exhibited an **improvement** in photometric performance after being subjected to heat. Conversely, the performance of both plastic-faced RPMs (model 88 and Mini-markers) declined. The most dramatic change is apparent among the model 948 markers which exhibited a nearly 34% average increase in SI when compared to before the heat cycles.

Average changes in SI resulting from each of the eight heat cycles are presented in Table 5-3, without regard to RPM model. These data indicate the somewhat erratic nature of the changes in RPM performance as a function of repeated heating. Note that the photometric performance does not appear to follow a simple increment or decrement until some asymptotic performance is realized. Rather, following each heat cycle performance may be better or worse than the preceding cycle. Averaged over all marker types, the best optical performance was obtained after seven heat cycles.

The clearest picture of the influence of the heat on RPMs is provided by the interaction of RPM type and heat cycle. Figure 5-4 graphically depicts the influence of each cycle on the average percent change in SI for each of the four RPM types. The observed differences between the performance of glass-faced (911 & 948) and

Table 5-3. Mean percent change in SI after heat-treating as a function of heat cycle.

Heat Cycle	7	8	2	3	6	5	4	1
Mean % Change	17.8	10.4	9.4	4.7	2.1	-1.2	-1.8	-3.6

Means underscored by a common line do not differ significantly, $p>.05$.

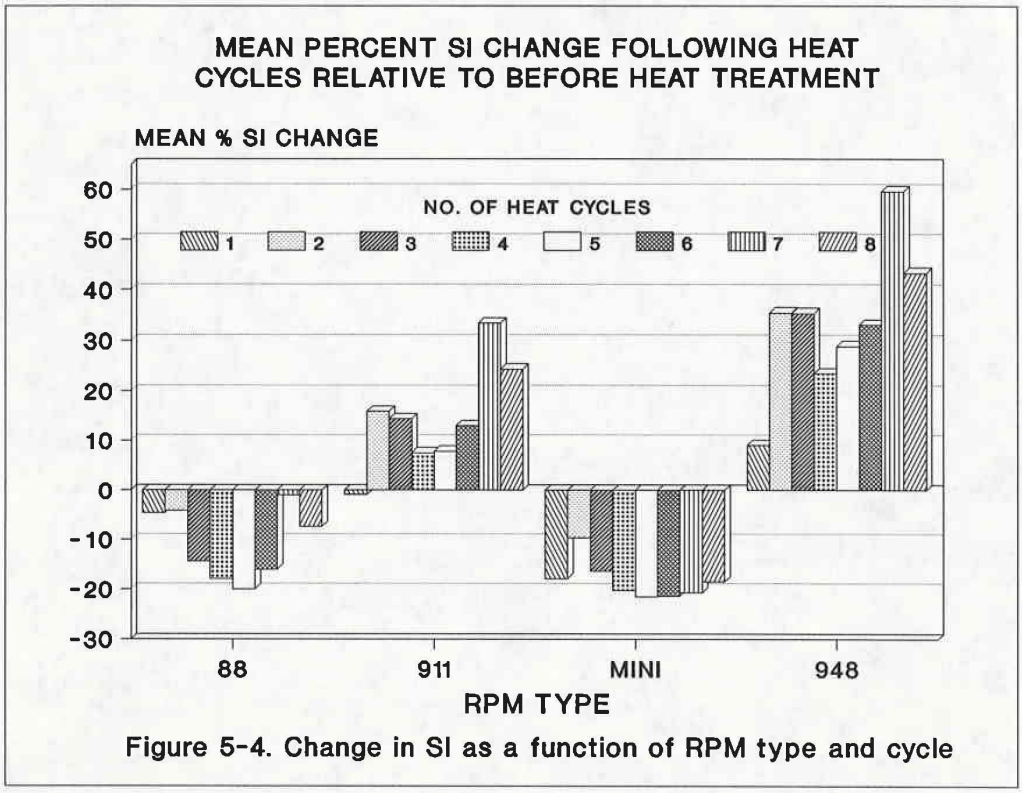


Figure 5-4. Change in SI as a function of RPM type and cycle

plastic (88 & Mini) RPMs following heat treatment are easily seen by inspection of the Figure. Also evident are the inconsistencies in RPM performance from cycle to cycle. Somewhat greater consistency between cycles was evidenced by the plastic-faced model 88 and Mini-markers than by the glass 911s and 948s. The **average** change in SI of the plastic RPMs, especially the Mini-markers, however, approached or exceeded the maximum performance degradation allowed by Test Method Tex-846-B.

Cold Stress

The absolute SI and the percent change in SI following each cold cycle are provided in Tables B-3 and B-4, respectively. The same type of analysis was performed on the cold stressed RPMs as reported above for the heated RPMs. The percent change data were subjected to a 4 (RPM type) x 3 (cold cycle) repeated measures analysis of variance to assess the influence of cyclical cold exposure on RPM photometric performance.

Like the previously reported analysis of heat treated RPMs, the results of this analysis indicate a statistically significant effect on the amount of change in SI after cold treatment as a function of cold cycle, $F(2,68) = 14.34$, $p<.0001$, and as result of the interaction between RPM type and cold cycle, $F(6,68) = 5.84$, $p<.0001$. Unlike the effect of heat, however, RPMs exposed to low temperature did not change differentially as a function of the main effect of RPM type, $F(3,34) = 1.23$, $p = 0.3123$.

The mean change in SI resulting from each of the three cold cycles, without regard to RPM type, are shown in Table 5-4. Overall, the first two cold cycles produced very small changes in SI. The final cold cycle did result in SI changes that, while still relatively modest, were significantly greater than that of the previous cycles.

The mean change in SI to each marker type, averaged over all three cold cycles, is shown in Table 5-5.

Table 5-4. Mean percent change in SI after cold-treating as a function of cold cycle.

Cold Cycle	1	2	3
Mean % Change	2.94	1.16	11.15

Means underscored by a common line do not differ significantly, $p < .05$.

Table 5-5. Mean percent change in SI after cold-treating as a function of RPM type.

RPM Type	948	911	88	Mini
Mean % Change	1.28	1.64	4.87	11.81

Means do not differ significantly, p >.31.

As was the case with the effect of heat on RPM performance, the graphical depiction of the significant cold cycle by RPM type interaction provides the clearest indication of the effect of repeated exposure to low temperatures. Inspection of Figure 5-5 demonstrates the relatively small effect of the cold treatment on all of the RPM types tested.

Discussion

The results of this study clearly demonstrate that repeated exposure to temperature extremes has differential effects on the optical performance of retroreflective RPMs. The explanation for the observed influence of high and low temperatures is less evident. Nonetheless, it appears that cyclic exposure to high ambient temperatures may contribute to reduced brightness of plastic-faced markers. The SI of glass-faced RPMs seems to improve with exposure to heat. Exposure to cold temperatures does not appear to have a substantial negative effect on either plastic or glass RPMs.

The temperatures to which the test RPMs were exposed are not outside the range that installed retroreflectors may experience. Considering that a hot mix asphaltic adhesive (Bitumen) is often used for adhering RPMs to the roadway, the 140 degree maximum temperature employed in this test may be lower than that which RPMs should withstand without significant change in performance. The bottom surface of RPMs are exposed to a thermal shock exceeding 350 degrees at the time of application. The relationship between that kind of short duration, but high intensity, thermal loading and the present longer exposure to lower temperatures is the subject of Thermal Stress Study 2.

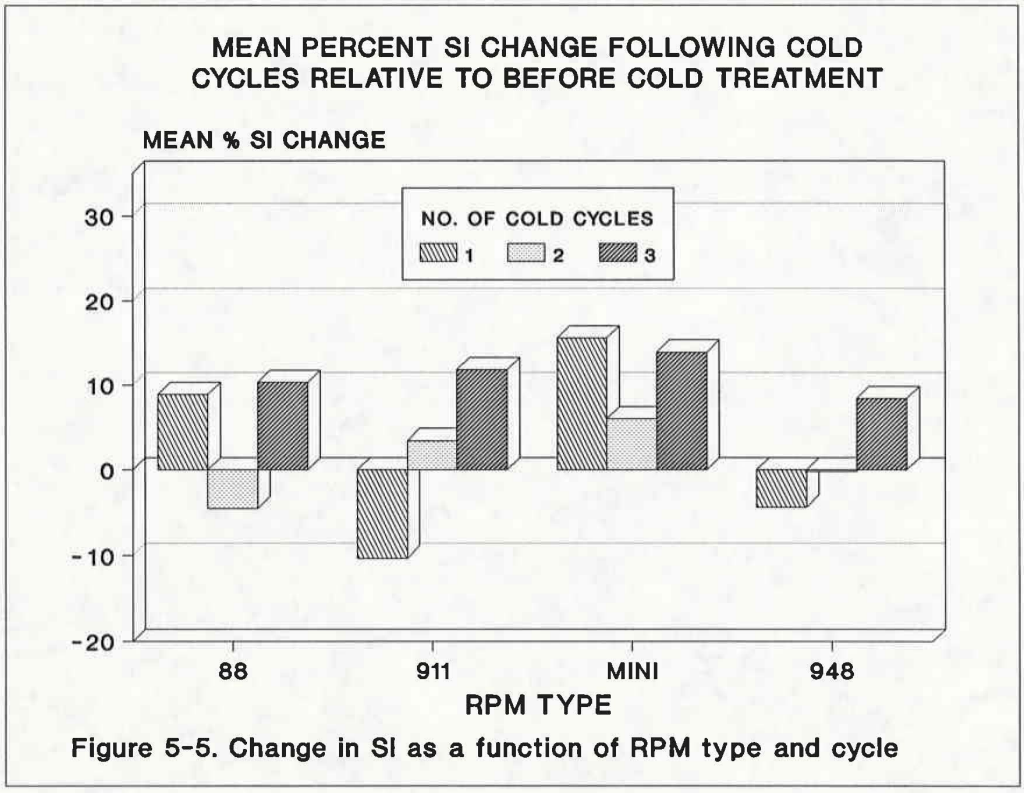


Figure 5-5. Change in SI as a function of RPM type and cycle

Thermal Stress Study 2: Thermal Shock from RPM Adhesive

Introduction

The results of Thermal Stress Study 1 raised the question of the effect, if any, on RPM specific intensity of thermal shock due to the heat applied to RPMs during installation. The bituminous adhesive used to affix RPMs to the road surface is heated to a temperature in the range of 350 to 400 degrees Fahrenheit. A pool of adhesive, at least as large as the base of the RPM, is placed on the road surface and the pavement marker is firmly positioned in the correct location.

In light of the results of Thermal Stress Study 1, several questions arise regarding the possible effects on RPM SI of exposure, albeit brief, to high temperatures during installation. Does the heat of installation affect the SI of RPMs? If there is a heat shock effect, does it affect the RPMs differently due to material (glass vs acrylic) or size (large vs small)? The present experiment was undertaken to answer these questions.

Method

Test Specimens

A random sample of four RPMs of each of four types was selected. The same RPM types used in Study 1 of this series were used here; i.e., Stimsonite Models 88, 911, and 948 and Ray-O-Lite Mini-markers. It will be recalled that the type 88 and Mini-markers are both acrylic-faced whereas the type 911 and 948 are glass-faced. Model 88 and 911 RPMs are standard 4 x 4 inch markers. The Mini-markers and Model 948 RPMs are both low profile. Each RPM has two reflective faces.

Test Procedure

The sample RPMs were cleaned and the specific intensity of each face was measured in the laboratory using the standard method described in Appendix A. These values were recorded and labeled "Pre-shock."

A quantity of bituminous adhesive was purchased from the District 17 SDHPT Office. The adhesive was heated to 360 degrees F. Pools of adhesive were poured on an asphalt concrete pavement surface and the test RPMs were pressed firmly in the hot adhesive in a random order. The air and pavement surface temperature at the time of installation was 75 degrees F. The RPMs were allowed to set for 20 hours. Low temperature during this time was 51 degrees F. After 20 hours, the markers were removed from the pavement and the specific intensity of each was remeasured in the laboratory. This provided the "Post-shock" measure.

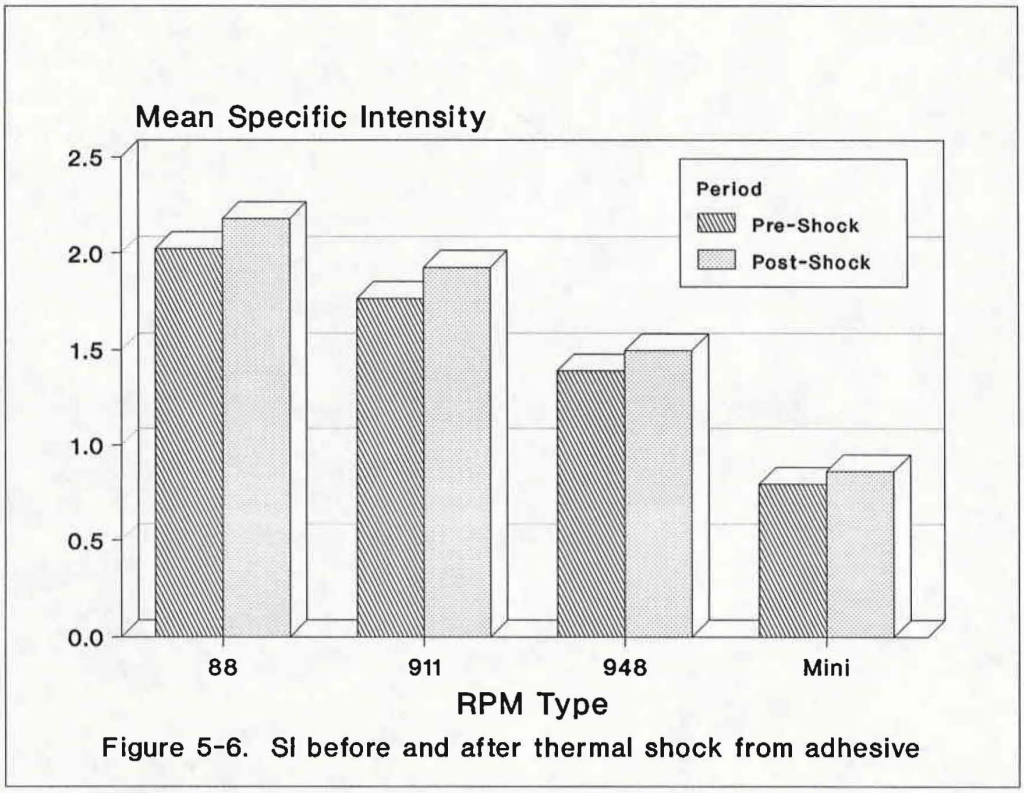


Figure 5-6. SI before and after thermal shock from adhesive

Results

The mean Pre-shock and Post-shock SI values for each RPM type are shown in Figure 5-6. These values were subjected to a repeated measures analysis of variance using the General Linear Model Procedure of SAS. Summary tables of this analysis are provided in Appendix B.

The analysis reveals significant differences among the mean SI values as a function of both period (Pre and Post) and RPM type ($p<.0001$). A small, but statistically significant increase in SI (from 1.49 to 1.62) was observed following exposure to the hot adhesive. The significant difference among RPM types was further evaluated using Tukey's Studentized Range (HSD) Test. The results of that test, summarized in Table 5-6, indicate that all four RPM types differed from one another. As expected, the larger RPMs exhibited higher SIs than the smaller, low profile RPMs. Although the interaction between period and RPM type is significant, examination of the mean SIs for each type and period reveals an increase on the order of only 7%-9% for each of the RPM types (see Table 5-7). These differences are rather small, particularly in comparison with the magnitude of differences in the percentage of change among the RPM types observed in Thermal Stress Study 1. Unlike the effect of exposure to the longer term lower temperature conditions comparable to environmental ambient temperatures, the

heat shock resulting from application of RPM adhesive does not appear to have a detrimental effect on the SI of any of the RPM types tested.

Table 5-6. Tukey's Studentized Range (HSD) Test for variable: SI

Alpha= 0.05 df= 28 MSE= 0.001817
Critical Value of Studentized Range= 3.861
Minimum Significant Difference= 0.0412

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	TYPE
A	2.1012	16	88
B	1.8455	16	911
C	1.4438	16	948
D	0.8306	16	mini

Table 5-7. Specific intensity as a function of RPM type and period.

Type	Period	N	Mean SI	% Change From Pre to Post
88	pre	8	2.024	
88	post	8	2.179	7.66
911	pre	8	1.765	
911	post	8	1.926	9.12
948	pre	8	1.391	
948	post	8	1.497	7.62
Mini	pre	8	0.797	
Mini	post	8	0.864	8.41

Abrasion Studies

Newly installed retroreflective raised pavement markers (RPMs) provide reflection of vehicle headlamps at night far in excess of the visual detection thresholds of virtually all drivers under nearly all ambient conditions. Pavement marker retroreflectivity, however, has been observed to decline very rapidly. In some cases, as shown previously in Figure 5-1, RPM retroreflectivity falls to less than 20 percent of its initial value in as short as six months. While a number of factors contribute to the decline in RPM effectiveness, physical damage to both the clear protective surfaces of RPMs and to the retroreflective elements themselves appears to be a primary causative factor. A major source of this damage is repeated impacts by the tires of passing vehicles. Tires may break or chip reflectors and scratch the clear RPM surface. This abrasion is likely accelerated in areas where especially high concentrations of dirt, dust, and sand are commonly found in the highway environment.

Considerable anecdotal evidence has been offered concerning the relative merits of different types of RPMs in resisting physical damage. Two studies were undertaken to provide more objective information about the endurance of RPMs when subjected to physical abuse under controlled and repeatable conditions. In the first, RPMs were subjected to abrasion in the laboratory using a device that applies an abrasive material to the reflective surface of RPMs under constant pressure. The second study evaluated the effects of vehicle tire impacts on RPMs under controlled closed-course conditions.

Abrasion Study 1: Laboratory Abrasion of RPMs

In order to isolate the influence of abrasion on RPM reflectivity, whether resulting from environmental dirt, dust, sand, impacts from vehicle tires, or a combination of these factors, from other sources of RPM degradation, a laboratory test was devised that subjected RPMs to constant, controlled amounts of abrasion. This test used a specially designed "Abrasion Box" to expose RPMs to an abrasive surface with constant pressure.

Abrasion Box Design

A wooden box with fixtures that support and hold most varieties of retroreflective pavement markers was constructed. The **RPM holder** was constructed such that an RPM's reflective surface is positioned normal to the horizontal plane of the box. The **abrading element** consists of a free-floating block wrapped with foam padding that is covered with garnet cloth. The padding allows the abrasive garnet cloth to conform to any RPM surface irregularities, permitting optimal uniformity of abrasion. A lead weight is fixed on the top of the floating block. The entire abrading element is contained in a **sliding shelf** that allows movement of the abrading