

element over the specimen RPM. The abrading element and the complete abrasion box are shown in Figures 5-7 and 5-8, respectively.

Abrasion Procedure

The standard procedure for the abrasion of the pavement markers was as follows. The specific intensity of the specimen RPM is determined in the laboratory. It is then placed in the appropriate fixture in the abrasion box. A lead weight is placed on the abrading element such that a pressure of 1.25 psi is applied to the RPM. Because the retroreflective surfaces of different RPMs vary in area, different weights are needed to exert the standard 1.25 psi.

Once in place, the reflector is ready to be abraded. The shelf, containing the abrading element, is slid over the RPM. This constitutes one pass. Abraded RPM material collected in the garnet cloth is blown out every 5 passes for glass-faced RPMs and every 3 passes for plastic-faced markers. New garnet cloth is used for each test specimen.

After each pass for plastic and every 5 passes for glass RPMs, the reflector is removed, brushed lightly with a clean cloth, and then measured again to determine its SI. Typically, the procedure is repeated until the RPM's specific intensity is less than 5% of its original value.

Typical Results

Although numerous RPM samples have been abraded in the fixture described above, data from a single set of RPMs so abraded will serve to illustrate the typical findings.

Figure 5-9 depicts the change in SI of two glass-faced Model 911 RPMs and three plastic-faced Model 88s as a function of the number of abrader passes to which they were subjected. The SI of all three 88s was reduced to less than 0.5 by fewer than 20 abrader passes. In contrast, 20 passes produced some, but much less, SI decline in the 911s. Additional passes, in one case up to 100, resulted in no further decrement. The differences between plastic- and glass-faced RPMs in the laboratory abrasion test is illustrated further by inspection of Figures 5-10 and 5-11. These figures are photomicrographs of a Model 88 and Model 911 marker, respectively, after 10 abrasion passes. Comparison of the two pictures indicates the greater severity of the scratches on the Model 88 and, consequently, the greater masking of the cube corner reflective elements. In general, reflectors with plastic faces required only about 1/10 the number of abrading passes of their glass-faced counterparts to produce equivalent SIs. The Ray-O-Lite Mini markers, which have a plastic face the manufacturer describes as "hardened," proved slightly more resistant to abrasion than the other plastic-faced markers.

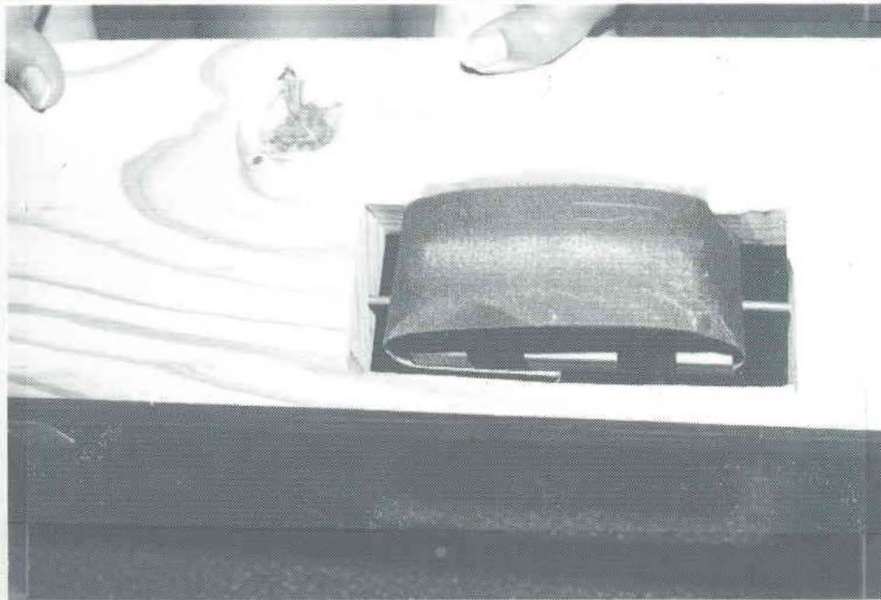


Figure 5-7. Photograph of abrading element of laboratory abrasion box.

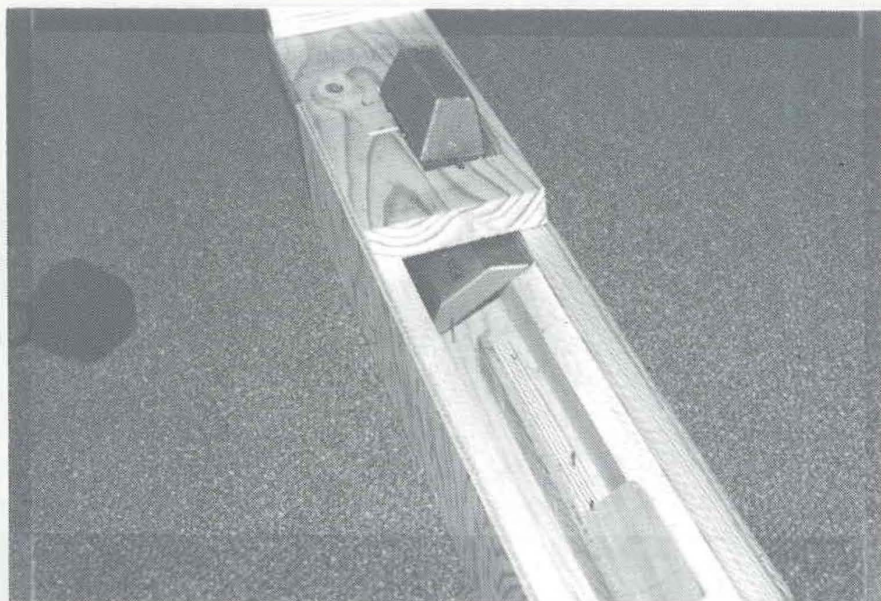


Figure 5-8. Photograph of laboratory RPM abrasion box.

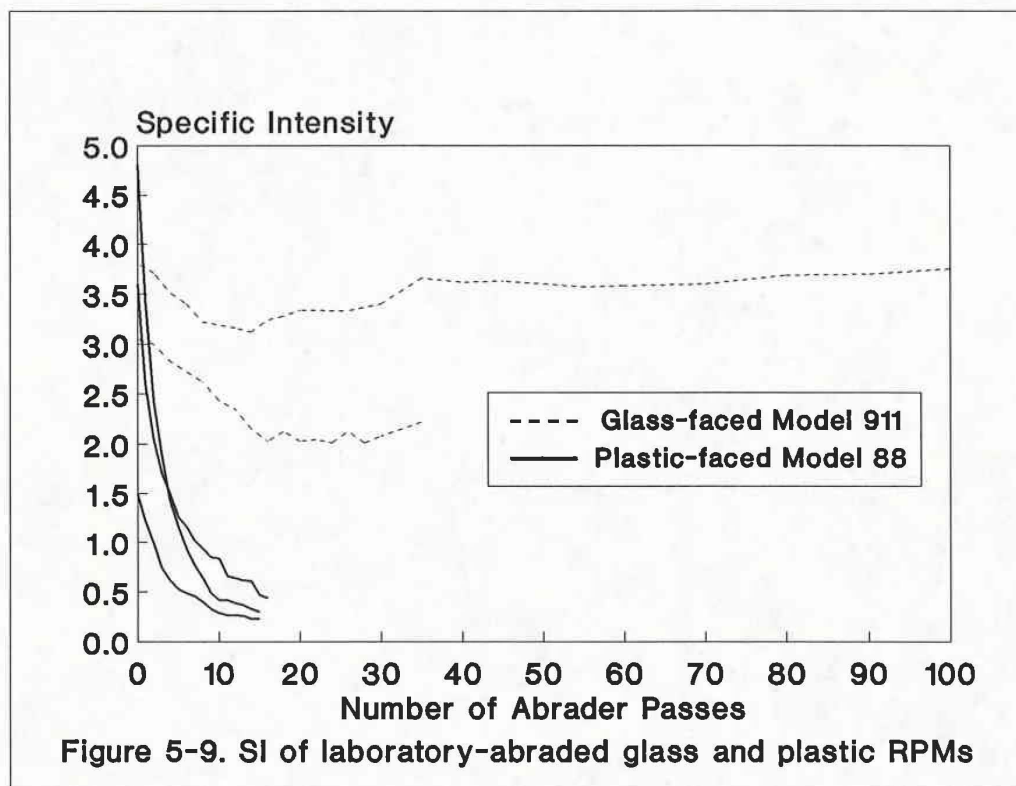




Figure 5-10. Photomicrograph of a plastic-faced Model 88 RPM subjected to 10 abrader passes.



Figure 5-11. Photomicrograph of a glass-faced Model 911 RPM subjected to 10 abrader passes.

Abrasion Study 2: The Effect of Tire Impacts on RPM Photometric Performance

This study was designed to provide information about the endurance of RPMs when subjected to physical abuse sustained from repeated tire impacts under controlled and repeatable simulated highway conditions.

Method

Test Specimens. A total of 28 RPMs (providing 56 retroreflective surfaces) were installed on an asphalt road surface on the runway complex at the Texas A&M Riverside Campus. The RPMs were applied by Texas SDHPT personnel using the hot-mixed bituminous adhesive typically used for RPM installation. Five or six new RPMs of each of five models were installed. The number and pertinent characteristics of the test specimens are provided in Table 5-8. The primary distinctions among the various RPM models tested lies in size, 2 x 4 inch low profile vs 4 x 4 inch RPMs, and in the exposed material on the marker face, acrylic vs glass.

Test Procedure. The specific intensity (SI) of each test RPM was determined in the laboratory before installation and on the test pavement before and after being subjected to tire impacts. Photometric measurements obtained after installation were accomplished using the Infrared Field Measurement Device (IRFMD), described in Section 3, that was developed as part of the RPM project.

Each test marker face was exposed to a total of 4400 tire impacts. Tire impacts were provided by driving a 1979 Pontiac Grand Am back and forth over the line of RPMs a total of 1100 round trips at approximately 40 mph. The test vehicle was equipped with steel belted radial tires maintained at the manufacturer's recommended pressure.

Table 5-8. Tire impact study test RPMs.

Number*	Manufacturer	Model	Size	Surface Material
6	Ray-O-Lite	28	4x4 in	Methyl Methacrylate
6	Stimsonite	88	4x4 in	Methyl Methacrylate
5	Stimsonite	911	4x4 in	Untempered Glass
5	Ray-O-Lite	Mini	2x4 in	Methyl Methacrylate
6	Stimsonite	948	2x4 in	Untempered Glass

*Each RPM has two retroreflective faces.

The test pavement and tire treads were kept relatively free, compared to actual highway conditions, of dirt, sand and small pebbles or other debris that might tend to accelerate RPM wear for the first 3600 impacts (900 vehicle passes). After 3600 tire impacts, an equal amount of dry blasting sand was poured over each RPM after every 50 vehicle passes to intentionally accelerate wear. Following a total of 3800 impacts, the sand was dampened, further increasing the abrasion introduced by tire impacts. All test RPMs were exposed to the same environmental conditions over the 5-month duration of the study, i.e., mostly hot, humid, sunny days, with occasional but infrequent exposure to rain.

The specific intensity of each reflective surface was measured after 1200, 2400, 3600, 3800, 4200, and 4400 tire impacts. Immediately before each SI measurement, the RPMs' reflective surface was cleaned with a commercial glass cleaner and a soft cloth to remove accumulated surface dirt. Periodic visual inspections of the markers were made and photographs were taken in addition to the photometric measurements.

Results

Photometric Measurements. Comparisons in durability among the RPM models were made on two measures: the absolute SI after tire impacts and the percent change in SI as a function of impacts. RPMs differ substantially in initial specific intensity, due both to individual marker differences and, especially, to the different retroreflective surface areas provided by standard and low profile markers. The percent change measure provides a convenient way to directly compare markers with different original characteristics. At the same time, analysis of absolute SI provides the opportunity to examine marker brightness in relation to threshold levels necessary for visibility on the highway. Both independent variables were analyzed by means of a series of analyses of variance (ANOVAs) to determine the influence of the number of tire impacts and type of RPM on marker durability. Although the number of tire impacts appears to be a continuous variable (from 0 to 4400 impacts), it is treated in the analyses as a discrete variable because of the intermittent addition of sand to the RPMs. Summary tables for all statistical analyses are provided in Appendix B as Tables B-4 and B-5.

The first analysis was conducted to determine the overall effect of tire impacts and RPM type on changes in SI. Originally, it was intended that the baseline for defining change in SI would be the pre-impact SI of each test RPM. Due to problems encountered with the field measurement system, the initial SI measurements were neither sufficiently valid nor reliable. The baseline for all comparisons, therefore, is RPM SI after 1200 impacts (300 vehicle passes). The percent SI change data were subjected to a 5(RPM type) x 6(level of impacts) repeated measures ANOVA using the General Linear Models Procedure of SAS (SAS Institute, 1988). The

results of this analysis reveal a statistically significant effect on the percent change in SI after tire impacts as a function of both the number of impacts, $F(5,255) = 438.43$, $p < .0001$, and RPM type, $F(4,51) = 17.82$, $p < .0001$. The interaction between number of impacts and RPM type is also significant, $F(20,255) = 21.82$, $p < .0001$. This analysis indicates that the effect of tire impacts on the change in reflectivity of RPMs is dependent on both the number of impacts and RPM type.

Table 5-9 shows the average percent change in SI following the six levels of tire impacts, without regard to RPM type. Several points of interest are apparent in this table. First, overall reflectivity increased about 6% after 2400 impacts. This increase could be real, resulting from an initial polishing effect of the tires on the clean, new RPM faces. More likely, this apparent increase is an artifact arising from the inherent variability in the measurement of SI with the Infrared Field Measurement Device which was undergoing design modifications at the time these measurements were taken. Second, although statistically significant changes were observed through the first 3800 impacts, these changes are of little practical significance. Not until 4000 impacts did the average SI decrease to a point where subjective differences in visibility may be observed. It will be recalled that this point coincides with the addition of damp sand to the roadway to accelerate degradation.

The differential effect of tire impacts on different RPM types is shown in Table 5-10. Averaged over all levels of impacts, the RPM models tested all performed significantly different from each other. Notable in this table is the distinct difference observed between the two glass-faced RPM models and the three acrylic-faced markers. Also notable is the comparison within like-faced RPMs. Of the two glass-faced RPMs, the low profile 948 was less affected by tire impacts than the standard sized 911. Similarly, among the plastic-faced markers, the smaller "Mini" proved more durable than the two standard size markers.

Table 5-9. Average percent change in SI over all RPM models as a function of number of tire impacts (referenced to SI after 1200 impacts).

Impacts:	2400	3800	3600	4000	4200	4400
Mean % Change:	6.4	-3.7	-4.9	-28.7	-57.7	-61.4

Means underscored by a common line are not significantly different, $p > .05$.

Table 5-10. Average percent change in SI over all tire impacts as a function of RPM model.

Model:	(Glass face)		(Plastic face)		
	948	911	Mini	28	88
Mean % Change:	-6.6	-13.2	-29.9	-33.4	-40.6

The differences in marker durability discussed to this point have been all been relative to the markers' initial SI (to be precise, relative to SI after 1200 impacts). In order to assess the influence of tire impacts on the absolute SI of each marker type, an additional ANOVA was performed. In this analysis, the measure of RPM performance was absolute SI rather than change in SI. The results of this analysis again reveal significant differences due to the number of impacts, RPM type, and the interaction between these two variables.

The overall influence of the number of tire impacts on absolute SI is essentially the same as that for the percent change measure. That is, statistically significant, but small, reductions in SI are observed through the first 3800 impacts. Larger effects are evident after 4000 impacts (and the introduction of damp sand to the roadway). Substantial decrements in brightness are seen by 4200 impacts. Comparisons among the impact levels are shown in Table 5-11.

Averaged over all levels of impact, the mean SI of the standard size markers is greater than that of the low profile RPMs. For both standard (4 x 4 in) and low profile (2 x 4 in) markers, the glass-faced markers exhibit higher specific intensities than the plastic markers when exposed to tire impacts. These comparisons are evident in Table 5-12.

Table 5-11. Average SI over all RPM models as a function of number of tire impacts.

Impacts:	2400	1200	3800	3600	4000	4200	4400
Mean SI:	2.31	2.22	2.10	2.10	1.51	0.85	0.76

Means underscored by a common line are not significantly different, $p > .05$.

Table 5-12. Average SI over all tire impacts as a function of RPM model.

Model:	(4x4 in RPMs)			(2x4 in RPMs)	
	911	88	28	948	Mini
Mean SI:	2.37	1.95	1.80	1.24	1.12

Both analyses reported thus far reveal significant interactions between RPM type and number of impacts. These interactions are depicted graphically in Figures 5-12 and 5-13 for percent change and absolute SI, respectively. Evident in these figures is the differential effect of the level of tire impacts depending on RPM type.

Inspection of Figure 5-12 suggests that when RPMs are exposed to a relatively small number of tire impacts under clean roadway conditions, none of the RPM types tested changed very much. As the number of impacts increased, and the road conditions were made more conducive to abrasion by the introduction of sand, distinct differences are apparent as a function of RPM type. Specifically, performance of the glass-faced RPMs deteriorated at a much slower rate than the performance of the plastic-faced markers.

Figure 5-13 shows the effect of tire impacts on absolute SI as a function of RPM type. Initially, all of the 4 x 4 inch markers are brighter than the low profile 2 x 4 inch RPMs, irrespective of surface material. As the number of tire impacts and abrasiveness of the environment increase, however, the absolute brightness of the plastic markers decreases to a significantly lower level than that of the glass markers, regardless of size. This effect is most notable in the performance of the plastic Model 88 and the glass Model 948 markers. Early in the testing process, the 88s averaged the highest SI. At the end of testing, the 88s exhibited the poorest performance. This is contrasted with the 948s which were initially the least bright RPMs. Because they deteriorated less than any other RPM type, the average absolute SI of the 948s was second only to the Model 911s at the end of testing.

Visual and Photographic Inspection. In addition to the photometric measurements discussed above, the test RPMs were inspected and photographed periodically throughout the test period. Photomicrographs (40x) taken after testing was completed provided for closer examination of the RPM reflective surfaces.

Differences in the deterioration of the test RPMs resulting from repeated tire impacts was visually apparent for the various RPM types. In general, the plastic-faced RPMs evidenced a more

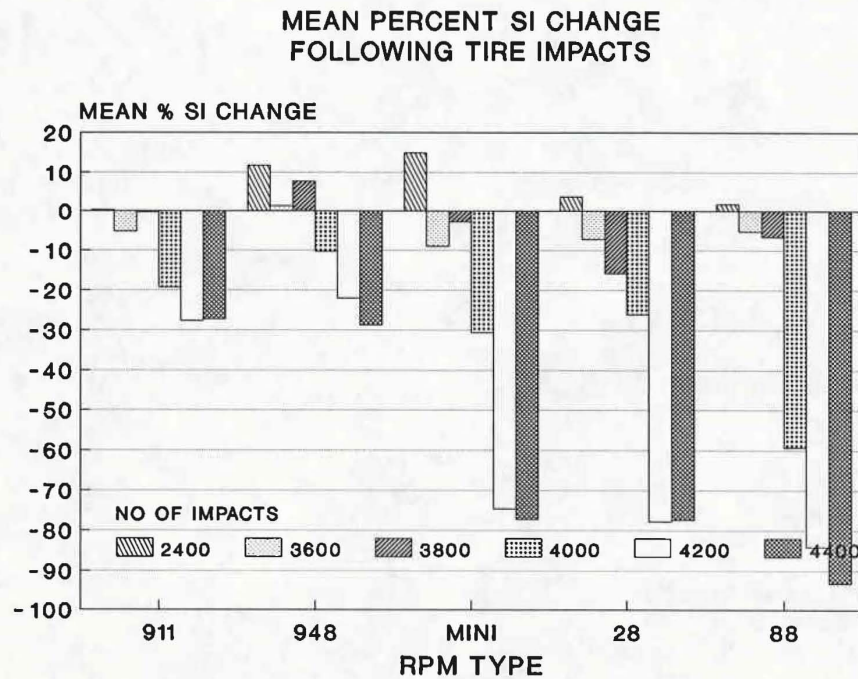


Fig. 5-12. SI % change as a function of RPM type and impacts

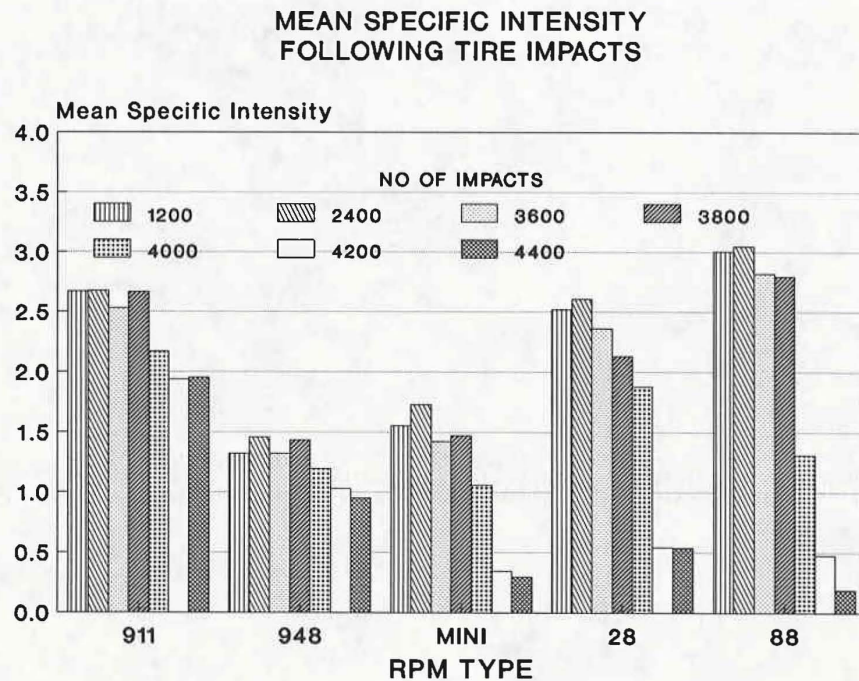


Figure 5-13. SI as a function of RPM type and impacts

uniform wear pattern than the glass markers. Under close examination with the unaided eye, this wear took on the appearance of a slight haze over the reflective surface. As illustrated in Figure 5-14, however, most of the plastic markers did not appear to be damaged to a great extent after 4400 impacts. Examination of the 40 power photomicrographs of the plastic RPMs reveals innumerable small scratches in an essentially random pattern. This abrasion pattern is evident in Figure 5-15. It is this abundance of scratches which result in the generally poor photometric performance of the plastic RPMs after repeated tire impacts.

Unlike the plastic RPMs, the glass markers reveal more obvious physical damage to the naked eye. Typically, pitting, chipping or cracking of the glass superstrate is evident along the top margin of the glass. This phenomenon, shown in Figure 5-16, is much more pronounced on the 4 x 4 inch Model 911 markers than on the low profile 948s. In addition, on a few of the larger glass markers, small pieces of the glass face were completely missing after testing. Viewed under 40 power magnification, the glass markers showed some evidence of the small scratches typical of the plastic-faced RPMs, but at a clearly much lower frequency. A typical photomicrograph of a glass RPM is provided as Figure 5-17. Whereas the scratches on the plastic faces were often sufficient to obscure the cube corner substrate, this was not the case with the glass markers.

CONCLUSIONS

Although glass markers evidenced more easily visible damage from tire impacts, the SI of these markers was shown to be better maintained under the accelerated wear conditions of the present endurance tests than that of plastic-faced RPMs. Larger RPMs, regardless of surface material, are initially brighter than smaller markers. Among the plastic RPMs tested, the superiority of the 4x4 RPMs was no longer evident at the conclusion of testing. Of the two glass-faced models, the larger markers remained significantly brighter than the low profile RPMs throughout testing. The average SI of the smaller markers, however, remained at an acceptable level throughout testing. In addition, these markers maintained a larger proportion of their new SI than did the larger markers.

The Standard Specifications (SDHPT, 1982) refer to Specification D-9-4200 for RPMs, which in turn invokes Test Method Tex-430-A "Method for Testing the Impact Resistance of Pavement Markers," as the sole test of durability of these devices. This is a test in which a 200 lb steel ball is dropped on a rubber-padded RPM from a height of 5 feet. All markers currently bought by SDHPT meet this specification. Based on the impact tests (using a motor vehicle) conducted in this research, no changes to Tex-430-A are indicated. The Department might consider an abrasion test patterned on the laboratory method described above to evaluate the other aspect of durability, wear and tear. The abrasion box is very

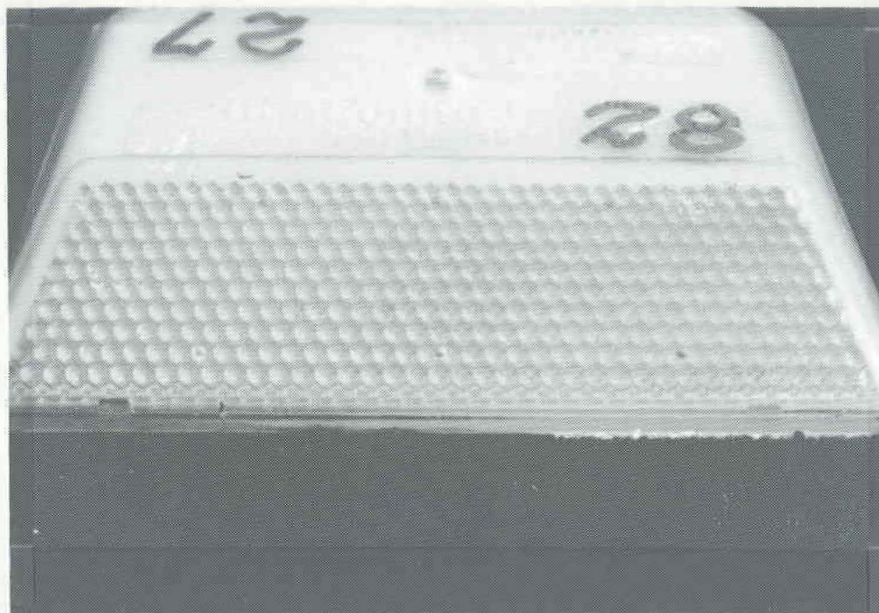


Figure 5-14. Photograph of plastic-faced Model 88 RPM (ID# 28) after 4400 tire impacts.

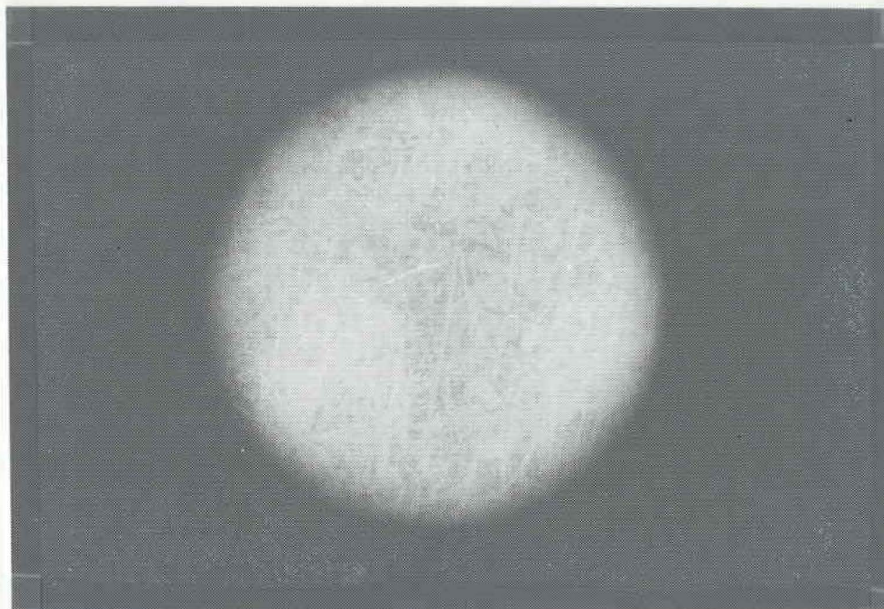


Figure 5-15. Photomicrograph of plastic-faced Model 88 RPM (ID# 28) after 4400 tire impacts.

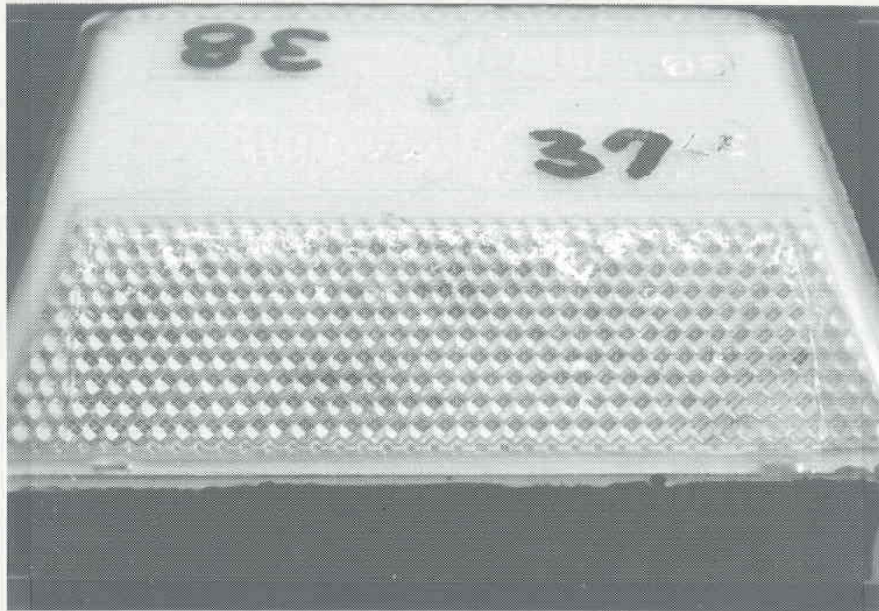


Figure 5-16. Photograph of glass-faced Model 911 RPM (ID# 37) after 4400 tire impacts.



Figure 5-17. Photomicrograph of glass-faced Model 911 RPM (ID# 37) after 4400 tire impacts.

simple to make. Alternatively, the actual run-over test protocol could be adopted for a durability test. The latter test, however, is labor-intensive, and probably not practicable on a continuing inspection basis.

Based on the results of the present testing, it is reasonable to expect that under actual highway conditions, glass-faced RPMs will experience less change in photometric performance and subsequently less subjective loss of brightness over extended exposure to tire impacts than like-sized plastic markers. Differences will be especially pronounced where the environment is particularly dusty or sandy and at RPM installations especially prone to tire impact. These likely include installations on high volume roadway segments with horizontal curves, passing zones, and narrow lane width highways.

6. FEASIBILITY OF RPM RESTORATION

It has been shown that cleaning the accumulated dirt and road grime from the reflective surfaces of RPMs significantly improves their specific intensity. It has been further demonstrated that abraded RPMs, particularly plastic-faced markers, exhibit higher SIs when they are wet than when they are dry (see, for example, Figure 5-2). Presumably, water serves to fill the myriad small scratches and, at least partially and temporarily, restore the integrity of the surface. Discussions of this phenomenon among project staff led to attempts to more permanently restore the surface of damaged RPMs.

To this end, selected abraded RPMs that were used in the study of the effects of tire impacts on RPM photometric performance (reported in Section 5) were treated with a clear acrylic spray. Both plastic- and glass-faced markers were treated. The initial results of the informal experimentation with the degraded markers were sufficiently promising to warrant additional, more controlled, study of the feasibility of restoring the reflectivity of plastic-faced RPMs.

Method

Eight Model 88 RPMs were selected at random from our stock of pavement markers to serve as test specimens. The specific intensity of both reflective faces of each marker was measured using the standard method described elsewhere. One face was selected at random from each marker to be the test specimen. The selected face was abraded using garnet cloth until the SI was less than 10% of its original value. At this point, the markers were divided into two treatment groups. One group was treated by spraying the abraded face with a clear acrylic (Krylon, No.1303, Crystal Clear). The other group was treated by coating the face with a clear epoxy (Hardman, Double/Bubble, No. 04001).

Treatment of the "acrylic" group was accomplished by spraying the abraded face from a distance of 3 to 5 inches until the surface was completely coated and the coating just began to puddle. The epoxy used on the second group was a two-part epoxy. After thoroughly mixing the resin and hardener, the mixture was applied to the surface of the test RPMs with a 3 x 5 inch index card until smooth.

A discussion with a technical representative of Borden, Inc., manufacturer of Krylon brand spray coatings, suggested that the acrylic spray coating would deteriorate rapidly in the face of moisture. If RPM restoration is to be practical, it is necessary that any improvements in SI realized from the treatments can be maintained in the operational environment. Therefore, two brief tests of the durability of the restored RPMs were undertaken.

Following restoration, all test specimens were subjected to 14 days of weather and then to a series of tire impacts.

During the weathering period, conducted in December, RPMs were subjected to both freezing temperatures and rain. Air temperature ranged from a low of 2 degrees F to a high of 73 degrees. Measurable rainfall occurred on 5 days of the 14-day test.

For the tire impact test, the RPMs were installed on the same pavement surface used in the previously reported impact test. This test comprised 400 impacts under the same conditions as the "clean" impacts of the earlier test.

The SI of each marker was determined in the laboratory when new and after each experimental treatment, providing a total of five SI evaluations of each RPM as follows:

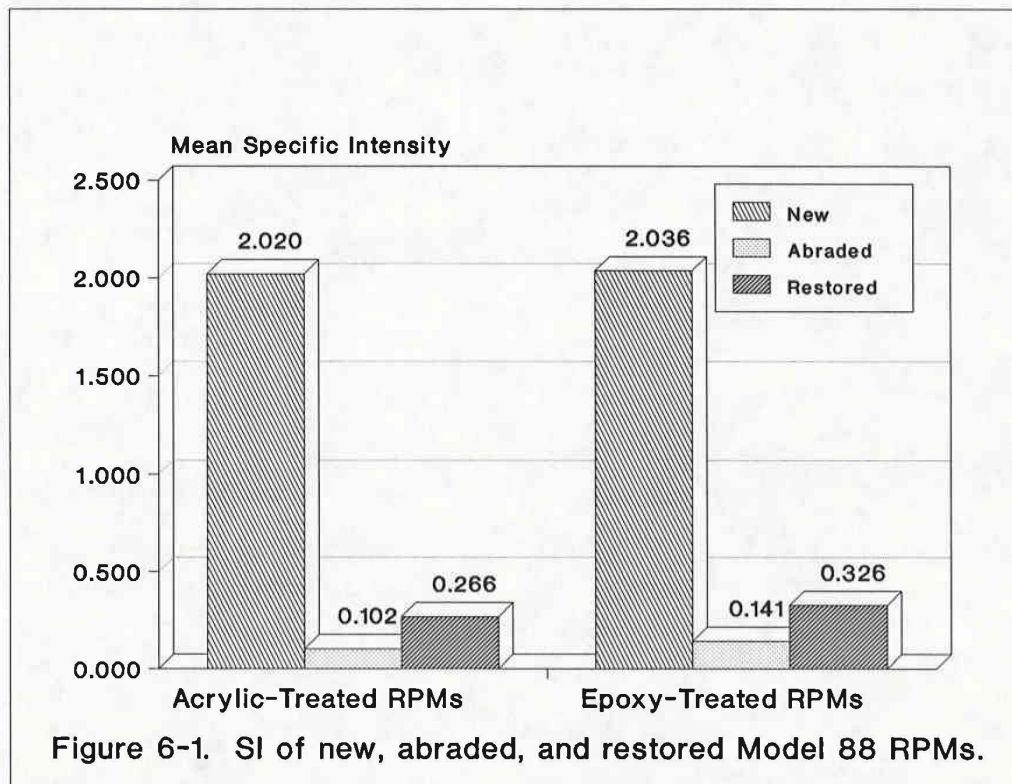
1. New
2. After abrasion
3. After restoration treatment (acrylic or epoxy)
4. After weathering
5. After tire impacts

Results and Discussion

The average SI of the "acrylic" and "epoxy" RPM groups for each evaluation period are provided in Table 6-1. Also indicated in the table is the average percent of the new SI value obtained at each measurement. The average SI of the abraded faces is on the order of 5% of the original value. After restoration, both the acrylic and epoxy treated RPMs showed improvement in SI. The small difference between the two restoration materials is not statistically significant ($t = .702$, $df=6$, $p > .51$). Restoration, by either method, more than doubled the SI of the markers. On a percentage basis, this is an impressive improvement. In absolute terms, however, the average SI of all restored markers was only 0.296. Figure 6-1 depicts the average change in SI from new-to-

Table 6-1. Mean specific intensity of restoration test RPMs.

Measurement Period	"Acrylic"		"Epoxy"	
	Mean SI	% Of New	Mean SI	% Of New
New	2.020	-	2.036	-
After abrasion	0.102	5.0	0.141	6.9
After restoration	0.266	13.2	0.326	16.0
After weathering	0.248	12.3	0.280	13.8
After tire impacts	0.282	14.0	0.278	13.7



abraded-to-restored. As is evident in Figure 6-1, although both restoration methods resulted in greater than 100% improvement in the SI of severely degraded markers, the restored RPMs exhibited specific intensities of only about 15 percent of their original new values.

The limited weathering and tire impact tests conducted with the restored RPMs produced little change in marker brightness. The minor differences, apparent in Table 6-1 and Figure 6-2, between the restored SI values and those values after weathering and tire impacts, suggests restored RPMs could withstand at least short-term exposure to operating conditions.

The present restoration study was not exhaustive in either the materials used or application techniques. Nor did this effort consider the cost-effectiveness of restoration. It is conceivable that other coating materials or application methods might provide a higher degree of rejuvenation. Any additional efforts in that regard should consider methods that can be adapted to mass application of the restorative to in-service RPMs. If an effective material is found that can be applied practically, a cost-effectiveness study must be undertaken to assure that the costs associated with restoration do not exceed the costs of purchasing and installing replacement markers.

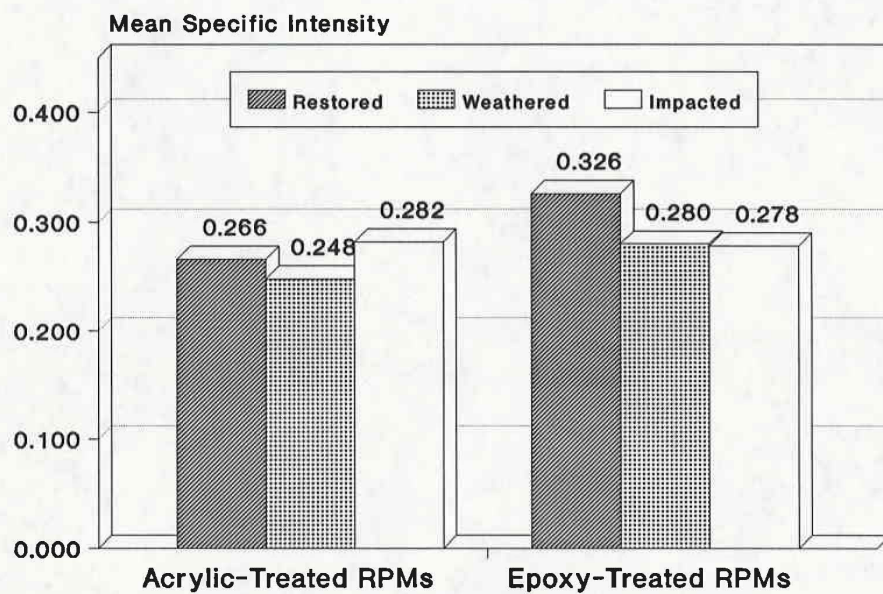


Figure 6-2. SI of weathered and tire impacted restored RPMs

7. RAISED RETROREFLECTIVE PAVEMENT MARKER PURCHASING TRENDS IN OTHER STATES

In response to a query from the project technical monitor, an informal telephone survey of other state practices and experience with retroreflective raised pavement markers was conducted. After some preliminary study, three states with similar climates to Texas and with flexibility in purchasing practices were contacted. These states were California, Florida, and Georgia.

California

The contact in California was Mr. Earl Shirley, chief of the Division of New Technology and Research for CalDOT. Except for the High Sierras and other locations in which snow clearance is a big factor, all parts of California use glass-faced Stimsonite RPMs. In the past these have been Model 911 units, but practice in recent years has been to purchase nothing but the low profile Model 948. California has had problems with RPM adhesives in the past, but not since moving to bituminous compounds. TTI research (Tielking and Noel, 1988) was instrumental in making the switch to these adhesives. The 948s have performed very well for CalDOT, according to Mr. Shirley.

Florida

Mr. Charles Peoples and Dr. Raymer of the Materials and Research Engineer Office in Gainesville were the contacts. Florida is very eclectic in their purchase of retroreflective RPMs. They buy Stimsonite Model 88 plastic-faced units for "temporary" use on surfaces that will soon be resurfaced. They also buy Ray-O-Lite Model 28 RPMs for similar usage. Florida refers to such devices as Class A. The preference is to use the more expensive but much more long-lived glass-faced Stimsonite Model 911 and 948, which Florida designates Class B. Florida experienced some problems in 1988 with 911 markers breaking up or cracking after a short period of use, due, apparently, to a quality control problem in Stimsonite, but have had no trouble recently. Model 911 predominates in installations in Florida, with 948s a close second. Some Caliguide octagonal units are also used in certain applications with good results. Like California, the change to bituminous adhesives (especially for 948s) has alleviated the marker loss problem.

Georgia

Mr. Gerry Gossett of the Materials and Research Division of Georgia Highways reported that his state uses Stimsonite Model 948 exclusively. In 1989 Georgia will have over 2 million in service, with an annual replacement ratio of 1:4 (500,000 per year). Georgia has tested a number of other devices and settled on the Model 948, which they consider to have an average life of 2 years. Georgia uses a method of measuring SI which was devised by

Stimsonite. The method involves a 10-foot tube and 0 degree entrance angle. The measure thus made may or may not be equivalent to the ASTM or SAE method. Using their method, Georgia considers an RPM to be below an acceptable range when its SI is less than 0.5 candela per incident foot-candle, a very conservative criterion. They have had no problems with the 948s since turning to bituminous adhesives for installation, with 98 percent retention on asphalt and 95 percent on concrete road surfaces.

8. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Measurement Technologies

1. Established procedures for measurement of the specific intensity of small, effectively point source, retroreflectors found in both Society of Automotive Engineers and American Society for Testing and Materials recommended practices yield measurements that are at variance with State Department of Highways and Public Transportation Test Method Tex 842-B by a factor of π (3.1416). Other states have different measurement procedures, derived from manufacturer recommendations, which also yield different results. Although States use different methods for measuring the retro-reflectivity of raised pavement markers, two national standards exist: ASTM E 809-81 Standard Practice for Measuring Photometric Characteristics of Retroreflectors and SAE Standard J594f - Reflex Reflectors.

2. A method for measuring raised pavement marker retro-reflectivity in place, i.e., installed on the highway, was developed. This vehicle-installed system uses an externally mounted infrared source and receiver, with an in-vehicle logic circuit, display and recorder. The system can be used at highway speeds, but as currently configured requires running the vehicle tires over the RPMs measured to assure accurate aiming. Multiple passes over a string of markers are necessary to assure accuracy of measurement. The system records directly in specific intensity.

Driver Visual Thresholds

1. There is no one value for minimum specific intensity that can be specified independent of required sight distance, roadway geometrics and traffic conditions. A marker which may be perfectly visible on a dark night on a highway without opposing traffic headlamps may become completely invisible to even the youngest, keenest-sighted driver under urban conditions with a lot of glare. Older drivers may have great difficulty seeing even brand new RPMs under seeing conditions they routinely encounter in city traffic. Sight distances also differ for amber, red, and crystal retroreflectors. Threshold detection of amber RPMs (as a point of light, not necessarily identifiable as amber per se) requires lower specific intensity than either red or crystal. Tabled values of threshold SI for various conditions of weather, sight distance, and opposing traffic provide RPM SI levels at which replacement should be considered.

2. From a driver perception standpoint, it makes no difference whether an RPM is damaged, but the remaining part is still retroreflective, or an RPM is intact, but its surface

8. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

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Driver Visual Thresholds

1. There is no one value for minimum specific intensity that can be specified independent of required sight distance, roadway geometrics and traffic conditions. A marker which may be perfectly visible on a dark night on a highway without opposing traffic headlamps may become completely invisible to even the youngest, keenest-sighted driver under urban conditions with a lot of glare. Older drivers may have great difficulty seeing even brand new RPMs under seeing conditions they routinely encounter in city traffic. Sight distances also differ for amber, red, and crystal retroreflectors. Threshold detection of amber RPMs (as a point of light, not necessarily identifiable as amber per se) requires lower specific intensity than either red or crystal. Tabled values of threshold SI for various conditions of weather, sight distance, and opposing traffic provide RPM SI levels at which replacement should be considered.

2. From a driver perception standpoint, it makes no difference whether an RPM is damaged, but the remaining part is still retroreflective, or an RPM is intact, but its surface

degraded, if the light delivered to the eyes is the same. Just because an RPM face is damaged, it does not necessarily have to be replaced. The SI may still be within acceptable limits. However, if breakage extends through the plastic prism layer to the aluminum coating, moisture will probably detach or corrode the coating. Such an RPM will soon lose all retroreflectivity and should be replaced.

Raised Pavement Marker Durability

1. Studies of otherwise comparable glass- and plastic-faced RPMs removed from service after known amounts of exposure to highway conditions show a significant superiority in remaining SI for glass-faced RPMs.

2. Although abraded plastic-faced RPMs improve in SI when they are wet, they only do so if they are reasonably clean. Abraded RPMs improve much less under wet conditions if they are dirty.

3. Although heat/cold thermal cycling such as that encountered in many Districts on highways affects the retroreflectivity of both glass-faced and plastic only RPMs, glass-faced RPMs tend to improve by a significant margin, as much as 34% after being subjected to elevated temperatures, while plastic-faced RPMs decline somewhat under temperature stress. No explanation for this behavior was provided by RPM manufacturers, who have also noted this phenomenon. The thermal shock that each RPM is subjected to on being installed using 340 to 370 degree F bituminous mastic was not found to have significant detrimental effects on any of the RPMs that the Texas SDHPT is currently installing on Texas highways.

4. In both laboratory tests and in controlled access field tests in which all the different RPMs currently purchased by SDHPT were subjected to run-over by a test vehicle, glass-faced RPMs were far superior to plastic-faced RPMs. Whereas 10 passes of a weighted garnet cloth abrader would effectively eliminate the retroreflective performance of any plastic-faced RPM, as many as 100 passes on glass-faced RPMs produced very little degradation. These results were replicated with an actual vehicle in the run-over tests. The tests conducted indicate the most durable RPM now being purchased by SDHPT is the Model 948 Stimsonite RPM.

5. On plastic-faced RPMs subjected to abrasion, myriads of scratches in the outer surface scatter light rather than transmit it directly to the reflective cube-corner prism array immediately underneath. The greatly reduced light that does get to the reflective surfaces is scattered yet again as it leaves the retroreflector through the scratched outer surface. Glass-faced reflectors are far more abrasion-resistant. If the thin glass layer is shattered, then scatter is greater than with an abraded

plastic-faced RPM. Plastic-faced RPMs degrade rather quickly after they are installed to some low asymptotic level, and then unless they are broken, decline rather slowly thereafter. Glass-faced RPMs stay bright unless they are damaged in such a way that the glass face shatters all over the reflective surface but stays in place. Under those conditions, they "go out" abruptly. If the glass face cracks away, then the plastic face directly underneath acts just like an originally all-plastic RPM. A glass-faced RPM may have several broken or chipped areas on it and in day-light look much more damaged than a plastic-faced RPM installed near it, but may well perform much better as a retroreflective device.

Feasibility of RPM Restoration

1. Since clean but abraded plastic-faced RPMs can be temporarily restored to some of their original retroreflective performance by wetting the surface and thus filling in the scratches, a preliminary study was done to see if a clear coating of some kind would produce more lasting results. In such a way, degraded RPMs could be restored to some condition of use and replacement postponed under certain conditions. Restoration, using an acrylic and an epoxy coating, more than doubled the effective SI of a group of abraded plastic-faced RPMs. Tire abrasion tests and brief exposure to harsh December temperature extremes on the roof of a Texas A&M University building were encouraging.

Experience of Other States with Retroreflective RPMs

1. Three States with similar weather conditions to Texas were contacted: Florida, Georgia, and California. All reported adhesion problems which have much improved since adopting a bituminous mastic. Although some quality control problems have occurred in the past with glass-faced RPMs, all three states use them extensively if not exclusively because of their superior durability with regard to retroreflectivity.

RECOMMENDATIONS

1. The Infrared Field Measurement System developed by TTI under this project is in prototype form. A brief informational videotape on this system has been prepared and forms part of this final report. The system should be further developed into final production form and tested in at least one SDHPT district.

2. The tabled threshold information contained in Section 4 should be considered for use as a tool by the districts in deciding when to replace RPMs. Until such time as the on-road RPM measurement system is fully developed and made available, samples of RPMs suspected to be performing below an acceptable level would need to be removed from the roadway for laboratory measurement. Alternatively, a procedure could be developed in which reference RPMs with specific intensities matching the predetermined minimum

acceptable SI for particular applications are prepared. The reference RPM could then be temporarily installed adjacent to in-service RPMs which are suspected of being below acceptable SI values, thereby providing a point of reference for subjective visual comparisons. Preparation of the reference samples could be accomplished by obscuring a portion of the reflective surface of a new RPM with tape, as discussed in Section 4, pages 31 and 35. Both logistic and worker-safety concerns mitigate against routine use of such a procedure or its implementation for verifying the retroreflective performance of large numbers of individual RPMs. Rather, this approach should be considered in cases where a substantial number of RPMs appear, upon visual inspection, to be of questionable utility. Visual comparisons, using the appropriate reference RPM can then be made to verify or refute that replacement is advisable.

To simplify its use, the information tabled in Section 4 could be synthesized into a simple algorithm suitable for personal computers readily available in district offices.

3. Maintenance supervisors should be advised that just because part of an RPM face is cracked or broken, it does not necessarily mean the RPM is no longer usable. The threshold and durability studies indicated that even if more than half the surface is badly damaged, the specific intensity of the remaining portion may be sufficient to provide adequate reflectivity. This is especially true for glass-faced units.

4. Plastic-faced RPMs will work well in protected areas or for short-term installations, but otherwise will degrade rather rapidly to unacceptable levels of performance, as compared to glass-faced RPMs. For most applications, we recommend that SDHPT consider the use of glass-faced RPMs.

5. Further study of clear coatings suitable for application by maintenance crews in maintenance zones is warranted from the results obtained in this study, if SDHPT decides to continue to install large numbers of plastic-faced RPMs. Methods of application (which includes cleaning the RPMs) would also have to be developed. The cost/benefit of such an approach, and when it would be used, also needs to be studied.

6. The SDHPT has all the necessary equipment in its D-9 Laboratory to adopt the ASTM E 809-81 Standard Practice for Measuring Photometric Characteristics of Retroreflectors for measuring the retroreflectivity of raised pavement markers and other similar small devices. Tex-842-B should be updated to this procedure, or modified to reference this procedure. This will place Texas in conformance with a national standard.

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APPENDIX A

**TTI Photometric Laboratory
Raised Pavement Marker Measurement Procedure**

Basic Photometric Equipment

The Photometric Laboratory at the Riverside Campus of Texas A&M University is furnished with a Tektronix J16 Digital Photometer. The J16 Digital Photometer/Radiometer is a compact, battery- or AC-operated instrument primarily intended for calibrated measurements of the intensity of radiation over the 250 to 1200 nanometer (nm) wave-length range. This instrument is equipped with a 1 degree luminance probe, an 8 degree luminance probe, and both cosine-corrected and uncorrected illuminance probes. The illuminance and luminance probes each have a photodiode sensor with a filter to match its response to that of the C.I.E Photopic Curve. The AC power supply is used in the laboratory but the battery pack is available for portable operation. The bottom of all probes and the J16 case have a standard 1/4 - 20 mounting socket for use on optical benches or tripods. The range of measurement for the illuminance probes is 0.001 to 1,999 Foot Candles. The range of measurement for the luminance probes is 0.1 to 199,900 Foot Lamberts. The 8 degree luminance probe is usable from infinite focus to 18 inches from the front of the lens.

Test Procedure for Evaluating Raised Pavement Markers

The following procedure is used for determining the specific intensity of new retroreflective raised pavement markers. Slight modifications to this procedure are necessary to accommodate evaluation of dirty or wet RPMs.

1. The test specimens are selected from the stock of markers stored in the laboratory located at the Texas A & M University Riverside Campus. The markers are washed in warm water and mild detergent and allowed to air dry.
2. Immediately prior to testing, the faces of the RPMs are cleaned with commercial glass cleaner and a soft cloth.
3. The alignment of the measurement apparatus is checked and, if necessary, corrected prior to each session. The arrangement of the apparatus is such that the incident light beam strikes the RPM perpendicular to, and at the level of, the base of the reflecting face.
4. The Illuminance Probe (Tektronix Model J6501) of the Tektronix Photometer (Model J16) is located adjacent to, and approximately 11 inches in front of, the light source. It is positioned 3/4 inch above a line from the filament of the light source and the leading edge of the base of the test specimen. This arrangement allows an entrance angle of 0 degrees and an angle of 0.2 degrees from the RPM to the illuminance probe.
5. At this point, the lab is darkened and the J16 is calibrated.

A 180 degree Illuminance Probe (Tektronix Model J6511) is connected via the 25-foot attached cable to the main body and the probe is covered. In this condition, the calibration adjustment is manipulated such that the instrument reads zero on the lowest scale.

6. The light source is turned on. The light source is a Q-Beam Spotlight (Brinkman Model 800-1600-0) which has an intensity of approximately 300,000 Candles. The power supply for this source is a 12 Volt battery charger connected to line voltage. Illuminance at the front of the goniometer is measured by removing the cover of the J6511 probe and holding it in the position of the test specimen at the front of the goniometer. This value is recorded, in foot-candles, as Incident Illuminance (E_i). This measurement is repeated at the end of each test session and, if a large number of specimens are to be examined, approximately every 30 minutes.

7. The Illuminance Probe (Tektronix Model J6501), is now connected to the main body via an Interconnecting Cable (Tektronix Part No. 012-0414-02) and the illuminance of the empty goniometer is recorded, in foot-candles, as Ambient Illuminance (E_a). This measurement is also repeated at the end of each test session and, if a large number of specimens are to be examined, approximately every 30 minutes.

8. The goniometer has been modified to allow the placement of a moveable back plate to be placed in positions to ensure that all RPMs of each type are in exactly the same place in relation to the light source and measurement probe. The back plate is positioned for the RPM type under test and the clean, dry specimen is placed on the stage and the illuminance is measured and recorded, in foot-candles, as Probe Illuminance (E_p).

9. The values recorded, along with the dimension of the test apparatus, are used to calculate the specific intensity of the specimen RPM as follows:

$$SI = (E_r \times D^2) / E_i$$

where

SI = specific intensity

E_r = $E_p - E_a$ = Reflected Illuminance (foot-candles)

D = Distance (ft) from the RPM to Illuminance Probe (Model J6501)

Appendix B

Statistical Summary Tables

This Appendix contains summary tables for the analyses of variance conducted for several of the empirical studies reported in Section 5 of this report. Tables are provided for the following studies:

Tables B-1 and B-2.

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

Table B-3

Thermal Stress Study 2: Thermal Shock from RPM Adhesive

Table B-4 and B-5

Abrasion Study 2: The Effect of Tire Impacts on RPM Photometric Performance

Table B-1. Heat stress ANOVA summary tables.
(Section 5: Thermal Stress Study 1)

General Linear Models Procedure Class Level Information						
Class	Levels	Values				
TYPE	4	88 911 948 MINI				
CYCLE	8	1 2 3 4 5 6 7 8				
RPM	40	26A 26B 27A 27B 28A 28B 29A 29B 30A 30B 31A 31B 32A 32B				
		33A 33B 34A 34B 35A 35B 36A 36B 37A 37B 38A 38B 39A 39B				
		40A 40B 44A 44B 45A 45B 46A 46B 47A 47B 48A 48B				

Number of observations in data set = 320

General Linear Models Procedure					
Dependent Variable: % DELTA SI					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	67	177047.6415	2642.5021	164.13	0.0001
Error	252	4057.2323	16.1001		
Corrected Total	319	181104.8738			
	R-Square	C.V.	Root MSE	%DELTA SI Mean	
	0.977597	84.96692	4.012496	4.72242188	

General Linear Models Procedure					
Dependent Variable: % DELTA SI					
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TYPE	3	135218.7284	45072.9095	2799.54	0.0001
RPM(TYPE)	36	14124.1489	392.3375	24.37	0.0001
CYCLE	7	15177.4145	2168.2021	134.67	0.0001
TYPE*CYCLE	21	12527.3496	596.5405	37.05	0.0001
Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	3	135218.7284	45072.9095	2799.54	0.0001
RPM(TYPE)	36	14124.1489	392.3375	24.37	0.0001
CYCLE	7	15177.4145	2168.2021	134.67	0.0001
TYPE*CYCLE	21	12527.3496	596.5405	37.05	0.0001

General Linear Models Procedure					
Dependent Variable: % DELTA SI					
Tests of Hypotheses using the Type III MS for RPM(TYPE) as an error term					
Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	3	135218.7284	45072.9095	114.88	0.0001

Table B-2. Cold stress ANOVA summary tables.
(Section 5: Thermal Stress Study 1)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
TYPE	4	88 911 948 MINI
CYCLE	3	1 2 3
RPM	39	50A 50B 51A 51B 52A 52B 53A 53B 54A 54B 55B 56A 56B 57A 57B 58A 58B 59A 59B 60A 60B 61A 61B 62A 62B 63A 63B 64A 64B 65A 65B 66A 66B 67A 67B 68A 68B 69A 69B

Number of observations in data set = 117

NOTE: Due to missing values, only 114 observations can be used in this analysis.

Dependent Variable: %DELTA SI

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	45	25927.55363	576.16786	7.48	0.0001
Error	68	5240.53856	77.06674		
Corrected Total	113	31168.09219			
	R-Square	C.V.	Root MSE	%DELTA SI Mean	
	0.831862	172.7358	8.778767	5.08219298	

Dependent Variable: %DELTA SI

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TYPE	3	2069.01122	689.67041	8.95	0.0001
RPM(TYPE)	34	18994.08028	558.64942	7.25	0.0001
CYCLE	2	2158.15368	1079.07684	14.00	0.0001
TYPE*CYCLE	6	2706.30844	451.05141	5.85	0.0001
Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	3	2069.01122	689.67041	8.95	0.0001
RPM(TYPE)	34	18994.08028	558.64942	7.25	0.0001
CYCLE	2	2211.02433	1105.51217	14.34	0.0001
TYPE*CYCLE	6	2706.30844	451.05141	5.85	0.0001

Dependent Variable: %DELTA SI

Tests of Hypotheses using the Type III MS for RPM(TYPE) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	3	2069.011225	689.670408	1.23	0.3123

Table B-3. Summary ANOVA tables.
(Section 5: Thermal Stress Study 2)

Class Level Information

Class	Levels	Values
TYPE	4	88 911 948 mini
PERIOD	2	post pre
ID	32	01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32

Number of observations in data set = 64

Dependent Variable: SI

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	35	19.76548131	0.56472804	310.76	0.0001
Error	28	0.05088363	0.00181727		
Corrected Total	63	19.81636494			

R-Square	C.V.	Root MSE	SI Mean
0.997432	2.740950	0.042629	1.55528125

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE [RPM type]	3	14.71922156	4.90640719	2699.87	0.0001
PERIOD [pre or post]	1	0.23985506	0.23985506	131.99	0.0001
TYPE*PERIOD	3	0.02381131	0.00793710	4.37	0.0121
ID(TYPE)	28	4.78259338	0.17080691	93.99	0.0001

Tests of Hypotheses using the Type III MS for ID(TYPE) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	3	14.71922156	4.90640719	28.72	0.0001

Tukey's Studentized Range (HSD) Test for variable: SI

NOTE: This test controls the type I experimentwise error rate, but generally has a higher type II error rate than REGWQ.

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 B-4. Summary ANOVA tables: Percent change.
(Section 5: Abrasion Study 2)

General Linear Models Procedure					
Dependent Variable: %CHANGE					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	80	380974.4363	4762.1805	44.93	0.0001
Error	255	27029.9532	105.9998		
Corrected Total	335	408004.3895			
	R-Square	C.V.	Root MSE	%CHANGE Mean	
	0.933751	41.16680	10.29562	-25.009524	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	4	56343.1913	14085.7978	132.89	0.0001
ID(TYPE)	51	40309.5783	790.3839	7.46	0.0001
IMPACTS	5	232365.9056	46473.1811	438.43	0.0001
TYPE*IMPACTS	20	46250.9769	2312.5488	21.82	0.0001

Tests of Hypotheses using the Type III MS for ID(TYPE) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	4	56343.19127	14085.79782	17.82	0.0001

Duncan's Multiple Range Test for variable: %CHANGE

Alpha= 0.05 df= 255 MSE= 105.9998

Number of Means	2	3	4	5
Critical Range	3.543	3.725	3.843	3.931

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	TYPE
A	-6.751	72	948
B	-13.238	60	911
C	-29.863	60	MINI
D	-33.447	72	28
E	-40.594	72	88

Duncan's Multiple Range Test for variable: %CHANGE

Alpha= 0.05 df= 255 MSE= 105.9998

Number of Means	2	3	4	5	6
Critical Range	3.865	4.064	4.193	4.289	4.370

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	IMPACTS
A	6.389	56	2400
B	-3.691	56	3800
B	-4.916	56	3600
C	-28.732	56	4000
D	-57.721	56	4200
D	-61.386	56	4400

Table B-5. Summary ANOVA tables: SI.
(Section 5: Abrasion Study 2)

General Linear Models Procedure

Dependent Variable: SI

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	85	339.1615941	3.9901364	47.38	0.0001
Error	306	25.7718424	0.0842217		
Corrected Total	391	364.9334365			

R-Square	C.V.	Root MSE	SI Mean
0.929379	17.13364	0.290210	1.69380102

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	4	78.3296424	19.5824106	232.51	0.0001
ID(TYPE)	51	59.6160226	1.1689416	13.88	0.0001
IMPACTS	6	139.1668197	23.1944699	275.40	0.0001
TYPE*IMPACTS	24	55.0855229	2.2952301	27.25	0.0001

Tests of Hypotheses using the Type III MS for ID(TYPE) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	4	78.32964243	19.58241061	16.75	0.0001

Duncan's Multiple Range Test for variable: SI

Alpha= 0.05 df= 306 MSE= 0.084222

Number of Means	2	3	4	5
Critical Range	0.092	0.097	0.100	0.103

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	TYPE
A	2.3714	70	911
B	1.9505	84	88
C	1.7975	84	28
D	1.2433	84	948
E	1.1243	70	MINI

Duncan's Multiple Range Test for variable: SI

Alpha= 0.05 df= 306 MSE= 0.084222

Number of Means	2	3	4	5	6	7
Critical Range	0.109	0.115	0.118	0.121	0.123	0.125

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	IMPACTS
A	2.3107	56	2400
A	2.2220	56	1200
B	2.1025	56	3800
B	2.0986	56	3600
C	1.5148	56	4000
D	0.8464	56	4200
D	0.7616	56	4400