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16. Abstract The Texas Department of Transportation implements a smoothness specification based on inertial profile measurements. This specification includes a localized roughness provision to locate defects on the final surface based on measured surface profiles. To identify defects, the existing methodology uses the deviations between the average of the left and right wheel path profiles, and its moving average as determined using a 25-ft base length. Stations where the deviations exceed 150 mils in magnitude are considered defect locations. While this methodology provides an objective approach for evaluating localized roughness based on profile data, some districts have introduced an additional step to determine the need for corrective work. Specifically, these districts have used a bump rating panel to select, from among the defects identified using the existing procedure, those bumps and dips that will require correction based on the panel’s opinion of the severity of the defects from a ride quality point of view. Clearly, a standard methodology needs to be developed so that consistency in ride quality assurance testing can be maintained. Otherwise, differences in results of quality assurance tests between projects within a district and between districts can easily arise because of differences in road user perception of ride quality. Consequently, this project examined the existing methodology for evaluating localized roughness to develop recommendations for an improved methodology that engineers can use to objectively decide where corrective work is necessary so as to maintain consistency in quality assurance testing of pavement smoothness.			
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EVALUATE METHODOLOGY TO DETERMINE LOCALIZED ROUGHNESS

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DISCLAIMER

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- Ryan Barborak — Construction Division/Texas Department of Transportation
- Todd Copenhaver — Maintenance Division/Texas Department of Transportation
- Darlene Goehl — Bryan District/Texas Department of Transportation
- Gerry Harrison — Materials & Pavements/Texas A&M Transportation Institute
- Jason Huddleston — Materials & Pavements/Texas A&M Transportation Institute
- Stephen Kasberg — Bryan District/Texas Department of Transportation
- Mark McDaniel — Maintenance Division/Texas Department of Transportation
- Andy Naranjo — Construction Division/Texas Department of Transportation
- Harry Pan — Construction Division/Texas Department of Transportation
- Travis Patton — Construction Division/Texas Department of Transportation
- William Pecht — Construction Division/Texas Department of Transportation
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- Andrew Wimsatt — Materials & Pavements/Texas A&M Transportation Institute

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CHAPTER 1. INTRODUCTION

The Texas Department of Transportation (TxDOT) has been implementing a smoothness specification based on inertial profile measurements since 2002 beginning with Special Specification (SS) 5880. Later, Item 585 of the 2004 standard specifications (*1*) superseded this special specification. For quality assurance (QA) testing, Item 585 includes pay adjustment schedules that are tied to the average international roughness index (IRI) computed at 528-ft intervals, and a localized roughness provision to locate defects on the final surface based on measured surface profiles. Figure 1 illustrates the current methodology to identify defects based on profile measurements collected from ride quality assurance tests on Item 585 projects.

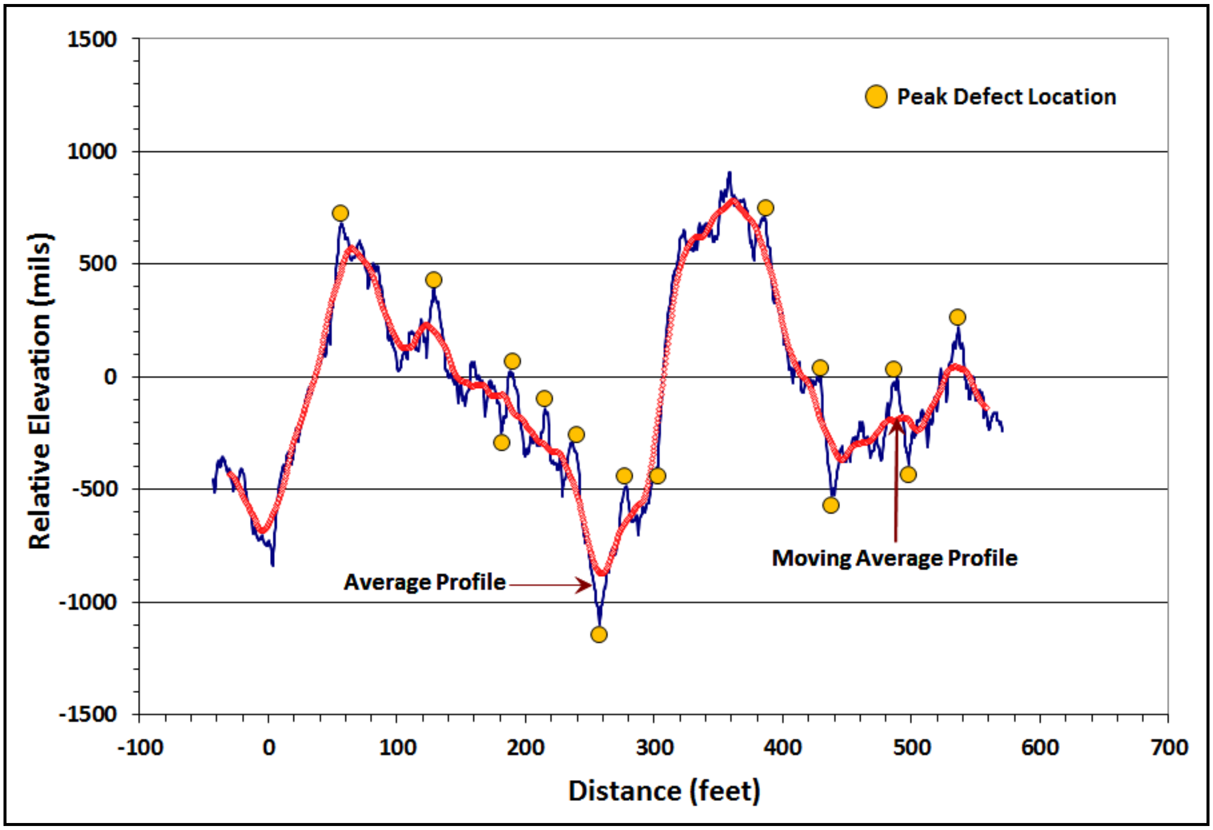


Figure 1. Illustration of Methodology for Identifying Defects on Item 585 Projects.

To identify defects, the methodology illustrated in Figure 1 uses the deviations between the average of the left and right wheel path profiles, and its moving average as determined using a 25-ft base length. This methodology is implemented in TxDOT's Ride quality program, which is used for QA testing of initial pavement smoothness under Item 585. In Figure 1, the blue line represents the average profile, while the red line represents its 25-ft moving average. Note that the moving average profile does not start and end at the same locations as the average profile since the calculation of the moving average requires a 12.5-ft lead-in and a 12.5-ft lead-out. In practice, this lead-in and lead-out will be included in the 100-ft leave-out segments at the project ends, which are tested using Surface Test Type A under Item 585. If one computes the IRI of the average profile illustrated in Figure 1, the resulting index would be 167 in/mile. In contrast, the IRI of the moving average profile is 44 in/mile. Thus, hypothetically, if one can correct the average profile to be like the moving average, a smoother pavement would result. This premise provides the rational for using the deviations between the average profile and its moving average to evaluate localized roughness. The specific procedure implemented in TxDOT's Ride Quality program to evaluate localized roughness is a modification of the methodology described in reference (*2*).

At each station, the Ride Quality program computes the difference between the average profile elevation and the elevation based on the moving average. Stations where the differences exceed 150 mils in magnitude are considered defect locations. In this analysis, a positive difference indicates a bump while a negative difference indicates a dip. In Figure 1, the yellow dots identify the stations where the defect magnitudes are at their maximum. To provide guidance for corrective work, the Ride Quality program reports the stations where the defects are at their peaks, as well as the widths of the defect intervals within which the deviations between the average profile and its moving average are above 150 mils.

While the above methodology provides an objective approach for evaluating localized roughness based on profile data, some districts have introduced an additional step to determine the need for corrective work. Specifically, these districts have used a bump rating panel to select, from among the defects identified by the Ride Quality program, those bumps and dips that will require correction based on the panel's opinion of the severity of the defects from a ride quality point of view. Clearly, a standard methodology needs to be developed so that consistency in QA testing can be maintained. Otherwise, differences in results of quality assurance tests between projects within a District and between Districts can easily arise because of differences in road user perception of ride quality. Consequently, this project examined the existing bump criteria in the Item 585 ride specification to establish an improved methodology that Engineers can use to objectively decide where corrective work is necessary so as to maintain consistency in QA testing of ride quality.

To investigate relationships between existing bump criteria and road user perception of defect severity, the Texas A&M Transportation Institute (TTI), in cooperation with TxDOT, organized and conducted bump rating panel surveys to develop a procedure that relates the need for corrective work (based on a road user's perspective) to characteristics determined from profile measurements. This approach is similar in concept to the original development of the present serviceability index (PSI) during the AASHO Road Test (*3*). This landmark undertaking developed, among other things, an equation to estimate a road user's rating of a pavement's present serviceability based on physical measurements of roadway surface characteristics, primarily, longitudinal and transverse roughness (as measured by slope variance and rut depth), and amount of cracking and patching. TxDOT also employed ride rating panels in the late 1960s to develop models for estimating pavement serviceability index (*4, 5*), and again in the late 1990s (*6*) to develop a ride equation that reflects more current vehicle design and usage, and to migrate from the 0.2- to the 0.1-mile reporting interval for serviceability index (SI). This latter change was also made to achieve consistency with the proposed 0.1-mile interval for ride quality assurance testing in the draft TxDOT ride specification developed around that time.

The fact that certain Districts have used bump rating panels reflects the importance of considering road user perception to determine the need for correcting defects identified from profile measurements. Using the existing criteria based solely on profile measurements is simply not sufficient. To address this need and improve upon the existing methodology, researchers carried out the following tasks during the one-year period of this particular study:

1. Plan and conduct bump rating panel surveys to collect data on defect severity and need for corrections based on the subjective opinions of an experienced panel of road users.
2. Analyze the data from the bump surveys to investigate relationships between profile characteristics and road user perception of localized roughness.
3. Provide recommendations on modifications to the existing methodology for evaluating localized roughness, and how TxDOT should proceed with its implementation.

The following chapters of this report document each of the above tasks.

CHAPTER 2. BUMP RATING PANEL SURVEYS

ESTABLISHING BUMP SURVEY SECTIONS

To establish test sections on which to run the bump surveys, researchers collected profile data on existing pavements around the Bryan-College Station area to identify candidate survey routes. Researchers analyzed the data from these tests to identify defects and establish candidate sections on which the bump panel ratings can be conducted. In this analysis, researchers used the methodology for evaluating localized roughness in the current Item 585 ride specification except that:

1. Defects were identified by wheel path instead of using the average profile.
2. The defect width was defined to be the distance between the intersections of the measured profile and its 25-ft moving average.

Figure 2 illustrates a sample of the results obtained from this analysis over a 528-ft section of continuously reinforced concrete pavement (CRCP) located along the inside lane of the southbound frontage road along SH6 south of College Station. Segments of the profile shown in red identify defects found from analyzing the left wheel path profile. The locations of the defects as well as their amplitudes are shown at the top of the chart given in Figure 2. The starting and ending locations of each defect are where the moving average profile intersects the measured wheel path profile on the lane tested. This definition of defect width provides the interval within which the measured profile deviates from its 25-ft moving average. Note that this interval is wider than the defect width reported by the Ride Quality program, which only includes stations where the deviations exceed the 150-mil threshold of the existing bump template defined in TxDOT Test Method Tex-1001-S (*7*). Defining the defect width as explained herein and using the measured wheel path profile in lieu of the average profile provide consistency with the original methodology proposed by Fernando and Bertrand (*2*) for determining localized roughness.

From (ft)	To (ft)	Est. Defect Magnitude (mil)	Max. Defect at (ft)
36.59	44.49	640.91	39.78
45.53	50.25	281.56	47.37
50.25	62.31	-332.70	52.08
150.02	160.24	267.44	153.37
161.04	172.07	-239.84	166.23
269.36	283.18	379.81	274.23
283.18	291.57	-238.32	287.34
297.56	306.51	-232.22	302.99
346.05	357.63	-245.47	352.20
410.59	419.06	274.70	414.11

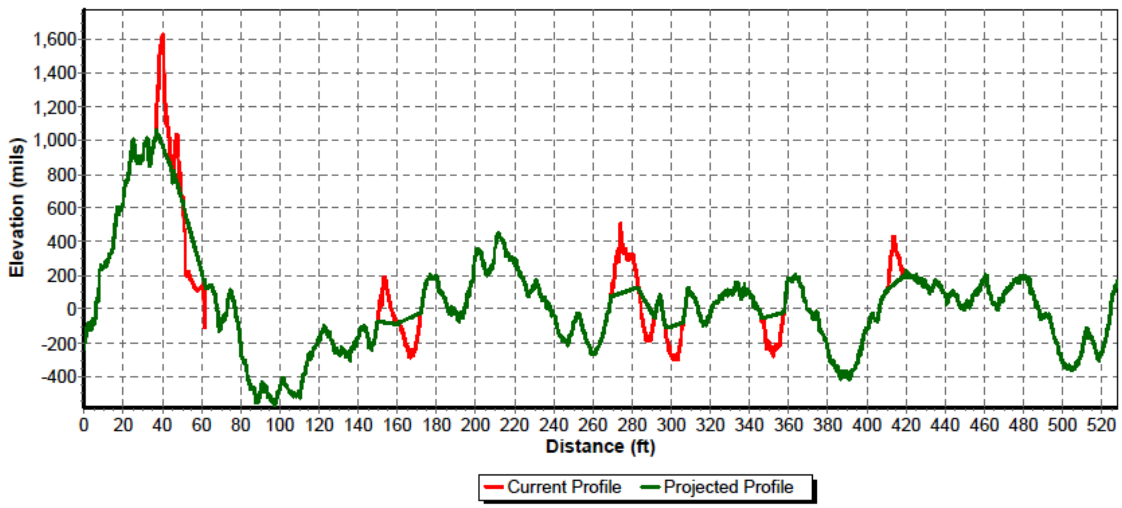


Figure 2. Sample Results from Analysis of Wheel Path Profiles to Identify Defects.

Researchers note that in tests conducted on TxDOT project 0-4863 (*8*), measured dynamic loads from an instrumented 18-wheeler were found to exhibit high variability at locations where defects are found along the pavement surface. This project showed that TxDOT's existing Ride Quality bump template, when used with the individual wheel path profiles, identified the locations of defects associated with high dynamic load variability. Project 0-4863 found that evaluating the defects based on the average profile tends to mask the defects that exist along the individual wheel paths, particularly on pavement sections where there are significant differences between the left and right wheel path IRIs. Given that the individual wheel path profiles are the measured data from the inertial profiler, using the current bump template with the individual wheel path profiles should give a better assessment of the localized roughness that exists on a given project, in terms of where the defects are, and the magnitudes of these defects. In Figure 2, the estimated magnitude of each defect is the maximum deviation of the measured wheel path profile from the moving average. This deviation is positive for bumps and negative for dips. The location where the maximum deviation occurs is also given in the figure.

Researchers used the results from the profile analysis to identify candidate sections for the bump rating panel surveys. To establish the defect locations for these surveys, researchers drove over the candidate sections in a full-size pickup truck to assess the severity of the defects from a ride quality point of view. From this drive through, researchers identified defect locations and established the sections for the bump rating panel surveys. The following preliminary findings are noted from this effort:

1. The existing methodology to evaluate localized roughness provides an objective approach for identifying defects based on measured profile. However, the criteria used do not necessarily identify defects that significantly diminish road user perception of ride quality. Indeed, the drive through of candidate bump sections identified defect locations that were barely felt based on a "seat of the pants" judgment call.
2. The magnitude of the defect and its width (as determined from the starting and ending limits) appear to influence the degree by which the road user senses the defect while riding in a vehicle. A 1-inch bump in 25 ft does not generate the same sensation as a 1-inch bump in 5 ft. Thus, the ratio of the defect magnitude to its width appears to be a significant variable in determining the need for corrective measures.
3. Differences in defect magnitudes and locations between wheel paths appear to influence road user perception of ride quality to the degree by which such differences affect vehicle pitch and roll in areas of localized roughness. In view of this observation, it becomes important to look at the wheel path profile to evaluate localized roughness.
4. In practice, an area of localized roughness may have several defects. Thus, road user perception can be an aggregate reaction to a group of defects as opposed to any single bump or dip.

Table 1 shows the limits of the selected test sections for the bump rating panel surveys. All sections are located along the frontage roads of SH6 south of College Station and comprise both hot-mix asphalt concrete (HMAC) and CRC pavements. Figure 3 and Figure 4 show the north and south ends, respectively, of the HMAC sections while Figure 5 and Figure 6 show the CRCP sections. Because of their locations along the SH6 frontage roads, and the availability of turnarounds, the research team was able to run the bump rating panel surveys in loops. This approach was necessary given that the defects found within a given section cannot all be rated in one pass of the survey vehicle.

Table 1. Selected Test Sections for Bump Rating Panel Surveys.

Section ID	Description	Section Limits[1]		Length (lane-miles)	Test Lanes	Number of defect groups[2]
		Start	End			
HMACS	Southbound HMAC section	N30.55746° W96.25659°	N30.51279° W96.20722°	4.286	Southbound outside lane	33
HMACN	Northbound HMAC section	N30.51315° W96.20653°	N30.55798° W96.25504°	4.263	Northbound outside lane	27
CRCPS1	Southbound CRCP section 1	N30.49325° W96.18402°	N30.48998° W96.18076°	0.636	Southbound outside and inside lanes	21
CRCPS2	Southbound CRCP section 2	N30.46042° W96.14925°	N30.45583° W96.14413°	0.938	Southbound outside and inside lanes	14
CRCPN1	Northbound CRCP section 1	N30.49053° W96.18001°	N30.49460° W96.18409°	0.810	Northbound outside and inside lanes	9
CRCPN2	Northbound CRCP section 2	N30.45517° W96.14207°	N30.46074° W96.14819°	1.158	Northbound outside and inside lanes	14

[1] GPS coordinates of end points along centerline of frontage road
[2] Total number of defect groups in test lanes. Each defect group represents an area of localized roughness.

Figure 3. North End Points of HMAC Sections on SH6 Frontage Roads (Dotted Squares Denote Section End Points).

Figure 4. South End Points of HMAC Sections on SH6 Frontage Roads (Dotted Squares Denote Section End Points).

Figure 5. CRCPS1 and CRCPN1 Sections along SH6 Frontage Roads (Dotted Squares Denote Section End Points).

Figure 6. CRCPS2 and CRCPN2 Sections along SH6 Frontage Roads (Dotted Squares Denote Section End Points).

RUNNING THE BUMP SURVEYS

In accordance with the research work plan, the TxDOT technical project director assembled a panel of pavement experts who rode the sections and rated the defects. The composition of the panel included engineers with experience in the following areas:

- Asphalt and concrete pavement design, maintenance, rehabilitation, and reconstruction.
- Assessment of pavement condition.
- Materials testing.
- Geotechnical investigations.
- Bridges.

Table 2 identifies the participants to the bump rating panel surveys conducted in this project. For these surveys, researchers collected panel ratings using the test vehicles listed in Table 3. TTI technicians operated these vehicles during the surveys. For consistency, researchers grouped panel members with the drivers as shown in Table 4.

Table 2. List of Participants to the TxDOT Bump Rating Panel Surveys.

Name	Division/Agency
Ryan Barborak	Construction/Texas Department of Transportation
Todd Copenhaver	Maintenance/Texas Department of Transportation
Emmanuel Fernando	Materials & Pavements/Texas A&M Transportation Institute
Darlene Goehl	Bryan District/Texas Department of Transportation
Gerry Harrison	Materials & Pavements/Texas A&M Transportation Institute
Jason Huddleston	Materials & Pavements/Texas A&M Transportation Institute
Stephen Kasberg	Bryan District/Texas Department of Transportation
Mark McDaniel	Maintenance/Texas Department of Transportation
Magdy Mikhail	Maintenance/Texas Department of Transportation
Andy Naranjo	Construction/Texas Department of Transportation
Harry Pan	Construction/Texas Department of Transportation
Travis Patton	Construction/Texas Department of Transportation
William Pecht	Construction/Texas Department of Transportation
Rick Seneff	Roadside & Physical Security/ Texas A&M Transportation Inst.
Roger Walker	Computer Science Engineering/University of Texas at Arlington
Andrew Wimsatt	Materials & Pavements/Texas A&M Transportation Institute

Table 3. List of Vehicles Used in TxDOT Bump Rating Panel Surveys.

Year, Make & Model	License Plate No.	TxDOT Inventory No.	Wheelbase (inches)
2007 Chevrolet 2500 Van	Tx102-6206	29-3236H	135 ¾
2010 Chevrolet Impala Sedan	Tx109-6077	29-42-E	111
2012 Chevrolet 2500 HD Truck	Tx113-1808	29-4012-K	155 ¼

Table 4. Grouping of Raters and Drivers.

Rater	Driver		
	Gerry Harrison	Jason Huddleston	Rick Seneff
Ryan Barborak	X		
Todd Copenhaver			X
Darlene Goehl		X	
Stephen Kasberg		X	
Mark McDaniel			X
Andy Naranjo	X		
Harry Pan			X
Travis Patton[1]		X	
William Pecht	X		
Andrew Wimsatt[2]		X	

[1]Not available on the first day of surveys; rated only in truck and van.
[2]Substituted for Travis Patton on first day of surveys; rated only in sedan.

Prior to the surveys, researchers marked the defect stations with stakes to help drivers identify the defects in each section. These stakes were also painted following a color-coding scheme that established the sequence in which the defects were to be rated. Table 5 shows this color-coding scheme. It was necessary to sequence the ratings of defects to provide enough time for a rater to complete his or her rating sheet in the time it took to go from one defect group to the next. Thus, anywhere from 2 to 5 passes of the test vehicles were made on the different sections to rate all of the defects.

Table 5. Color-Coding to Sequence the Ratings in Each Section.

Color	Pass on which to Rate Defect
	1
	2
	3
	4
	5

Prior to the surveys, researchers also conducted two briefing sessions, one for the drivers, and another for the rating panel members. During the driver briefing session, the researchers rode over each section with the drivers to show the locations of the defect groups and describe how these defects were marked. Each driver was given a list of the defects on each section that showed the defect locations and the sequence for rating the defects according to the color scheme described earlier. The researchers also explained how the surveys were to be conducted and demonstrated how each driver would notify the raters of an approaching defect, and when and how to signal his group to rate. This briefing session continued until each driver felt confident about conducting the bump rating panel surveys.

The bump rating panel briefing was held in one of the function rooms of the Holiday Inn at College Station. The technical project director and the drivers also attended this briefing, which covered the following topics:

- Bump survey routes.
- Current TxDOT method to evaluate localized roughness.
- The purpose for running the bump surveys in this project.
- How the bump surveys will be conducted.
- Training exercise to be conducted after the briefing session and before the actual bump rating panel surveys.

The survey sections were presented earlier in this chapter. Within each section, researchers established groups of defect stations of varying defect amplitudes and widths. Figure 7 illustrates the defect groups along a 528-ft section of the CRC pavement located along the inside lane of the SH6 southbound frontage road south of College Station. The defect groups are identified as A, B, C, D, and E in the figure.

As noted previously, anywhere from 2 to 5 passes were made on the test sections to rate all of the defect groups. This item was noted during the briefing. The researchers also explained the rating form to be completed by the panel during the surveys. As shown in Figure 8, the top of the form has check boxes to identify the section, test vehicle, position of rater inside the vehicle, and the run number. The run number was initially intended to identify repeat ratings. However, because of time constraints, each defect group was only rated once by each rater on each of the three test vehicles.

From (ft)	To (ft)	Est. Defect Magnitude (mil)	Max. Defect at (ft)	
36.59	44.49	640.91	39.78	A
45.53	50.25	281.56	47.37	A
50.25	62.31	-332.70	52.08	A
150.02	160.24	267.44	153.37	B
161.04	172.07	-239.84	166.23	B
269.36	283.18	379.81	274.23	C
283.18	291.57	-238.32	287.34	C
297.56	306.51	-232.22	302.99	C
346.05	357.63	-245.47	352.20	D
410.59	419.06	274.70	414.11	E

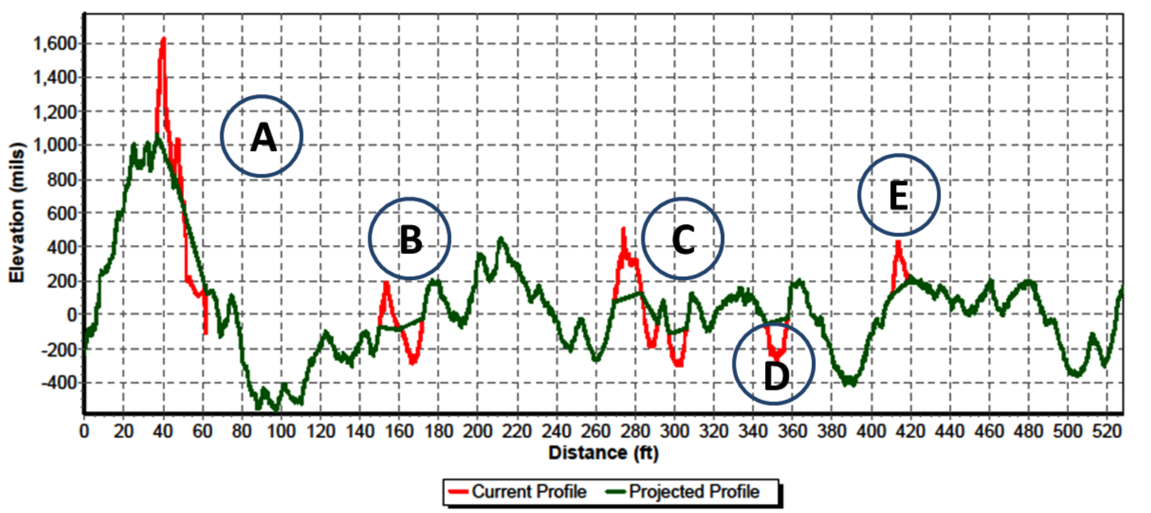
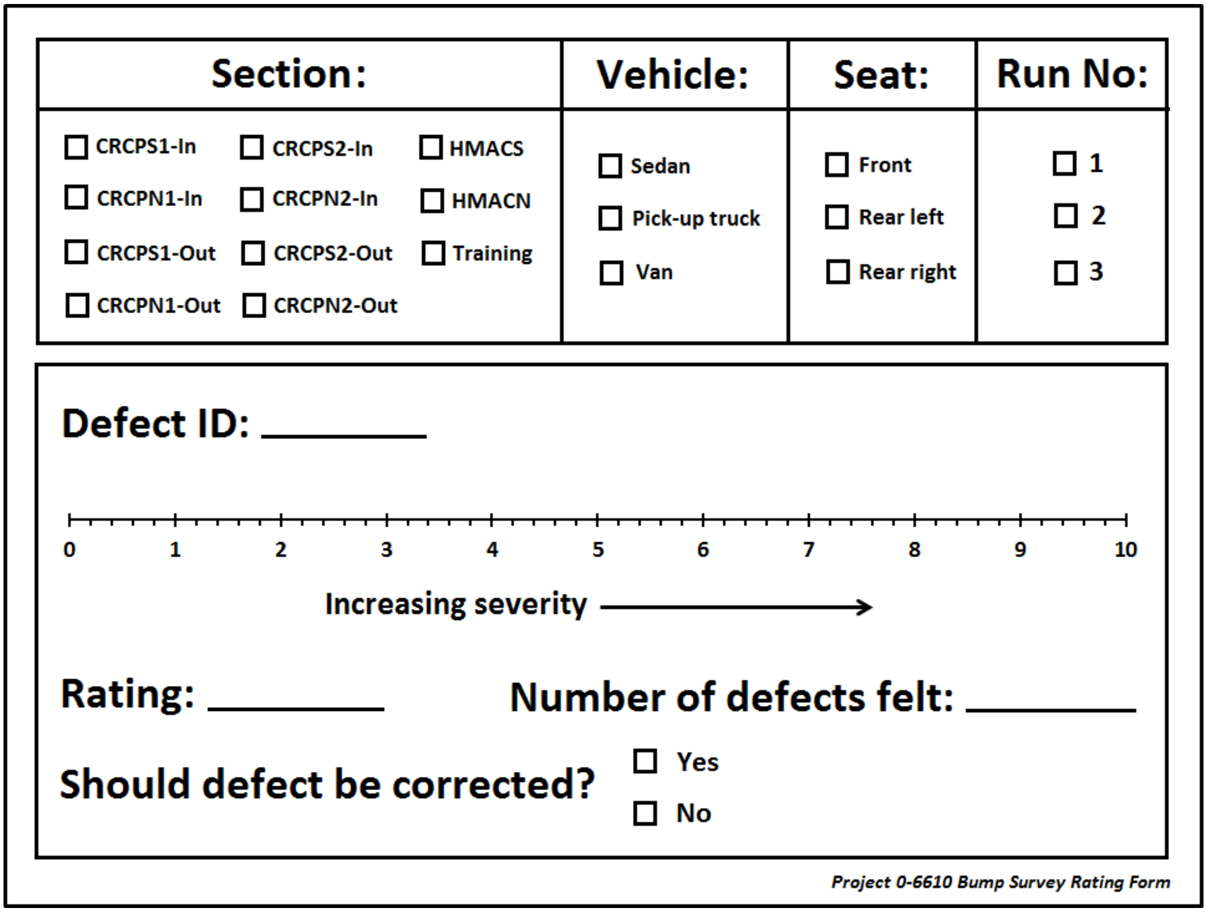


Figure 7. Illustration of Defect Groups Established in Each Survey Section.


Section:
☐ CRCPS1-In ☐ CRCPS2-In ☐ HMACS
☐ CRCPN1-In ☐ CRCPN2-In ☐ HMACN
☐ CRCPS1-Out ☐ CRCPS2-Out ☐ Training
☐ CRCPN1-Out ☐ CRCPN2-Out

Vehicle:
☐ Sedan
☐ Pick-up truck
☐ Van

Seat:
☐ Front
☐ Rear left
☐ Rear right

Run No:
☐ 1
☐ 2
☐ 3

Defect ID: ________

0 1 2 3 4 5 6 7 8 9 10

Increasing severity →

Rating: ________ Number of defects felt: ________

Should defect be corrected? ☐ Yes ☐ No

Project 0-6610 Bump Survey Rating Form

Figure 8. Bump Rating Panel Survey Form.

The bottom of the form is where the rater enters his or her rating for the given defect group. During the briefing, raters were instructed to rate each defect on a 0 to 10 scale, with 0 indicating that the rater felt no perceptible sensation while riding over the defect, and 10 indicating a defect that was harsh and notably uncomfortable to the rater. The raters were asked to write down their rating on the blank provided in the form. However, the rater was also given the option to mark his/her rating on the scale shown if this was easier for him/her to do. During the briefing, the researchers advised that if the rater marks the scale, that he/she write down the rating on the blank provided as soon as it was possible to do so, such as during the time between passes on a given section. The raters were also instructed to identify the defect on the form, whether the defect needed to be corrected or not, and how many defects he/she felt. The drivers provided the defect IDs for the raters to enter on the form.

For the actual surveys, each rater was given three books of rating forms, one for each test vehicle. Each book contained pages of rating forms to cover all the defects found within the test sections plus enough extra pages in case a rater would require more forms. The forms in a given book were spiral bound to make it easy to flip from page to page, and to lay a page flat on one's clipboard or lap during the surveys.

Drivers were instructed to run their test vehicles at 50 mph within each test section, which is within the 55 mph posted speed limit on the SH6 frontage roads. Upon completing the runs on all test sections, drivers were instructed to proceed to the designated staging area, and wait for the other vehicles. This staging area (illustrated in Figure 9) is at the Millican exit along SH6. This area is where drivers and raters switched vehicles. During the briefing session, raters were instructed to switch positions as they move from one test vehicle to another. Thus, each rater got to occupy the front passenger seat, the left rear seat, and the right rear passenger seat. At any one time, each vehicle had four occupants, the driver and the three raters with him.

Figure 9. Staging Area Used during Bump Surveys.

After the briefing session, everyone in the room proceeded to the designated staging area at the SH6 Millican exit. From there, the raters were driven on a section of the SH6 southbound frontage road to rate defects and go through training runs prior to the actual surveys. Researchers established the training section adjacent to the HMACS test section identified in Table 1. Researchers established 29 defect groups within this training section.

The training exercise served as a dress rehearsal for the drivers and raters who participated in the surveys. Each rater was given a separate book of rating forms to use during this training exercise. Based on the results from this training, researchers made the following adjustments to the original test plan:

1. Nine defect stations were removed from the list of defect groups to increase the time available for rating. The original test plan allowed at least 5 seconds for a rater to complete the rating sheet for a given defect. At a 50 mph test speed, this meant at least a 367-ft separation between consecutive defects. A common feedback from the raters and drivers during the training was that not enough time was given to complete the rating sheet for a given defect. The suggestion was made to allow at least 7 seconds for rating. Thus, the research supervisor identified and removed 9 defects from the list to increase the time

interval between ratings to at least 7 seconds. This decision trimmed down the number of defect stations from 118 to 109, with a good balance of 55 defects on the HMAC sections and 54 defects on the CRCP sections. Table 6 to Table 15 show the defect stations rated during the surveys. These tables also show the sequence of rating the defects for the given sections.

2. To reduce the amount of information to write down on the form during each run on a given section, everyone agreed to fill in as much information on the rating forms prior to running a given section. Thus, each driver would find a safe spot to park on the side of the road and tell the raters the defects to be rated on the upcoming run. The raters would then prepare the corresponding number of rating forms to rate these defects.
3. To further reduce the amount of information required on a given run, the decision was made to drop the number of defects felt by the rater as an input to the rating form, and to use the measured profile to determine this value. Originally, researchers included this entry in the rating form to provide additional information with which to investigate relationships between the panel rating data, and information from the measured profile. However, based on the feedback received from the training exercise, researchers decided to drop this variable, and have the panel members focus on rating the defect severity and the need for correction, which are the most important variables in these surveys.

While the drivers tried to stick close to the test plan, adjustments during the actual surveys were unavoidable. These adjustments occurred when the driver and/or the raters missed a given defect. When these events took place, the group either combined that defect with the other defects to be rated on the next pass, or made an additional run. Common reasons cited for missing a defect were:

1. The stake identifying the defect was missing or got knocked down. When this happened, the driver would radio or text the assigned person at the staging area who then reset the stake. There was an instance when drivers missed three defect stations because the cones holding the stakes at these stations disappeared.
2. The driver could not see the stake because it blended in with the surrounding environment under the prevailing light conditions and shadows. When this happened, the researcher texted the driver to let him know that the stake is in place, and remained at that station until after the driver's next pass.

The actual bump rating panel surveys were completed in two days. After the training exercise, each group was able to rate all the defects in their assigned vehicle during the same day. The ratings on the other two vehicles were completed the following day, at which time the raters turned in their rating books.

Table 6. Defect Stations along HMAC Section on Northbound Outside Lane of SH6 Frontage Roads.

Defect Group ID	Location from Start of Section (ft)	Pass to Rate Defect Group
B	764	1
D	898	3
E	1285	1
E	1292	1
E	1301	1
F	1336	2
F	1362	2
G	2581	1
G	2593	1
G	2606	1
G	2617	1
H	2636	2
H	2642	2
I	3510	1
J	3564	2
K	4235	3
L	4384	2
M	4760	1
M	4772	1
N	6217	1
O	6334	2
P	7306	1
Q	10,051	1
R	12,353	1
S	12,472	2
T	14,067	3
U	14,334	1
U	14,368	1
V	16,062	3
V	16,073	3
W	16,229	1
X	16,272	2
Y	21,531	1
Z	21,671	2
AA	22,229	1

Table 7. Defect Stations along HMAC Section on Southbound Outside Lane of SH6 Frontage Roads.

Defect Group ID	Location from Start of Section (ft)	Pass to Rate Defect Group
B	458	2
C	499	3
C	510	3
D	857	1
E	1731	1
F	2477	1
G	2515	2
H	5053	1
I	5591	1
J	6392	3
K	6583	1
L	8019	1
L	8045	1
M	10,172	1
N	10,229	2
P	12,660	1
P	12,670	1
P	12,686	1
Q	13,431	1
R	14,408	1
S	14,522	2
T	14,678	3
U	14,919	1
V	15,730	1
W	16,774	1
X	18,740	3
Y	18,954	2
Y	18,966	2
Y	18,977	2
Z	19,048	1
AA	20,455	1
AA	20,460	1
AA	20,473	1
AA	20,488	1
BB	20,729	2
CC	21,209	1
CC	21,243	1

Table 7. Defect Stations along HMAC Section on Southbound Outside Lane of SH6 Frontage Roads (continued).

Defect Group ID	Location from Start of Section (ft)	Pass to Rate Defect Group
EE	22,247	2
EE	22,266	2
EE	22,272	2
FF	22,307	1
GG	22,553	3

Table 8. Defect Stations along CRCP Section 1 on Northbound Outside Lane of SH6 Frontage Roads.

Defect Group ID	Location from Start of Section (ft)	Pass to Rate Defect Group
A	60	1
A	84	1
B	456	2
C	1295	3
D	2029	4
D	2053	4

Table 9. Defect Stations along CRCP Section 1 on Northbound Inside Lane of SH6 Frontage Roads.

Defect Group ID	Location from Start of Section (ft)	Pass to Rate Defect Group
A	61	1
A	67	1
A	72	1
A	81	1
B	457	2
C	936	3
D	1293	4
E	2029	5
E	2044	5
E	2054	5

Table 10. Defect Stations along CRCP Section 1 on Southbound Outside Lane of SH6 Frontage Roads.

Defect Group ID	Location from Start of Section (ft)	Pass to Rate Defect Group
A	83	1
B	274	2
B	288	2
E	728	5
F	788	1
F	823	1
G	873	2
H	968	3
I	1076	4
I	1107	4
J	1511	5
J	1519	5

Table 11. Defect Stations along CRCP Section 1 on Southbound Inside Lane of SH6 Frontage Roads.

Defect Group ID	Location from Start of Section (ft)	Pass to Rate Defect Group
A	83	1
A	153	1
B	261	2
B	274	2
B	303	2
C	414	3
D	548	4
G	906	2
H	984	3
H	997	3
I	1044	4
I	1067	4
J	1116	5
J	1140	5
K	1219	1

Table 12. Defect Stations along CRCP Section 2 on Northbound Outside Lane of SH6 Frontage Roads.

Defect Group ID	Location from Start of Section (ft)	Pass to Rate Defect Group
A	149	1
B	195	2
C	336	3
C	346	3
C	370	3
D	1220	1
E	2019	2
E	2032	2
F	2054	3
F	2069	3
F	2077	3
G	2220	1
H	2937	2
H	2950	2

Table 13. Defect Stations along CRCP Section 2 on Northbound Inside Lane of SH6 Frontage Roads.

Defect Group ID	Location from Start of Section (ft)	Pass to Rate Defect Group
A	73	1
A	82	1
B	141	2
C	180	3
C	187	3
D	334	4
E	2020	1
F	2933	2
F	2949	2

Table 14. Defect Stations along CRCP Section 2 on Southbound Outside Lane of SH6 Frontage Roads.

Defect Group ID	Location from Start of Section (ft)	Pass to Rate Defect Group
A	27	1
B	81	2
B	91	2
C	353	3
D	1018	1
E	1179	2
F	1297	3
G	1780	1
H	2378	2
H	2389	2
H	2404	2

Table 15. Defect Stations along CRCP Section 2 on Southbound Inside Lane of SH6 Frontage Roads.

Defect Group ID	Location from Start of Section (ft)	Pass to Rate Defect Group
A	81	1
A	91	1
B	695	2
C	1140	1
C	1161	1
C	1177	1
D	1216	3
E	1809	2
F	2393	4
F	2404	4

CHAPTER 3. ANALYSIS OF BUMP SURVEY DATA

INTRODUCTION

This chapter describes the analysis of the panel ratings from the bump surveys conducted in this project. This analysis aims to provide researchers with a basis for proposing revisions to TxDOT's existing Ride Quality bump template. As reported in the previous chapter, researchers established six sections along the SH6 frontage roads south of College Station, and identified pavement defects that were rated during the surveys. Briefly, 109 defect groups were identified in the 6 sections–55 in the two HMA sections and 54 in the four CRC pavements. Each defect group had one or more defects.

A bump panel consisting of nine TxDOT Engineers was asked to rate each defect group. A number between 0 and 10 was assigned to describe the severity of the bump, where the higher the rating, the greater the bump severity. Three different vehicle types were used. Each rater was asked to rate the defect group on each vehicle. Thus with nine raters, each bump was individually rated 27 times – nine raters in three different vehicle types. The rater was also asked to indicate whether the defect needed corrective action by checking *Yes* or *No* on the form provided. This chapter focuses on analyzing the ratings and relating these ratings to physical characteristics of the pavement profiles, which were also collected as part of the bump rating panel surveys.

ANALYSIS OF THE SURVEY VARIABLES

A large set of defects were selected for the rating session, resulting in a very large set of variables. A master database was generated consisting of the measured physical characteristics of each defect along with the subjective ratings of each rater. Since each rater measured the bump three times in three different vehicles, an entry was made in the database for the rater's name, vehicle, driver, and position in the vehicle. Researchers collected profile measurements on the survey sections to determine the size of each defect and its width. As discussed in Chapter 2, there were cases where several defects were close to one another making it difficult to rate the individual defects at 50 mph. For these cases, defect groups were established, where each group consisted of from 1 to 4 defects. A rating was then given for each defect group. There were 109 defect groups. As each defect was identified, the physical characteristics of each defect were recorded. These characteristics included the section, pavement type, number of defects in each group, defect number within the group, location of the defect, magnitude of the defect (bump or dip), and defect width. Table 16 identifies the variables researchers entered into the database detailing the physical characteristics of the various defects and the subjective ratings made by each rater:

Table 16. Variables Entered into the Bump Survey Database.

1. Bump rating ID	9. Seat (position in vehicle)
2. Section ID	10. Rating given for defect (0-10)
3. Pavement type	11. Correction needed? (Yes or No)
4. Number of defects within a group	12. Magnitude of 1st defect
5. Rating pass	13. Location of 1st defect
6. Vehicle	14. Width of 1st defect
7. Driver	15. (Magnitude, location, and width were repeated for each defect in group)
8. Rater	

In addition to these variables, other statistics or variables were identified and added such as the absolute value of the maximum defect height, sum of the defect widths, average width of the defects, and amplitude-to-width ratio for a given defect group. These additional variables are discussed later in the modeling process.

On examining the data, researchers found significant variation between individual raters in both the ratings of bump severity, and the need for corrective action. Likewise, as expected, the ratings over the same section varied depending on the vehicle types. For example, Figure 10 illustrates the rating distribution between all raters within the different vehicle types for the cases where corrective action was required. It is noted that raters tended to give higher severity ratings (or defects were more noticeable) when traveling in the van than when the same defects were rated in the sedan. For comparison, Figure 11 provides an example of the ratings given by one of the pavement engineers who indicated corrective action was required within the vehicle types. For this rater, a total of 55 defect groups were classified as needing corrective action when in the van, 74 when in the truck, and 42 when in the sedan.

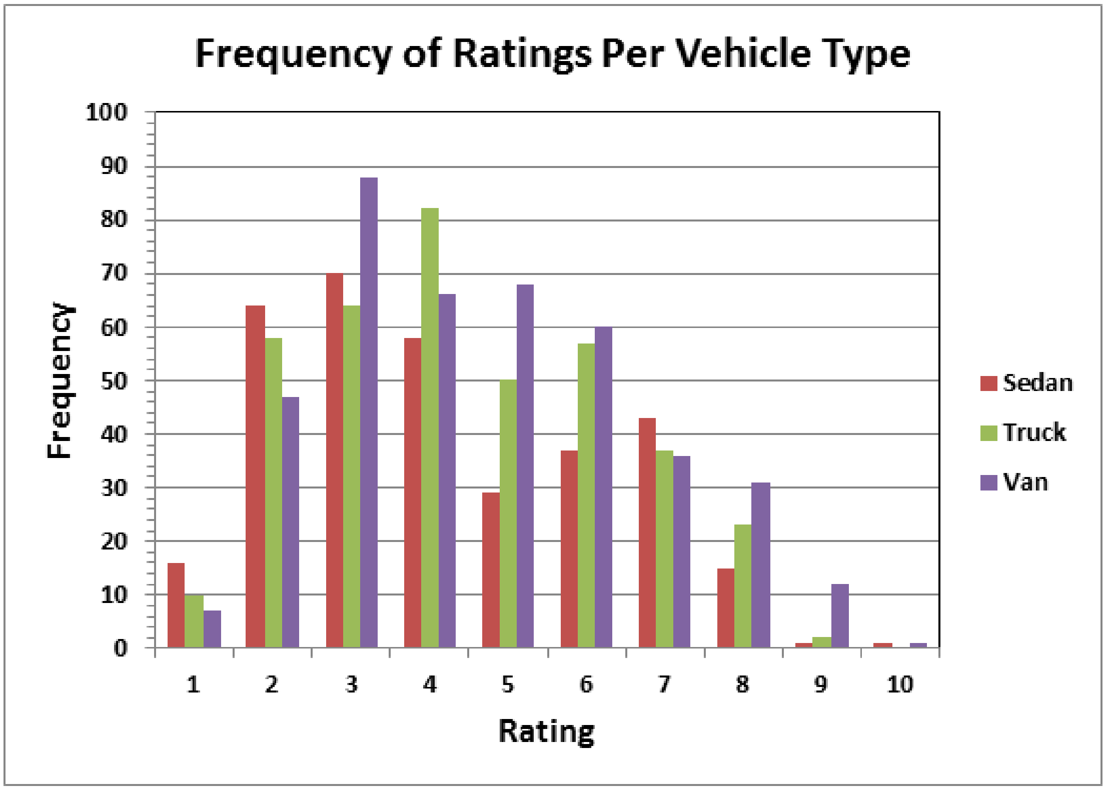


Figure 10. Variations in Ratings between Vehicles for all Raters Indicating Corrective Action Required.

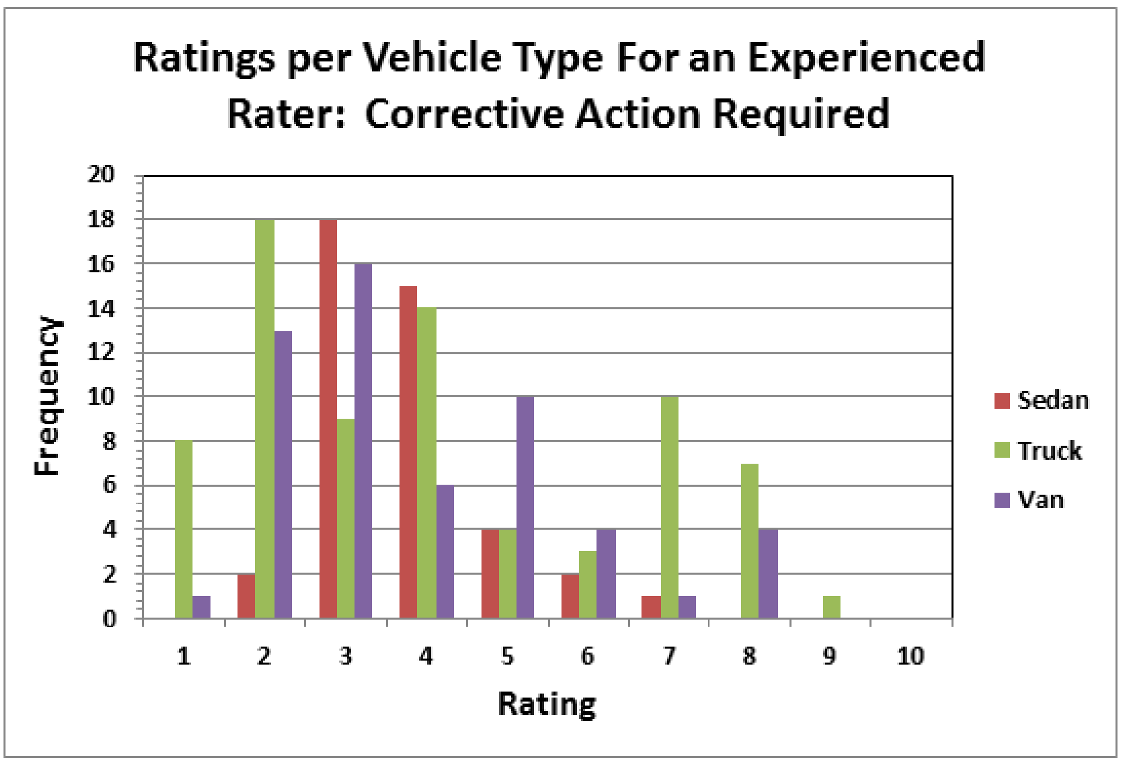


Figure 11. Variations in Ratings between Vehicles Indicating Corrective Action Required (Rater with Broad Pavement Engineering Experience).

A rater with relatively less experience in pavement condition assessment was driven in the same vehicle and over the same defects and gave very different ratings. This rater is consistent in that he always gave a rating of 3 when corrective action was selected. The only variation for this rater was in the number of defect groups classified as needing corrective action. When in the van, this rater found 13 defect groups requiring corrective action. When in the truck, the rater found 11, and when in the sedan, the rater only identified 2 defects requiring corrective work.

The mean of all ratings from panel members selecting corrective action is 4.107 with a standard error of 0.974. The mean of all ratings given by panel members indicating no corrective action required is 1.549 with a standard error of 0.647. Table 17 shows the means and standard deviations of the ratings based on the need for corrective action and by vehicle type. This table also shows the 95 percent confidence intervals of the average ratings. Figure 12 and Figure 13 provide plots of all the average ratings by vehicle type.

Considering all vehicles, Table 17 shows that the confidence intervals do not overlap between the two levels that define the need for corrective work. This result indicates that average ratings are significantly different between the two levels, with the mean rating for corrective work being significantly higher than the mean rating for defects where no corrective action is necessary. This same observation is observed for each vehicle type.

Table 17. Means and Standard Deviations of Ratings by Vehicle Type.

Vehicle Type	**Mean**	**Standard Deviation**	**95% Confidence Interval**	
All vehicles			**Lower**	**Upper**
Corrective Action	4.107	0.974	3.928	4.285
No Corrective Action	1.549	0.647	1.462	1.637
Van				
Corrective Action	4.486	1.034	4.164	4.809
No Corrective Action	1.606	0.634	1.451	1.761
Truck				
Corrective Action	4.091	1.009	3.768	4.414
No Corrective Action	1.579	0.653	1.422	1.736
Sedan				
Corrective Action	3.669	0.638	3.450	3.888
No Corrective Action	1.471	0.654	1.319	1.622

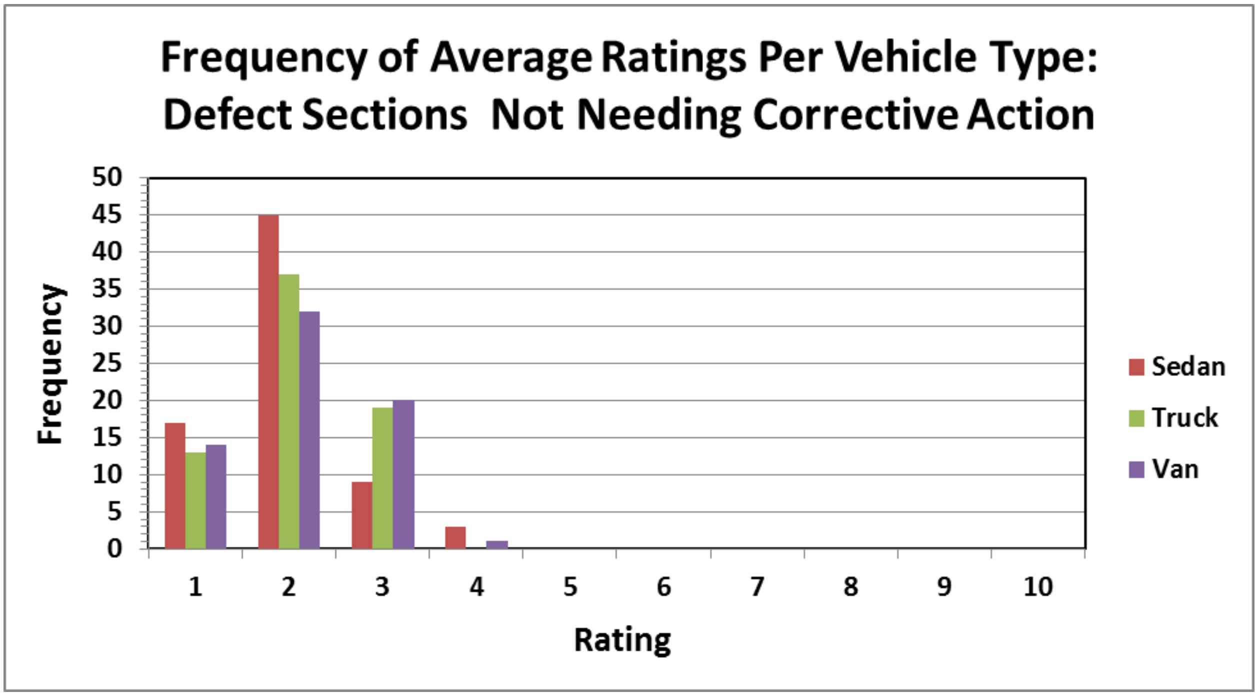


Figure 12. Variations in Average Ratings between Vehicles Where Raters Indicated No Corrective Action Needed.

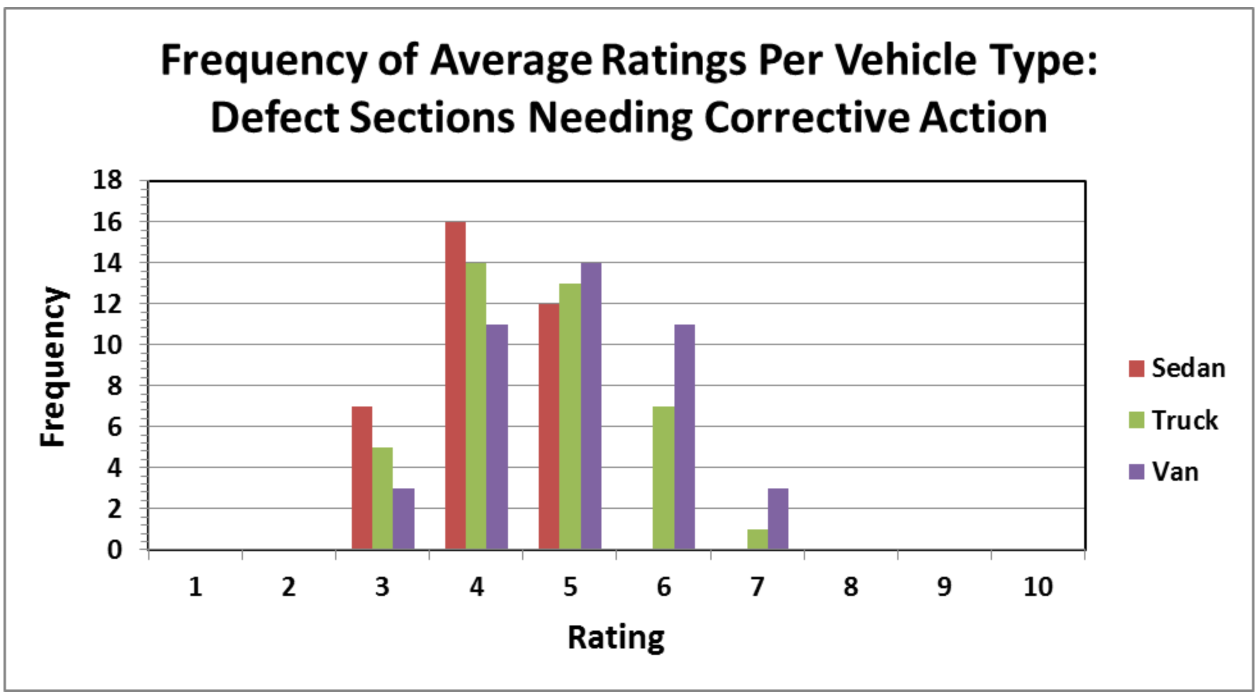


Figure 13. Variations in Average Ratings between Vehicles Where Raters Indicated Corrective Action Needed.

MODEL VARIABLES

A major objective of researchers was to determine if physical characteristics of the profile could be used to classify the severity of a defect and answer the question, "does the defect require corrective action or not?" This model would work to standardize the rating procedure and provide engineers with an objective method for determining the need for corrective work based on profile measurements.

To identify candidate variables that might be used in such a model, researchers considered physical characteristics of the measured wheel path profiles such as those identified previously. The following variables were included in the model development:

1. Pavement type – CRCP or HMA.
2. Maximum defect amplitude (mils) – Each defect group has one or more defects. The bump or dip amplitude is defined as the maximum absolute value of deviations greater than 150 mils from a 25-ft moving average. A positive deviation indicates a bump, and a negative deviation a dip. Note that this is the same definition used in TxDOT's existing Ride Quality procedure.
3. Average defect width (feet) – The bump or defect width is defined as the distance between the two points where the profile crosses the 25-ft running average. For multiple defects in a defect group, this statistic is the average of those widths.
4. Sum of defect amplitudes (mils) – Similar to the maximum defect amplitude, this variable is the sum of all defect amplitudes in a group.
5. Sum of defect widths (feet) – Similar to the sum of defect amplitudes, this is the sum of all defect widths in a defect group.
6. Amplitude-to-width ratio – The ratio of the sum of defect amplitudes to the sum of defect widths.
7. Sum of Type I IRIs (in/mile) – Researchers evaluated the contribution of a given defect to the IRI of a 528-ft section in two ways. The first method is based on the difference between the IRI computed from the existing wheel path profile and the IRI based on the simulated profile after correcting only defect *j*. This difference is referred to as the Type I IRI contribution for defect *j* as illustrated in Figure 14. The sum of the Type I IRIs is the sum of the computed Type I IRI contributions for the defects within a given group.
8. Sum of Type II IRIs (in/mile) – Figure 15 illustrates the second method for evaluating the contribution of a given defect to the section IRI. This method, referred to as the Type II IRI contribution, is based on the difference between the IRI computed from the simulated wheel path profile after correcting all defects except defect *j*, and the IRI computed from the simulated profile with all defects fixed. The sum of the Type II IRIs is the sum of the computed Type II IRI contributions for the defects within a given group.
9. Maximum Type I IRI (in/mile) – This is the maximum of the Type I IRIs in a defect group.
10. Maximum Type II IRI (in/mile) – This is the maximum of the Type II IRIs in a defect group.

11. Weighted average amplitude – Average of the defect amplitudes weighted by the widths of the defects in the group.
12. Number of ratings – number of defect groups rated by each rater. Each of the nine raters rode in three vehicles for a total of 27 possible ratings per defect group.
13. Average defect rating – Average of ratings given for each defect group.
14. Proportion of *Yes* Votes – Proportion of those raters indicating corrective action required to the total number of ratings for the given defect group. This was used as the independent variable in the logistic regression model.

Table 18 provides a list of the variables and values used in the logistic regression analysis. The next section presents the models developed from this analysis.

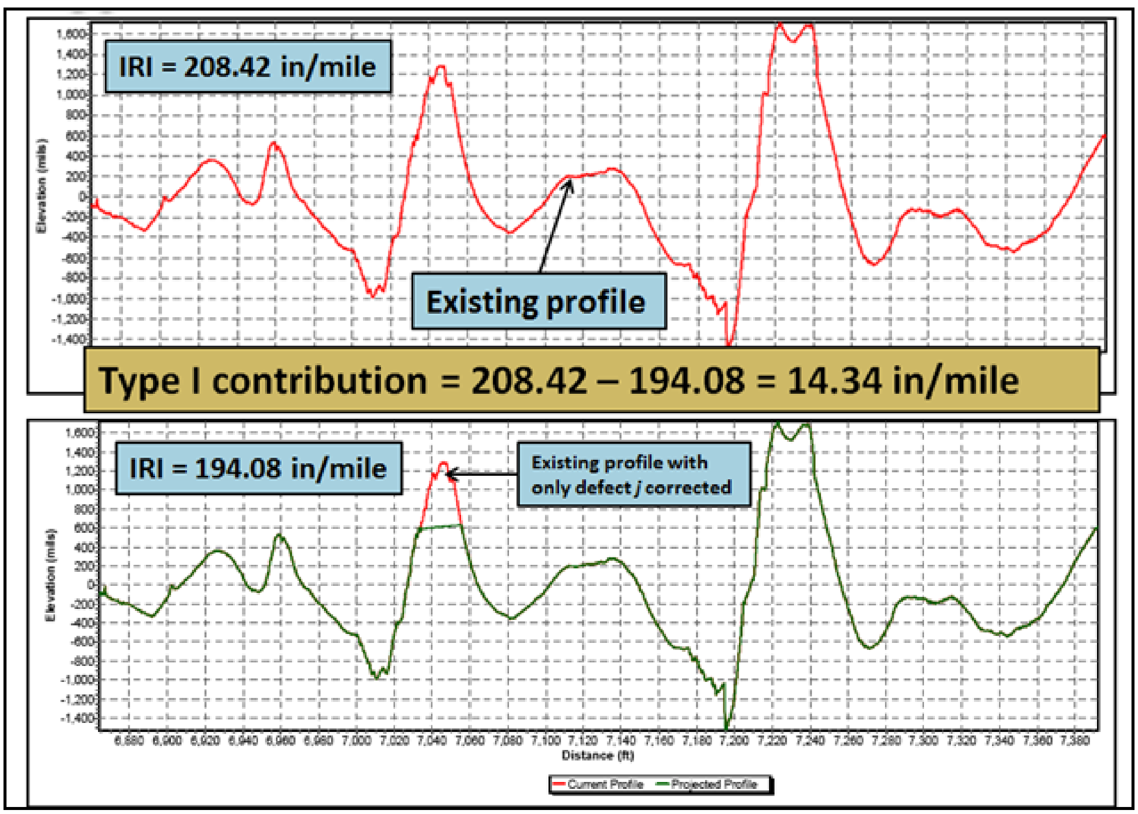


Figure 14. Type I IRI Contribution.

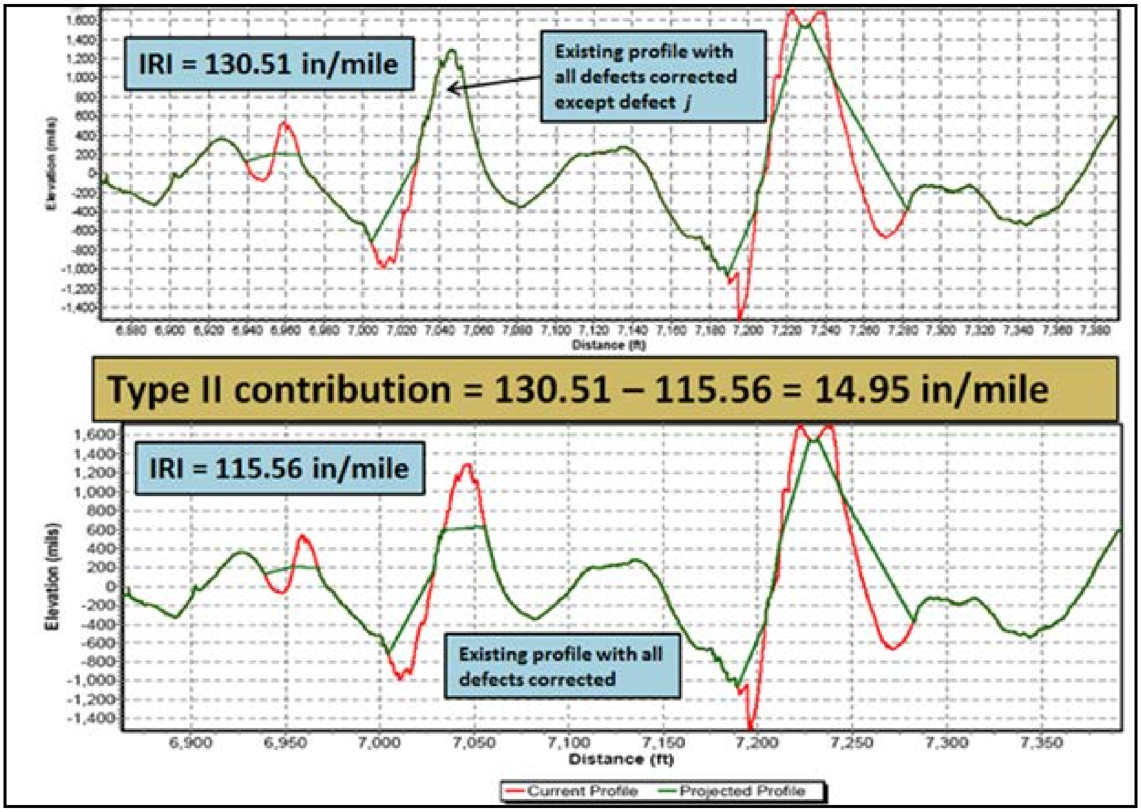


Figure 15. Type II IRI Contribution.

Table 18. Variables Used in Logistic Regression Analysis.

Section ID	Defect Group	Pavement Type	Average defect rating	Maximum defect ampl. (mils)	Average defect width (ft)	Sum of defect ampl. (mils)	Sum of defect widths (ft)	Maximum Type I IRI (in/mile)	Proportion of *Yes* votes	Correct defect?
CRCP_N1_IL	A	1	4.00	530	5.35	1453	21.40	7.27	0.67	1
CRCP_N1_IL	B	1	1.27	543	43.00	543	43.00	12.51	0.15	0
CRCP_N1_IL	C	1	2.34	227	14.00	227	14.00	4.60	0.41	0
CRCP_N1_IL	D	1	1.69	557	40.00	557	40.00	9.34	0.19	0
CRCP_N1_IL	E	1	4.91	645	10.33	1475	31.00	18.79	0.82	1
CRCP_N1_OL	A	1	5.03	753	4.50	1497	9.00	14.19	0.82	1
CRCP_N1_OL	B	1	0.62	481	35.00	481	35.00	10.62	0.07	0
CRCP_N1_OL	C	1	1.09	599	44.00	599	44.00	8.38	0.07	0
CRCP_N1_OL	D	1	4.69	355	6.50	611	13.00	4.95	0.85	1
CRCP_N2_IL	A	1	3.30	369	14.00	646	28.00	8.52	0.56	1
CRCP_N2_IL	B	1	4.27	397	22.00	397	22.00	17.20	0.83	1
CRCP_N2_IL	C	1	3.36	502	13.00	844	26.00	6.98	0.56	1
CRCP_N2_IL	D	1	1.51	202	5.00	202	5.00	1.68	0.15	0
CRCP_N2_IL	E	1	2.99	294	20.00	294	20.00	13.16	0.48	0
CRCP_N2_IL	F	1	4.03	560	15.00	961	30.00	15.32	0.67	1
CRCP_N2_OL	A	1	3.74	531	14.00	531	14.00	3.62	0.70	1
CRCP_N2_OL	B	1	2.90	378	9.00	378	9.00	4.60	0.41	0
CRCP_N2_OL	C	1	2.29	331	19.33	938	58.00	9.81	0.37	0
CRCP_N2_OL	D	1	1.44	233	8.00	233	8.00	1.72	0.15	0
CRCP_N2_OL	E	1	4.34	480	10.00	713	20.00	8.58	0.74	1
CRCP_N2_OL	F	1	4.25	330	6.33	814	19.00	4.30	0.70	1
CRCP_N2_OL	G	1	2.54	273	9.00	273	9.00	5.64	0.35	0

Table 18. Variables Used in Logistic Regression Analysis (continued).

Section ID	Defect Group	Pavement Type	Average defect rating	Maximum defect ampl. (mils)	Average defect width (ft)	Sum of defect ampl. (mils)	Sum of defect widths (ft)	Maximum Type I IRI (in/mile)	Proportion of *Yes* votes	Correct defect?
CRCP_N2_OL	H	1	5.40	585	8.00	975	16.00	21.77	0.85	1
CRCP_S1_IL	A	1	1.87	295	10.00	562	20.00	4.02	0.22	0
CRCP_S1_IL	B	1	3.31	667	11.67	1283	35.00	12.61	0.59	1
CRCP_S1_IL	C	1	1.73	357	11.00	357	11.00	4.56	0.22	0
CRCP_S1_IL	D	1	1.24	308	38.00	308	38.00	9.43	0.04	0
CRCP_S1_IL	G	1	1.57	247	9.00	247	9.00	2.96	0.15	0
CRCP_S1_IL	H	1	1.65	261	9.50	513	19.00	5.72	0.11	0
CRCP_S1_IL	I	1	1.77	265	12.50	491	25.00	3.92	0.19	0
CRCP_S1_IL	J	1	1.96	291	13.50	563	27.00	6.85	0.15	0
CRCP_S1_IL	K	1	1.34	235	12.00	235	12.00	3.28	0.11	0
CRCP_S1_OL	A	1	3.68	265	10.00	265	10.00	1.94	0.63	1
CRCP_S1_OL	B	1	1.60	468	12.00	880	24.00	7.97	0.19	0
CRCP_S1_OL	E	1	1.37	319	25.00	319	25.00	6.15	0.00	0
CRCP_S1_OL	F	1	1.01	391	35.00	661	70.00	9.88	0.07	0
CRCP_S1_OL	G	1	1.34	543	24.00	543	24.00	12.21	0.04	0
CRCP_S1_OL	H	1	1.03	419	39.00	419	39.00	10.02	0.00	0
CRCP_S1_OL	I	1	1.60	239	9.00	470	18.00	4.03	0.19	0
CRCP_S1_OL	J	1	1.31	232	15.00	457	30.00	6.17	0.11	0
CRCP_S2_IL	A	1	5.36	414	8.50	823	17.00	7.92	0.96	1
CRCP_S2_IL	B	1	0.70	748	58.00	748	58.00	9.37	0.00	0
CRCP_S2_IL	C	1	2.44	863	20.67	1558	62.00	18.78	0.41	0
CRCP_S2_IL	D	1	1.36	319	12.00	319	12.00	5.79	0.11	0

Table 18. Variables Used in Logistic Regression Analysis (continued).

Section ID	Defect Group	Pavement Type	Average defect rating	Maximum defect ampl. (mils)	Average defect width (ft)	Sum of defect ampl. (mils)	Sum of defect widths (ft)	Maximum Type I IRI (in/mile)	Proportion of *Yes* votes	Correct defect?
CRCP_S2_IL	E	1	1.46	199	11.00	199	11.00	3.14	0.15	0
CRCP_S2_IL	F	1	4.54	611	9.50	1127	19.00	18.61	0.74	1
CRCP_S2_OL	A	1	4.42	258	7.00	258	7.00	0.57	0.78	1
CRCP_S2_OL	B	1	5.11	425	12.50	773	25.00	6.52	0.82	1
CRCP_S2_OL	C	1	0.46	625	50.00	625	50.00	6.91	0.00	0
CRCP_S2_OL	D	1	1.17	564	46.00	564	46.00	11.53	0.07	0
CRCP_S2_OL	E	1	1.86	671	61.00	671	61.00	11.60	0.15	0
CRCP_S2_OL	F	1	1.06	327	38.00	327	38.00	11.97	0.04	0
CRCP_S2_OL	G	1	0.96	313	49.00	313	49.00	12.43	0.00	0
CRCP_S2_OL	H	1	4.22	438	7.67	981	23.00	17.84	0.73	1
HMACN	AA	2	1.60	267	30.00	267	30.00	13.40	0.22	0
HMACN	B	2	1.27	189	14.00	189	14.00	4.91	0.19	0
HMACN	D	2	0.87	201	15.00	201	15.00	1.65	0.04	0
HMACN	E	2	4.37	666	11.67	1667	35.00	14.40	0.85	1
HMACN	F	2	3.16	282	26.50	492	53.00	9.99	0.41	0
HMACN	G	2	4.32	520	10.75	1368	43.00	10.93	0.78	1
HMACN	H	2	4.01	290	8.50	446	17.00	4.47	0.85	1
HMACN	I	2	4.59	515	15.00	515	15.00	13.55	0.82	1
HMACN	J	2	3.74	335	12.00	335	12.00	1.71	0.67	1
HMACN	K	2	0.93	203	13.00	203	13.00	3.45	0.04	0
HMACN	L	2	1.27	164	19.00	164	19.00	7.48	0.07	0
HMACN	M	2	1.09	288	10.50	544	21.00	5.47	0.07	0

Table 18. Variables Used in Logistic Regression Analysis (continued).

Section ID	Defect Group	Pavement Type	Average defect rating	Maximum defect ampl. (mils)	Average defect width (ft)	Sum of defect ampl. (mils)	Sum of defect widths (ft)	Maximum Type I IRI (in/mile)	Proportion of *Yes* votes	Correct defect?
HMACN	N	2	1.92	326	12.00	326	12.00	6.15	0.26	0
HMACN	O	2	1.45	257	8.00	257	8.00	2.83	0.26	0
HMACN	P	2	0.85	288	9.00	288	9.00	3.79	0.04	0
HMACN	Q	2	3.99	358	4.00	358	4.00	7.82	0.78	1
HMACN	R	2	2.23	327	8.00	327	8.00	6.71	0.33	0
HMACN	S	2	2.05	222	12.00	222	12.00	4.42	0.37	0
HMACN	T	2	1.62	368	9.00	368	9.00	7.86	0.22	0
HMACN	U	2	1.98	223	10.00	415	20.00	5.67	0.26	0
HMACN	V	2	2.54	365	11.50	684	23.00	5.26	0.44	0
HMACN	W	2	2.40	291	24.00	291	24.00	9.82	0.37	0
HMACN	X	2	2.39	178	42.00	178	42.00	5.60	0.44	0
HMACN	Y	2	2.50	292	6.00	292	6.00	9.86	0.41	0
HMACN	Z	2	1.68	239	13.00	239	13.00	3.65	0.26	0
HMACS	AA	2	3.27	486	11.00	1223	44.00	9.25	0.70	1
HMACS	B	2	2.72	218	8.00	218	8.00	3.27	0.59	1
HMACS	BB	2	0.30	197	0.72	197	0.72	0.43	0.00	0
HMACS	C	2	3.43	389	17.00	674	34.00	10.89	0.78	1
HMACS	CC	2	2.59	566	31.00	721	62.00	6.22	0.56	1
HMACS	D	2	1.62	202	9.00	202	9.00	3.39	0.22	0
HMACS	E	2	2.39	155	2.00	155	2.00	2.94	0.52	1
HMACS	EE	2	1.55	274	4.00	655	12.00	2.63	0.15	0
HMACS	F	2	5.31	525	21.00	525	21.00	14.99	0.82	1

Table 18. Variables Used in Logistic Regression Analysis (continued).

Section ID	Defect Group	Pavement Type	Average defect rating	Maximum defect ampl. (mils)	Average defect width (ft)	Sum of defect ampl. (mils)	Sum of defect widths (ft)	Maximum Type I IRI (in/mile)	Proportion of *Yes* votes	Correct defect?
HMACS	FF	2	4.83	536	17.00	536	17.00	25.56	0.93	1
HMACS	G	2	4.82	410	10.00	410	10.00	8.10	0.89	1
HMACS	GG	2	2.12	447	7.00	447	7.00	9.09	0.48	0
HMACS	H	2	3.07	280	8.00	280	8.00	7.52	0.59	1
HMACS	I	2	1.81	1334	56.00	1334	56.00	8.52	0.26	0
HMACS	J	2	2.26	341	11.00	341	11.00	4.34	0.41	0
HMACS	K	2	2.05	207	20.00	207	20.00	6.02	0.30	0
HMACS	L	2	0.98	1182	36.50	1495	73.00	11.82	0.11	0
HMACS	M	2	3.19	440	11.00	440	11.00	8.76	0.70	1
HMACS	N	2	3.81	524	11.00	524	11.00	9.31	0.82	1
HMACS	P	2	5.31	1053	12.00	1810	36.00	13.29	0.85	1
HMACS	Q	2	1.49	173	10.00	173	10.00	1.95	0.15	0
HMACS	R	2	2.06	217	8.00	217	8.00	5.34	0.44	0
HMACS	S	2	1.43	246	10.00	246	10.00	4.78	0.26	0
HMACS	T	2	1.08	259	7.00	259	7.00	3.19	0.07	0
HMACS	U	2	0.70	156	6.00	156	6.00	2.35	0.07	0
HMACS	V	2	0.80	160	4.00	160	4.00	3.15	0.04	0
HMACS	W	2	0.85	160	4.00	160	4.00	4.14	0.11	0
HMACS	X	2	1.32	174	21.00	174	21.00	7.27	0.26	0
HMACS	Y	2	3.63	555	12.33	1193	37.00	11.85	0.59	1
HMACS	Z	2	2.87	366	7.00	366	7.00	11.03	0.56	1

MODEL DEVELOPMENT

Two models are of interest in this project. The most important model from a practical point of view is one that relates the need for corrective action to physical profile characteristics. Of lesser importance, but perhaps of interest, is a model for predicting the defect rating based on the proportion of raters who said *Yes* on the question of should the defect be corrected.

For the first case, researchers used logistic regression for model development. For the second case, standard linear regression was used. The following sections present the results from the modeling effort.

Logistic Regression to Predict Need for Correction

Researchers used the independent variables identified previously in a stepwise logistic regression analysis to determine a model that relates profile physical characteristics to the need for correcting a given defect. From this data, the stepwise analysis selected a subset of the variables used in the regression. Table 18 identifies five independent variables that were found to have statistical significance at above the 95 percent level. These variables are the maximum defect amplitude, average defect width, sum of defect amplitudes, sum of defect widths, and the maximum Type I IRI contribution. Researchers note that for cases where there is only one defect in a group, the first four of these variables reduce to the defect amplitude and width, and the maximum Type I IRI contribution is the Type I IRI contribution of that same defect to the section IRI.

The stepwise logistic regression analysis identified a two- and a three-variable model to predict the need for corrective action on a given defect. Researchers used logistic regression (*9*) since the decision to correct is binary, that is, does the defect need correction or not. For this case, the decision to perform corrective action is based on whether the proportion of raters who voted *Yes* on the need for corrective work meets the selected threshold. In Table 18 for example, if the proportion of *Yes* votes is greater than 0.5 (representing a simple majority), the need for correction is coded as 1, i.e., correct the defect. Otherwise, the need for correction is coded 0 (do not correct).

Researchers used the stepwise logistic regression procedure in the Statistical Analysis System (SAS) to identify models for predicting the need for corrective work using the independent variables identified previously. This analysis identified a number of prediction equations based on the following logistic model:

$$y = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \cdots + \beta_n x_n)}}$$

Equation 1

where,

y = predicted defect correction index ($0 \le y \le 1$).

x_i = i^{th} independent variable (i =1 to n).

β_i = i^{th} model coefficient (i =1 to n).

n = number of independent variables.

Researchers determined the three-variable model given in Table 19 from the stepwise logistic regression analysis. As shown in this table, two of the independent variables (sum of defect amplitudes and sum of defect widths) are statistically significant at greater than the 99 percent level as indicated by the small p-values for these variables. The third variable (maximum Type I IRI contribution) is statistically significant at above the 95 percent level. The three-variable model shown in Table 19 gave the best results in terms of predictive accuracy. For this reason, researchers favor it over the other models identified in the logistic regression analysis. In practice, one would use the parameter estimates given in Table 19 along with the applicable values of the independent variables to predict the defect correction index (DCI) according to the logistic model given by Equation 1. If the predicted DCI is more than 0.5, then corrective work is needed for the given defect.

As shown in Table 20, the model is 84.4 percent correct in predicting the need for corrective work based on the total number of defects rated in the bump surveys. Two types of errors are identified in the table. The Type A error is where the majority of raters indicated corrective action was needed; however, the model indicated otherwise. In contrast, the Type B Error is where the majority of raters indicated no corrective action was needed; however, the model predicted just the opposite.

As shown in Table 20, the three-variable model misclassified 12 of the 109 defects as not needing correction when the majority of raters said otherwise on those same defects (a Type A error of 11.01 percent). Similarly, the model misclassified 5 of the 109 defects as needing correction for a Type B error of 4.59 percent. Researchers note that two different software packages were used to perform the logistic regression – SAS developed by the SAS Institute, and Matlab developed by Mathworks Incorporated. Both gave the same results for the selected model.

Table 19. Coefficients of Three-Variable Logistic Model.

Parameter	Estimate	Wald chi-square	Pr > chi-square
Intercept	-2.1923	14.8398	0.0001
Sum of defect amplitudes	0.00597	15.8864	<0.0001
Sum of defect widths	-0.1317	14.1709	0.0002
Max. Type I IRI contribution	0.1497	4.0745	0.0435

Table 20. Goodness-of-Fit Statistics for Three-Variable Model.

Actual	**Predicted**		**Total**
	Yes	No	
Yes	27	12	39
No	5	65	70
Total	32	77	109
	% Correct	84.40	
	% Error	15.60	
	Type A error (%)	11.01	
	Type B error (%)	4.59	

Using logistic regression, researchers also determined a two-variable model to predict the need for corrective work. This model is a little more compatible with the current TxDOT Ride Quality procedure, which uses the deviation from the 25-ft moving average in determining defects. The contribution of the defect to the section IRI is not included in this model. Rather, the model predicts the defect correction index based on the maximum defect amplitude and the average defect width. Both variables are computed in a similar manner as in TxDOT's Ride Quality program with the exception of the defect width. The Ride Quality program defines the defect width as the interval where the deviations between the average profile and its moving average are more than 150 mils. For the logistic models evaluated in this project, the defect width is defined as the distance between the two points where the measured wheel path profile crosses the 25-ft running average profile.

As noted, the two-variable model uses the maximum defect amplitude and the average defect width as independent variables to predict the need for correction. Table 21 shows the model coefficients determined from the logistic regression analysis. As shown, both independent variables are statistically significant at above the 99 percent level with *p*-values smaller than 0.0001.

Table 21. Coefficients of Two-Variable Logistic Model.

Parameter	Estimate	Wald chi-square	Pr > chi-square
Intercept	−1.4383	6.7654	0.0093
Max. defect amplitude	0.00906	19.1642	<0.0001
Average defect width	−0.1974	15.3804	<0.0001

Table 22 shows goodness-of-fit statistics for the two-variable model. This model has a Type A error of 11.93 percent and a Type B error of 8.26 percent. Overall, the model correctly predicted the need for corrective work on 87 of the 109 defects rated during the surveys for a 79.82 percent agreement factor. This statistic is slightly lower than the 84.4 percent agreement factor determined for the three-variable model.

Table 22. Goodness-of-Fit Statistics for Two-Variable Model.

Actual	Predicted		Total
	Yes	No	
Yes	26	13	39
No	9	61	70
Total	35	74	109
	% Correct	79.82	
	% Error	20.18	
	Type A error (%)	11.93	
	Type B error (%)	8.26	

Researchers note that thresholds other than 0.5 were used to evaluate models for predicting the need for corrective work based on defect characteristics computed from measured profiles. However, a 0.5 threshold gave the highest agreement factor for both the two- and three-variable models presented in this chapter. As expected, thresholds higher than 0.5 led to higher Type A errors, while thresholds lower than 0.5 led to higher Type B errors. Thus, a threshold of 0.5 gave the most balanced results.

Linear Regression to Predict Average Defect Rating

Researchers also determined the relationship between the proportion of *Yes* votes to correct a given defect, and the average of the ratings for that defect. For this evaluation, researchers performed a simple linear regression where the average severity rating for a given defect is the dependent variable, and the actual proportion of *Yes* votes to correct the same defect is the independent variable, i.e., number of raters indicating corrective action to the total number of raters. Thus, the independent variable ranges between zero and one. The regression analysis yielded the following model:

$$R = \beta_0 + \beta_1 * C$$ **Equation 2**

where,

R	=	averaging rating for a given defect.
C	=	proportion of *Yes* votes for corrective work.
β_0	=	0.7098.
β_1	=	4.5426.

The model has an R^2 of 93.3 percent and a standard error of the estimate (SEE) of 0.3581. Figure 16 illustrates the goodness-of-fit of the model.

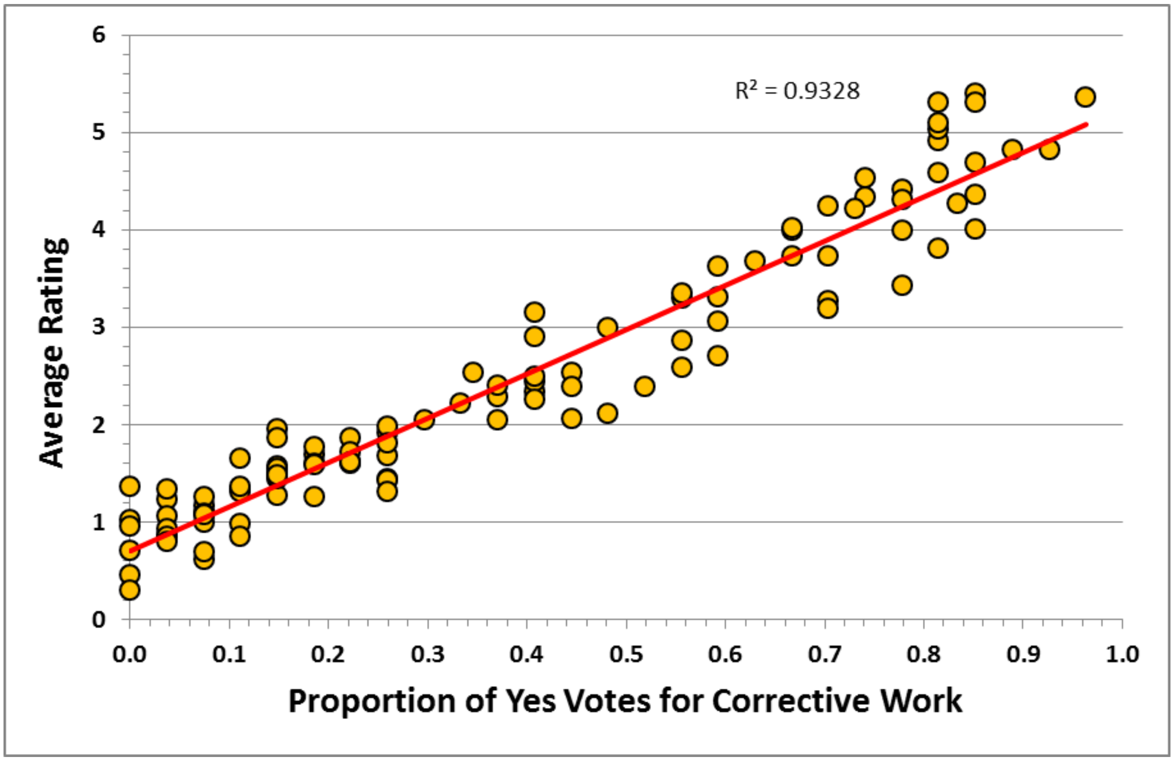


Figure 16. Relationship between Average Severity Rating and Proportion of Yes Votes to Correct a Given Defect.

SUMMARY

This task evaluated relationships to predict the need for corrective work based on defect characteristics determined from measured profile. Two different models were presented. The 3-variable model gives a slightly better agreement factor than the 2-variable model but will require slightly more modifications to the existing Ride Quality program for implementation. The main modification would be the addition of new code to calculate the contribution of a given defect to the section IRI. However, researchers do not expect this modification to be extensive. Both models use independent variables based on defect amplitude and width, which are currently computed in the existing Ride Quality program. However, differences in the calculation of defect width between the existing program and the models presented in this chapter will require additional program revisions to implement either model. Recommendations for revising TxDOT's existing methodology to evaluate localized roughness are presented in the succeeding chapter of this report.

CHAPTER 4. RECOMMENDATIONS FOR EVALUATING LOCALIZED ROUGHNESS

INTRODUCTION

In the previous chapter, researchers developed equations for predicting the need to correct defects identified from profile measurements of the pavement surface. These equations can be used for ride quality assurance testing on Item 585 projects to make decisions for correcting bumps and dips based on objective profile measurements. Researchers studied these equations to establish recommendations for revising the existing TxDOT methodology to evaluate localized roughness from inertial profile measurements. This chapter presents these recommendations, which are based on using the defect correction index from Chapter 3.

RECOMMENDED CHANGES TO EXISTING METHODOLOGY FOR EVALUATING LOCALIZED ROUGHNESS

Researchers considered the following criteria to develop recommendations on revisions to TxDOT's existing methodology for evaluating localized roughness:

- Agreement with the bump panel ratings in terms of the number of defects correctly classified as needing corrective work, and
- Ease of implementing the proposed revisions within the current TxDOT framework for acceptance testing of pavement smoothness.

As presented in Chapter 3, two alternative equations were developed for calculating the defect correction index (DCI) to determine the need for corrective work. These equations are based on the logistic model and are given as follows:

$$y = \frac{1}{1 + e^{-(-2.1923 + 0.00597 x_1 - 0.1317 x_2 + 0.1497 x_3)}}$$

Equation 3

where,

y	=	defect correction index.
x_1	=	sum of defect amplitudes (mils).
x_2	=	sum of defect widths (ft).
x_3	=	maximum Type I contribution to section IRI (in/mile).

$$y = \frac{1}{1+e^{-(-1.4383+0.00906x_4 - 0.1974x_5)}}$$

Equation 4

where,

x_4 = maximum defect amplitude (mils).

x_5 = average defect width (ft).

As noted in Chapter 3, the 3-variable model in Equation 3 gives a slightly better agreement factor than the 2-variable model in Equation 4 but will require slightly more modifications to the existing Ride Quality program for implementation. The main modification would be the addition of new code to calculate the contribution of a given defect to the section IRI. However, researchers do not expect this modification to be extensive for the following reasons:

- The existing program already identifies defects based on the deviation of the average profile from its 25-ft moving average.
- The existing program already computes the International Roughness Index from the measured wheel path profiles.

Thus, the main change would be to add a loop to compute the IRI based on the simulated profile of the 528-ft section after correcting a given defect. The number of cycles in this loop will equal the number of defects found within the section. At each cycle, the program will compute the IRI based on the simulated profile assuming that only the defect for the given cycle is corrected within the section. The program will then compute the Type I IRI contribution by taking the difference between the IRI of the measured profile (which is already computed in the existing program), and the IRI calculated in the current loop cycle. Researchers realize that, while this change is conceptually simple, the actual program modifications would require a cooperative effort between TxDOT and the researchers who performed the development work in this research project.

Consequently, researchers recommend that TxDOT support a 1-year implementation project to revise the current Ride Quality program and pilot test the modified program on actual Item 585 projects. The following program modifications are recommended:

1. Equation 3 and Equation 4 use independent variables based on defect amplitude and width, which are currently computed in the existing Ride Quality program. However, the existing program computes the defect amplitude based on the average of the left and right wheel path profiles. TxDOT needs to revise the program to compute and report the defect amplitude

based on the measured profile for each wheel path, similar to the calculation of the IRI by wheel path, which the program currently does.
2. The Ride Quality program should also be modified to report the defect width as the distance between consecutive points where the measured wheel path profile intersects its 25-ft moving average. Currently, the defect width is calculated as the interval where the magnitudes of the deviations between the average profile and its moving average exceed 150 mils.
3. In lieu of using the 5-ft bump penalty gap to group closely spaced defects, TxDOT should modify the Ride Quality program to group defects found within an 80-ft interval. This recommendation is based on the defect groups rated during the bump surveys, where the maximum group length was 80 ft. As explained in the previous chapter, researchers grouped defects that were closely spaced since it would not be possible to rate the individual defects at the selected survey test speed of 50 mph. Thus, the rating given for a defect group corresponds to an aggregate severity rating for all the defects found in that group. Researchers note that the recommended defect group size of 80 ft is about the length traveled in one second at a speed of 55 mph.
4. TxDOT should also modify the Ride Quality program to permit the calculation of the Type I IRI contribution as explained previously and as illustrated in Chapter 3.

Researchers estimate that the above modifications can be completed within the initial four months of the proposed implementation project. Once the modifications are completed, the revised program should then be pilot tested on a number of TxDOT projects where Item 585 is included in the plans. As noted at the beginning of this section, researchers considered two criteria in developing the recommendations for revising the current methodology to evaluate localized roughness. In terms of these criteria, Equation 3 provides slightly better agreement with the panel ratings. However, Equation 4 is slightly easier to implement within the existing TxDOT framework to evaluate localized roughness. Thus, researchers recommend pilot testing the revised Ride Quality program to determine which of the two equations would work best in practice. The following section provides an illustration of how the two equations would be used in practice to determine the need for corrective work based on the measured wheel path profiles.

EXAMPLE APPLICATION OF PROPOSED EQUATIONS TO DETERMINE NEED FOR CORRECTING DEFECTS IDENTIFIED FROM PROFILE MEASUREMENTS

To illustrate the application of the proposed equations to determine the need for corrections based on the defect correction index, researchers obtained profile data collected from quality assurance testing of pavement smoothness on a new CRCP project located south of College Station in the Bryan District. Table 23 identifies the PRO files used in this illustrative example. These files were provided by the Bryan District.

Table 23. PRO Data Files from Smoothness Quality Assurance Tests on SH6 CRCP Project South of College Station.

PRO File Name	Test Lane	Starting Station	Length of Run (miles)
NAVASOTA,SH.6, NB. L-1, STA. 556+503	L1	556+50.3	1.994
NAVASOTA,SH.6, NB. L-2, STA. 556+501	L2	556+50.1	1.985
NAVASOTA,SH.6, SB. L-1, STA. 425+002	R1	425+00.2	2.976
NAVASOTA,SH.6, SB. L-2, STA. 425+004	R2	425+00.4	2.987
NAVASOTASH6,NB.L-1,2	L1	412+50.0	2.997
NAVASOTASH6,NB.L-2,3	L2	412+50.0	2.993
NAVASOTASH6,SB.L-1,4	R1	253+50.0	3.125
NAVASOTASH6,SB.L-2-,5	R2	253+50.0	3.125

Data were collected using the Ames Model 8200 profiler owned by Southern Crushed Concrete, which is affiliated with Webber, the company that placed the continuously reinforced concrete pavements along this new highway construction project. This particular profiler is equipped with the Ames TriODS shown in Figure 17, which uses three lasers for surface profile measurement per wheel path.

Table 24 illustrates the calculation of the defect correction index using the 3-variable model given in Equation 3. This illustration is based on the measured left wheel path profile on the northbound outside lane (L1) of the project beginning at station 412+50.0. The calculation of the DCI in this example is explained as follows:

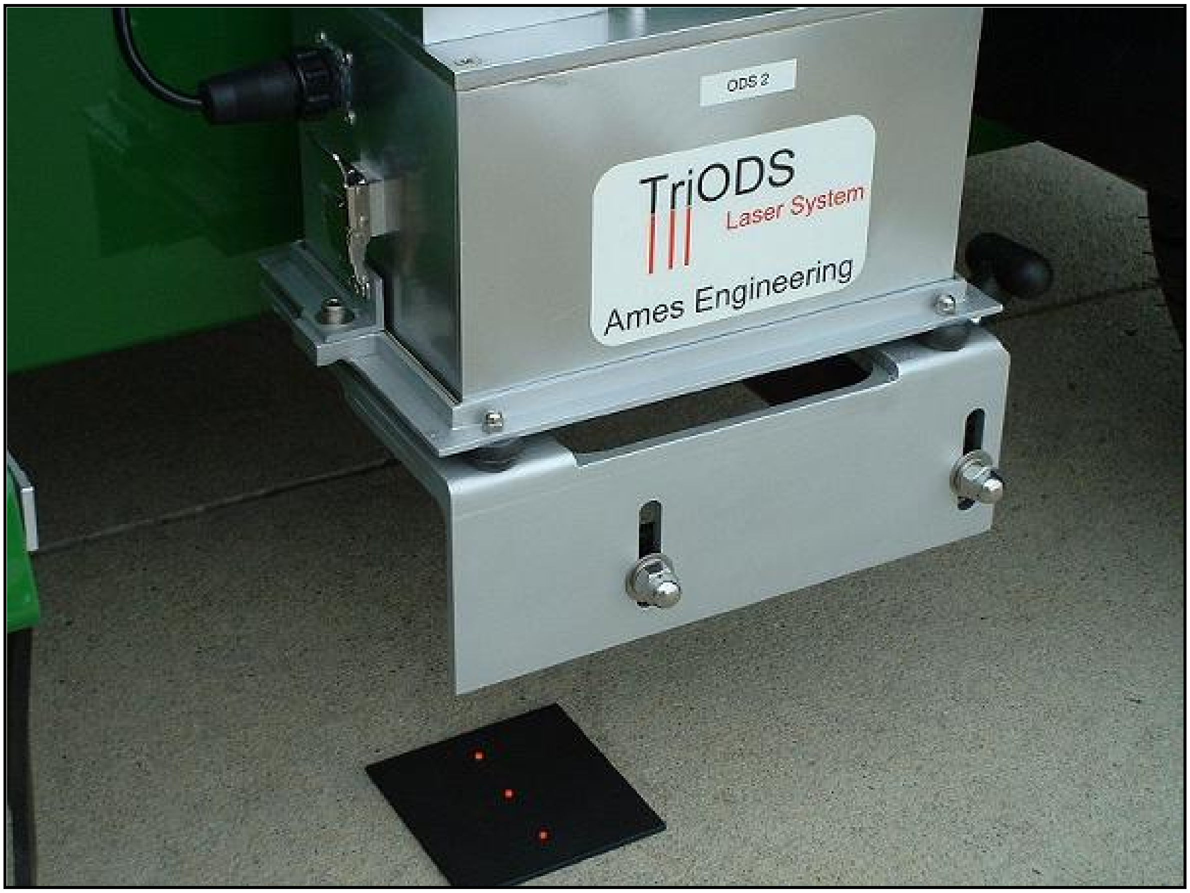


Figure 17. TriODS Three-Laser System from Ames Engineering.

1. Evaluate the 25-ft moving average of the measured wheel path profile and determine the deviations between the moving average profile and the measured profile as is done in the existing Ride Quality program. Identify the locations where the deviations exceed 150 mils in magnitude.
2. Determine the locations where the moving average profile intersects the measured wheel path profile. Locate deviations exceeding 150 mils in magnitude based on the two closest intersection points that bound these deviations. This step establishes the beginning and ending locations of each defect shown in Table 24.
3. For each defect found in step 2, find the maximum deviation between the measured profile and its 25-ft moving average. Report this deviation as the defect height. As may be seen in Table 24, a positive deviation identifies a bump in the profile, while a negative deviation indicates a dip.
4. Determine the Type I IRI contribution of each defect as explained previously. In this example, the computed Type I IRI contribution of each defect is given in column 5 of Table 24. This variable is needed to compute the DCI using Equation 3.
5. Group defects along the measured wheel path located within an 80-ft interval of each other. The defect groups are color-coded in Table 24, where defects belonging to the same group

are identified by the same color. Defects that are not color-coded (specifically those located within the interval beginning at 3417.5 to 15,630.7 ft) are referred to as singular defects. Table 24 shows five of these defects, and four distinct defect groups with more than one defect per group. Researchers note that a singular defect may also be considered as a defect group with only one defect. If one takes this perspective, there are 5 + 4 = 9 defect groups shown in Table 24.

6. Take the absolute value of each defect identified from the bump template analysis in step 1 and step 2. Column 6 of Table 24 shows the absolute values determined in this step.
7. Compute the width of each defect, which is simply the difference between the ending and starting locations given in Table 24.
8. For each defect group, determine the sum of the amplitudes and the sum of the defects found within that group. In addition, determine the maximum of the Type I IRI contributions computed for the same defects. These calculations are given in columns 8, 9, and 10 of Table 24.
9. Calculate the defect correction index using Equation 3 with the input variables determined from step 8. This index ranges from 0 to 1.
10. Compare the DCI from step 9 with the recommended threshold of 0.5. If the DCI is greater than 0.5, then have the contractor correct the defects within that group. Otherwise, no corrective work is done on the defect group. Of the nine defect groups found along the left wheel path, Table 24 shows that five groups with a total of 13 defects will need corrective work.

Table 24. Computed DCIs Using Equation 3 on Left Wheel Path Profile of SH6 L1 Lane from Station 412+50.0.

Defect Type	From (ft)	To (ft)	Defect height (mils)	Type I IRI (in/mile)	Abs. Defect Ampl. (mils)	Defect Width (ft)	Sum of Ampl. (mils)	Sum of Widths (ft)	Maximum Type I IRI (in/mile)	DCI using Equation 3	Correct defect?
Bump	1522.9	1538.4	173.60	0.65	173.6	15.5	1013.96	42.9	6.78	0.3156	No
Bump	1539.0	1547.0	192.78	2.69	192.78	8.0					
Dip	1547.0	1553.6	-192.00	4.21	192	6.6					
Dip	1583.8	1587.3	-162.15	2.08	162.15	3.5					
Bump	1600.7	1610.0	293.43	6.78	293.43	9.3					
Dip	1610.0	1619.1	-220.73	4.24	220.73	9.1	1160.08	26.6	6.94	0.9063	Yes
Bump	1619.1	1625.8	162.55	3.37	162.55	6.7					
Bump	1645.8	1649.2	396.81	6.94	396.81	3.4					
Bump	1659.0	1666.4	379.99	0.00	379.99	7.4					
Dip	1690.4	1696.4	-238.01	5.65	238.01	6.0	1364.76	41.7	6.51	0.8081	Yes
Dip	1697.1	1702.6	-163.58	3.57	163.58	5.5					
Bump	1702.6	1713.4	292.76	6.51	292.76	10.8					
Bump	1719.3	1719.8	249.24	0.01	249.24	0.5					
Bump	1730.1	1735.5	176.15	3.89	176.15	5.4					
Dip	1752.5	1766.0	-245.02	4.96	245.02	13.5					
Bump	3417.5	3418.1	917.80	4.06	917.8	0.6	917.8	0.6	4.06	0.9785	Yes
Bump	3596.0	3596.6	379.55	1.63	379.55	0.6	379.6	0.6	1.63	0.5594	Yes
Bump	8046.7	8047.6	429.33	1.56	429.33	0.9	429.3	0.9	1.56	0.6191	Yes
Bump	15024.2	15024.9	327.48	1.68	327.48	0.7	327.5	0.7	1.68	0.4805	No
Bump	15630.2	15630.7	151.02	0.19	151.02	0.5	151.0	0.5	0.19	0.2095	No
Bump	15760.7	15779.3	179.20	5.77	179.2	18.6	378.88	30.8	5.77	0.0422	No
Dip	15779.3	15791.5	-199.68	2.41	199.68	12.2					

The same analysis is done on the measured right wheel path profile of the test lane. Table 25 summarizes the results from this analysis. As this table shows, the DCI method using Equation 3 will require corrections on six defect groups along the right wheel path. In this case, the total number of defects to be corrected is 12.

In a similar manner, the DCI analysis is done on the other PRO data files collected from ride quality assurance tests on the CRCP project. If the results from this analysis are compiled, the total number of defects to be corrected on each test lane is projected to be as shown in Table 26. For comparison purposes, the number of defects to be corrected based on the existing Ride Quality program is also shown. Table 26 indicates that the total number of defects to be corrected based on Equation 3 is 92 (63 on the left wheel path and 29 on the right wheel path of the lanes tested). In comparison, the current Ride Quality program found a total of 77 defects needing correction. This result is 15 less than the number of defects from the DCI analysis.

Researchers note that the number of defects from the Ride Quality program is based on the calculated average profile on each test lane. In contrast, the number of defects from the DCI analysis is based on the measured wheel path profiles. Researchers are of the opinion that this analysis is more accurate compared to the Ride Quality bump template analysis, which uses the average profile. In terms of identifying defects, the Ride Quality program will not always give an accurate representation of the shape of the defect and its location. If the defects on the left and right wheel paths are about at the same locations on the lane tested, and the shapes of the defects are similar, then the average profile could provide a good approximation of the defect magnitude and location. However, these two conditions are not always observed in practice. Thus, evaluating localized roughness based on the average profile could lead to inaccurate results, making it difficult to determine where the correction should be made, and the size or magnitude of this correction.

Table 25. Computed DCIs Using Equation 3 on Right Wheel Path Profile of SH6 L1 Lane from Station 412+50.0.

Defect Type	**From (ft)**	**To (ft)**	**Defect Height (mils)**	**Type I IRI (in/mile)**	**Abs. Defect Ampl. (mils)**	**Defect Width (ft)**	**Sum of Ampl. (mils)**	**Sum of Widths (ft)**	**Maximum Type I IRI (in/mile)**	**DCI using** Equation 3	**Correct Defect?**
Bump	4022.4	4023.5	697.16	2.7	697.16	1.1	697.16	1.1	2.7	0.9028	Yes
Bump	7772.1	7772.7	204.38	0.5	204.38	0.6	204.38	0.6	0.5	0.2736	No
Bump	11246.2	11254.5	210.31	4.7	210.31	8.3	210.31	8.3	4.7	0.2098	No
Bump	11470.6	11471.6	424.55	1.3	424.55	1.0	424.55	1.0	1.3	0.5999	Yes
Bump	13724.9	13725.6	439.37	1.0	439.37	0.7	439.37	0.7	1.0	0.6197	Yes
Bump	14717.2	14717.8	232.92	0.9	232.92	0.6	508.55	1.3	0.9	0.6915	Yes
Bump	14748.0	14748.7	275.63	0.6	275.63	0.7					
Bump	14821.6	14822.2	504.87	1.8	504.87	0.6	689.26	1.1	1.8	0.8857	Yes
Bump	14840.9	14841.4	184.39	0.8	184.39	0.5					
Bump	15658.0	15679.5	437.98	1.3	437.98	21.5	1458.10	52.4	4.5	0.5708	Yes
Dip	15679.5	15690.5	-152.78	2.2	152.78	11.0					
Bump	15690.5	15700.3	198.18	1.3	198.18	9.8					
Bump	15710.2	15712.5	201.91	0.0	201.91	2.3					
Bump	15733.5	15741.3	467.25	4.5	467.25	7.8					
Bump	15758.3	15777.3	169.08	3.1	169.08	19.0	430.53	28.7	5.1	0.0667	No
Dip	15777.3	15787.0	-261.45	5.1	261.45	9.7					

Table 26. Comparison of Defects to be Corrected: DCI Analysis Using Equation 3 vs. Ride Quality Program.

Lane	Starting Station	Length (miles)	DCI Analysis Using Equation 3		Ride Quality Program		
			LWP	RWP	Average Profile	LWP	RWP
L1	556+50.3	1.994	0	0	1	9	3
L2	556+50.1	1.985	0	0	1	7	4
R1	425+00.2	2.976	3	0	1	11	16
R2	425+00.4	2.987	0	0	6	18	10
L1	412+50.0	2.997	13	12	13	22	16
L2	412+50.0	2.993	2	2	6	15	9
R1	253+50.0	3.125	45	15	46	66	31
R2	253+50.0	3.125	0	0	3	8	7
Total		22.182	63	29	77	156	96

Given the above perspective, it is more useful to compare the defect count from the DCI analysis with the corresponding number of defects from a Ride Quality analysis based on the individual wheel path profiles instead of the average profile. Since the existing program averages the left and right wheel path profiles to evaluate localized roughness, researchers generated PRO files by wheel path using the data from the Bryan District. Thus, for each PRO file given in Table 23, two PRO files were generated, one for each measured wheel path, with each file having the same left and right wheel path elevations.

Researchers then used TxDOT's Ride Quality program (release 2012.08.07) to determine the defect counts by wheel path, with the spike suppression option turned on in the program. The last two columns of Table 26 show the defect counts from this analysis. As expected, there are significantly more defects identified using the wheel path profile compared to the average profile. Using the wheel path profiles, the Ride Quality program identified a total of 252 defects compared to the 77 defects found using the average profile. In contrast, the DCI analysis using Equation 3 found a total of 92 defects on both wheel paths of the lanes tested.

In a similar manner, researchers used Equation 4 of the DCI method to determine the need for corrections based on the same profile measurements collected on the SH6 new CRCP project. This analysis follows many of the steps outlined previously but with the following exceptions:

- Calculating the Type I IRI contribution of each defect is not required.
- The maximum amplitude and the average width of the defects found within a group are determined to compute the defect correction index using Equation 4.

Table 27 and Table 28 illustrate the computed DCIs from this analysis using the same wheel path profiles researchers analyzed to generate the results given in Table 24 and Table 25. Researchers processed the remaining test profiles collected on the SH6 new CRCP construction project to determine the need for corrective work on the lanes tested. Table 29 shows the number of defects requiring correction on each lane based on Equation 4. For comparison, the corresponding number of defects to be corrected using Equation 3 is also given for each test lane in Table 29.

Along the left wheel path, Equation 4 gives a total of 67 defects requiring corrective work. This total is slightly higher than the corresponding number of 63 defects determined using Equation 3. The difference on the right wheel path is more significant. On this wheel path, the DCI analysis using Equation 4 found a total of 44 defects requiring corrections compared to a total of 29 defects based on Equation 3. Overall, Equation 4 identified a total of 111 defects that require corrective work compared to the 92 defects found using Equation 3. These totals are still lower than the 252 defects that are projected to require correction using the measured wheel path profiles with the existing Ride Quality program.

Table 27. Computed DCIs Using Equation 4 on Left Wheel Path Profile of SH6 L1 Lane from Station 412+50.0.

Defect Type	From (ft)	To (ft)	Defect Height (mils)	Abs. Defect Ampl. (mils)	Defect Width (ft)	Max. Ampl. (mils)	Avg. Width (ft)	DCI using Equation 4	Correct Defect?
Bump	1522.9	1538.4	173.60	173.6	15.5	293.43	8.6	0.3838	No
Bump	1539.0	1547.0	192.78	192.78	8.0				
Dip	1547.0	1553.6	-192.00	192	6.6				
Dip	1583.8	1587.3	-162.15	162.15	3.5				
Bump	1600.7	1610.0	293.43	293.43	9.3				
Dip	1610.0	1619.1	-220.73	220.73	9.1	396.81	6.7	0.6993	Yes
Bump	1619.1	1625.8	162.55	162.55	6.7				
Bump	1645.8	1649.2	396.81	396.81	3.4				
Bump	1659.0	1666.4	379.99	379.99	7.4				
Dip	1690.4	1696.4	-238.01	238.01	6.0	292.76	7.0	0.4606	No
Dip	1697.1	1702.6	-163.58	163.58	5.5				
Bump	1702.6	1713.4	292.76	292.76	10.8				
Bump	1719.3	1719.8	249.24	249.24	0.5				
Bump	1730.1	1735.5	176.15	176.15	5.4				
Dip	1752.5	1766.0	-245.02	245.02	13.5				
Bump	3417.5	3418.1	917.80	917.8	0.6	917.8	0.6	0.9988	Yes
Bump	3596.0	3596.6	379.55	379.55	0.6	379.55	0.6	0.8678	Yes
Bump	8046.7	8047.6	429.33	429.33	0.9	429.33	0.9	0.9067	Yes
Bump	15024.2	15024.9	327.48	327.48	0.7	327.48	0.7	0.8007	Yes
Bump	15630.2	15630.7	151.02	151.02	0.5	151.02	0.5	0.4579	No
Bump	15760.7	15779.3	179.20	179.2	18.6	199.68	15.4	0.0648	No
Dip	15779.3	15791.5	-199.68	199.68	12.2				

Table 28. Computed DCIs Using Equation 4 on Right Wheel Path Profile of SH6 L1 Lane from Station 412+50.0.

<table>
<tr><th>Defect Type</th><th>From (ft)</th><th>To (ft)</th><th>Defect Height (mils)</th><th>Abs. Defect Ampl. (mils)</th><th>Defect Width (ft)</th><th>Max. Ampl. (mils)</th><th>Avg. Width (ft)</th><th>DCI using Equation 4</th><th>Correct Defect?</th></tr>
<tr><td>Bump</td><td>4022.4</td><td>4023.5</td><td>697.16</td><td>697.16</td><td>1.1</td><td>697.16</td><td>1.1</td><td>0.9906</td><td>Yes</td></tr>
<tr><td>Bump</td><td>7772.1</td><td>7772.7</td><td>204.38</td><td>204.38</td><td>0.6</td><td>204.38</td><td>0.6</td><td>0.5732</td><td>Yes</td></tr>
<tr><td>Bump</td><td>11246.2</td><td>11254.5</td><td>210.31</td><td>210.31</td><td>8.3</td><td>210.31</td><td>8.3</td><td>0.2366</td><td>No</td></tr>
<tr><td>Bump</td><td>11470.6</td><td>11471.6</td><td>424.55</td><td>424.55</td><td>1.0</td><td>424.55</td><td>1.0</td><td>0.9012</td><td>Yes</td></tr>
<tr><td>Bump</td><td>13724.9</td><td>13725.6</td><td>439.37</td><td>439.37</td><td>0.7</td><td>439.37</td><td>0.7</td><td>0.9171</td><td>Yes</td></tr>
<tr><td>Bump</td><td>14717.2</td><td>14717.8</td><td>232.92</td><td>232.92</td><td>0.6</td><td rowspan="2">275.63</td><td rowspan="2">0.6</td><td rowspan="2">0.7172</td><td rowspan="2">Yes</td></tr>
<tr><td>Bump</td><td>14748.0</td><td>14748.7</td><td>275.63</td><td>275.63</td><td>0.7</td></tr>
<tr><td>Bump</td><td>14821.6</td><td>14822.2</td><td>504.87</td><td>504.87</td><td>0.6</td><td rowspan="2">504.87</td><td rowspan="2">0.6</td><td rowspan="2">0.9538</td><td rowspan="2">Yes</td></tr>
<tr><td>Bump</td><td>14840.9</td><td>14841.4</td><td>184.39</td><td>184.39</td><td>0.5</td></tr>
<tr><td>Bump</td><td>15658.0</td><td>15679.5</td><td>437.98</td><td>437.98</td><td>21.5</td><td rowspan="5">467.25</td><td rowspan="5">10.5</td><td rowspan="5">0.6740</td><td rowspan="5">Yes</td></tr>
<tr><td>Dip</td><td>15679.5</td><td>15690.5</td><td>-152.78</td><td>152.78</td><td>11.0</td></tr>
<tr><td>Bump</td><td>15690.5</td><td>15700.3</td><td>198.18</td><td>198.18</td><td>9.8</td></tr>
<tr><td>Bump</td><td>15710.2</td><td>15712.5</td><td>201.91</td><td>201.91</td><td>2.3</td></tr>
<tr><td>Bump</td><td>15733.5</td><td>15741.3</td><td>467.25</td><td>467.25</td><td>7.8</td></tr>
<tr><td>Bump</td><td>15758.3</td><td>15777.3</td><td>169.08</td><td>169.08</td><td>19.0</td><td rowspan="2">261.45</td><td rowspan="2">14.4</td><td rowspan="2">0.1299</td><td rowspan="2">No</td></tr>
<tr><td>Dip</td><td>15777.3</td><td>15787.0</td><td>-261.45</td><td>261.45</td><td>9.7</td></tr>
</table>

Table 29. Comparison of Defects to be Corrected: DCI Analysis Using Equation 3 vs. DCI Analysis Using Equation 4.

Lane	Starting Station	Length (miles)	DCI Analysis Using Equation 3		DCI Analysis Using Equation 4	
			LWP	RWP	LWP	RWP
L1	556+50.3	1.994	0	0	1	0
L2	556+50.1	1.985	0	0	0	0
R1	425+00.2	2.976	3	0	0	0
R2	425+00.4	2.987	0	0	2	0
L1	412+50.0	2.997	13	12	8	13
L2	412+50.0	2.993	2	2	3	4
R1	253+50.0	3.125	45	15	49	26
R2	253+50.0	3.125	0	0	4	1
Total		22.182	63	29	67	44

CONCLUDING REMARKS

Evaluating localized roughness by wheel path is expected to result in a better assessment of the type of defect, locations of defects, and their magnitudes. This method should make it easier for TxDOT and contractors to locate the defects, determine the appropriate grinding depths, and provide a better product. However, careful consideration must be given on how penalties will be assessed in a modified specification where defects are evaluated using the wheel path profile. Given the comparisons between the proposed DCI analysis and the existing Ride Quality program, it appears that the proposed method will identify more defects and consequently higher penalties. An alternative for TxDOT to consider is continue assessing penalties using the average profile, but report the defect locations and magnitudes by wheel path based on the DCI method, and have the contractor correct those defects. In this way, no change is made in the current method of assessing penalties. However, the DCI method is used to provide guidance on which defects need to be corrected on Item 585 projects. The proposed pilot testing of the modified Ride Quality program would provide additional useful data to make sound decisions on implementing the DCI analysis procedure developed in this research project.

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