Pavement Texture Evaluation and Relationships to Rolling Resistance at MnROAD

Minnesota Department of Transportation

RESEARCH SERVICES

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The Transtec Group, Inc.

June 2013

Research Project
Final Report 2013-16

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16. Abstract

Measurements of pavement surface texture were conducted on the test cells at the MnROAD research facility. The testing was performed using a mobile, line-laser-based, texture profiler that provides results in both the longitudinal and transverse directions. In addition to common texture metrics–for example, mean profile depth (MPD)–a variety of other metrics are calculated and reported. This includes the texture level in third-octave wavelength bands (the texture spectrum) and metrics that can distinguish between upward and downward oriented texture (for example, skew).

These texture metrics are combined with other pavement surface characteristics measured on the same MnROAD test cells into a single database. The other surface characteristics are coefficient of rolling resistance (CRR), roughness, friction, and tire-pavement noise. Using the results in the database, multivariable linear regression analyses are conducted to investigate the dependency of the CRR on the other surface characteristics. The performance of the various regression analyses is compared and variable combinations yielding good performing models for CRR are presented. Among the conclusions is that many possible combinations of surface characteristic variables are shown to be eligible for a model to predict CRR.

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Pavement Texture Evaluation and Relationships to Rolling Resistance at MnROAD

Final Report

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EXECUTIVE SUMMARY

This report presents the results of a two-phase project utilizing the test cells at the Mn/ROAD research facility. The project phases are:

1. Measurements of pavement texture; and
2. Linear regression analyses to investigate the dependency of the coefficient of rolling resistance (CRR) to other pavement surface characteristics.

In the measurement phase, pavement surface texture measurements were conducted on the test cells at the Mn/ROAD research facility. The testing was performed using a mobile, line-laser-based, texture profiler that provides results with two significant attributes.

- Texture is obtained in both the longitudinal and transverse directions. This is particularly important for portland cement concrete pavements which typically have a surface texture dependent on direction.
- Results in the longitudinal direction include the texture spectra.

In addition to the common texture metric, mean profile depth (MPD), a variety of other metrics are calculated and included with the reported results. This includes metrics that can distinguish between upward and downward oriented texture (for example, skewness).

In the regression analyses phase, pavement surface characteristic data from multiple measurement sources are combined into a single database. Using the database, a variety of multivariable linear regression analyses are performed to investigate the dependency of CRR on the other surface characteristics. The performances of the various regression analyses are compared and sample variable combinations yielding good performing models for CRR are presented.

Significant results include:

1. There are many possible combinations of surface characteristic variables that can predict CRR.
2. Using the entire set of test cells in regression analyses yields relatively poor performance of the model. Therefore, the data are analyzed separately in pavement groupings:
    a. Asphalt;
    b. PCC longitudinal and transverse tine, drag, and/or broom finished; and
    c. PCC with diamond grind finish.

   Furthermore, the variables that best predict CRR are different between the asphalt and PCC pavements.
3. Better regression results are obtained when the data from the Mainline and Low Volume Roads are treated separately as a qualitative variable. This indicates there is an uncontrolled factor in the data. This could be, for example, the difference in traffic loading (equivalent single axle load or ESAL) between the Mainline and Low Volume Roads.

Chapter 1. Introduction

1.1 Purpose

This document reports the results of a project covering:

1. Measurements of pavement surface texture on the test cells at the Mn/ROAD research facility.
2. A study of multi-variable linear regression analysis between the coefficient of rolling resistance (CRR) and other surface characteristics of the Mn/ROAD test cells.

In the texture measurement phase, all the test cells on both the mainline and low volume roads were evaluated in both lanes, in a single wheel path, with a repeat run. For the few cells with multiple texture strips, each strip was evaluated instead of a wheel path. There are two significant features of the texture profiler used to conduct the measurements:

- The profiler uses a line laser which provides the capability to evaluate texture in the longitudinal and transverse directions. This is particularly important for portland cement concrete (PCC) pavements which typically have a surface texture dependent on direction. Reported results include texture in both the longitudinal and transverse directions.
- The profiler is a mobile device (as opposed to a stationary device) which provides the capability to measure texture versus distance and perform frequency analysis of the texture. Reported results include longitudinal texture spectra in third-octave bands with center wavelengths from 160 to 3.15 mm.

In addition to the common texture metric, mean profile depth (MPD), a variety of other metrics are calculated and included in the reported results. Included are metrics that can distinguish between upward and downward oriented texture (for example, skewness) and spectral based metrics.

These texture metrics are combined with other pavement surface characteristics measured on the same Mn/ROAD test cells into a single database. The other surface characteristics are CRR, roughness, friction, and tire-pavement noise.

Using the database, linear regression analyses are performed to investigate the dependency of CRR on the other surface characteristics. Regression analyses with up to four dependent variables (three quantitative and one qualitative) are evaluated. The performances of the various regression analyses are compared and variable combinations yielding good performing regressions are presented.

1.2 Scope

This report presents the results of linear regression analyses with CRR as a dependent variable and other surface characteristics as independent variables. There are many combinations of the independent variables that yield valid regression results and can serve as a basis for a model to predict CRR. This report presents many of these successful combinations. However, this report is not intending to identify or propose a particular set of surface characteristics as a definitive choice for modeling CRR.

1.3 Organization

Chapters 2 and 3 cover the measurement portion of this project. Chapter 2 provides details of the test setup, instrumentation, and the measurement process. Chapter 3 presents some of the measured results.

Chapters 4 through 7 cover the regression analysis portion of this project. Chapter 4 explains the contents of the surface characteristics database which contains the data and variables for use in the regression analyses. Chapter 5 describes the linear regression methods and Chapter 6 presents the results of the analyses. Chapter 7 reviews and compares the regression results and shows some sample CRR models.

Some detailed information is available in the appendices. Appendix A summarizes the MnROAD test cell pavements including photographs of the pavement surfaces. Appendix B describes how a measured surface profile is processed into texture metrics. Appendix C gives equations for the texture metrics.

Chapter 2. Texture Test Setup, Equipment, and Measurement Process

2.1 Test Project Details

2.1.1 Performing Contractor

Texture measurements were performed by:

The Transtec Group, Inc.
6111 Balcones Drive
Austin, Texas, 78731 USA

Phone: +1 (512) 451 6233
Fax +1 (512) 451 6234
www.TheTranstecGroup.com

2.1.2 Personnel

- Project Manager: Dr. Robert O. Rasmussen
- Project Engineer: Mr. Richard Sohaney
- Field Technician: Mr. R.P. Watson

2.1.3 Test Date and Location

Texture measurements were performed over three days: October 31 to November 2, 2011.

The measurements were performed at the MnDOT's MnROAD research facility near Monticello, MN.

MnROAD
9011 77th Street NE
Monticello, MN 55362

2.2 Texture Profiler

2.2.1 Description

Texture measurements were performed with a line-laser-based texture profiler. Use of a line laser (as opposed to a spot laser) provides the capability to measure texture in the transverse direction as illustrated in Figure 2-1. Texture in the longitudinal direction is measured by moving the laser longitudinally along the test section. Longitudinal motion is accomplished by mounting the laser on a mobile, robotic platform with speed and direction control. Other sensors included on the mobile platform include:

- Accelerometer – to establish an inertial reference elevation;
- Wheel encoder – to determine the precise position of the robot;
- GPS – to establish a global position of the robot for reference;
- Time – to determine speed and for global reference; and
- Digital imaging system – for a visual record of the surface.

Customized software simultaneously acquires and stores data from the laser and other sensors. The entire measurement system is shown in Figure 2-2 and is referred to as RoboTex. It is a complete texture profiler meeting the requirements of ISO 13473-3: 2002 [1].

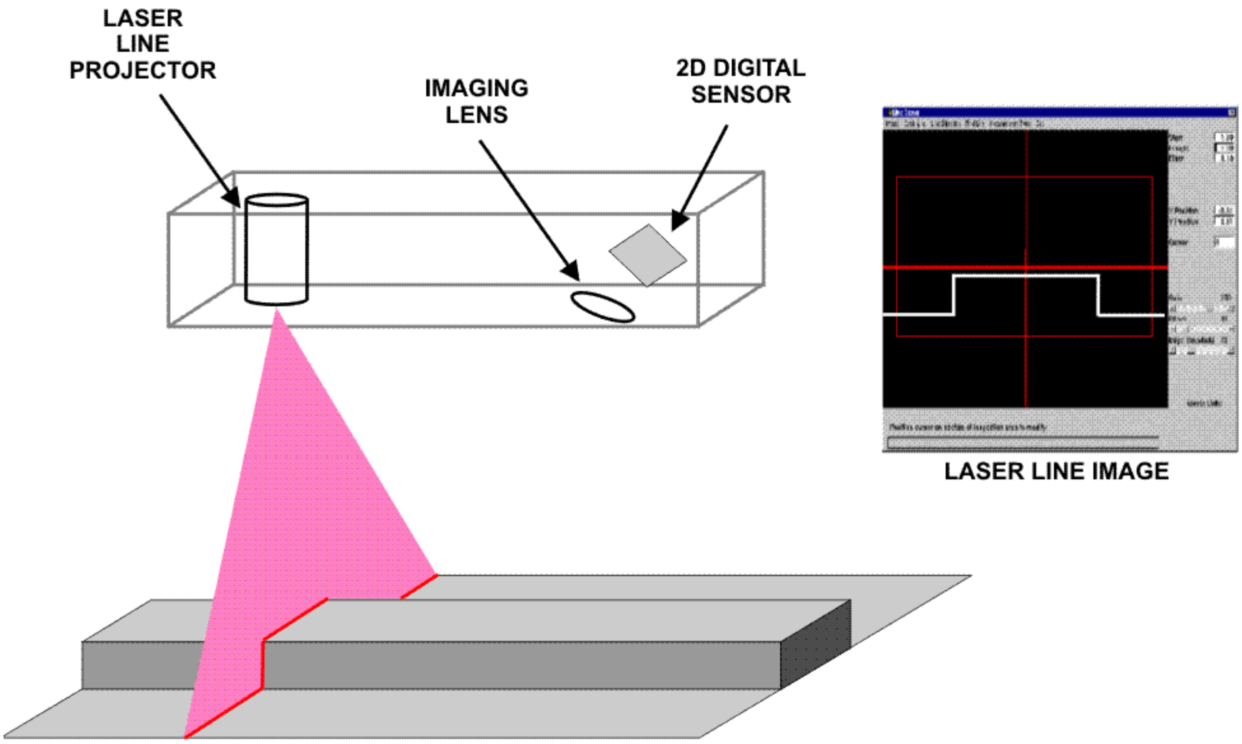

Figure 2-1. Schematic of a line laser. (Source: LMI Technologies, Inc. Reprinted with permission.)

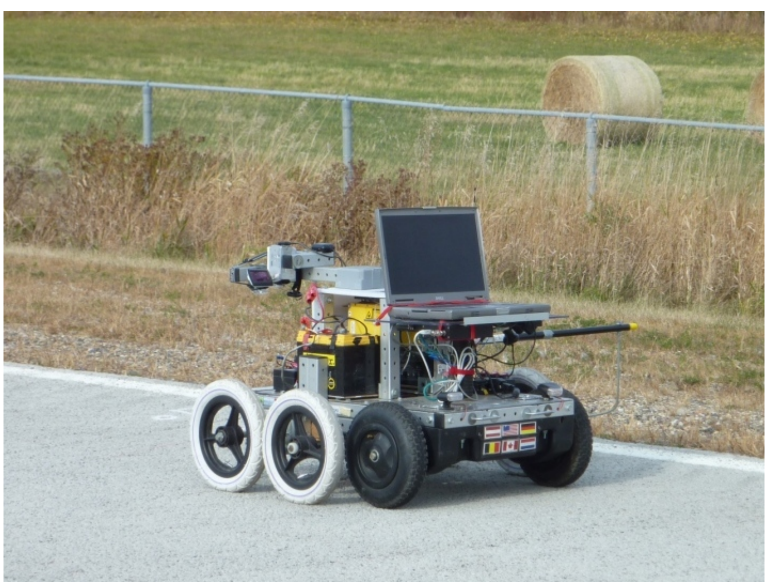

Figure 2-2. RoboTex texture profiler on the MnROAD Low-Volume road.

2.2.2 Laser

The line laser used for the texture measurements is:

- Manufacturer: LMI Technologies, Inc.
- Model number: RoLine 30427.
- Serial number: 06001.

2.3 Cells Evaluated

All the cells on the Low-Volume road and the Mainline were evaluated. With few exceptions, the texture was evaluated in the right wheel path of both lanes and in both the eastbound and westbound directions. A few cells on the Mainline were evaluated in the left wheel path because the pavement surface in the right wheel path was patched and not uniform along the length of the test cell. On the Low-Volume road, cell 37 contains multiple strips of diamond ground PCC pavement. In this case, each strip was evaluated instead of the wheel path. Table 2-1, Table 2-2, and Table 2-3 list the cell numbers, subsection numbers, exceptions, and other comments for the test cells on the Mainline, Low-Volume Road – South Section, and Low-Volume Road – North Section.

MnROAD test cell numbers are not geographically sequential. So, for convenience, the tables have a column labeled "West to East Sequence Number" containing a number assigned in geographical sequence (west to east) to aid in matching the test cell to a physical location. Also, the test cell and subsection numbers may have changed over time and variations of the numbering system may exist in other data sets. The west to east sequence number can be used to aid in aligning test cell numbering across data sets.

Table 2-1. Cell numbering and comments for the test cells on the Mainline.

West to East Sequence Number	Cell Number	Subsection	Comments and Exceptions
1	1		
2	2		
3	3		
4	4		
5	5	505	
6	5	605	
7	5	305	Left wheel path evaluated in the driving lane.
8	5	405	Left wheel path evaluated in the driving lane.
9	6	306	
10	6	406	
11	7		
12	8		
13	9	113 to 513	
14	60	114 to 914	Left wheel path evaluated in the driving lane.
15	61		Left wheel path evaluated in the driving lane.
16	62		Left wheel path evaluated in the driving lane.
17	63		Cells 63 and 96 combined in the driving lane.
18	96		Cells 63 and 96 combined in the driving lane.
19	70		
20	71		
21	72		
22	72	A	
23	12		
24	13		
25	14		
26	15		
27	16		
28	17		
29	18		
30	19		
31	20		
32	21		
33	22		
34	23		

Table 2-2. Cell numbering and comments for the test cells on the Low-Volume Road – South Section.

West to East Sequence Number	Cell Number	Subsection	Comments and Exceptions
35	24	A	Lead-in section without fog seal.
		B	Section with fog seal applied.
		C	Lead-out section without fog seal.
36	85		
37	86		
38	87		
39	88		
40	89		
41	27		
42	28		
43	77		
44	78		
45	79		
46	31		
47	32		
48	52		
49	53		
50	54		

Table 2-3. Cell numbering and comments for the test cells on the Low-Volume Road – North Section.

West to East Sequence Number	Cell Number	Subsection	Comments and Exceptions
51	33		
52	34		
53	35		
54	36		
55	37	A	Strip A is outside, next to the shoulder.
		B	Strip B – center outside.
		C	Strip C – center inside.
		D	Strip D is inside, next to the center strip.
56	38		
57	39		
58	40		

2.4 Test Cell Boundary Markers

Aluminum channel pieces are placed on the pavement to mark the start and end boundaries of the test cell. The markers are 0.5 in (12.7 mm) high and 0.875 in (22.2 mm) wide as shown in Figure 2-3.

Figure 2-3. Aluminum channel used to mark the test section boundaries.

During the measurement process, the profiler is guided over the boundary markers which produce an exaggerated texture value that allows the start and end of the test cell to be identified in the data. The profiler starts some distance before the start of the test cell to allow time for the speed and sensors to stabilize before reaching the surface to measure. Similarly, the profiler stops some distance after the end of the test cell to allow time for it to decelerate from test speed to a stop. Typically, the lead-in distance is less than 30 feet, and the lead-out distance is less than 10-feet. The setup is illustrated in Figure 2-4.

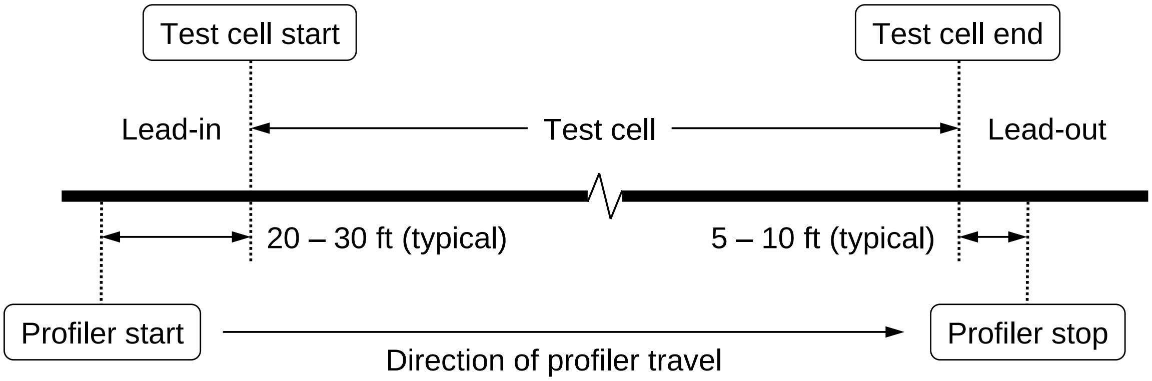

Figure 2-4. Schematic showing the relative positions of the profiler start and stop, the test cell start and end, and the lead-in and lead-out distances.

Chapter 3. Texture Results

3.1 Description of Texture Metrics

3.1.1 Texture Direction: Longitudinal and Transverse

The line-laser-based texture profiler used in this study is capable of measuring texture in the longitudinal (in the direction of traffic flow) and transverse (across the lane) directions. Readers familiar with measuring mean texture depth using the common volumetric or *sand patch* method (for example, ASTM E965) may not be familiar with the concept of direction associated with texture. With the volumetric method, glass beads are spread on the pavement surface to form a circular patch from which a single texture value is determined. The method does not distinguish between longitudinal and transverse directions.

However, pavement surface texture can be different in different directions. This is most evident on PCC pavements which have distinct surface striations and/or grooves in the direction of the tining, dragging, or grinding operation. The texture is different depending on whether the surface is viewed parallel or perpendicular to the striations or grooves. With the profile method, the texture measurement is performed along a line (not a patch). By orienting the measurement line longitudinally or transversely, the texture is measured in different directions.

In this report, “Lg” and “Tr” are used as prefixes on texture variables to designate longitudinal and transverse directions, respectively. In this context, “Lg” should not be confused with the logarithm operator. For example, LgMPD designates MPD (mean profile depth) in the longitudinal direction. TrMPD designates MPD in the transverse direction.

3.1.2 Summary of Texture Metrics

Table 3-1 summarizes the various texture metrics resulting from the measurements. The process by which the texture metrics are derived from a measured 3-dimensional elevation profile is described in Appendix B. Additional equations for the metrics are presented in Appendix C.

Table 3-1. Summary description of the reported texture metrics.

Metric	Name	Brief Description
MPD	Mean profile depth	Following ISO 13473-1: 1997 [2] and ASTM E1845 – 09 [3]
MaxPeak	Maximum peak	Maximum elevation, minimum elevation, and distance from maximum to minimum elevation.
MaxValley	Maximum valley	
MaxHeight	Maximum height	
RoughAvg	Average roughness	Average absolute value (rectified) elevation.
RMS	Root mean square	Square root of the average squared elevation.
Rpk	Reduced peak height	Following ISO 13565-2:1996 [4]
Rk	Core roughness depth	
Rvk	Reduced valley depth	
RkTotal	Total roughness	
Skew	Skewness	The third standardized moment.
160, 100, … 4.0, 3.15	Third-octave band texture levels.	Spectral based texture. Texture level in third-octave bands. The number in the metric name (160, 100, … 3.15) is the band center wavelength in mm.

3.2 MPD Results

3.2.1 Overview

Figure 3-1 and Figure 3-2 show charts of average MPD for all the cells in the longitudinal and transverse directions, respectively. Some general observations and trends:

- The range of MPD in both directions is from 0.25 to 2.3 mm.
- The porous and pervious pavements have the greatest MPD.
- In the longitudinal direction, the PCC pavements have lower MPD than the hot-mix asphalt (HMA) pavements.

3.2.2 HMA Pavements

Figure 3-3 shows a chart of average MPD in the longitudinal and transverse directions for the cells with HMA pavements. Some general observations and trends:

- For HMA pavements, MPD is independent of direction. The MPD in the longitudinal and transverse directions are nearly equal.
- Fog seal has the least texture.
- The 12.5 mm dense grade HMA surfaces have MPD ranging from 0.4 to 0.8 mm.
- The rank order of the HMA pavements from least to greatest texture is
    1. Fog seal.
    2. 12.5 mm dense-graded HMA.
    3. Bonded wearing courses.
    4. Chip seals.
    5. Porous.

3.2.3 PCC Pavements

Figure 3-4 shows a chart of average MPD in the longitudinal and transverse directions for the cells with PCC pavements. For many of the PCC pavements, the MPD varies with direction. This is expected because the surface texture of PCC pavements is usually applied predominantly in either the longitudinal or transverse direction. Figure 3-5 shows the difference between transverse and longitudinal MPD for the PCC pavements. The following trends and conclusions are drawn from the charts.

- PCC pavement surface texture is often not isotropic, that is, MPD is not the same in all directions.
- Difference between transverse and longitudinal MPD is greatest for the diamond grind surfaces.

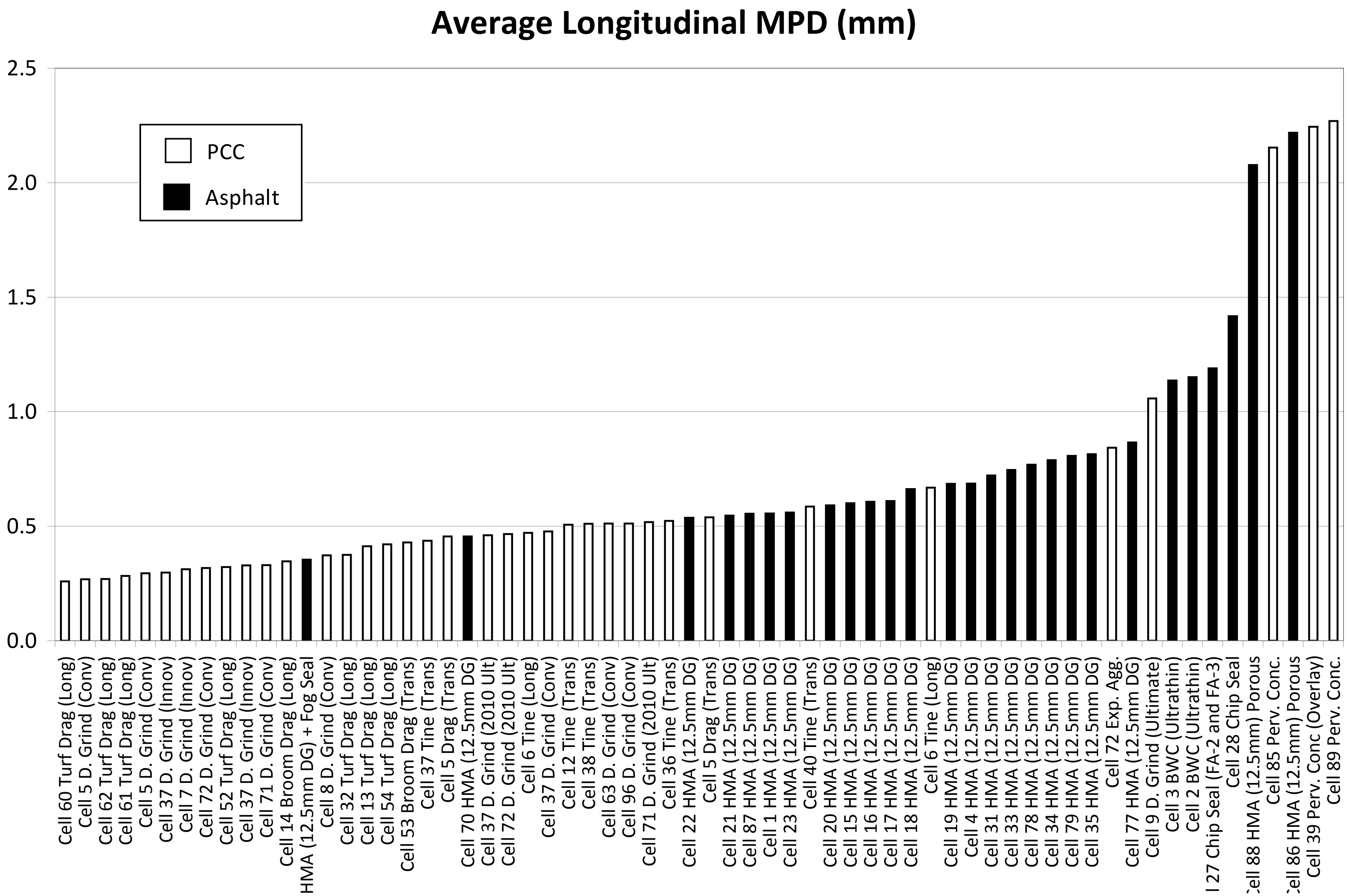

Figure 3-1. Average longitudinal MPD (mm) for all the cells.

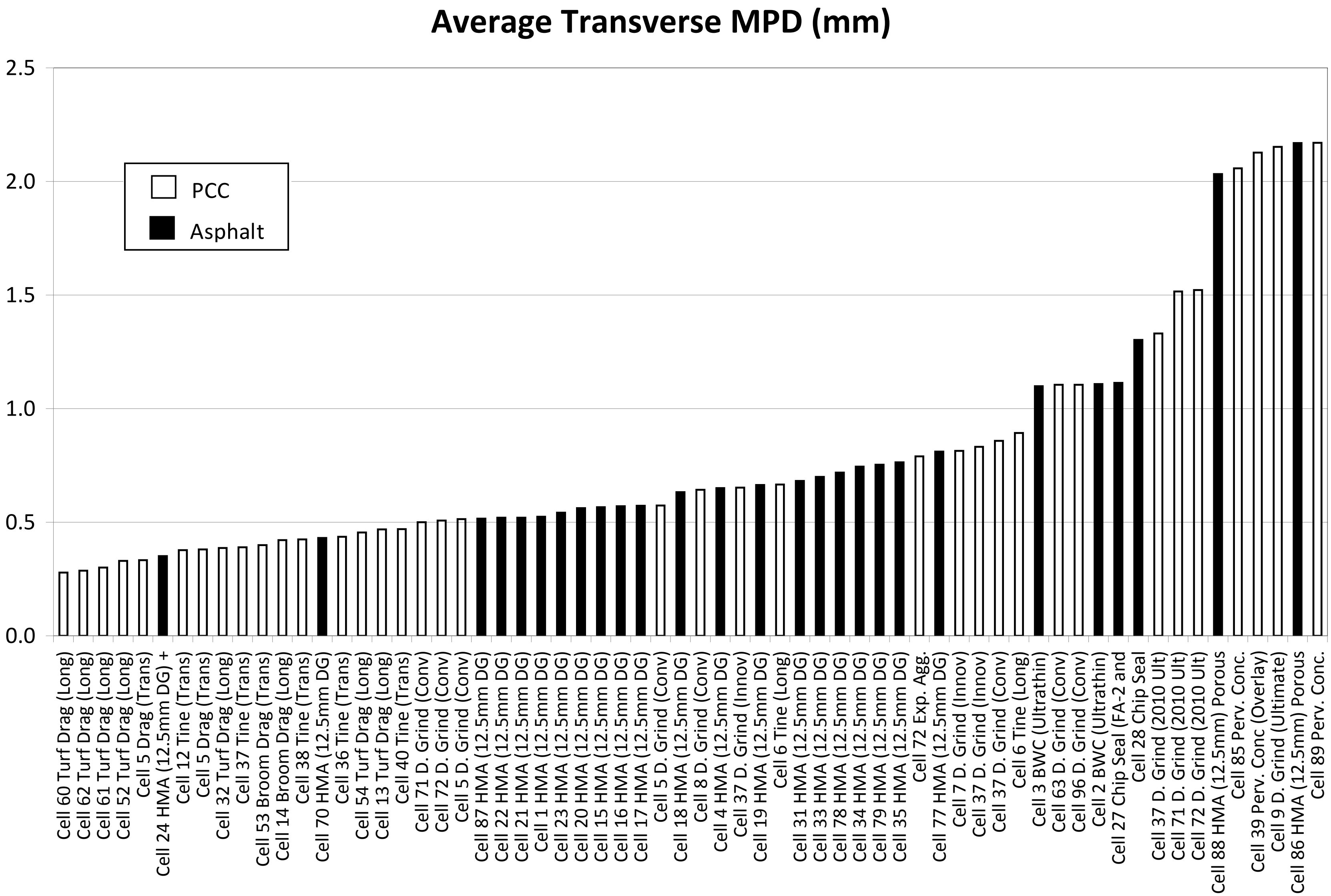

Figure 3-2. Average transverse MPD for all the cells.

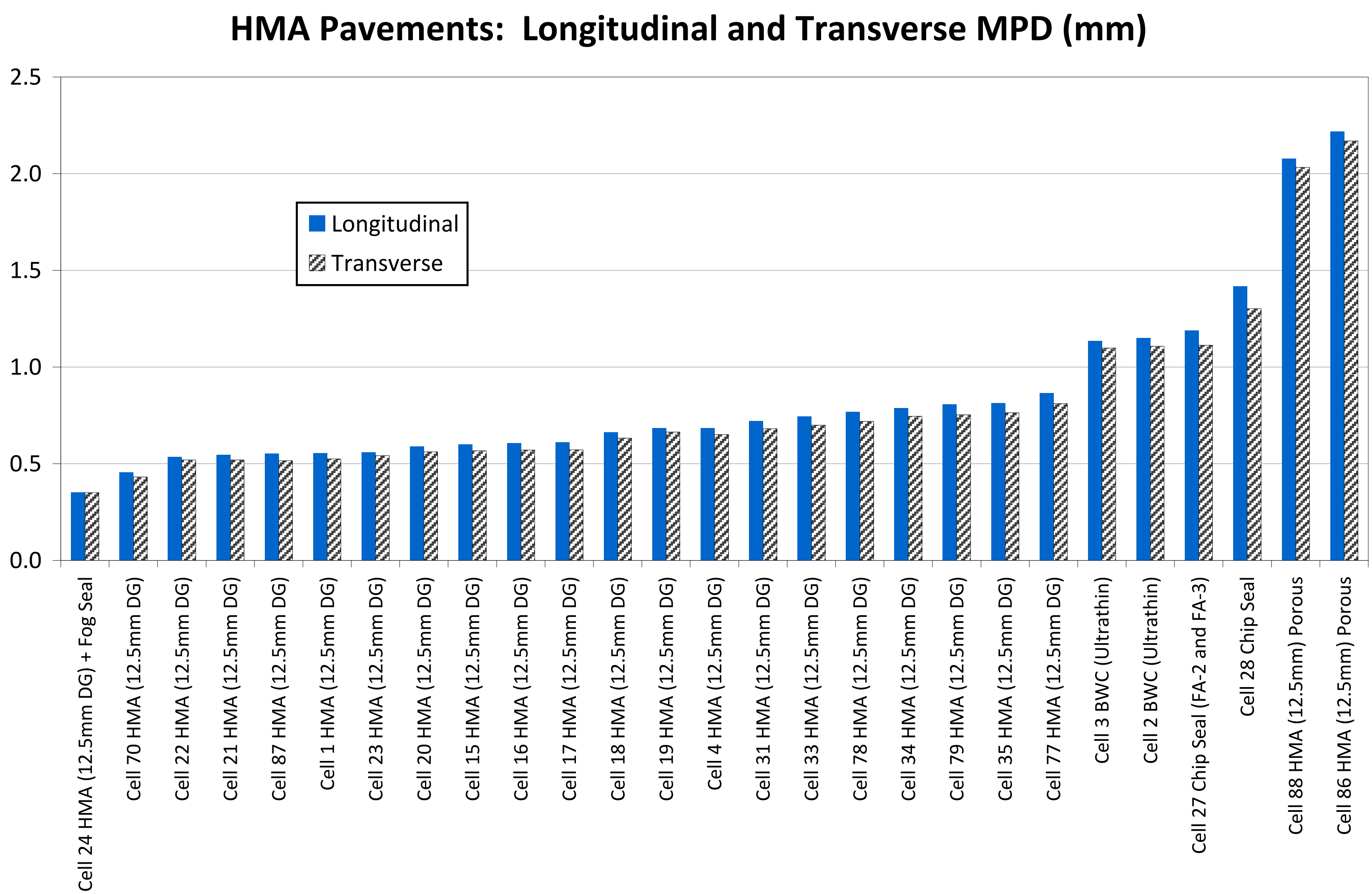

Figure 3-3. Longitudinal and transverse MPD for cells with HMA pavement.

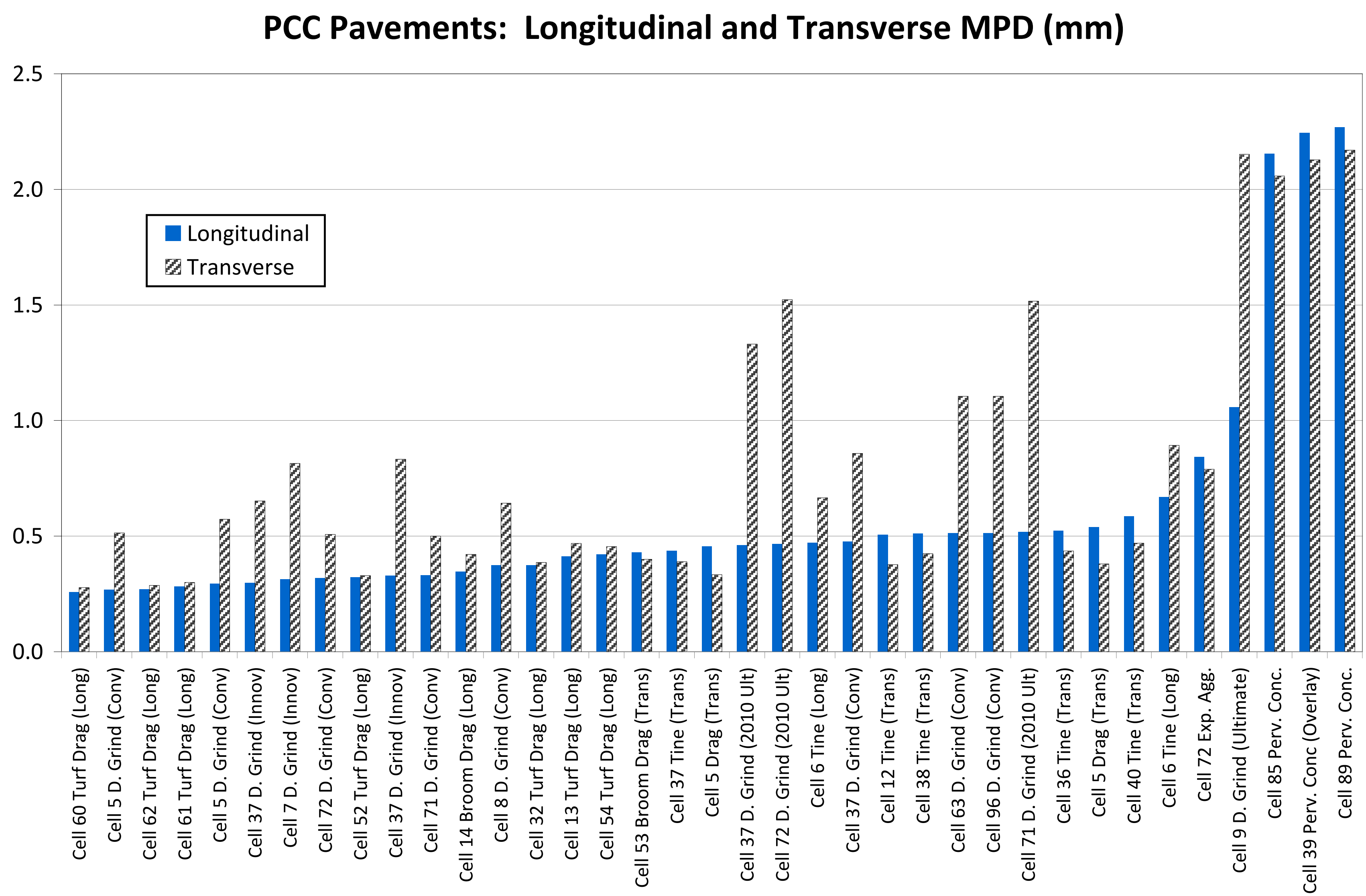

Figure 3-4. Longitudinal and transverse MPD for cells with PCC pavement.

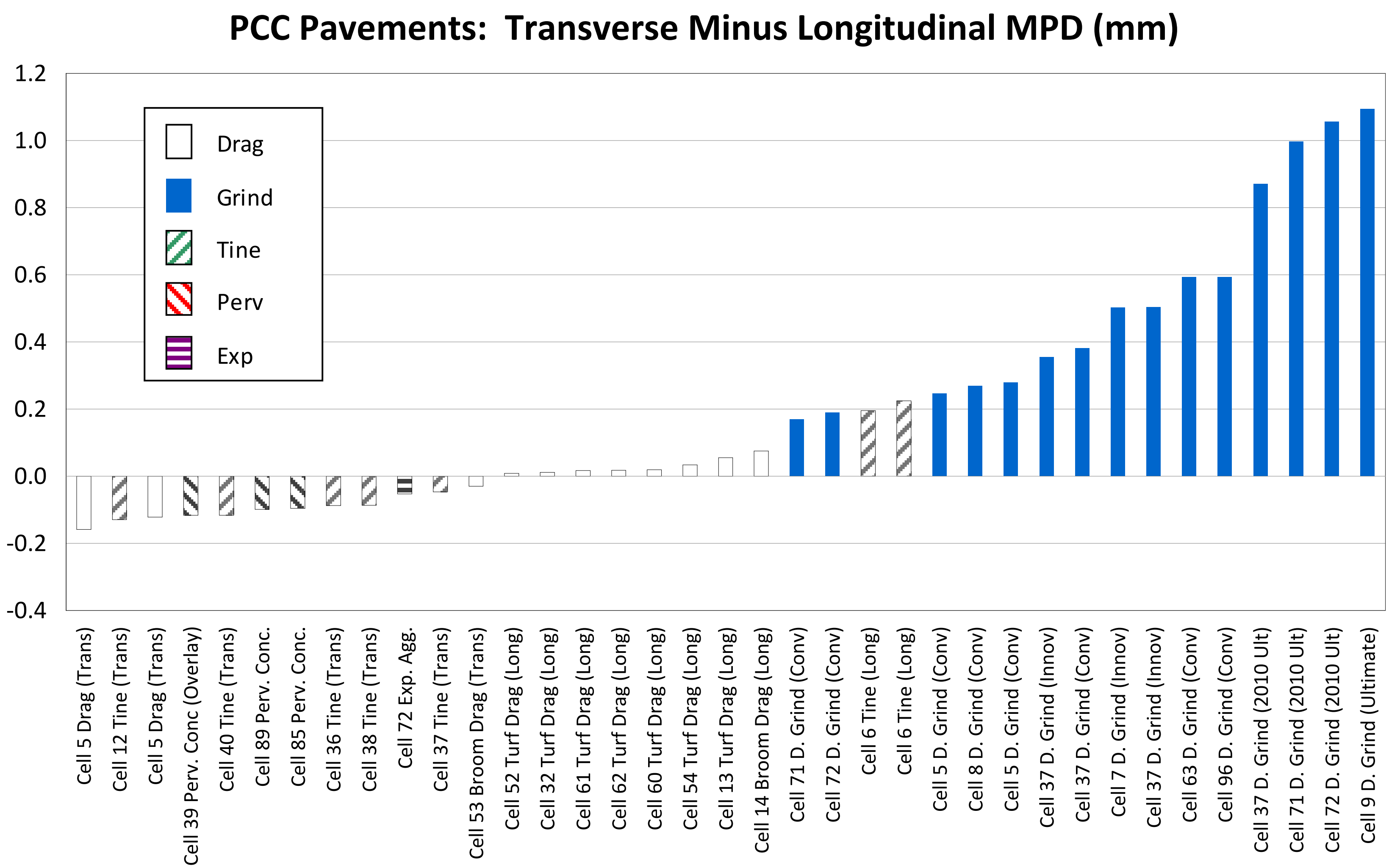

Figure 3-5. Difference in transverse and longitudinal MPD for PCC pavements.

3.3 Skewness Results

3.3.1 What is Skewness

Formally, skewness is a measure of the asymmetry of a statistical distribution about its mean. Skewness is a metric of interest because when applied to pavement texture profiles, it can distinguish between positive and negative oriented texture. These concepts are illustrated in Figure 3-6 which shows three sample elevation profiles and their corresponding elevation distributions.

In the middle profile of Figure 3-6, the peaks and valleys appear to be equal, that is, the height and rate of occurrence of the peaks are about the same as the valleys. In fact, if the middle elevation profile is viewed upside down, it is difficult to discern that it is flipped over. The elevation profile is symmetric about the horizontal mean line and this symmetry is reflected in the profile distribution; the upper and lower tails of the distribution are nearly the same shape.

Consider the upper profile in Figure 3-6. The valleys in this profile are more pronounced than the peaks. This texture is considered to be *negative* oriented. The corresponding elevation distribution is asymmetric; the distribution's downward tail is more extended than the upper tail. The skewness for the upper profile is negative.

The lower profile in Figure 3-6 is the reverse of the upper profile. In the lower profile, the peaks are more pronounced than the valleys and this texture is considered to be *positive* oriented. Its elevation distribution is also asymmetric; the upper tail is more extended than the lower tail. The skewness for the lower profile is positive.

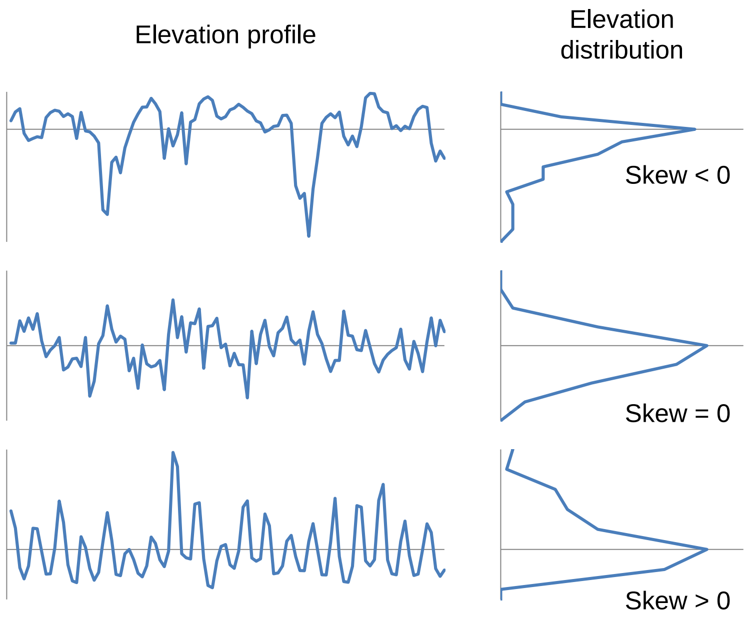

Figure 3-6. Three elevation profiles and corresponding elevation distributions. Upper profile has negative skewness, middle profile has zero skewness, and lower profile has positive skewness.

3.3.2 Overview of Skewness Results

Figure 3-7 and Figure 3-8 show charts of texture skewness for all the test cells in the longitudinal and transverse directions. Some general observations and trends:

- The texture is predominantly negative oriented; most of the cells have texture skewness less than zero.
- PCC pavements have larger negative skewness than the HMA pavements.
- The largest negative skewness occurs with the transverse tined PCC.

3.3.3 HMA Pavements

Figure 3-9 shows a chart of texture skewness in the longitudinal and transverse directions for the cells with HMA pavement. Some general observations and trends:

- Most of the HMA surfaces have negative oriented texture (skewness is less than zero).
- The bonded wearing courses have the greatest negative skewness.
- The porous HMA surfaces are among those with the greatest negative skewness.
- The chip seals have positive oriented texture (skewness is greater than zero).

3.3.4 PCC Pavements

Figure 3-10 shows a chart of average skewness in the longitudinal and transverse directions for the cells with PCC pavements. Some cells have greater skewness in the longitudinal direction and some in the transverse. Figure 3-11 shows the difference between transverse and longitudinal skewness for the PCC pavements. The following trends and conclusions are drawn from the charts.

- Most of the PCC pavements have negative oriented surface texture (skewness less than zero).
- Transverse tine surfaces have the greatest negative oriented texture in the longitudinal direction.
- The ultimate and innovative diamond grind surfaces have the greatest negative oriented texture in the transverse direction.

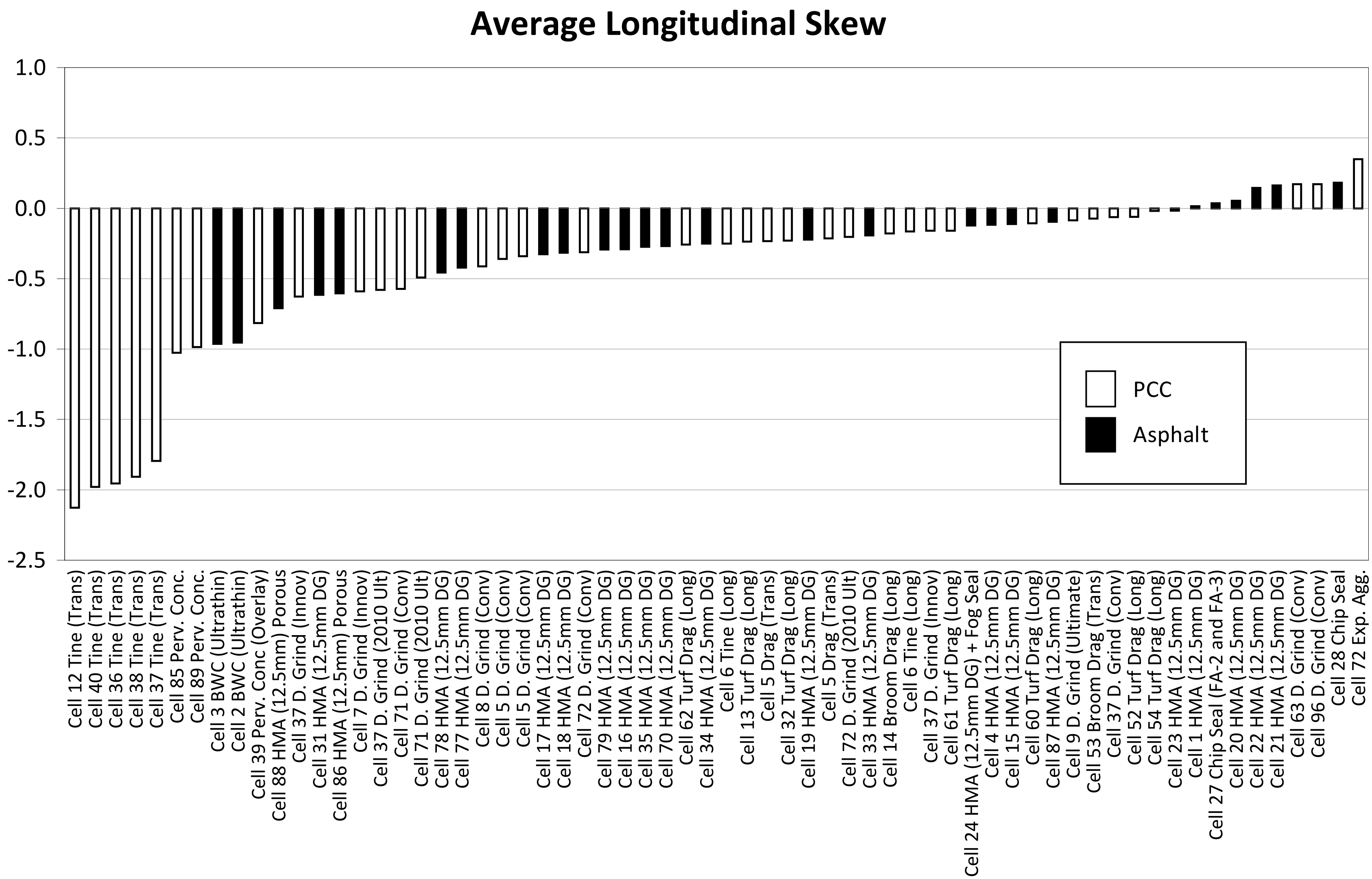

Figure 3-7. Average skewness in the longitudinal direction for all cells.

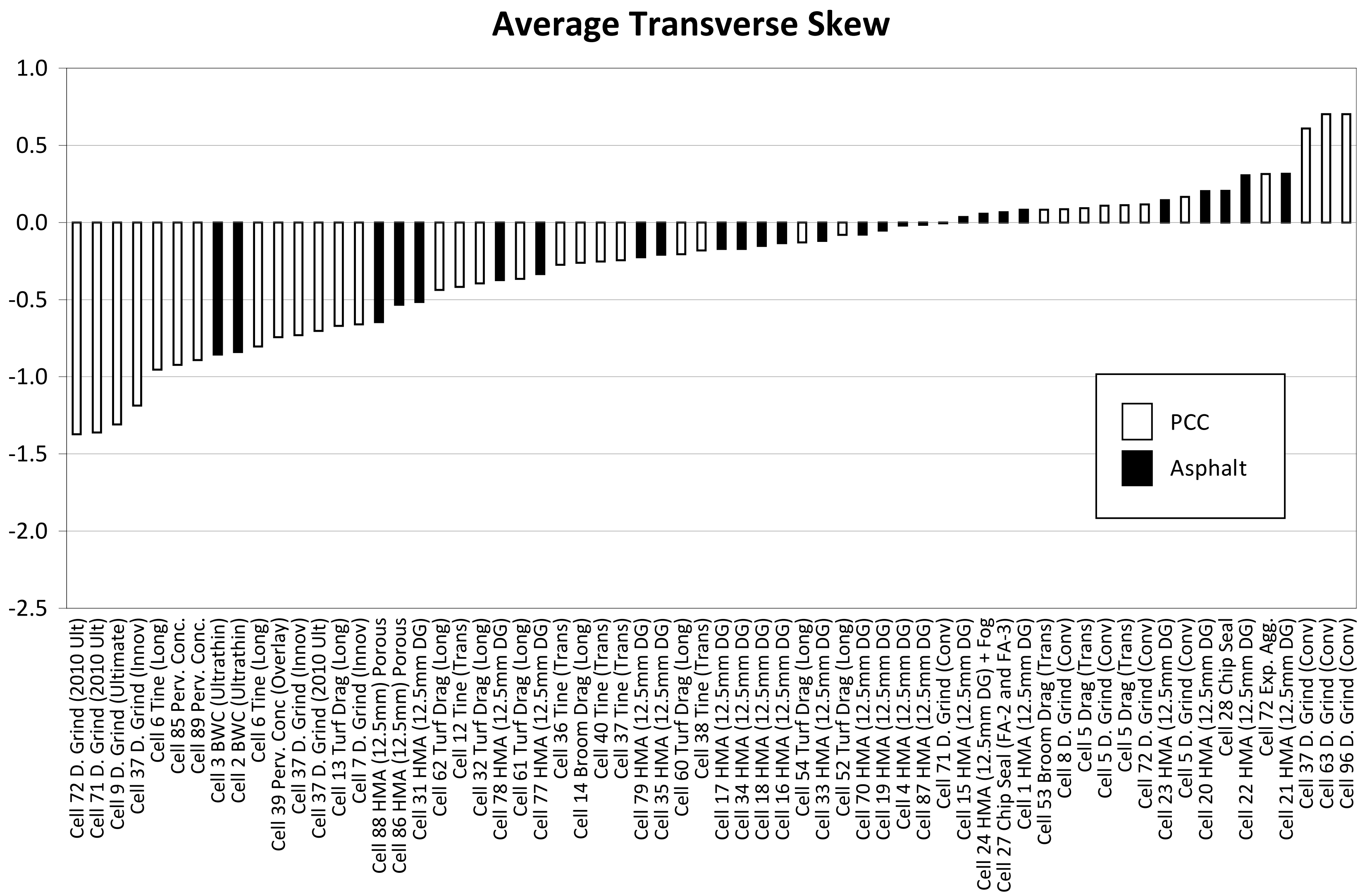

Figure 3-8. Average skewness in the transverse direction for all cells.

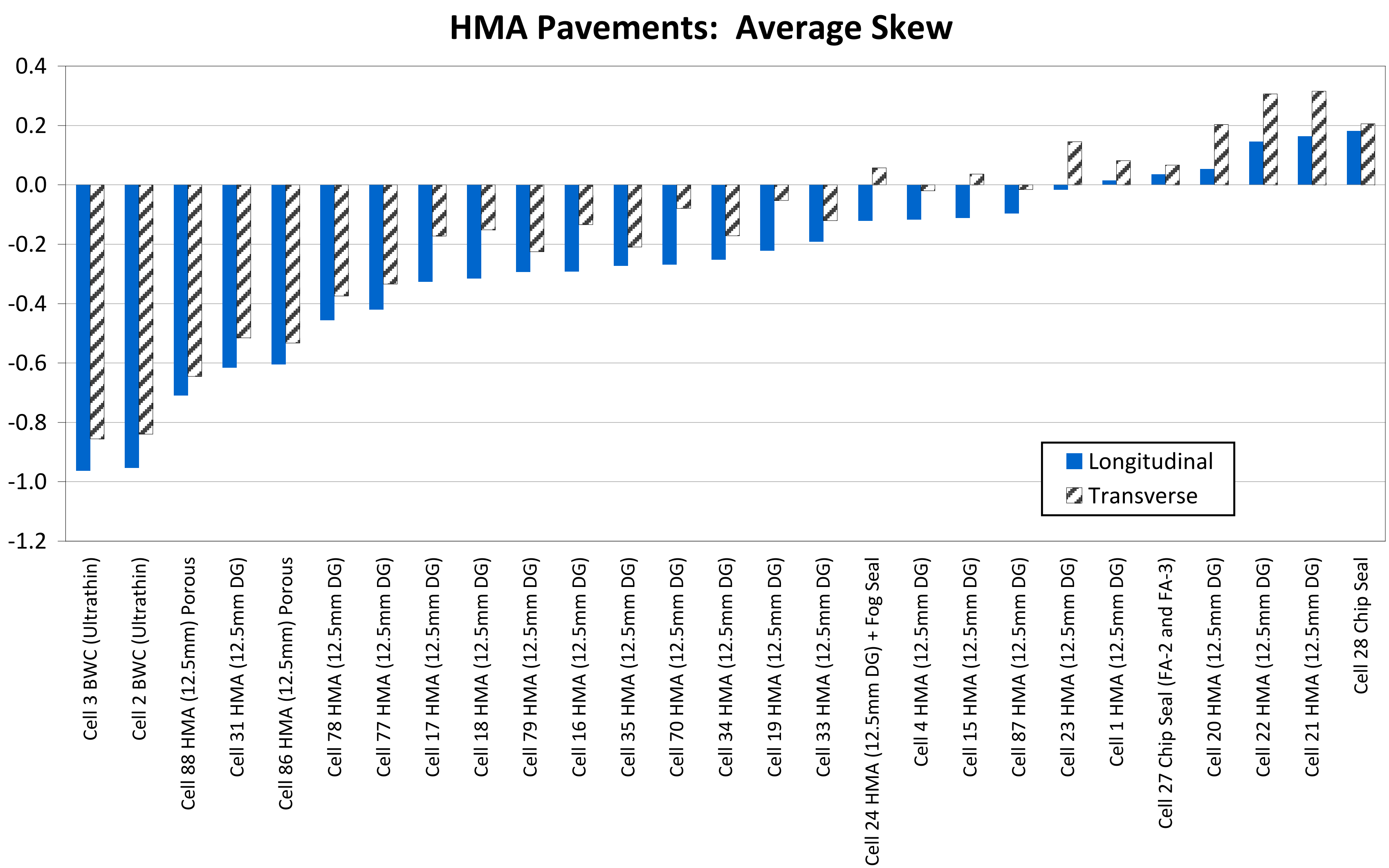

Figure 3-9. Texture skewness for cells with HMA pavements.

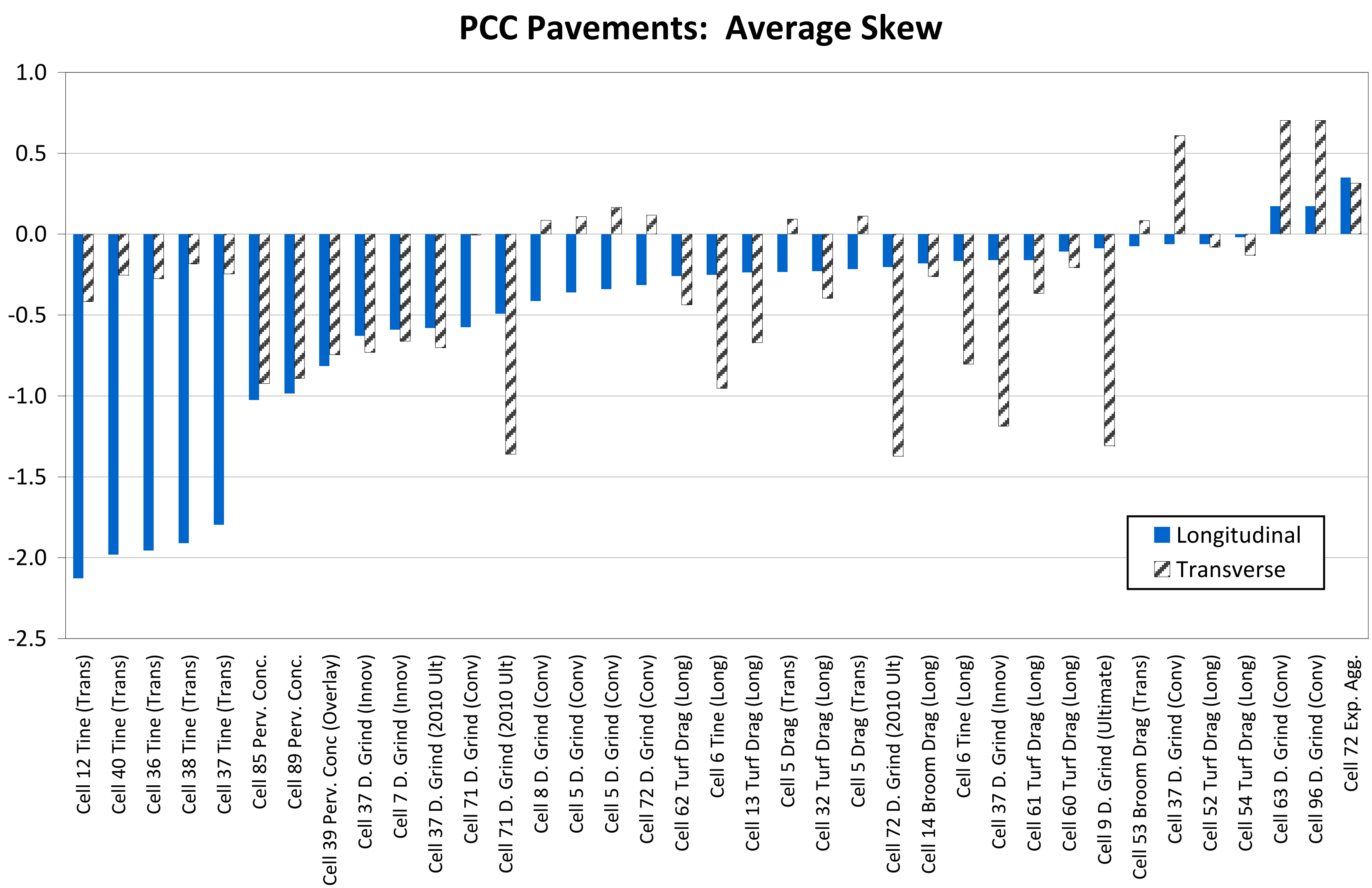

Figure 3-10. Longitudinal and transverse skewness for cells with PCC pavements.

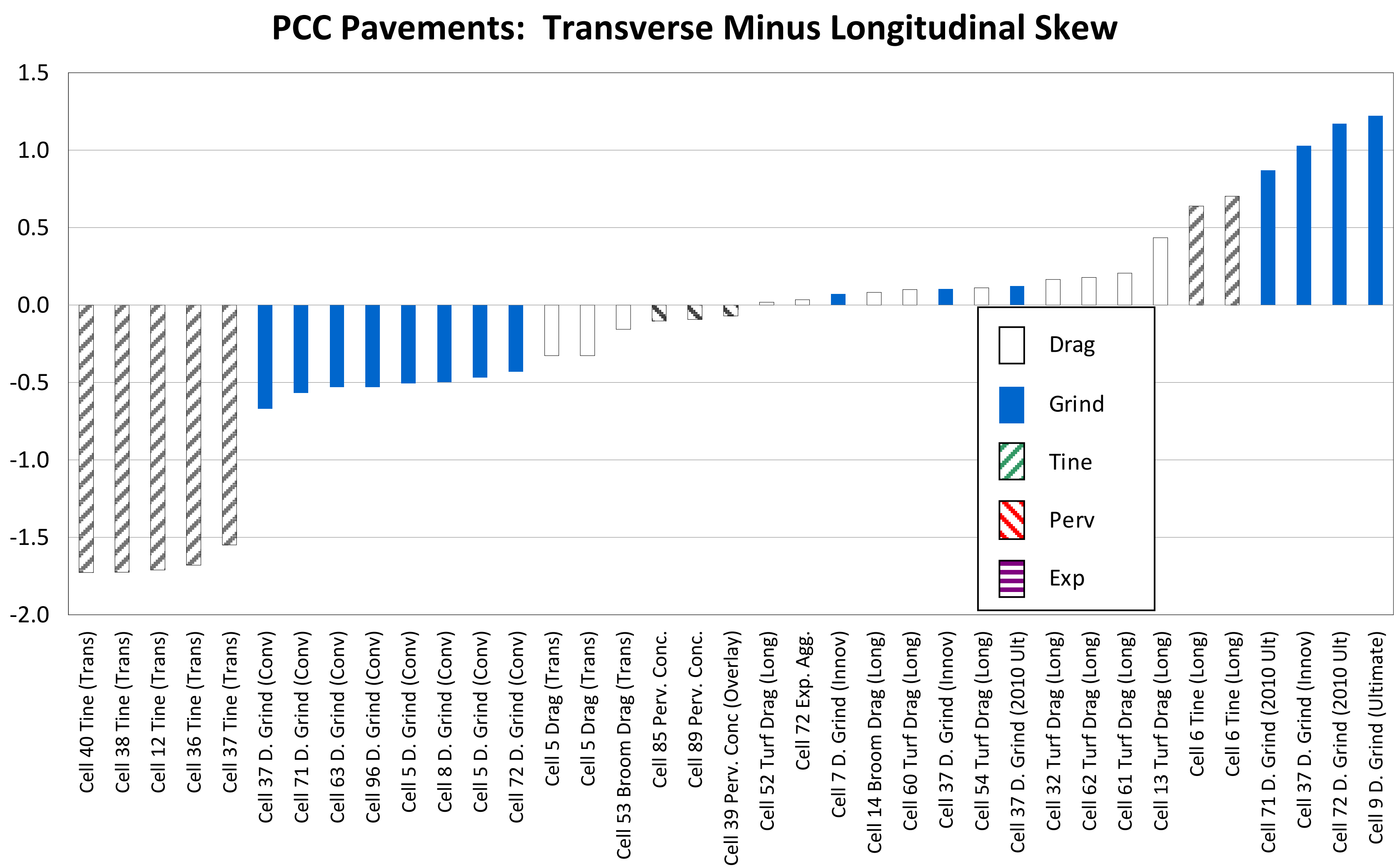

Figure 3-11. Difference between transverse and longitudinal skewness for cells with PCC pavement.

Chapter 4. Surface Characteristics and Rolling Resistance Database

In addition to the texture data described in the previous chapters, the MnROAD facility has data for other surface characteristics including:

- Coefficient of rolling resistance.
- Roughness.
- Friction.
- Tire-pavement noise.

This data has been collated, aligned, and assembled into a database for the purpose of evaluating linear regression analyses relating the coefficient of rolling resistance to the other surface characteristics. This chapter describes this database.

4.1 Coefficient of Rolling Resistance

The source for the CRR data is measurement results from a rolling resistance study conducted at MnROAD in the fall of 2011 [6]. The measurements were performed using a special test trailer developed by the Technical University of Gdańsk, Poland (Figure 4-1).

Figure 4-1. Rolling resistance test trailer. (Source: MnDOT [6]. Reprinted with permission.)

The study measured CRR using three different tires at four different speeds. The three tires are:

1. SRTT: Uniroyal, Tiger Paw, P225/60R16 (standardized by ASTM F 2493)
2. AV4: Avon, AV4, 195R14C
3. ME16: Michelin, Energy Saver, 225/60R16

The four measurement speeds are 50, 80, 110, and 130 km/h (31, 50, 68, and 81 mph). However, not all tires and speeds were evaluated on all cells. Table 4-1 lists the tire and speed combinations. In addition to the measured CRR data, average CRR of all three tires at 50, 80, and 110 km/h is calculated and included in the database.

Other details of the CRR measurement testing conditions and procedures, such as tire loading, tire pressure, and number of repeat runs, are in the study report [6].

Table 4-1. Test tire and speed (km/h) combinations for CRR data on the Mainline and Low-Volume Road.

Tire	Mainline	Low-Volume Road
SRTT	50 80 110 130	50 80
AV4	50 80 110	50 80
ME16	50 80 110	50 80
Avg tire	50 80 110	50 80

In the database, the CRR is designated by the tire identifier and test speed, for examples, *SRTT 80* and *Avg tire 50*.

4.2 Surface Characteristics

4.2.1 Why so many variables?

The most commonly recognized metrics for pavement texture, roughness, and friction include:

- Macrotexture depth (MPD using a profile method or MTD using a volumetric method).
- The International Roughness Index (IRI).
- Friction number (from locked wheel skid trailer testing).

Each of these metrics is in use because it is designed to meet a specific objective. MPD is designed to measure macrotexture depth similar to the volumetric (sand patch) method. IRI is designed to measure the ride response of a vehicle driving on the road. Locked wheel friction simulates conditions for a vehicle under hard braking. However, these objectives, macrotexture depth, ride comfort, and skid forces, may not be optimum or suitable for predicting rolling resistance. For this reason, many other surface characteristic variables are included in the database. The rest of this section identifies all these variables.

Often, people use the surface characteristic term and the metric interchangeably. For example, “the pavement texture is 0.60 mm” instead of “the pavement has an MPD (macrotexture depth) of 0.60 mm”. Another example, “the road roughness is 85 in/mile” instead of “the road has an IRI of 85 in/mile”. Contrary to common use, in this report and database, the term “texture” is referring to the surface characteristic of texture and the set of associated texture variables, not to the single macrotexture metric MPD. The same applies to the terms “roughness” and “friction”.

4.2.2 Texture

All the texture variables listed in Table 3-1 (page 10) are included in the surface characteristics database. For the set of non-spectral texture variables (for example, MPD and RMS), the 10th, 50th, and 90th percentile values are include in the database. (These percentile values are explained in Section A-8, page B-7.) Table 4-2 describes additional, calculated texture variables that are include in the database.

Table 4-2. Additional texture variables

Variable Name	Description	Comments
L 50 – 160 mm	Covers wavelength bands from 50 to 160 m.	"Lumped band" texture levels calculated by energy summing specific third-octave waveband levels as defined by ISO 13473-4.
L 3.15 – 50 mm	Covers wavelength bands from 3.15 to 50 mm.	
L 3.15 – 8 mm	Covers wavelength bands from 3.15 to 8 mm.	
SMTD	SMTD = MPD / RMS	These are all variations of a peak metric divided by RMS. They are calculated for the longitudinal and transverse directions, and for the 10th, 50th, and 90th percentiles.
CF	Crest factor = Peak / RMS	
RdCF	Reduced crest factor = Rpk / RMS	

4.2.3 Roughness (IRI)

Roughness data is from measurements by road profile equipment. The data include international roughness index (IRI) and elevation power spectral density in third-octave wavebands. The IRI data are from the MnROAD Data Release version 1.0, measurements dated September 2011. Two IRI measurements are included in the database, designated IRI_RUN (M-KM) and ROLINE_IRI (M-KM). The spectral based profile levels are calculated from raw profile data provided by MnDOT using the ProVAL software application [7]. In addition, three lumped band roughness levels are calculated from various third-octave bands. Table 4-3 lists the roughness variables in the surface characteristics database.

Table 4-3. Roughness variables.

Variable Name	Description	Comments
L 25, 20, … 0.08 m	Roughness level in third-octave wavelength bands.	Spectral based roughness. Roughness level in third-octave bands. The number in the variable name (25, 20,… 0.08) is the band center wavelength in meters.
Long wave (5 – 25)	Covers wavelength bands from 5 to 25 m.	"Lumped band" roughness levels calculated by energy summing specific third-octave waveband levels.
Short wave (0.5 – 5)	Covers wavelength bands from 0.5 to 5 m.	
Lmega (0.08 – 0.5)	Covers wavelength bands from 0.08 to 0.5 m, which is most of the mega texture wavelength range (0.05 to 0.5 m).	
IRI_RUN (M-KM)	International Roughness Index.	
ROLINE_IRI (M-KM)		

4.2.4 Friction

Friction data are from measurements by locked wheel tests and by continuous friction measuring equipment. Table 4-4 lists the four friction variables in the surface characteristics database.

The friction numbers measured by locked wheel tests are from the MnROAD Data Release version 1.0; measurements dated September 2011. Friction numbers measured by continuous friction measuring equipment are from equipment demonstrations by The Transtec Group during the summer of 2012.

Table 4-4. Friction variables.

Variable Name	Description	Comments
Smooth tire	Friction number using a smooth tire.	Friction numbers measured by locked wheel (skid trailer) testing.
Ribbed tire	Friction number using a ribbed tire	
Grip Tester	Grip number	Friction number measured by a Findlay Irving Grip Tester, a continuous friction measuring device.
HFT	HFT friction number	Friction number measured by a Dynatest 6875H Highway Friction Tester (HFT), a continuous friction measuring device.

4.2.5 Noise

Noise data are from tire-pavement noise measurements using the On-Board Sound Intensity (OBSI) method. The data are from the MnROAD Data Release version 1.0; measurements dated September 2011. There are 13 noise variables in the database: 12 variables that are the sound intensity levels in third-octave bands from 400 to 5000 Hz plus the overall OBSI level.

4.3 Database Alignment

The MnROAD test facility has many test cells, each cell has two lanes, and each lane has multiple wheel paths. The various surface characteristics in the database have been measured by at least three different parties. Each party's results may be organized slightly different in terms of cell identifiers, tests run in different lanes and/or wheel paths, and test cells that do not have data. *Database alignment* refers to organizing the data sets from these multiple sources so that they are consistent and can be combined into a single database.

4.3.1 Test Cells and lanes

Table 4-5 and Table 4-6 list the test cells and the numbering used in this study. The cells are listed in the tables in their physical west to east sequence, not in cell number order. There are 30 test cells on the Mainline road and 24 on the Low-Volume Road; a total of 54 test cells.

Table 4-5. Cell numbers and associated pavements on the Mainline road.

Cell No.	Sub Cell	Experiment	Surface Type
1		Original HMA Cell	12.5 mm Dense Graded Superpave
2		SemMaterials FDR Study	Ultra-Thin Bonded Wearing Course
3		SemMaterials FDR Study	Ultra-Thin Bonded Wearing Course
4		SemMaterials FDR Study	12.5 mm Dense Graded Superpave
5	505-605	Thin Unbonded Concrete Overlay of PCC - 5 inch over broken joints	Transverse Broom
5	305-405	Thin Unbonded Concrete Overlay of PCC - 5 inch over original PCC joints	Longitudinal Tine + Conventional Grind
6	306-406	Composite Pavement Experiment - Doweled	Longitudinal Tine + Turf Drag
7		5 year design PCC - Widened lane - PASB - longer panel	Innovative Diamond Grind
8		5 year design PCC - Widened lane - PASB - Supplemental Steel	Conventional Diamond Grind
9		5 year design PCC - Widened lane - PASB	Ultimate Diamond Grind (2008)
60		Thin Bonded Concrete Overlay of HMA - 5 inch - sealed	Turf Drag
61		Thin Bonded Concrete Overlay of HMA - 5 inch - unsealed	Turf Drag
62		Thin Bonded Concrete Overlay of HMA - 4 inch - sealed	Turf Drag
63		Thin Bonded Concrete Overlay of HMA - 4 inch - unsealed	Conventional Diamond Grind
96		Thin Bonded Concrete Overlay of HMA - 5 by 6 panels	Conventional Diamond Grind
70		SHRP II Composite Pavement Study - DL Doweled, PL Not Doweled	12.5 mm Dense Graded Superpave
71		SHRP II Composite Pavement Study - Diamond Grind Surface	2010 Ultimate Diamond Grind (driving lane) Conventional Diamond Grind (passing lane)
72		SHRP II Composite Pavement Study - EAC Surface	Exposed Aggregate
12		10 year design PCC - Drained base	Transverse Tine
13	113-513	PCC Thickness Optimization	Longitudinal Turf Drag
14	114-914	Thin Bonded Concrete Overlay of HMA	Longitudinal Broom Drag
15		Warm Mix Asphalt Overlay	12.5 mm Dense Graded Superpave
16		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave
17		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave
18		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave
19		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave
20		Low Temperature Cracking, RAP Study	12.5 mm Dense Graded Superpave
21		Low Temperature Cracking, RAP Study	12.5 mm Dense Graded Superpave
22		Low Temperature Cracking, RAP Study	12.5 mm Dense Graded Superpave
23		Taconite railroad ballast, WMA Surface	12.5 mm Dense Graded Superpave

Table 4-6. Cell numbers and associated pavements on the Low-Volume Road.

Cell No.	Sub Cell	Experiment	Surface Type
24		Aging Study, WMA Control	12.5 mm Dense Graded Superpave, Fog seals each year in 100-ft sections
85		Pervious Concrete Experiment - Low-Volume Road - Sand subgrade	Pervious Concrete
86		Porous HMA Study	Porous Hot Mixed Asphalt
87		Porous Pavement Study - Control Section	12.5 mm Dense Graded Superpave
88		Porous HMA Study	Porous Hot Mixed Asphalt
89		Pervious Concrete Experiment - Low-Volume Road - Clay subgrade	Pervious Concrete
27		Geocomposite Capillary Barrier Drain	Chip Seals (FA-2 and FA-3)
28		Stabilized Full Depth Reclamation	Double Chip Seal
77		Fly Ash Study, Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave
78		Fly Ash Study, Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave
79		Fly Ash Study, Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave
31		2004 LVR Taconite Superpave	12.5 mm Dense Graded Superpave
32		LVR design PCC - Thin Slab	Longitudinal Turf Drag
52		5 year design PCC - Load testing - FRP dowels	Longitudinal Turf Drag
53		60- year PCC	Transverse Broom
54		PCC mix experiment - Mesabi Select aggregates	Longitudinal Turf Drag
33		Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave
34		Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave
35		Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave
36		LVR design PCC - SUBGRADE R70 subgrade - doweled	Transverse Tine
37		LVR design PCC - SUBGRADE R70 subgrade -undoweled	Transverse Tine (inside lane) Various diamond grinds (outside lane)
38		LVR design PCC - Standard base - doweled	Transverse Tine
39		Porous Concrete Overlay Experiment	Pervious Overlay
40		LVR design PCC - 7-5.5-7 inch Trapezoidal - undoweled	Transverse Tine

4.3.2 Lanes
Each road has two lanes. On the Mainline, the lanes are referred to as the driving and passing lanes (right hand and left hand lanes, respectively). On the Low-Volume Road (which is an oval), the lanes are referred to as inside and outside lanes. The surface characteristic data (CRR, texture, etc.) for each lane of each test cell is in the database.

4.3.3 Wheel Paths
Surface characteristic data for one wheel path for each lane is included in the database. Effort was made to use data for each characteristic from the same wheel path. But, this is not always possible because the different surface characteristic measurements are performed in different wheel paths. Table 4-7 lists the wheel paths corresponding to the measurements in the database.

Table 4-7. Wheel paths corresponding to the surface characteristic measurements in the database.

Measurement	Mainline	Low-Volume Road	Exceptions
CRR	Center	Center	
Texture	Right	Right	On the Mainline, driving lane, cells 5-305/405, 60, 61, and 62 are left wheel path.
Roughness	Right	Right	
Grip Tester	Right	Left	
HFT	Left	Left	
Skid friction	Unknown	Unknown	
Noise	Right	Right	

4.3.4 Total Number of Records
In the database, there are a total of 54 test cells. Each cell occurs twice, once of each lane. Surface characteristic data are included for one wheel path on each lane. This gives a total of 108 entries or records in the database. With a few exceptions, each record has a complete CRR, texture, friction, roughness, and noise data set. Notable exceptions are test cells 1 and 23 on the Mainline. These cells are at the very beginning and end of the road where tests conducted at high speeds (such as rolling resistance and friction) may have safety issues.

Chapter 5. Analysis Method

5.1 Multiple Regression Analysis

5.1.1 Governing equation

Multivariate linear regression analysis is used to explore relationships between the rolling resistance coefficient and the other surface characteristic variables. This is a standard analysis approach and is found in many statistical handbooks and texts [8]. The general form for the analysis is:

$$y = \beta_n x_n + \cdots + \beta_1 x_1 + \beta_0 \tag{5-1}$$

Where:

y = the known dependent variable,
x_i = known explanatory or independent variables,
β_i = unknown regression coefficients, and
β_o = unknown regression constant.

There are many more known than unknown variables and the system of equations is solved using a least squares criteria.

In this study, the dependent variable is the rolling resistance coefficient and the explanatory variables are the other surface characteristics; texture, friction, roughness, and noise. Using the surface characteristic variable names in Equation (5-1), a sample regression equation is:

$$CCR = \beta_2 MPD + \beta_1 IRI + \beta_0 \tag{5-2}$$

5.1.2 Non-Linear Relationships

Non-linear relationships can be analyzed by using a transformed explanatory variable. For example,

$$y = \beta_n Log(x_2) + \cdots + \beta_1 x_1 + \beta_0 \tag{5-3}$$

In this study, the waveband texture and roughness variables are transformed to decibel levels and then used in the regression analyses.

5.1.3 Interaction Terms

Interaction between explanatory variables can be analyzed by including product terms. For example,

$$y = \beta_3 x_1 x_2 + \beta_2 x_2 + \beta_1 x_1 + \beta_0 \tag{5-4}$$

Effectively, a third explanatory variable is created from the product of two other explanatory variables

Regression analyses with interaction terms were investigated. But the regression results with interaction terms were not significantly better than without the terms.

5.1.4 Qualitative Explanatory Variables

Qualitative (or dummy variables) allow "groupings" of explanatory variables to be included in a regression analysis. An example of a grouping is pavement type; asphalt or PCC. The linear regression equation using a qualitative variable is:

$$y = \beta_n x_n + \ldots + \beta_1 x_1 + \beta_0 + \beta_q Q \tag{5-5}$$

Where:

x_i are the quantitative explanatory variables,
β_i are the regression coefficients for the quantitative variables
β_q is the regression coefficient for the qualitative explanatory variable, and
Q is the qualitative variable = 1 when the qualitative grouping is satisfied (true).
= 0 when the grouping is not satisfied (false).

Effectively, a qualitative variable is an additional explanatory variable but it takes on values of zero or one. For example, consider the following regression equation with two quantitative explanatory variables (MPD and IRI) and a qualitative variable based on road (Mainline or Low-Volume Road):

$$CCR = \beta_2 MPD + \beta_1 IRI + \beta_0 + \beta_3 Road \tag{5-6}$$

When the data are associated with a cell on the Mainline, the variable *Road* is equal to one. When the cell is on the Low-Volume Road, variable *Road* is equal to zero. For cells on the Mainline, Equation (5-6) reduces to:

$$CCR = \beta_2 MPD + \beta_1 IRI + (\beta_0 + \beta_3) \tag{5-7}$$

For cells on the Low-Volume Road:

$$CCR = \beta_2 MPD + \beta_1 IRI + \beta_0 \tag{5-8}$$

Qualitative explanatory variables can also be handled by simply breaking the full database into two sets, for example, one set with just the data from the Mainline and a second set with just the data from the Low-Volume Road. Separate regression analyses can be conducted on each set. The advantage of including the qualitative variable over splitting the database into multiple sets is that the regression results yields a p-value for the qualitative variable, which is an indicator of the significance of that variable.

5.1.5 Standardized Variables

Explanatory variables in the regression analyses have very different ranges. For example, friction values range from 30 to 60 and MPD values range from 0.2 to 2.0 mm. The regression coefficients are scaled corresponding to the variable ranges which makes it difficult to know the relative significance of each explanatory variable to the dependent variable.

For this reason, the data can be pre-conditioned by scaling to zero mean and standard deviation of one. Data in this condition is referred to as *standardized* data and the resulting regression coefficients are referred to as *standardized coefficients*. Compare the relative values of the standardized coefficients to directly assess the relative significance of the explanatory variables. For example, consider a regression analysis using MPD and HFT Friction as explanatory variables.

$$CCR = \beta_2 MPD + \beta_1 \left(HFT\ \ Friction\right) + \beta_0 \tag{5-9}$$

Regression analysis using non-standardized data results in the following coefficients:

$\beta_2 = 0.001051$
$\beta_1 = 0.001683$

Using standardized data results in these coefficients:

$\beta_2 = 0.755$
$\beta_1 = 0.183$

From the relative values of the standardized coefficients, the influence of MPD on CRR is four times that of HFT Friction. This relative significance is not readily revealed by the non-standardized coefficients.

Note that qualitative explanatory variables are not included in the standardized scaling. They must maintain values of zero and one.

5.2 Solver

The *LINEST* function in Microsoft Excel is used to solve the linear regression equations. Excel's LINEST function has an option to output statistical quantities including:

- $SE\beta_i$ = standard error for the coefficients β_i.
- Standard error of the estimate (SEy).
- Coefficient of determination (r-squared value).
- Analysis degrees of freedom.

From the output of the LINEST function, other parameters are calculated.

$$t\text{-}value_i = \beta_i / SE\beta_i \tag{5-10}$$

Where:

$t\text{-}value_i$ = value to use in the Student's t-distribution to evaluate significance,
$SE\beta_i$ = the standard error of the estimate of β_i, and
β_i = the regression coefficients.

Then, the p-value (significance level) is given by:

$$p\text{-}value_i = TDIST(t\text{-}value_i, dof) \tag{5-11}$$

Where:

p-value$_i$ = probability associated with regression coefficient *i*,
TDIST = two-tailed Student's t-distribution function,
t-value$_i$ = value at which to evaluate the Student's t-distribution, and
dof = the statistical degrees of freedom in the analysis.

Visual Basic for Applications (VBA) modules are used to execute the LINEST function on multiple combinations of variables and save the results in Excel worksheets for analysis.

5.3 Criteria for Assessing Regression Results

Three criteria are used in this study to judge the results of regression analysis:

1. Coefficient of determination (r-squared value),
2. Significance levels (p-values), and
3. Signs of the coefficients.

The r-squared value indicates how much of the variability in the dependent variable is explained by the explanatory variables. Higher r-squared values indicate a better fit.

The p-value indicates the probability that the coefficient for the explanatory variable is due to chance. In this study, a criterion of p-value ≤ 0.05 is placed on all explanatory variables. Analyses with a p-value > 0.05 for any explanatory variable are rejected. Note that a p-value ≤ 0.5 is not a guarantee that the coefficient is not due to chance. In this study, there are a large number of explanatory variables which results in hundreds of analyses satisfying the p-value criteria. At the 0.05 significance level, expect 5 out of 100 of these may be due to chance.

The signs of the regression coefficients must make physical sense. For example, a direct relationship between CRR and friction is expected, that is, increasing friction increases CRR. Similar expectations are held for roughness variables. Regression analyses that results in a negative coefficient for a friction or roughness variable violate engineering expectations. Therefore, results with negative friction and roughness coefficients are not accepted. Negative texture coefficients must be considered case-by-case because some texture variables may have an indirect relationship with CRR, for example, valley depth.

5.4 Dependent and Explanatory Variables

The database contains 13 CRR variables corresponding to data from various tires, speeds, and even averages across tires. Any of these can be used as a dependent variable in linear regression analyses. From the rolling resistance study report [6] there is strong correlation between CRR measured with each tire; each is offset from the others by a constant. Therefore, a single tire can be selected for regression analyses investigations and the results are easily extended to the other tires. For this study, the SRTT tire is selected.

With respect to speed, the 80 km/h (50 mph) test speed is selected because:

- It is closer than 50 km/h (30 mph) to highway speeds,
- Data for this speed are available for all the test cells, and

- According to reference [6], the lengths of the test cells are not conducive to reliable CRR test measurements at speeds greater than 80 km/h.
- Reduce complexity.

Therefore, the SRTT 80 variable is the dependent variable in all the regression analyses in this study.

The explanatory variables are:
- Texture,
- Roughness, and
- Friction

The noise variables are not used as explanatory variables in the linear regression analyses in this study. Tire-pavement noise is a function of the tire and the other pavement surface characteristics; similar to rolling resistance. Therefore, noise is considered to be more of a dependent variable than an explanatory variable. Nevertheless, strong correlation is observed in this data set between low frequency tire-pavement noise levels and CRR for the diamond grind textured PCC pavements (and weak correlation for the other pavement groupings). Most likely, this correlation is due to both variables having a strong dependence on the texture of the diamond grind PCC pavements. This suggests a topic for another investigation; the dependency of tire-pavement noise on texture.

5.5 Groupings and Qualitative Variables

5.5.1 Pavement Groupings

Conducting regression analyses on the entire MnROAD data set, without any grouping, yields relatively poor results (relatively low r-squared values). It is rational to group the data by type of pavement; namely, asphalt and PCC. These two materials have different properties which may be expected to affect rolling resistance in different fashions. Even within the PCC pavements, there are surface textures with very different properties, longitudinally textured (tine, broom, and drag), transversely textured, and diamond grind textured. Each of these different textures may be expected to have different interactions with rolling resistance.

Table 5-1 lists the results of t-Tests (using MS Excel) comparing the means of CRR from the asphalt and PCC samples, and from the PCC, grind and non-grind samples (for the SRTT tire at 80 km/h). In a t-Test, the p-value is an indicator of the likelihood of the hypothesis that the two samples being compared are from populations with different means (averages). Usually, the criteria used to accept the hypothesis is $p \leq 0.05$. In Table 5-1, the p-values are much less than the 0.05 criteria, indicating the asphalt and PCC samples are very likely from different distributions, and within the PCC pavements, the non-grind and grind samples are from different distributions.

Table 5-1. t-Test results for two CRR sample sets; asphalt and PCC, and PCC grind and non-grind. Samples are from results for the SRTT tire at 80 km/h.

Statistic	Asphalt	PCC	PCC, grind	PCC, non-grind
Mean	0.007812	0.007291	0.008243	0.006949
Variance	5.17E-07	7.04E-07	4.11E-07	3.69E-07
Observations	48	53	14	39
Hypothesized Mean Difference	0		0	
df	99		22	
t Stat	3.358		6.568	
P(T<=t) one-tail	0.0006		0.0000	
t Critical one-tail	1.660		1.717	
P(T<=t) two-tail	0.0011		0.0000	
t Critical two-tail	1.984		2.074	

These t-Test results, along with the behavior and performance of the samples in linear regression analyses, supports treating the data in separate pavement groupings. Therefore, for this study, the MnROAD test cells are divided into the following pavement groupings.

- Asphalt: includes all the asphalt pavements.
- PCC, non-grind: includes transverse and longitudinally textured PCC (tine, drag, and broom).
- PCC, grind: includes conventional and next generation diamond grinds.

Regression analyses are performed separately on each pavement group.

5.5.2 Qualitative Variable, Road

Table 5-2 lists the results of t-Tests (using MS Excel) comparing the means of CRR from the Mainline and Low-Volume Roads for three sample sets; all test cells, cells with asphalt pavement, and cells with PCC, non-grind pavement (for the SRTT tire at 80 km/h). Note the very low p-values in the table for the cases of all cells and PCC, non-grind cells. The asphalt sample set is borderline, just slightly greater than 0.05 for the two-tailed case. However, when the road is included as a qualitative explanatory variable in the regression analyses, the p-value for the qualitative variable is usually very low (less than 0.05) indicating the variable is significant.

This indicates there is an uncontrolled factor in the data. This could be, for example, the difference in traffic loading between the Mainline and Low-Volume Roads. Therefore, a qualitative variable, *Road*, is included as an explanatory variable in the regression analyses with the Asphalt and PCC, non-grind pavement groupings. All the test cells with PCC, grind pavement that are included in the analyses in this study are on the Mainline, and a qualitative variable for *Road* is not used.

Table 5-2. t-Test results comparing CRR sample means for the Mainline and Low-Volume Road for three sample sets; all test cells, asphalt test cells, and PCC non-grind cells. Samples are from results for the SRTT tire at 80 km/h.

	All Test Cells		Asphalt		PCC non grind	
Statistic	**Mainline**	**LVR**	**Mainline**	**LVR**	**Mainline**	**LVR**
Mean	0.007842	0.00716	0.007618	0.008006	0.007313	0.006638
Variance	4.82E-07	6.73E-07	6.92E-07	2.86E-07	3.92E-07	1.47E-07
Observations	56	45	24	24	18	21
Hypothesized Mean Difference	0		0		0	
df	86		39		27	
t Stat	4.443		-1.923		3.981	
P(T<=t) one-tail	0.0000		0.0309		0.0002	
t Critical one-tail	1.663		1.685		1.703	
P(T<=t) two-tail	0.0000		0.0618		0.0005	
t Critical two-tail	1.988		2.023		2.052	

5.6 Excluded Cells

There are a few test cells in the database that are excluded from the regression analyses. These are summarized in Table 5-3. The number of excluded data records (test cells and lanes) is seven.

Table 5-3. Test cells excluded from the regression analyses.

Cell	Road / Lane	Explanation
1	Mainline / both lanes	CRR data not available.
23	Mainline / both lanes	CRR data not available.
28	LVR / both lanes	CRR data outliers.
37	LVR / outside lane	Inconsistent and/or unknown wheel paths.

Test cell 28 on the Low-Volume Road is excluded because it is an outlier as evidenced in Figure 5-1 which shows a normal quantile (probability) plot of the SRTT 80 data. In a normal quantile plot, the tendency for the data to follow a straight line is a measure of how closely the data follows a standard normal distribution. The two outlying points at the upper left correspond to data for test cell 28, inside and outside lanes. Possible reasons for cell 28's outlier behavior is there was poor compaction during construction and, at the time of the rolling resistance measurements, chip loss and surface deterioration were observed.

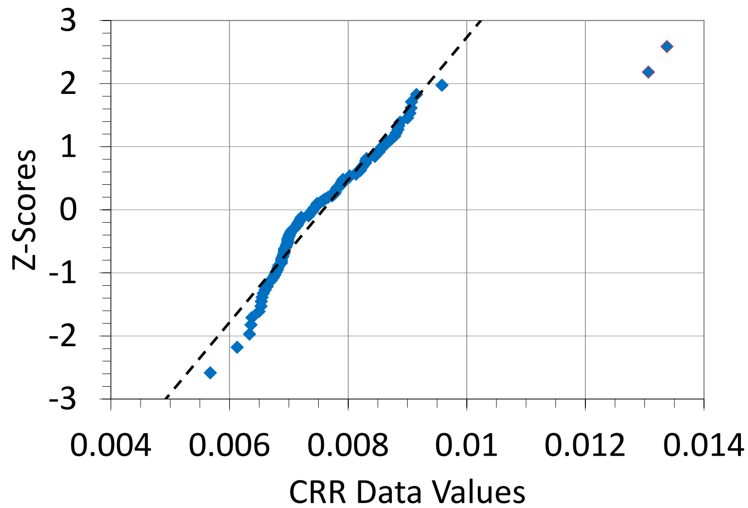

Figure 5-1. Normal quantile plot of the CRR data for the SRTT 80 tire.

The outside lane of test cell 37 on the Low-Volume Road has PCC pavement with four tracks of various diamond grinds. This lane of test cell 37 is excluded from the regression analyses because it is not known which track was used to measure for each surface characteristic.

5.7 Degrees of Freedom

There are 108 data records in the database with seven of these excluded from regression analyses for a total of 101 data records available for analysis. The data record count for each pavement grouping is summarized in Table 5-4.

Table 5-4. Number of data records included in the regression analyses for each pavement grouping and road.

Pavement Grouping	Mainline	LVR	Total
Asphalt	24	24	48
PCC, non-grind	18	21	39
PCC, grind	14	0	14
All	66	45	101

Table 5-5 lists the resulting number of degrees of freedom in a linear regression analysis with one, two, and three quantitative explanatory variables. For the Asphalt and PCC, non-grind pavement groups, the extra qualitative explanatory variable is accounted for in the degrees of freedom listed in the table.

Table 5-5. Number of statistical degrees of freedom.

	Number of Quantitative Explanatory Variables		
Pavement Grouping	One	Two	Three
Asphalt	45	44	43
PCC, non-grind	36	35	34
PCC, grind	12	11	10

5.8 Presentation of Results

The large number of explanatory variables means there are a large number of possible combinations that can be used in a linear regression analysis. For example, there are 105 texture and 31 roughness variables in the database. This gives a total number of texture and roughness variable combinations or analyses of 105 × 31 = 3,255. Of the 3,255 regression analyses, there may be a subset of two to four hundred that yield valid results. In this report, the following instruments are used to communicate the results about the valid analyses.

Graph of r-squared versus count –
An example of an r-squared versus count graph is in Figure 6-1 on page 42. This graph shows the r-squared values for the results in order of decreasing r-squared value. Key information revealed by this graph:

- The maximum r-squared value obtained (at the left end of the trace corresponding to a count equal to 1).
- The range for the top ten r-squared values (to the left of the vertical, dashed line).
- The range for the top-50 r-squared values (the horizontal axis stops at 50).

Table of prominent variables –
An example of a table of prominent variables is Table 6-1 on page 43. This table lists the explanatory variables associated with the analyses that yielded greatest r-squared values.

Table of the top ten results –
An example of a top ten table is Table 6-2 on page 44. This table lists the following results for the ten regression analyses with the greatest r-squared values.

- r-squared values.
- The explanatory variables.
- Regression coefficients for the explanatory variables.
- Standardized regression coefficients.
- p-values.

Charts of r-squared versus explanatory variable –
Examples of this chart are in Figure 6-2 on page 45. The graph shows the r-squared values associated with each of the explanatory variables. Key information revealed by this chart includes:

- Which explanatory variables are associated with the greatest r-squared values.
- Which explanatory variables or groups of variables produce valid results.
- Which explanatory variables do not produce valid results (identified by variables for which there are no r-squared values).
- Which variables possibly are appearing by chance even though the p-value ≤ 0.05 criterion is met. These are identified by isolated or "rogue" points, for example, in the upper chart of Figure 6-7 on page 54, the isolated point at the 125 mm waveband and r-squared value of 0.6. If this variable was not really due to chance, then there is expected to be a column of multiple valid results and some valid results for the neighboring wavebands (160 and 100 mm) giving a similar appearance as the 10 to 4 mm bands in the same figure.

Chapter 6. Regression Analyses Results

This chapter presents the performance of linear regression analyses with CRR as the dependent variable and various combinations of the other surface characteristics as explanatory variables. The objective is to explore which explanatory variables, and how many, are effective at contributing toward modeling CRR. The various regression analyses are identified as follows.

- **Single variable**: analyses using a single texture, roughness, or friction variable.
- **MPD – IRI**: analyses using MPD and IRI as variables.
- **Texture – roughness**: analyses using combinations of one texture and one roughness variable.
- **Texture – friction**: analyses using combinations of one texture and one friction variable.
- **Texture – texture**: analyses using combinations of two texture variables.
- **Texture – roughness – friction**: analyses using combinations of one texture, one roughness, and one friction variable.
- **Texture – texture – roughness**: analyses using combinations of two texture variables and one roughness variable.

6.1 Single Variable Analyses

Single variable regression analyses have the form of Equation (6-1).

$$CCR = \beta_1 Variable + \beta_0 + \beta_q Road \qquad (6\text{-}1)$$

Where the qualitative variable is not used ($\beta_q = 0$) for the PCC, grind pavements.

There are 105 texture, 31 roughness, and 4 friction variables in the database. This gives a total number of 140 single variable regression analyses for each pavement grouping. Of these, the following number yielded valid regression results.

- Asphalt pavements: 122
- PCC, non-grind pavements: 103
- PCC, grind pavements: 50

Figure 6-1 through Figure 6-4 show the r-squared values obtained with single variable analysis for each of the pavement groupings. Table 6-1 lists the variables that generate the highest r-squared values. Table 6-2 list the regression results for the top ten analyses for each pavement grouping.

Observations:

- With the asphalt pavements, most of the texture variables yield r-squared values above 0.70.
- For the PCC, grind pavements, texture variable longitudinal skewness (LgSkew) correlates to CRR.
- With the PCC, grind pavements, very few of the roughness variables correlate with CRR (at the 0.05 significance level, p-value ≤ 0.05).

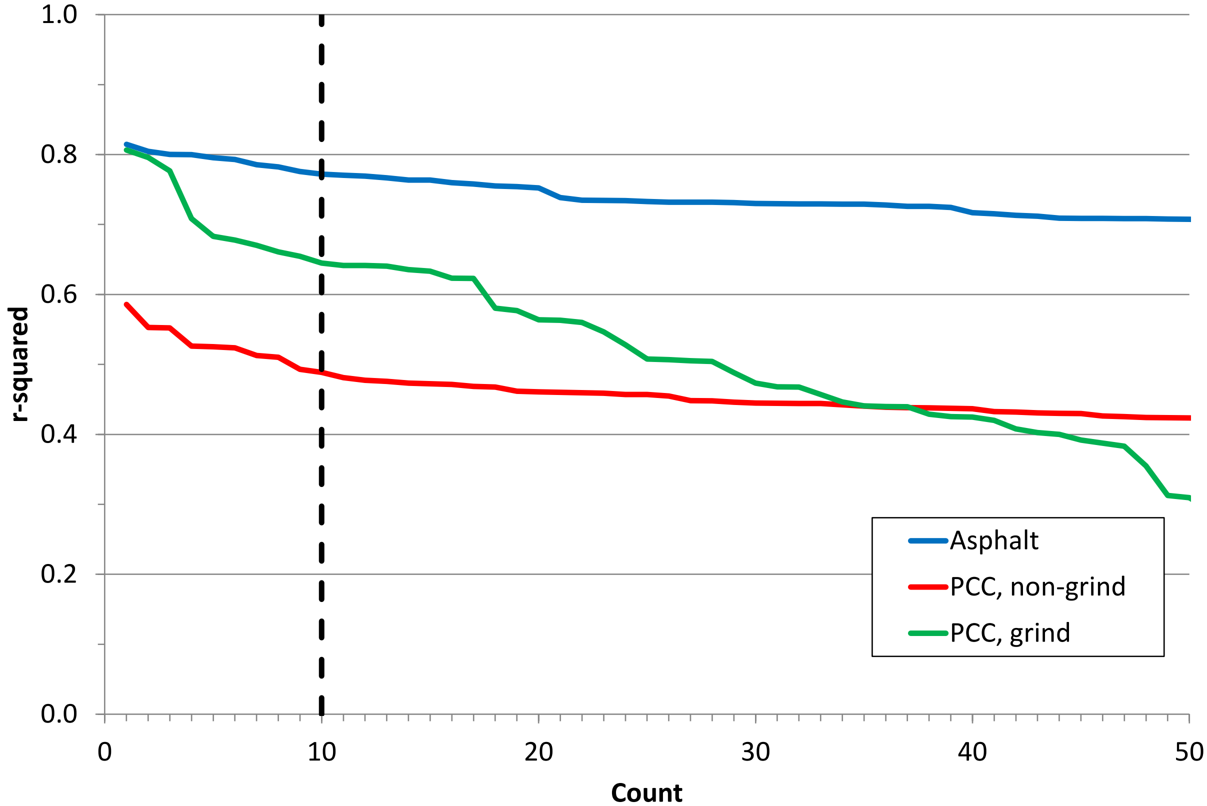

Figure 6-1. r-squared values generated by single variable analyses for each of the pavement groupings.

Table 6-1. Variables generating significant results (high r-squared values) for single variable analyses.

Pavement Grouping	Max r-squared	Texture Variables	Roughness Variables	Friction Variables
Asphalt	0.81	Level in bands: • 63 mm • 50 mm • 40 mm • 31.5 mm Lumped bands: • 3.15 to 50 mm • 50 to 160 mm	None with r-squared > 0.40	None with r-squared > 0.40
PCC non-grind	0.59	Level in bands: • 160 mm • 125 mm • 100 mm Lumped bands: • 50 to 160 mm	Level in bands: • 1.25 m	Smooth tire friction number (r-squared = 0.48)
PCC grind	0.81	Longitudinal: • Skewness	None with r-squared > 0.60	Ribbed tire friction number (r-squared = 0.62)

Table 6-2. Top ten results for each pavement grouping for single variable regression analyses.

Pavement Grouping	Variable	r-sq	p-values Var	p-values Road	Regression Coefficients β_1	β_0	β_q
Asphalt	Text: L 63 mm	0.81	0.0000	0.0000	1.282E-4	4.412E-03	1.086E-03
	Text: L 40 mm	0.80	0.0000	0.0000	1.217E-4	4.948E-03	9.664E-04
	Text: L 3.15 – 50 mm	0.80	0.0000	0.0000	1.220E-4	4.290E-03	9.552E-04
	Text: L 50 mm	0.80	0.0000	0.0000	1.248E-4	4.611E-03	1.028E-03
	Text: L 31.5 mm	0.80	0.0000	0.0000	1.186E-4	5.605E-03	9.047E-04
	Text: L 50 – 160 mm	0.79	0.0000	0.0000	1.354E-4	3.134E-03	1.100E-03
	Text: L 80 mm	0.79	0.0000	0.0000	1.310E-4	4.324E-03	1.093E-03
	Text: L 25 mm	0.78	0.0000	0.0000	1.097E-4	6.944E-03	8.316E-04
	Text: L 20 mm	0.78	0.0000	0.0000	1.134E-4	6.011E-03	7.819E-04
	Text: L 3.15 mm	0.77	0.0000	0.0000	1.132E-4	7.169E-03	7.271E-04
PCC, non-grind	Text: L 160 mm	0.59	0.0000	0.0000	8.587E-5	3.671E-03	1.099E-03
	Rough: 1.25 m	0.55	0.0001	0.0000	5.546E-5	3.941E-03	1.070E-03
	Text: L 125 mm	0.55	0.0001	0.0000	7.974E-5	3.909E-03	1.100E-03
	Text: L_100 mm	0.53	0.0003	0.0000	7.114E-5	4.251E-03	1.053E-03
	Rough: 0.63 m	0.53	0.0003	0.0000	4.175E-5	4.672E-03	1.042E-03
	Text: L 50 - 160 mm	0.52	0.0003	0.0000	7.117E-5	3.707E-03	1.053E-03
	Text: L 80 mm	0.51	0.0005	0.0000	6.517E-5	4.494E-03	1.026E-03
	Text: 90% LgRpk	0.51	0.0006	0.0000	9.337E-4	6.178E-03	8.559E-04
	Rough: 0.5 m	0.49	0.0011	0.0000	3.440E-5	5.024E-03	1.001E-03
	Text: L 5 mm	0.49	0.0013	0.0000	3.529E-5	6.671E-03	8.392E-04
PCC, grind	Text: 10% LgSkew	0.81	0.0000	—	1.493E-3	1.015E-2	0
	Text: 50% LgSkew	0.80	0.0000	—	1.264E-3	9.306E-3	0
	Text: 90% LgSkew	0.78	0.0000	—	9.982E-4	8.608E-3	0
	Text: 10% LgSMTD	0.71	0.0002	—	3.457E-3	1.424E-3	0
	Text: 90% TrCF	0.68	0.0003	—	5.465E-4	7.062E-3	0
	Text: 50% LgSMTD	0.68	0.0003	—	3.031E-3	2.359E-3	0
	Text: 50% TrCF	0.67	0.0003	—	6.360E-4	6.965E-3	0
	Text: 90% TrSMTD	0.66	0.0004	—	6.745E-4	6.980E-3	0
	Text: 90% TrSkew	0.65	0.0005	—	5.957E-4	8.242E-3	0
	Text: 50% TrSMTD	0.64	0.0005	—	7.400E-4	6.913E-3	0

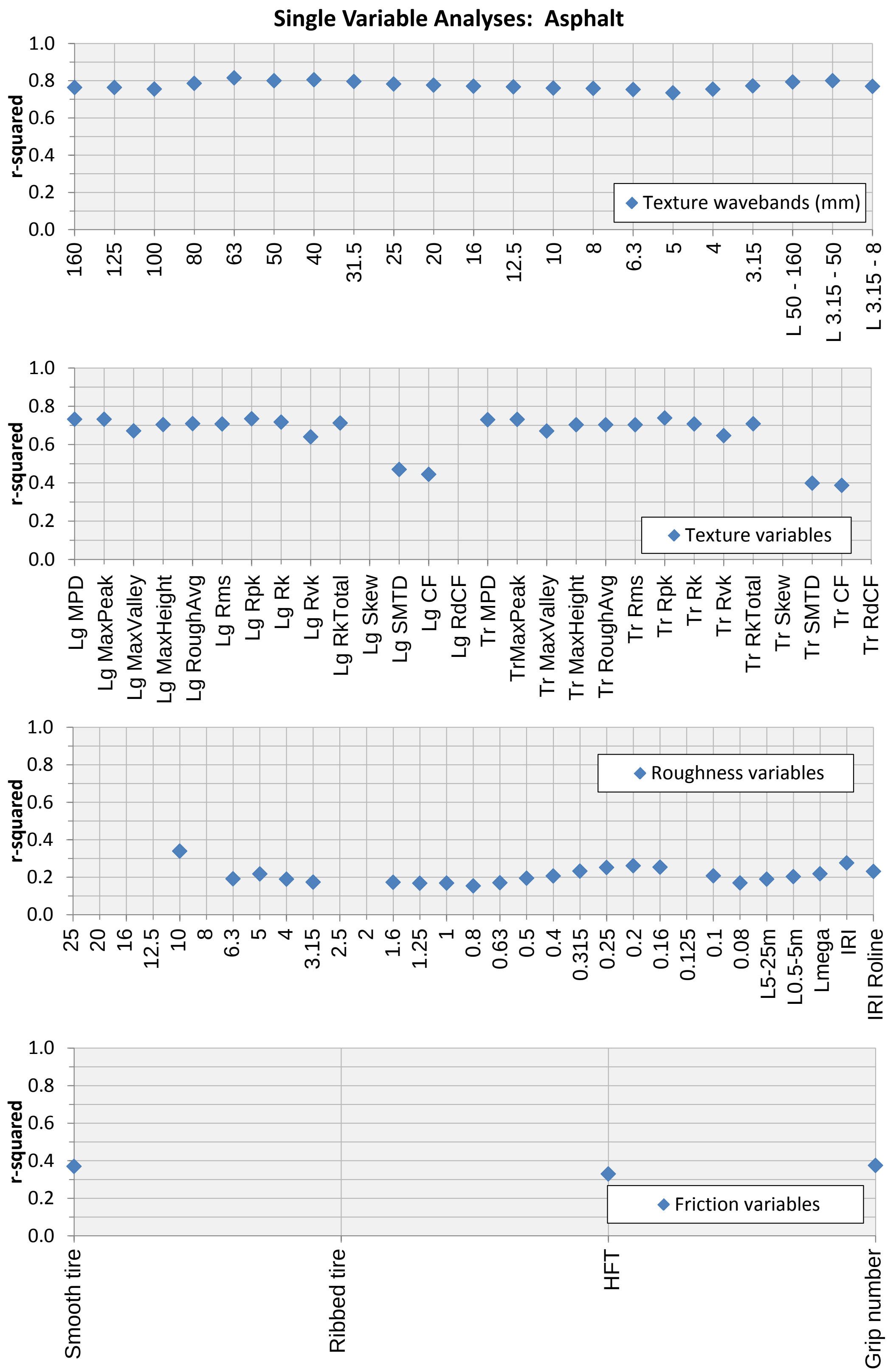

Figure 6-2. Asphalt pavement: r-squared values for texture (upper chart), roughness (center chart), and friction (lower chart) variables.

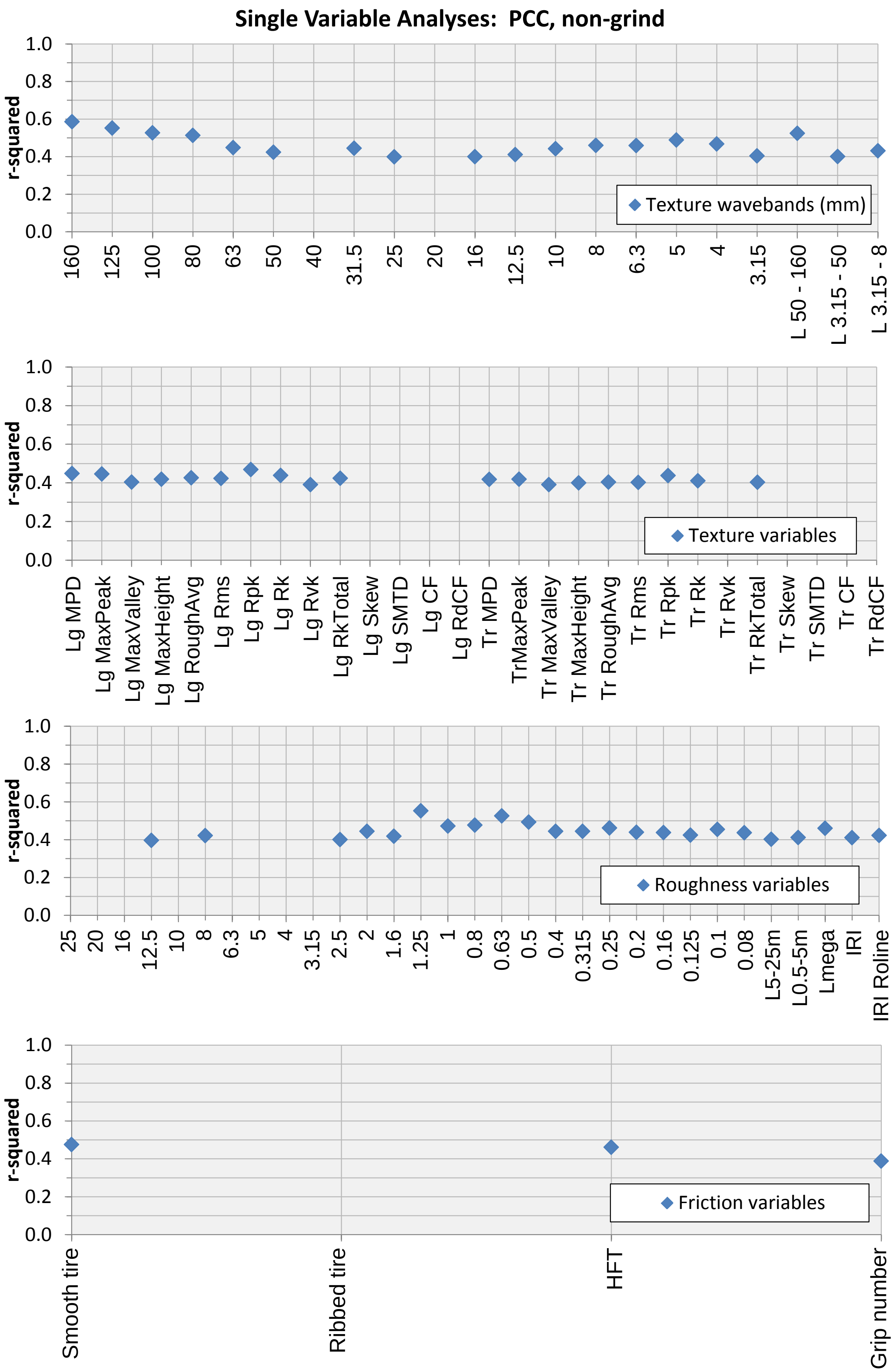

Figure 6-3. PCC, non-grind pavement: r-squared values for texture (upper chart), roughness (center chart), and friction (lower chart) variables.

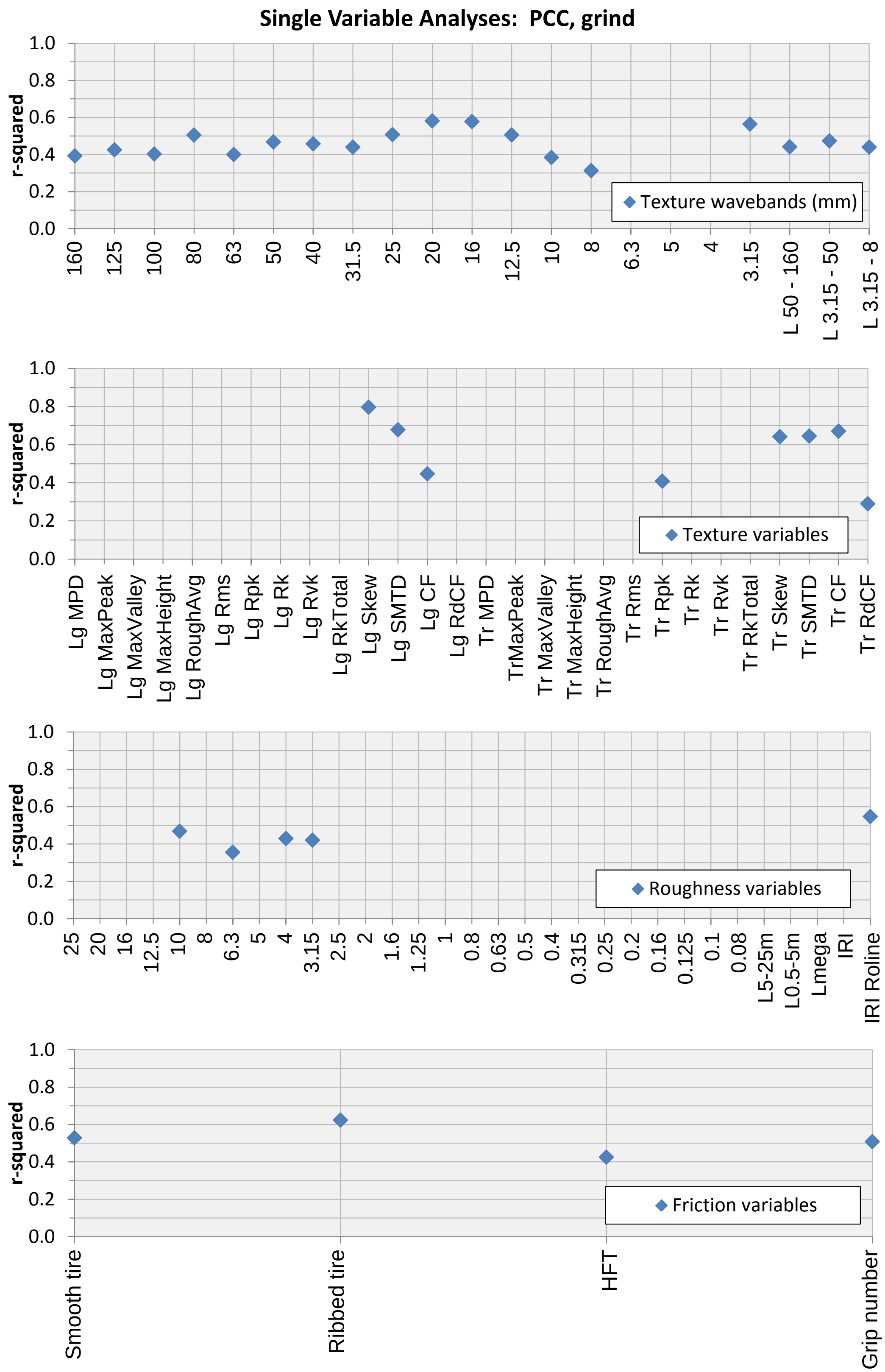

Figure 6-4. PCC, grind pavement: r-squared values for texture (upper chart), roughness (center chart), and friction (lower chart) variables.

6.2 MPD – IRI Analyses

Rolling resistance models consisting of the texture variable MPD and roughness variable IRI is proposed in the literature [9]. This section presents the linear analysis results using these two variables. The MPD – IRI regression analyses have the form of Equation (6-2).

$$CCR = \beta_2 MPD + \beta_1 IRI + \beta_0 + \beta_q Road \tag{6-2}$$

Where the qualitative variable is not used ($\beta_q = 0$) for the PCC, grind pavements.

For the results in this section, the MPD variable is the 50% longitudinal MPD (50% LgMPD). The IRI variable is either of the IRI_RUN(M-KM) or ROLINE_IRI_(M-KM); whichever yields the better results.

Table 6-3. Results for MPD – IRI analyses.

Pavement Grouping	r-sq	p-values			Regression Coefficients			
		MPD	IRI	Road	β_2	β_1	β_0	β_q
All cells	0.35	0.0000	0.0001	0.0000	1.125E-3	-3.377E-4	6.960E-3	7.394E-4
Asphalt	0.73	0.0000	0.7906	0.0000	1.189E-3	-3.066E-5	6.544E-3	7.675E-4
PCC, non-grind	0.45	0.2001	0.7724	0.0000	3.082E-4	3.323E-5	6.249E-3	8.910E-4
PCC, grind	0.29	0.0617	0.0566	–	8.085E-3	-2.087E-3	8.367E-3	0

Observations:

- None of the analyses generate good results as evidenced by a low r-squared value, p-value is much greater than 0.05, coefficient for IRI (β_1) is negative, or a combination of these.

6.3 Texture – Roughness Analyses

Regression analyses using combinations of texture and roughness variables have the form of Equation (6-3).

$$CCR = \beta_2 Texture + \beta_1 Roughness + \beta_0 + \beta_q Road \quad (6\text{-}3)$$

Where the qualitative variable is not used ($\beta_q = 0$) for the PCC, grind pavements.

There are 105 texture and 31 roughness variables in the database. This gives a total of 3,255 combinations of texture and roughness variables. Of these, the following number yielded valid regression results.

- Asphalt pavements: 222
- PCC, non-grind pavements: 233
- PCC, grind pavements: 101

Figure 6-5 through Figure 6-8 show the r-squared values obtained with texture – roughness analyses for each of the pavement groupings. Table 6-4 lists the variables that generate the highest r-squared values. Table 6-5 list the regression results for the top ten analyses for each pavement grouping.

Observations:

- For the asphalt pavements, texture in wavelength bands 16 mm and greater do not yield valid regression results.
- For the PCC, non-grind pavements, only four non-spectral texture variables yield valid regression results, and these four are all in the transverse direction. One of these is transverse skewness (TrSkew).
- For the PCC, grind pavements, longitudinal skewness (LgSkew) yields high r-squared value.

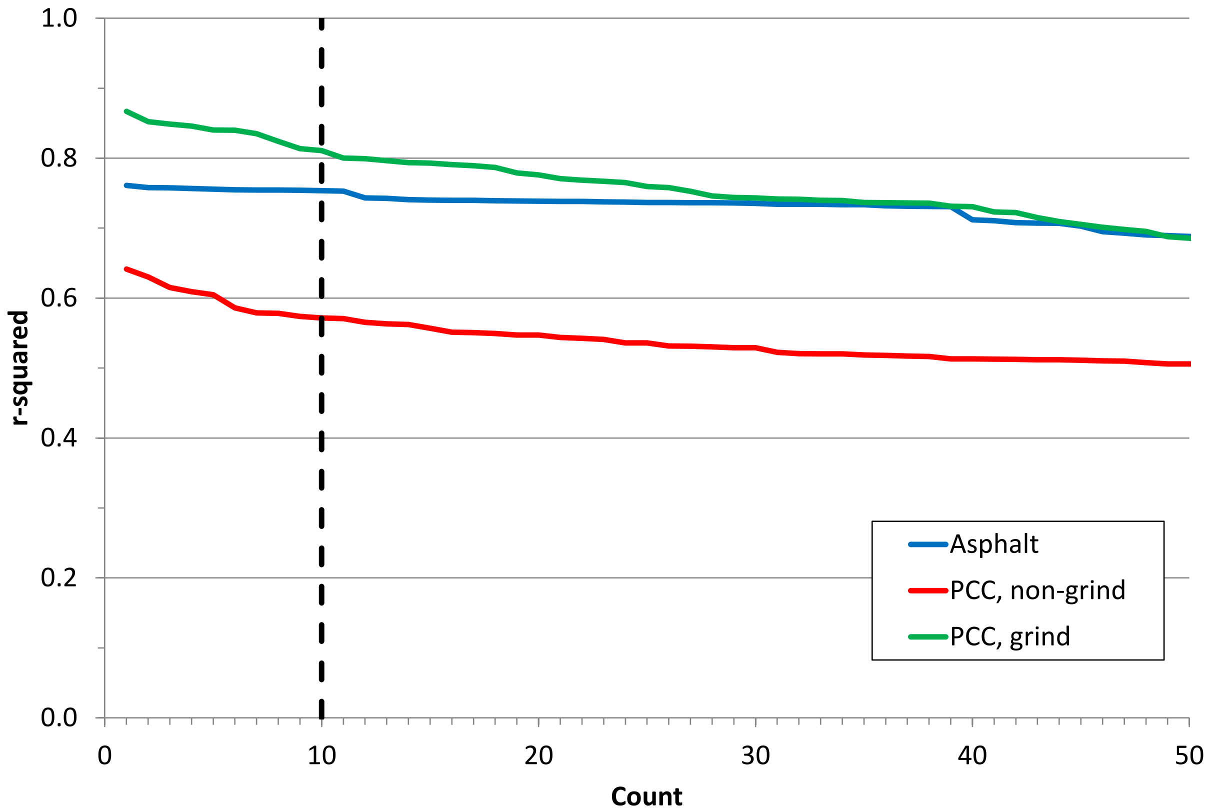

Figure 6-5. r-squared values generated by texture – roughness analyses for each of the pavement groupings.

Table 6-4. Variables generating significant results (high r-squared values) for texture – roughness analyses.

Pavement Grouping	Max r-squared	Texture Variables	Roughness Variables
Asphalt	0.79	Wavebands: • 12.5 mm … 3.15 mm Lumped bands: • 3.15 to 8 mm band Longitudinal and transverse: • MPD • MaxPeak • MaxHeight • RoughAvg • Rms • Rpk • Rk • RkTotal	Level in bands • 25 m • 5 m
PCC non-grind	0.73	Transverse: • Transverse Skewness • Transverse SMTD • Transverse CF	Level in bands: • 1.25 m • 0.63 m • Bands 1.25 m and less Lumped bands • Lmega • IRI • IRI Roline
PCC grind	0.87	Longitudinal • Skewness • SMTD Transverse: • MaxValley • Rms • Rvk • RkTotal • Skewness • SMTD • CF	Level in bands: • 3.15 m • 0.2 m • 0.16 m • 0.1 m Lumped bands • IRI

Table 6-5. Top ten results for each pavement grouping for texture - roughness regression analyses.

				p-values			Regression Coefficients				Standardized Coefficients	
Pave-ment	Texture Variable	Roughness Variable	r-sq	Texture	Rough	Road	β_2	β_1	β_0	β_q	β_2	β_1
Asphalt	L 3.15 mm	5 m	0.79	0.0000	0.0472	0.0000	1.074E-4	2.722E-5	5.818E-3	8.050E-04	0.824	0.161
	L 3.15 – 8 mm	5 m	0.79	0.0000	0.0361	0.0000	1.189E-4	2.877E-5	5.319E-3	8.192E-04	0.823	0.171
	L 10 mm	5 m	0.79	0.0000	0.0146	0.0000	1.103E-4	3.358E-5	5.106E-3	7.793E-04	0.806	0.199
	L 12.5 mm	5 m	0.79	0.0000	0.0424	0.0000	1.035E-4	2.808E-5	5.781E-3	7.790E-04	0.815	0.167
	L 8 mm	5 m	0.79	0.0000	0.0173	0.0000	1.234E-4	3.297E-5	5.934E-3	8.098E-04	0.810	0.196
	L 4 mm	5 m	0.78	0.0000	0.0174	0.0000	1.322E-4	3.319E-5	6.369E-3	8.354E-04	0.813	0.197
	L 6.3 mm	5 m	0.78	0.0000	0.0188	0.0000	1.380E-4	3.294E-5	6.228E-3	8.544E-04	0.816	0.195
	50% TrRpk	25 m	0.77	0.0000	0.0158	0.0000	2.796E-3	2.024E-5	5.186E-3	7.960E-04	0.850	0.185
	90% TrRpk	25 m	0.77	0.0000	0.0125	0.0000	2.286E-3	2.113E-5	5.145E-3	8.027E-04	0.850	0.194
	50% Lg MaxPeak	25 m	0.77	0.0000	0.0116	0.0000	1.010E-3	2.136E-5	5.142E-3	8.471E-04	0.859	0.196
PCC, non-grind	10% TrSkew	1.25 m	0.73	0.0000	0.0000	0.0000	9.258E-4	6.628E-5	4.151E-3	1.126E-03	0.433	0.703
	10% TrSkew	0.63 m	0.72	0.0000	0.0000	0.0000	9.779E-4	5.272E-5	4.934E-3	1.115E-03	0.458	0.695
	50% TrSkew	1.25 m	0.72	0.0001	0.0000	0.0000	8.793E-4	7.307E-5	3.572E-3	1.145E-03	0.434	0.775
	90% TrSkew	1.25 m	0.70	0.0002	0.0000	0.0000	9.508E-4	7.678E-5	3.241E-3	1.116E-03	0.442	0.814
	50% TrSkew	0.63 m	0.69	0.0001	0.0000	0.0000	9.024E-4	5.726E-5	4.442E-3	1.126E-03	0.446	0.755
	90% TrCF	1.25 m	0.69	0.0004	0.0000	0.0000	1.010E-3	7.979E-5	6.758E-4	1.238E-03	0.428	0.846
	50% TrCF	1.25 m	0.69	0.0004	0.0000	0.0000	1.024E-3	8.495E-5	4.111E-4	1.208E-03	0.455	0.901
	90% TrSkew	0.63 m	0.68	0.0002	0.0000	0.0000	9.831E-4	6.057E-5	4.135E-3	1.097E-03	0.457	0.799
	90% TrSMTD	1.25 m	0.68	0.0007	0.0000	0.0000	1.167E-3	7.749E-5	8.284E-4	1.211E-03	0.406	0.822
	50% TrSMTD	1.25 m	0.67	0.0011	0.0000	0.0000	1.147E-3	8.425E-5	5.183E-4	1.195E-03	0.432	0.893
PCC, grind	50% LgSkew	0.16 m	0.87	0.0000	0.0261	-	1.313E-3	2.844E-5	8.687E-3	0	0.927	0.279
	50% LgSkew	0.1 m	0.87	0.0000	0.0348	-	1.347E-3	3.076E-4	4.102E-3	0	0.950	0.272
	90% LgSkew	0.16 m	0.85	0.0000	0.0399	-	1.035E-3	2.789E-5	7.974E-3	0	0.914	0.274
	90% LgSkew	0.1 m	0.85	0.0000	0.0444	-	1.066E-3	3.094E-4	3.329E-3	0	0.941	0.273
	50% TrRvk	IRI_RUN(M-KM)	0.84	0.0000	0.0000	-	-5.386E-4	1.374E-3	6.873E-3	0	-2.244	1.933
	50% TrMaxValley	IRI_RUN(M-KM)	0.83	0.0000	0.0000	-	7.006E-4	1.529E-3	7.008E-3	0	2.443	2.152
	10% TrRvk	IRI_RUN(M-KM)	0.83	0.0000	0.0001	-	-5.856E-4	1.281E-3	6.956E-3	0	-2.122	1.802
	90% TrMaxValley	IRI_RUN(M-KM)	0.83	0.0000	0.0001	-	7.272E-4	1.394E-3	7.118E-3	0	2.267	1.962
	90% TrRvk	IRI_RUN(M-KM)	0.83	0.0000	0.0001	-	-4.829E-4	1.363E-3	6.935E-3	0	-2.227	1.918
	10% TrMaxValley	IRI_RUN(M-KM)	0.82	0.0000	0.0001	-	6.841E-4	1.563E-3	7.062E-3	0	2.485	2.199

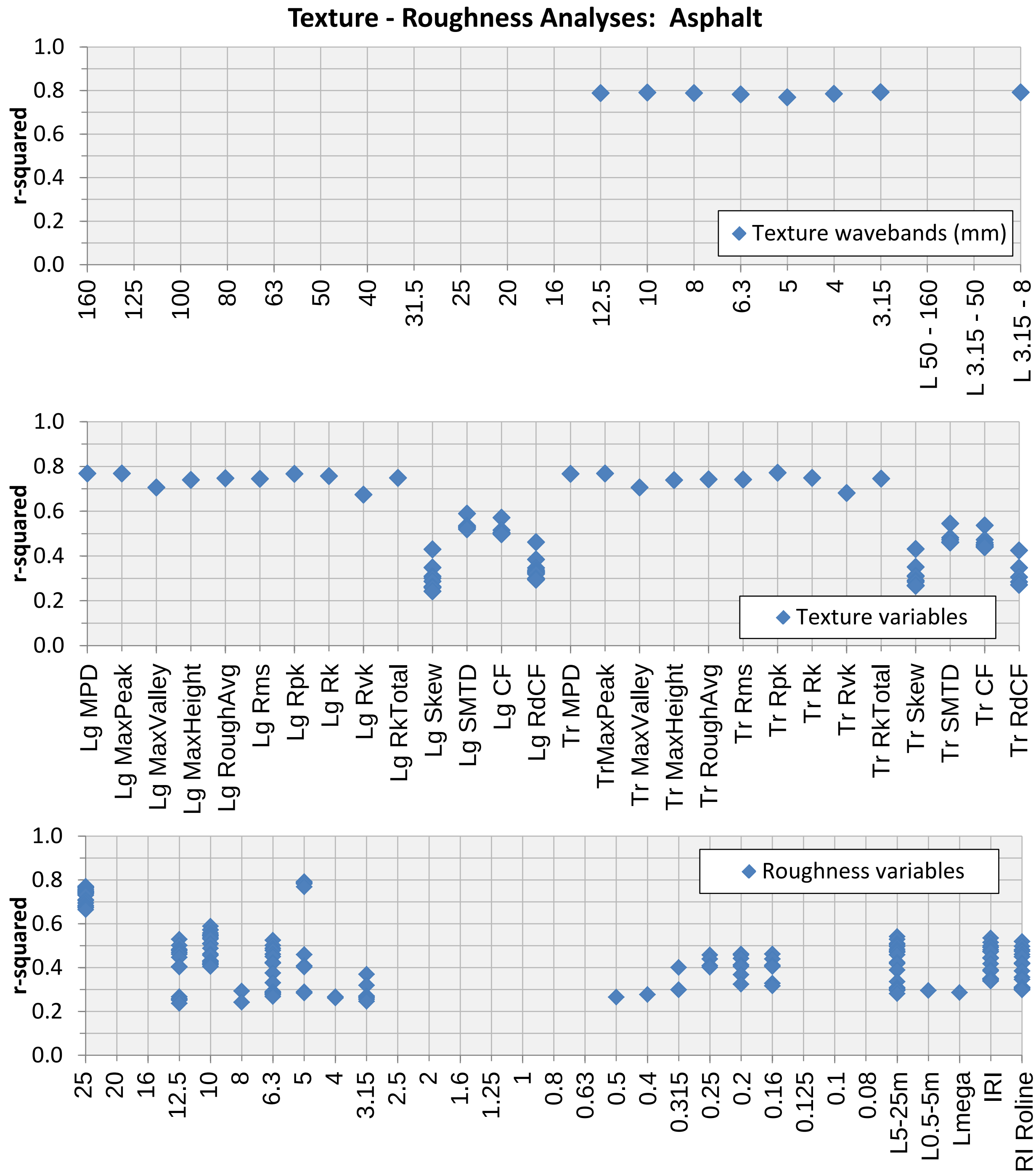

Figure 6-6. Asphalt pavement: r-squared values for texture wavebands, mm (upper chart), 50 percentile texture variables (center chart), and roughness variables (lower chart).

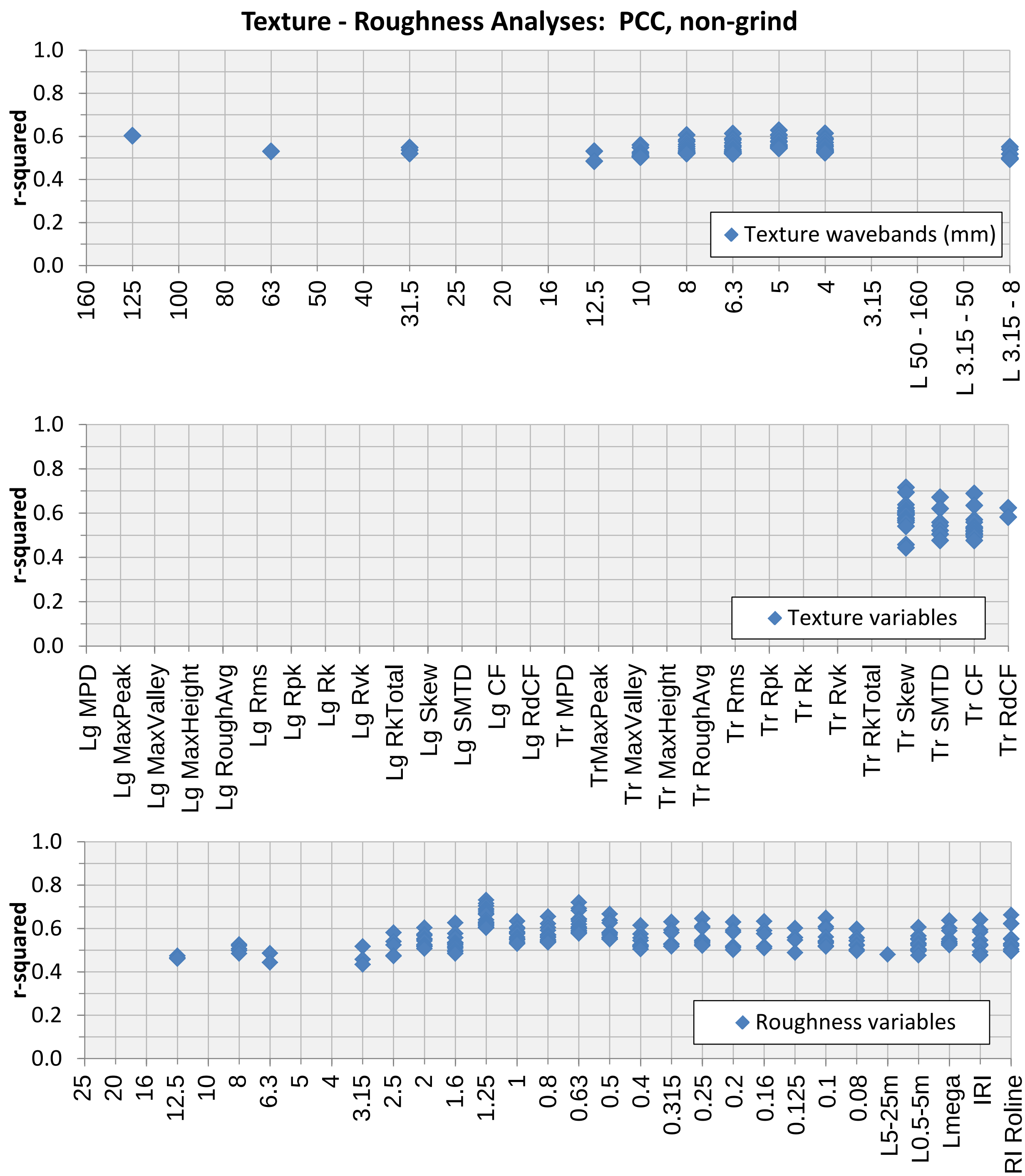

Figure 6-7. PCC, non-grind pavement: r-squared values for texture wavebands, mm (upper chart), 50 percentile texture variables (center chart), and roughness variables (lower chart).

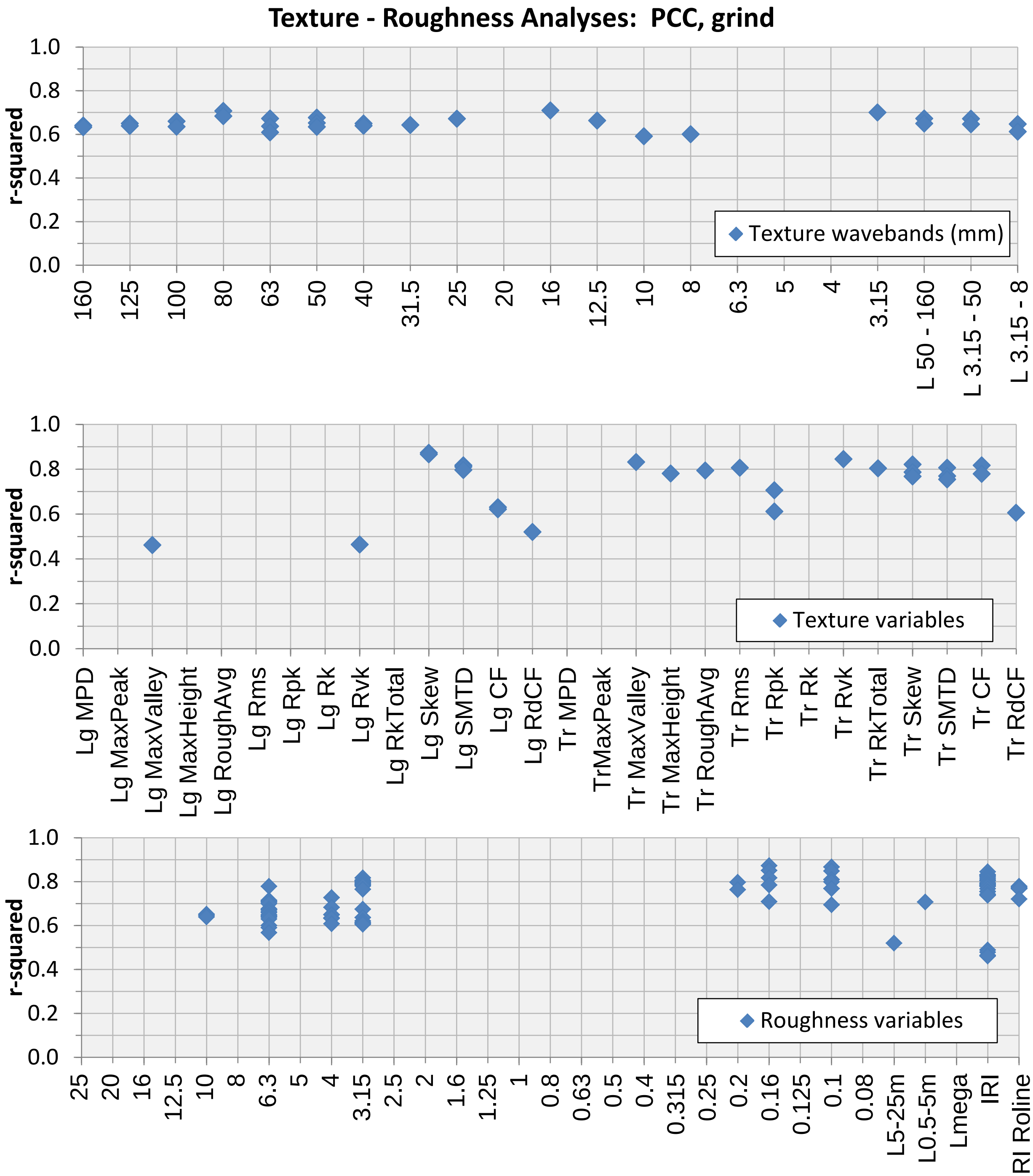

Figure 6-8. PCC, grind pavement: r-squared values for texture wavebands, mm (upper chart), 50 percentile texture variables (center chart), and roughness variables (lower chart).

6.4 Texture – Friction Analyses

Regression analyses using combinations of texture and friction variables have the form of Equation (6-4).

$$CCR = \beta_2 Texture + \beta_1 Friction + \beta_0 + \beta_q Road \tag{6-4}$$

Where the qualitative variable is not used ($\beta_q = 0$) for the PCC, grind pavements.

There are 105 texture and 4 friction variables in the database. This gives a total of 420 combinations of texture and friction variables. Of these, the following number yielded valid regression results.

- Asphalt pavements: 95
- PCC, non-grind pavements: 77
- PCC, grind pavements: 57

Figure 6-9 through Figure 6-12 show the r-squared values obtained with texture – friction analyses for each of the pavement groupings. Table 6-6 lists the variables that generate the highest r-squared values. Table 6-7 list the regression results for the top ten analyses for each pavement grouping.

Observations:

- For asphalt pavements, none of the spectral texture variables and neither of the texture skewness variables yield valid regression results.
- For PCC, non-grind pavements, most of the spectral texture variables do not yield valid regression results. The transverse skewness variable yields a high r-squared value.
- For PCC, grind pavements, most of the spectral texture variables yield valid regression, while most of the other texture variables do not.

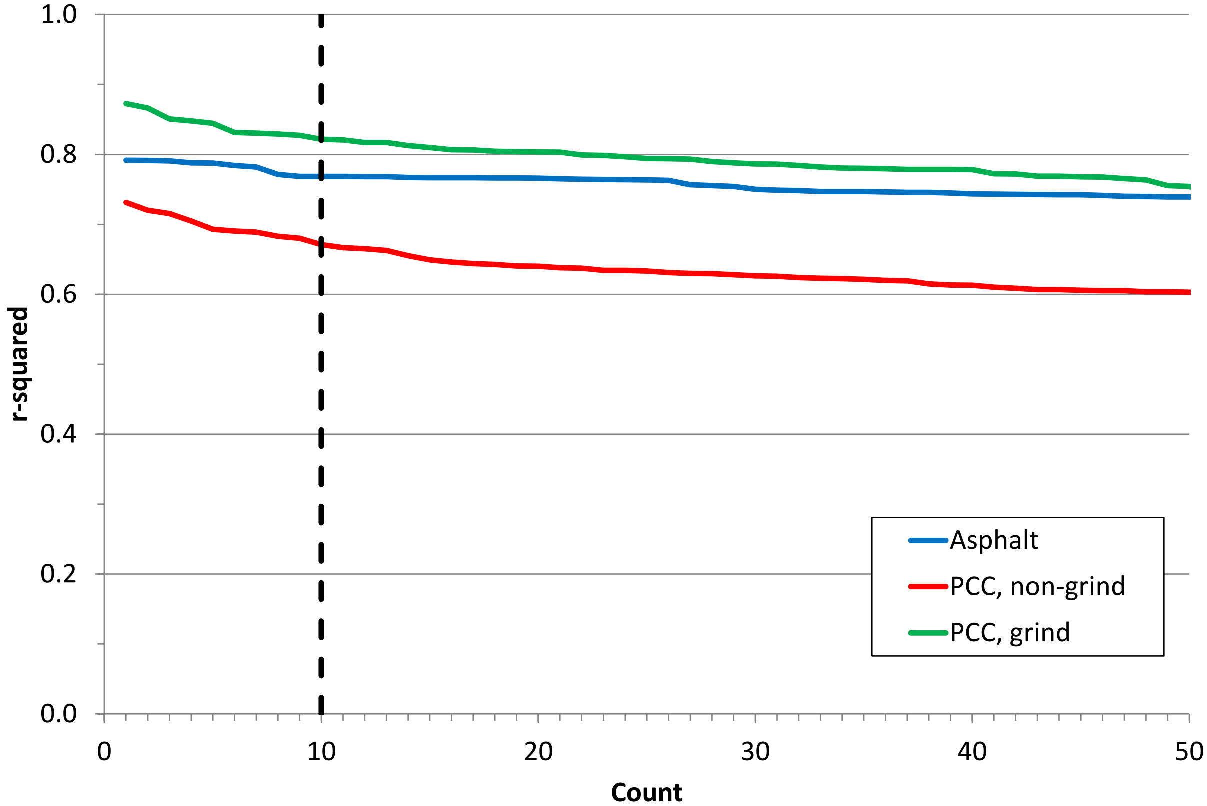

Figure 6-9. r-squared values generated by texture – friction analyses for each of the pavement groupings.

Table 6-6. Variables generating significant results (high r-squared values) for texture – friction analyses.

Pavement Grouping	Max r-squared	Texture Variables	Friction Variables
Asphalt	0.76	Longitudinal and transverse: • Rpk • MaxPeak • MPD	Friction numbers: • HFT • Grip Tester
PCC non-grind	0.64	Level in bands: • 160 mm • 125 mm • 100 mm Transverse: • Skewness Longitudinal • 90% Rpk • MPD • MaxPeak	Friction numbers: • Ribbed tire • Smooth tire
PCC grind	0.87	Level in bands: • 50 mm … 20 mm Lumped bands: • 3.15 – 50 mm Longitudinal • Skewness	Friction numbers: • Ribbed tire • Grip Tester

Table 6-7. Top ten results for each pavement grouping for texture - friction regression analyses.

Pave-ment	Texture Variable	Friction Variable	r-sq	p-values Texture	p-values Friction	p-values Road	Regression Coefficients β_2	β_1	β_0	β_q	Standardized Coefficients β_2	β_1
Asphalt	90% TrRpk	HFT	0.76	0.0000	0.0270	0.0000	2.01E-03	1.79E-03	5.330E-3	6.844E-4	0.748	0.194
	90% TrRpk	Grip Tester	0.76	0.0000	0.0379	0.0000	2.06E-03	1.52E-03	5.663E-3	7.679E-4	0.766	0.182
	90% LgRpk	HFT	0.76	0.0000	0.0273	0.0000	2.24E-03	1.80E-03	5.273E-3	7.020E-4	0.749	0.195
	50% LgRpk	HFT	0.76	0.0000	0.0494	0.0000	2.64E-03	1.62E-03	5.397E-3	7.043E-4	0.758	0.176
	50% TrMaxPeak	HFT	0.76	0.0000	0.0418	0.0000	9.16E-04	1.68E-03	5.473E-3	7.067E-4	0.755	0.182
	90% LgRpk	Grip Tester	0.75	0.0000	0.0367	0.0000	2.30E-03	1.54E-03	5.601E-3	7.867E-4	0.766	0.185
	90% LgMPD	HFT	0.75	0.0000	0.0392	0.0000	9.40E-04	1.70E-03	5.380E-3	7.272E-4	0.758	0.185
	90% TrMPD	HFT	0.75	0.0000	0.0291	0.0000	9.33E-04	1.79E-03	5.383E-3	7.089E-4	0.749	0.195
	50% TrMPD	HFT	0.75	0.0000	0.0419	0.0000	1.05E-03	1.68E-03	5.470E-3	7.129E-4	0.755	0.183
	90% TrMaxPeak	HFT	0.75	0.0000	0.0274	0.0000	8.00E-04	1.81E-03	5.374E-3	7.013E-4	0.746	0.197
PCC, non-grind	L 160mm	Ribbed tire	0.64	0.0000	0.0257	0.0000	9.02E-05	2.87E-05	1.881E-3	1.306E-3	0.660	0.283
	10% TrSkew	Smooth tire	0.62	0.0011	0.0001	0.0000	8.08E-04	2.26E-05	6.288E-3	9.558E-4	0.378	0.524
	90% LgRpk	Ribbed tire	0.61	0.0000	0.0053	0.0000	1.13E-03	3.97E-05	3.816E-3	1.151E-3	0.564	0.391
	L 125mm	Ribbed tire	0.60	0.0000	0.0377	0.0000	8.37E-05	2.80E-05	2.176E-3	1.302E-3	0.632	0.276
	50% TrSkew	Smooth tire	0.59	0.0043	0.0001	0.0000	7.05E-04	2.46E-05	5.949E-3	9.606E-4	0.348	0.570
	L 100mm	Ribbed tire	0.58	0.0001	0.0451	0.0000	7.50E-05	2.78E-05	2.535E-3	1.253E-3	0.587	0.274
	90% LgMPD	Ribbed tire	0.57	0.0001	0.0069	0.0000	4.23E-04	4.04E-05	3.824E-3	1.193E-3	0.546	0.399
	90% LgMaxPeak	Ribbed tire	0.57	0.0001	0.0071	0.0000	3.60E-04	4.04E-05	3.823E-3	1.188E-3	0.542	0.398
	50% LgRpk	Ribbed tire	0.57	0.0001	0.0066	0.0000	1.34E-03	4.09E-05	3.823E-3	1.178E-3	0.538	0.403
	10% TrSkew	Grip Tester	0.57	0.0064	0.0011	0.0000	6.91E-04	1.82E-03	6.064E-3	9.759E-4	0.324	0.476
PCC, grind	10% LgSkew	Ribbed tire	0.87	0.0009	0.0470	–	1.12E-03	3.11E-05	8.076E-3	0	0.672	0.334
	L 20 mm	Grip Tester	0.85	0.0002	0.0009	–	1.16E-04	3.35E-03	4.935E-3	0	0.665	0.530
	90% LgSkew	Grip Tester	0.85	0.0002	0.0427	–	8.36E-04	1.92E-03	7.194E-3	0	0.738	0.304
	L 16 mm	Grip Tester	0.85	0.0002	0.0011	–	1.21E-04	3.34E-03	4.950E-3	0	0.661	0.528
	L 3.15 mm	Grip Tester	0.84	0.0002	0.0011	–	1.22E-04	3.38E-03	6.175E-3	0	0.655	0.534
	L 25 mm	Grip Tester	0.84	0.0002	0.0006	–	9.83E-05	3.67E-03	5.507E-3	0	0.648	0.581
	L 40 mm	Grip Tester	0.83	0.0003	0.0004	–	1.10E-04	3.89E-03	3.538E-3	0	0.641	0.616
	L 3.15 - 50 mm	Grip Tester	0.82	0.0004	0.0007	–	1.07E-04	3.76E-03	3.086E-3	0	0.634	0.594
	L 31.5 mm	Grip Tester	0.81	0.0006	0.0006	–	1.06E-04	3.87E-03	4.219E-3	0	0.625	0.613
	L 50 mm	Grip Tester	0.81	0.0006	0.0010	–	1.03E-04	3.72E-03	3.475E-3	0	0.624	0.589

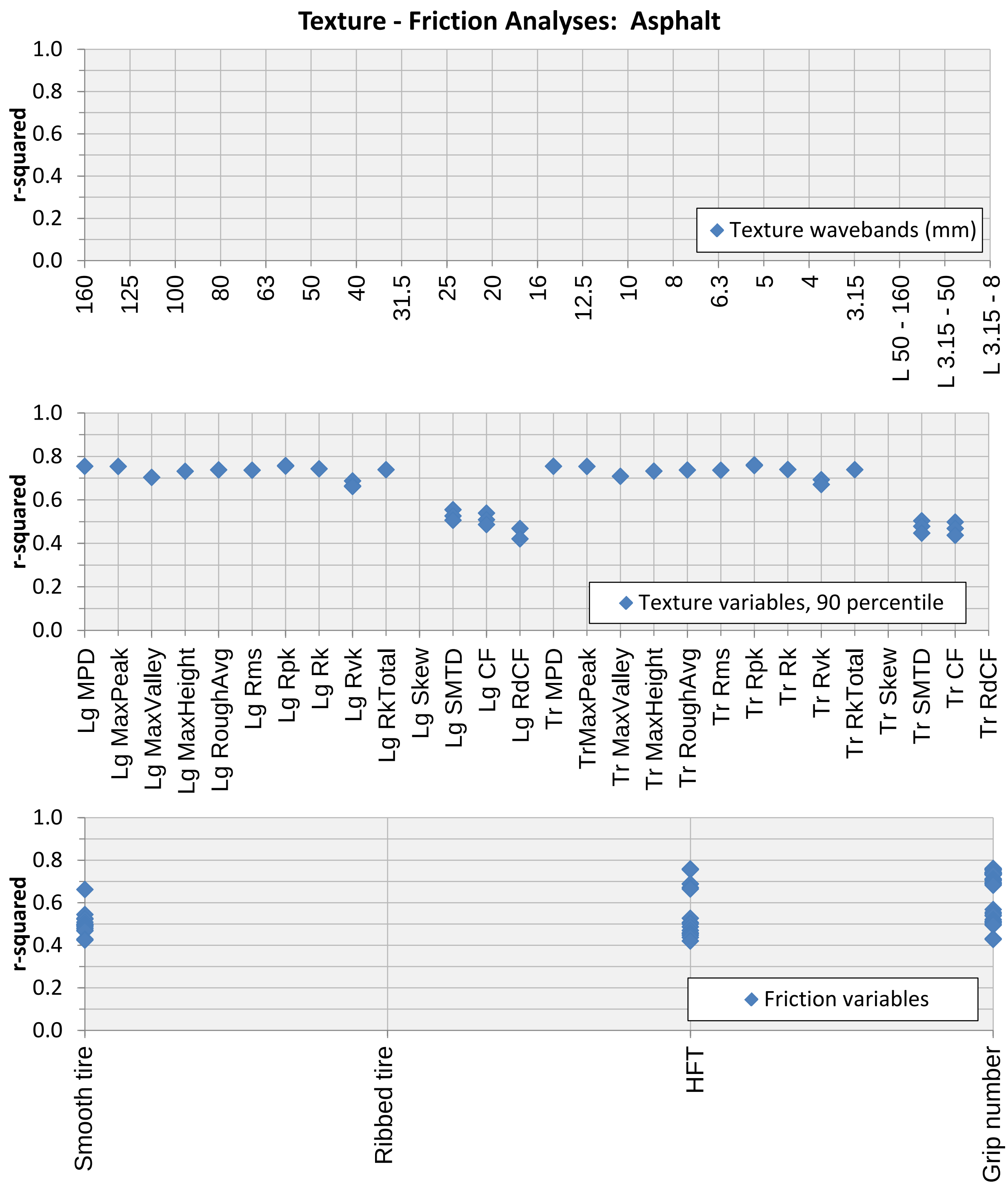

Figure 6-10. Asphalt pavement: r-squared values for texture wavebands, mm (upper chart), 90 percentile texture variables (center chart), and friction variables (lower chart).

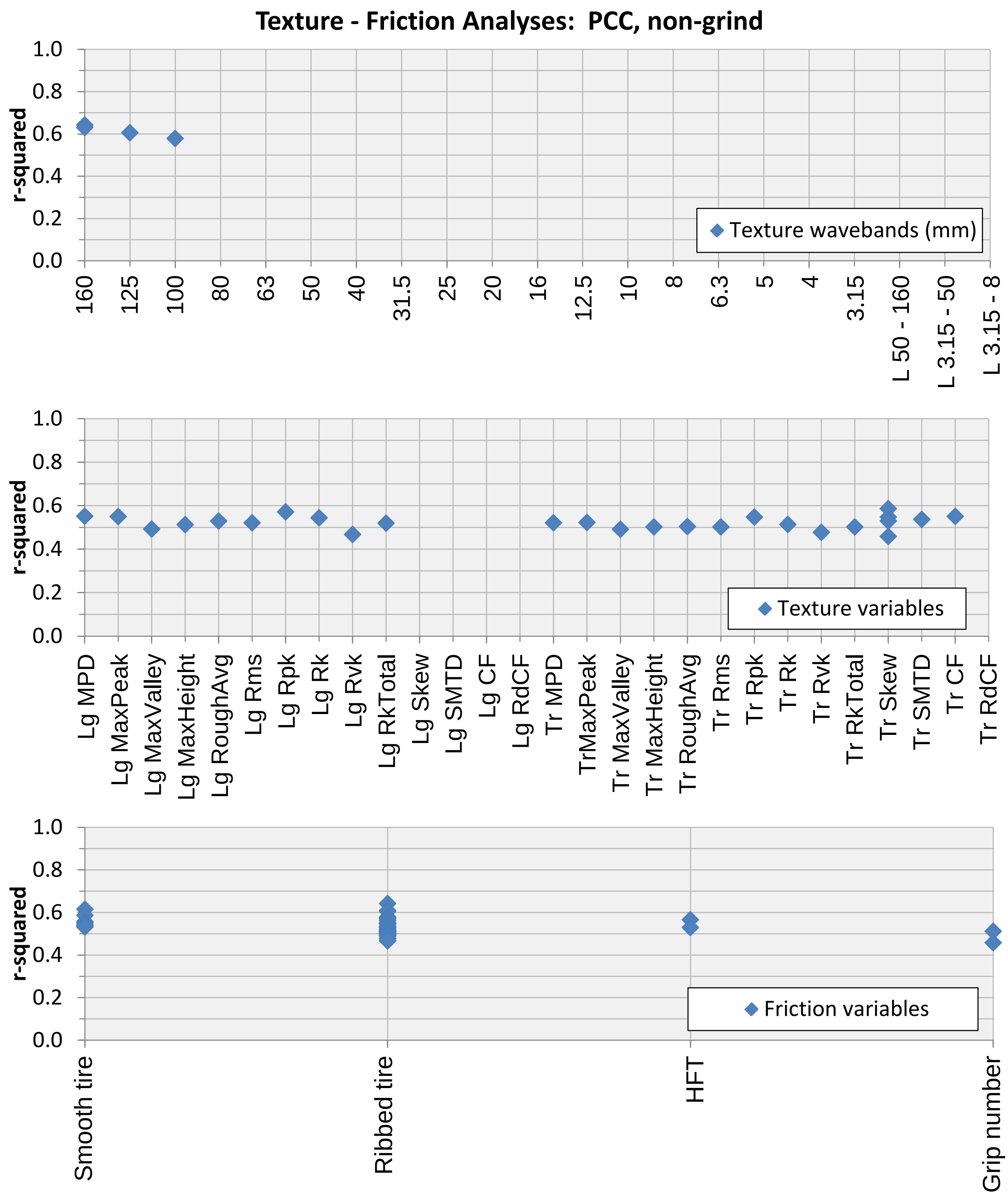

Figure 6-11. PCC, non-grind pavement: r-squared values for texture wavebands, mm (upper chart), 50 percentile texture variables (center chart), and friction variables (lower chart).

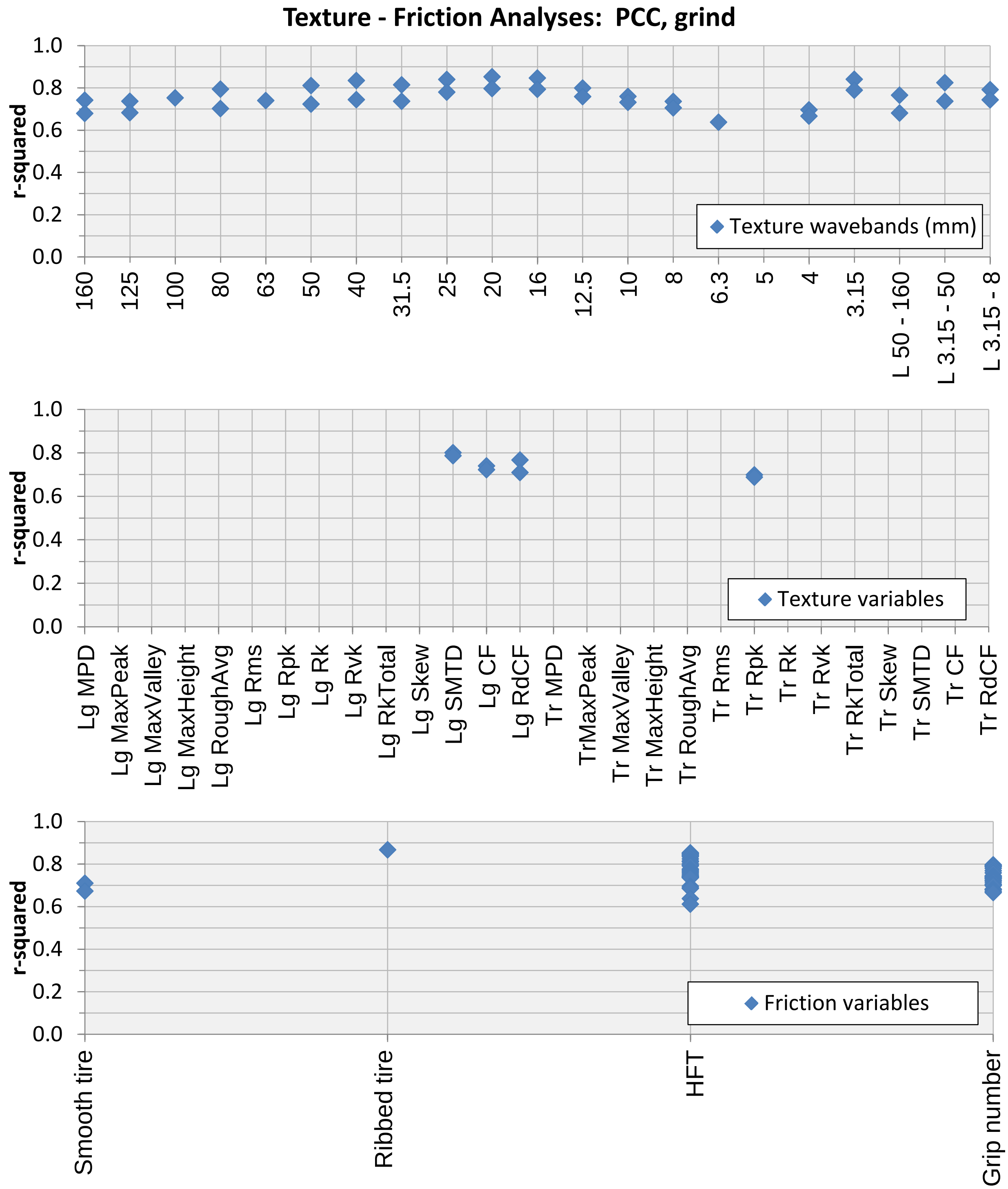

Figure 6-12. PCC, grind pavement: r-squared values for texture wavebands, mm (upper chart), 50 percentile texture variables (center chart), and friction variables (lower chart).

6.5 Texture – Texture Analyses

Regression analyses using a combination of two texture variables have the form of Equation (6-4).

$$CCR = \beta_2 Texture_2 + \beta_1 Texture_1 + \beta_0 + \beta_q Road \qquad (6\text{-}5)$$

Where the qualitative variable is not used ($\beta_q = 0$) for the PCC, grind pavements.

Many of the texture variables are related and relatively collinear, for examples 50% MPD and 90% MPD, or levels in adjacent wavebands. Therefore the texture variables in this group of analyses are limited as follows:

$Texture_2$ consists of the 21 waveband variables, and
$Texture_1$ consists of the 28 fifty percentile variables.

The ten and ninety percentile texture variables are not included. This gives a total of 588 combinations of texture variables for analysis for each pavement grouping. Of these, the following number yielded valid regression results.

- Asphalt pavements: 17
- PCC, non-grind pavements: 116
- PCC, grind pavements: 434

Figure 6-13 through Figure 6-16 show the r-squared values obtained with texture – texture analyses for each of the pavement groupings. Table 6-8 lists the variables that generate the highest r-squared values. Table 6-9 list the regression results for the top ten analyses for each pavement grouping.

Observations:

- For the asphalt pavements, the number of valid analyses is relatively small. The 5 mm waveband texture variable is the only waveband variable yielding valid analyses in combination with other 50% texture variables. Regression analyses using combinations of texture – texture variables are not good at describing the CRR.
- For the PCC, grind pavements, many combinations of texture variables yield valid results.

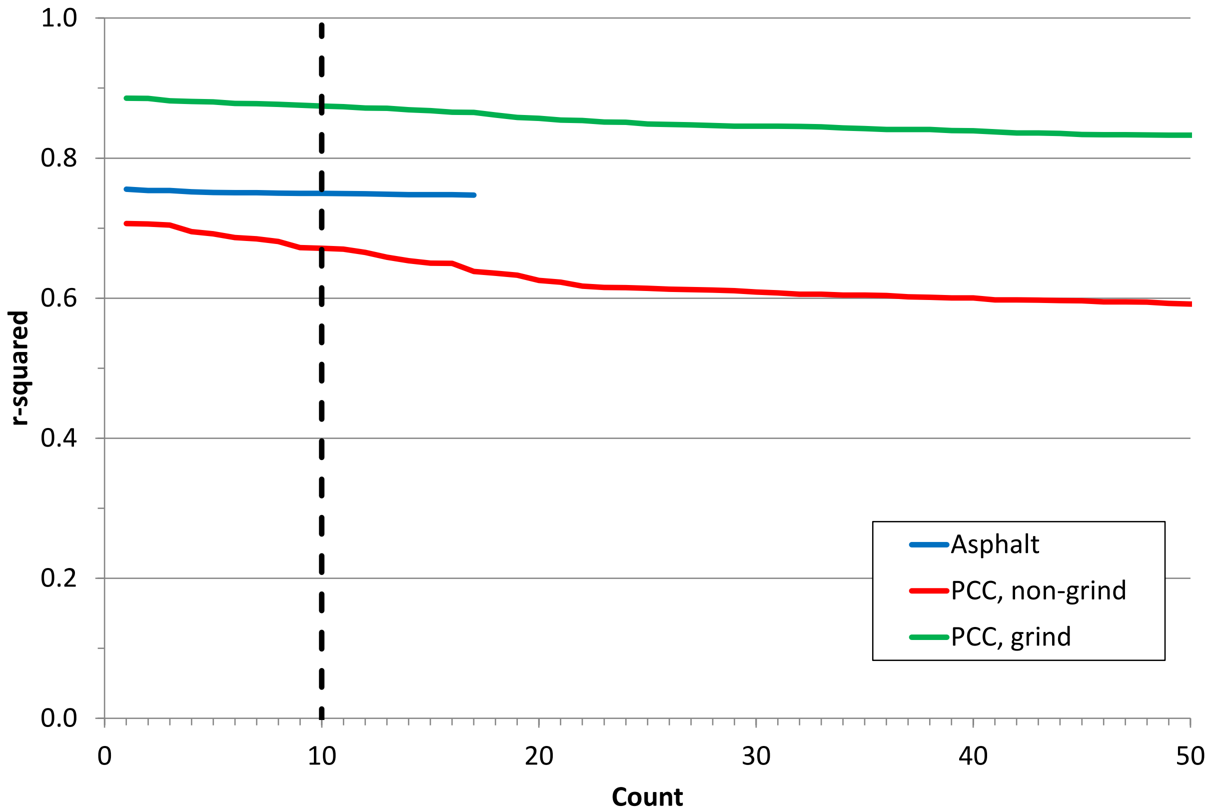

Figure 6-13. r-squared values generated by texture – texture analyses for each of the pavement groupings.

Table 6-8. Variables generating significant results (high r-squared values) for texture – texture analyses.

Pavement Grouping	Max r-squared	Texture Waveband Variables	50% Texture Variables
Asphalt	0.77	Level in bands: • 5 mm	Longitudinal and transverse: • MPD • MaxPeak • MaxValley • MaxHeight • RoughAvg • RMS • Rpk • RkTotal
PCC non-grind	0.72	Level in bands: • 160 mm • 10 mm … 4 mm	Longitudinal: • LgSkew • LgRdCF Transvers: • TrSkew
PCC grind	0.90	Level in bands: • 50 mm … 16 mm • 4 mm • 3.15 mm Lumped bands: • 3.15 – 50 mm • 3.15 – 8 mm	Longitudinal • LgRdCF Transverse: • TrSkew • TrRdCF

Table 6-9. Top ten results for each pavement grouping for texture - texture regression analyses.

Pave-ment	Texture Waveband Variable	50 Percentile Texture Variable	r-sq	p-values: Texture Wave-band	p-values: 50% Texture	p-values: Road	Regression Coefficients: β_2	Regression Coefficients: β_1	Regression Coefficients: β_0	Regression Coefficients: β_q	Standardized Coefficients: β_2	Standardized Coefficients: β_1
Asphalt	L 5 mm	50% LgRdCF	0.77	0.0000	0.0200	0.0000	1.517E-4	-1.120E-3	1.057E-2	6.717E-4	0.809	-0.195
	L 5 mm	50% TrRpk	0.76	0.0350	0.0242	0.0000	8.118E-5	1.506E-3	7.304E-3	7.800E-4	0.433	0.458
	L 5 mm	50% LgRpk	0.76	0.0236	0.0247	0.0000	8.460E-5	1.543E-3	7.318E-3	7.934E-4	0.451	0.444
	L 5 mm	50% TrMaxPeak	0.76	0.0214	0.0296	0.0000	8.665E-5	5.245E-4	7.407E-3	7.960E-4	0.462	0.432
	L 5 mm	50% LgMaxPeak	0.76	0.0256	0.0331	0.0000	8.605E-5	5.128E-4	7.371E-3	8.057E-4	0.459	0.436
	L 5 mm	50% TrMaxHeight	0.76	0.0022	0.0343	0.0000	1.013E-4	1.574E-4	7.599E-3	7.823E-4	0.540	0.357
	L 5 mm	50% TrMPD	0.76	0.0214	0.0346	0.0000	8.780E-5	5.926E-4	7.419E-3	7.994E-4	0.468	0.426
	L 5 mm	50% LgMaxHeight	0.76	0.0025	0.0364	0.0000	1.012E-4	1.472E-4	7.580E-3	7.798E-4	0.539	0.356
	L 5 mm	50% LgMPD	0.76	0.0297	0.0383	0.0000	8.593E-5	5.942E-4	7.366E-3	8.078E-4	0.458	0.436
	L 5 mm	50% LgRkTotal	0.76	0.0050	0.0383	0.0000	9.791E-5	1.786E-4	7.558E-3	7.890E-4	0.522	0.373
PCC, non-grind	L 5 mm	50% LgSkew	0.72	0.0000	0.0000	0.0000	6.708E-5	5.430E-4	7.300E-3	6.933E-4	0.833	0.655
	L 4 mm	50% LgSkew	0.72	0.0000	0.0000	0.0000	6.385E-5	5.923E-4	7.249E-3	6.804E-4	0.870	0.714
	L 160 mm	50% TrSkew	0.71	0.0000	0.0003	0.0000	1.028E-4	7.593E-4	3.508E-3	1.139E-3	0.752	0.375
	L 6.3 mm	50% LgSkew	0.71	0.0000	0.0000	0.0000	6.418E-5	5.949E-4	7.180E-3	6.638E-4	0.862	0.717
	L 8 mm	50% LgSkew	0.70	0.0000	0.0000	0.0000	6.036E-5	5.873E-4	7.008E-3	6.761E-4	0.856	0.708
	L 10 mm	50% LgSkew	0.70	0.0000	0.0000	0.0000	5.996E-5	6.248E-4	6.601E-3	6.789E-4	0.887	0.753
	L 4 mm	50% LgRdCF	0.69	0.0000	0.0000	0.0000	6.458E-5	1.084E-3	4.702E-3	6.916E-4	0.880	0.703
	L 5 mm	50% LgRdCF	0.69	0.0000	0.0000	0.0000	6.677E-5	9.691E-4	5.008E-3	7.058E-4	0.829	0.628
	L 8 mm	50% LgRdCF	0.68	0.0000	0.0000	0.0000	6.128E-5	1.080E-3	4.470E-3	6.870E-4	0.869	0.700
	L 10 mm	50% LgRdCF	0.68	0.0000	0.0000	0.0000	6.184E-5	1.173E-3	3.839E-3	6.889E-4	0.914	0.761
PCC, grind	L 3.15 mm	50% LgRdCF	0.90	0.0000	0.0001	–	1.488E-4	3.600E-3	2.775E-3	0	0.798	0.578
	L 40 mm	50% TrSkew	0.90	0.0003	0.0000	–	8.873E-5	5.580E-4	6.754E-3	0	0.518	0.681
	L 16 mm	50% LgRdCF	0.89	0.0000	0.0001	–	1.458E-4	3.502E-3	1.421E-3	0	0.795	0.562
	L 20 mm	50% TrRdCF	0.89	0.0000	0.0002	–	1.351E-4	4.376E-4	6.351E-3	0	0.776	0.558
	L 20 mm	50% LgRdCF	0.89	0.0000	0.0002	–	1.382E-4	3.474E-3	1.470E-3	0	0.793	0.558
	L 25 mm	50% TrSkew	0.89	0.0005	0.0001	–	7.885E-5	5.301E-4	8.215E-3	0	0.520	0.647
	L 3.15 - 8 mm	50% LgRdCF	0.89	0.0000	0.0000	–	1.925E-4	4.266E-3	1.254E-3	0	0.809	0.685
	L 3.15 - 50 mm	50% TrSkew	0.89	0.0005	0.0001	–	8.698E-5	5.462E-4	6.308E-3	0	0.513	0.666
	L 31.5 mm	50% TrSkew	0.89	0.0005	0.0000	–	8.584E-5	5.622E-4	7.289E-3	0	0.508	0.686
	L 25 mm	50% TrRdCF	0.88	0.0000	0.0001	–	1.176E-4	4.849E-4	7.191E-3	0	0.775	0.618

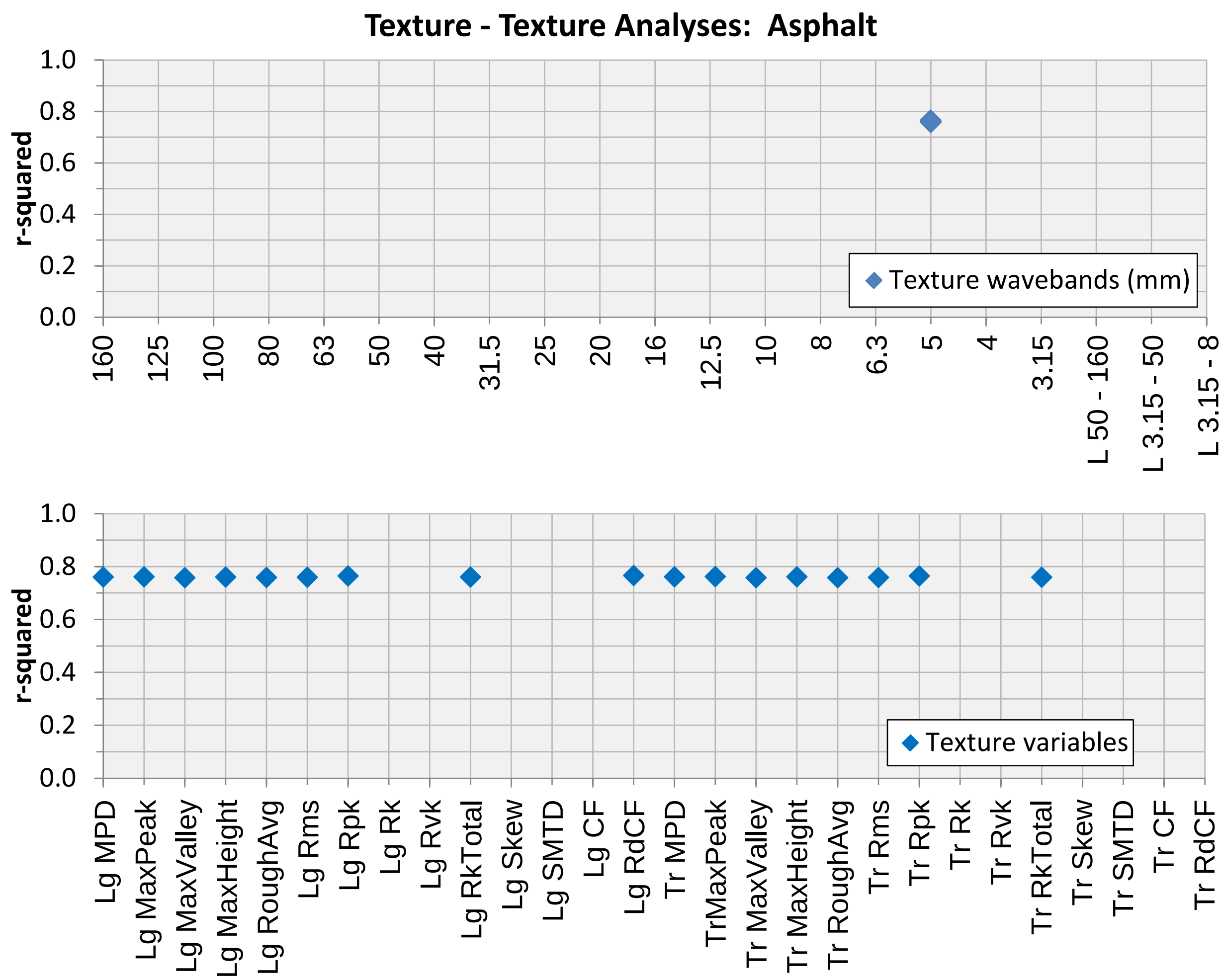

Figure 6-14. Asphalt pavement: r-squared values for texture wavebands, mm (upper chart) and 50 percentile texture variables (lower chart).

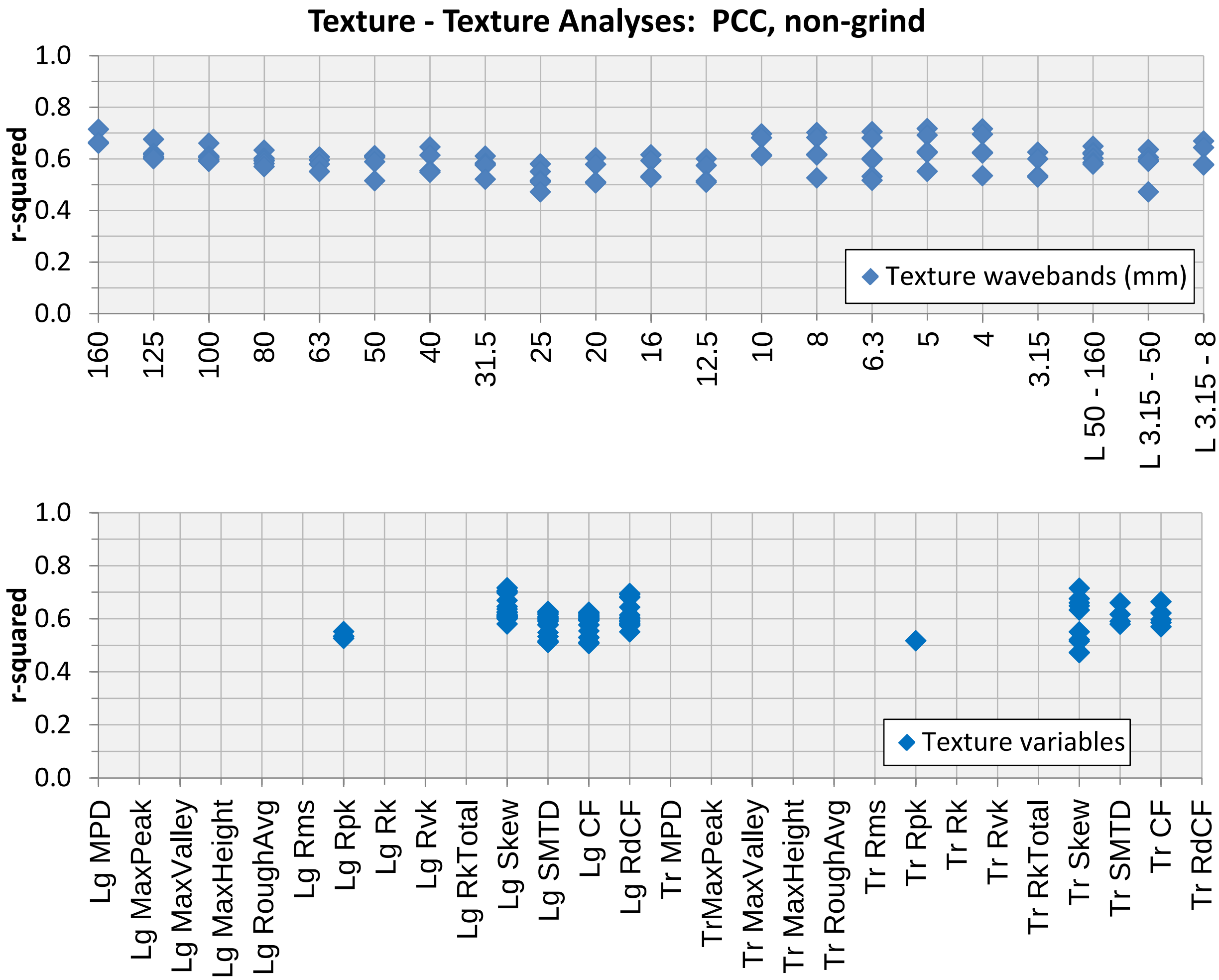

Figure 6-15. PCC, non-grind pavement: r-squared values for texture wavebands, mm (upper chart) and 50 percentile texture variables (lower chart).

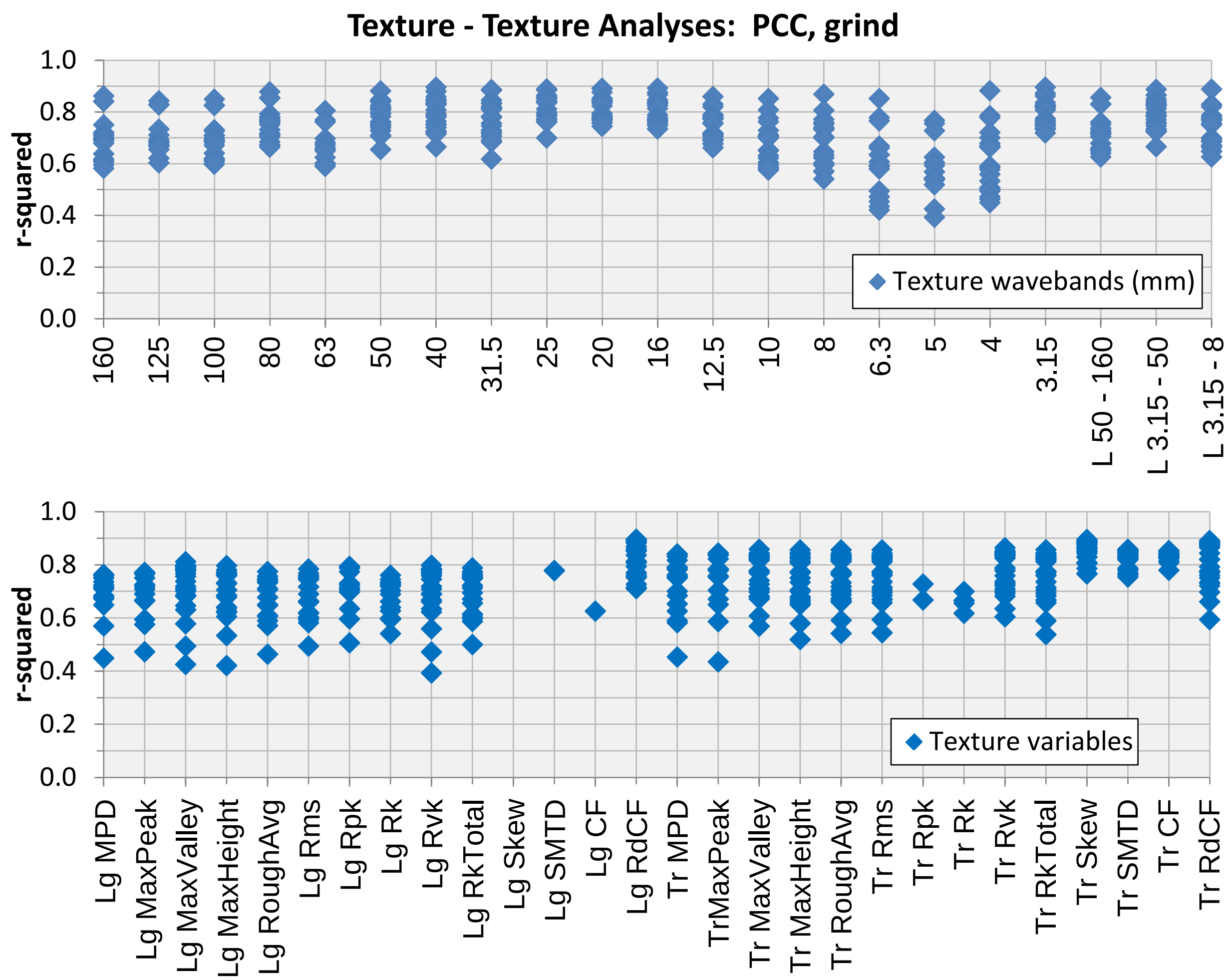

Figure 6-16. PCC, grind pavement: r-squared values for texture wavebands, mm (upper chart) and 50 percentile texture variables (lower chart).

6.6 Texture – Roughness – Friction Analyses

Regression analyses using combinations of texture, roughness, and friction variables have the form of Equation (6-6).

$$CCR = \beta_3 Texture + \beta_2 Roughness + \beta_1 Friction + \beta_0 + \beta_q Road \qquad (6\text{-}6)$$

Where the qualitative variable is not used ($\beta_q = 0$) for the PCC, grind pavements.

To reduce the number of analyses, the texture variables are limited to just the waveband variables and the 50 percentile variables; the 10 and 90 percentile variables are excluded. This gives 49 texture, 31 roughness, and 4 friction variables for a total of 6076 combinations of variables to analyze for each pavement grouping. Of these, the following number yielded valid regression results.

- Asphalt pavements: 176
- PCC, non-grind pavements: 487
- PCC, grind pavements: 461

Figure 6-17 through Figure 6-20 show the r-squared values obtained with texture – texture analyses for each of the pavement groupings. Table 6-10 lists the variables that generate the highest r-squared values. Table 6-11 list the regression results for the top ten analyses for each pavement grouping.

Observations:

- For the asphalt pavements, none of the combinations with texture waveband variables produce valid regression results.

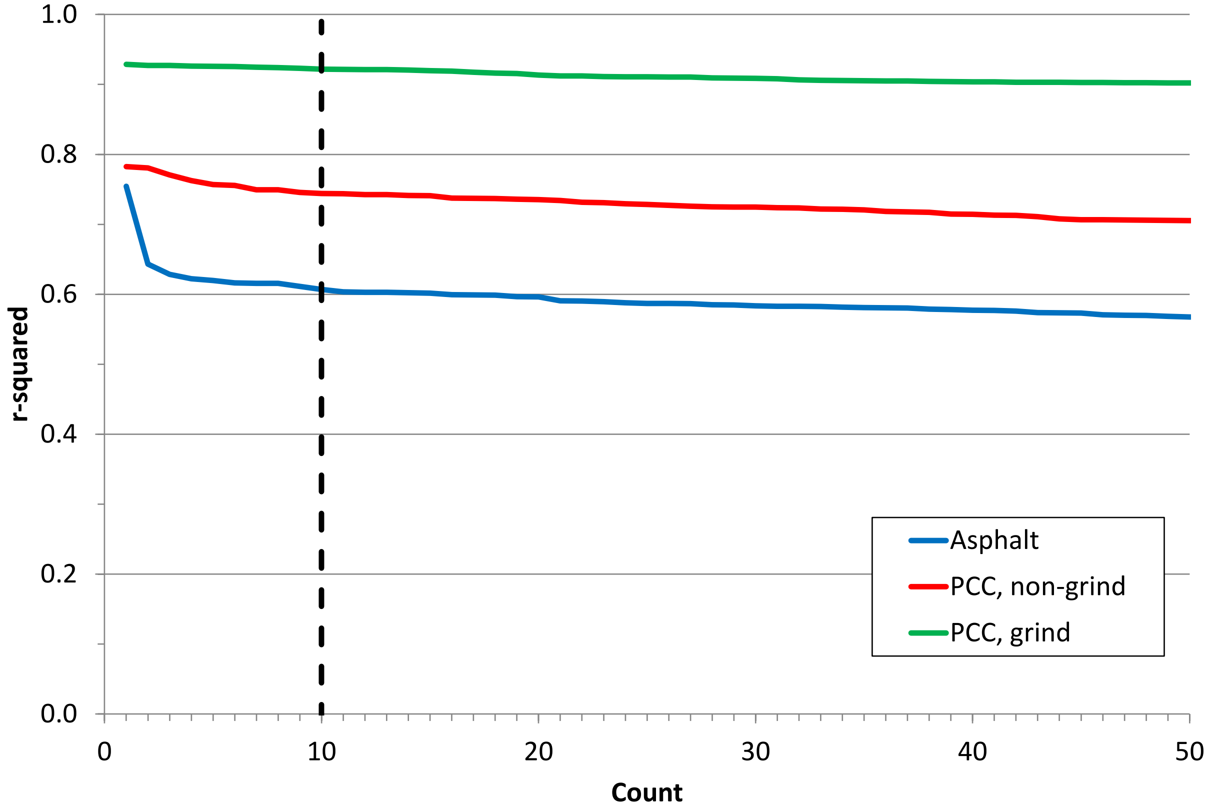

Figure 6-17. r-squared values generated by texture – roughness – friction analyses for each of the pavement groupings.

Table 6-10. Variables generating significant results (high r-squared values) for texture – roughness – friction analyses.

Pavement Grouping	Max r-squared	Texture Variables	Roughness Variables	Friction Variables
Asphalt	0.76	Transverse: • RoughAvg • SMTD • CF Longitudinal • SMTD • CF	Level in bands: • 25 m • 12.5 m … 5 m Lumped bands • 5 – 25 m • IRI	Friction numbers: • Grip Tester • Smooth tire • HFT
PCC non-grind	0.79	Level in bands: • 160 mm • 125 mm • 100 mm • 80 mm Lumped bands • 50 to 160 mm Transverse: • Skew • SMTD • CR • RdCF	Level in bands: • 1.25 m • 0.63 m Lumped bands: • IRI Roline	Friction numbers: • Ribbed tire • Smooth tire • HFT
PCC grind	0.94	Level in bands: • 20 mm … 6.3 mm • 4 mm • 3.15 mm Lumped bands: • 3.15 – 50 mm • 3.15 – 8 mm Longitudinal: • Skew • SMTD • CR Transverse: • Rpk	Level in bands: • 25 m • 6.3 m • 3.15 m … 0.16 m • 0.1 m Lumped bands: • 0.5 – 5 m • Lmega	Friction numbers: • HFT • Grip Tester • Ribbed tire

Table 6-11. Top ten results for each pavement grouping for texture – roughness – friction regression analyses.

Pave-	Variables				p-values				Regression Coefficients					Standardized Coefficients		
ment	Texture	Roughness	Friction	r-sq	Texture	Rough	Friction	Road	B_3	β_2	β_1	β_0	β_q	B_3	β_2	β_1
Asphalt	TrRoughAvg	25m	HFT	0.76	0.0000	0.0312	0.0496	0.0000	1.945E-3	1.880E-5	1.611E-3	4.463E-3	7.511E-4	0.746	0.172	0.175
	LgSMTD	10 m	HFT	0.65	0.0002	0.0022	0.0070	0.0000	-1.480E-3	5.732E-5	2.628E-3	5.229E-3	8.158E-4	-0.426	0.390	0.285
	LgCF	10 m	HFT	0.64	0.0004	0.0020	0.0071	0.0000	-1.242E-3	5.895E-5	2.687E-3	4.978E-3	8.384E-4	-0.405	0.401	0.292
	LgSMTD	IRI_RUN	HFT	0.63	0.0006	0.0089	0.0016	0.0000	-1.402E-3	3.704E-4	3.172E-3	7.206E-3	8.111E-4	-0.403	0.361	0.344
	LgSMTD	6.3 m	HFT	0.63	0.0001	0.0105	0.0011	0.0001	-1.537E-3	4.752E-5	3.298E-3	5.548E-3	7.699E-4	-0.442	0.325	0.358
	LgSMTD	5 m	HFT	0.63	0.0010	0.0131	0.0006	0.0001	-1.370E-3	4.766E-5	3.561E-3	5.200E-3	6.300E-4	-0.394	0.283	0.387
	LgSMTD	10 m	Smooth tire	0.63	0.0003	0.0038	0.0452	0.0000	-1.516E-3	5.686E-5	1.171E-5	6.696E-3	9.203E-4	-0.436	0.387	0.234
	LgSMTD	10 m	Grip Tester	0.63	0.0003	0.0016	0.0458	0.0000	-1.515E-3	6.133E-5	1.878E-3	5.809E-3	9.401E-4	-0.436	0.418	0.226
	TrSMTD	10 m	HFT	0.62	0.0012	0.0016	0.0049	0.0000	-1.459E-3	6.176E-5	2.857E-3	4.701E-3	8.565E-4	-0.372	0.420	0.310
	LgCF	IRI_RUN	HFT	0.62	0.0015	0.0079	0.0015	0.0000	-1.162E-3	3.836E-4	3.255E-3	6.978E-3	8.338E-4	-0.379	0.373	0.353
PCC, non-grind	50% TrSkew	ROLINE IRI	Ribbed tire	0.79	0.0000	0.0000	0.0000	0.0000	1.024E-3	4.258E-4	6.038E-5	2.446E-3	1.685E-3	0.505	1.043	0.595
	50% TrSkew	0.63m	Ribbed tire	0.79	0.0002	0.0000	0.0003	0.0000	7.481E-4	6.745E-5	4.240E-5	1.457E-3	1.499E-3	0.369	0.890	0.418
	50% TrSkew	1.25m	Ribbed tire	0.77	0.0004	0.0000	0.0097	0.0000	7.424E-4	7.814E-5	2.971E-5	1.553E-3	1.382E-3	0.367	0.829	0.293
	50% TrCF	0.63m	Ribbed tire	0.76	0.0021	0.0000	0.0002	0.0000	7.710E-4	7.315E-5	4.724E-5	-1.080E-3	1.569E-3	0.342	0.965	0.466
	50% TrSkew	0.63m	Smooth tire	0.76	0.0000	0.0000	0.0057	0.0000	9.699E-4	4.522E-5	1.430E-5	4.419E-3	1.206E-3	0.479	0.596	0.331
	50% TrSkew	0.63m	Grip Tester	0.75	0.0000	0.0000	0.0064	0.0000	9.121E-4	4.927E-5	1.207E-3	4.079E-3	1.266E-3	0.450	0.650	0.316
	50% TrCF	1.25m	Ribbed tire	0.75	0.0010	0.0000	0.0050	0.0000	8.739E-4	8.929E-5	3.293E-5	-1.372E-3	1.463E-3	0.388	0.947	0.325
	50% TrCF	1.25m	Grip Tester	0.75	0.0000	0.0000	0.0056	0.0000	1.147E-3	7.408E-5	1.313E-3	-1.224E-4	1.351E-3	0.509	0.785	0.343
	50% TrSMTD	0.63m	Ribbed tire	0.75	0.0040	0.0000	0.0002	0.0000	8.723E-4	7.336E-5	4.820E-5	-1.106E-3	1.570E-3	0.329	0.967	0.475
	50% TrSkew	1.25m	Grip Tester	0.75	0.0000	0.0000	0.0454	0.0000	8.735E-4	6.289E-5	9.170E-4	3.498E-3	1.233E-3	0.431	0.667	0.240
PCC, grind	L 10 mm	3.15 m	HFT	0.94	0.0051	0.0002	0.0000	–	7.146E-5	6.378E-5	6.253E-3	6.611E-4	0	0.306	0.489	0.607
	L 20 mm	1.6 m	Grip Tester	0.94	0.0000	0.0042	0.0000	–	1.215E-4	3.803E-5	4.130E-3	2.800E-3	0	0.697	0.321	0.653
	L 16 mm	1.6 m	Grip Tester	0.94	0.0000	0.0034	0.0000	–	1.283E-4	3.944E-5	4.138E-3	2.734E-3	0	0.699	0.333	0.655
	L 3.15 mm	3.15 m	HFT	0.94	0.0064	0.0007	0.0001	–	6.282E-5	5.756E-5	5.744E-3	1.494E-3	0	0.337	0.442	0.557
	L 16 mm	3.15 m	HFT	0.94	0.0066	0.0008	0.0001	–	6.234E-5	5.709E-5	5.700E-3	9.034E-4	0	0.340	0.438	0.553
	L 3.15 mm	1.6 m	Grip Tester	0.94	0.0000	0.0032	0.0000	–	1.301E-4	4.039E-5	4.196E-3	3.983E-3	0	0.698	0.341	0.664
	L 16 mm	2 m	Grip Tester	0.93	0.0000	0.0042	0.0000	–	1.218E-4	3.398E-5	3.876E-3	3.180E-3	0	0.664	0.310	0.613
	L 3.15 – 8 mm	3.15 m	HFT	0.93	0.0078	0.0003	0.0000	–	7.288E-5	6.233E-5	6.089E-3	8.373E-4	0	0.306	0.478	0.591
	L 3.15 mm	2 m	Grip Tester	0.93	0.0000	0.0040	0.0000	–	1.233E-4	3.473E-5	3.925E-3	4.376E-3	0	0.661	0.317	0.621
	LgSkew	3.15 m	HFT	0.93	0.0092	0.0064	0.0028	–	6.065E-4	4.850E-5	4.468E-3	3.212E-3	0	0.428	0.372	0.433

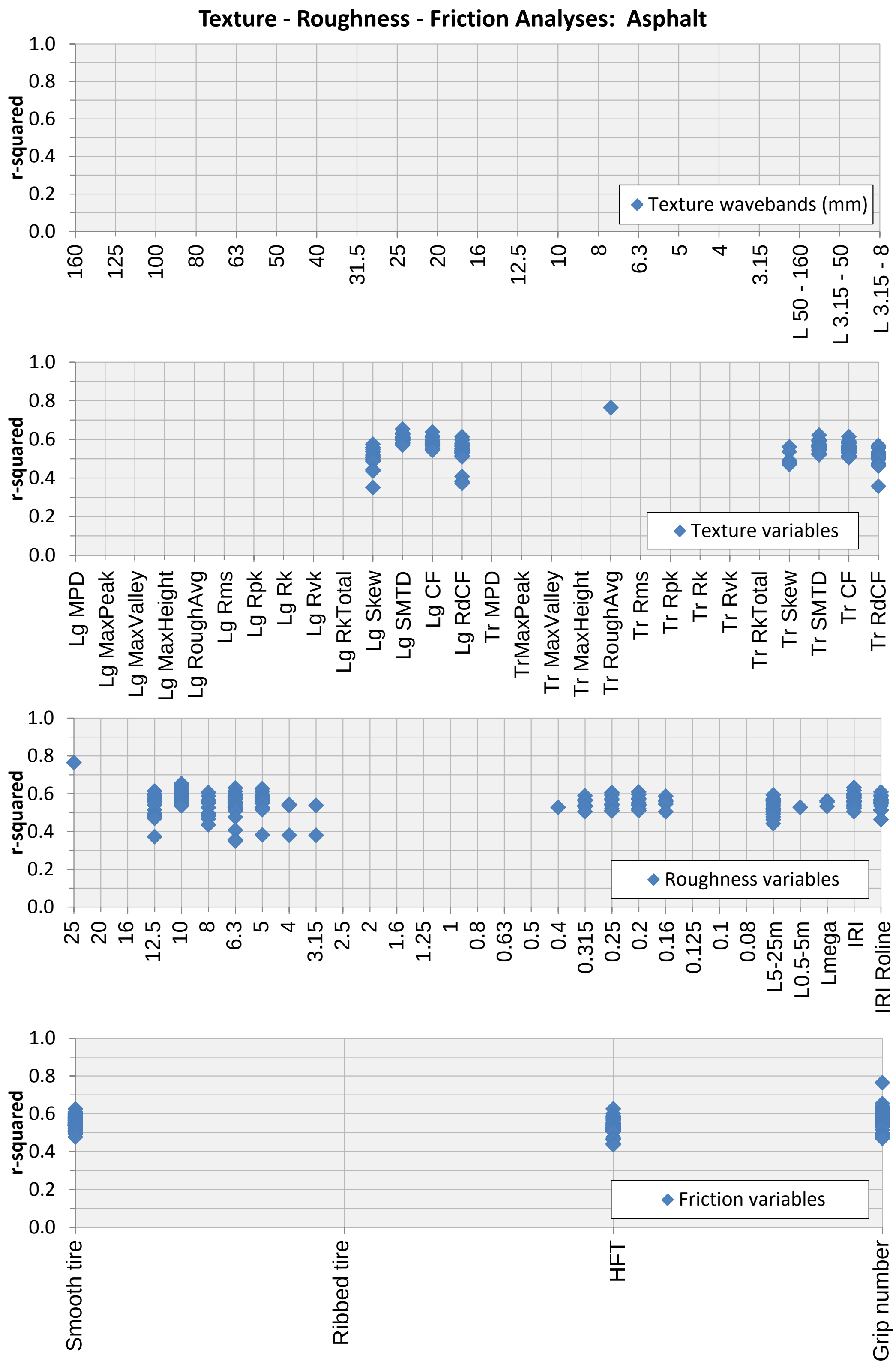

Figure 6-18. Asphalt pavement: r-squared values for texture wavebands, mm (top chart), 50 percentile texture (2nd chart), roughness (3rd chart) and friction variables (bottom chart).

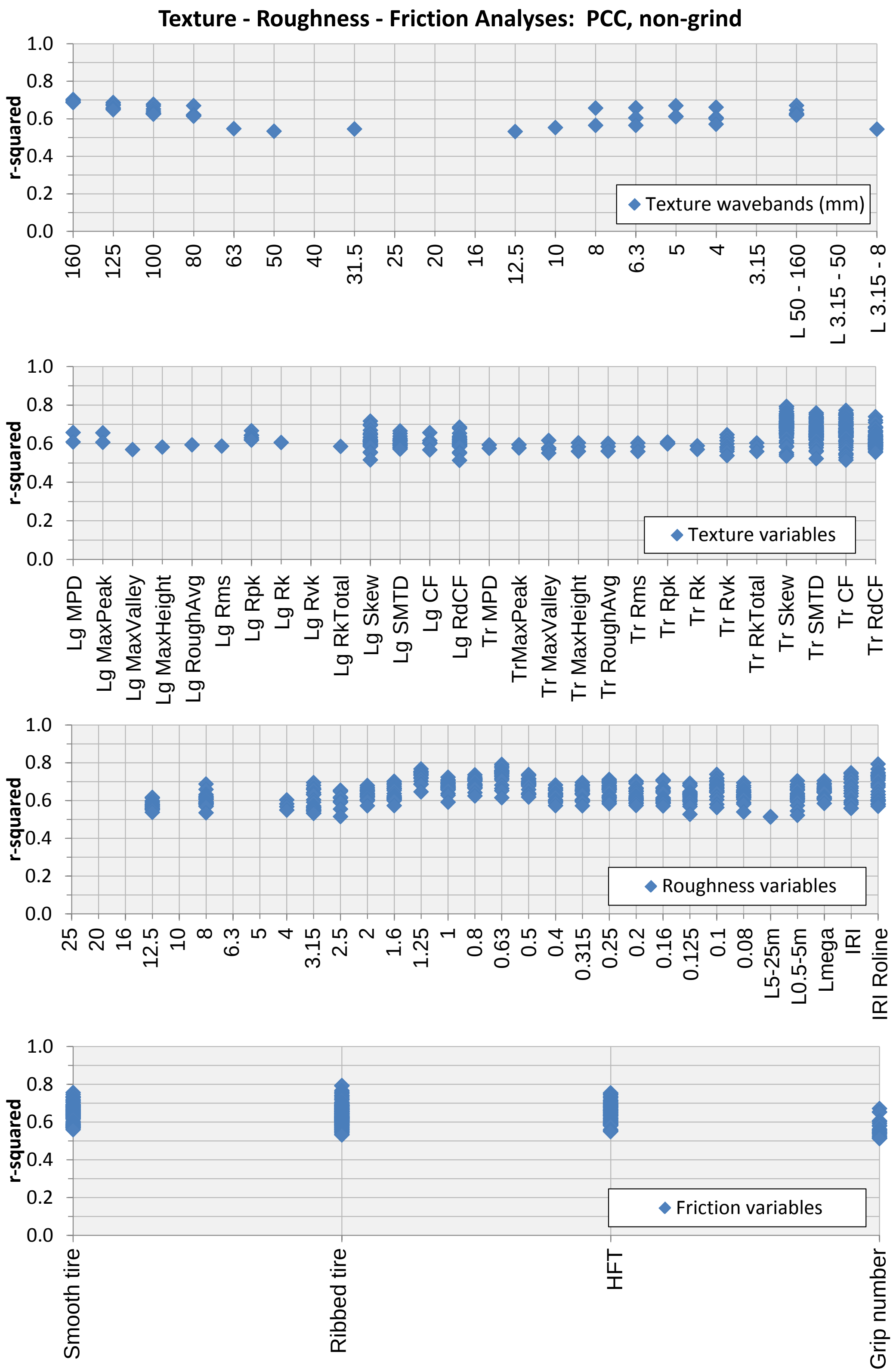

Figure 6-19. PCC, non-grind pavement: r-squared values for texture wavebands, mm (top chart), 50 percentile texture (2nd chart), roughness (3rd chart) and friction variables (bottom chart).

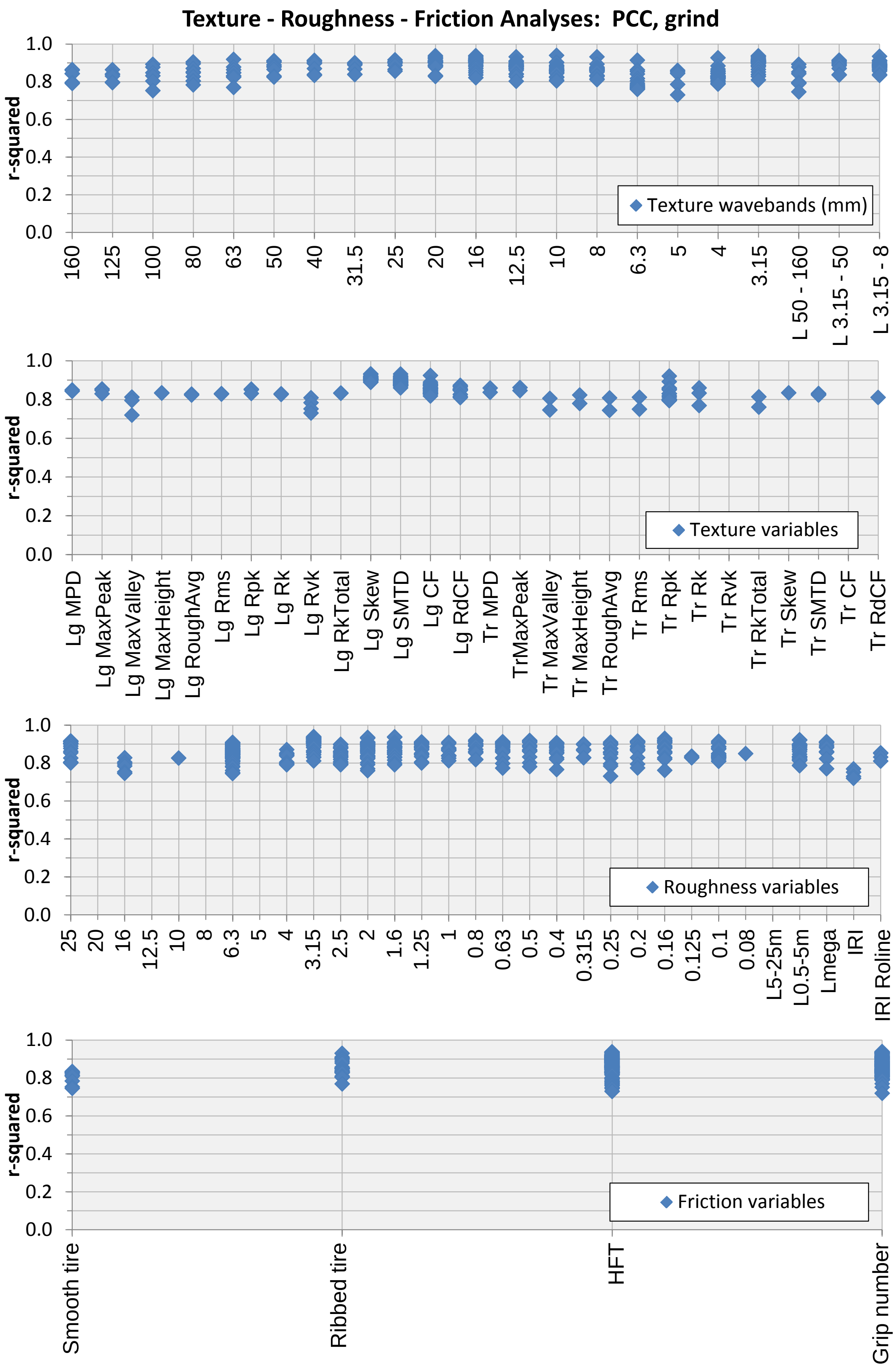

Figure 6-20. PCC, grind pavement: r-squared values for texture wavebands, mm (top chart), 50 percentile texture (2nd chart), roughness (3rd chart) and friction variables (bottom chart).

6.7 Texture – Texture – Roughness Analyses

Regression analyses using combinations of two texture variables and one roughness variable have the form of Equation (6-7).

$$CCR = \beta_3 Texture_2 + \beta_2 Texture_1 + \beta_1 Roughness + \beta_0 + \beta_q Road \qquad (6\text{-}7)$$

Where the qualitative variable is not used ($\beta_q = 0$) for the PCC, grind pavements.

Many of the texture variables are related and relatively collinear, for examples 50% MPD and 90% MPD, or levels in adjacent wavebands. Therefore the texture variables in this group of analyses are limited as follows:

$Texture_2$ consists of the 21 waveband variables, and
$Texture_1$ consists of the 28 fifty percentile variables.

The above criteria governing the number of texture variables and using 31 roughness variables gives a total of 18,228 combinations of variables to analyze for each pavement grouping. Of these, the following number yielded valid regression results.

- Asphalt pavements: 30
- PCC, non-grind pavements: 1620
- PCC, grind pavements: 492

Figure 6-21 through Figure 6-24 show the r-squared values obtained with texture – texture analyses for each of the pavement groupings. Table 6-12 lists the variables that generate the highest r-squared values. Table 6-13 list the regression results for the top ten analyses for each pavement grouping.

Observations:

- For the asphalt pavements, the number of valid analyses is very small compared to the total number of combinations (30:18,228 = 0.16 %). Only two roughness variables occur in the set of valid analyses. Most likely, these are occurring by chance considering there are 18,000 combinations and the significance criteria (p-value requirement) is set at 0.05. Regression analyses using combinations of texture – texture – roughness variables are not good at describing the CRR.

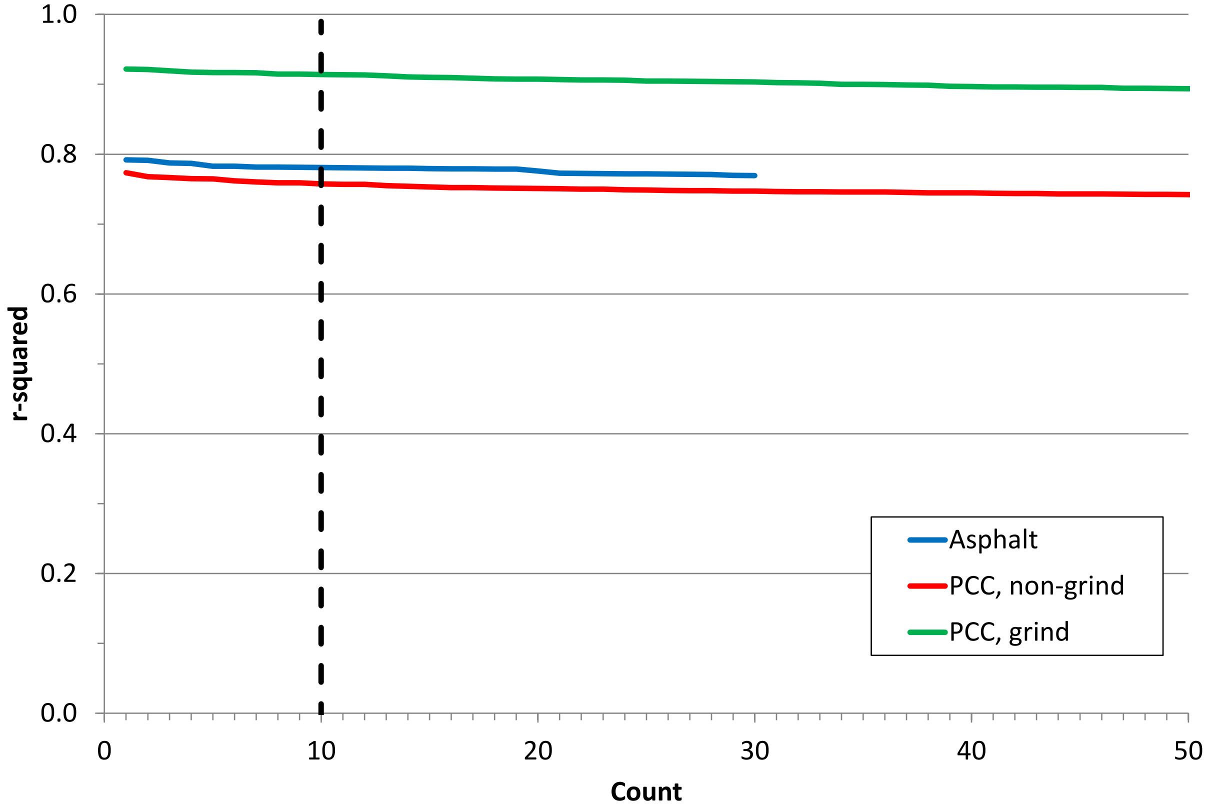

Figure 6-21. r-squared values generated by texture – texture – roughness analyses for each of the pavement groupings

Table 6-12. Variables generating significant results (high r-squared values) for texture – texture – roughness analyses.

Pavement Grouping	Max r-squared	Texture Waveband Variables	50 Percentile Texture Variables	Roughness Variables
Asphalt	0.80	Transverse: • 125 mm • 100 mm • 8 mm • 6.3 mm • 5 mm • 4 mm	Longitudinal and transverse: • MaxPeak • MaxHeight • RoughAvg • RMS • Rpk • Rk • RkTotal	Level in bands: • 25 m • 5 m
PCC non-grind	0.78	Level in bands: • 160 … 63 mm • 31.5 mm • 10 …4 mm Lumped bands • 50 to 160 mm	Longitudinal and transverse: • Skew • SMTD • CF	Level in bands: • 12.5 m • 2 m • 1.25 … 0.5 m Lumped bands: • 5 – 25 m • Lmega • IRI Roline
PCC grind	0.93	Level in bands: • 80 mm • 50 … 16 mm • 8 mm • 6.3 mm • 4 mm • 3.15 mm Lumped bands: • 50 – 160 mm • 3.15 – 50 mm • 3.15 – 8 mm	Longitudinal: • RdCF Transverse: • Skew • SMTD • CF • RdCF	Level in bands: • 20 m • 16 m • 3.15 m • 2 m • 1.6 m • 0.8 m • 0.63 m • 0.1 m Lumped bands: • IRI

Table 6-13. Top ten results for each pavement grouping for texture – texture – roughness regression analyses.

Variables					p-values				Regression Coefficients					Standardized Coefficients		
Pave-ment	Texture Waveband	50% Texture	Rough	r-sq	Texture Wave-band	50% Text	Rough	Road	B_3	β_2	β_1	β_0	β_q	B_3	β_2	β_1
Asphalt	L 125 mm	TrRpk	25 m	0.80	0.0137	0.0323	0.0351	0.0000	7.640E-5	1.348E-3	1.678E-5	4.033E-3	1.030E-3	0.547	0.410	0.154
	L 125 mm	LgRpk	25 m	0.80	0.0088	0.0348	0.0374	0.0000	7.929E-5	1.373E-3	1.655E-5	3.978E-3	1.049E-3	0.567	0.395	0.152
	L 100 mm	TrRpk	25 m	0.80	0.0231	0.0278	0.0299	0.0000	6.930E-5	1.427E-3	1.744E-5	4.142E-3	1.020E-3	0.516	0.434	0.160
	L 100 mm	LgRpk	25 m	0.80	0.0144	0.0294	0.0319	0.0000	7.241E-5	1.451E-3	1.721E-5	4.082E-3	1.041E-3	0.539	0.417	0.158
	L 100 mm	LgMaxPeak	25 m	0.79	0.0295	0.0485	0.0287	0.0000	7.125E-5	4.956E-4	1.791E-5	4.098E-3	1.049E-3	0.530	0.422	0.164
	L 8 mm	TrRpk	25 m	0.79	0.0401	0.0360	0.0478	0.0000	6.594E-5	1.460E-3	1.626E-5	5.973E-3	7.808E-4	0.433	0.444	0.149
	L 4 mm	LgRpk	25 m	0.79	0.0272	0.0284	0.0491	0.0000	7.206E-5	1.532E-3	1.613E-5	6.211E-3	8.064E-4	0.443	0.441	0.148
	L 4 mm	TrRpk	25 m	0.79	0.0476	0.0290	0.0457	0.0000	6.795E-5	1.516E-3	1.647E-5	6.166E-3	7.950E-4	0.418	0.461	0.151
	L 6.3 mm	TrRpk	25 m	0.79	0.0491	0.0266	0.0426	0.0000	7.011E-5	1.533E-3	1.669E-5	6.065E-3	8.059E-4	0.415	0.466	0.153
	L 6.3 mm	LgRpk	25 m	0.79	0.0296	0.0274	0.0461	0.0000	7.439E-5	1.548E-3	1.636E-5	6.105E-3	8.179E-4	0.440	0.445	0.150
PCC, non-grind	L 160 mm	TrSkew	1.25 m	0.78	0.0025	0.0000	0.0023	0.0000	6.102E-5	8.974E-4	4.364E-5	2.905E-3	1.236E-3	0.447	0.443	0.463
	L 125 mm	TrSkew	1.25 m	0.78	0.0040	0.0000	0.0004	0.0000	5.393E-5	9.137E-4	4.942E-5	2.895E-3	1.262E-3	0.407	0.451	0.524
	L 5 mm	LgSMTD	1.25 m	0.78	0.0000	0.0000	0.0000	0.0000	6.030E-5	9.880E-4	4.645E-5	2.807E-3	9.537E-4	0.749	0.638	0.492
	L 100 mm	TrSkew	1.25 m	0.78	0.0050	0.0000	0.0002	0.0000	4.939E-5	9.443E-4	5.127E-5	3.011E-3	1.248E-3	0.386	0.466	0.544
	L 4 mm	LgSMTD	1.25 m	0.77	0.0000	0.0000	0.0000	0.0000	5.913E-5	1.112E-3	4.654E-5	2.502E-3	9.338E-4	0.806	0.719	0.493
	L 50-160 mm	TrSkew	1.25 m	0.77	0.0064	0.0000	0.0001	0.0000	4.754E-5	9.313E-4	5.255E-5	2.641E-3	1.249E-3	0.370	0.460	0.557
	L 6.3 mm	LgSMTD	1.25 m	0.77	0.0000	0.0000	0.0000	0.0000	5.815E-5	1.088E-3	4.913E-5	2.351E-3	9.398E-4	0.781	0.703	0.521
	L 5 mm	LgCF	1.25 m	0.77	0.0000	0.0001	0.0001	0.0000	6.095E-5	8.538E-4	4.579E-5	2.826E-3	9.527E-4	0.757	0.636	0.485
	L 80 mm	TrSkew	1.25 m	0.77	0.0081	0.0000	0.0001	0.0000	4.275E-5	9.311E-4	5.416E-5	3.113E-3	1.238E-3	0.349	0.460	0.574
	L 4 mm	LgCF	1.25 m	0.77	0.0000	0.0000	0.0001	0.0000	6.006E-5	9.677E-4	4.581E-5	2.508E-3	9.314E-4	0.818	0.721	0.486
PCC, grind	L 3.15 mm	LgRdCF	20 m	0.93	0.0000	0.0000	0.0437	–	1.401E-4	3.824E-3	2.604E-5	8.871E-4	0	0.752	0.614	0.200
	L 20 mm	LgRdCF	20 m	0.93	0.0000	0.0000	0.0351	–	1.302E-4	3.719E-3	2.753E-5	-4.508E-4	0	0.747	0.597	0.211
	L 16 mm	LgRdCF	20 m	0.93	0.0000	0.0000	0.0444	–	1.373E-4	3.735E-3	2.642E-5	-4.159E-4	0	0.748	0.600	0.203
	L 3.15 - 50 mm	TrSkew	2 m	0.93	0.0002	0.0000	0.0393	–	8.533E-5	5.738E-4	2.239E-5	5.438E-3	0	0.504	0.700	0.204
	L 3.15 - 8 mm	LgRdCF	20 m	0.93	0.0000	0.0000	0.0430	–	1.812E-4	4.460E-3	2.702E-5	-6.165E-4	0	0.762	0.716	0.207
	L 16 mm	TrSkew	0.1 m	0.93	0.0001	0.0002	0.0167	–	1.139E-4	4.481E-4	2.966E-4	2.351E-3	0	0.621	0.547	0.262
	L 31.5 mm	TrSkew	2 m	0.93	0.0002	0.0000	0.0405	–	8.421E-5	5.895E-4	2.238E-5	6.401E-3	0	0.498	0.719	0.204
	L 31.5 mm	TrSkew	1.6 m	0.92	0.0002	0.0000	0.0467	–	8.818E-5	6.057E-4	2.434E-5	6.282E-3	0	0.521	0.739	0.205
	L 50 mm	TrSkew	2 m	0.92	0.0002	0.0000	0.0377	–	8.271E-5	5.745E-4	2.306E-5	5.682E-3	0	0.500	0.701	0.211
	L 80 mm	TrSkew	3.15 m	0.92	0.0017	0.0001	0.0333	–	6.760E-5	4.748E-4	3.248E-5	5.251E-3	0	0.421	0.579	0.249

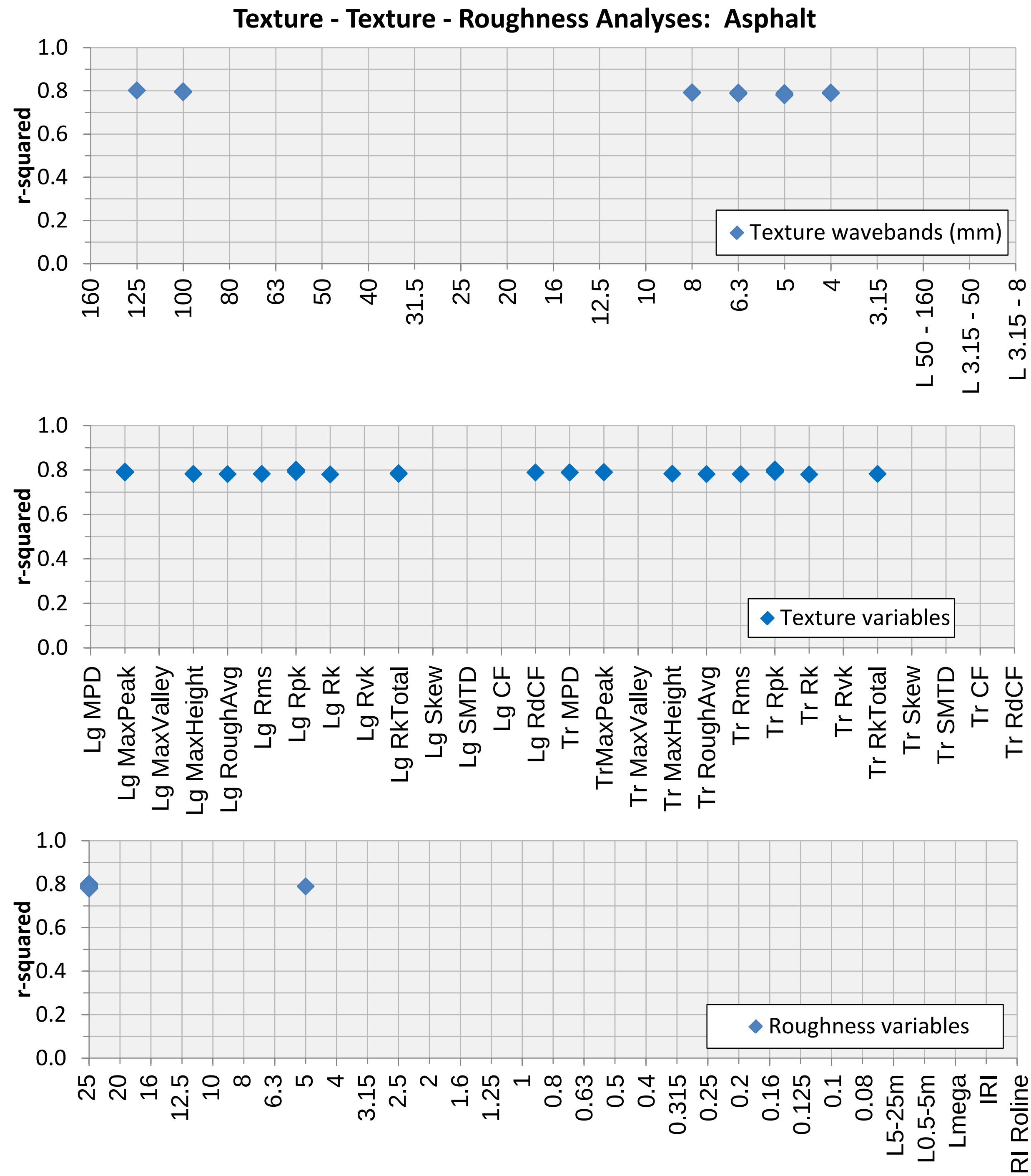

Figure 6-22. Asphalt pavement: r-squared values for texture wavebands, mm (upper chart), 50 percentile texture variables (center chart), and roughness variables (lower chart).

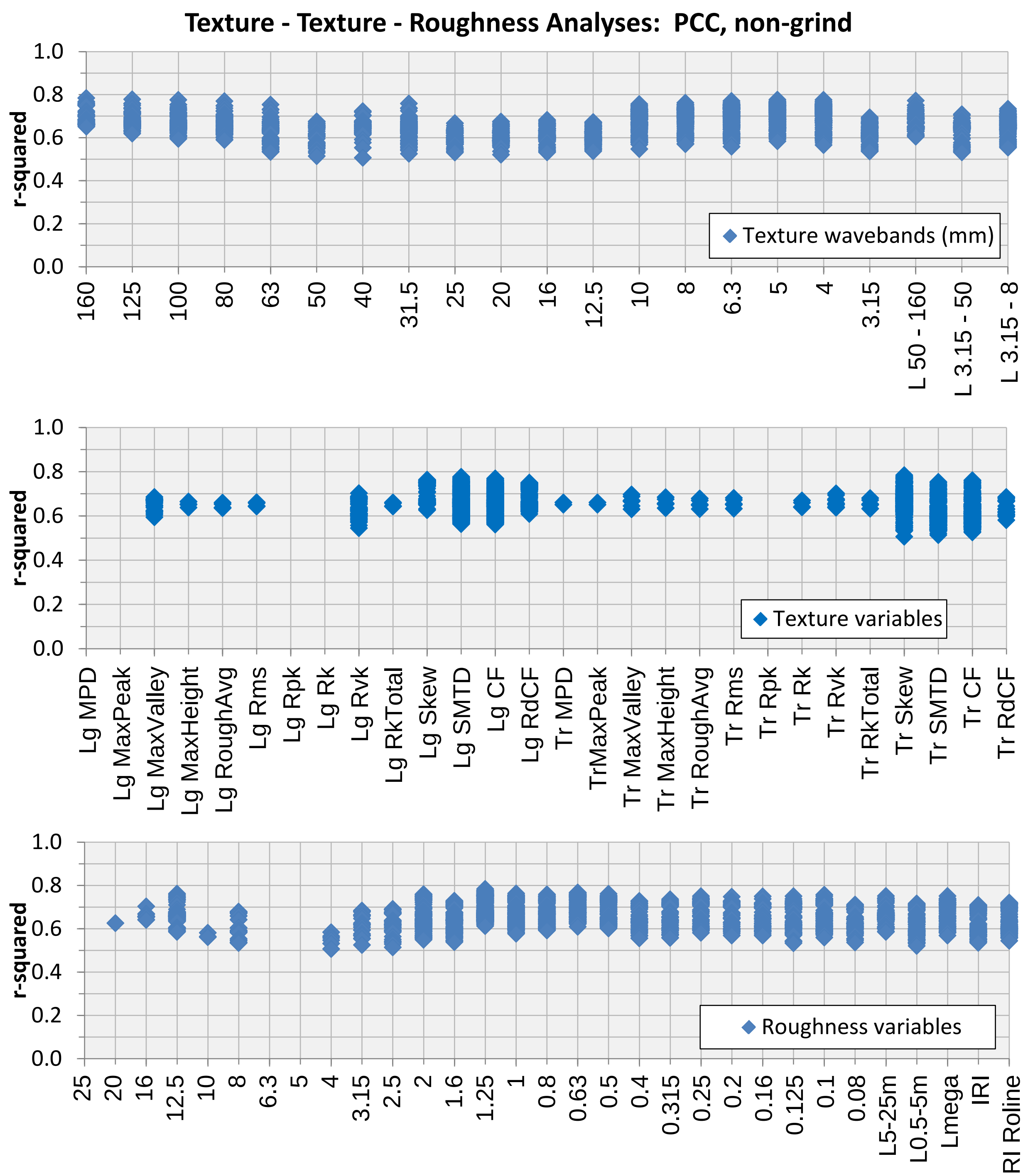

Figure 6-23. PCC, non-grind pavement: r-squared values for texture wavebands, mm (upper chart), 50 percentile texture variables (center chart), and roughness variables (lower chart).

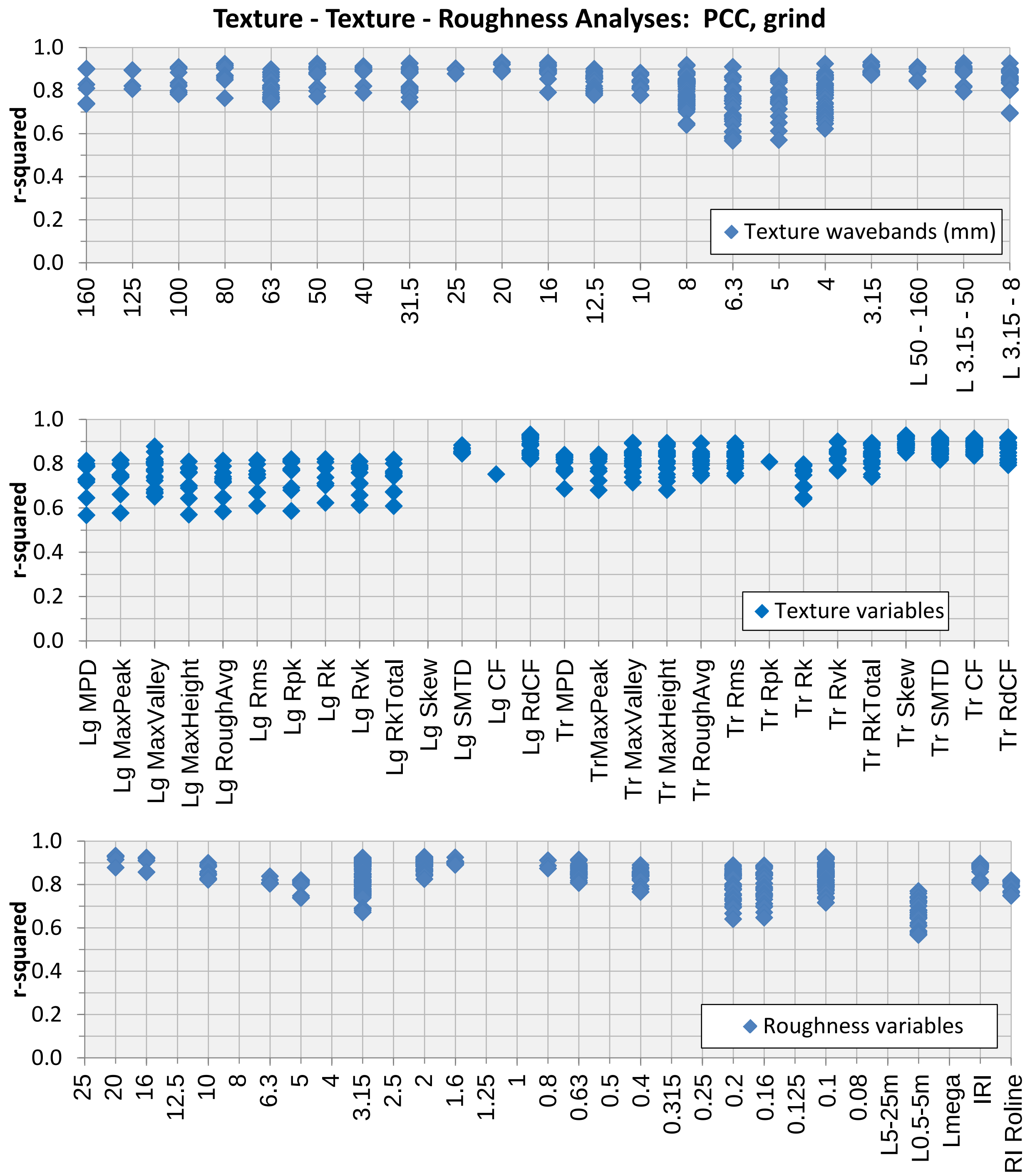

Figure 6-24. PCC, grind pavement: r-squared values for texture wavebands, mm (upper chart), 50 percentile texture variables (center chart), and roughness variables (lower chart).

Chapter 7. Analysis Comparisons and Sample CRR Models

This section compares the performance of the various regression analyses presented in Chapter 6 and shows the performance of some models relating the coefficient of rolling resistance to the other surface characteristics.

Various criteria can be conceived to be used to judge the performance of a regression analysis, for examples:

- Maximum r-squared value (best fit).
- Minimize the number of explanatory variables (simpler is better).
- Use commonly measured, non-obscure, explanatory variables (known quantities).
- Some combination or balance of these.

The analyses yielding absolute maximum r-squared values are listed in the top ten tables earlier in this chapter. Presented in this section are sample models selected based on prioritizing the simpler and common concepts while keeping r-squared high.

For each pavement grouping, the performance of the single variable analyses is considered as a baseline. It is the simplest of the various analyses. Relative to the baseline performance, the effect of adding additional explanatory variables is assessed. From this, a sample model for predicting coefficient of rolling resistance is shown for each pavement type.

7.1 Asphalt

Figure 7-1 shows the performance of the various regression analyses for the asphalt pavement grouping. From the graph, adding explanatory variables does not necessarily produce regression results better than the single variable analyses. In fact, the single variable analyses can be considered best.

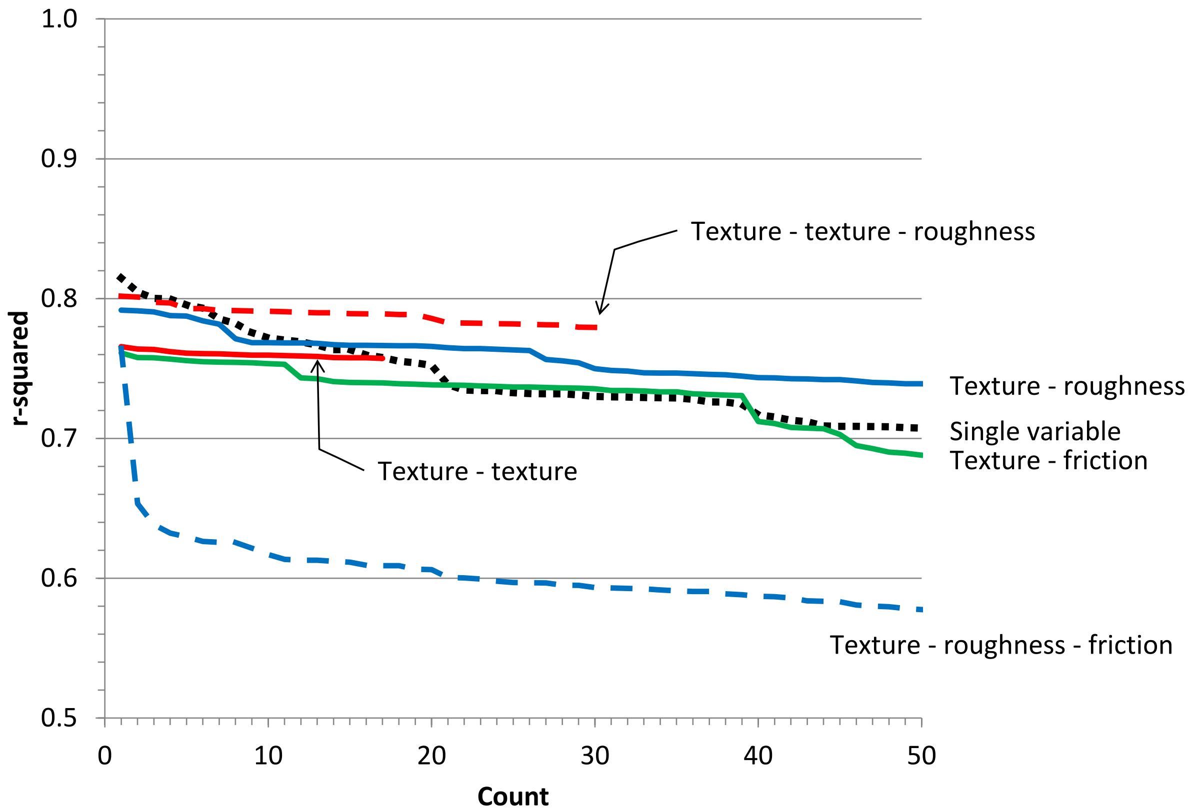

Figure 7-1. r-squared values obtained from the various multi-variable regression analyses for asphalt pavements.

A sample model using a single texture variable with r-squared value of 0.80 is given by Equation (7-1).

$$CRR_{estimate} = 1.220 \times 10^{-4} \times (Texture, L\ 3.15\ to\ 50\ mm) + 4.290 \times 10^{-3} + 9.552 \times 10^{-4} \times Road \quad (7\text{-}1)$$

Figure 7-4 graphs the estimated versus measured CRR.

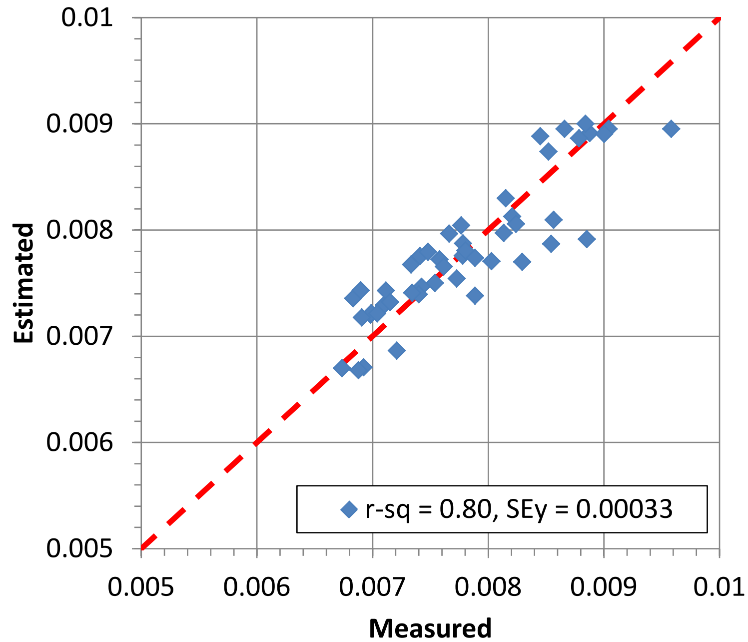

Figure 7-2. Measured versus estimated CRR using the model in Equation (7-1) on test cells with asphalt pavement. Dashed red line is the 1:1 (x=y) line. "r-sq" is the coefficient of determination for the regression. SEy is the standard error of the estimate.

7.2 PCC, Non-Grind

Figure 7-3 shows the performance of the various regression analyses for the PCC, non-grind pavement grouping. The graph clearly shows that adding explanatory variables increases the performance of the regression analyses over the single variable baseline. A rank order of the regression performance by r-squared value is:

1. Texture – texture – roughness.
2. Texture – roughness – friction.
3. Texture – roughness (tied with texture – roughness).
3. Texture – texture (tied with texture – roughness).
5. Texture – friction.
6. Single variable.

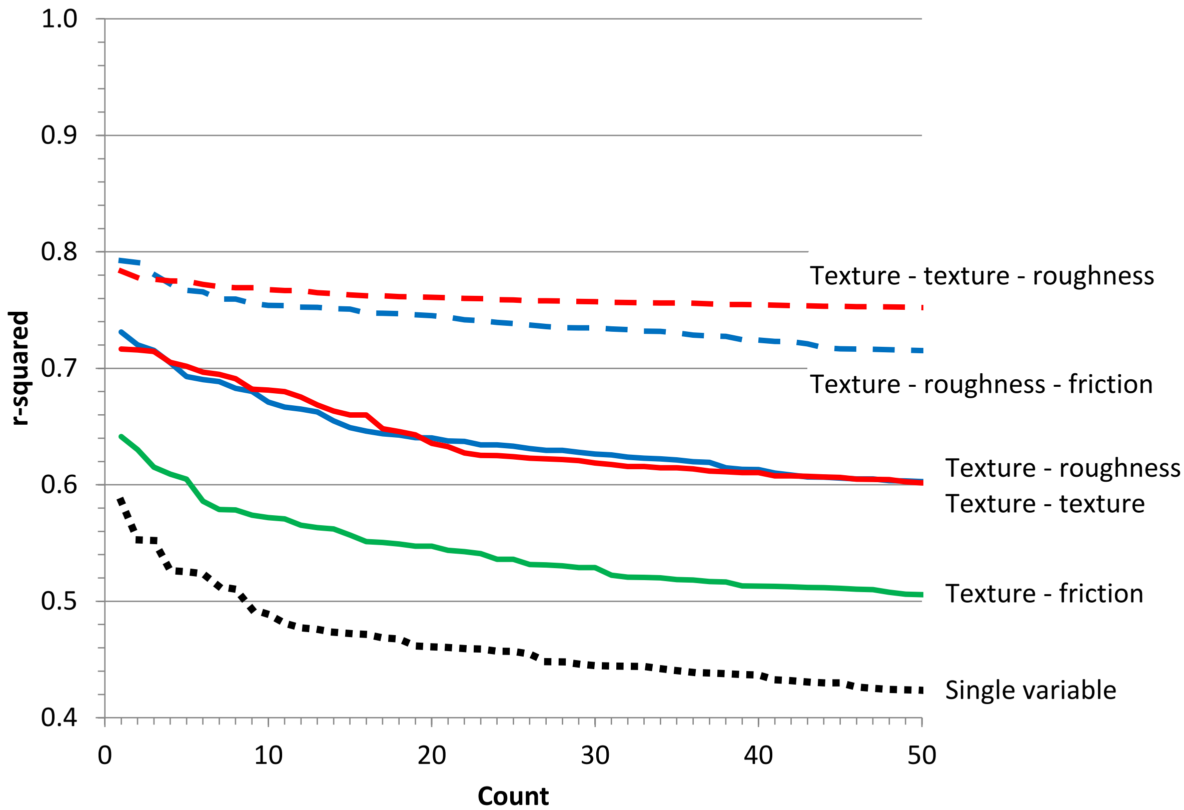

Figure 7-3. r-squared values obtained from the various multi-variable regression analyses for PCC, non-grind pavements.

Significant increase in r-squared value is obtained using three variables. A sample model using two texture variables and one roughness variable with r-squared value of 0.77 is given by Equation (7-2).

$$\begin{aligned} CRR_{estimate} = 4.754 \times 10^{-5} \times (Texture, L\ 50\ to\ 160\ mm) \\ + 9.313 \times 10^{-4} \times (50\%\ TrSKEW) \\ + 5.255 \times 10^{-5} (Roughness, L\ 1.25\ m) \\ + 1.249 \times 10^{-3} \\ + 2.641 \times 10^{-3} \times Road \end{aligned} \quad (7\text{-}2)$$

Figure 7-4 graphs the estimated versus measured CRR.

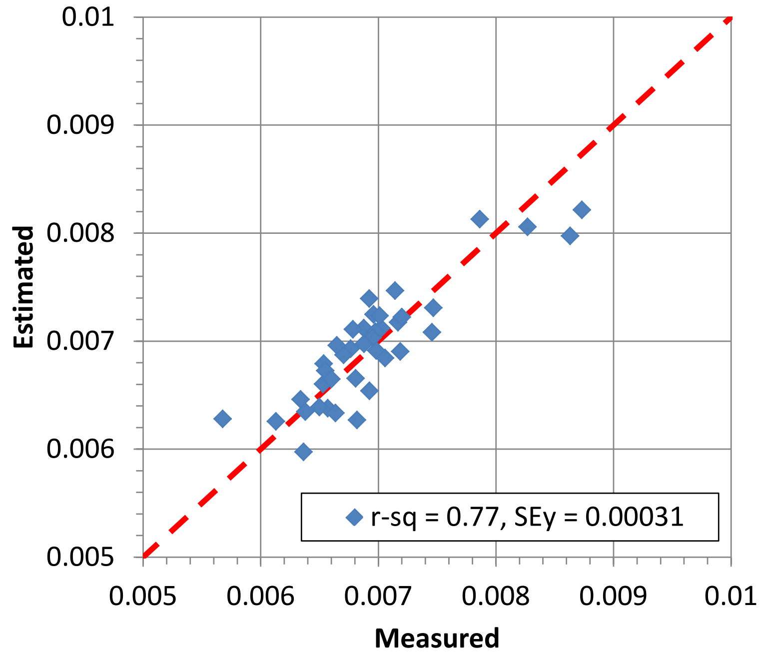

Figure 7-4. Measured versus estimated CRR using the model in Equation (7-2) on test cells with PCC, non-grind pavement. Dashed red line is the 1:1 (x=y) line. "r-sq" is the coefficient of determination for the regression. SEy is the standard error of the estimate.

7.3 PCC, Grind

Figure 7-5 shows the performance of the various regression analyses for the PCC, grind pavement grouping. The graph shows that adding explanatory variables increases the performance of the regression analyses over the single variable baseline. A rank order of the regression performance by r-squared value is as follows, although, the top two are very close.

1. Texture – roughness – friction.
2. Texture – texture – roughness.
5. Texture – texture.
3. Texture – roughness.
3. Texture – friction.
6. Single variable.

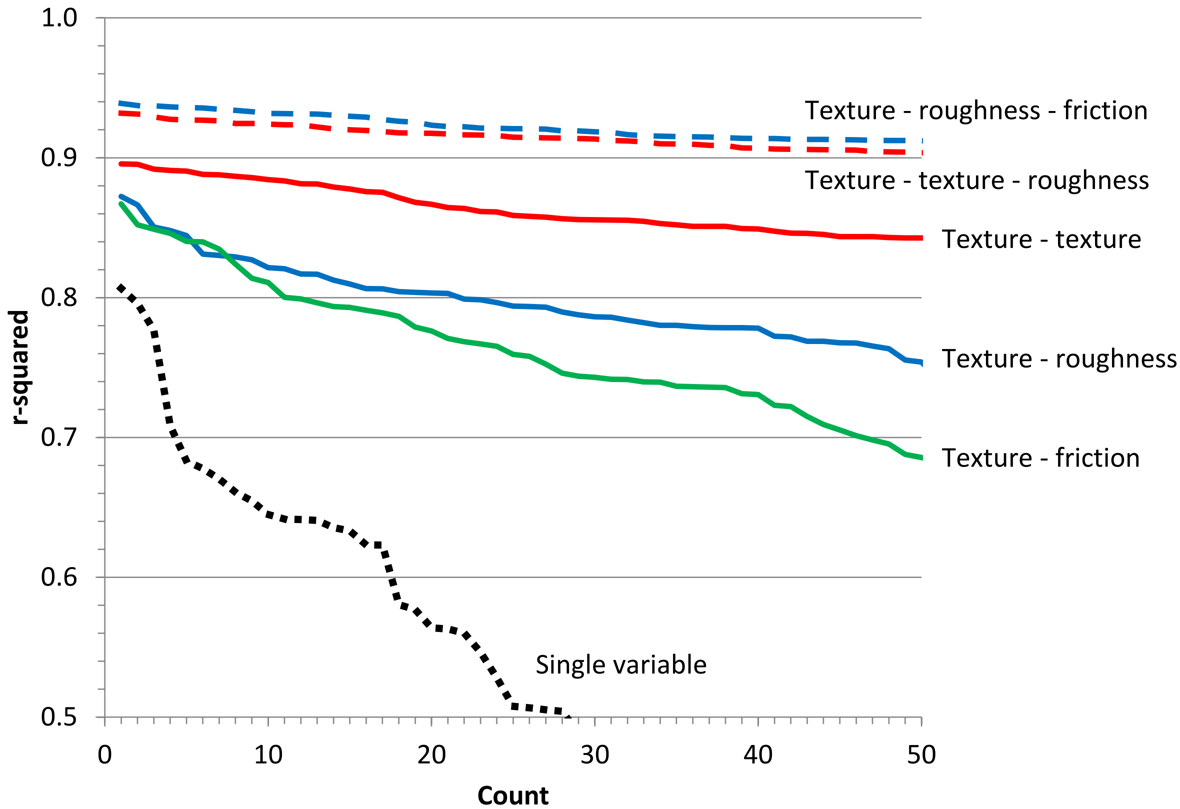

Figure 7-5. r-squared values obtained from the various multi-variable regression analyses for PCC, grind pavements.

A sample model using two texture variables and one roughness variable with r-squared value of 0.93 is given by Equation (7-3).

$$\begin{aligned} CRR_{estimate} = {} & 8.533 \times 10^{-5} \times (Texture, L\ 3.15\ to\ 50\ mm) \\ & + 5.738 \times 10^{-4} \times (50\%\ TrSKEW) \\ & + 2.239 \times 10^{-5} (Roughness, L\ 2.0\ m) \\ & + 5.438 \times 10^{-3} \end{aligned} \tag{7-3}$$

Figure 7-6 graphs the estimated versus measured CRR.

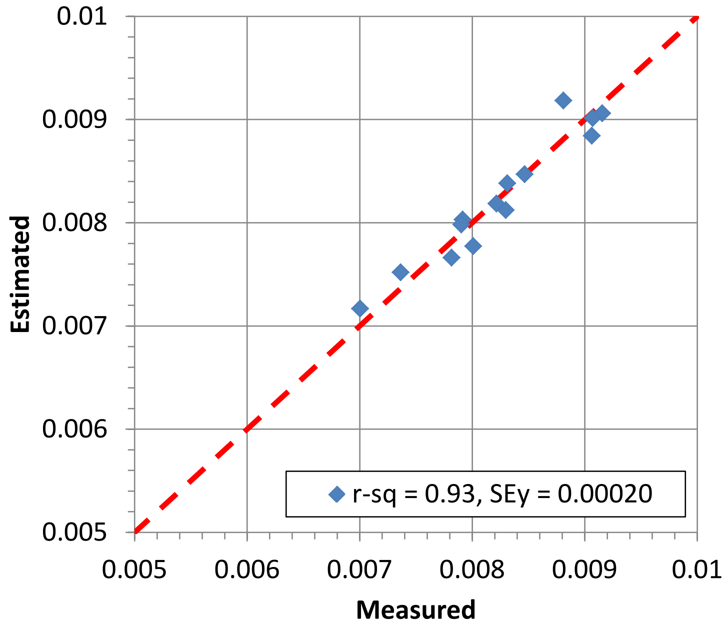

Figure 7-6. Measured versus estimated CRR using the model in Equation (7-3) on test cells with PCC, grind pavement. Dashed red line is the 1:1 (x=y) line. "r-sq" is the coefficient of determination for the regression. SEy is the standard error of the estimate.

Chapter 8. Conclusions

Texture measurements on all the MnROAD test cells were performed using a line-laser-based texture profiler. Measurement results yield numerous texture metrics in addition to the usual macrotexture depth (MPD). In addition, use of a line-laser profiler produced separate texture results in the longitudinal and transverse directions, which is most relevant to PCC pavements. These texture data are collated with data for other MnROAD test cell surface characteristics (rolling resistance, roughness, friction, and tire-pavement noise) into an aligned database. The database is used for multivariable linear regression analyses to investigate the dependency of CRR on pavement surface characteristics.

Results of the multivariable regression analyses study include:

1. There are many possible combinations of surface characteristic variables that can predict CRR.
2. Using the entire set of test cells in regression analyses yields relatively poor performance of the model. Good results are obtained when the data are analyzed separately in pavement groupings:
    a. Asphalt;
    b. PCC longitudinal and transverse tine, drag, and/or broom finished; and
    c. PCC with diamond grind finish.

   Furthermore, the variables that best predict CRR are different between the asphalt and PCC pavements.
3. Better regression results are obtained when the data from the Mainline and Low-Volume Roads are treated separately as a qualitative variable. This indicates there is an uncontrolled factor in the data. This could be, for example, the difference in traffic loading between the Mainline and Low-Volume Roads.

These regression analysis results are subject to the limitations in the data collection process and measurement results. For example, all the data were not collected on the same date, although most were collected within a period of a few months. Data are not compensated for the air and pavement temperature at the time of the measurements. In addition, all results are based on the data set for the MnROAD test cells and for the SRTT tire at 80 km/h. To test for universal applicability, the suggested models need to be evaluated using data from other roads and tires.

Chapter 9. References

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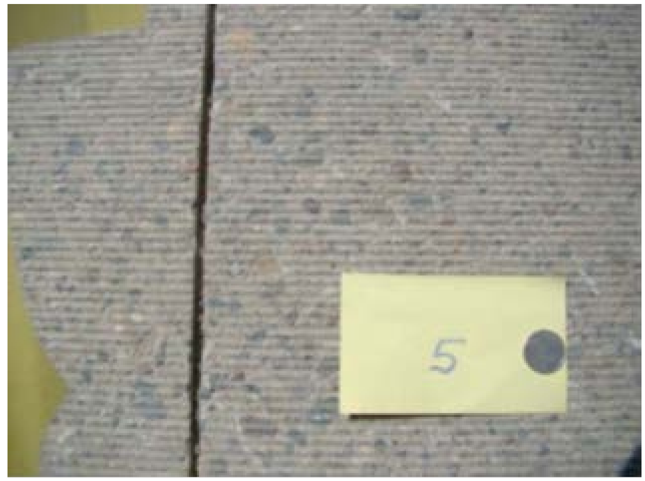
Appendix A. Summary of Test Cell Pavements

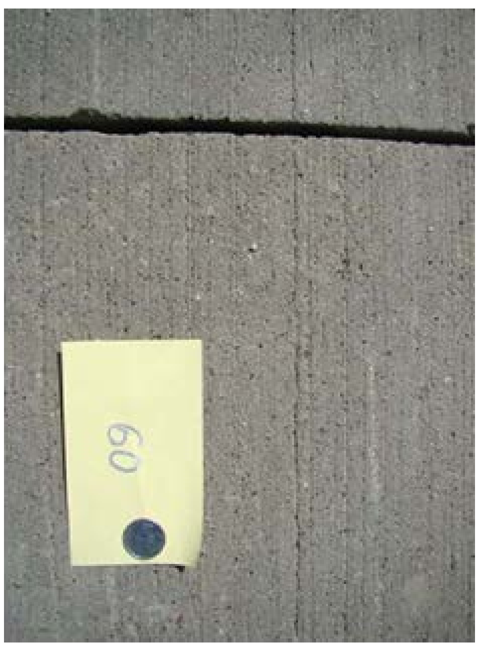
This Appendix contains a list of pavement surface descriptions and photographs for the MnROAD test cells.

Table A-1. Summary of test cell pavement surfaces. (Source: MnDOT [6]. Reprinted with permission.)

Cell	Sub-Cell	Experi-ment	Surface Type	Picture
1		Original HMA Cell	12.5 mm Dense Graded Superpave	
2		SemMaterials FDR Study	Ultra Thin Bonded Wearing Course	

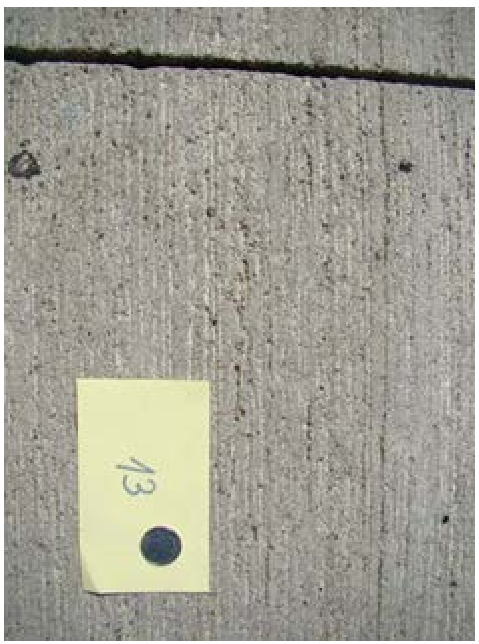
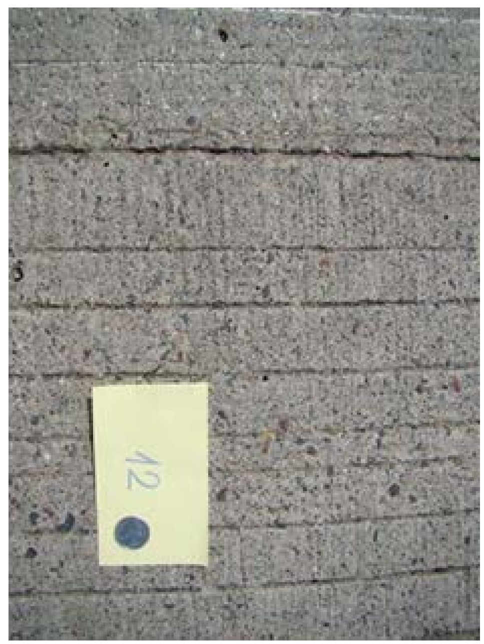
3		SemMaterials FDR Study	Ultra Thin Bonded Wearing Course	
4		SemMaterials FDR Study	12.5 mm Dense Graded Superpave	
5	505 605		Transverse Broom	

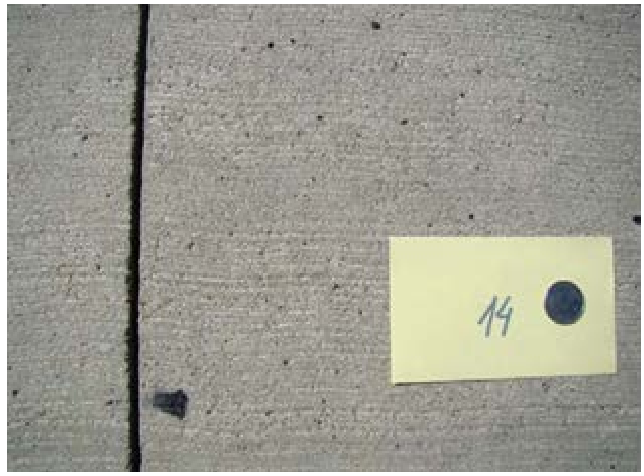
5	305 405		Longitudinal Tine + Conventional Grind	
6	306 406		Longitudinal Tine + Turf	
7		5 year design PCC -Widened lane - PASB - longer panel	Innovative Diamond Grind	

8		5 year design PCC -Widened lane - PASB -Supplemental Steel	Conventional Diamond Grind	
9		5 year design PCC -Widened lane - PASB	Ultimate Diamond Grind (2008)	
60		Thin Bonded Concrete Overlay ohm - 5 inch -sealed	Turf	

61		Thin Bonded Concrete Overlay ohm – 5 inch -unsealed	Turf	
62		Thin Bonded Concrete Overlay ohm - 4 inch -sealed	Turf	
63		Thin Bonded Concrete Overlay ohm - 4 inch -unsealed	Conventional Diamond Grind	

96		Thin Bonded Concrete Overlay ohm - 5 by 6 panels	Conventional Diamond Grind	
70		SHRP II Composite Pavement Study DL Doweled, PL Not Doweled	12.5 mm Dense Graded Superpave	
71		SHRP II Composite Pavement Study Diamond Grind Surface	2010 Ultimate Diamond Grind (Driving)Conventional Diamond Grind (Passing)	

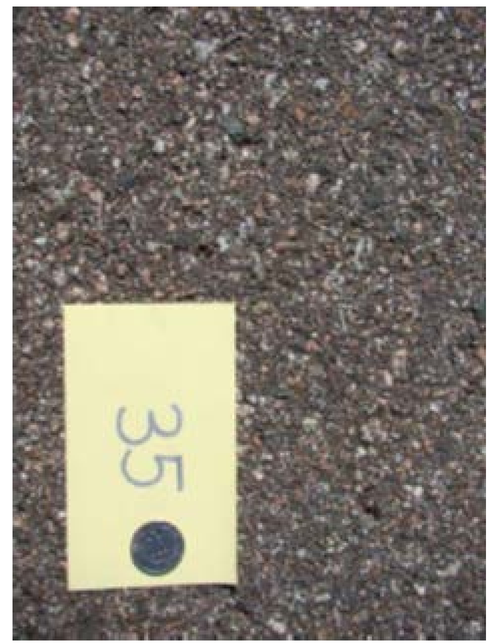
13	12	72
513 413 313 213 113		
PCC Thickness Optimization - 5 inch Flat Plate Dowels -12 and 15 foot panel lengths	10 year design PCC - Drained base	SHRP II Composite Pavement Study EAC Surface
Longitudinal Turf Drag	Transverse Tine	Exposed Aggregate
		

14	914 814 714 614 514 414 314 214 114		Longitudinal Broom Drag	
15		Warm Mix Asphalt Overlay	12.5 mm Dense Graded Superpave	
16		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave	

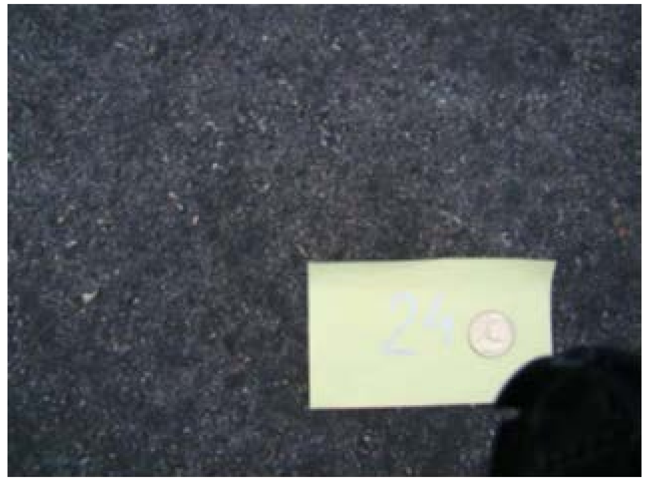
17		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave	
18		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave	
19		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave	

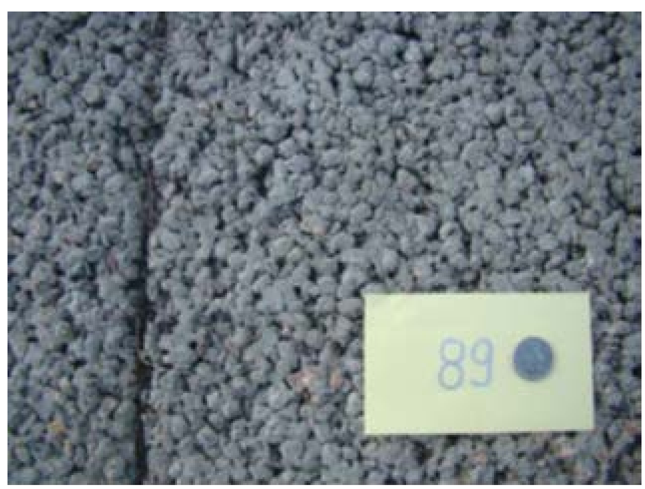
20		Low Temperature Cracking, RAP Study	12.5 mm Dense Graded Superpave	
21		Low Temperature Cracking, RAP Study	12.5 mm Dense Graded Superpave	
22		Low Temperature Cracking, RAP Study	12.5 mm Dense Graded Superpave	

23		Taconite railroad ballast, WMA Surface	12.5 mm Dense Graded Superpave	
33		Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave	
34		Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave	

35		Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave	
36		LVR design PCC -SUBGRADE R70subgrade -doweled	Transverse Tine	
37		LVR design PCC -SUBGRADE R70subgrade -undoweled	Conventional Diamond Grind (TS3)Innovative Diamond Grind (TS 1 and 2)2010 Diamond Grind (TS 5) Transverse Tine (TS 4 and Inside)	

38		LVR design PCC -Standard base - doweled	Transverse Tine	
39		Porous Concrete Overlay Experiment	Pervious Overlay	
40		LVR design PCC - 7-5.5-7 inch Trapezoidal - undoweled	Transverse Tine	

24		Aging Study, WMA Control	12.5 mm Dense Graded Superpave, Fog seals each year in 100-ft sections	
85		Pervious Concrete Experiment -Low-Volume Road - Sand subgrade	Pervious Concrete	
86		Porous HMA Study	Porous Hot Mixed Asphalt	

87		Porous Pavement Study - Control Section	12.5 mm Dense Graded Superpave	
88		Porous HMA Study	Porous Hot Mixed Asphalt	
89		Pervious Concrete Experiment -Low-Volume Road - Clay subgrade	Pervious Concrete	

27		Geocomposite Capillary Barrier Drain	Chip Seals (FA-2 and FA-3)	
28		Stabilized Full Depth Reclamation	Double Chip Seal	
77		Fly Ash Study, Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave	

78		Fly Ash Study, Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave	
79		Fly Ash Study, Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave	
31		2004 LVR Taconite Superpave	12.5 mm Dense Graded Superpave	

32		LVR design PCC -Thin Slab	Longitudinal Turf Drag	
52		5 year design PCC - Load testing - FRP dowels	Longitudinal Turf Drag	
53		60-year PCC	Transverse Broom	

54		PCC mix experiment -Mesabi Select aggregates	Longitudinal Turf Drag	

Appendix B. Processing Texture Profiles

This appendix describes the general method used for calculating longitudinal and transverse texture metrics from a 3-dimensional elevation profile.

B.1 3-D Elevation Profile

The process of calculating a texture metric begins with a sampled (digitized) 3-dimensional elevation profile generated by the texture profiler. Figure A-1 illustrates a representation of a portion of such a profile. The X-direction is longitudinal, Y is transverse, and Z is vertical elevation. The distance between samples is 0.0394 in (1 mm) in the transverse and 0.0197 in (0.5 mm) in longitudinal directions.

The width (in the transverse direction) of the 3-dimensional profile is governed by the width of the line laser on-board the profiler. For the RoboTex profiler, the line width is 100 samples which translates to a profile width of 3.94 in (100 mm). The length of the 3-dimensional profile depends on the length of the test section. For example, a 500 ft (152.4 m) test section will have 304800 samples. Thus, the 3-dimensional profile is really a very long and narrow strip; 100 samples wide and hundreds of thousands of samples long. In general, an individual elevation profile sample, z, is referred to by its coordinate position as z(x,y).

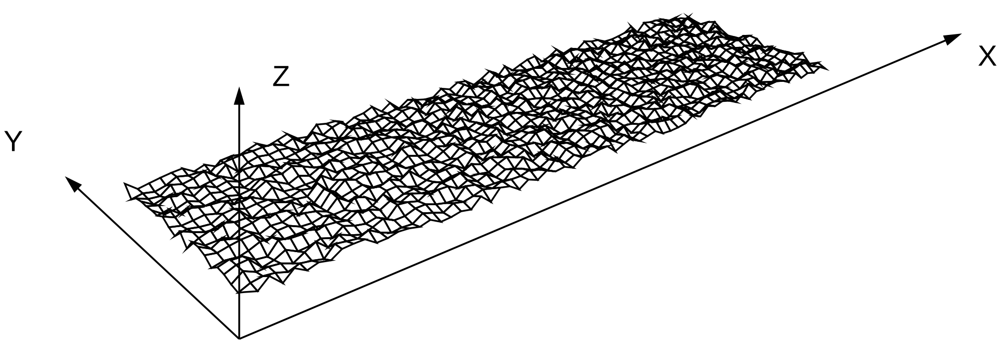


Figure B-1. Representation of a digitized 3-dimensional elevation profile.

B.2 Base Length and Calculation Area

Texture metrics are calculated from a subset of the full 3-dimensional profile. The length of the subset is referred to as the “base length” and is illustrated in Figure A-2. In the longitudinal direction, the base length is equal to 3.94 in (100 mm) for non-spectral texture metrics (for example, MPD). For spectral based texture metrics, the base length is 7.0 ft (2.13 m).

In the transverse direction, the base length is equal to the width of the 3-dimensional profile; also 3.94 in (100 mm). Spectral based texture metrics are not calculated in the transverse direction because the profile width is too short for that purpose.

The area defined by the longitudinal and transverse base lengths is referred to as the calculation area.

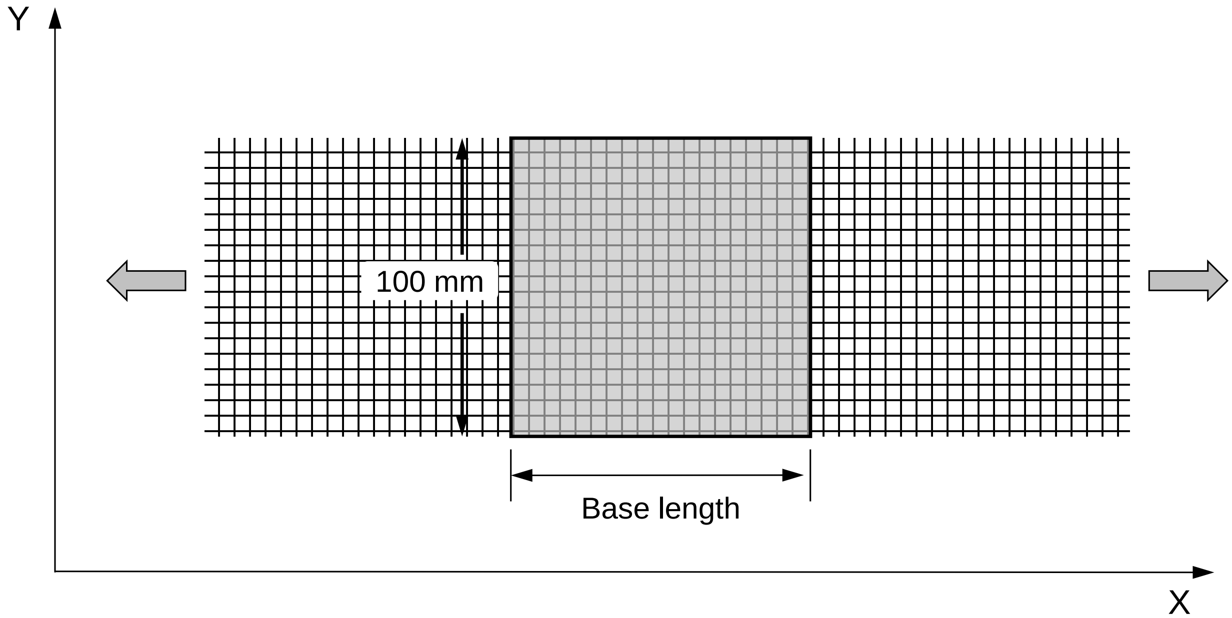


Figure B-2. Plan view of a portion of a 3-dimensional profile with longitudinal and transverse base lengths identified. The highlighted area is referred to as the calculation area.

B.3 Longitudinal and Transverse Profiles

Various cross sections of the calculation area can be taken of the 3-dimensional elevation profile in Figure A-2 and viewed as 2-dimensional profiles.

Figure A-3 shows an example cross section in the longitudinal (X) direction. Sample points can be numbered in sequence; 1, 2, 3, and etc. Note, the letter “i” is used to designate a general sample number in the longitudinal (X) direction.

Figure A-4 shows an example cross section in the transverse (Y) direction. Again, samples can be numbered in sequence, 1, 2, 3, and etc. Note, the letter “j” is used to designate a general sample number in the transverse (Y) direction.

The number of possible longitudinal cross sections within the calculation area is equal to 100, one at each of the transverse samples. Similarly, the number of possible transverse cross sections within the calculation area is equal to the number of samples in the base length, which is also 100.

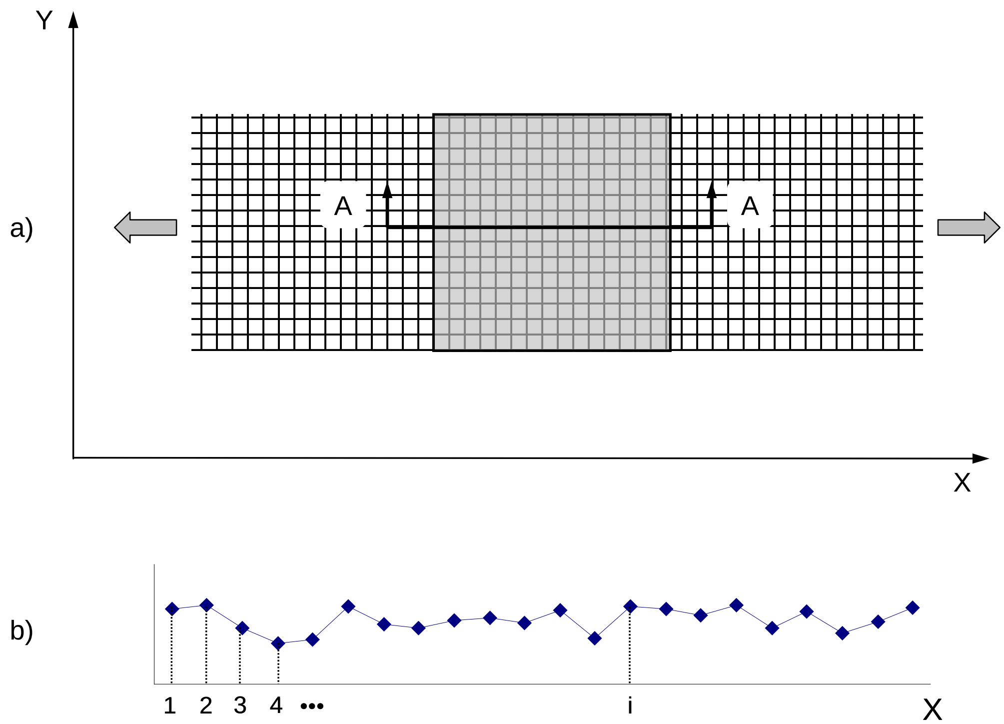


Figure B-3. a) Plan view of a portion of the 3-dimensional profile with calculation area highlighted. b) 2-dimensional profile obtained from the full 3-dimensional profile at cross section A-A.

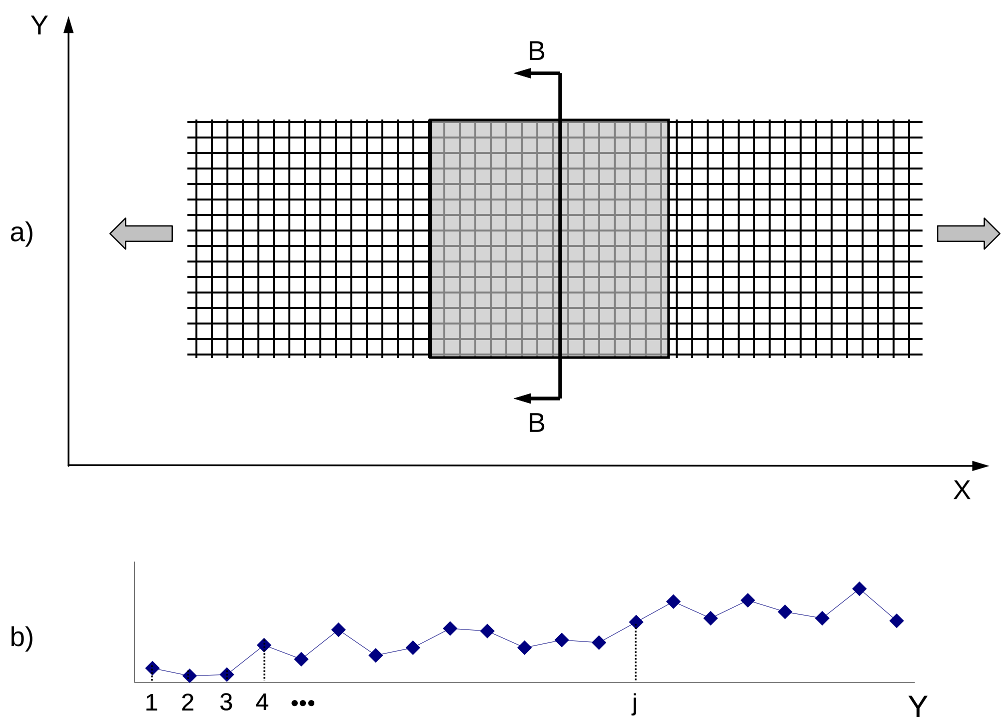


Figure B-4. a) Plan view of a portion of the 3-dimensional profile with calculation area highlighted. b) 2-dimensional profile obtained from the full 3-dimensional profile at cross section B-B.

B.4 Detrending

Texture metrics are calculated from 2-dimensional profiles extracted from the calculation area. Prior to calculating a texture metric, the elevation profile is “detrended”. Detrending transforms the profile so that the average elevation and average slope over the base length is zero. This process is illustrated in Figure A-5.

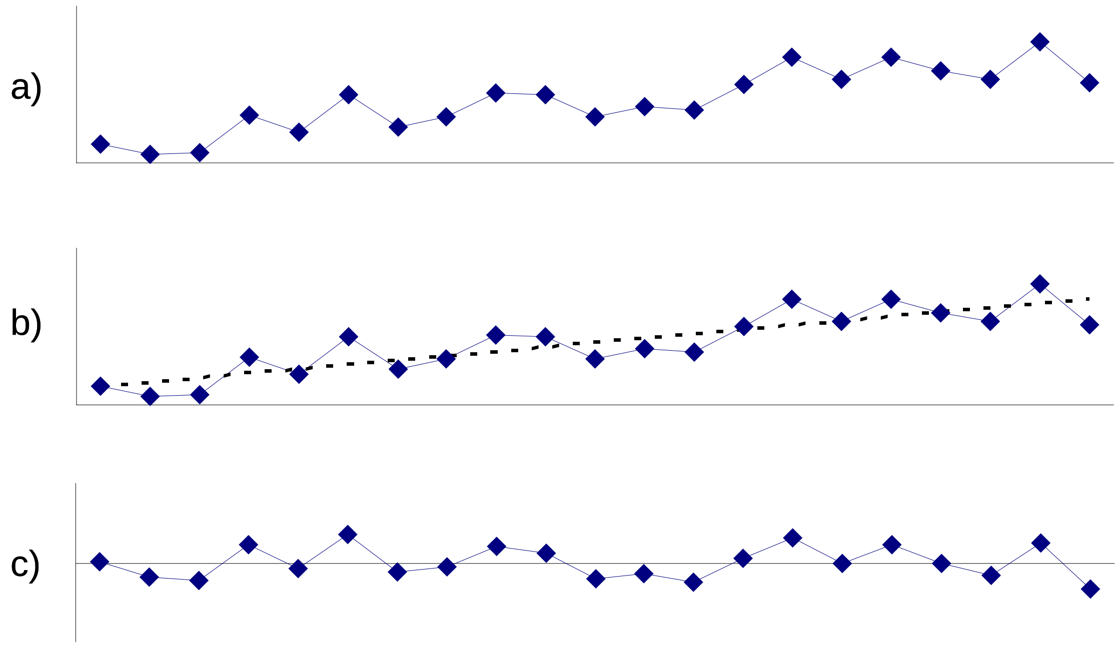


Figure B-5. Detrending a profile. a) Original elevation profile. b) Original profile with linear trend (straight dashed line) superimposed. c) Detrended profile obtained by subtracting the linear trend from the original profile. The detrended profile has average elevation and average slope equal to zero.

B.5 Texture Calculations

Texture calculations are performed on the 2-dimensional profiles extracted from the calculation area and after detrending.

Let F(z) represent the general texture metric which is a function of “z”, the elevation samples of a 2-dimensional profile. Then, $LgF_j(z)$ is the longitudinal texture metric calculated from the longitudinal 2-dimensional profile from the cross section at transverse sample j. The total number of longitudinal texture values that can be calculated within one calculation area is equal to 100, one at each of the transverse samples.

Similarly, $TrF_i(z)$ is the transverse texture metric calculated from the transverse 2-dimensional profile from the cross section at longitudinal sample i. The total number of transverse texture values that can be calculated within one calculation area is equal to the number of samples in the base length, which is 200 for a 100 mm base length.

The functions F(z) for the various texture metrics in the data files are defined in Section Appendix C. But, for example, here are equations for RMS texture in the longitudinal and transverse directions.

Longitudinal RMS texture is given by:

$$LgRMS_j = \sqrt{\frac{\sum_{i=1}^{N} z_{i,j}^2}{N}} \tag{B-1}$$

Where:
LgRMSj = the RMS texture in the longitudinal direction for the 2-dimensional profile at transverse sample j, and
N = the number of samples in the longitudinal base length.

Transverse RMS texture is given by:

$$TrRMS_i = \sqrt{\frac{\sum_{j=1}^{N} z_{i,j}^2}{M}} \tag{B-2}$$

Where:
TrRMSi = the RMS texture in the transverse direction for the 2-dimensional profile at longitudinal sample i, and
M = the number of samples in the transverse base length.

B.6 Longitudinal and Transverse Medians

The longitudinal texture value for the calculation area is the median of the longitudinal texture values over the calculation area.

$$LgF = Median(LgF_j)\Big|_{j=1}^{M} \tag{B-3}$$

Where:
LgF_j = the longitudinal texture value at transverse sample j, and
M = the number of samples across the transverse width of the calculation area.

Similarly, the transverse texture value for the calculation area is the average of the transverse texture values over the calculation area.

$$TrF = Median(TrF_i)\Big|_{i=1}^{N} \tag{B-4}$$

Where:
  TrF_i = the transverse texture value at longitudinal sample i, and
  N = the number of samples along the longitudinal base length of the calculation area.

B.7 Texture versus Distance

Texture as a function of distance along the test section is obtained by shifting the calculation area by 2 in (50.8 mm) along the length of the 3-dimensional profile, as illustrated in Figure A-6. (Note in the figure, a transverse offset of the calculation area is shown for illustration purposes only. A transverse offset is not used in the texture calculations.) For metrics with a base length of 3.94 in (100 mm) this is effectively an overlap of 50 %. For spectral based texture metrics in the longitudinal direction with base length of 7.0 ft (2.13 m), the 2-inch shift is an effective overlap of 98 %. Table A- summarizes these base lengths, shifts, and percent overlaps.

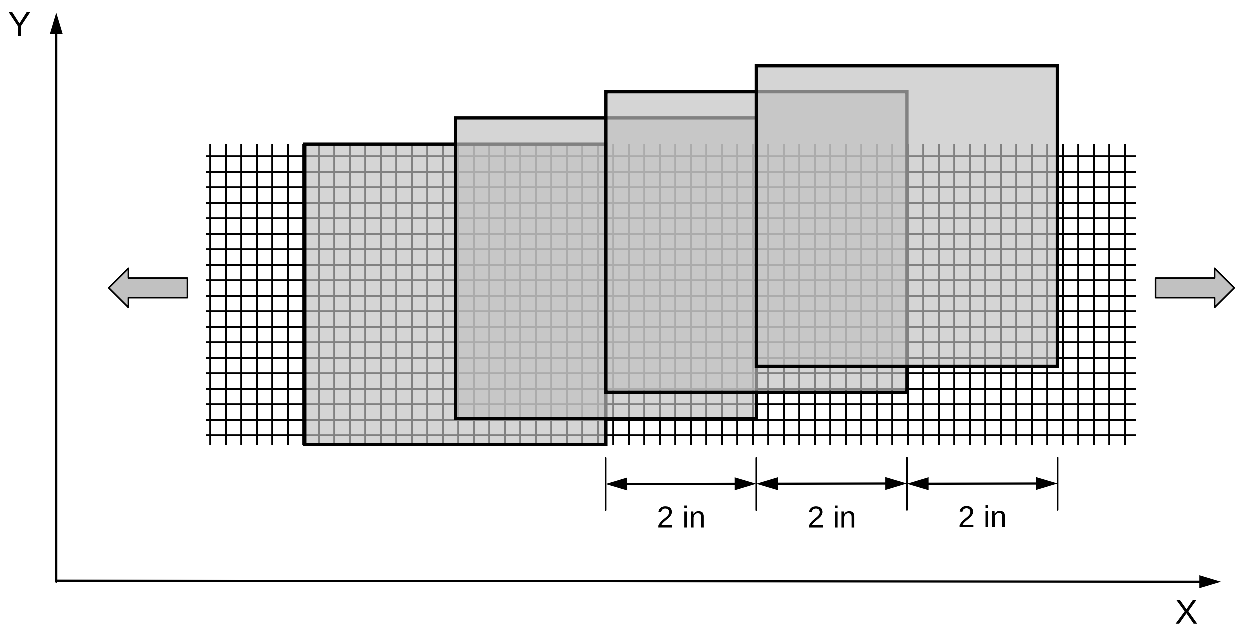


Figure B-6. Schematic representation of sequential calculation areas, each shifted 2 inches in the longitudinal direction relative to its predecessor. For illustration purposes, the calculation areas are also offset in the transverse (Y) direction; the transverse offset is not applied in the texture calculations.

Table B-1. Summary of base length, calculation area shift, and effective overlap.

Direction	Metric Type	Base Length	Shift	Effective Overlap
Longitudinal	Non-spectral	3.94 in (100 mm)	2 in (50 mm)	50 %
	Spectral	84 in (2.13 m)	2 in (50 mm)	98 %
Transverse	Non-spectral	3.94 in (100 mm)	Not applicable	Not applicable
	Spectral	Not applicable	Not applicable	Not applicable

The spatial position of the averaged longitudinal and transverse texture metric for the calculation area is considered to be at the center of the calculation area. The result is a longitudinal and transverse texture value at 2-inch (100 mm) intervals for the length of the test section.

B.8 Statistics over the Test Section

From the texture values at 2-inch intervals as described in the preceding section, statistical quantities can be calculated for the metric over the entire length of the test section. Example statistics include average, standard deviation, and 10th, 50th, and 90th percentile values.

Appendix C. Texture Metric Definitions

C.1 MPD

Mean Profile Depth calculated according to standard ISO 13473-1 [2].

Equation:

$$MPD = \frac{Peak_1 - Peak_2}{2} \tag{C-1}$$

where:
$Peak_1$ = peak texture elevation in the first half of the base length, and
$Peak_2$ = peak texture elevation in the second half of the base length.

C.2 MaxPeak, MaxValley, and MaxHeight

MaxPeak is the maximum elevation in the base length, z_{max}

MaxValley is the minimum elevation in the base length, z_{min}. The minimum peak is reported as a value less than zero.

MaxHeight is the distance from the maximum peak to the maximum valley.

$$MaxHeight = MaxPeak - MaxValley \tag{C-2}$$

C.3 RoughAvg

Average roughness given by

$$RoughAvg = \frac{\sum_{n=1}^{N} |z_n|}{N} \tag{C-3}$$

where:
z_n = elevation of sample n of the detrended texture profile,
$| \ |$ = the absolute value operator, and
N = number of samples in the base length.

C.4 RMS

Root mean square given by

$$RMS = \sqrt{\frac{\sum_{n=1}^{N} z_n^2}{N}} \qquad \text{(C-4)}$$

where:

z_n = elevation of sample n of the detrended texture profile,
N = number of samples in the base length.

C.5 Rpk, Rk, Rvk, and RkTotal

These metrics are calculated using the linear material ratio curve (or Abbott curve) as defined in ISO 13565-2: 1996 [4], Geometrical Product Specifications (GPS)-Surface Texture: Profile Method; Surfaces Having Stratified Functional Properties-Part 2: Height Characterization Using the Linear Material Ratio Curve.

One property of these metrics is that they can discriminate distinguish between positive and negative oriented texture.

Rpk = Reduced peak height.
Rk = Core roughness depth.
Rvk = Reduced valley depth.

$$RkTotal = Rpk + Rk + Rvk \qquad \text{(C-5)}$$

C.6 Skewness

Third standardized moment given by:

$$skew = \frac{\left(\sum_{n=1}^{N} z_n^3\right)/N}{\sigma^3} \qquad \text{(C-6)}$$

Where:

z_n = elevation of sample n of the detrended texture profile,
N = number of samples in the base length, and
σ = standard deviation of the profile samples in the base length (which is equal to the RMS).

C.7 Third-Octave Band Texture Levels

RMS level of the elevation profile in the third-octave band expressed as a decibel with reference of 10^{-6} m. The number in the metric name (160, 125, … 3.15) is the band center wavelength in mm. Spectral based band levels are calculated following ISO 13473-4: 2008 [5]. Frequency domain transformation is accomplished using an FFT operation with a base length equal to 7 ft (2.134 m) and Hanning window. RMS amplitudes in third-octave bands are synthesized from the resulting constant bandwidth spectrum. The conversion from RMS amplitude to decibel level is given by:

$$L_n = 10 \times Log_{10}\left(\frac{RMS_n}{10^{-6}}\right) \tag{C-7}$$

Where:

L_n = decibel level in third-octave band with center wavelength n in mm, and
RMS_n = root mean square texture in third-octave band with center wavelength n.