STUDY OF FLEXIBLE DELINEATOR POST PERFORMANCE AND REVISION OF EXISTING ACCEPTANCE CRITERIA

Final Report to

Nevada Department of Transportation

Submitted by

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ABSTRACT

Flexible post-mounted delineators are typically ground-mounted plastic posts with reflective sheeting that are used to delineate roadsides, interchanges, and other areas in which safety is a concern. These devices are designed to withstand multiple impacts as opposed to metal guide posts; flexible delineator posts (FDPs) limit damage to the impacting vehicle along with alleviating the potential for injury to vehicle occupants.

Some products that meet current acceptance criteria and are on the Nevada Department of Transportation's (NDOT's) Qualified Product List (QPL) have exhibited dissatisfactory in-service performance. The excessive replacement of FDPs that have cracked or broken, have lost large portions of reflective sheeting, or have lost a significant degree of stiffness has led to a higher life-cycle costs than expected. This study was undertaken to address these problems and to develop realistic pre-qualification specifications/criteria so that such problems can be mitigated in the future.

The procedure adopted in the study included the following activities: (1) a well-designed statewide survey of NDOT FDP field performance, (2) a FDP field performance survey in a few other states with similar climate, (3) analysis of vehicle-impact data collected by the National Transportation Product Evaluation Program (NTPEP), (4) correlation of NTPEP test (impact and UV exposure tests) data with actual FDP field performance in Nevada, (5) review of current pre-qualification pass/fail criteria used by other states, (6) development of a pre-qualification procedure for FDPs for Nevada, and (6) re-qualification of FDPs that are currently on NDOT's QPL.

The recommended guidelines for pre-qualification of FDPs along with a commentary that summarizes the details of the procedure are presented in Appendix E.

STUDY OF FLEXIBLE DELINEATOR POST PERFORMANCE AND REVISION OF EXISTING ACCEPTANCE CRITERA

1.0 INTRODUCTION

Flexible delineator posts (FDPs) which are widely used along roadways are ground-mounted plastic posts with reflective sheeting that is used to delineate roadsides, interchanges and other areas in which safety is a concern. The *National Cooperative Highway Research Program Report 350* (NCHRP 350) describes these devices as "small and lightweight Category 1 Devices which cause very little change in speed of an impacting vehicle, and the passenger compartment of the striking vehicle is unlikely to be penetrated by any part of these devices." Specifically, these devices are designed to yield rather than resist an impact, avoiding both personal injury and damage to the striking vehicle. In addition to the NCHRP 350, the *Manual on Uniform Traffic Control Devices* (MUTCD) gives specific standards regarding size, color, placement etc. In many states such general federal guidelines have been set as the first level of pre-qualification of FDPs.

The Nevada Department of Transportation (NDOT) has identified another level of pre-qualification that addresses the *durability* of the FDPs. Products that satisfy these acceptance criteria are put on the Qualified Product List (QPL) and subsequently, only those products that are on QPL are selected for use either by NDOT maintenance personnel or accepted for use on construction projects. Many products that are on NDOT's QPL have exhibited dissatisfactory performance. Some products that meet current acceptance criteria and are on the Nevada Department of Transportation's (NDOT's) Qualified Product List (QPL) have exhibited dissatisfactory in-service performance. The excessive replacement of FDPs that have cracked or broken, have lost large portions of reflective sheeting, or have lost a significant degree of stiffness has led to higher life-cycle costs than expected. This study was undertaken to address these problems and to develop realistic pre-qualification specifications/acceptance criteria so that such problems can be mitigated in the future.

The activities that were undertaken in this study shall be summarized as follows:

1) Identify the problem,
2) Critically review existing NDOT's QPL specifications and their applicability,
3) Conduct a well-designed statewide survey of NDOT FDP field performance and determine the dominant failure modes for FDPs and the extent of those failure modes,
4) Undertake a field performance survey in a few other states with a similar climate,
5) Review and analyze vehicle impact data collected by the National Transportation Product Evaluation Program (NTPEP),
6) Correlate NTPEP impact response data collected under a controlled testing environment to data collected regarding actual field performance in Nevada,

7) Develop similar comparisons between other test response data and field performance for other failure modes,
8) Review current pass/fail criteria used by other states in the western United States in the specifications included in their FDP pre-qualification procedure,
9) Synthesize Items 6 and 7 to arrive a set of defensible pass/fail criteria that can be used as specifications to pre-qualify FDPs, and
10) Re-qualify products that are currently on NDOT's Qualified Products List.

The recommended pre-qualification criteria along with a commentary are provided in Appendix E.

2.0 FLEXIBLE DELINEATOR POSTS SELECTED FOR THIS STUDY

Earlier on it was decided that the FDP acceptance criteria/specifications to be developed should be solidly based on the field performance of FDPs in Nevada. Therefore, only those products that have been pre-qualified by the existing Nevada QPL specifications have been considered in the study. A list of those products is presented in Table 1.

Table 1: FDP Products on NDOT's QPL

Products
Carsonite CGD1,CGDU
Carsonite HWD1, HWDU
Carsonite CFRM-400 (Curve Flex)
Carsonite CRM-375 (Roadmarker)
Safe-Hit 248-GP3
Davidson Plastics FG500
Flexstake HD
Carsonite Survivor

Although all these products were included in Nevada field performance survey, Flexstake HD and Carsonite Survivor (bottom two) were subsequently disregarded due to a lack of nationally available testing data for those products. Only the first six products identified above were considered in the study.

3.0 RESEARCH METHODLGY

3.1 Statement of the Problem

The first step in any problem-solving situation is to first understand the breadth of the problem. At the onset of our project we conducted several meetings with NDOT personnel to get a better understanding of two things: the extent of FDP failure and the general causes of failure. It was made clear in those meetings that the FDP failures are common and substantial resources are being spent to replace failing FDPs. The existing acceptance criteria/specifications are not working well in terms of predicting the field performance of FDPs. They need to be revised so that unacceptable FDPs will not be pre-qualified for use. We also came away from the meetings with a clear understanding about how the FDPs are failing. The following four distresses were identified as dominant modes of failure: impact failure, wind loading failure, reflective sheeting failure, and ultraviolet light (UV) or brittleness failure.

Another important issue that transpired at the meetings relates to the final recommendation of pass/fail criteria. These specifications should be impartial, without preference to any particular product; and they should be, if possible, based on readily available test data, preferably a national database of test responses collected under a set of reliable, well-documented, and consistent test procedures. Such a database has indeed been generated under a well-designed testing program undertaken by the National Transportation Product Evaluation Program (NTPEP). It will be seen later that we have utilized this national database in the development of the FDP acceptance/specifications. In addition, the specifications to be formulated should utilize Nevada FDP field performance in the development.

The research philosophy adopted in this study may be summarized as follows:

- Step 1: Rank the field performance of FDPs relative to each of the four failure modes identified above.

- Step 2: Rank the test response data (e.g. from NTPEP) of FDPs. As pointed out subsequently in this report, many different attributes may be used to rank the data.

- Step 3: Select a failure mode (e.g. impact failure), and compare the rankings obtained in Step 1 and 2 and see which attribute used in Step 2 gives the “best correlation” between the rankings.

- Step 4: Use Spearman Correlation Coefficient, which is a widely-used statistical parameter, to evaluate the strength (or significance) of the “best-correlation” obtained in Step 3. If it passes the criterion specified by Spearman, then the correlation is considered to be “significant” (i.e. not considered random coincidence). More details on the calculation of this coefficient and the corresponding significance evaluation criterion are presented subsequently.

- Step 5: Repeat Steps 3 and 4 for all the modes of failure.

3.2 Summary of Current NDOT Acceptance Criteria/Specifications

Pre-qualification specifications are not exactly the same in all states but there seems to be a general consistency (theme) among most of them. Altogether four tests in a lab environment and one test in the field are outlined in NDOT's *Materials Manual.* A brief summary of these tests are provided below:

- Heat Resistance Bend Test: Determine whether a product is capable of straightening itself after bending without evidence of cracking or fracture when subject to an oven at 120˚ F for two hours.
- Cold Resistance Bend Test: Determine whether a product is capable of straightening itself after bending without evidence of cracking or fracture when subject to freezing at -10˚ F for four hours.
- Cold Resistance Impact Test: Determine whether a FDP suspended horizontally can withstand an impact to its mid-span from a 2 pound ball that is dropped from a vertical distance of 5 feet. The FDP should show no signs of fracturing, cracking, or splitting.
- Colorfastness Test: Determine whether a FDP can maintain its coloring after 1000 hours in a weatherometer machine (ASTM G26).
- Impact Resistance Field Test: Determine whether a sample population of three FDPs can withstand 15 impacts each while at 90˚ to oncoming vehicle moving at 35 mph, and 10 impacts each while at 75˚ to oncoming vehicle moving at 50 mph. Failure is defined as the post's inability to self-erect, withdrawal from ground such that it can be easily removed, loss of a significant portion of post due to fracture and shear, and loss of 50% reflectivity.

A close examination of the existing specifications raises many concerns and questions. These include: (1) What is the limit to the amount of permanent tilt after a vehicle impact that can be considered acceptable? (2) How does one objectively evaluate "self-erecting"? (3) What are the effects of changing material properties (e.g. strength and brittleness etc.) caused by weathering and UV light exposure have on the FDP performance in Nevada and how are they accounted for? (4) What is the environmental condition (e.g. winter or summer) under which the vehicle impact tests are to be performed? (5) How is the problem of inconsistency between FDP acceptance criteria/specifications of Nevada and others states addressed?

Furthermore, there is another general concern relative to these specifications. The question is how are these tests and the corresponding pass/fail criteria related to "actual" FDP failures in Nevada (i.e. local loading and environmental conditions). As pointed out earlier, in essence what is needed is a set of specific and readily quantifiable guidelines, which should preferably be based on correlating response data collected from a nationally accepted testing program and field performance of FDPs in Nevada. In such an undertaking, all FDP failure modes should be addressed.

3.3 NDOT Field Performance Survey

It was decided that a survey should be conducted among NDOT maintenance crews to understand the extent of FDP failure and to collect field information that can be used later in the study in conjunction with test response data (e.g. NTPEP test data). A well-designed questionnaire with the help of NDOT personnel was developed so that we can identify and readily rate the performance of various FDPs used in Nevada. This questionnaire included product specific questions such as,

- What products do they use?
- Relative percentages of each product used,
- How long does each product last?
- What kinds of failure modes are predominant with each product?
- Relative distribution of failure modes per product, etc.

In addition, the questionnaire also included general non-product specific questions such as,

- How a "failure" in each mode is defined by the maintenance crew?
- In which season does most failures occur? etc.

Subsequently, a second questionnaire was also sent to NDOT maintenance districts to get additional product specific data and to gain better understanding of not only the overall longevity of the FDPs, but also how each specific product was failing. A complete list of the questionnaire is presented in Appendix A.

As many as eleven maintenance crews responded to the survey. In some cases, repeated telephone calls were made to clarify the responses to the survey and the survey was updated when required. The maintenance crews that responded are: Reno, Fallon (two crews in Fallon), Elko, Winnemucca, Hawthorne, Gardnerville, Wadsworth, Wellington, Tonopah, and Las Vegas.

The completed surveys are presented in Appendix A. The first useful information for this survey is how each crew viewed "what constitutes as failure". The final pass/fail criteria (average values) as defined by NDOT field crews are shown in Table 2.

Additional useful information from the survey was the data on the extent of each of the FDP failure modes. The number one cause of failure is Impact at 38%, followed by Wind Loading at 27%, Delamination of Sheeting at 21%, and Ultraviolet (UV) or Brittleness at 14%.

The survey also produced important data on relative field performance for each product. This data enabled us to rank the performance of each product, relative to all four modes of failure: vehicle impact, wind loading, reflective sheeting, and ultraviolet light (UV) or brittleness.

Table 2 – Average Values from Field Defined Pass/Fail Cut-Off Criteria

Failure Attributes	Pass/Fail Cut-off Value
Leaning Out of Plumb	4.5 inches
Cracks in Body	2 inches
Pulling Out of Ground	3 inches
Excessive Flapping Out of Plumb	6 inches
Loss of Sheeting Adhesion	30%
Breaking Off of Body from Top	1 in.

In order to make the field data from one maintenance crew comparable with that of another, we manipulated the field response data so that a "common denominator" exists. We accomplished this by first assigning 100 units to each product reported by the maintenance crew. We then multiplied this by the fraction of the product that fails within its expected service life to come up with a survival index (SI).

Table 3 – Field Ranking of Products by Failure Mode Based on Survival Index/Year (1 = Best; 6 = Worst)

Product Name	Impact Failure	Wind Load Failure	Sheet Failure	UV Brittleness
Carsonite CGDU	3	3	3	5
Carsonite HWDU	5	4	4	4
Carsonite CFRM 400	1	2	5	3
Carsonite CRM 375	6	5	6	6
Safe-Hit 248 GP3	2	1	2	2
Dav. Plastics FG 500	4	6	1	1

Dividing this by the expected lifespan of the product gives us the Survival Index per year (SI/yr). This Survival Index per year was evaluated for each of the four failure modes. The final step is to compute the statewide average SI/yr data from individual sets of data provided by the maintenance crew. Table 3 presents the ranking evaluated based on the statewide data on field performance. This field performance data was subsequently used to undertake the Spearman Correlation Coefficient calculations.

We also attempted to gather data from other states to arrive at the field performance of FDPs. With the help of NDOT personnel, who are familiar with the protocol associated with nationwide surveys, a much shorter and less extensive questionnaire was prepared and mailed to other states. Unfortunately, though there were questions and clarifications communicated via e-mail to the investigators of this study, no response was received. This left us no choice except to rely on the NDOT field-performance survey.

3.3 Synthesis of Vehicle Impact Response: NTPEP Data

It has been pointed out that the acceptance specifications to be developed should integrate field performance of FDPs in Nevada and data collected under a controlled environment that simulates field conditions. The Tennessee Department of Transportation conducts such a field test program for AASHTO called the National Transportation Product Evaluation Program (NTPEP). Over the years, extensive field response data under vehicle impact loading have been collected for a variety of FDPs. The manufacturers are informed about the tests and are requested to supply samples of their product for testing. Typically, the testing is carried out over two seasons (winter and summer) in Tennessee. These test data are well-documented and are readily available. The data extracted for the six FDP products are presented in Appendix A.

In the test, a car impacts eight flexible delineator posts at a speed of 55 mph for ten consecutive impacts (five in the winter and five in the summer). Four of the posts are in line with the tires of the car, while the other four are centered on the car's bumper (see Fig. 1). NTPEP test response data are presented in terms of list percentage for each impact defined in terms of permanent angle (θ_{impact} given in degrees) out of plumb, and the original angle (i.e. before test - $\theta_{initial}$ given in degrees) as,

$$\text{List (\%)} = (\theta_{impact} - \theta_{initial})\left(\frac{100}{90}\right) \qquad (1)$$

These list percentage values are available for each FDP sample for all ten impacts. The list percentages are measured after each vehicle pass and reported relative to the start of the test (i.e. change caused by each impact) for each impact, rather than incremental for each progressive impact. Contradictory to conventional view, the data show that the list values do not continually increase in subsequent impacts due to complex plastic (healing) behavior of the material. Other types of failure indications such as cracking, withdrawal from the ground, sheeting damage due to impact, and breakage etc. have also been recorded as footnotes in the NTPEP database. A careful synthesis of such data from footnotes, though cumbersome, was undertaken so that product failures with these indications can also be investigated.

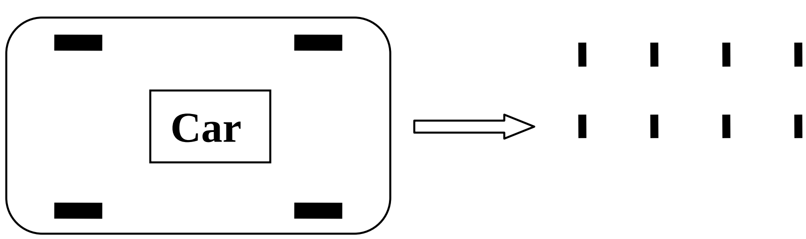

Figure 1 - NTPEP Impact Test

A review of the NTPEP test procedure reveals that every vehicle impact can be treated as an independent event (or data sample). In every vehicle pass, there are eight list response vales (four center and four bumper) and there are ten vehicle passes (five in winter and five in summer), giving a total of as much as 80 list values per FDP in a typical fully completed test. Table 4 shows the results (average) evaluated from the data extracted from the NTPEP database and corresponding ranking of performance (Rank 1 – for lowest list) for the six FDP products under study.

Table 4 - NTPEP Impact Performance Data
(Ranking Based on 1 = Best and 6 = Worst)

	Average list of eight samples per product for each impact (%)										10 Impact Ave (%)	10 Impact Ranking
	1	2	3	4	5	6	7	8	9	10		
Carsonite CGDU	1.10	3.46	4.01	6.66	5.14	0.96	1.79	2.20	2.63	2.90	2.44	2
Carsonite CGDU	1.38	1.53	1.10	1.80	1.65	1.80	1.38	1.79	2.63	2.90		
Carsonite HWDU	2.76	4.16	5.85	3.88	6.68	14.29	27.06	39.70	39.70	39.84	18.39	5
Carsonite CFRM 400	2.76	3.45	3.46	3.74	4.99	0.55	0.69	0.83	0.28	0.41	2.12	1
Carsonite CRM 375	4.43	5.41	5.70	6.41	35.29	51.10	51.53	51.53	51.53	52.35	31.53	6
Safe-Hit 248 GP3	1.39	3.05	3.18	2.76	3.18	1.39	2.91	3.18	2.76	3.18	2.70	3
Dav. Plastics FG 500	2.49	2.49	2.63	3.04	15.26	13.19	13.88	14.43	14.43	14.84	9.67	4

The NTPEP database was also analyzed for a pass/fail cutoff value of list using statistical modeling techniques. Calculations and worksheets associated with the statistical analysis are presented in Appendix B. The entire population of list responses (Appendix B, Table B1) for the six FDPs under study consists of 934 independent values (instead of product averages as shown in Table 4). The mean and the standard deviation of this population are 3.3% list and 2.9% list, respectively. The histogram for this population is presented in Appendix B, Figure B1. The Normal Scores Plot associated with this population reveals a near perfect linear relationship as depicted in Figure 2. This indicates that, in deed, we have a normal distribution. Normalized list response data are presented in Figure 3.

Two methods have been attempted to identify possible pass/fail cut-off list values that define unacceptable performance. One method was based on the average list value that corresponds to a 95% level of confidence. Table 5 shows average % list as a function of confidence interval and number of independent impacts and a 95% confidence level.

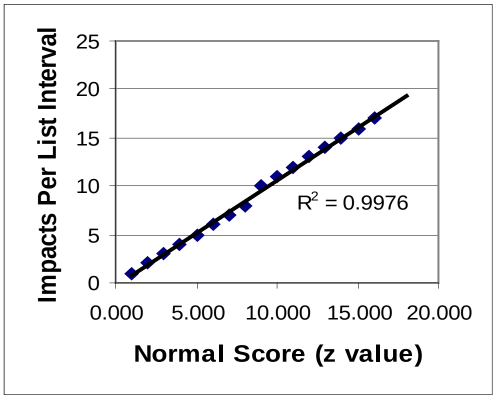

Figure 2 – Normal Scores Plot for NTPEP Listing Data

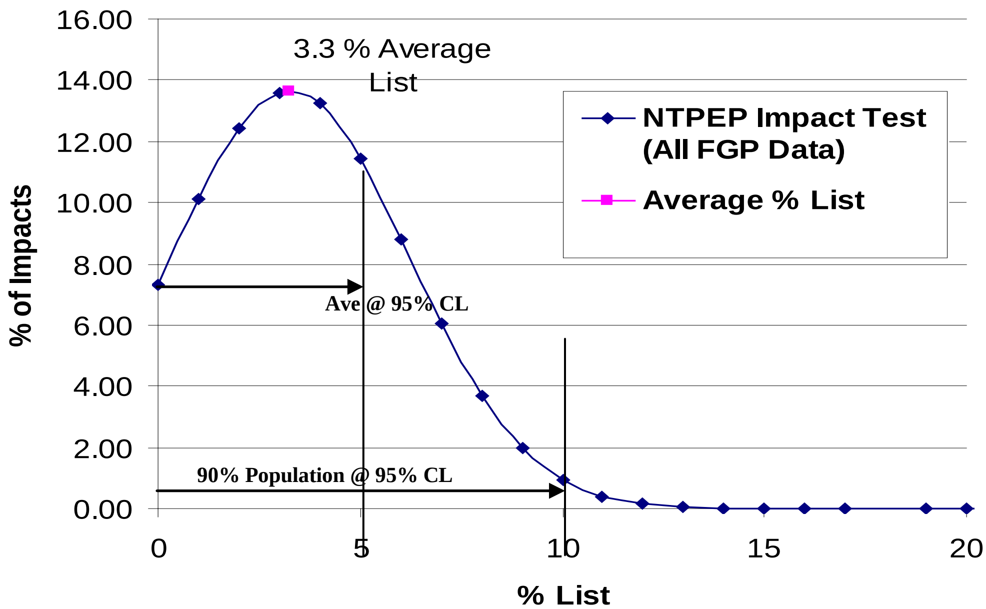

Figure 3 – Normalized NTPEP Data Showing Overall % List Distribution

The other method was based on evaluating % list value within 90% of the population and with 95% confidence. A one-tailed tolerance limit was used to find such values at different sample sizes as shown in Table 6. Subsequently, the results shown in Tables 5 and 6 have been used to arrive at the pass/fail criterion for list caused by vehicle impacts (see Section 3.8)

Table 5 – Confidence Interval for Various Sample Sizes (95% Confidence Level)

Number of Impacts	Confidence Interval (List %)	Pass/Fail Cut-off (List %)	Pass/Fail Cut-off (deg)	Pass/Fail Cut-off (in. out of plumb)
934	0.2	3.5	3.2	2.7
80	0.6	3.9	3.5	2.9
40	0.9	4.2	3.8	3.2
10	1.8	5.1	4.6	3.9
5	2.6	5.8	5.2	4.4

Table 6 – Tolerance Limit for Various Sample Sizes and 90% of the Population (95% Confidence Level)

Number of Impacts	Tolerance Interval (%)	Pass/Fail Cut-off (List %)	Pass/Fail Cut-off (deg)	Pass/Fail Cut-off (in. out of plumb)
934	4.0	7.2	6.5	5.5
80	4.5	7.8	7.0	5.9
40	4.9	8.2	7.4	6.2
10	6.8	10.0	9.0	7.6
5	9.9	13.1	11.8	10.0

3.5 Correlation Between NDOT Field and NTPEP Data: Impact Failure

The rankings developed for all failure modes from NDOT field data (Table 3) and NTPEP vehicle impact data (Table 4) have been reproduced in Table 7 for convenience. A technique known as Spearman Correlation Coefficient method is widely used to find out if in deed there is significant correlation (similarity) between any two rankings. In this method, the Spearman Correlation Coefficient (R), defined as,

$$R = 1 - \frac{6\sum D^2}{N(N^2 - 1)} \qquad (2)$$

is first computed. Here D is the difference between rankings for each sample (i.e. FDP product) and N is the number of samples (= 6 in our case). Depending on the number of samples used, Spearman gives critical values of the correlation coefficient (R_{min}) as a function of sample size (i.e. N) to check the significance of the correlation. For N = 6, the critical value R_{min} = 0.829. In other words, if computed value R (Equn. 2) satisfies the following limit state,

$$R \geq \quad 0.829 \qquad (3)$$

then the correlation between the two rankings is considered significant. This technique has found many applications in science and engineering and has been proven to be effective and robust.

Table 7 - Comparison Between NTPEP Impact and NDOT Field Rankings (1 = Best; 6 = Worst)

NTPEP Impact Ranking	Product Name	Field Impact Ranking	Field Wind Load Ranking	Field Sheet Failure Ranking	Field UV Brittleness Ranking
2	Carsonite CGDU	3	3	3	5
5	Carsonite HWDU	5	4	4	4
1	Carsonite CFRM 400	1	2	5	3
6	Carsonite CRM 375	6	5	6	6
3	Safe-Hit 248 GP3	2	1	2	2
4	Dav. Plastics FG 500	4	6	1	1
Measure of Similarity Between NTPEP Impact and NDOT Field Rankings, *R (Spearman Correlation Coefficient)*		.976	.657	.200	.314

The Spearman Correlation Coefficient values between rankings for each of the failure mode from NDOT field and NTPEP impact data have also been included in the table. It is clear from the table that for impact mode of failure, the R value between rankings from NDOT and NTPEP data is 0.976. Since this is well above R_{min} (0.829), this correlation is significant. It may be noted that R values between other modes of failure and NTPEP data are all much lower than R_{min} (i.e. insignificant correlation). An indication of insignificant correlation is an important result. Knowing that the factors that affect vehicle impact and other failure modes are not the same, a good correlation between two vehicle impact based rankings only (NDOT field and NTPEP data), lends credibility to the proposed approach.

3.6 Methodology for Other Modes of Failure

Other important failure modes are: wind loading, delamination of sheeting, and UV brittleness. Unlike the vehicle impact database of NTPEP, there is no well-documented study that has focused on these failure modes. However, as a part of the NTPEP test program, results of tests conducted using a weatherometer (ASTM D638) on the same FDPs for which the vehicle impact data exist have been documented. The test procedure adopted includes three samples (specimens) of each product and the use of the weatherometer to age (1000 hours) them. Subsequently, measurements of strength (tensile) and elongation to reach tensile failure were made for each specimen. In addition, strength and elongation results are also available for the three control specimens (i.e. no aging). Tables B3 and B4 in Appendix B show many material and shape attributes that can be formulated from this data. The six products in this study can then be ranked based on these material and shape attributes and then compared to the failure mode rankings in the field survey to find any similarity. Similarity is still measured using Spearman Correlation Coefficient where a value greater than .829 constitutes a valid correlation for a sample size of N = 6. Tables B5 through B12 in Appendix B show all our attempts at the comparisons. Only the most promising results have been selected and presented below.

Table 8 - Comparison Between NTPEP Absolute Elongation and NDOT Field Rankings (1 = Best; 6 = Worst)

NTPEP Ranking	Product Name	NDOT Field Rankings					
Δ Absolute Elongation (1)		Impact Ranking	Wind Load Ranking	Sheet Failure Ranking	UV Brittleness Ranking	Sheeting/UV Ranking	Wind/UV Ranking
5	Carsonite CGDU	3	3	3	5	5	3
4	Carsonite HWDU	5	4	4	4	3	4
3	Carsonite CFRM 400	1	2	5	3	4	2
6	Carsonite CRM 375	6	5	6	6	6	5
1	Safe-Hit 248 GP3	2	1	2	2	2	1
2	Dav. Plastics FG 500	4	6	1	1	1	6
Measure of Similarity Between NTPEP Absolute Elongation and NDOT Field Rankings, *R*		.600	.371	.714	.943	.885	.714

(1) See Appendix D for calculation definitions

Field rankings along with ranking obtained for the absolute change in elongation (NTPEP UV tests) are shown in Table 8. This table also includes two additional field performance rankings that combined two failure modes. These combined modes of failures are from (1) sheeting and UV brittleness and (2) wind and UV brittleness. As Table 8 points out, there is similarity between the field ranking for UV brittleness failure and ranking of NTPEP data (R = 0.943) for the change in absolute elongation (change of weathered specimen from the control specimen relative to elongation at failure). See Appendix D for definition of terms. Also, a similarity between the change in absolute elongation ranking and the combined field sheeting and UV brittleness failure (column 7, Table 8) ranking (R = 0.885) is observed. This suggests a link between material property changing with time and the delamination of reflective sheeting from the delineator post. This signifies that failures resulting from brittleness and sheeting failures may in fact be related and are affected more so by the UV exposure than by temperature changes. This is because NTPEP data on elongation change are obtained from a weatherometer that simulated UV exposure. It should be noted that temperature does in fact also play a role on sheeting performance, however, its role may already be represented in UV test results. The difference between the elongation of the original FDP (simulated by the control specimen in NTPEP UV test) and the weathered FDP (simulated by weathered specimen) indicates the ability of the selected FDP to deform (pliability). A higher difference signifies more flexibility to deform, which can result in a better performance relative to UV brittleness and sheeting delamination. Therefore, it is not surprising that a good match among the rankings in terms of Δ absolute elongation (column 1), field failure relative to UV brittleness alone (column 6), and the combined failure from sheeting and UV brittleness (column 7). The effects of UV exposure are irreversible for plastic materials properties but the effects of temperature are not wholly so. At certain temperatures for various types of plastic materials, plastics undergo what is called glass temperature. This is the temperature at which failure characteristics change from cold form bending (plastic behavior) to sudden breaking (brittle behavior). Although a FDP may be brittle in the winter, it may return to a more pliable state in the summer as temperature increases. A FDP that shows little change in its ability to elongate after UV weathering may in fact already be close to its glass temperature (some plastics do in deed have glass temperatures close to room temperature). It appears that the inability to elongate directly correlates with delamination of sheeting.

Table 9 – Average Sheeting Damage for FDP Products from NTPEP Impact Tests (1 = Best; 6 = Worst)

Products	First Season Ave. Sheeting Damage (%)	Second Season Ave. Sheeting Damage (%)	Δ Ave. Sheeting Damage (%) [1]	Δ Ave. Sheeting Damage Ranking
Carsonite CGDU	2.000	1.125	.875	3
Carsonite HWDU	10.625	17.625	-7.000	5
Carsonite CFRM 400	.625	14.875	-14.250	6
Carsonite CRM 375	10.000	10.000	0	4
Safe-Hit 248 GP3	5.125	.688	4.437	2
Dav. Plastics FG 500	7.500	.625	6.875	1

[1] See Appendix D for calculation definitions

Table 10 - Comparison Between NTPEP Change in Reflective Sheeting Damage and NDOT Field Rankings (1 = Best; 6 = Worst)

NTPEP Ranking: Δ Ave. Sheeting Damage Ranking [1]	Product Name	NDOT Field Rankings: Impact Ranking	Wind Load Ranking	Sheet Failure Ranking	UV Brittleness Ranking	Sheeting/UV Ranking	Wind/UV Ranking
3	Carsonite CGDU	3	3	3	5	5	3
5	Carsonite HWDU	5	4	4	4	3	4
6	Carsonite CFRM 400	1	2	5	3	4	2
4	Carsonite CRM 375	6	5	6	6	6	5
2	Safe-Hit 248 GP3	2	1	2	2	2	1
1	Dav. Plastics FG 500	4	6	1	1	1	6
Measure of Similarity Between NTPEP Change in Sheet Damage and NDOT Field Rankings, *R*		-0.086	-0.257	0.829	0.486	0.543	-0.257

[1] See Appendix D for calculation definitions

The sheeting failure can also be investigated utilizing the data from NTPEP vehicle impact tests. A part of the NTPEP data includes footnotes on such observations such as sheeting tearing off, splits in the body, pulling out of ground, and breaks in the FDP body. This data is presented in Appendix A. Cracking and splitting are too erratic and complex to define and therefore, any trends associated with such failures were not possible to quantify. However, the NTPEP data on sheeting damage show some parallel trends with that of the NDOT field survey on sheeting damage. The NTPEP data has been compiled by season and the difference in average sheeting damage between seasons for each product has been ranked and is shown in Table 9.

Table 10 shows the relationship between the NTPEP ranking for seasonal changes in sheeting damage and the NDOT field ranking for sheeting damage. A Spearman Correlation Coefficient of .829, which is right at the cut-off for similarity, confirms a strong relationship between the two rankings. The average sheeting damage data presented in Table 9 is a measure of damage caused by environmental exposure at the site. Since the vehicle impact loading is uniformly applied to all FDPs, the change in sheeting damage in two consecutive impact tests reflect the role of temperature and UV exposure on the post. Both the NTPEP UV test (Table 9) and the impact test (Table 10), when looked at together, represent the combined effects of temperature and weathering (UV exposure) on sheeting delamination. It should be noted that when the NDOT field crews report a failure that is due to delaminated sheeting, the FDP in question has most likely been in place for a season or two.

The last mode of failure to consider is wind loading. As mentioned before, wind loading is the second most significant cause of failure, according to the field survey results, constituting to as much as 27% of all the failures. Table 11 summarizes calculations from the NTPEP UV test and shows very strong similarity between NTPEP strain energy ranking and the field wind loading ranking.

Table 11 - Comparison Between NTPEP Change in Strain Energy and NDOT Field Rankings (1 = Best; 6 = Worst)

NTPEP Ranking	Product Name	NDOT Field Rankings					
Δ Strain Energy(1)		Impact Ranking	Wind Load Ranking	Sheet Failure Ranking	UV Brittleness Ranking	Sheeting/UV Ranking	Wind/UV Ranking
3	Carsonite CGDU	3	3	3	5	5	3
4	Carsonite HWDU	5	4	4	4	3	4
2	Carsonite CFRM 400	1	2	5	3	4	2
5	Carsonite CRM 375	6	5	6	6	6	5
1	Safe-Hit 248 GP3	2	1	2	2	2	1
6	Dav. Plastics FG 500	4	6	1	1	1	6
Measure of Similarity Between NTPEP Change in Strain Energy Ranking and NDOT Field Rankings, *R*		.771	1.00	-.029	.086	-.029	1.00

(1) See Appendix D for calculation definitions

The strain energy (see Appendix D for definition) is a measure of energy a FDP stores when the yield tensile load is applied and its change (weathered sample) reflects the role of weathering on energy stored. A common performance attribute, which relates to a measure of flexibility, between these rankings is the ability to stand up to repetitious loading after a period of weathering. Shape may also be expected to play a role because the drag forces and bending moments are a function of FDP shape. In particular, the shape will play a significant role in the first season. However, observations in Table B4, Appendix B that deal with wind drag effects, stiffness, deflection and maximum loads show very little correlation with the wind load failures reported by the NDOT field crews. That being said, there may be a very significant correlation between shape and wind loading failures when it comes to properties such as vortex shedding, damping, repetitious twisting, etc. that can only be confirmed in a lab setting. The actual wind drag effects for each of the FDPs has only been hypothesized for this study through the use of published bluff shapes (basic shapes). See Theoretical Wind Effect calculations shown in Table B4, Appendix B for details.

Another important observation from Table 11 is the perfect correlation between change in strain energy and the combined wind and UV brittleness failure. Both of the failure modes (wind and UV brittleness) are in fact related to the flexibility of the post and the strain energy measure seems to capture this phenomenon quite correctly.

3.7 Summary Other States' FDP Pre-qualification Specifications

Appendix C lists other states' FDP pre-qualification (acceptance criteria) specifications, which include descriptions of tests along with pass/fail cut-off values in those tests for qualification. Some states do not offer their own methods of testing, but rather rely directly on NTPEP data. Three states in the west give specific numbers regarding the degree of list that a FDP is allowed to lean without being considered as failure. These states are Arizona, Colorado, and Washington. For example, Arizona's pre-qualification specifications require that FDPs are to straighten themselves to within 5 degrees of their original position after ten impacts. Colorado does not currently pre-qualify their flexible delineator posts; nevertheless, they have specifications for FDP selection in their written specifications. Colorado's specifications require that a single FDP must return to within 10 degrees of vertical after 10 impacts head-on at 35 mph and after 5 impacts at an angle of 75° to the traffic face of the post at 55 mph. Washington's requirements are similar to Colorado's for pre-qualifying their flexible delineator posts except that the impact test must include 10 posts subjected to 7 impacts at 35 mph and 3 impacts at 55 mph. All impacts are head-on and must return to within 10 degrees of vertical, show no signs of cracking, pull out of ground no more than 3 inches, and lose no more than 50% of its sheeting. At least 7 out of 10 posts must pass the criteria.

For wind loading, only Arizona has any specific guidelines for failure identification. Arizona's specifications require that a 50 mph wind must not deflect devices more than 2 inches from the at-rest position. Washington does not have direct wind load testing guidelines but proposes a cyclic load test to be performed in a lab. A flexible delineator post must be able to maintain 80% of its bending strength after being subjected to 30,000 cycles in a cyclic testing machine with amplitude of 2 inches at 60 cycles per minute.

For weathering requirements, all states call for no discoloration or loss of pliability after 1000 hours in a weatherometer. However, Washington specifies that a FDP must maintain 80% of its unconditioned tensile strength in addition to the discoloration and pliability requirements.

3.8 Development of New Pre-qualification Pass/Fail Criteria

By reviewing the information such as NDOT field performance, NTPEP data analysis, rank correlations, and pre-qualification specifications adopted by other states, a set of criteria can be formulated to specifically suit the needs of NDOT.

Vehicle Impact

It is clear that the impact failure ranking that was derived from the field performance (Table 3) fits best with that of the NTPEP vehicle impact ranking (Table 4) as opposed to other modes of failure. See also the composite Table 7 for details. Table 2 shows how the different NDOT field crews have set their own failure criteria. The overall average for the out-of-plumb condition is roughly 4.5 inches which corresponds to 5.4 degrees out of plumb for a 48 inch tall FDP. This level of out-of-plumb also corresponds to a list of 6%. Knowing that (1) the most of the pre-qualification tests from other states refer to a sample size of around 10 and (2) a list of 10% represents 90% of the population at a 95% confidence level (see Table 6), we have selected this level of list as the cut-off for FDP failure. It may be noted that Colorado and Washington specify 11.1% list (10 degrees) as their cut-off. Using this criterion the six FDPs considered here can be assigned pass/fail as shown in Table 12.

Table 12 – Re-Qualification of FDPs Baseed on NTPEP Impact Testing: Impact Mode of Failure

Qualified Product list	10 Impact Ave (List %) (NTPEP Test Results [(1)]	Pass/Fail
Carsonite CGDU	2.44	Pass
Carsonite HWDU	18.39	Fail
Carsonite CFRM 400	2.12	Pass
Carsonite CRM 375	31.53	Fail
Safe-Hit 248 GP3	2.70	Pass
Davidson Plastics FG 500	9.67	Pass

[(1)] From Table 4

Wind Loading and UV Brittleness

It may be recalled that the rank correlation comparison (Table 11) between field wind-loading failure and NTPEP data on change in strain energy (ΔE_s) resulted in a perfect match. The combined ranking of both wind loading and UV brittleness failures also yielded the same result. The strain energy calculations are reproduced in Table 13. A plot of change in strain energy versus the field ranking is shown in Fig. 4. The lowest ranking FDP (Davison Plastics) and the highest ranking FDP (Safe-Hit) seem to be

Table 13 – Strain Energy Values from NTPEP UV Data and Rankings (1 = Best; 6 = Worst)

Product	Strain Energy to Yield Point, E_s (lb-in) (1)			Rankings for Δ Energy and Field Wind Loading
	Control	**Weather**	ΔE_s (%) (2)	
Carsonite CGDU/CGD1	719.7	703.5	-2.26	3
Carsonite HWDU/HWD1	839.8	784.9	-6.53	4
Carsonite CFRM 400	1550.5	1616.6	4.26	2
Carsonite CRM 375	407.1	380.3	-6.58	5
Safe-Hit 248 GP3	830.9	1090.7	31.27	1
Davidson Plastics FG 500	1133.1	915.8	-19.17	6

(1) (2) See Appendix D for calculation definitions

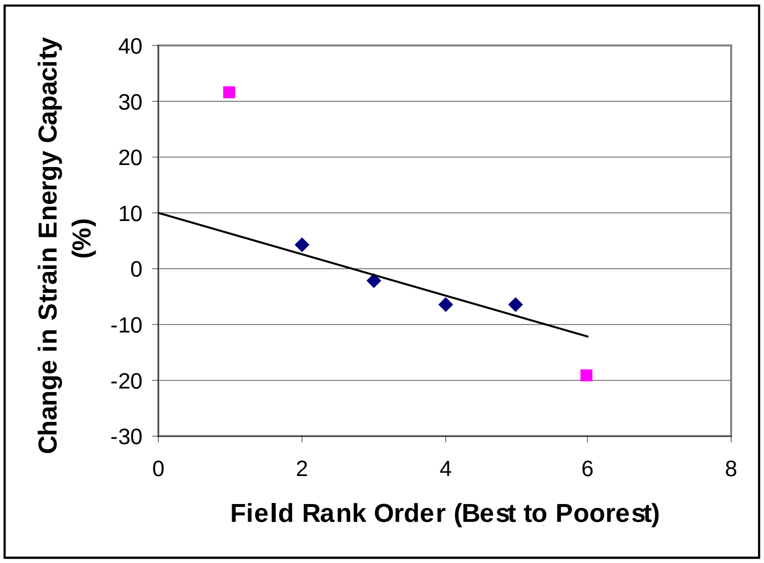

Figure 4 – Changes in Strain Energy after 1000 hours in a Weatherometer

the outliers as shown in figure. When these two data sets are removed, there exists a trend line and the average of the remaining ΔE_s values is –2.8%. A decision was made to round this value to –3% and specify this as the cut-off criteria for the wind-loading mode of failure. In other words, a FDP should be able to loose only up to 3% of its original strain energy after being subjected to weathering in a weatherometer for 1000 hrs. Using this criterion the six FDPs considered here can be assigned pass/fail as shown in Table 13.

Delamination of Sheeting

A similar approach can be followed for the delamination of sheeting mode of failure. NTPEP test results of change in sheeting damage over the season (shown in Table 9) along with NDOT field ranking for sheeting damage (see Table 3 and Table 10) are reproduced in Table 15. It may be recalled that the

Spearman correlation coefficient between these rankings is right at the cut-off value of 0.829 (sample size = 6). When the bottom performer in the NTPEP test data (Carsonite CRM 375) is removed from

Table 14 – Re-Qualification of FDPs Based on NTPEP UV Testing Data: Wind Loading Mode of Failure

Qualified Product list	ΔE_s (%) [1]	Pass/Fail
Carsonite CGDU	-2.26	Pass
Carsonite HWDU	-6.53	Fail
Carsonite CFRM 400	4.26	Pass
Carsonite CRM 375	-6.58	Fail
Safe-Hit 248 GP3	31.27	Pass
Davidson Plastics FG 500	-19.17	Fail

(1) See Appendix D for calculation definitions

Table 15 – Average Sheeting Damage for FDP Products from NTPEP Impact Tests and Rankings (1 = Best; 6 = Worst)

Product	Δ Ave. Sheeting Damage (%) [1,2]	Δ Ave. Sheeting Damage Ranking (Table 9)	NDOT Field Sheeting Damage Ranking (Table 3)
Carsonite CGDU/CGD1	0.875	3	3
Carsonite HWDU/HWD1	-7.000	5	4
Carsonite CFRM 400	-14.250	6	5
Carsonite CRM 375	0.0	4	6
Safe-Hit 248 GP3	4.437	2	2
Davidson Plastics FG 500	6.875	1	1

(1)See Appendix D for calculation definitions
(2)See Table 9

consideration, both the rankings become identical, indicating a strong correlation between field performance with change in sheeting damage over the season. A plot of change in sheeting damage and the field ranking is shown in Fig. 5. There is an outlier, which seems to be a discrepancy between field and NTPEP UV test data results. As shown in Fig. 5, once this data set is removed, there is a good linear correlation between change in sheeting damage over the season and field ranking. The average of the change in sheeting damage of the remaining data sets is –1.8%. A decision was made to specify a cut-off value to Δ Ave Sheeting Damage at –2% (change in sheeting damage after one season). In other words, roughly up to 2% more sheeting damage in the second season can be permitted before failure is indicated. Using this criterion the six FDPs considered here can be assigned pass/fail as shown in Table 16.

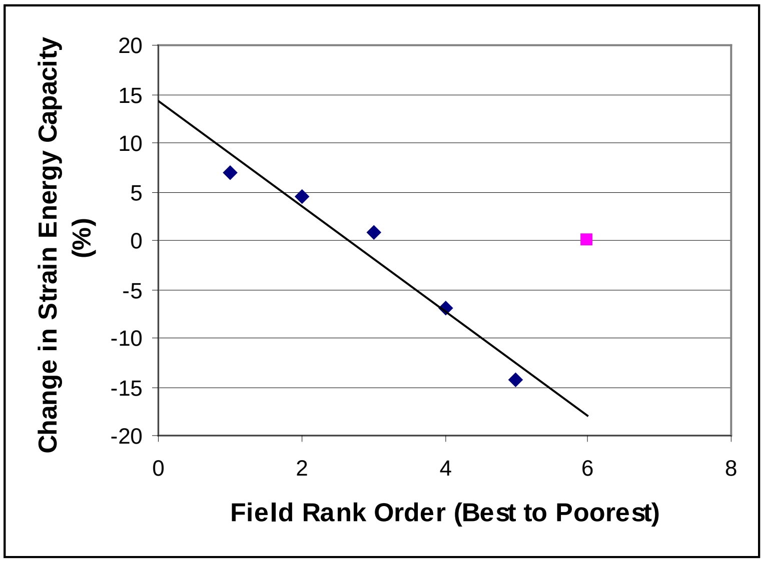

Figure 5 – Changes in Sheeting Damage Due to Impact after One Season

Table 16 – Re-Qualification of FDPs Based on NTPEP Impact Testing: Delamination of Sheeting Failure

Qualified Product list	Δ Ave. Sheeting Damage (%) (1,2)	Pass/Fail
Carsonite CGDU	.875	Pass
Carsonite HWDU	-7.000	Fail
Carsonite CFRM 400	-14.250	Fail
Carsonite CRM 375	0	Pass
Safe-Hit 248 GP3	4.437	Pass
Davidson Plastics FG 500	6.875	Pass

(1) See calculation definitions, Appendix D
(2) See Table 9

Cracking and Flexibility

As it has been argued before, cracking and breaking is a behavior that is hard to quantify and no apparent trends could be recognized from the available NTPEP data. There are many factors at work when it comes to cracking and breaking. A crack or break at the top of a post is not nearly as significant as a crack or break developing near its base. Also there is the issue of how to treat multiple cracks and breaks as opposed to just one large crack or break. Additionally, another concern is how big can a crack or break, get before FDP flexibility or stiffness is compromised? It is recommended, therefore, to treat these failure symptoms as service issues. Since this study achieves good correlation with NTPEP impact tests using percent list values, products pre-qualified with those results alone may also perform well against cracking and breaking. Cracking and breaking do play an indirect role in NTPEP vehicle impact tests because when the flexibility has diminished as a result of cracking and breaking, the net outcome is excess sheeting damage and higher list values.

Discoloration of FDPs

There are no national tests on this issue. The current NDOT specification is based on ASTM G26 and it seems to have worked well as this has not been flagged as a problem by the NDOT maintenance crews. We recommend (i.e. optional) that the current NDOT specification be kept as it is.

3.9 Recommended Pre-Qualification Criteria and Re-Qualification of FDPs Listed in NDOT's QPL

A review of many qualification criteria adopted by other states suggest that it is best to specify "cut-off" values and if a cut-off value is exceeded for a given product, then that product has failed the corresponding criterion. This step will lead to a set of consistent requirements and the qualification requirements are also much easier to interpret. To achieve this goal, it was required that the criteria associated with two of the modes of failure (wind loading and delamination of sheeting) be multiplied by –1. The Table 17 summarizes the revised pass/fail criteria for flexible delineator posts submitted for pre-qualification. Many cut-off criteria have been derived using NTPEP testing data.

Keeping with NTPEP data is a convenient means of verifying the performance of a FDP without the hassle and cost of developing a new test. The first criterion that must be met is available testing by NTPEP or similar testing by the manufacturer. Using a 10% list (9.0 degrees) as the cut-off criterion for vehicle impact loading, the pass/fail results achieved for existing FDP products on NDOT's QPL are reproduced in Table 18. Table 19 shows a similar table for the wind loading mode of failure with a pass/fail cut-off value of 3% change in strain energy followed by Table 20 that shows the sheeting damage mode of failure with its 2% change in seasonal sheeting damage criteria. Finally, Table 21 gives the overall re-qualification result obtained for all the FDPs on the NDOT's QPL. A summary of the pre-qualification requirements and data interpretation procedure that need to be adopted to check against the failure modes are summarized in Appendix E.

Table 17 – Recommended Pre-Qualification Criteria

Mode of Failure	Recommended Cut-off Criteria *	Description for Pass
Impact Loading	Listing average not to exceed 10% (9 degrees) for 10 impacts	Average of eight products being impacted simultaneously. See NTPEP test procedure.
Wind Loading	Loss of strain energy capacity after 1000 hrs in a weatherometer not to exceed 3% of the original strain energy capacity of the control specimen.	$E = \frac{P}{2\delta}$; $\frac{E_{contol} - E_{weathered}}{E_{control}} x100 \leq 3\%$
Delamination of Sheeting	Average loss of sheeting in the second season impact testing not to exceed 2% above the average loss of sheeting in the first season impact testing.	$\%Loss_{2nd\ season} - \%Loss_{1st\ season} \leq 2\%$
UV Brittleness	Same as wind loading criteria	Same as wind loading criteria
Discoloration (optional)	Subject FDP to 1000 hrs in a weatherometer (ASTM G26)	No discoloration should be observed (optional)

* The first pre-qualification requirement is that all flexible delineator posts to be considered must have been tested by NTPEP.

Table 18 – Re-Qualification of FDPs on NDOT's QPL Based on NTPEP Impact Testing: Impact Mode of Failure

Qualified Product list	Pass/Fail
Carsonite CGDU	Pass
Carsonite HWDU	Fail
Carsonite CFRM 400	Pass
Carsonite CRM 375	Fail
Safe-Hit 248 GP3	Pass
Davidson Plastics FG 500	Pass

Table 19 – Re-Qualification of FDPs in NDOT's QPL Based on NTPEP UV Testing Data: Wind Loading Mode of Failure

Qualified Product list	Pass/Fail
Carsonite CGDU	Pass
Carsonite HWDU	Fail
Carsonite CFRM 400	Pass
Carsonite CRM 375	Fail
Safe-Hit 248 GP3	Pass
Davidson Plastics FG 500	Fail

Table 20 – Re-Qualification of FDPs on NDOT's QPL Based on NTPEP Impact Testing: Delamination of Sheeting Failure

Qualified Product list	Pass/Fail
Carsonite CGDU	Pass
Carsonite HWDU	Fail
Carsonite CFRM 400	Fail
Carsonite CRM 375	Pass
Safe-Hit 248 GP3	Pass
Davidson Plastics FG 500	Pass

Table 21 – Overall Re-Qualification of FDPs on NDOT's QPL

Qualified Product list	Pass/Fail
Carsonite CGDU	Pass
Carsonite HWDU	Fail
Carsonite CFRM 400	Fail
Carsonite CRM 375	Fail
Safe-Hit 248 GP3	Pass
Davidson Plastics FG 500	Fail