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Preliminary Results: Measurement of Macrotexture on Surface Treatments and Survey of Bicyclist Ride Quality on Mon-198 and SLO-1 Test Sections

August 2013

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Part of Partnered Pavement Research Program (PPRC) Strategic Plan Element 4.47:
Impact of Chip Seal on Bicyclists

PREPARED FOR:

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Abstract:
This memorandum summarizes the results of measurements of macrotexture on a set of Caltrans pavement surface treatments, and the results of bicycle vibration measurements and a survey of bicyclists ride quality on a subset of those sections. The work was performed to address concerns raised by local bicyclists regarding the ride quality after a modified binder seal coat (chip seal) was placed on State Route 1 in San Luis Obispo County (SLO-1). The subset includes test sections for various surface treatments on existing chip seals on State Route 198 in Monterey County (Mon-198) and several locations on SLO-1. Macrotexture was measured in terms of mean profile depth (MPD). Three different test methods were used to measure MPD: the sand patch method and the laser texture scanner (LTS), which provide measurements on a small area at a single location (about 12 square inches [100 square cm]); and the inertial profiler (IP), which is mounted on a vehicle and provides a continuous measurement in the longitudinal direction. Also presented are preliminary statistical correlations between macrotexture, bicycle vibration, and bicyclist ride quality for the initial set of treatment sections surveyed to date, and preliminary modeling of the relationships between macrotexture, vibration, and perceived ride quality for bicyclists. Conclusions are presented regarding the MPD values measured on various road sections including those built with two 3/8" aggregate gradation chip seal specifications (one coarser than the other), and the variability of MPD found between sections built using the coarser 3/8" aggregate grading. Conclusions are also presented regarding the three MPD measurement methods. Findings are presented regarding the MPD values from other types of treatments, including possible treatments to be placed on SLO-1 to address bicyclist ride quality issue. Results are also presented regarding the effects of trafficking on MPD values. Correlations between bicycle vibration and MPD are shown, and between MPD, bicycle vibration, and bicyclist perception of ride quality and acceptability for use by bicycles. Recommendations are made regarding the use of additional rolling to reduce the texture of chip seals built using the coarser 3/8" aggregate grading, a preliminary range of MPD values that might be used to select chip seal specifications based on “acceptability” where bicyclist ride quality is an issue, and selection of remedial treatments for SLO-1 based on the Mon-198 test sections.

Keywords: chip seal, macrotexture, bicycle vibration, bicyclist ride quality, MPD

Proposals for implementation:

Related documents:

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PROJECT OBJECTIVES

The purpose of this project is to address the impact of surface treatments, particularly seal coats (also referred to as chip seals) on bicyclists. This will be achieved in two phases with the following objectives:

- Phase I: explore and evaluate alternative solutions and provide recommendations for improving the surface texture for cyclists on a section of State Route 1 in San Luis Obispo County where a chip seal was recently placed, and
- Phase II: evaluate the specifications of current chip seal strategies for potential improvements that would consider bicycle ride quality.

The following tasks will be performed to achieve these objectives:

Phase I

Task A: Evaluate existing and alternative surface textures based on (a) measurements of macrotexture on the SLO-1 section and on other sections identified by Caltrans, and (b) a survey of bicyclists' opinions regarding ride quality on some of those sections and other test sections on State Route 198 in Monterey County to be constructed in Phase II, Task C.

Task B: Determine the effectiveness of techniques that produce smoother texture during the construction of chip seals, in particular the use of either additional rubber-tired rolling after initial construction or the use of smooth steel rollers during initial construction (current specifications allow for either rubber-tired or smooth steel rollers during initial construction).

Task C: Deliver a preliminary technical memorandum, based on the results of Phase I Tasks A and B and whatever results are available from Phase II.

Phase II

Task A: Review existing chip seal specifications, including those used in California and nationwide, and the impact on bicyclists through a literature review and measurement of macrotexture for different maintenance treatments, and how they vary with the age of the treatment for different climates and traffic levels.

Task B: Identify changes in chip seal specifications that are likely to improve bicycle ride quality while maintaining the benefits of chip seals, based on the results from Phase I and Phase II, Task A.

Task C: Assist Caltrans with decisions regarding which treatments to include in the experiment design for construction of test sections on Monterey 198.

Task D: Where possible, perform additional rider surveys at organized ride events, including these:

- Best Buddies event in San Luis Obispo County on September 7, 2013
- Tour of Tahoe event in El Dorado and Placer counties on September 8, 2013
- Smaller rides organized by the following bicycle clubs in August and September 2013
    - Chico Velo Cycling Club in Butte County
    - Davis Bicycle Club in Solano and Yolo counties
    - Santa Rosa Cycling Club in Sonoma County
    - Alto Velo Racing Club and Silicon Valley Bicycle Coalition in Santa Clara County

Task E: Deliver a final report that documents the research effort, including appropriate recommendations to improve the use of chip seal surface treatment for bicycle users.

This technical memorandum documents the results of initial macrotexture measurements and bicycle vibration measurements, and of a survey given to volunteer bicyclists, including the results from Phase I Tasks A, B (except for one type of macrotexture not performed yet due to equipment malfunction), and C; the Phase II Task A literature review of pavement texture and survey of bicyclist ride quality; and Phase II, Task C.

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
Caltrans	California Department of Transportation
ETD	Estimated Texture Depth
ETW	Edge of Traveled Way
IP	Inertial Profiler
LTS	Laser Texture Scanner
MPD	Mean Profile Depth
MTD	Mean Texture Depth
SP	Sand Patch method

LIST OF TEST METHODS AND SPECIFICATIONS

ASTM E965-96 (2006)	Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique
ASTM E2157-09	Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter
ASTM E2380-09	Standard Test Method for Measuring Pavement Texture Drainage Using an Outflow Meter
ASTM E1845-09	Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	Km
		AREA		
in^2	square inches	645.2	Square millimeters	mm^2
ft^2	square feet	0.093	Square meters	m^2
yd^2	square yard	0.836	Square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	Square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	Grams	g
lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	Inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	Poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (Revised March 2003).

1 INTRODUCTION

1.1 Background

In 2012, the California Department of Transportation (Caltrans) placed a modified-binder seal coat (aggregate seal coats are also known as "chip seals") on State Route 1 (05-SLO-1-51.3/74.3; Contract No. 05-0T4004) between the city of Cambria and the San Luis Obispo (SLO)/Monterey (Mon) County Line. Construction began in September and concluded at the end of November. The chip seal was placed on the entire width of the pavement, including lanes and shoulders, between postmiles 51.3 and 74.3 except for a few locations, such as on bridges and the entrance to Hearst Castle. In this technical memorandum, this section is referred to as "SLO-1." References to other state highway sections in this memorandum follow the same naming convention, using their county abbreviation and route number.

The chip seal was placed as a preventive maintenance strategy to extend the service life of the existing pavement and to protect against water intrusion and further oxidation. In 1991, a hot-applied chip seal was placed along this entire stretch of highway.

In January 2013, shortly after completion of the chip seal construction, bicyclists using that section of SLO-1 alerted Caltrans about what they perceived as poor ride quality within the project limits.

To address this issue, the Caltrans District 5 Division of Maintenance worked with the Division of Maintenance Office of Asphalt Pavement and the Division of Research, Innovation, and System Information. The Office of Asphalt Pavement and District 5 prepared a scoping document titled "Chip Seal for Highway Including Bicycle Users" on January 24, 2013. Caltrans then requested that the University of California Pavement Research Center (UCPRC), through the Caltrans/UCPRC Partnered Pavement Research Center program, prepare a research work plan in response to the scoping document. The UCPRC developed a work plan titled "Impact of Chip Seal on Bicyclists," and a final version was approved by Caltrans on March 27, 2013. This work plan was updated on July 17, 2013 to include additional pavement sections and bicyclist surveys.

1.2 Objectives

The purpose of this project is to address the impact of the chip seals on bicyclists. This will be achieved in two phases with the following objectives:

- Phase I: explore and evaluate alternative solutions and provide recommendations for improving the surface texture for cyclists between postmiles 51.3 and 74.3 of State Route 1 in San Luis Obispo County where a chip seal was recently placed, and
- Phase II: evaluate the specifications of current chip seal strategies for potential improvements that would consider bicycle ride quality.

1.3 Approach

The following tasks will be performed to achieve the objectives:

Phase I

Task A: Evaluate existing and alternative surface textures based on (a) measurements of macrotexture on the SLO-1 section and on other sections identified by Caltrans, and (b) a survey of bicyclists' opinions regarding ride quality on some of those sections and other test sections on State Route 198 in Monterey County to be constructed in Phase II Task C.

Task B: Determine the effectiveness of techniques that produce smoother texture during the construction of chip seals, in particular the use of either additional rubber-tired rolling after initial construction or the use of smooth steel rollers during initial construction (current specifications allow for either rubber-tired or smooth steel rollers during initial construction).

Task C: Deliver a preliminary technical memorandum, based on the results of Phase I Tasks A and B, and whatever results are available from Phase II.

Phase II

Task A: Review existing chip seal specifications, including those used in California and nationwide, and their impact on bicyclists through a literature review and measurement of macrotexture for different maintenance treatments, and how they vary with the age of the treatment for different climates and traffic levels.

Task B: Identify changes in chip seal specifications that are likely to improve bicycle ride quality while maintaining the benefits of chip seals, based on the results from Phase I and Phase II Task A.

Task C: Assist Caltrans with decisions regarding which treatments to include in the experiment design for construction of test sections on Monterey 198.

Task D: Where possible, perform additional rider surveys at organized ride events, including these:

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  - Santa Rosa Cycling Club in Sonoma County
  - Alto Velo Racing Club and Silicon Valley Bicycle Coalition in Santa Clara County

Task E: Deliver a final report that documents the research effort, including appropriate recommendations to improve the use of chip seal surface treatment for bicycle users.

1.4 Scope of Technical Memorandum

This technical memorandum documents the results from Phase I Tasks A, B, and C, and Phase II Tasks A and C. Preliminary recommendations for Phase II Task B are also included.

Chapter 2 presents the results of an initial literature review that covers basic pavement surface texture concepts, typical texture characteristics and ranges for several types of asphalt surfaces built by Caltrans in the past, and a review of the available literature regarding pavement surface texture and bicyclist ride quality. Chapter 3 describes the test sections and experimental methods used for the field measurements on surface treatments, including the measurement methods for pavement macrotexture and bicycle vibration, and the survey form used to evaluate bicyclists ride quality for the initial surveys on SLO-1 and Mon-198. Chapter 4 presents the results and analyses of the pavement surface macrotexture measurements, including the results of bicycle vibration and bicyclist ride quality surveys on Mon-198 and SLO-1. Chapter 5 presents conclusions and recommendations. The appendices contain detailed results and statistical analyses of field measurements and the bicyclist ride quality surveys.

2 INITIAL LITERATURE REVIEW

2.1 Pavement Texture Measurement and Ride Quality

Pavement surface texture is an important characteristic that influences ride quality. There are four components of pavement surface texture that are defined based on the maximum dimension (wavelength) of their deviation from a true planar surface: roughness (unevenness), megatexture, macrotexture, and microtexture. The definition of each component is shown in Figure 2.1 (*1*).

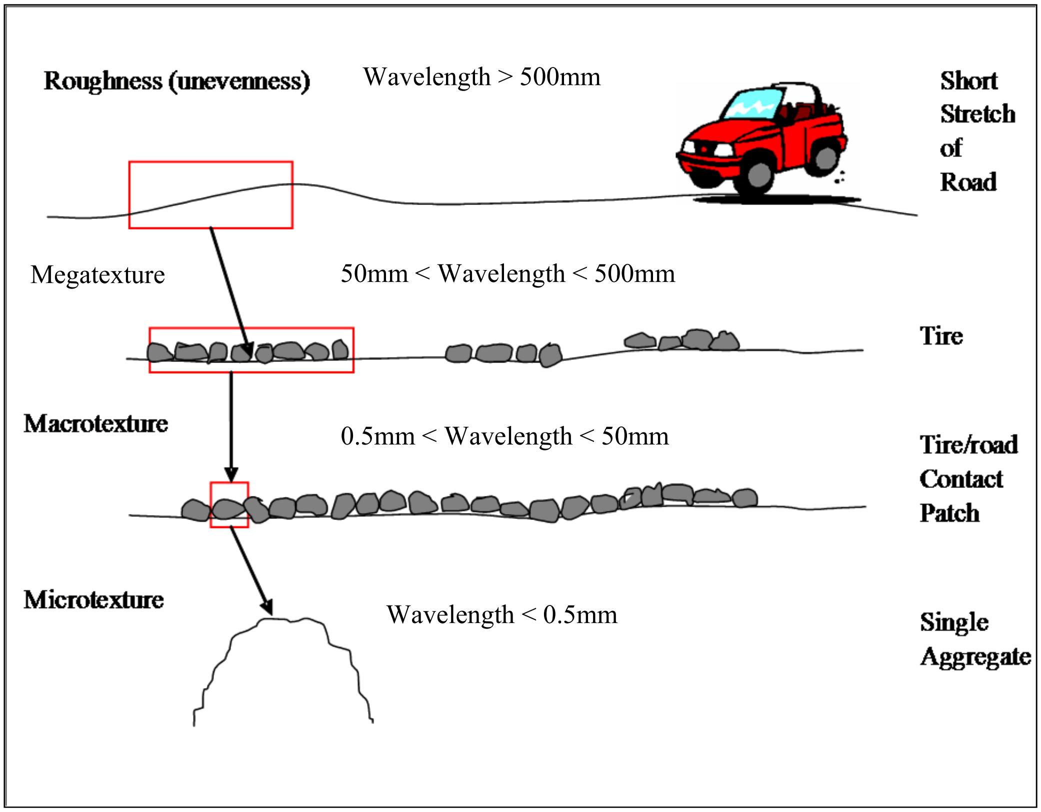


Figure 2.1: Pavement surface texture components and their wavelengths (*1*).
(Note: 500 mm = 1.64 ft, 50 mm = 0.164 ft or 2.0 in., 0.5 mm = 0.02 in.)

Figure 2.2 shows the relationship among the four components and their influence on the functional performance of pavement. The figure notes that vehicle ride quality is primarily affected by megatexture and roughness; for bicycles, however, an examination of macrotexture might be more critical as the surface texture in this range of wavelengths is most likely to directly affect the ride quality through vibration.

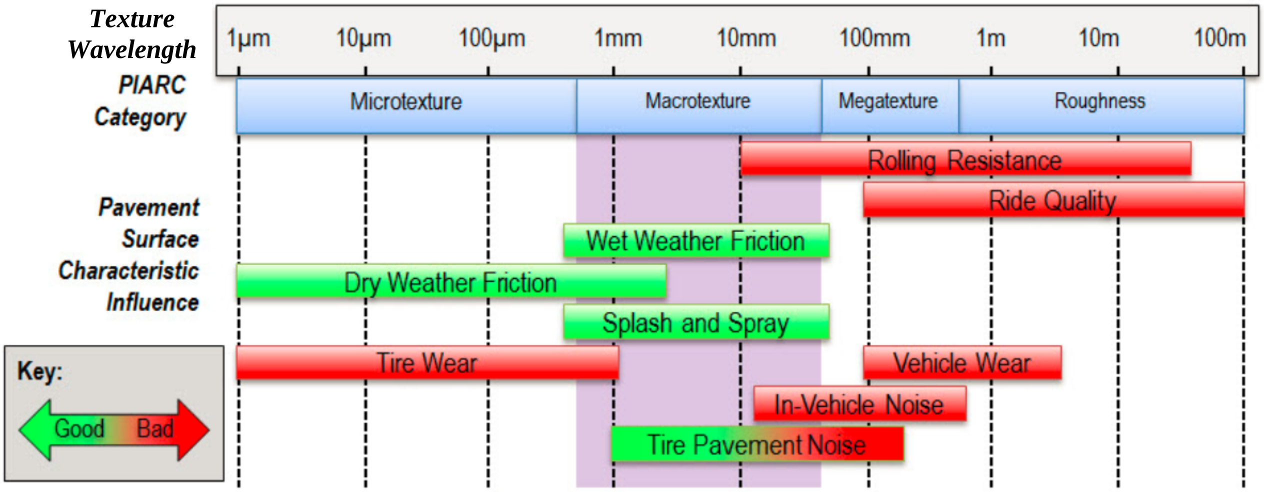


Figure 2.2: Influence of pavement surface texture components on functional performance (*1*).

Macrotexture is typically measured in terms of the mean profile depth (MPD) or mean texture depth (MTD), which are closely related parameters. Different methods can be used to measure MPD and MTD, including the Sand Patch method (SP, ASTM E965), or use of the Outflow Meter (OM, ASTM E2380), the Laser Texture Scanner (LTS, ASTM E2157/ASTM E1845), or the Inertial Profiler (IP, ASTM E1845).

As background, the pavement surface macrotexture in terms of MPD for most hot-mix asphalt (HMA) materials used on California state highways typically ranges from approximately 0.5 mm to 1.5 mm, as shown in Figure 2.3, with the macrotexture of some large-stone open-graded materials (F-mixes) that were used for a time on the North Coast going up to approximately 2.0 mm (*5*). Generally, the surface macrotexture of in-service asphalt pavements with hot-mix asphalt surfaces increases with time (*5*) due to raveling (loss of fines around large aggregates) from traffic, oxidation of the asphalt, and rainfall, as shown in Figure 2.4. The figure also shows that for some materials there may be an initial reduction in MPD after construction, which is due to embedment and polishing of surface aggregates.

Measurements of MPD have not been made on the surface treatments (different types of chip seals, microsurfacings, slurry seals, cape seals) used on California state highways. However, these technologies can be applied to pavement with surface treatments and are used in this study for assessing bicyclist ride quality.

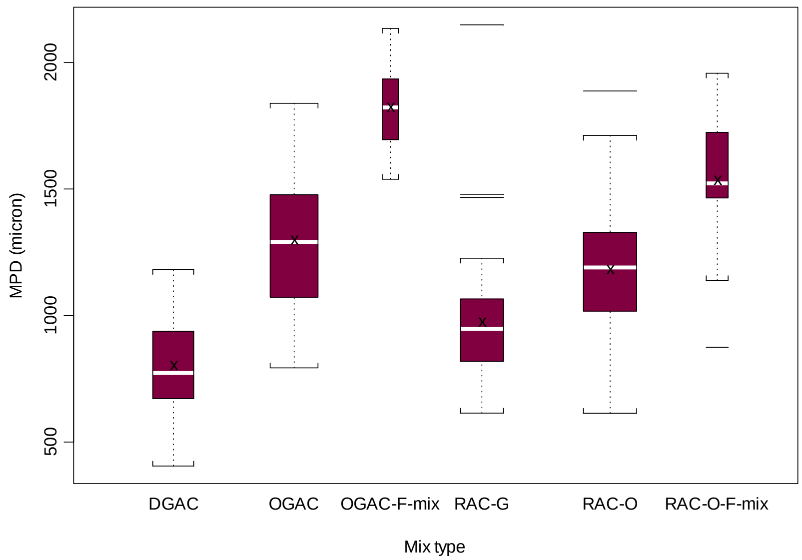


Figure 2.3: Pavement macrotexture (MPD) ranges for different hot-mix asphalt mixture types considering all ages from new to 16 years of service (*5*).

Notes on Figure 2.3:

1. DGAC is conventional dense-graded asphalt concrete (currently called hot-mix asphalt, HMA), OGAC is conventional or polymer-modified open-graded asphalt concrete, OGAC-F mix is large-aggregate Oregon F-type open-graded asphalt concrete, RAC-G is rubberized gap-graded asphalt concrete (currently called RHMA-G), RAC-O is rubberized open-graded asphalt concrete (currently called RHMA-O), and RAC-O-F is rubberized F-type open-graded asphalt concrete.
2. 1,000 microns = 1 millimeter. Both units are typically used for MPD.
3. MPD measurements were made with an inertial profiler measuring in the right wheelpath.
4. The center line is the mean value, the "x" is the mean value, the colored box indicates the 25^{th} and 75^{th} percentiles (first and third quartiles, Q1 and Q3), the brackets are the minimum and maximum values except for outliers, and the additional lines are outliers defined as being more than 1.5 x (Q3-Q1).

2.2 Cycle Vibration and Bicyclist Ride Quality

A few studies about bicycle vibration were found in the literature. However, these studies mostly focused on the vibration-caused damage to bicycle frames and handlebars and on optimal frame designs for mountain bicycles and other off-road bicycles (*6-10*). No studies were found in the available literature regarding the relationship between bicyclist ride quality and bicycle vibration.

2.3 Pavement Macrotexture and Bicyclist Ride Quality

Many studies were found that investigated the interactions of human behavior regarding transportation mode choice (car versus bicycle) considering variables such as typical vehicle speeds, vehicle traffic flow, road width, availability of bicycle paths, etc. (*11-13*). No specific data were found in the literature regarding the effect of bicycle vibration on bicyclist ride quality as caused by pavement macrotexture and their effect on mode choice.

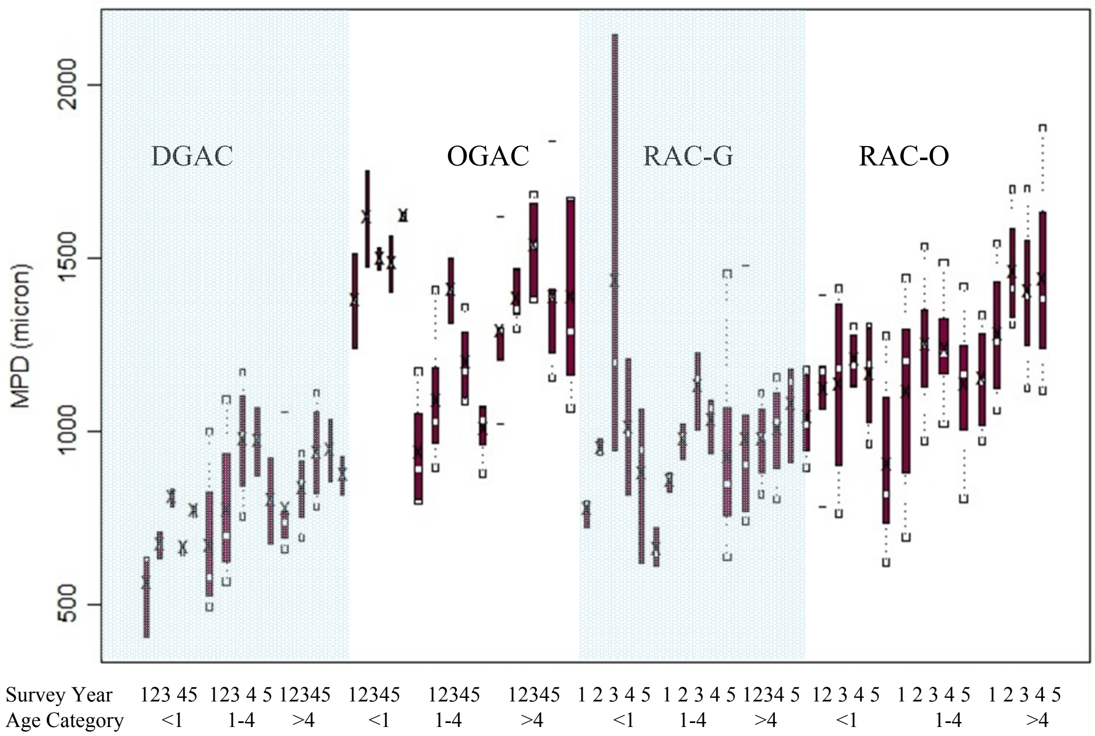


Figure 2.4: Comparison of MPD values for four commonly used asphalt surface mix types in California for different initial age categories (age category, survey years) and for five years of data collection (*5*).

Notes on Figure 2.4:

1. The Survey Year is the year of measurement, and five surveys were performed over the past eight years.
2. The Age category represents the number of years that the surface type was in service at the time of the first-year survey.

3 SURFACE TEXTURE MEASUREMENT AND BICYCLIST SURVEY

3.1 Road Sections Used for Macrotexture Measurements and Bicyclist Survey

Table 3.1 shows a list of road sections used for macrotexture measurements and/or bicyclist surveys, including the measurement method and the timing of the measurements. The geographic distribution of the road sections around the state is shown in Figure 3.1. Figure 3.2 to Figure 3.5 show the measurement locations on subsections of SLO-1 and Mon-198.

Table 3.1: Road Sections Used in the Study

Section	Treatment	Measurement Subsections	Measurements		Bicyclist Survey
			MPD	Bicycle Vibration	
SLO-1	3/8" modified binder chip seal		IP, LTS, SP April 2013 (Figure 3.2)	July 2013, Cambria to Piedras Blancas	
		Additional rolling subsection	IP, LTS, SP April – May 2013 (Figure 3.2)		
		Bicycle survey subsections		July 12, 2013, with multiple bicyclists; July 23, 2013, with single bicyclist, multiple speeds, pressures (Figure 3.3)	July 2013
Mon-198	3/8" modified binder chip seal		IP, LTS, SP April 2013 (Figure 3.4)		
		Treatment test sections	LTS July 2013 (Figure 3.5)	July 13, 2013, with multiple bicyclists; July 23, 2013, with single bicyclist, multiple speeds, pressures	July 2013
SLO-41	Microsurfacing		IP, LTS, SP April 2013		
SLO-227	3/8" modified binder chip seal		IP, LTS, SP April 2013		
Mono-395	3/8" asphalt rubber (AR) chip seal		IP, LTS, SP April 2013		

Note on Table 3.1:

1. MPD macrotexture measurement method: IP = inertial profiler; LTS = laser texture scanner; SP = sand patch

Figure 3.1: Geographic distribution around the state of road sections used in the study.

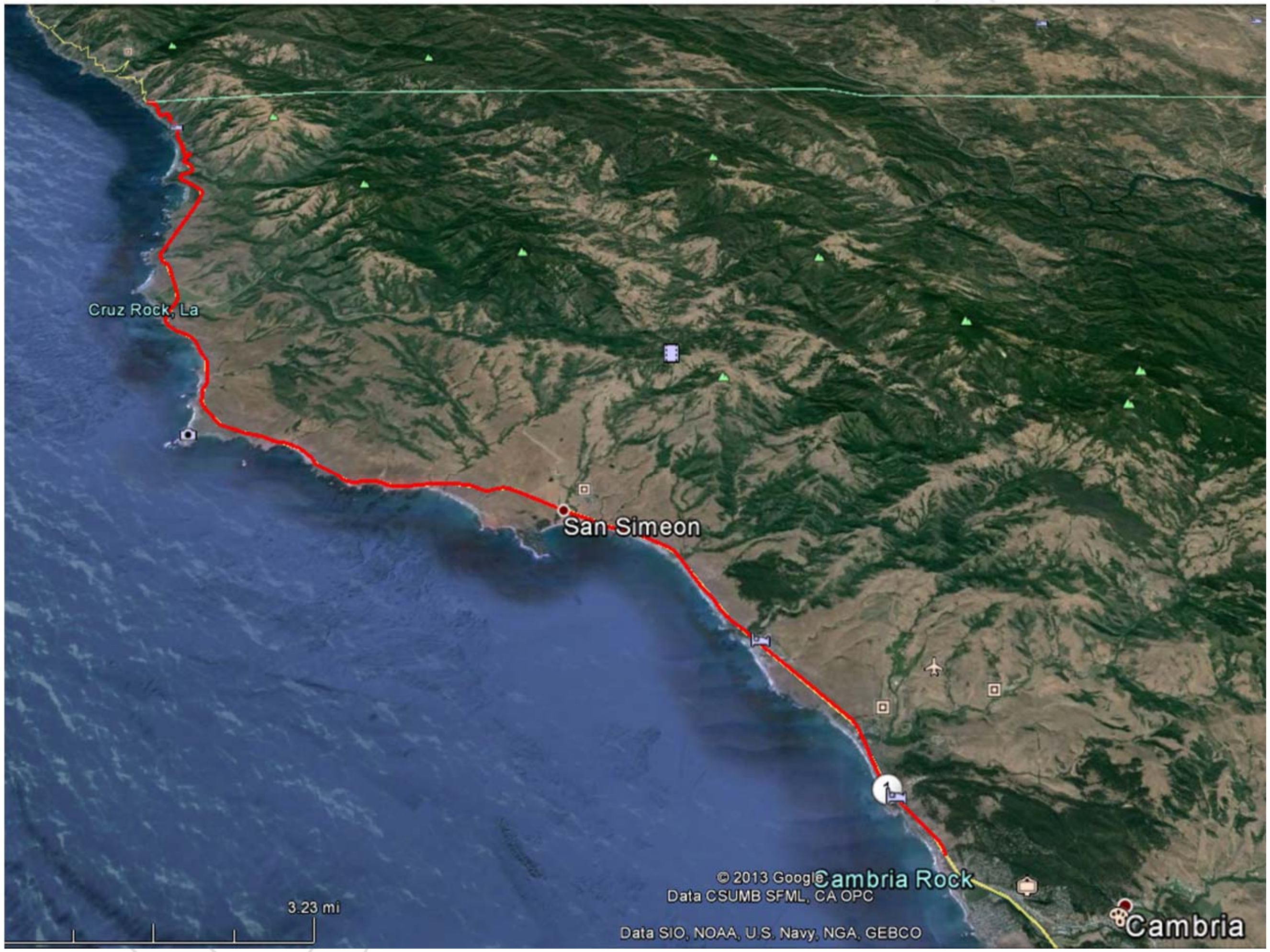


Figure 3.2: Section for MPD measurement with inertial profiler on SLO-1 (PM 51.3 – PM 74.3).

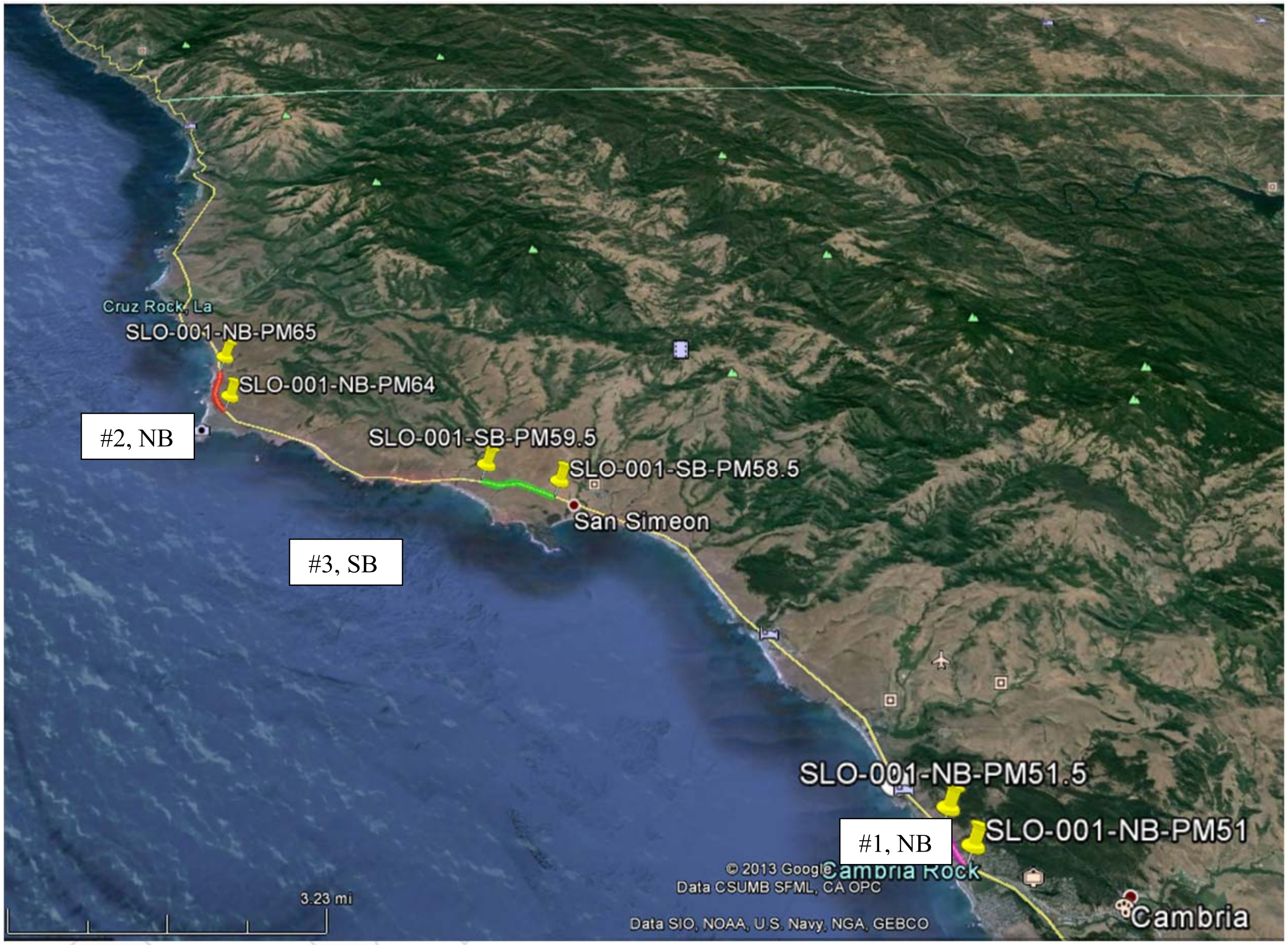


Figure 3.3: Subsections on SLO-1 used for the three bicycle ride quality surveys.

Section #1, *Northbound (NB)*, PM 51 to PM 52.5

(PM 51 is about 0.05 miles south of Weymouth Street in Cambria.)

Section #2, *Northbound (NB)*, PM 64 to PM 65

(PM 64 is about 0.25 miles north of the driveway to the lighthouse.)

Section #3, *Southbound (SB)*, PM 59.5 to PM 58.5

(PM 59.5 is southbound between section #1 and section #2, north of San Simeon Bay and north in front of the Castle.)

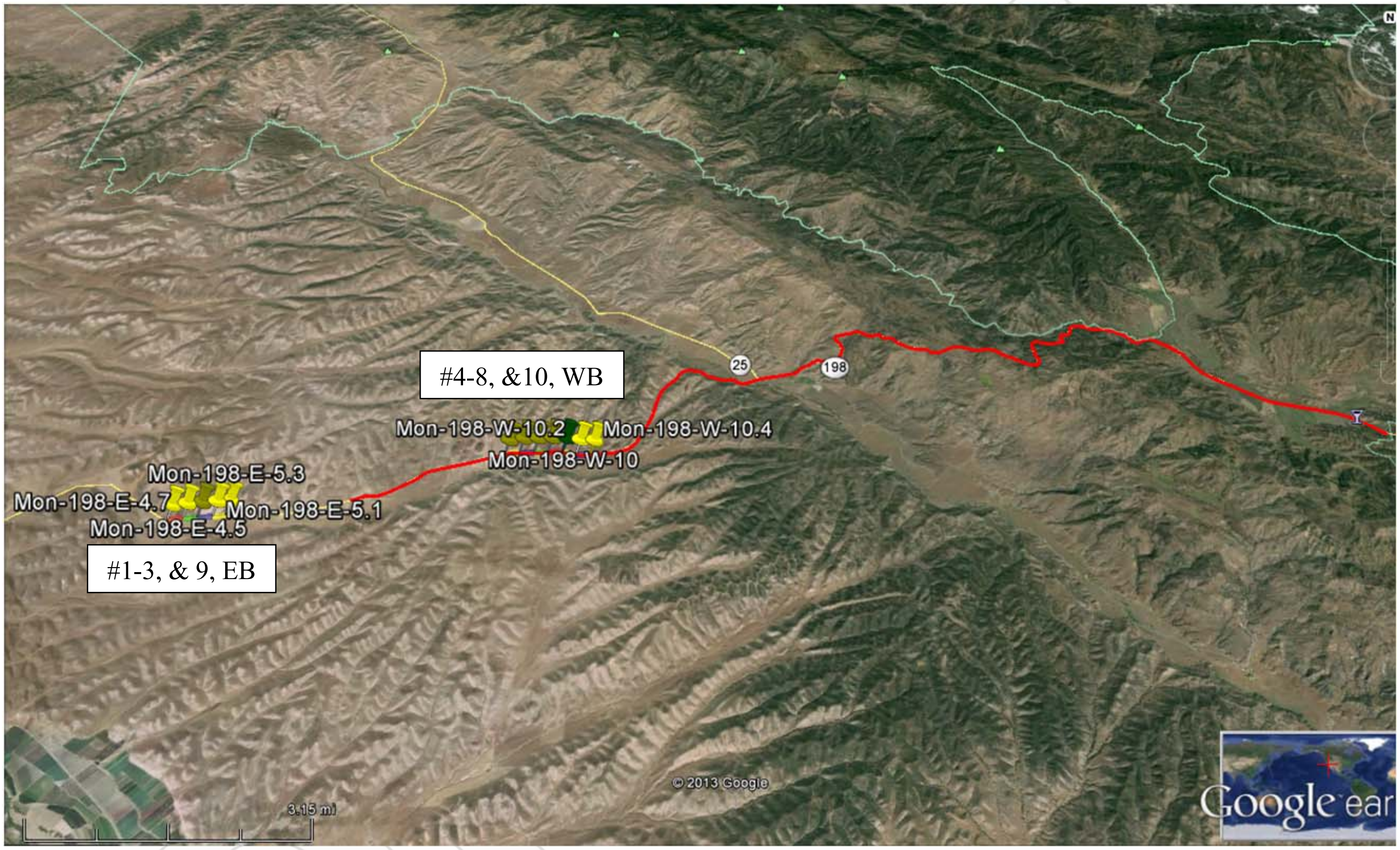


Figure 3.4: Section for MPD measurement with inertial profiler on Mon-198 (PM 7.0 – PM 25.8, in red line), also showing locations of treatment test subsections.

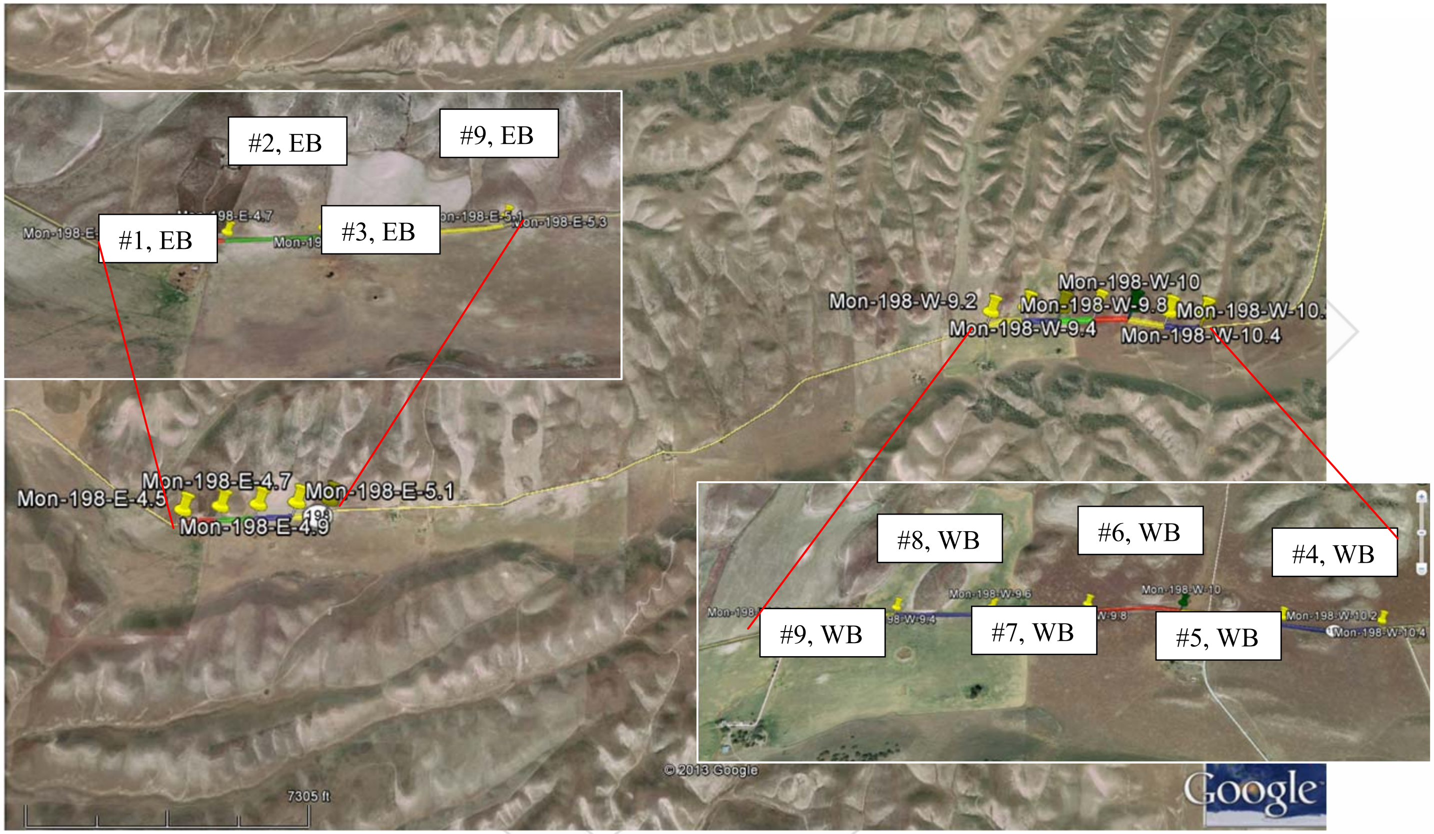


Figure 3.5: Treatment test section locations on Mon-198.
(See Table 3.4 for section details.)

Section #1, *Eastbound (EB)*, PM 4.5 to PM 4.7

Section #2, *Eastbound (EB)*, PM 4.7 to PM 4.9

Section #3, *Eastbound (EB)*, PM 4.9 to PM 5.1

Section #9, *Eastbound (EB)*, PM 5.1 to PM 5.3 (HMA placed in 2000)

Section #4, *Westbound (WB)*, PM 10.4 to PM 10.2

Section #5, *Westbound (WB)*, PM 10.2 to PM 10.0

Section #6, *Westbound (WB)*, PM 10.0 to PM 9.8

Section #7, *Westbound (WB)*, PM 9.8 to PM 9.6

Section #8, *Westbound (WB)*, PM 9.6 to PM 9.4

Section #10, *Westbound (WB)*, PM 9.4 to PM 9.2 (new chip seal on Mon-198 [Control])

Table 3.2 provides the locations and some construction information about the road sections on which macrotexture was measured. The aggregate (also referred to as "screenings") gradation ranges specified for each section are shown in Table 3.3.

The binder used for the chip seals on SLO-1, Mon-198, and SLO-227 is called a "modified binder" that meets a non-Standard Special Provision (nSSP). In the nSSP, the binder used is referred to as a PG 76-22TR and consists of base asphalt modified with scrap tire crumb rubber (10 percent by weight minimum) and polymer. The binder used for the chip seal on Mono-395 was asphalt rubber binder with a PG 64-28 base binder. Asphalt rubber binder must contain between 18 and 22 percent crumb rubber modifier (CRM), with CRM required to contain 75.0 ± 2.0 percent scrap tire rubber and 25.0 ± 2.0 percent high natural rubber by total weight of CRM. Scrap tire crumb rubber must be from any combination of automobile tires, truck tires, or tire buffings.

Although a 3/8" chip seal is shown for all of the chip seal projects shown in Table 3.2, two gradation specifications were used. As can be seen in Table 3.3, the gradation used on SLO-1, Mon-198, and Mono-395 was coarser than that used on SLO-227. The 3/8" seal coat specification used on SLO-227 when it was built in 2009 followed the Caltrans 2006 Standard Specifications for the "Medium 3/8" max" gradation specification. The 3/8" aggregate gradation used on SLO-1, Mon-198, and Mono-395 was part of a non-Standard Special Provision for Modified Binder Seal Coat when it was built in 2012. Because of the potential for confusion in naming of the two gradations used on SLO-227 and the other three projects, and changes in naming over time, the finer gradation used on SLO-227 is referred to in the rest of this technical memorandum as the "finer 3/8" gradation," and the coarser gradation[1] used on SLO-1, Mon-198, and Mono-395 is referred to as the "coarser 3/8" gradation." SLO-41 used a microsurfacing, which is a dense-graded seal coat with a finer gradation than the chip seals, as can be seen in Table 3.3.

The details of the test sections used for the Phase I bicyclist ride quality survey on Mon-198 and SLO-1 are summarized in Table 3.4, and the gradations for the Mon-198 treatments for which information was available are shown in Table 3.5.

[1] The coarser gradation used on SLO-1, Mon-198, and Mono-395 is now included in the Caltrans Revised Standard Specifications (July 19, 2013 version). The Revised Standard Specifications include gradations for three types of binders, adding new gradations for chip seals with asphalt rubber binder in addition to those for asphaltic emulsion and polymer-modified asphaltic emulsion binders called out in the 2010 Standard Specifications. In the Revised Standard Specifications the gradation used on SLO-1, Mon-198, and Mono-395 is referred to as "Fine 3/8" max Asphalt Rubber Seal Coat Screenings Gradation."

Table 3.2: Phase I Test Section Locations and Construction Information

Road	Treatment	Binder Type	Binder Grade	Aggregate Gradation[a]	Postmiles (mile)	Location [b]	Embedment Rolling Type	Year of Construction
SLO-1	3/8" modified binder seal coat[d]	Modified binder[h]	PG 76-22TR	Coarser 3/8"	51.4 – 70.8	Shoulders, outer wheelpaths	Rubber tire with additional rubber tire rolling on short section	2012
Mon-198	3/8" modified binder seal coat[e]	Modified binder[h]	PG 76-22TR	Coarser 3/8"	7.0 – 25.8	Shoulders, outer lanes	Rubber tire	2012
Mon-198 test sections and control sections	Test sections, chip seal control	See Table 3.4		See Table 3.5	4.5 – 5.1 9.4 – 10.4	Shoulders [c], inner wheelpaths[c]	Various	2013 for test sections, 2012 for new chip control, 2000 for previous HMA overlay
SLO-41	Microsurfacing	Microsurfacing emulsion		Microsurfacing Type II	R15.96 – R18.08	Shoulders, outer wheelpaths	—	2011
SLO-227	3/8" modified binder seal coat[f]	Modified binder[h]	PG 76-22TR	Finer 3/8"	0.9 – 7.1	Shoulders, outer wheelpaths	Rubber tire	2009
Mono-395	3/8" asphalt rubber seal coat[g]	Asphalt rubber	PG 64-28 base asphalt	Coarser 3/8"	12.6 – 35.3 and 40.1 – 44.9	Shoulders, outer wheelpaths	Rubber tire with steel roller on short section	2012

[a] See Table 3.3 for aggregate gradation bands for all sections other than Mon-198 test sections.
[b] Mostly measured at 6 inches (150 mm) inside and outside the Edge of Traveled Way (ETW), which is the white stripe separating the outside lane and the shoulder.
[c] Laser texture scanner only at this time. Continuous measurements with inertial profiler will be completed as soon as texture laser repairs are completed.
[d] Caltrans, "Notice to Bidders and Special Provisions," Contract No. 05-0T4004, Standard Specifications dated 2006. Bids opened March 2012.
[e] Caltrans, "Notice to Bidders and Special Provisions," Contract No. 05-1A4204, Standard Specifications dated 2006. Bids opened March 2012.
[f.] Caltrans, "Notice to Bidders and Special Provisions," Contract No. 05-0Q9504, Standard Specifications dated 2006. Bids opened January 2009.
[g.] Caltrans, "Notice to Bidders and Special Provisions," Contract No. 09-347404, Standard Specifications dated 2006. Bids opened April 2011.
[h.] Modified binder suppliers required to certify 10 percent minimum tire rubber modifier in binder.

Table 3.3: Gradation Bands for Various Treatments for Different Projects

Sieve Sizes		Percentage Passing		
		Chip Seals		Microsurfacing
mm	(in.)	SLO-227 3/8" [a]	SLO-1, Mon-198, Mono-395 3/8" [b]	SLO-41 (Microsurfacing Type II)[c]
19	3/4"	---	100	-
12.5	1/2"	100	95 – 100	-
9.5	3/8"	85 – 100	70 – 85	100
4.75	No. 4	0 – 15	0 – 15	94 – 100
2.36	No. 8	0 – 5	0 – 5	65 – 90
1.15	No. 16			40 – 70
0.6	No. 30			24 – 50
0.075	No. 200	0 – 1	0 – 1	5 – 15

[a] 2006 Standard Specifications "Medium 3/8" max" screenings gradation for polymer-modified emulsion; referred to in this technical memorandum as "finer 3/8" gradation."

[b] nSSP for modified-binder seal coats and also included in Revised Standard Specifications (19 July 2013) as "Fine 3/8" max" for Asphalt Rubber Seal Coats; referred to in this technical memorandum as "coarser 3/8" gradation."

[c] 2010 Standard Specifications

Table 3.4: Details of Test Sections on Mon-198 and SLO-1 Used for Bicycle Ride Quality Surveys

Treatment #	Route	PM	Treatment Type	Survey Section No.	
				EB* or NB	WB or SB
1	Mon-198	PM 4.5/4.7	5/16" PME seal coat	1	6
2	Mon-198	PM 4.7/4.9	Modified-binder seal coat — 3/8" Modified gradation	2	5
3	Mon-198	PM 4.9/5.1	Modified-binder seal coat — Utilizing a steel roller	3	4
—	Mon-198	***PM 5.1/9.4***	***Existing surface; no treatment***	—	—
8	Mon-198	PM 9.4/9.6	Slurry seal	12	11
7	Mon-198	PM 9.6/9.8	Sand seal	13	10
6	Mon-198	PM 9.8/10.0	1/4" PME seal coat — Second application of a double chip seal	14	9
5	Mon-198	PM 10.0/10.2	Microsurfacing	15	8
4	Mon-198	PM 10.2/10.4	Cinder seal	16	7
9	Mon-198	PM 5.1/5.3	HMA overlay placed in 2000	17	18
10	Mon-198	PM 9.2/9.4	New coarser 3/8" chip seal on Mon-198, same as treatment #3 except with rubber-tired roller (Control)	20	19
11	SLO-1	PM 51.0/51.5	New 2012 chip seal on SLO-1 (Control)	21	
11	SLO-1	PM 64.0/65.0	New 2012 chip seal on SLO-1 (Control)	22	
11	SLO-1	PM 58.5/59.5	New 2012 chip seal on SLO-1 (Control)		23

*****Notes: EB = eastbound direction, WB = westbound direction, SB = southbound direction, NB = northbound direction.
PME = polymer-modified emulsion

Table 3.5: Gradation Bands for Various Treatments (#) for Different Test Sections on Mon-198

Sieve Sizes		Percentage Passing							
mm	(in.)	Chip Seals					Double Chip Seal		
		5/16" PME Seal Coat (#1)[a]	Modified-Binder Seal Coat —3/8" Modified Gradation (#2)[b]	Modified-Binder Seal Coat —Using a Steel Roller (#3)[c]	Cinder seal (#4)[b]	Micro-surfacing (#5)[d]	1/4" PME Seal Coat - Second Application of a Double Chip Seal (#6)[e]	Sand Seal (#7)[f]	Slurry Seal (#8)[d]
19	3/4"	-	-	100	-		-	-	
12.5	1/2"	-	100	95 – 100	-		-	-	
9.5	3/8"	100	90 – 100	70 – 85	-	100	100	100	100
4.75	No. 4	0 – 50	0 – 15	0 – 15	-	94 – 100	60 – 85	95 – 100	94 – 100
2.36	No. 8	0 – 15	0 – 5	0 – 5	100	65 – 90	0 – 25	65 – 95	65 – 90
1.18	No. 16	0 – 5	-	-		40 – 70	0 – 5	-	40 – 70
0.6	No. 30	0 – 3	-	-		25 – 50	0 – 3	-	25 – 50
0.15	No. 100	-	-	-			—	2 – 12	
0.075	No. 200	0 – 2	0 – 1	0 – 1		5 – 15	0 – 2	0 – 8	5 – 15

[a] From 2010 Standard Specifications per Mon-198 special provisions.
[b] From Mon-198 special provisions.
[c] Coarser 3/8 gradation" also used on SLO-1, Mono-395 from nSSP, now in Revised Standard Specifications (July 19, 2013)
[d] 2010 Standard Specifications
[e] Assumed to be from 2010 Standard Specifications
[f] From Standard Specifications 90-1.02C(4)(c) Fine Aggregate Grading

3.2 Macrotexture Measurement Methods

In this study, macrotexture measurements were taken using the sand patch (SP) method, the laser texture scanner (LTS), and the inertial profiler (IP).

The sand patch and LTS tests are performed on a small patch of pavement less than 8 inches by 8 inches square, and they measure macrotexture over that small two-dimensional area. In the sand patch test, sand is spread over the pavement and then scraped flat. The volume of sand that it took to fill the surface voids and the area of the sand-filled surface are measured to provide a measure of the texture in terms of Mean Texture Depth (MTD). The LTS consists of a laser mounted in a small box that moves back and forth over the surface and provides a three-dimensional image used for calculating macrotexture in terms of Mean Profile Depth (MPD). The inertial profiler measurement is performed using a high-speed spot laser mounted on a vehicle operating at highway speed. The IP provides a one-dimensional measure of the pavement surface in the wheelpath measured at high speed (approximately 64 Hz) that is used to calculate macrotexture in terms of MPD. Table 3.6 summarizes the measurement equipment and the standards used.

Table 3.6: Summary of Measurement Methods for Pavement Surface Characteristics Used in This Study

Method	Equipment	Standard	Index	Operational Notes	Sample Size Notes
Sand Patch	Spreader disc and sand	ASTM E965	MTD	Requires traffic closure, takes about 20 minutes for one test	Single location measurement
Laser Texture Scanner	Moving laser	ASTM E1845/ ASTM E2157	MPD/MTD	Requires traffic closure, takes about 20 minutes for one test	Single location measurement
Inertial Profiler	High speed laser	ASTM E1845	MPD/ MTD	Performed using equipment mounted on vehicle operating at highway speeds	Continuous measurement

Note: MPD is mean profile depth, MTD is mean texture depth.

It can be seen from Table 3.6 that MTD and the MPD are the primary indices used to characterize macrotexture. In a study performed by the Permanent International Association of Road Congresses (PIARC), it was found that both volumetric MTD and MPD are highly correlated with the speed constant (SP) of the International Friction Index (IFI) (*13*). To allow conversions to either of these macrotexture indices, the following relationships were developed (*14*):

For estimating MTD from Circular Texture Meter (CTM)-derived measurements of MPD (ASTM E2157):

$$EMTD = 0.947 \times MPD + 0.069 \text{ (mm)} \qquad \textbf{(3.1)}$$

For estimating MTD from inertial profiler-derived measurements of MPD (ASTM E1845):

$$EMTD = 0.80 \times MPD + 0.20 \text{ (mm)} \qquad \textbf{(3.2)}$$

3.3 Bicycle Vibration Measurement Method

3.3.1 Instrumentation

Each bicycle used to measure bicycle vibration on the SLO-1 and Mon-198 sections was instrumented with a three-axis accelerometer (Model X16-1C, Golf Coast Data Concepts) and a GPS receiver (PHAROS iGPS-500). Depending on the space available on each particular bicycle, the accelerometer was mounted with its base either parallel to or normal to the ground when the bicycle was in an upright position. The objective was to have one of the three axes measuring accelerations in the direction normal to the ground. The accelerometer took samples at 200 Hz, while the GPS was set to record the location and speed of the bicycle every second. Figure 3.6 shows a bicycle instrumented with accelerometers at three typical mounting positions, with a GPS unit on the handle bar.

The data from the accelerometer and GPS were synchronized using their respective time stamps. Riders were asked to stop for 10 seconds at each section boundary when evaluating the continuous test sections on Mon-198. This rest period between test sections permitted accurate synchronization of accelerometer data and GPS data even if the time stamp on the accelerometer was off by several seconds.

Some acceleration data collected using an Apple iPhone were also obtained from one of the volunteers who participated in the Mon-198 survey. Those data have not yet been compared with the results presented in this memorandum. Acceleration data have also been collected using the inertial profiler but they have not yet been compared with the vibration measurements included in this memorandum.

Figure 3.6: Bicycle instrumented with accelerometers (red circles) at three typical mounting locations and a GPS unit on the handle bar (blue circle).

3.3.2 Data Processing Procedure

For this study, bicycle vibration is represented by the average acceleration measured in the direction normal to the ground. The following procedure was followed to process the data and determine the bicycle vibration for any given road segment:

1. Synchronize bicycle speed (from GPS) and vibration data (from accelerometer) using the time stamps, and apply offset to the time stamp of the vibration data when necessary.
2. Find the start and end times for a given test section using GPS location.
3. Extract the bicycle speed and vibration data corresponding to a given test section (An example of the extracted data is shown in Figure 3.7).
4. Remove the portion of the data from when bicycle speed was less than 5 mph.

5. Divide the data into one-second long subsections and calculate the average vibration for each second as the average value of the absolute difference between vibration and gravity (1.0 g).
6. Normalize the average vibration for each second to 16 mph by dividing it by the average bicycle speed and multiplying it by 16 mph (26 km/h).
7. Take the weighted average vibration for the whole test section using travel length as the weight. Use this weighted average vibration to represent the overall bicycle vibration for the test section.

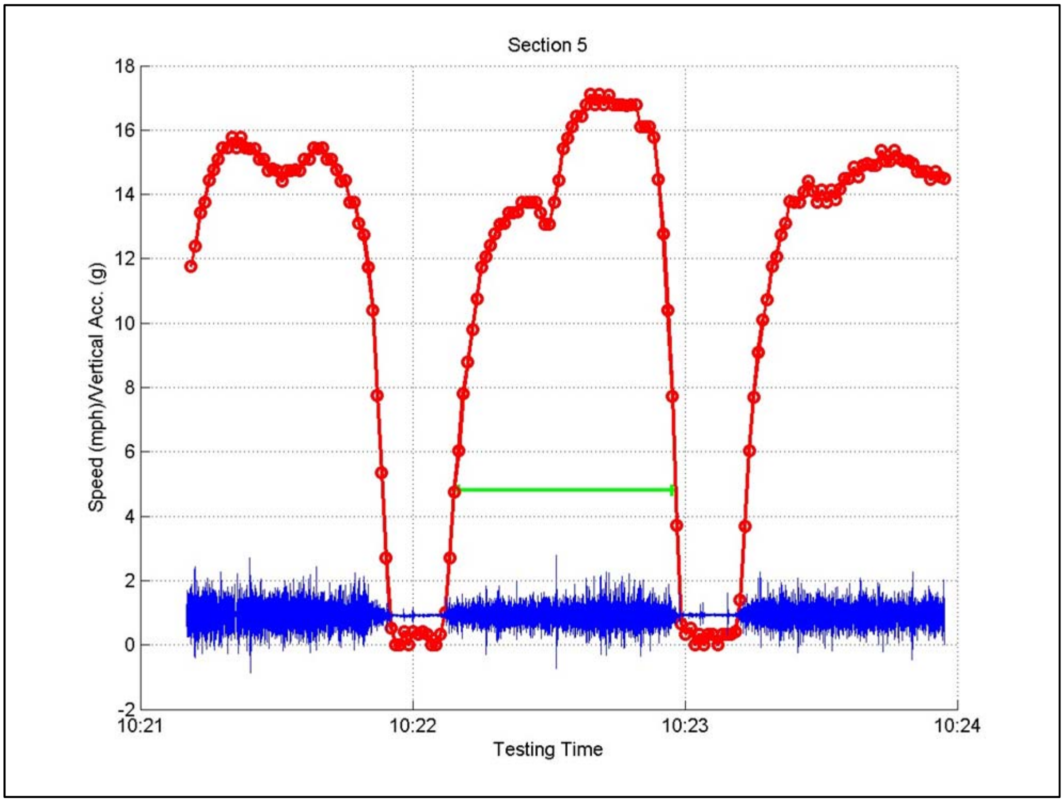


Figure 3.7: Extract of bicycle speed with corresponding acceleration data on Section 5 of Mon-198.
Note: **the red line with circles shows speed (mph), the blue line shows acceleration (g), and the green line shows the test section portion used for analysis where speed > 5 mph.**

3.3.3 Phase I Data Collection

UCPRC staff conducted test rides on local roads near Davis, California, to evaluate the instrumentation system and develop the data analysis procedure before using it for this study. A list of bicycle vibration evaluations on the Phase 1 sections is shown in Table 3.7. The testing conducted on July 12 and 13, 2013, allowed evaluation of bicycle vibration on various pavement surfaces, while the testing conducted on July 23, 2013, allowed evaluation of the effects of speed and tire pressure on bicycle vibration.

Table 3.7: List of Bicycle Vibration Evaluations on Phase 1 Sections

Date	Route	Bicycles	Testing Description
July 12, 2013	SLO-1 sections north of Cambria, CA	Two aluminum bicycles, one carbon bicycle	Various speeds, uncontrolled (3 riders) and 100 to 120 psi tire pressure
July 13, 2013	Mon-198 test sections east of King City, CA	Three aluminum bicycles, two carbon bicycles	Various speeds, uncontrolled (3 riders) and 100 to 120 psi tire pressure
July 23, 2013	Mon-198 sections east of King City, CA	One aluminum bicycle	12 combinations of speed (~8, ~13, ~17 mph, and normal speed) and tire pressure (60, 80 and 100 psi), three accelerometers were used, each mounted differently (see Figure 3.6).

3.4 Bicyclist Ride Quality Survey Method

3.4.1 Survey Sample of Surface Treatments and Participants

Cyclists were given a survey to complete based on their experience riding on the Mon-198 test sections on Saturday, July 13, 2013. The forms used in the survey—including the pre-ride, in-ride and post-ride surveys—are presented in Appendix E. The pre-ride survey asked the participants demographic questions, such as age, gender, and income, as well as questions about their bicycle and typical riding habits. The in-ride survey asked the riders to rate each section, first in terms of whether they considered it “acceptable” or “not acceptable” (with no further instructions given to define those terms), and second on a scale of 1 to 5 with 1 being the worst possible condition and 5 the best. The post-ride survey asked questions similar to those in the pre- and in-ride surveys, as an aid for interpreting the results. Some of the volunteer bicycle riders also rated three locations on the SLO-1 chip seal over the course of the following week using the same survey forms. The results of all the surveys have been included in the preliminary analyses presented in this memo.

Volunteer cyclists were solicited from San Luis Obispo County bicycle clubs. An additional volunteer came from the Silicon Valley Bicycle Club and another was both the pavement preservation program director of the Washoe County Regional Transportation Commission and a friend of the UCPRC Principal Investigator. A total of 24 volunteers participated in the Mon-198 survey. However, one rider did not fill out the background information in the pre-ride survey and did not respond to repeated follow up requests for that information, and therefore was eliminated from the statistical analyses. A total of 11 volunteers participated in the SLO-1 survey.

This was an anonymous survey, and participants were only identified by their number.

3.4.2 Survey Method on Mon-198 Test Sections

The steps and schedule for the survey on Saturday, July 13, 2013, were as follows.

- Meet at junction of US 101 and SR 198 at 9:00 a.m.
- 9:00 a.m. to 10:00 a.m. – Sign in, sign waivers, do first part of survey (pre-ride survey), safety talk, explain testing instructions.
- 10:00 a.m. to 10:15 a.m. – Drive personal vehicles to start of sections with bicycles. Park in the closure as directed.
- 10:15 a.m. to 10:45 a.m. – Ride first set of sections (three sections). Ride one direction (eastbound), stopping at end of each section to fill out ratings form, then turn around at the end of the whole set of sections and ride back (westbound) using the bicycle counterflow within the lane.
- 10:45 a.m. to 11:15 a.m. – Reload bicycles onto personal vehicles, drive to next set of sections, and unload.
- 11:15 a.m. to 12:15 p.m. – Ride the second set of sections (five sections). Ride one direction (westbound), stopping at end of each section to fill out ratings form, then turn around at the end of the whole set of sections and ride back (eastbound), again using the bicycle counterflow within the lane.
- 12:15 p.m. to 12:30 p.m. – Pack up bicycles and drive back to US 101.

This entire process took about four hours.

Instructions to the riders were as follows:

1. Riders ride up on the right side of the lane. Immediately rate each section (in-ride survey) at its end. Turn around at the top of the closure.
2. Riders ride down on the left side of the same lane. Immediately rate each section at its end (in-ride survey).
3. Once everyone is done, put bicycles on cars and move to the next set of sections. Do NOT ride to the next set of sections. Your car will need to be towed.
4. Repeat on second set of sections and do the in-ride survey.
5. Fill out the post-ride survey when you fill out the last section in-ride survey form.
6. Take an extra survey form and do the rating (SLO-1 survey) if you want to rate the SLO 1 project.

Riders agreed to follow these rules:

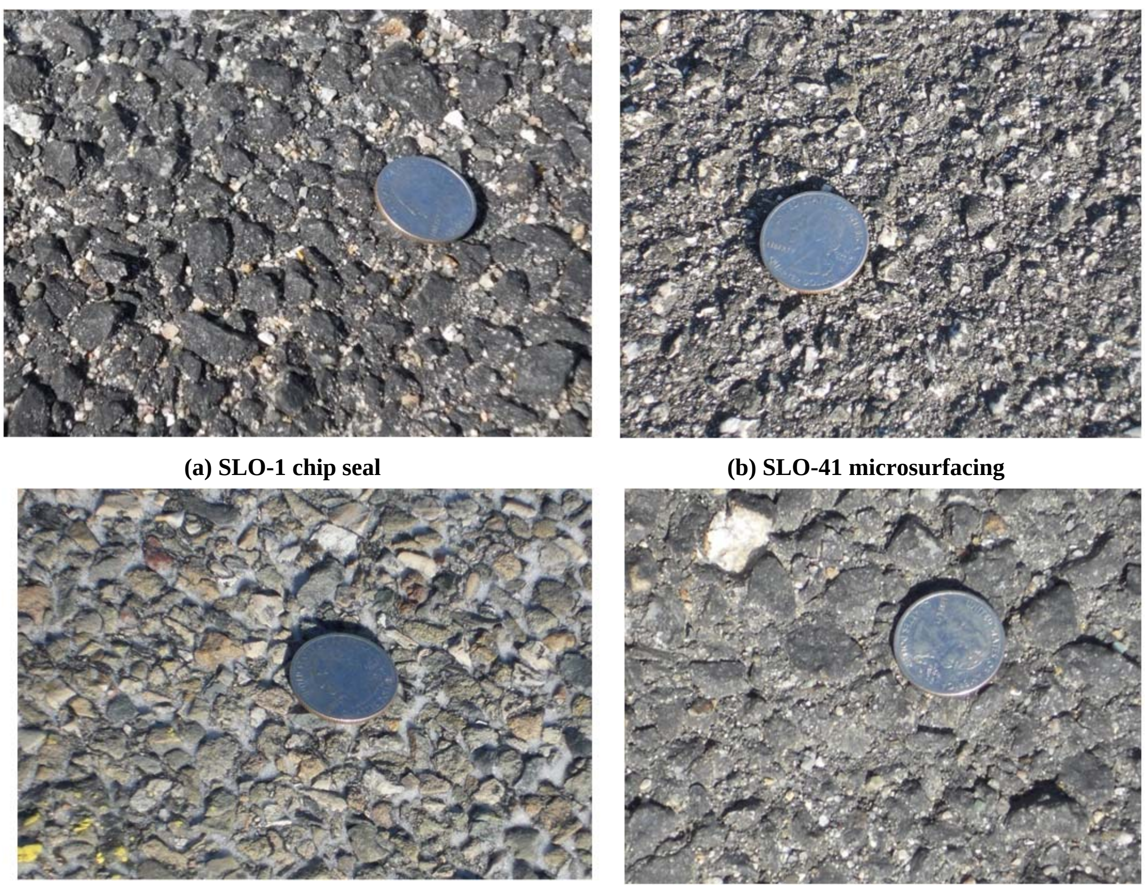
a. Ride at your normal speed on each section.
b. Complete the in-ride survey form at the end of each section.
c. Do NOT discuss your perceptions of the sections during the survey.
d. Do NOT publish information about your experience in the survey until the UCPRC report has been delivered to Caltrans, reviewed, and released to the public for comment by Caltrans District 5.

4 MEASUREMENT RESULTS AND ANALYSES

As shown in Table 3.1, pavement surface macrotexture measurements were taken using the laser texture scanner (LTS), inertial profiler (IP), and the sand patch method on the five road sections and eight test sections on Mon-198. Bicycle vibration was measured on the Mon-198 sections and on select locations on SLO-1. The main results of the LTS and IP measurements are summarized in this chapter; results from the sand patch method measurements appear in Appendix A.

4.1 Surface Appearance

Figure 4.1 shows typical close-up photographs taken of SLO-1, SLO-227, Mon-198, and SLO-41. The SLO-1 and Mon-198 chip seals with the coarser 3/8" gradation appear to have larger aggregates compared to those on SLO-227 with the finer 3/8" gradation. SLO-41 is a microsurfacing which uses a finer aggregate gradation than the chip seals. Appendix B contains close-up photographs taken of each of the test sections on Mon-198.



(a) SLO-1 chip seal **(b) SLO-41 microsurfacing**

(c) SLO-227 chip seal **(d) Mon-198 chip seal**

Figure 4.1: Example photographs of pavement surface macrotexture.

4.2 Macrotexture Measured Using Laser Texture Scanner (LTS)

The pavement macrotexture was measured using the laser texture scanner method at different locations for each road section. As shown in Figure 4.2, the measurements were mainly performed at locations approximately 6 inches (150 mm) inside and outside the white Edge of Traveled Way (ETW) stripes, where most bicyclists ride. Most sections and locations were measured for both directions of travel. The results of measured macrotexture, in terms of MPD, from SLO-227, SLO-1, SLO-41, and Mon-198 (prior to placement of test sections) are presented in Figure 4.3.

(a) Mon-198 PM 10.05

(b) SLO-1 PM 60.5

Figure 4.2: Examples of close-up photo views of LTS testing on pavement surface.

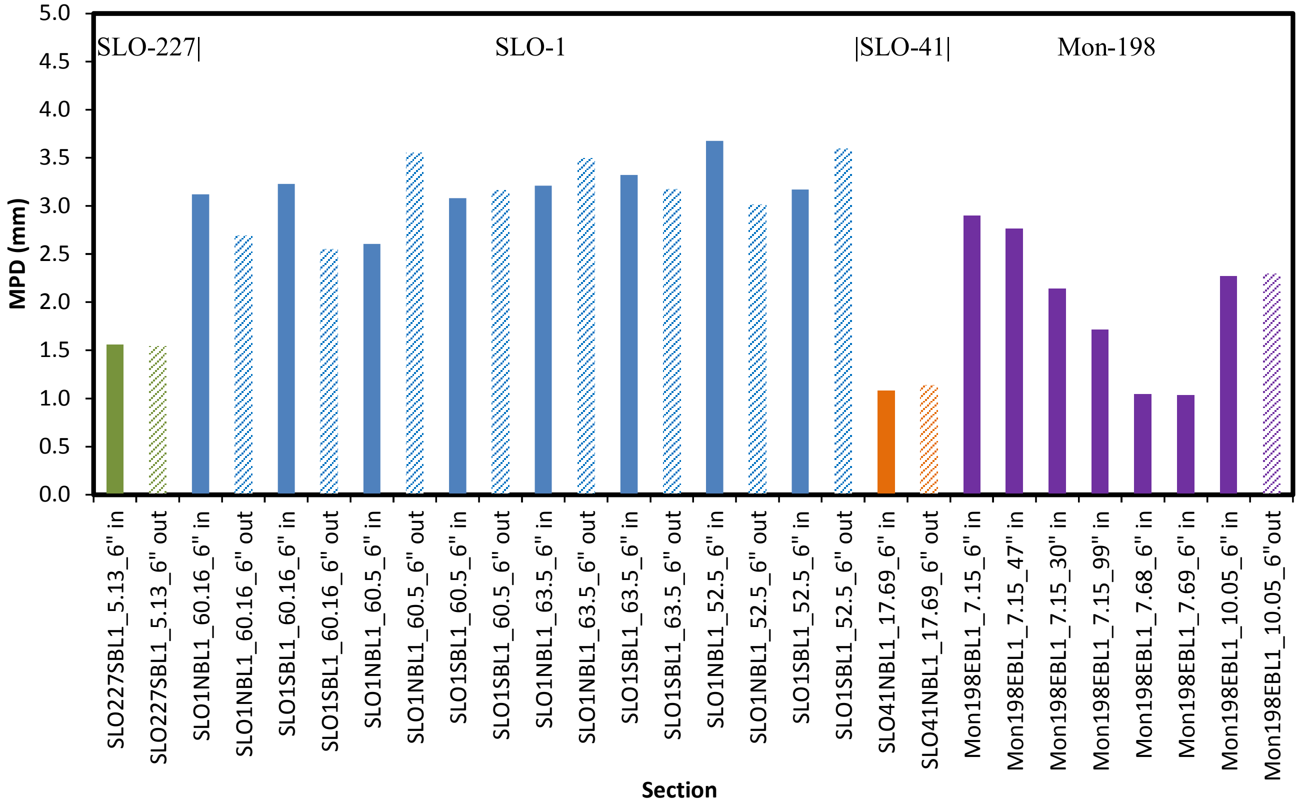


Figure 4.3: MPD from LTS for different road sections (SLO-227, SLO-1, SLO-41, and Mon-198). (Inside Edge of Traveled Way [ETW] measurements are shown with solid bars; outside ETW measurements shown with patterned bars.)

The MPD values measured in April 2013 on SLO-227 (finer gradation chip seal) and SLO-41 (microsurfacing) were smaller than those of coarser gradation chip seals on SLO-1 and Mon-198, except at Mon-198 EB PM 7.68. The MPD values ranged from approximately 1.0 mm to 1.5 mm for SLO-227 and SLO-41, and from approximately 2.0 mm to 3.5 mm for SLO-1 and Mon-198. The values on Mon-198 were somewhat lower overall than those on SLO-1, although both sections were constructed following the same specification. The MPD values on SLO-227 were much lower than those on Mon-198 and SLO-1. The differences in MPD values are most likely due to the differences in aggregate gradation used on these projects, as well as a longer embedment time on SLO-227. The MPD values on the microsurfacing of SLO-41 were similar to those of the chip seal of SLO-227. The macrotexture on SLO-1 was generally higher than those of all the other road sections included in this study to date.

Generally, the MPD values on the outside of white ETW stripe (labeled “out”) were slightly higher than those on the inside (labeled “in”), as shown in Figure 4.3; this was most likely due to additional embedment and reorientation of the aggregate in the seal coats due to trafficking.

Figure 4.4 summarizes the additional macrotexture measurements—in terms of LTS-measured MPD—taken in July 2013 on the Mon-198 test sections and the three locations on SLO-1 used for the bicyclist ride quality surveys. In the following discussion and in Figure 4.4 and Figure 4.5, these are referred to as *treatment sections* and *survey sections,* respectively.

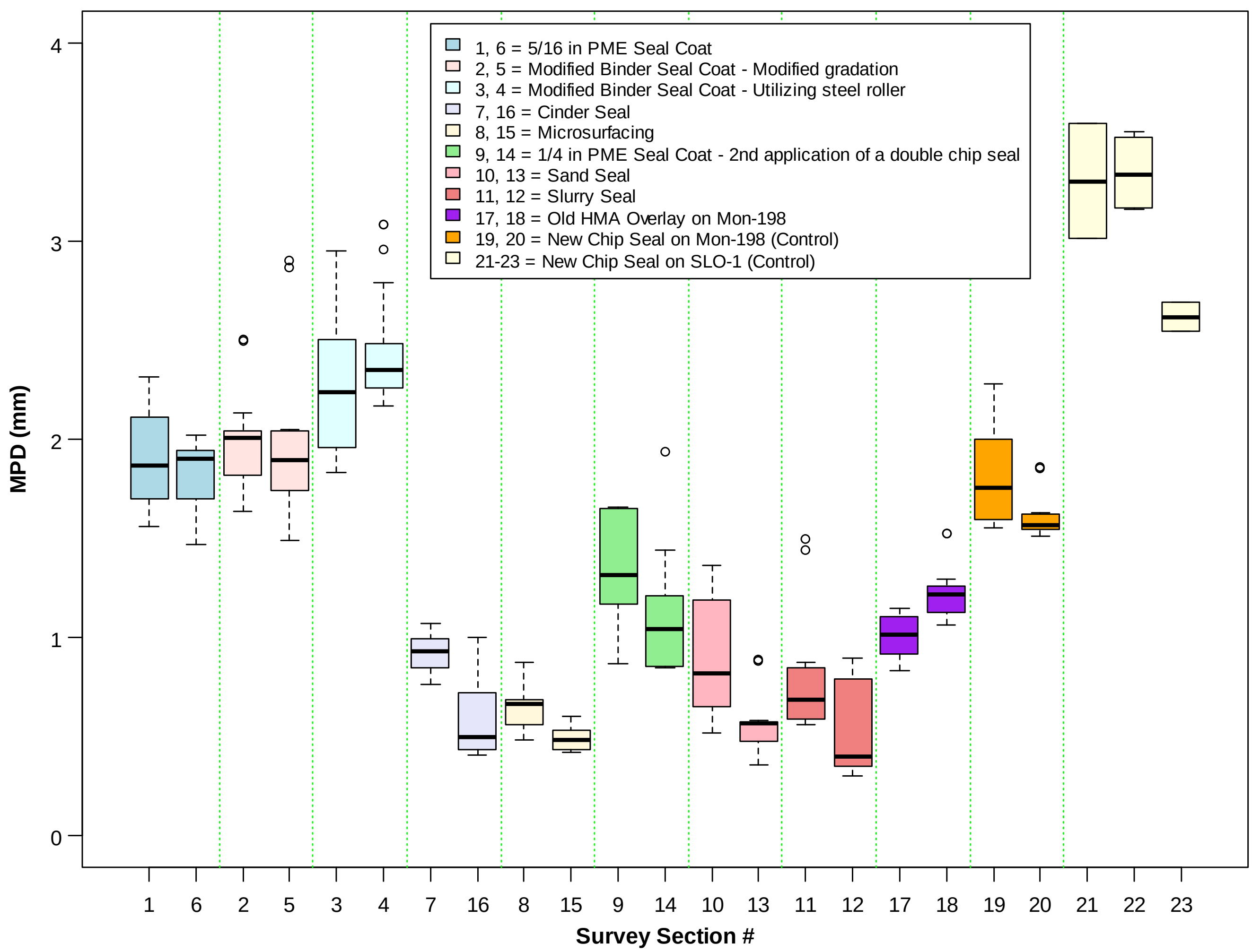


Figure 4.4: MPD from LTS for the inside of the ETW (left) and the left wheelpath (right) for each of the Mon-198 test sections and three locations on SLO-1.

In Figure 4.4, a pair of averaged measurements appears side by side for each of the Mon-198 test sections, and for the SLO-1 test sections for the three locations shown Table 3.4, which the cyclists rode on for the ride quality survey (that is, they are "survey sections").

1. For the Mon-198 sections:
    a. The first measurement (the one on the left) shows the average of several postmiles in each test section, taken 6 inches (150 mm) inside the ETW stripe.
    b. The second measurement (the one on the right) shows the average of several postmiles in each test section taken in the left wheelpath.
2. For the SLO-1 sections: the values shown for each location are the averages of measurements taken 6 inches on each side of the ETW strip.

It can be seen in Figure 4.4 that the MPD values on the Mon-198 test sections were the same or lower for the wheelpath compared to the ETW measurements, indicating the effects of traffic compaction during hot weather in the one month between construction in mid-June and MPD measurement in mid-July. From similar measurements taken inside and outside the ETW stripe on SLO-1 after one year of trafficking, it can be seen that not as much traffic-related embedment occurred in the relatively cooler climate on that highway.

Figure 4.5 shows LTS MPD values averaged from the two directions (wheelpath and ETW) in Figure 4.4 for each of the treatment test sections on Mon-198, and the average of the three locations used as bicyclist survey sections on SLO-1. The control section for Mon-198, which is the coarser 3/8" chip seal and appears as survey sections 19 and 20 in the legend of Figure 4.4 and as treatment section 10 in the legend of Figure 4.5, had MPD values between approximately 1.5 and 2.0 mm. The old HMA found on Mon-198 (survey sections 17 and 18 in the legend in Figure 4.4, and treatment section 9 in the legend of Figure 4.5) had a lower MPD. Two of the three MPD measurements on SLO-1 (survey sections 21 through 23 in the legend of Figure 4.4, and treatment section 11 in the legend of Figure 4.5) had MPD values above 3.0 mm, and all three of the SLO-1 MPD values were considerably higher than those of any of the Mon-198 test sections or the Mon-198 control sections, even though the SLO-1 and Mon-198 control sections were built with the same specifications.

It can be seen from the results shown in Figure 4.5 that the use of the steel roller (treatment 3) did not reduce the MPD value as compared to the MPD value from treatment 10, which is the same treatment but with aggregate embedment using a rubber-tired roller. It must be considered that treatment 10 also had one year of trafficking compared with treatment 3 which only had a few months of trafficking prior to testing. However, the MPD measurement on the shoulder of treatment 10 is lower than the measurements on treatment 3, indicating that the gradations may be somewhat different, although within the same specification, or that the steel roller in place of the rubber-tired roller did not make much difference in the constructed texture.

In Figure 4.4 and Figure 4.5 it can be seen that the 5/16" PME seal coat (treatment 1) and the modified binder seal coat with a modified gradation (treatment 2) both have somewhat greater MPD than the control section (treatment 10) even though they have somewhat finer gradations, as can be seen in Table 3.5. Treatments 1 and 2 both had less traffic than treatment 10, which had been constructed a year earlier, and it can be seen that the shoulder and wheelpath values for treatments 1 and 2 have about the same MPD while the MPD values differ for the shoulder and wheelpath of treatment 10. However, the value for the shoulder of treatment 10 is about the same as those of the wheelpaths of treatments 1 and 2, indicating that they have similar texture regardless of when they were originally constructed. Treatments 1 and 2 should have their MPD measured again after a year of traffic to see if there is a significant change in their texture.

The five treatments applied on top of the Mon-198 chip seal (treatments 4 through 8 in Figure 4.5 and Table 3.4) all had MPD values less than the control section (treatment 10, coarser 3/8" chip seal). The cinder seal, microsurfacing, slurry seal, and sand seal had the lowest MPD values, between approximately 0.5 and 1.2 mm. The double chip seal consisting of a second application of smaller stone chips (1/4") placed on the existing 3/8" chip had MPD values between approximately 1.0 and 1.5 mm. All of the treatments showed lower MPD values for the left wheelpath compared with just inside the ETW, indicating additional traffic compaction in the one hot month since construction. Similar embedment may not be applicable on SLO-1 or other cooler coastal climates.

As noted, most of the treatments placed on Mon-198 were effective in reducing the MPD values. It is unknown whether application of these treatments on SLO-1 would result in the same final MPD values seen on Mon-198, or whether the change (difference between initial and final) in MPD values seen on Mon-198 would be achieved on SLO-1. If the treatments produced the same change in MPD found on the Mon-198 sections instead of the final values on Mon-198, then the cinder seal, microsurfacing, slurry seal, and sand seal would be expected to reduce the SLO-1 MPD values from around 3.0 mm to about 2.0 mm, while the double chip seal would reduce the SLO-1 MPD values to about 2.6 mm. These values should be kept in mind when reviewing the results of the correlation of MPD, bicycle vibration, and bicyclist ride quality in Section 4.6 of this technical memorandum.

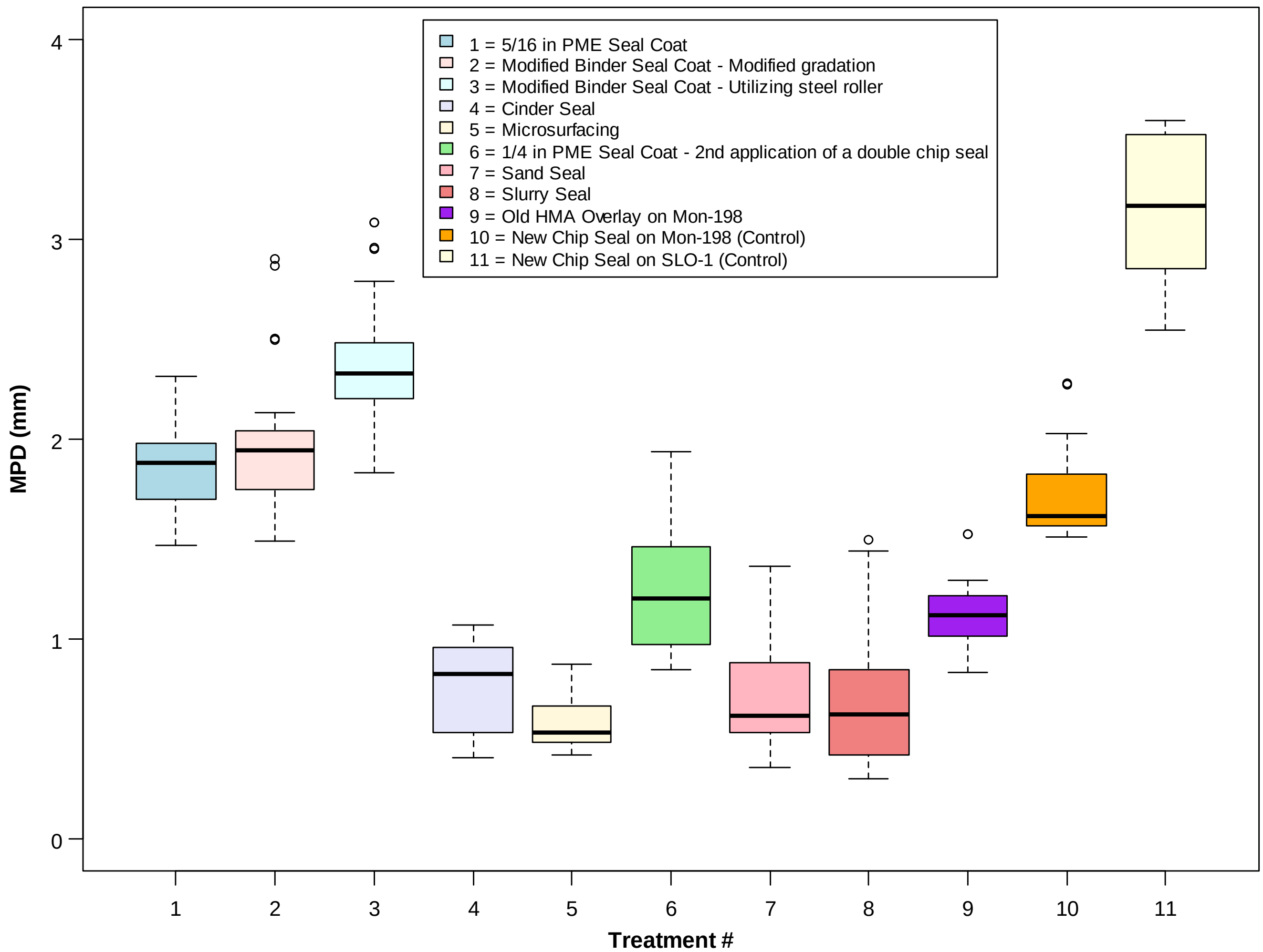
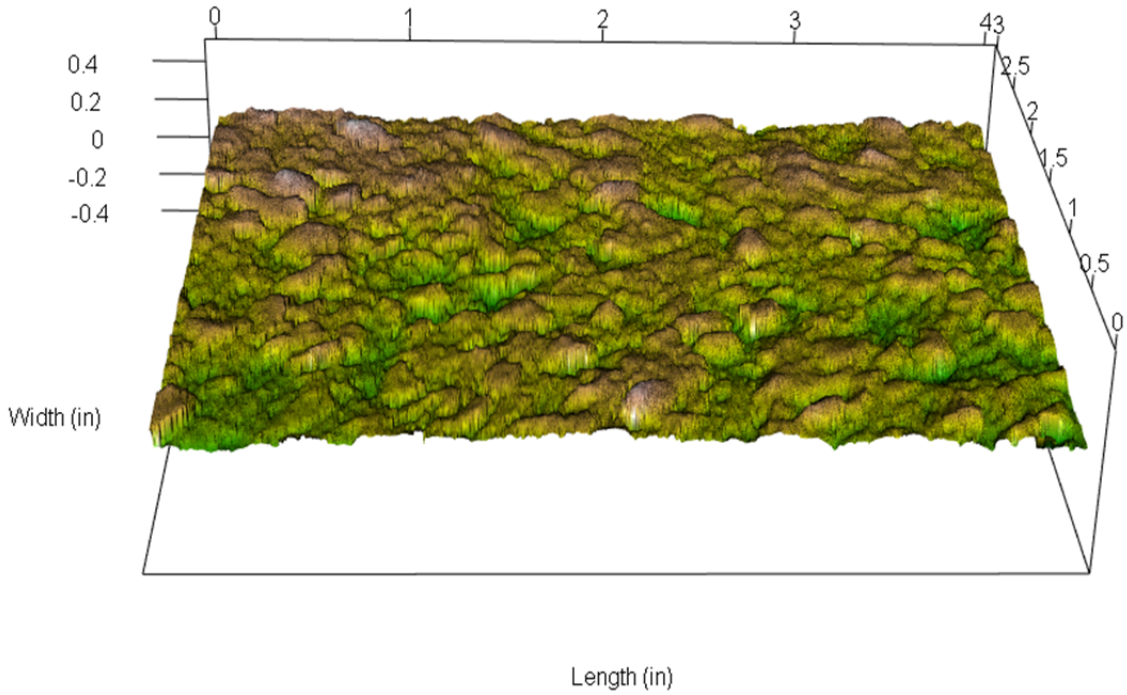


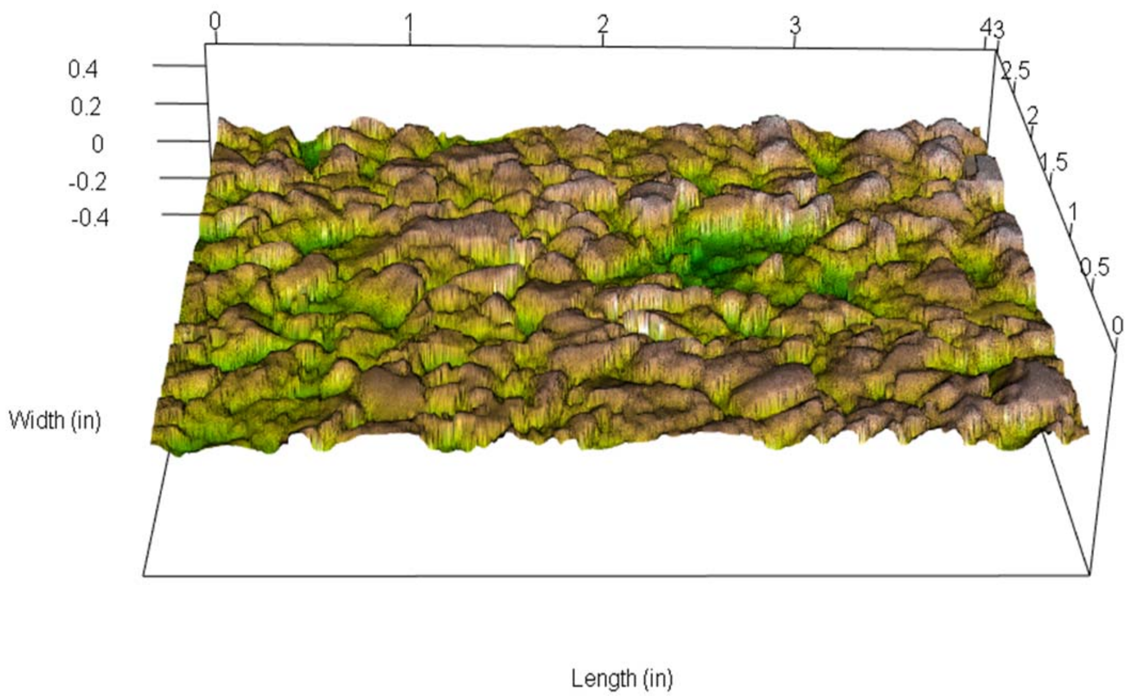
Figure 4.5: Averaged MPD from LTS by treatment type for all Mon-198 and SLO-1 bicyclist ride quality survey test sections.
(Note: refer to Table 3.4 for treatment descriptions.)

4.3 3D Macrotexture Images from Laser Texture Scanner (LTS)

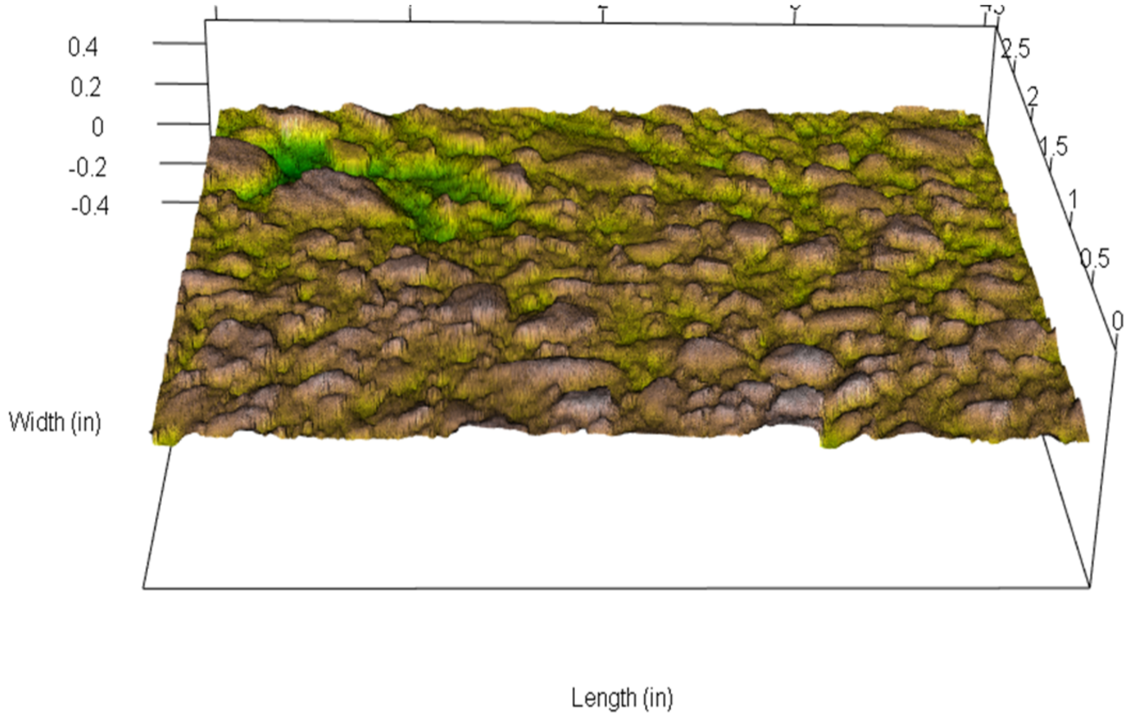
In addition to MPD measurement, the LTS produces 3D images of the pavement surface. Some examples of 3D macrotexture images from the sections included in this study are shown in Figure 4.6. The size of the LTS scanned area is 4 × 3 inches (100 × 75 mm). It can be seen from the figure that the surfaces of SLO-41 (microsurfacing) and SLO-227 (finer 3/8" chip seal) (Figure 4.6a and b, respectively) have less macrotexture than the two coarser 3/8" chip seals on Mon-198 (except at PM 6.81 with its dense-graded asphalt material [Figure 4.6c]) and SLO-1 (Figure 4.6d and e). More images of 3D macrotexture for the different sections and at different locations can be found in Appendix C. The 3D macrotexture images for the new test sections on Mon-198 are also shown in Appendix C.



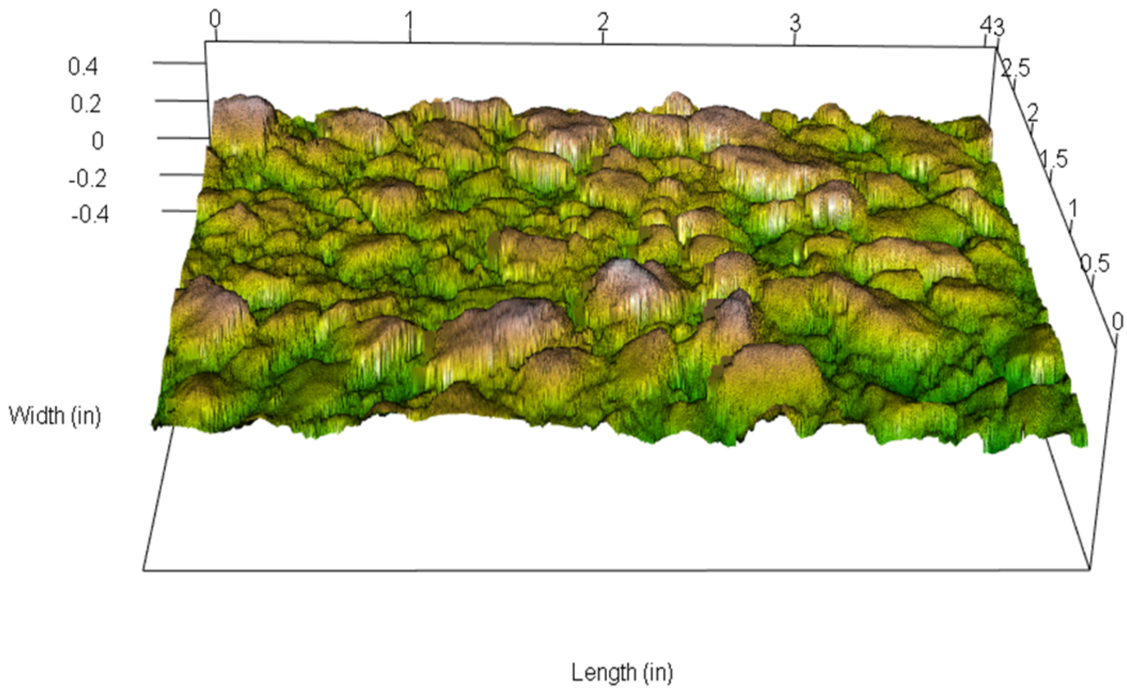
(a) Microsurfacing on SLO-41 NB PM 17.69 placed in 2010



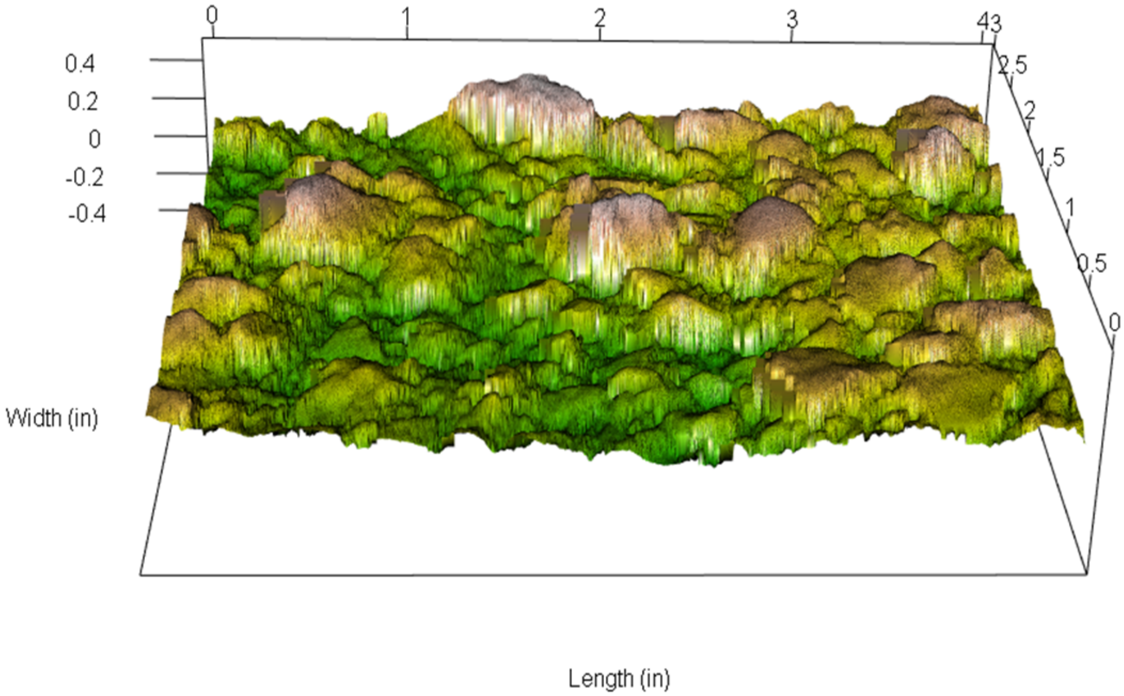
(b) Finer 3/8" gradation chip seal on SLO-227 SB PM R5.13 placed in 2009



(c) Dense-graded asphalt on Mon-198 EB PM 6.81



(d) Coarser 3/8" gradation chip seal on Mon-198 EB PM 10.05 placed in 2012



(e) Coarser 3/8" gradation chip seal on SLO-1 SB PM 60.5 placed in 2012

Figure 4.6: Example 3D macrotexture images from LTS for pavement surface treatments on different sections.

4.4 Macrotexture Measured Using Inertial Profiler (IP)

In this part of the study, macrotexture was measured using the vehicle-mounted inertial profiler (IP) shown in Figure 4.7. Measurements taken with the IP followed a continuous line for the entire length of each section included in this study, except for the test sections on Mon-198 that will be tested at a later date with this same apparatus. Where possible, the IP was run both inside (near the wheelpath) and outside of the ETW stripe (on the shoulder), and in both directions of travel. The average macrotexture was calculated as mean profile depth (MPD) for every meter along each line measured.

When analyzing the first results from the IP, it was discovered that the macrotexture of some of the pavement surface treatments, in terms of MPD, was greater than the 2 mm MPD default range of the sensor, and this resulted in erroneous values. Afterward, the IP's sensor range was increased to 5 mm and those sections were measured again several weeks later. Although increasing the sensor range resulted in lower resolution measurements, the resolution was sufficient for the purposes of this study.

Figure 4.7: Instrumented vehicle with an inertial profiler (IP).

4.4.1 Continuous Macrotexture Results of Different Pavement Sections Using IP

The measured macrotextures of different pavement sections using the IP with the 5 mm sensor range are presented in Figure 4.8 through Figure 4.14. Due to data storage limitations, some sections longer than about 20 km (12 mi) were divided into smaller subsections for measurement (e.g., SLO-1 and Mono-395). It can be seen from the figures that the MPD values from SLO-41 (microsurfacing) and SLO-227 (chip seal) are approximately within the range of 0.5 mm to 1.0 mm, while the MPD range for the chip seals on Mon-198, Mono-395, and SLO-1 is approximately 1.5 mm to 4.0 mm. There are subsections within the sections on SLO-1, Mon-198, and Mono-395 where MPD values are lower because they have either dense-graded asphalt concrete surfaces or they are concrete bridge decks. An example is shown for SLO-1 in Figure 4.12. It can also be seen that the MPD on the shoulders (outside of ETW) of SLO-1 (Figure 4.12) is generally higher than that in the wheelpath, as was also shown by the sand patch (see Appendix A) and LTS measurements. The difference between the shoulder and inside the ETW stripe is particularly large for Mono-395, and is due to trafficking on the inside of the ETW.

It was expected that macrotexture would initially decrease after construction under normal traffic. In order to determine if that process could be accelerated, additional rolling was conducted daily on a 1,000 ft (300 m) test section on SLO-1 to simulate the effects of traffic over time. The rolling was applied daily for three weeks in March and April of 2013, months after the chip seal construction, with intermittent days off due to weather, holidays, and unavailability of the crew. After that period, the MPD of the test sections with the rubber-tired rolling (northbound) and normal traffic rolling (southbound) was measured using the IP, with the results shown in Figure 4.15.

Additional steel-wheel rolling was performed on a section of shoulder on Mono-395 and Figure 4.11, and although the postmile where this was done has not yet been obtained from District 9, it appears that none of those shoulder sections has significantly reduced macrotexture. It appears, based on the results in Figure 4.11 and Figure 4.15, that the additional rolling with a steel roller on Mono-395 had no noticeable effect on the macrotexture.

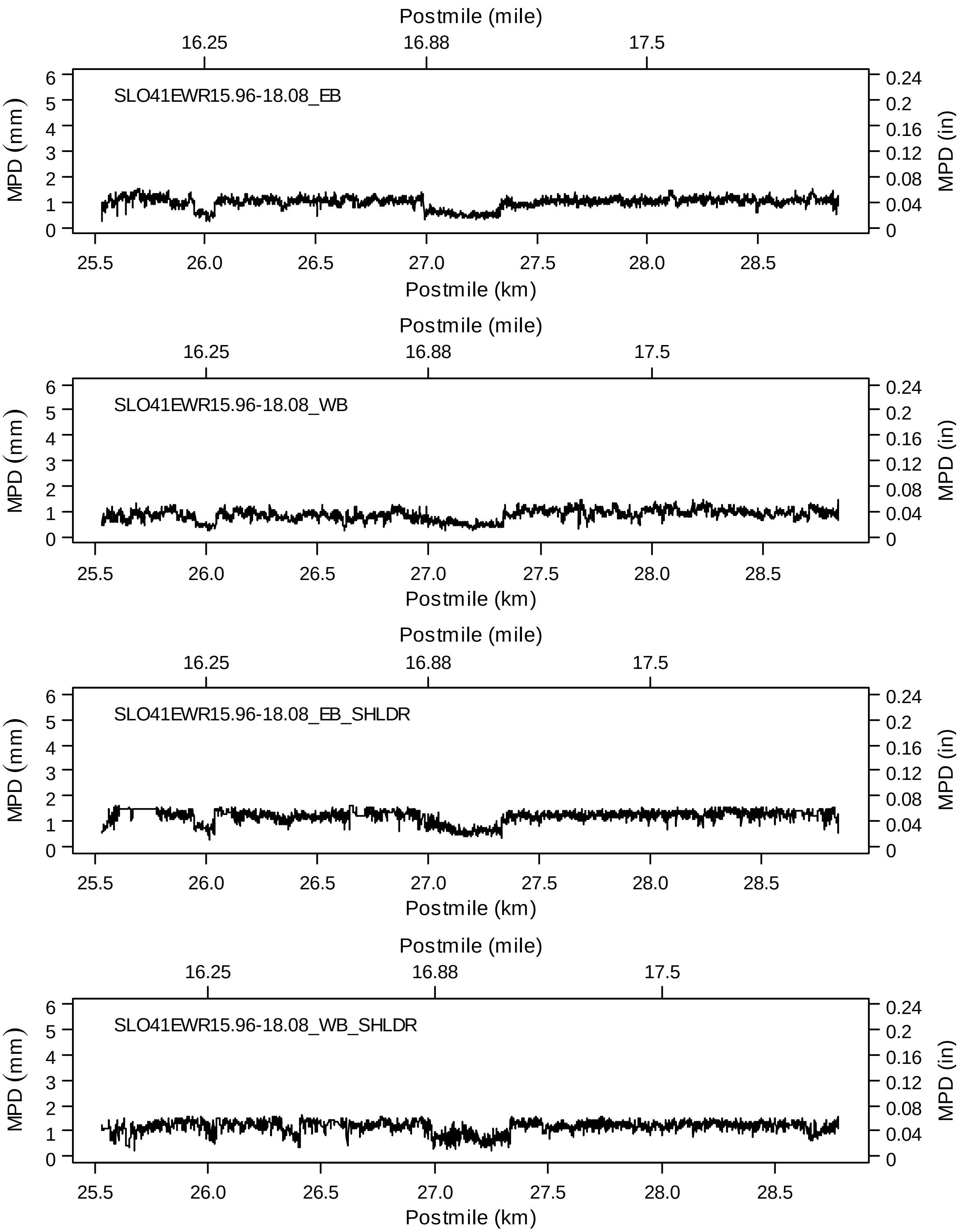


Figure 4.8: Macrotexture measured using IP for SLO-41 (microsurfacing).

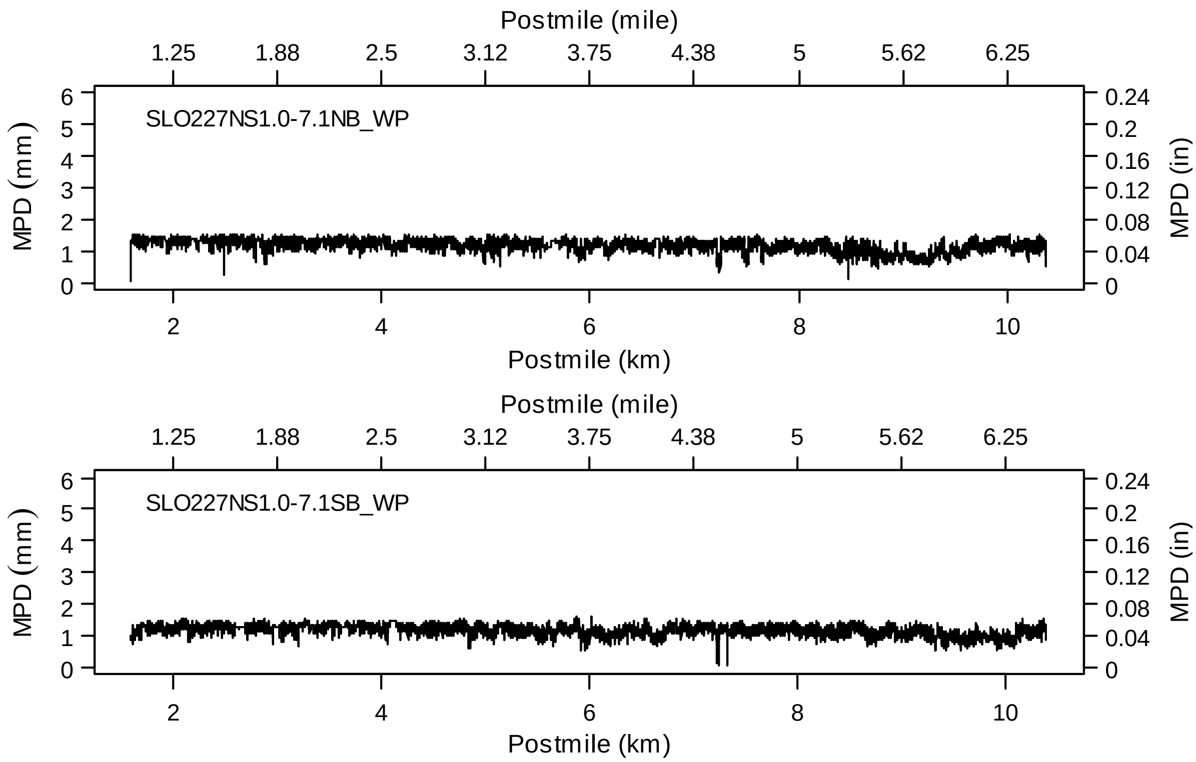


Figure 4.9: Macrotexture measured using IP for SLO-227 (chip seal).

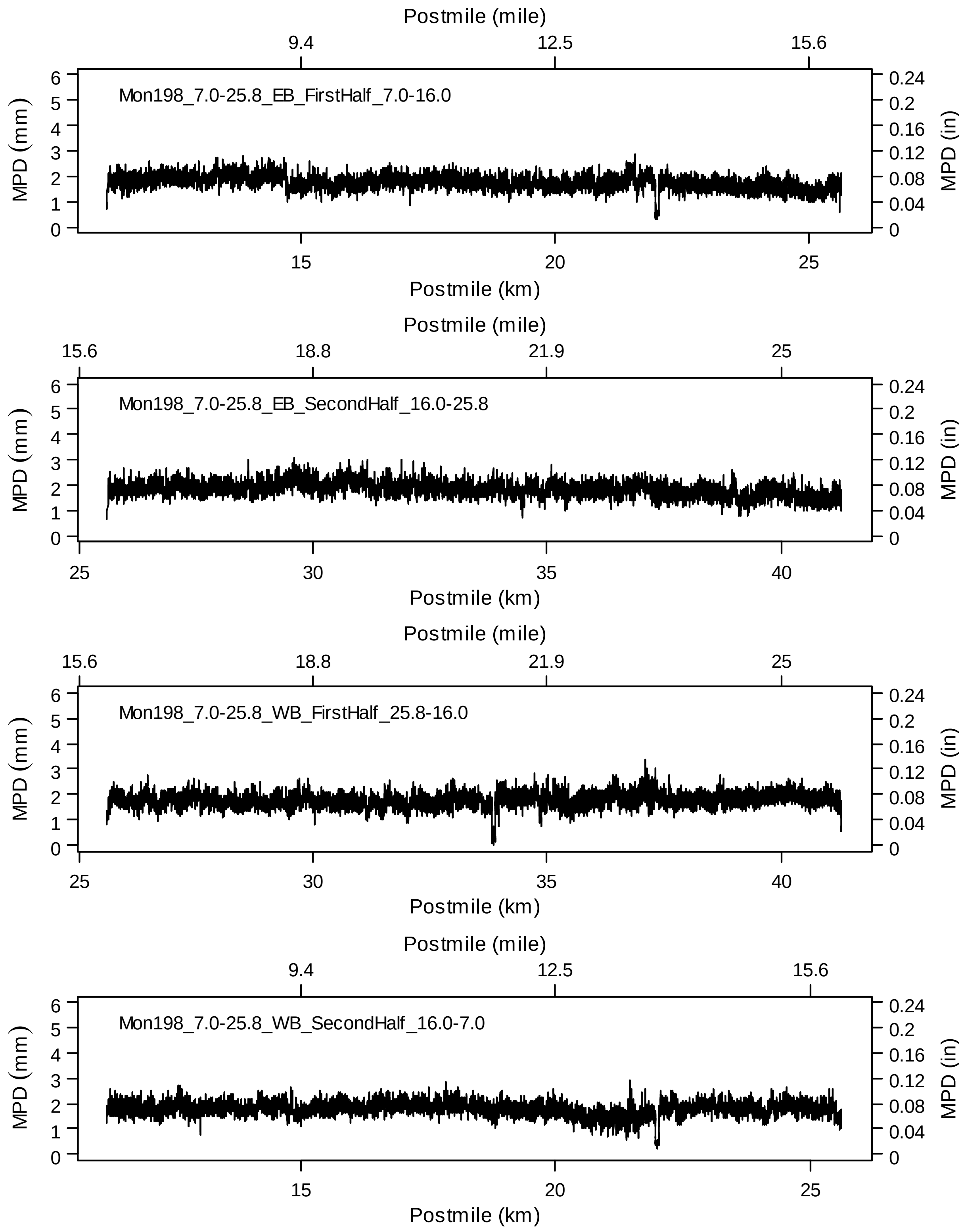


Figure 4.10: Macrotexture measured using IP for Mon-198 (chip seal).

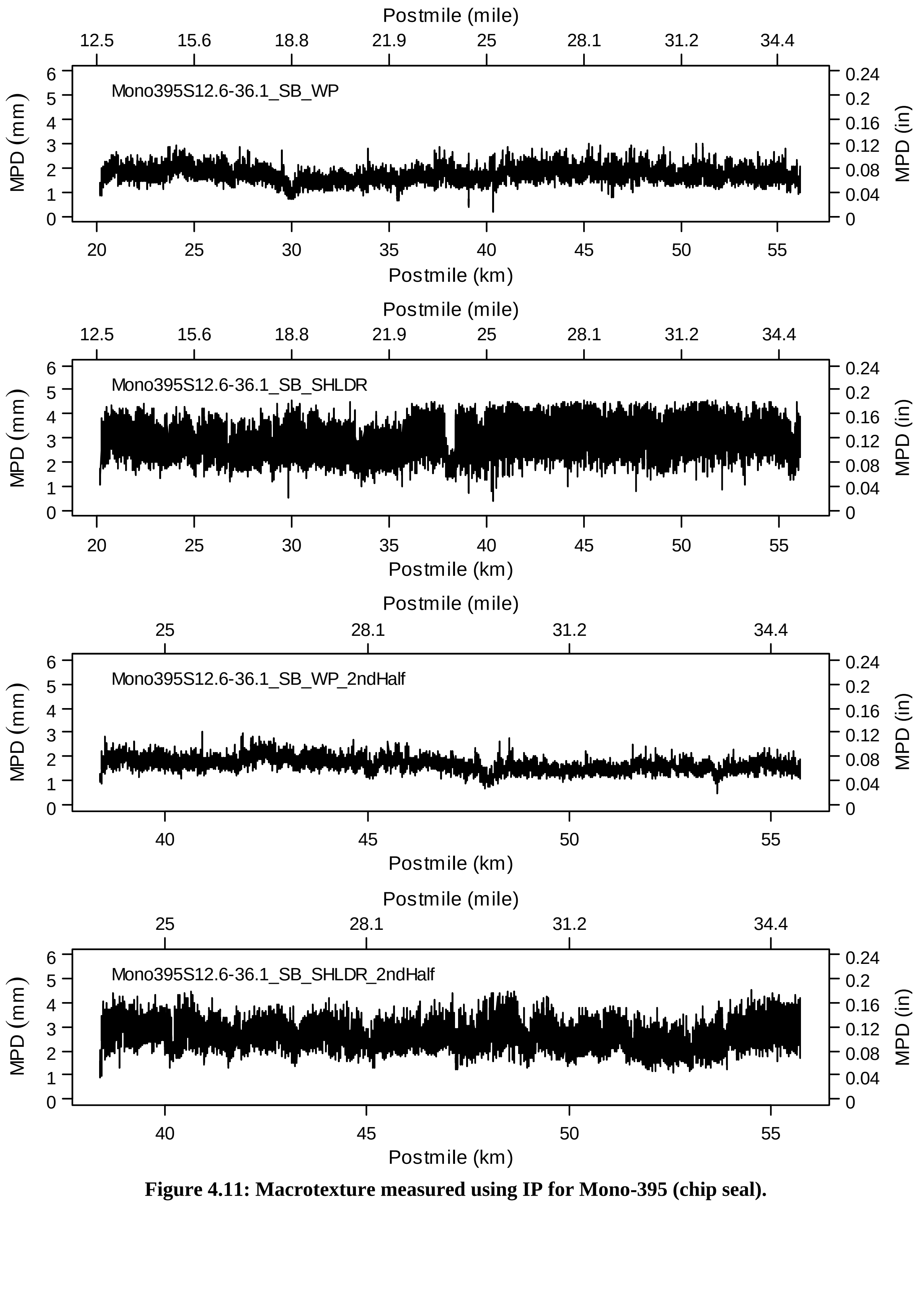


Figure 4.11: Macrotexture measured using IP for Mono-395 (chip seal).

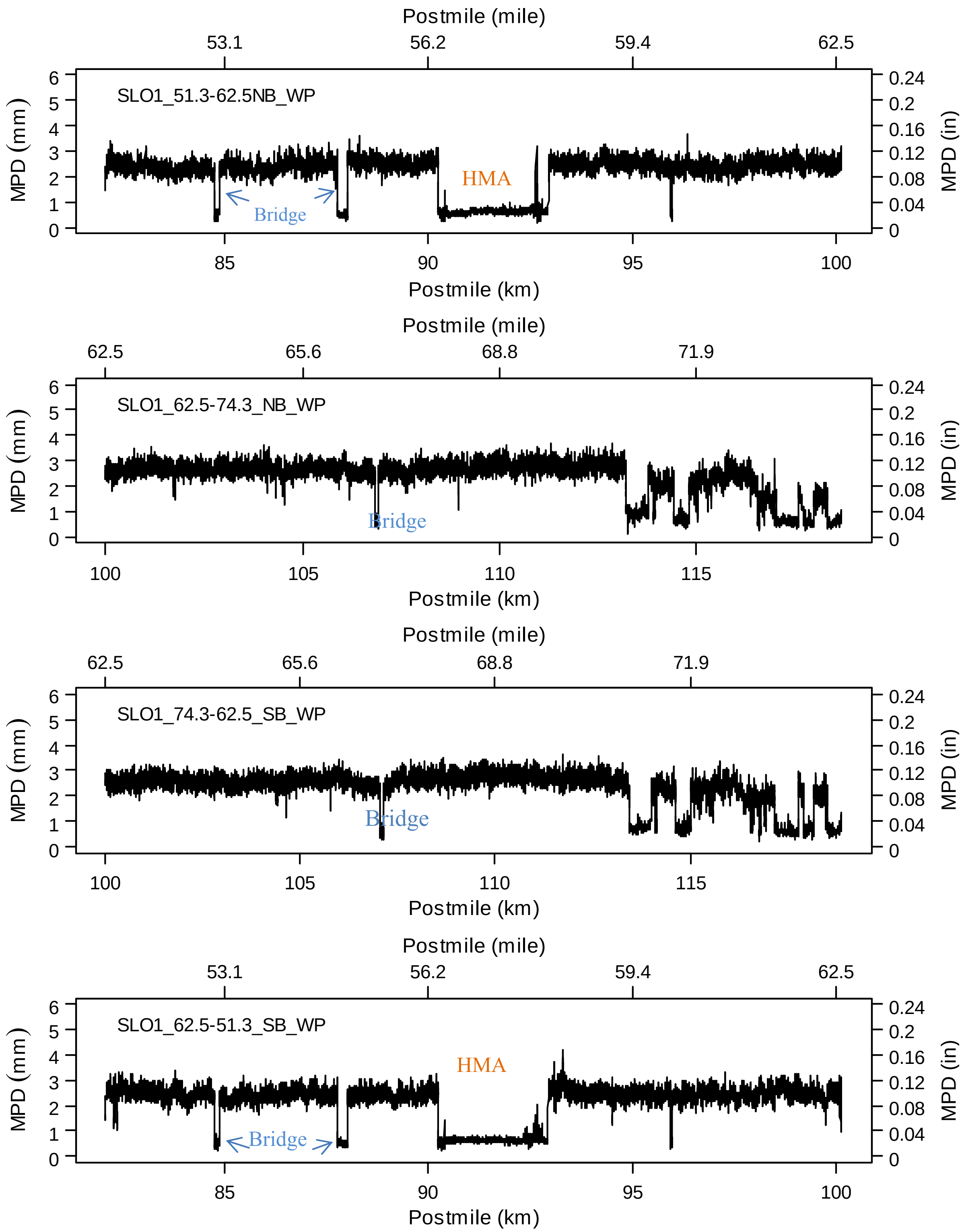


Figure 4.12: Macrotexture measured using IP for SLO-1 in right wheelpath (chip seal).

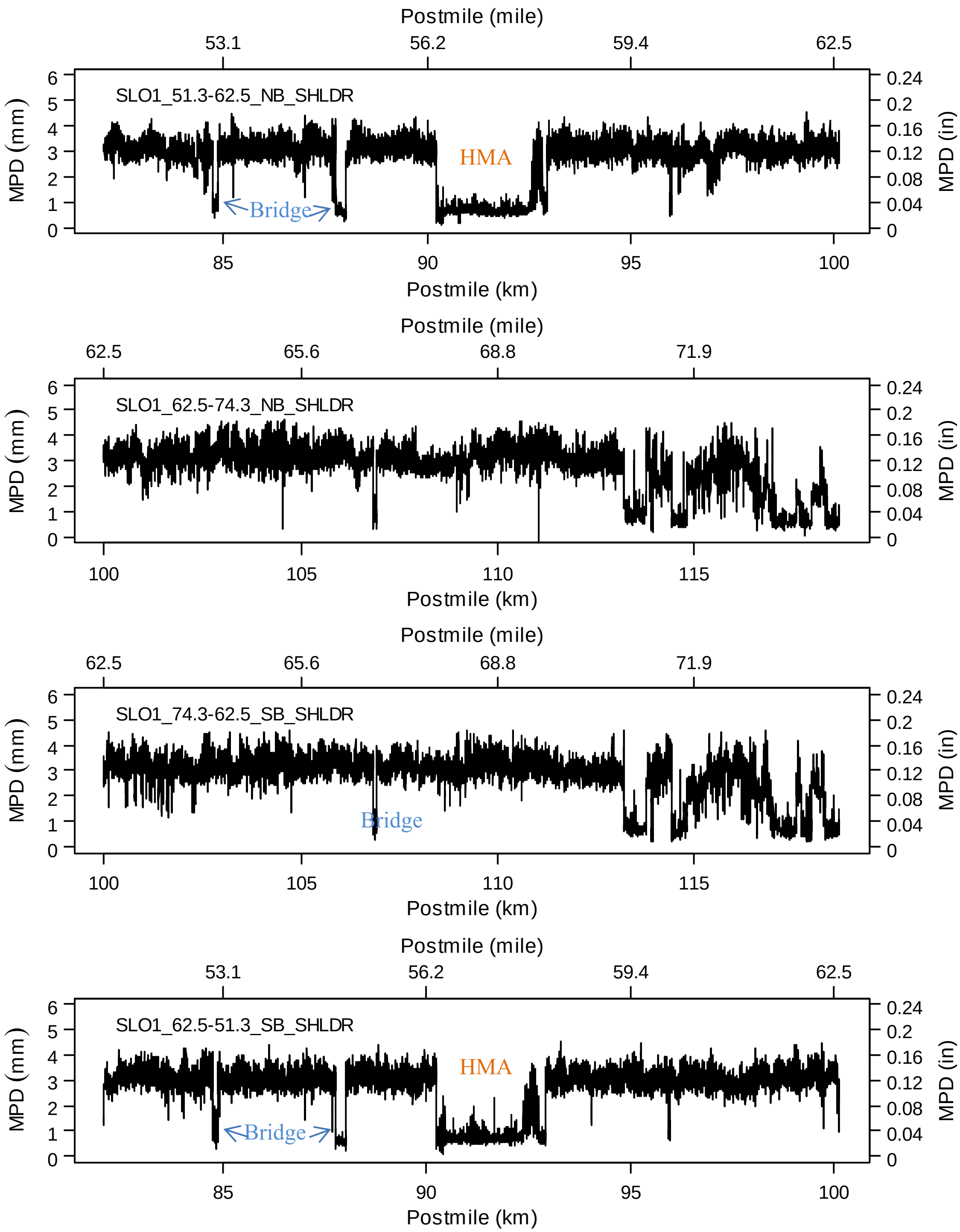


Figure 4.13: Macrotexture measured using IP for SLO-1 on shoulder (chip seal).

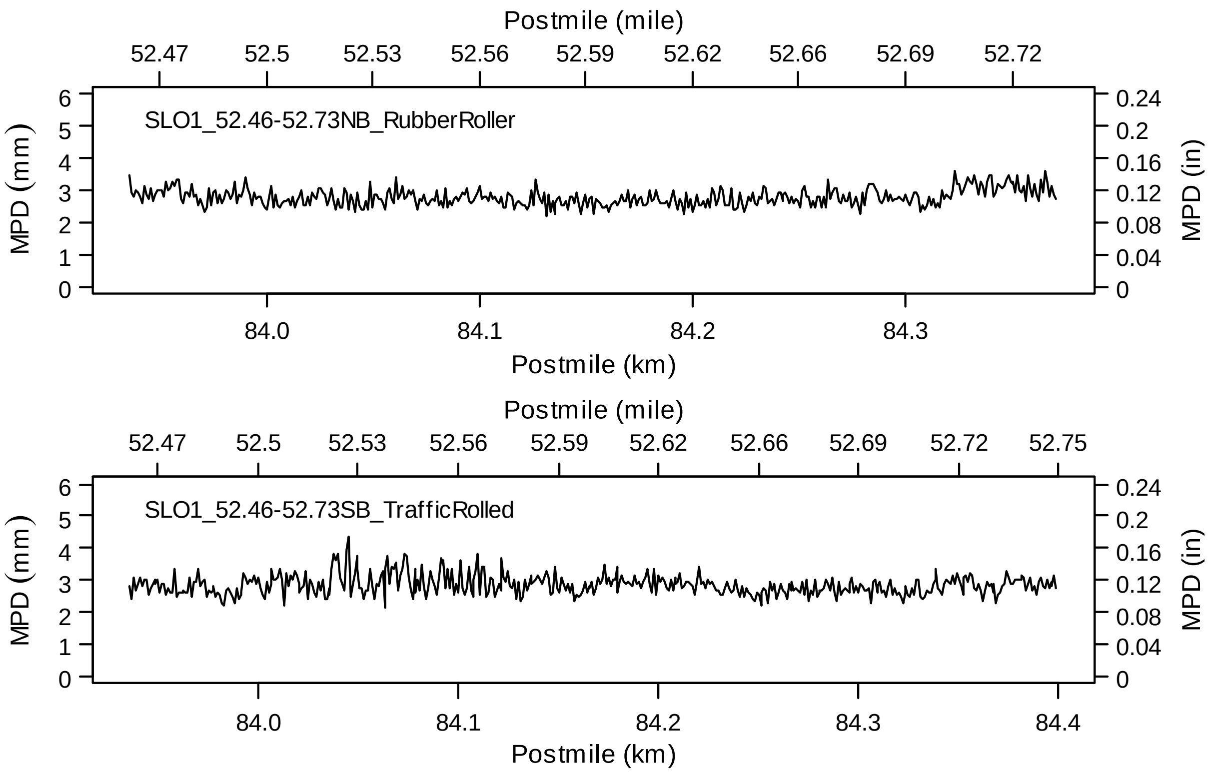


Figure 4.14: Macrotexture measured using IP for the subsection on SLO-1 with additional rolling.

4.4.2 Summary of Macrotexture Measurements from IP

The descriptive statistics for MPD measured by the inertial profiler are presented in Table 4.1. For most sections, the mean and the median of MPD were very close because of the sections' relative uniformity. On SLO-1, the mean value includes the different materials (chip seal, HMA, and bridge deck) that are part of the section. The HMA and bridge deck on SLO-1 had smaller MPD values than the chip seal on SLO-1 (see Figure 4.12, Figure 4.13, and Appendix D for the distribution of MPD measured by IP for the different pavement sections, with two significant peaks for SLO-1). The median values for MPD on SLO-1 in Table 4.1 include the chip seal only (i.e., dense-graded HMA and bridges have been excluded).

Figure 4.15 shows a plot of the median, mean, and standard deviation of measured MPD from the IP for different sections. In the figure, the difference between the medians and the means of IP-measured MPD on SLO-1 can be easily observed. It can also be seen that the values for the shoulder sections that were subjected to additional rolling fall in between those of the shoulder without additional rolling for the larger adjacent measurement section (PM 51.3 to 62.5 on the northbound shoulder) and the measurement inside the ETW. However, the inertial profiler-measured median MPD values are 3.02 mm for the shoulder without rolling, 2.74 mm for the additional rubber-tire rolling section, and 2.37 mm for the wheelpath, which indicates that the additional rolling did not have much effect on the macrotexture. The results also show that the northbound shoulder of SLO-1 had greater macrotexture than the southbound shoulder.

When looking at the variability within each section, as shown in Table 4.1 in terms of the standard deviation of MPD, the lengths of the sections must also be considered. Assuming that variability is not uniformly distributed across the entire 23 mile chip seal construction project due to day-to-day differences during construction in weather, materials, and other construction variables, very short sections, such as the additional rolling section on SLO-1 (0.27 miles), would not be expected to have as much variation. The standard deviation is highest on the shoulders of SLO-1, which has measurement lengths of about 10 miles, and somewhat lower in the wheelpaths, showing that traffic removes some of the variability. Additional rolling may have also removed some of the variability, but it is difficult to tell because of the difference in the lengths of the mainline sections and the additional rolling test sections. Mono-395 and Mon-198, which were built with the same specification and have measurement lengths similar to that of SLO-1, have much lower variability.

Table 4.1: Descriptive Statistics of MPD Measured by the Inertial Profiler

Road	Section	N	Mean	Std.Dev.	Min	Q1 [1]	Median	Q3 [1]	Max
SLO-41	SLO41EWR15.96-18.08_EB	3,331	0.98	0.23	0.26	0.90	1.03	1.13	1.54
	SLO41EWR15.96-18.08_WB	3,302	0.87	0.22	0.24	0.72	0.89	1.03	1.46
	SLO41EWR15.96-18.08_EB_SHLDR	3,311	1.19	0.25	0.30	1.11	1.25	1.37	1.63
	SLO41EWR15.96-18.08_WB_SHLDR	3,244	1.15	0.25	0.25	1.04	1.20	1.33	1.61
SLO-227	SLO227NS1.0-7.1NB_WP	8,780	1.17	0.20	0.05	1.07	1.20	1.31	1.55
	SLO227NS1.0-7.1SB_WP	8,802	1.16	0.18	0.07	1.05	1.18	1.29	1.60
Mon-198	Mon198_7.0-25.8_EB_FirstHalf_7.0-16.0	14,437	1.74	0.28	0.28	1.57	1.74	1.92	2.84
	Mon198_7.0-25.8_EB_SecondHalf_16.0-25.8	15,694	1.83	0.29	0.68	1.64	1.83	2.03	3.06
	Mon198_7.0-25.8_WB_FirstHalf_25.8-16.0	15,695	1.77	0.28	0.03	1.60	1.76	1.93	3.38
	Mon198_7.0-25.8_WB_SecondHalf_16.0-7.0	14,417	1.79	0.28	0.23	1.63	1.80	1.97	2.90
Mono-395	Mono395S12.6-36.1_SB_WP	36,004	1.71	0.30	0.19	1.51	1.69	1.89	3.02
	Mono395S12.6-36.1_SB_SHLDR	35,964	2.88	0.60	0.37	2.46	2.87	3.30	4.56
	Mono395S12.6-36.1_SB_WP_2ndHalf	17,327	1.67	0.28	0.48	1.47	1.65	1.84	3.01
	Mono395S12.6-36.1_SB_SHLDR_2ndHalf	17,339	2.63	0.52	0.92	2.26	2.60	2.96	4.51
SLO-1	SLO1_51.3-62.5NB_WP	18,066	2.12	0.73	0.15	2.13	2.37	2.56	3.65
	SLO1_62.5-74.3_NB_WP	18,686	2.33	0.73	0.15	2.22	2.58	2.78	3.68
	SLO1_74.3-62.5_SB_WP	18,894	2.29	0.69	0.19	2.20	2.51	2.72	3.66
	SLO1_62.5-51.3_SB_WP	18,052	2.13	0.73	0.21	2.14	2.38	2.57	4.17
	SLO1_51.3-62.5_NB_SHLDR	18,045	2.70	0.95	0.13	2.68	3.02	3.27	4.53
	SLO1_62.5-74.3_NB_SHLDR	18,691	2.76	0.95	-0.19 [3]	2.51	3.03	3.39	4.62
	SLO1_74.3-62.5_SB_SHLDR	18,677	2.77	0.91	0.19	2.59	3.03	3.34	4.57
	SLO1_62.5-51.3_SB_SHLDR	18,057	2.70	0.91	0.12	2.66	2.99	3.24	4.51
	SLO1_52.46-52.73NB_RubberRoller [2]	436	2.78	0.27	2.19	2.58	2.74	2.94	3.58
	SLO1_52.46-52.73SB_TrafficRolled [2]	464	2.85	0.31	2.12	2.63	2.82	3.02	4.35

Notes

1. Q1 and Q3 indicate the first and third quartile values.
2. The bottom two rows are for the rolling test on SLO-1.
3. The negative value for minimum MPD for SLO1_62.5-74.3_NB_SHLDR indicates negative texture, meaning that the majority of texture is below the mean plane (indentations).

Figure 4.16 presents the averaged median MPD of the surfaces as measured by the IP for each section in both directions; the averages shown are for the shoulder (outside of ETW), inside the shoulder (inside of ETW), and both combined. SLO-1 and Mono-395 had the largest average MPD (1.7 mm to 3.0 mm, median) compared to the other sections tested (≤ 1.8 mm, median). The MPD outside the ETW (shoulders), where most bicyclists travel when a shoulder is available, was larger than that inside the ETW. As noted in the previous figure, the additional rolling applied to the shoulder on SLO-1 did not have much effect on reducing MPD according to the inertial profiler measured MPD values. The macrotexture on Mon-198, which was used for the evaluation of treatments to reduce high macrotexture on SLO-1, was less than that of SLO-1.

The relative values for the microsurfacing on SLO-41, the finer 3/8" chip seal on SLO-227, and the coarser chip seals on SLO-1 and Mon-198 generally follow those found with the LTS. The coarser 3/8" chip seal on the Mono-395 shoulder has values close to those on the SLO-1 shoulder.

The wheelpaths on SLO-1 show a reduction in MPD compared with the shoulders. The variability is also reduced in the wheelpath as can be seen by comparison of the standard deviations in Figure 4.15. The MPD values in the wheelpaths of Mono-395 are similar to those in the wheelpaths of Mon-198, which are somewhat lower than those of the wheelpaths of SLO-1, likely due to the hotter temperature on Mono-395 and Mon-198 compared with SLO-1, which resulted in greater embedment due to traffic.

(Note: Problems developed with the IP equipment before MPD measurements could be taken on the Mon-198 test sections. These measurements will be collected once the IP equipment is repaired.)

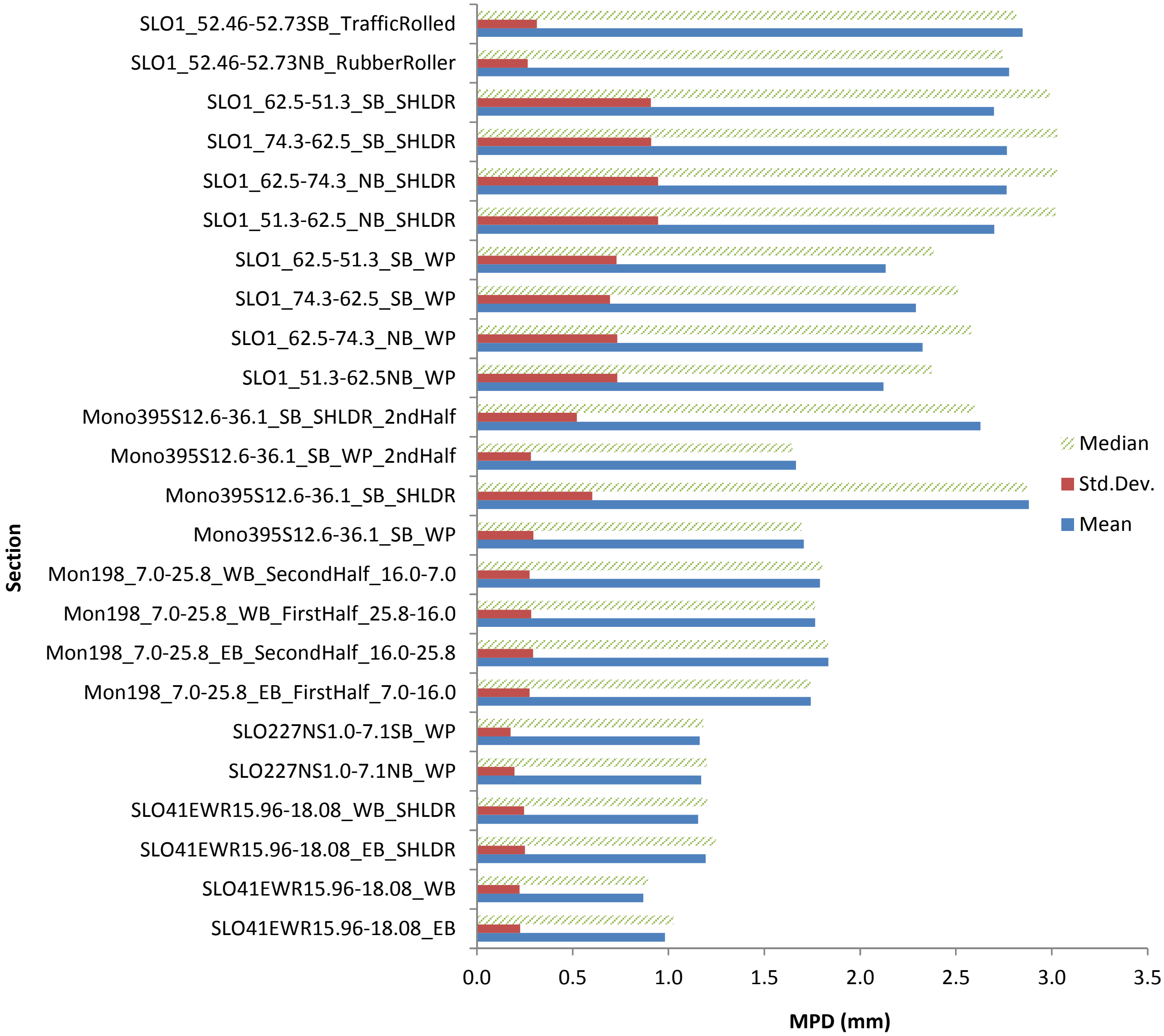


Figure 4.15: Median, mean, and variation of MPD measured from IP for different sections. (Note: SHLDR is for outside of ETW; WP is for inside of ETW.)

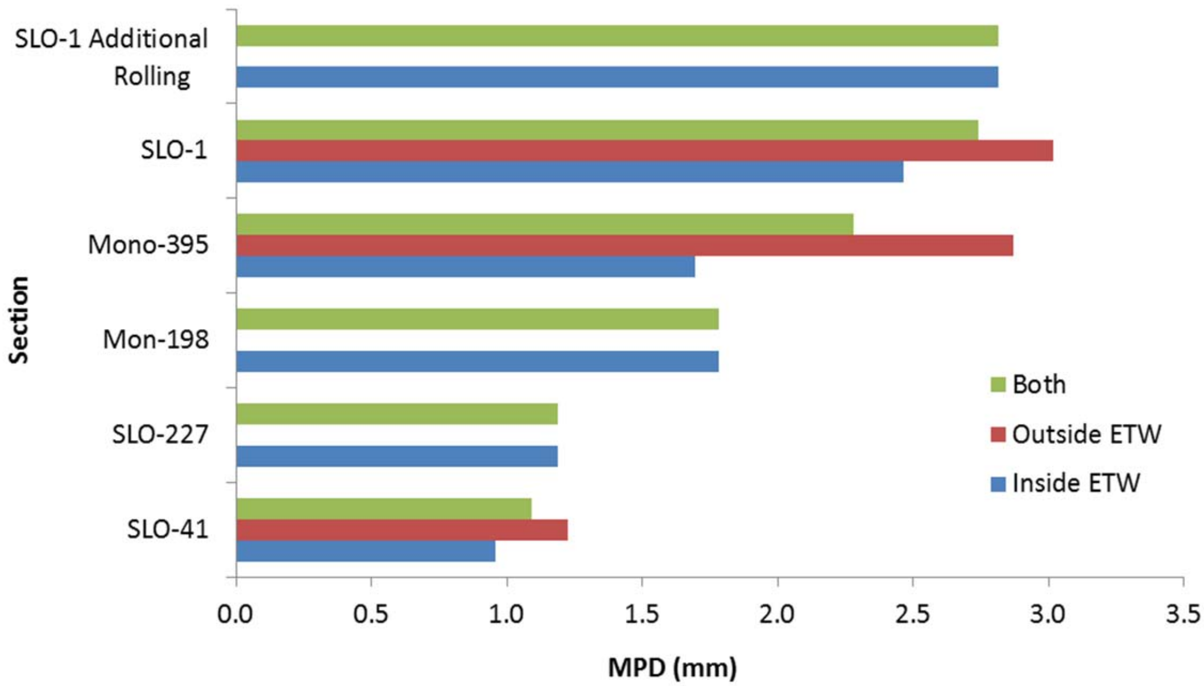


Figure 4.16: Average of median MPD of chip seal measured with IP outside of the ETW, inside of the ETW, and both averaged for each section.
(Note: some sections that have no shoulder provided no data for outside of ETW.)

4.5 Bicycle Vibration Results on Mon-198 and SLO-1

Bicycle vibrations were measured on test sections on Mon-198 and on SLO-1. In this study, bicycle vibration is presented in terms of the average vertical acceleration (measured in the direction normal to the ground). The procedure followed to calculate vibration for a given test section appears in Section 3.3.2.

4.5.1 Factors Affecting Bicycle Vibration

To evaluate the effects of speed and tire pressure on bicycle vibration, on July 23 one aluminum bicycle was used to measure vibration on the Phase 1 test sections using 12 combinations (see Table 3.7) of speed and tire pressure. Three accelerometers were mounted on this bicycle (see Figure 3.6): one on its fork and two under its seat, which also permitted evaluation of the effect of sensor-mounting position. The effects of sensor-mounting position will be investigated for the final report. Factors such as wind speed, wind direction, and road incline could not be controlled and were therefore not investigated in the bicycle vibration measurements performed in this study.

Effect of Speed on Bicycle Vibration

Bicycle vibrations were measured under four different speed groups: three with a narrowly controlled speed range and one under normal riding with speed not intentionally controlled. The *high* controlled speed ranged between 19 and 23 mph, the *medium* controlled speed ranged between 14 and 17 mph, and the *slow* control speed ranged between 6 and 9 mph. The *uncontrolled* speed was achieved when the cyclist rode at a level of moderate exertion.

The bicycle vibrations measured at the different speeds are shown in Figure 4.17 for the different treatments on Mon-198. Note that the bicycle vibrations have already been normalized to 16 mph as part of the data processing procedure. As shown in Figure 4.17, bicycle vibrations were roughly the same across the four speed groups for individual treatments except those measured under the slow speed. This anomaly is attributed to the difficulty in maintaining the slow speed; the rider reported that he frequently had to brake to maintain slow speed. The fact that bicycle vibrations measured under uncontrolled (referred to in figures as “normal”) speed are the roughly the same as those measured under medium and high speed indicates that the speed normalization can effectively account for the variation in bicycle speed when extensive braking is absent.

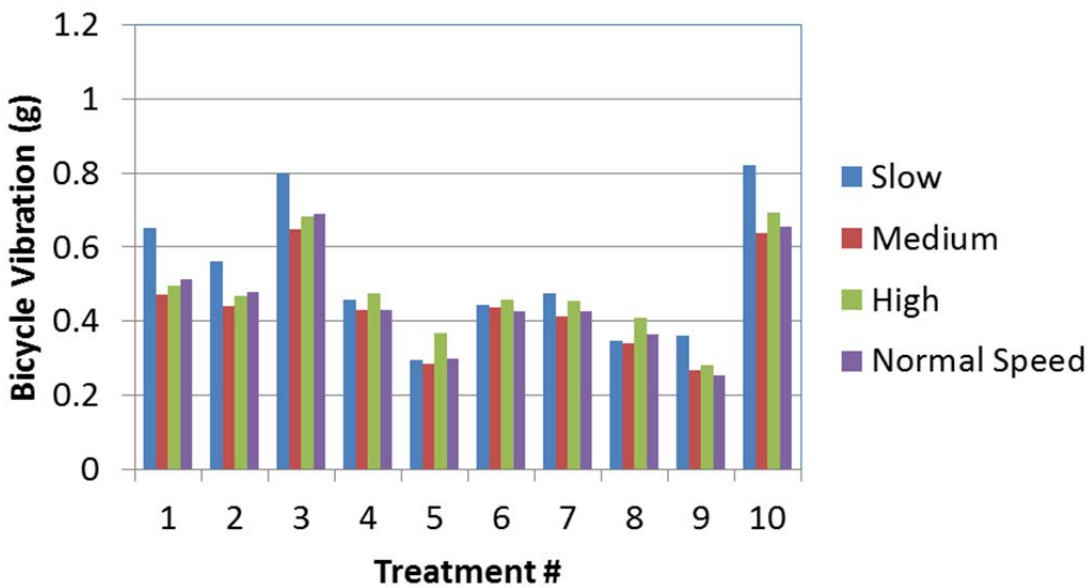


Figure 4.17: Bicycle vibration measured at different speeds for Mon-198 sections.
(See Table 3.4 for a description of each treatment #; Normal Speed indicates different speeds for different riders.)

Effect of Tire Pressure on Bicycle Vibration

The data from the aluminum bicycle and single rider that were used to measure vibration on July 23 also included measurements with the tires inflated to three different tire pressures to allow this factor's effect on vibration to be evaluated. The pressures considered were 60 psi (413 kPa), 80 psi (551 kPa), and 100 psi (689 kPa), respectively.

The bicycle vibrations measured with different tire pressures are shown in Figure 4.18 for the different treatments on Mon-198. Note that the data processing procedure did not include normalization for tire pressure. These results show that tire pressure has a roughly linear effect on bicycle vibration within the range of pressures used. In other words, increasing tire pressure increases bicycle vibration. The increase in bicycle vibration is in proportion to the increase in tire pressure.

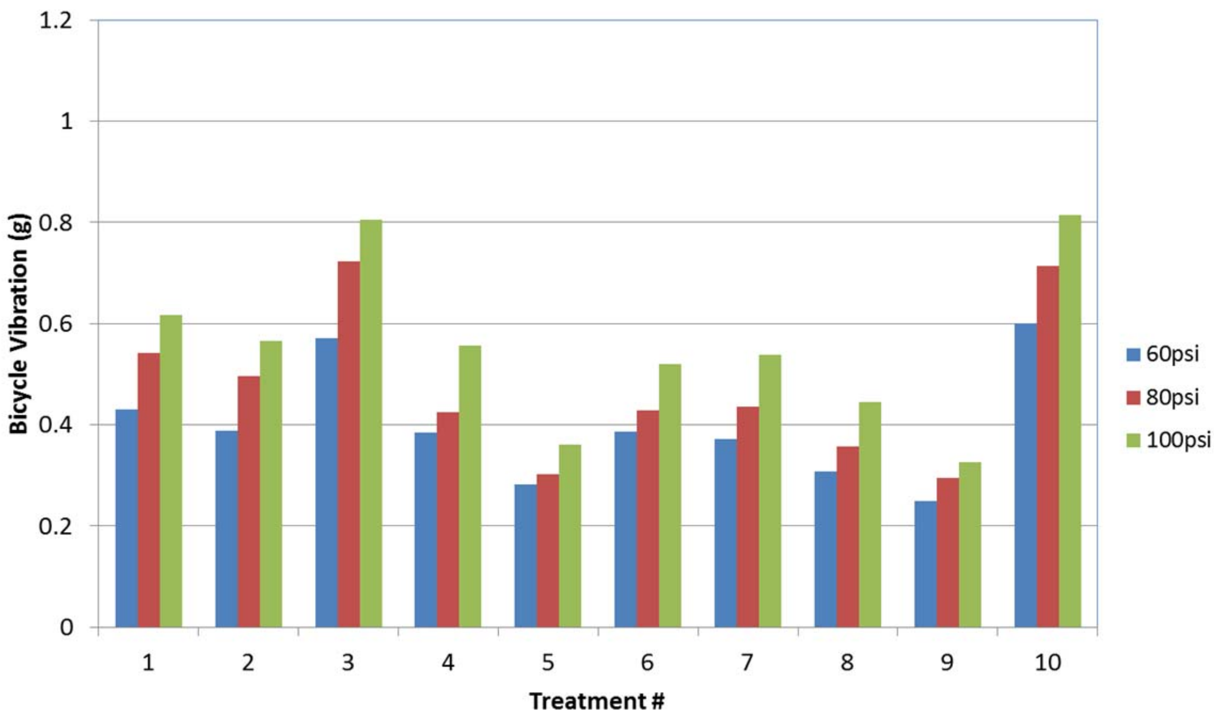


Figure 4.18: Bicycle vibration measured with different tire pressures on Mon-198 sections.
(See Table 3.4 for a description of each treatment #.)

Effect of Bicycle Frame Material on Vertical Acceleration

The data measured on July 12 and 13 on SLO-1 and Mon-198 (see Table 3.7) with several bicycles and different riders were used to evaluate the effect of bicycle frame materials on bicycle vibration. The vibrations measured using bicycles made of different materials are shown in Figure 4.19 for the different surface treatments. Note that no bicycle material normalization was included as part of the data processing procedure. Figure 4.19 indicates that bicycle vibrations measured using carbon bicycles are consistently higher than values measured using aluminum bicycles. The difference varies between 0.1 to 0.2 g.

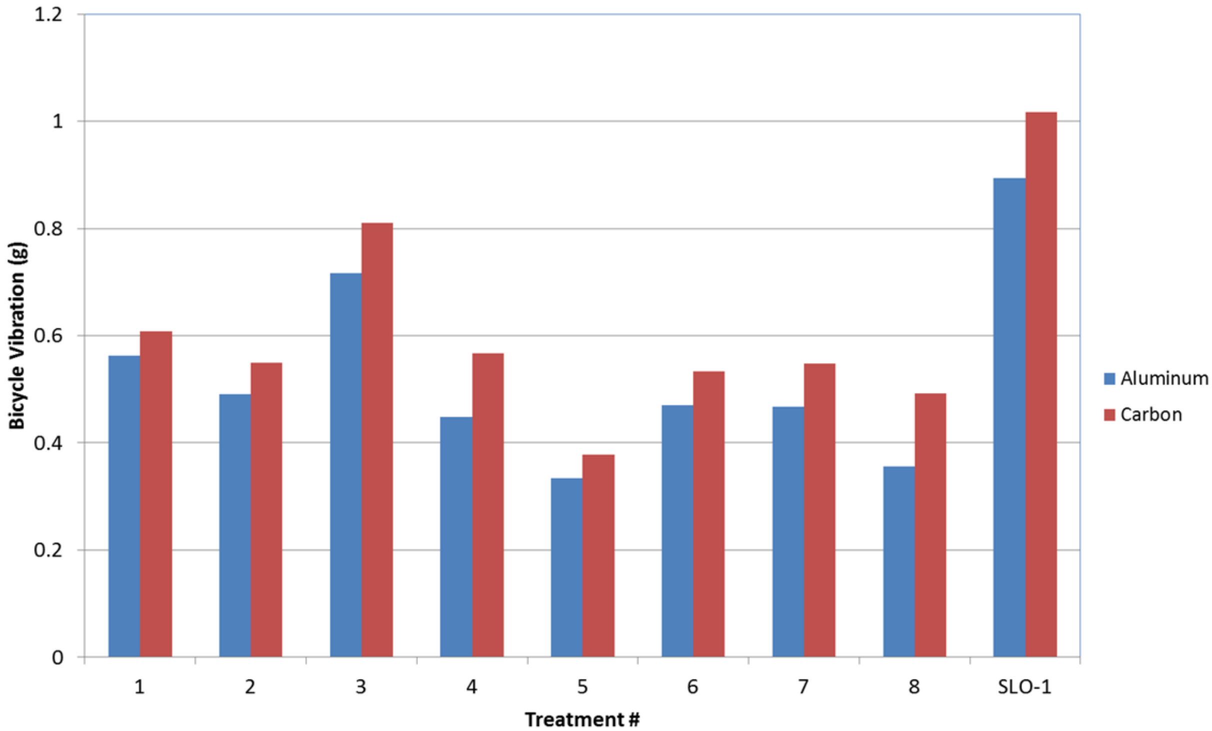


Figure 4.19: Bicycle vibration measured with different frame material for Mon-198 sections. (See Table 3.4 for a description of each treatment #; SLO-1 is treatment 11; data not collected for treatments 9 and 10 with different types of bicycle frames.)

4.5.2 Bicycle Vibration on Mon-198 and SLO-1 Test Sections

The next part of the study was the overall assessment of vibration on the Mon-198 and SLO-1 test sections. To accomplish this, bicycle vibration was measured using the data collected from different bicycle frames and riders on July 12, 13, and 23 along two lines on the Mon-198 test sections and SLO-1 survey sections. On Mon-198, one line was 6 inches (150 mm) inside the ETW, and the other was in the left wheelpath. On SLO-1, one line was just inside the ETW and the other was just outside the ETW. Bicycle vibrations could only be measured along the ETW for the SLO-1 sections because there was no traffic closure when measurements were taken. Bicycle vibration is presented in Figure 4.20 with the results separated into the two lines, and in Figure 4.21 with results for the two lines combined.

The bicycle vibration ranged from approximately 0.25 g to 1.10 g for the road sections of SLO-1 and Mon-198. The values on Mon-198 were overall significantly lower than those on SLO-1, although all the sections were constructed following the same specification.

Figure 4.20 shows that on many of the Mon-198 sections the bicycle vibration values are roughly the same for the wheelpath and the ETW measurements. On some of the Mon-198 sections differences appear between the ETW and left wheelpath that are the opposite of the MPD differences seen in Figure 4.4 and Figure 4.5. These may reflect variability of the correlation, and may also reflect the fact that on two of the Mon-198 sections (treatments 9 and 10 in Figure 4.21) the vibration data is from only one bicycle/rider (July 23) while on the other treatments the vibration data is from all of the different instrumented bicycles (July 13). These questions will be explored further for the final report.

The control section for Mon-198 (survey sections 19 and 20 in Figure 4.20, and treatment section 10 in Figure 4.21), had vibration values between approximately 0.65 and 0.82 g. This section showed considerable differences in vibration between the left wheelpath and the ETW, mirroring the differences in MPD that occurred in the year between construction and macrotexture testing. The old HMA overlay found on Mon-198 (survey sections 17 and 18, and treatment section 9, in Figure 4.20 and Figure 4.21, respectively) had the lowest vibration of about 0.30 g.

From the results shown in Figure 4.20 and Figure 4.21, it can be seen that the 5/16" PME chip seal and the 3/8" chip seal with a modified gradation (treatments 1 and 2) had lower vibration than the coarser 3/8" chip seal (control, treatment 10) or the same coarser 3/8" chip seal with steel wheel rolling (treatment 3). It can also be seen in Figure 4.20 that for the relatively untrafficked condition just inside the ETW, the steel roller (treatment 3, survey section 4) reduced the vibration compared to the same treatment where the chips were embedded with a rubber-tired roller (treatment 10, survey section 20) but that trafficking in the wheelpath over approximately a year had a bigger effect (treatment 10, survey section 19) in the hot summertime environment of Mon-198.

Figure 4.21 also shows that the five other treatments (treatments 4 to 8) all had bicycle vibration values less than the control section (treatment 10) and higher values than the old HMA overlay (treatment 9). The microsurfacing had the lowest bicycle vibration value, about 0.35 g.

As noted, all of the treatments reduced the bicycle vibration, as compared to the untreated control section on Mon-198. It is not known whether application of these treatments on SLO-1 would result in the same bicycle vibration values seen on Mon-198 (for example, about 0.4 mm for treatment 8 in Figure 4.21), or whether the difference between the remedial treatment bicycle vibration and the control bicycle vibration of about 0.4 g (change from treatment 10 [control] to treatment 8 in Figure 4.21) would be applicable to SLO-1. If the difference in vibration were the result of the treatments instead of the values seen on Mon-198, then the cinder seal, double chip seal, slurry seal, and sand seal would be expected to reduce the SLO-1 vibration values from around 1.0 g to about 0.7 g, while the mirosurfacing would reduce the SLO-1 vibration values to about 0.55 g. These values should be kept in mind when reviewing the results of correlation of MPD, bicycle vibration, and bicyclist ride quality in Sections 4.6 and 4.7 of this technical memorandum.

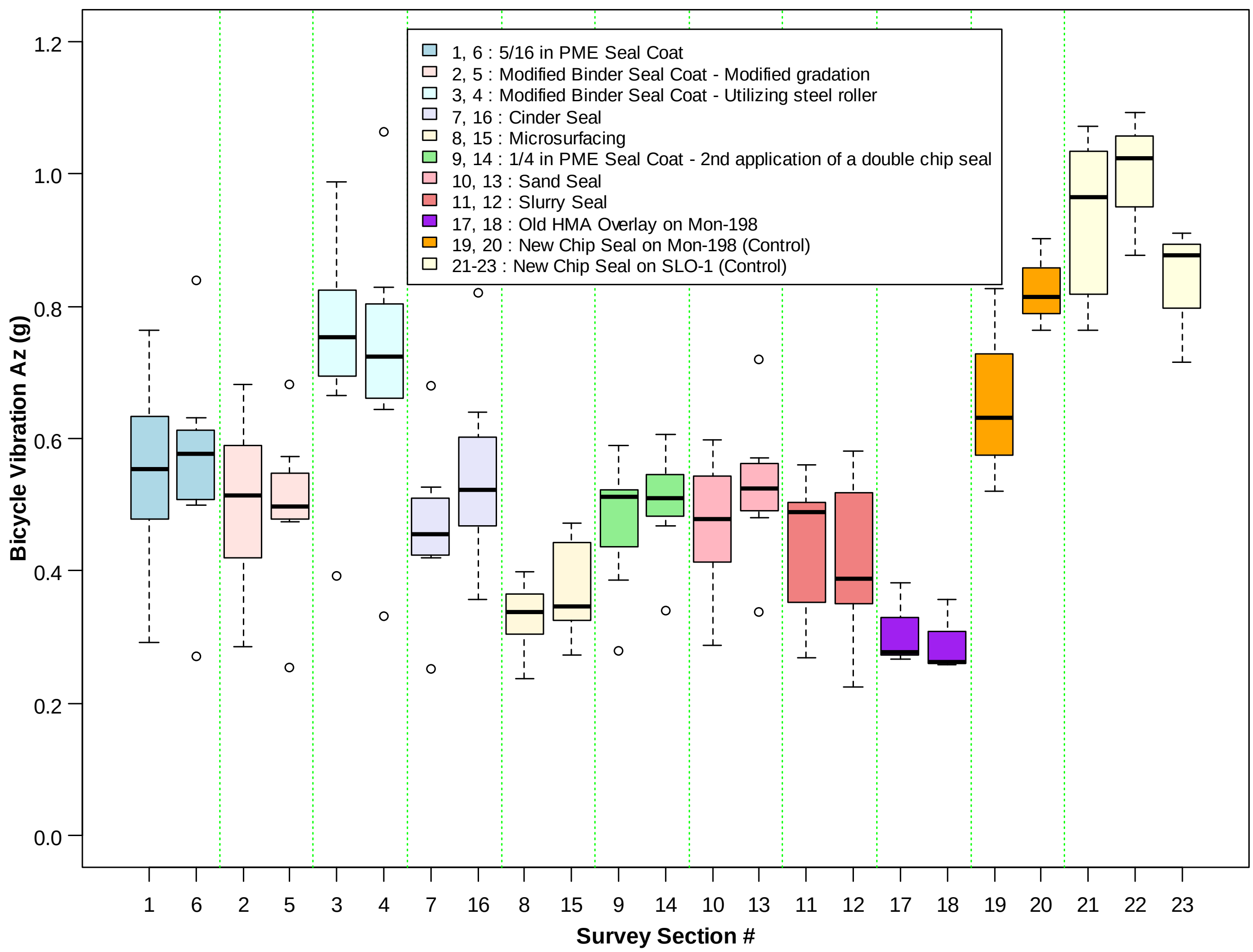


Figure 4.20: Bicycle vibration along the inside of ETW (left) and the left wheelpath (right) for each of the Mon-198 test sections, and along the ETW for three different test sections on SLO-1.

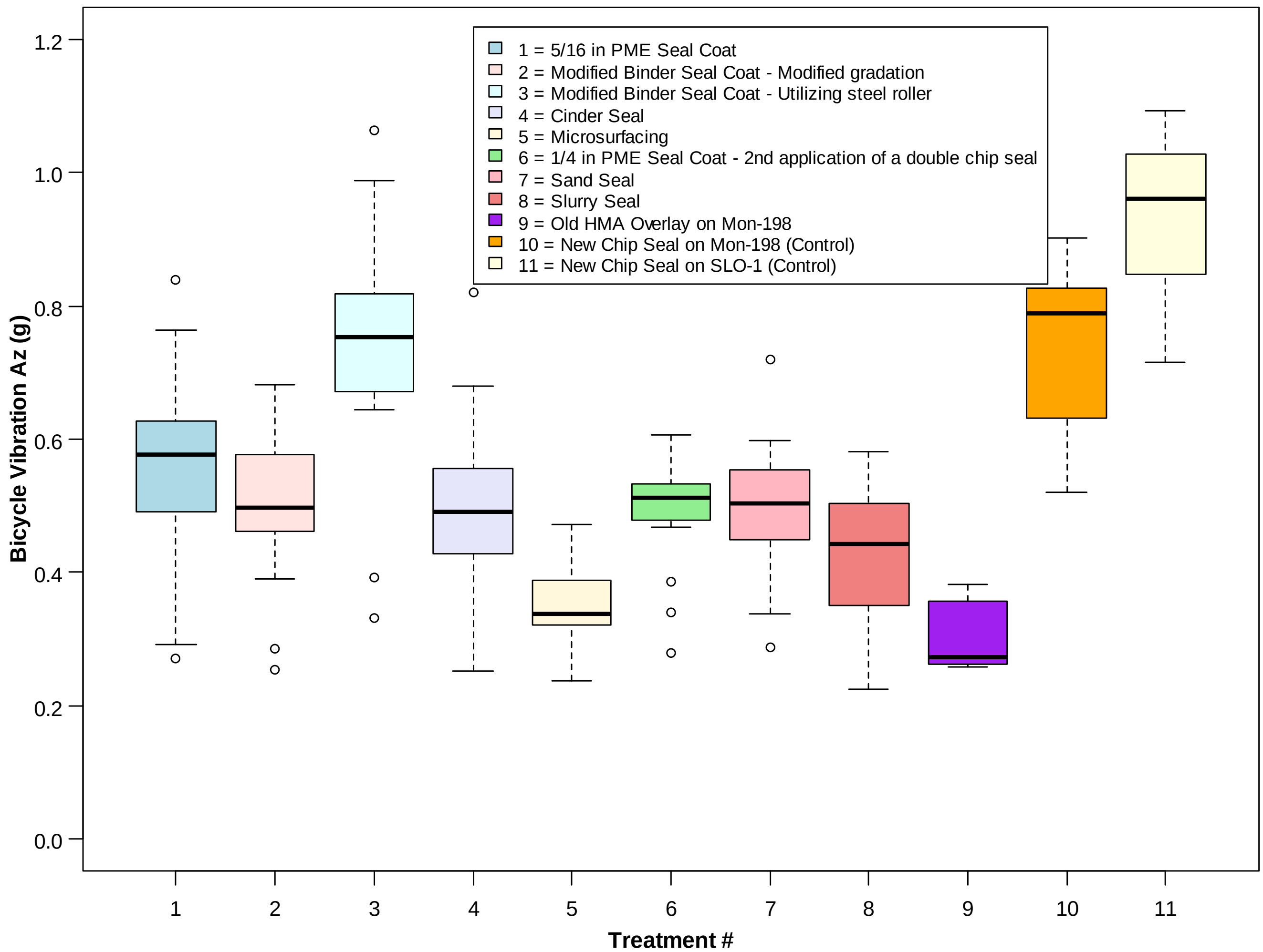


Figure 4.21: Bicycle vibration by treatment type for all Mon-198 and SLO-1 test sections.

4.6 Correlations Between Macrotexture, Vibration, and Ride Quality

The bicyclist ride quality survey was conducted on the eight Mon-198 test sections and three SLO-1 bicyclist survey subsections. On Mon-198 the eight test sections were divided into 16 survey sections reflecting two paths taken by the bicyclists on each test section, one along the ETW and one in the left wheelpath. On SLO-1 the survey was conducted at three sections. A total of 23 effective participant samples from the Mon-198 survey and 11 effective participant samples from the SLO-1 survey were used for the analysis. The survey forms (pre-ride, in-ride, and post-ride) and raw survey results appear in Appendix E and Appendix F, respectively.

As shown in Figure 4.22, the correlation analysis considered the average macrotexture (MPD) of each Mon-198 and SLO-1 survey section measured using the LTS, the average normalized vibration (vertical acceleration in *g*, referred to as Az, *g)* of each survey section measured using accelerometers on all the instrumented bicycles, average reported bicyclist speeds (Speed), the ratio of survey participants who rated the pavement “acceptable”

(Acceptability), and the ride quality level rated on a 1-to-5 scale (Ride quality level) on each survey section. The MPD and vibration results from the old HMA overlay (treatment 9) and coarser 3/8" chip seal chip seal (treatment 10) on Mon-198 are not included in the correlation plots because the bicycle ride quality survey was not performed on those sections.

The main observations from the correlation include the following:

a. High correlations were revealed between MPD, vertical bicycle acceleration, bicyclist acceptability, and ride quality level.
b. No significant correlation was found between other variables and bicyclist speed (small set of speeds).
c. Vibration appears to be somewhat more sensitive to MPD when MPD values are above 2 mm.
d. The relationship between MPD and ride quality is approximately linear.
e. The approximate range of MPD for bicyclist ride quality "Acceptability" is based on a straight line interpolation in Figure 4.22 for the percentage of participants who rated sections as "Acceptable":
    - 80 percent found 2.0 mm acceptable
    - 60 percent found 2.3 mm acceptable
    - 50 percent found 2.5 mm acceptable
    - 40 percent found 2.7 mm acceptable.
f. The average ride quality level rating for an MPD of 2 mm was approximately 3 on a scale of 1 to 5, and the average rating for an MPD of 2.7 is about 2 on the same 1 to 5 scale.

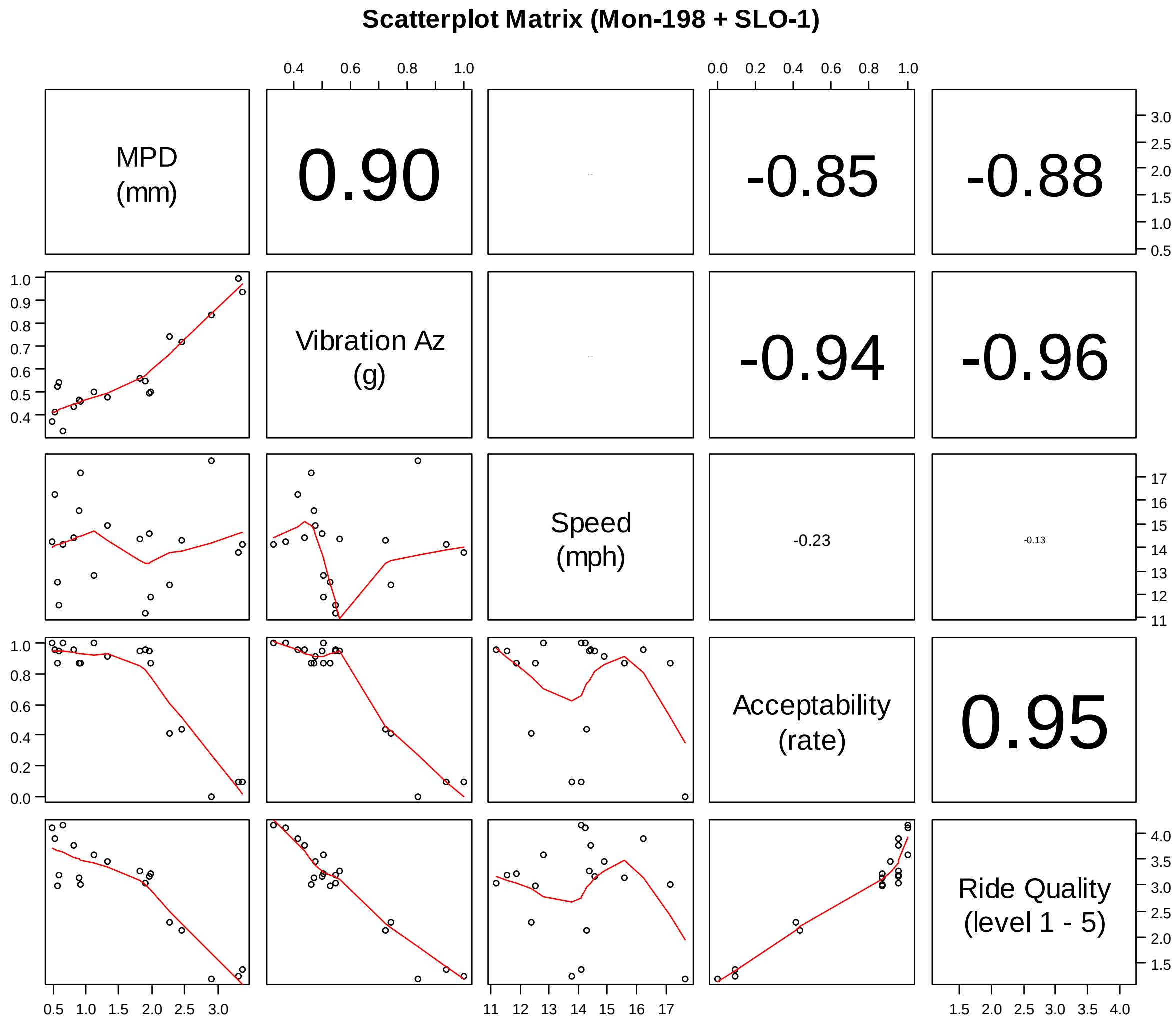


Figure 4.22: Correlations between MPD, acceleration, bicycling speed, bicyclist acceptability, and ride quality level (Mon-198 test sections).
Note: Scatterplots and smooth fitted lines are shown in lower panels. Correlations between variables are shown in upper panels, with the size of the type within the box proportional to absolute correlation.

4.7 Initial Modeling Results

Some of the initial results of modeling the effects of bicycle vibration and individual participant factors on the bicyclist ride quality rating are presented in this section, based on the survey results from the Mon-198 test sections.

4.7.1 Vertical Acceleration Assignment

The first step in modeling the relationship between bicyclist ride quality level and vertical acceleration was to assign vertical acceleration values to the cyclists whose bicycles had not been instrumented with accelerometers. The average standard deviation of the normalized vertical acceleration (SDNA) adjusted for speed was selected as the explanatory variable for modeling the bicyclists' opinions of the pavement. The tire pressure of the rider's bicycle was also used to assign SDNA to individuals. The rationale for selecting this assignment method was that (a) the influence of tire pressure on bicycle ride quality is well known and (b) average SDNA values had been determined at 60, 80, and 100 psi. Ideally, SDNA values would have been assigned based on frame type as well, due to the influence of frame material on bicyclist ride quality, but the SDNA values had all been determined on a carbon-frame road cycle.

4.7.2 Multilevel Modeling

The format of the bicycle-pavement data collected on Mon-198, with multiple observations made by the same individual, lends itself to multilevel modeling, which can be thought of as "ordinary regression models that have additional variance terms for handling non-independence due to group membership" (*15*). This describes the Mon-198 data situation well, though the pavement ride quality ratings are non-independent because they come from the same person. Put another way, "nesting individuals [*i.e., ride quality ratings*] within groups [*i.e., individuals*] can produce additional sources of variance (non-independence) in data" (*15*) (emphasis indicated by italic within brackets have been placed by authors of this memo).

Nevertheless, a first approximation of the link between bicyclist ride quality and vertical acceleration of the bicycle, by using a simple linear regression of average bicyclist ride quality rating for each of the eight Mon-198 sections by the average standard deviation of the SDNA at varying bicyclist speeds, results in an R-squared value of 0.93. However, adopting a multilevel modeling approach allows for the inclusion of other explanatory variables included in the survey, including the cyclist's reasons for bicycling, bicycling history, age, etc., to control for the independent contribution of the SDNA to bicyclist ride quality ratings.

The first step in multilevel random coefficient modeling is to determine "the levels at which significant variation exists" (*15*). Three statistical tests help to answer this question about the source of variance in the ride quality ratings: (1) determining the amount of variance in the bicyclist ride quality ratings that can be explained by the individual assigning the rating, (2) testing the reliability of the means of the bicyclist ride quality ratings by individuals, and (3) testing "whether the variance of the intercept is significantly larger than zero" (*15*). Using an unconditional means model—in which only a common intercept and the between-group and within-group error terms ("group" means individual in this case) are used to explain the variation in bicyclist ride quality—shows that the between-group variance is 0.196, and the within-group variance is 0.741. Therefore, the variance between individuals accounts for 0.20 of the total variance in bicyclist ride quality ratings. The average reliability of the individual bicyclist ride quality rating means is only slightly below the acceptability cutoff of 0.70 (0.675). And finally, contrasting the log-likelihood of the unconditional means model with that of a model without a random intercept yields a likelihood ratio value of 16.8, which is significant on a Chi-squared distribution with 1 degree of freedom at the 0.0001 level. These statistics indicate that the model should allow for random variation in bicyclist ride quality ratings among individuals.

A model was then built that addressed all three sources of variation in the data: within-individual variation, between-individual intercept variation, and between-individual slope variation. In the final model, the within-individual variation in bicyclist ride quality rating is explained by the SDNA, with a coefficient significant at the 0.0001 level. The between-individual intercept variation is explained by the following individual-level variables: age, ranking of ride enjoyment due to companions and due to windiness during the ride, and the number of purposes for which they ride, the coefficients for which were all significant at the 0.05 level. Furthermore, the SDNA value and the bicyclist ride quality slope is allowed to randomly vary across individuals and is specified to be a function of an individual-level variable, the number of miles ridden on a bicycle in the past week. This cross-level interaction coefficient is found to be significant at the 0.005 level.

4.7.3 Model Interpretation

The model coefficients (Table 4.2) indicate that for each individual, higher bicycle vibration (SDNA) values for a particular segment lead to lower bicyclist ride quality ratings, as expected. Older individuals gave higher bicyclist ride quality ratings than their younger counterparts, all else held equal, perhaps due to a lifetime of experience bicycle riding on a variety of roads. Similarly, the model shows that individuals whose enjoyment of a ride was least influenced by companions gave higher ride quality ratings than their peers. Perhaps these individuals were more willing to seek out inaccessible roads, where companions would hinder their ride, and thus have accumulated many rides on rougher terrain. Interestingly, those who rated wind low on their scale of influences of bicycle ride enjoyment and those who listed a larger number of bicycle riding purposes were likely to give lower ride quality ratings. Somewhat surprisingly, those individuals who had ridden more in the last week had steeper ranking slopes, suggesting that their greater experience allowed them to more confidently rate a given pavement treatment segment's ride quality level in either extreme—very positively or very negatively.

Table 4.2: Coefficients of the Models

Variation Explained	Variable	Coefficient Value	d.f.	t-value	p-value
	(Intercept)	-67.366	149	-2.579	0.011
Within-individual variation	SDNA	-2.94	149	-4.903	0.000
Between-individual intercept variation	Year Born	0.038	17	2.795	0.012
	Influence of Companions on Enjoyment	0.154	17	3.855	0.001
	Influence of Wind on Enjoyment	-0.12	17	-2.31	0.034
	Sum of Bicycle Ride Purposes	-0.16	17	-2.135	0.048
Between-individual slope variation	SDNA: Miles Ridden Last Week	-0.007	149	-3.208	0.002

4.7.4 Model Goodness of Fit Statistics

Firmly established and widely-accepted goodness of fit statistics are difficult to find for multilevel models. Nevertheless, the full model improves upon the null model as well as the same model without random effects at significant levels based on model comparisons of deviance levels with a Chi-squared distribution (Table 4.3 and Table 4.4). Furthermore, the sizeable decreases in the Akaike information criterion (AIC) and Bayes information criterion (BIC) between the three iterations of the model, from null to without random effects to full random effects, provide strong evidence that the full model is a significant improvement upon its predecessors.

Table 4.3: Deviance Difference Between Null and Full Models

Model	df	AIC	BIC	Log-likelihood	Likelihood Ratio	p-value
Null model	3	467.33	476.77	-230.66	-	-
Full model	11	378.90	413.13	-178.45	104.43	0.000

Table 4.4: Deviance Difference Between Full Model With and Without Random Effects

Model	df	AIC	BIC	Log-likelihood	Likelihood Ratio	p-value
Full model without random effects	9	402.08	430.09	-192.04	-	-
Full model	11	378.90	413.13	-178.45	27.18	0.000

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This technical memorandum summarizes the macrotexture characterization—in terms of the mean profile depth (MPD)—of different pavement surface treatments using three measurement methods. The memo also presents the results of measurements of bicycle vibration on many of those test sections, as well as the results of an initial survey to assess bicyclist ride quality on many of those sections. Lastly, this memorandum also presents preliminary correlations of macrotexture, bicycle vibration, and bicyclist ride quality, and initial efforts to develop models that explain how ride quality is determined by vibration and by demographic and bicycling behavior variables. The following conclusions have been drawn from the results and analyses presented:

1. The three macrotexture test methods—the sand patch method, the laser texture scanner (LTS), and the inertial profiler (IP)—can all be used to characterize pavement macrotexture, and they all produce similar macrotexture trend results. The MPD values measured by the sand patch method are higher than those from the LTS when there is greater macrotexture.
2. The chip seals on SLO-1 and Mono-395 had larger MPD, with median values ranging between 1.7 mm and 3.0 mm, compared to Mon-198, which had median values ranging between 1.7 mm and 1.8 mm.
3. The SLO-227 chip seal, which used a finer 3/8" aggregate gradation, had median MPD values of about 1.2 mm, considerably lower than those of the chip seals on SLO-1, Mon-198, and Mono-395 that used a coarser 3/8" aggregate gradation. This conclusion stands, even considering the variability between the latter three chip seals built with the same specification. The variability between those three chip seals is likely due to a combination of different materials, construction, and the effects of trafficking in different climates and for different periods of time for the texture measured in the wheelpath. (See Section 3.1 and Table 3.3 for details regarding the finer and coarser 3/8" chip seals.)
4. The MPD of the SLO-41 microsurfacing was about 1.2 mm, similar to that of the finer 3/8" chip seal placed on SLO-227.
5. The MPD of the shoulders (outside of Edge of Traveled Way [ETW]) is typically somewhat larger than that of inside of the ETW, and there is an even greater reduction where texture was measured in the wheelpaths. This indicates that traffic can reduce MPD under some circumstances, although it did so less on the SLO-1 sections, which are in a cooler climate than the other sections measured.
6. Additional rubber-tired rolling months after construction seemed to produce only a small reduction in MPD on SLO-1. Steel wheel rolling at the time of construction on one Mon-198 test section resulted in higher MPD than that of a section with a similar material and rubber-tired rolling at the time of construction. The effects of additional rolling on the Mono-395 section could not be seen in the

measured MPD values measured along the entire project, although additional information regarding the precise location of the additional rolling has not yet been obtained from District 9.

7. Two alternative chip seals with gradations different from the finer and coarser 3/8" chip seals placed elsewhere were constructed on Mon-198 in test sections. The MPD values near the shoulders of the two alternative chip seals (treatments 1 and 2) placed on Mon-198 in June 2013 were around 1.8 to 2 mm, which is similar to the roughly 1.7 to 1.8 mm near the shoulder of the coarser 3/8" chip seal placed in the summer of 2012 (treatment 10), but lower than the MPD values on SLO-1 and Mono-395 built with the same coarser 3/8" chip seal specification. Treatments 1 and 2 may have some reduction in MPD after a year of traffic, as occurred on treatment 3 where traffic reduced the MPD to about 1.6 mm in the wheelpath after a year. However, the two alternative chip seals had lower MPD values than the coarser 3/8" chip seal placed on SLO-1, which reflects the possibility for variation within the coarser 3/8" chip seal specification. It is somewhat uncertain whether these two alternatives can consistently produce MPD values lower than those on SLO-1 as they did on Mon-198.
8. The MPD values of the Mon-198 sections with the five treatments (cinder seal [treatment 4], microsurfacing [treatment 5], double chip [treatment 6], sand seal [treatment 7], and slurry seal [treatment 8]) applied to the existing chip seal were all lower than the MPD of the untreated chip seal section (shown as treatment 10).
9. As noted in the second conclusion, the MPD of the chip seal on Mon-198 is less than that of the chip seals on SLO-1 and Mono-395. It is unknown whether application of these treatments on SLO-1 would result in the same final MPD values seen on Mon-198, or whether the change (difference between initial and final) in MPD values seen on Mon-198 would be achieved on SLO-1. If the treatments produced the same change in MPD found on the Mon-198 sections instead of the final values on Mon-198, then the cinder seal, microsurfacing, slurry seal, and sand seal would be expected to reduce the SLO-1 MPD values from around 3.0 mm to about 2.0 mm, while the double chip seal would reduce the SLO-1 MPD values to about 2.6 mm. On the other hand, if the treatment resulted in the same final values on SLO-1 as on Mon-198, then the cinder seal, microsurfacing, slurry seal, and sand seal would be expected to produce MPD values of 0.5 to 1 mm, while the double chip seal would reduce the SLO-1 MPD values to about 1.2 mm.
10. High correlations were revealed between MPD, vertical bicycle acceleration, what bicyclists considered "acceptable," and ride quality level. No significant correlation was found between bicyclists' rating of ride quality and acceptability versus bicyclist speed, although only a small range of speeds was included in the study.

11. The range for what bicyclists considered an “acceptable” level of MPD was found to be approximately between 2.0 and 2.7 mm, with the following percentages of the riders participating in the Mon-198 and SLO-1 surveys rating that range of MPD values as follows:
    1. 80 percent found 2.0 mm acceptable.
    2. 60 percent found 2.3 mm acceptable.
    3. 50 percent found 2.5 mm acceptable.
    4. 40 percent found 2.7 mm acceptable.
12. An MPD of 2 mm results in an average ride quality rating of approximately 3 on a scale of 1 to 5, while an MPD of 2.7 mm results in an average rating of about 2 on the same scale.

5.2 Recommendations

Based on the results of this study, the following preliminary recommendations are provided for consideration in future efforts to investigate pavement macrotexture and its effect on bicyclist vibration and ride quality:

1. To account for bicycle traffic and bicyclist ride quality, modified binder with the finer 3/8" grading chips or smaller should be used and the coarser 3/8” grading should not be used. Clear guidance should be provided to the designer.
2. Measurement of macrotexture on a larger sample of the two chip seal test sections with alternative gradations tested on Mon-198 (treatments 1 and 2) should be performed to better determine the texture variability, as well as their viability when applied to roadways with bicycle traffic.
3. Mandating the use of a steel roller as opposed to allowing steel or rubber-tired rolling during construction to reduce MPD is not recommended.
4. The use of additional rolling after initial construction to reduce MPD is not recommended.
5. Consider either cinder seal, microsurfacing, slurry, or sand seal as a remediation treatment for SLO-1. The slurry and sand seals may be the better options because bleeding appeared on Mon-198 sections with microsurfacing and especially on the section with the cinder seal. The second application of a chip seal to produce a double chip seal may also be considered to improve ride quality but its surface texture may be coarser than that of the slurry or sand seals.

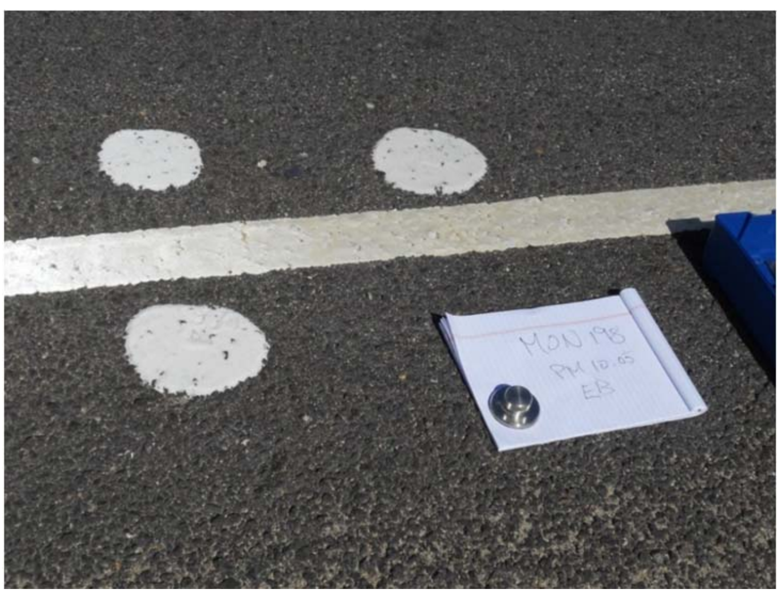
6 REFERENCES

1. Sandberg, U., and J.A. Ejsmont. *Tyre/road noise reference book*. 2002: INFORMEX, Harg, SE-59040 Kisa, Sweden.
2. Anderson, D.A., R.S. Huebner, J.R. Reed, J.C. Warner, and J.J. Henry. *NCHRP web document 16: Improved surface drainage of pavements. Project 1-29*. 1998. Transportation Research Board, National Research Council: Washington, D.C.
3. Flintsch, G., E. de León, K. McGhee, and I. Al-Qadi. *Pavement surface macrotexture measurement and applications*. Transportation Research Record: Journal of the Transportation Research Board. 2003. **1860**(1): p. 168-177.
4. Panagouli, O.K., and A.G. Kokkalis. *Skid resistance and fractal structure of pavement surface*. Chaos, Solitons & Fractals. 1998. **9**(3): p. 493-505.
5. Rezaei, A., J.T. Harvey, and Q. Lu. *Investigation of noise and ride quality trends for asphaltic pavement surface types:five-year results*. 2012. UCPRC-RR-2012-04, University of California Pavement Research Center: Davis, CA.
6. Bu, Y., T. Huang, Z. Xiang, X. Wu, and C. Chen. *Optimal design of mountain bicycle based on biomechanics.* Transactions of Tianjin University, 2010. **16**(1): p. 45-49.
7. Lorenzo, D.S.D., and M.L. Hull. *Quantification of structural loading during off-road cycling.* Journal of Biomechanical Engineering, 1999. **121**(4): p. 399-405.
8. McKenna, S., M. Hill, and M. Hull. *Methods for fatigue testing off-road bicycle handlebars based on assembly effects using two different stem designs.* Journal of Testing and Evaluation, 2003. **31**(2): p. 10.
9. McKenna, S.P., M.R. Hill, and M.L. Hull. *A single loading direction for fatigue life prediction and testing of handlebars for off-road bicycles.* International Journal of Fatigue, 2002. **24**(11): p. 1149-1157.
10. Wilczynski, H., and M.L. Hull. *A dynamic system model for estimating surface-induced frame loads during off-road cycling.* Journal of Mechanical Design, 1994. **116**(3): p. 816-822.
11. Pucher, J., J. Dill, and S. Handy. *Infrastructure, programs, and policies to increase bicycling: An international review.* Preventive Medicine, 2010. **50**: p. S106-S125.
12. Tal, G., and S. Handy. *Children's biking for nonschool purposes: getting to soccer games in Davis, California.* Transportation Research Record, 2008. (2074): p. 40-45.
13. Xing, Y., S.L. Handy, and P.L. Mokhtarian. *Factors associated with proportions and miles of bicycling for transportation and recreation in six small US cities.* Transportation Research Part D-Transport and Environment, 2010. **15**(2): p. 73-81.
13. Henry, J.J. *Evaluation of pavement friction characteristics*. 2000. NCHRP Synthesis 291, National Cooperative Highway Research Program (NCHRP): Washington, D.C.
14. P.I.A.R.C. *International PIARC experiment to compare and harmonize texture and skid resistance measurements.* 1995. Report No. AIPCR-01.040.T, PIARC: Brussels, Belgium.
15. Bliese, P. *Multilevel Modeling in R (2.5): A Brief Introduction to R, the multilevel package and the nlme package.* 2013. The R Project for Statistical Computing. *cran.r-project.org/doc/contrib/ Bliese_Multilevel.pdf.* (Accessed July 15, 2013.)

APPENDIX A: MACROTEXTURE MEASURED USING SAND PATCH (SP) METHOD

Pavement macrotexture was measured in terms of Mean Texture Depth (MTD) using the sand patch method at different locations for each road section. At least three measurements were conducted at each location. As shown in Figure A.1, the measurements were performed at approximately 6 inches [150 mm] both inside and outside the white edge of traveled way (ETW) stripes, where most bicyclists ride. Both traveling directions were measured for most sections. The results of measured macrotexture, in terms of MTD, are presented in Figure A.2.

(a) SLO-1 PM 60.16 coarser 3/8" gradation chip seal



(b) Mon-198 PM 10.05 coarser 3/8" gradation chip seal

Figure A.1: Example photographs of sand patch testing on pavement surface.

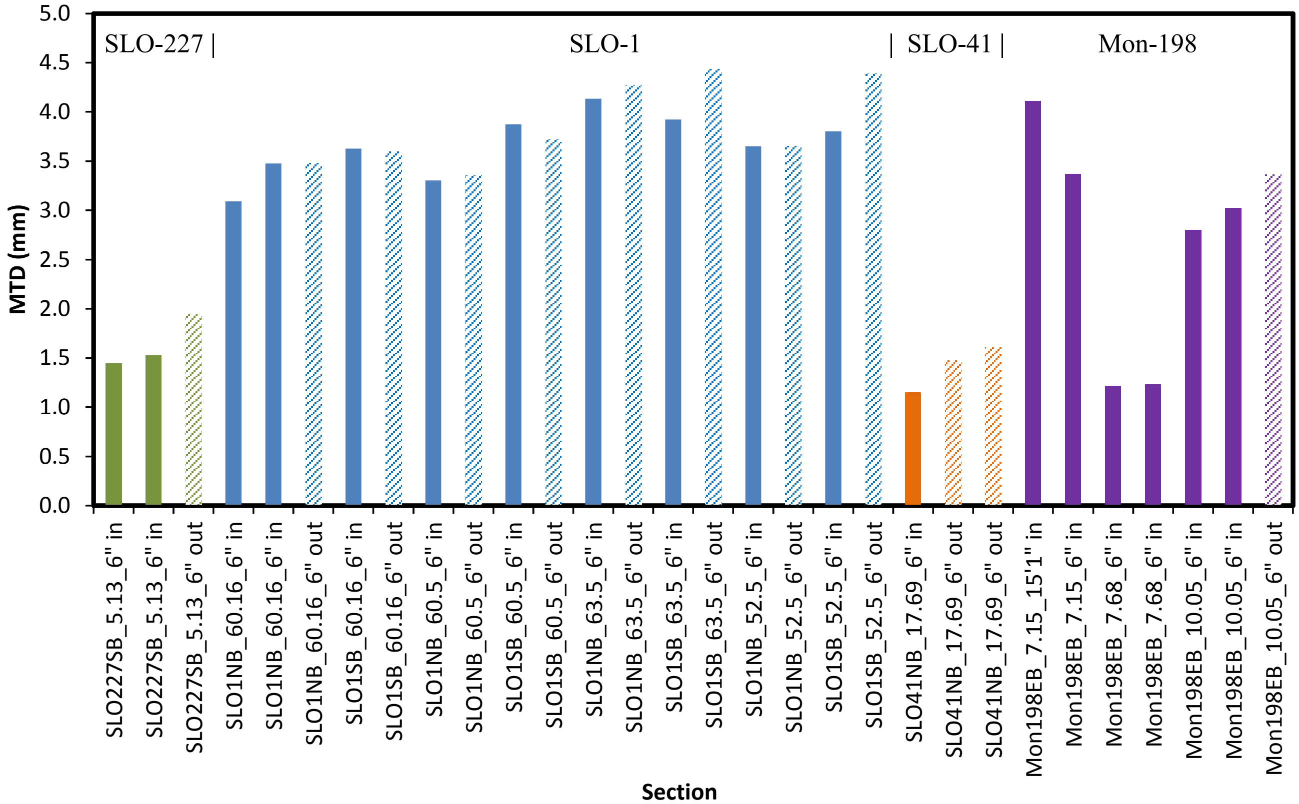


Figure A.2: MTD from sand patch testing for different road sections.
(Inside ETW measurements are shown with solid bars, Outside ETW measurements shown with patterned bars.)

The MTD values measured on SLO-227 (finer 3/8" gradation chip seal) and SLO-41 (microsurfacing) were relatively smaller than those of the coarser 3/8" gradation chip seals on SLO-1 and Mon-198, except at the location of Mon-198 EB PM 7.68, which is part of the same chip seal project built in 2012 with the coarser 3/8" gradation that had much lower MTD values. The MTD ranged from approximately 1.5 mm to 2.0 mm for the smoother road sections of SLO-227 and SLO-41. For the rougher road sections of SLO-1 and Mon-198, the MTD ranged from approximately 3.0 mm to 4.5 mm, which is approximately double the macrotexture of the smoother road sections of SLO-227 and SLO-41. The values on Mon-198 were somewhat lower overall than those on SLO-1, although both sections were built following the same specification. The values on the chip seal on SLO-227 were much lower than those on Mon-198 and SLO-1, reflecting the different gradation and a longer time for traffic embedment for the values inside the edge of traveled way. The MPD values on the microsurfacing on SLO-41 were similar to those of the chip seal on SLO-227.

Generally, the MTD at the outside of white stripe was slightly higher than that at the inside location, as shown in Figure A.2, most likely reflecting embedding and reorientation of the aggregate in the seals due to traffic compaction.

ASTM E1845 provides an equation for calculating the Estimated Texture Depth (ETD), which is the same as Mean Texture Depth, from MPD. The equation is the same as Equation (3.2):

$$ETD\ (mm) = 0.8MPD\ (mm) + 0.2 \qquad \textbf{(A.1)}$$

The ETD-calculated values using this equation and the MPD values from the LTS measurements are presented in Figure A.3. It can be seen that the LTS device is using the ASTM equation to calculate MTD (ETD when calculated using a laser device). Using the same equation in reverse [i.e., MPD_SP = (MTD_SP – 0.2)/0.8], the MPD from the sand patch as compared with the MPD from the LTS is shown in Figure A.4. The results show that MPD calculated from sand patch measurements is larger than those measured using the LTS for the same locations in this study.

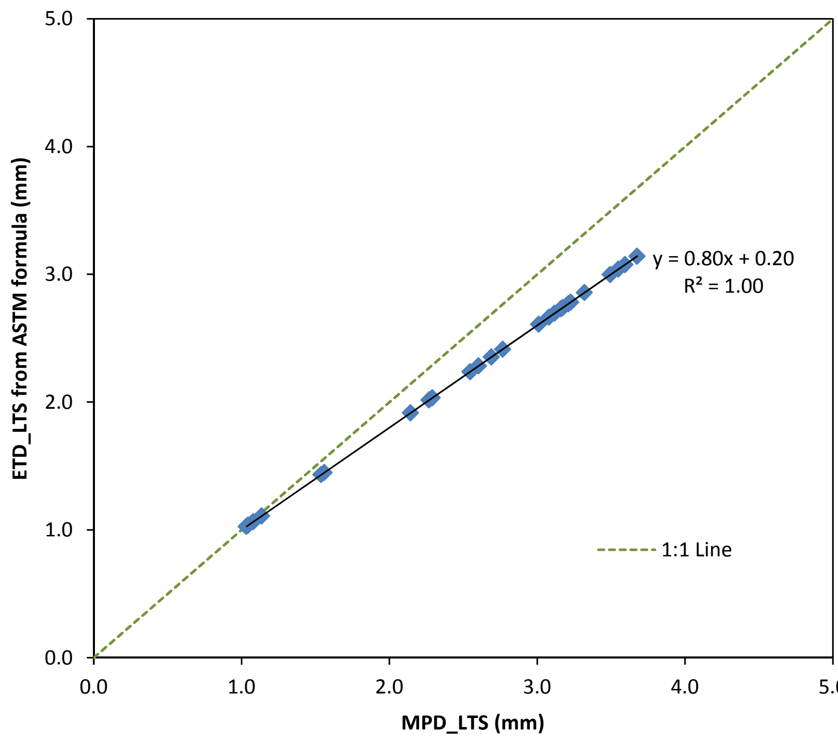


Figure A.3: Estimated Texture Depth (ETD, same as Mean Texture Depth) from MPD measured using LTS.

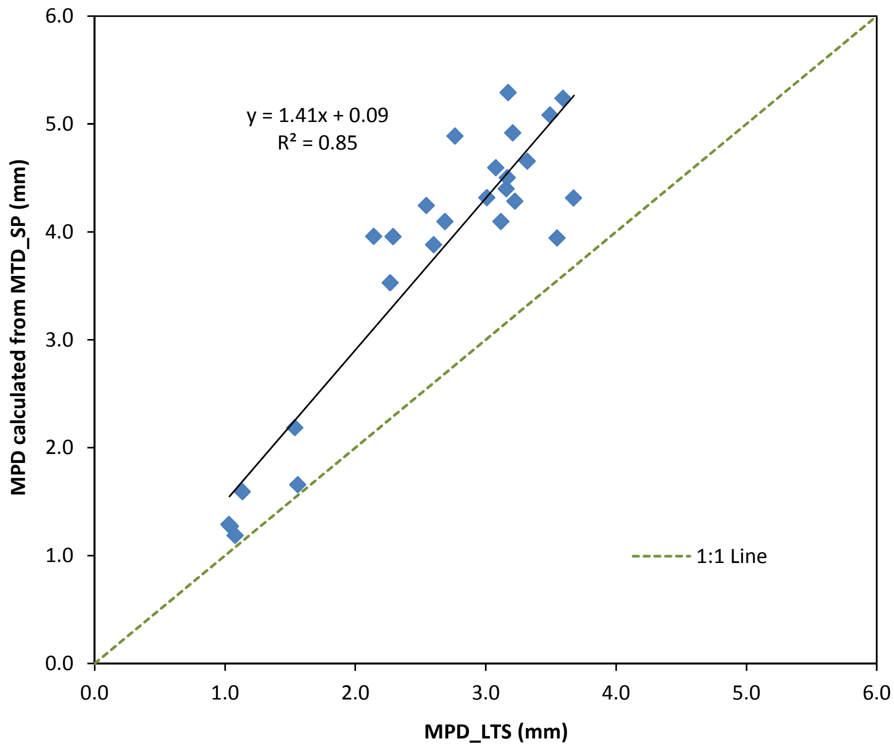
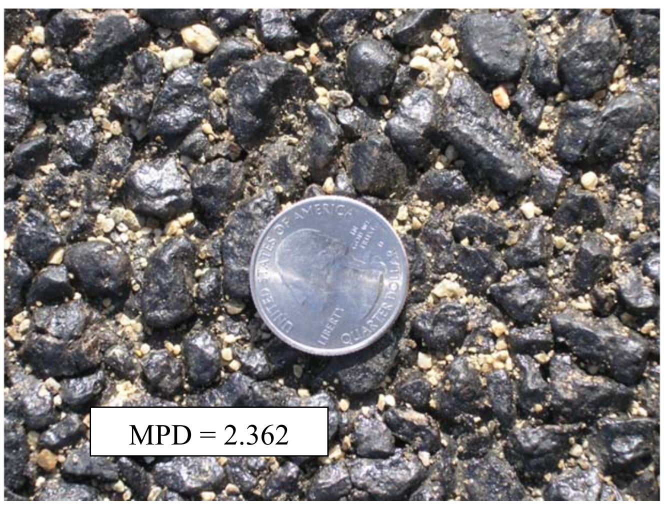


Figure A.4: Correlation between macrotexture parameters measured by sand patch (SP) and LTS. (MPD_SP is calculated from MTD_SP using the ASTM equation in reverse.)

APPENDIX B: PHOTOS AND MPD FROM LTS FOR TEST SECTIONS ON MON-198

#1 5/16" PME seal coat (PM 4.5-4.7)

#2 Modified-binder seal coat - Modified gradation (PM 4.7-4.9)



#3 Modified binder seal coat - Utilizing a steel roller (PM 4.7-4.9)

#4 Cinder seal (PM 10.4-10.2)

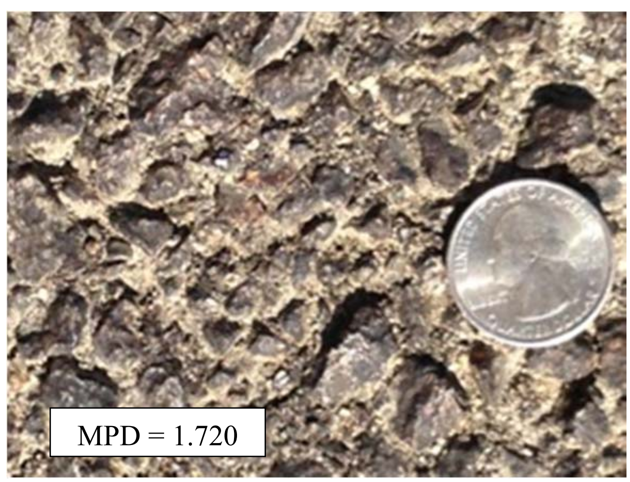
#5 Microsurfacing (PM 10.2-10.0)

#6 1/4" PME seal coat - double chip seal (PM 10.0-9.8)

#7 Sand seal (PM 9.8-9.6)

#8 Slurry seal (PM 9.6-9.4)

#9 Old HMA on Mon-198 (PM 5.1-5.3)



#10 New coarser 3/8" chip seal on Mon-198 (Control) (PM 9.4-9.2)

Figure B.1: Photographs of pavement surface macrotexture of test sections on Mon-198.

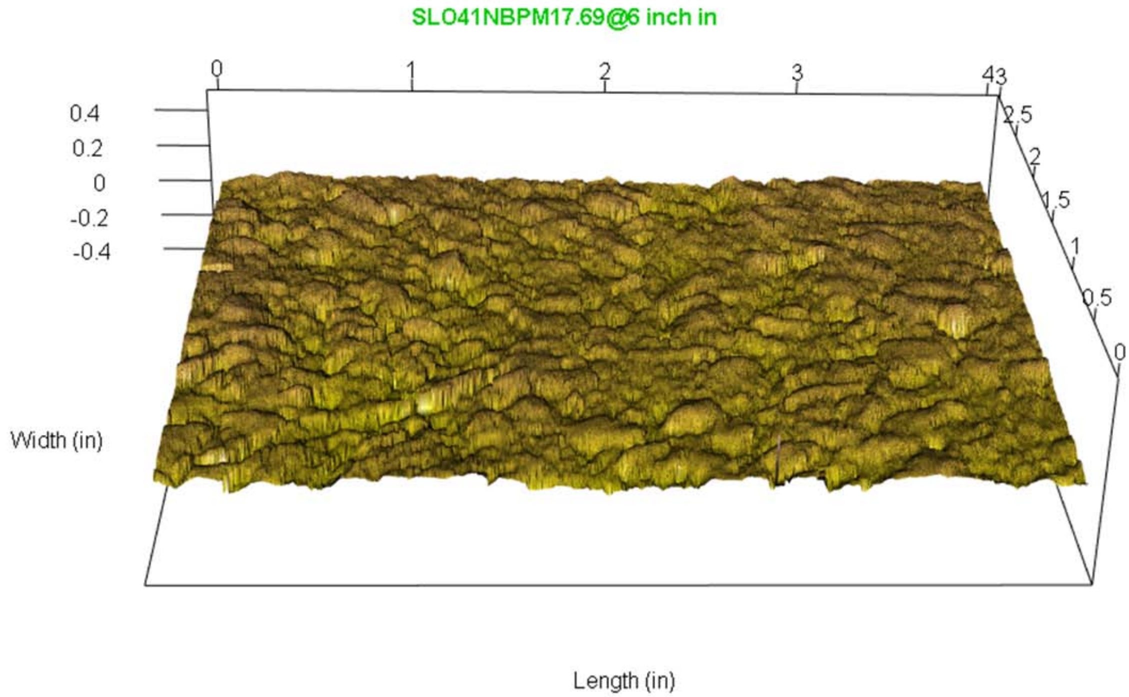
APPENDIX C: 3D MACROTEXTURE IMAGES FOR DIFFERENT ROAD SECTIONS

Table C.1: Summary of MPD Measured by LTS for All Road Sections

Route	Direction	PM (mile)	Location	Avg. MPD (mm)	Treatment	3D Figure in Appendix C
SLO-41	NB	17.69	6" inside ETW	1.081	Microsurfacing	C.1
SLO-41	NB	17.69	6" outside ETW	1.136	Microsurfacing	C.1
SLO-227	SB	5.13	6" inside ETW	1.561	Finer 3/8" chip seal	C.2
SLO-227	SB	5.13	6" outside ETW	1.539	Finer 3/8" chip seal	C.2
Mon-198	EB	7.15	6" inside ETW	2.901	Coarser 3/8" chip seal	C.3
Mon-198	EB	7.15	47" inside ETW	2.767	Coarser 3/8" chip seal	C.3
Mon-198	EB	7.15	30" inside ETW	2.144	Coarser 3/8" chip seal	C.3
Mon-198	EB	7.15	99" inside ETW	1.714	Coarser 3/8" chip seal	C.3
Mon-198	EB	7.68	6" inside ETW	1.046	Coarser 3/8" chip seal	C.3
Mon-198	EB	7.69	6" inside ETW	1.033	Coarser 3/8" chip seal	C.3
Mon-198	EB	10.05	6" inside ETW	2.270	Coarser 3/8" chip seal	C.3
Mon-198	EB	10.05	6" outside ETW	2.292	Coarser 3/8" chip seal	C.3
SLO-1	NB	60.16	6" inside ETW	3.119	Coarser 3/8" chip seal	C.4
SLO-1	NB	60.16	6" outside ETW	2.691	Coarser 3/8" chip seal	C.4
SLO-1	SB	60.16	6" inside ETW	3.227	Coarser 3/8" chip seal	C.4
SLO-1	SB	60.16	6" outside ETW	2.547	Coarser 3/8" chip seal	C.4
SLO-1	NB	60.5	6" inside ETW	2.604	Coarser 3/8" chip seal	C.4
SLO-1	NB	60.5	6" outside ETW	3.550	Coarser 3/8" chip seal	C.4
SLO-1	SB	60.5	6" inside ETW	3.080	Coarser 3/8" chip seal	C.4
SLO-1	SB	60.5	6" outside ETW	3.160	Coarser 3/8" chip seal	C.4
SLO-1	NB	63.5	6" inside ETW	3.211	Coarser 3/8" chip seal	C.4
SLO-1	NB	63.5	6" outside ETW	3.496	Coarser 3/8" chip seal	C.4
SLO-1	SB	63.5	6" inside ETW	3.321	Coarser 3/8" chip seal	C.4
SLO-1	SB	63.5	6" outside ETW	3.175	Coarser 3/8" chip seal	C.4
SLO-1	NB	52.5	6" inside ETW	3.677	Coarser 3/8" chip seal	C.4
SLO-1	NB	52.5	6" outside ETW	3.012	Coarser 3/8" chip seal	C.4
SLO-1	SB	52.5	6" inside ETW	3.169	Coarser 3/8" chip seal	C.4
SLO-1	SB	52.5	6" outside ETW	3.595	Coarser 3/8" chip seal	C.4
Test Sections and Control Sections on Mon-198						
Mon-198	EB	4.5 - 4.7	Inside ETW	1.90	#1 5/16" PME seal coat	C.5
Mon-198	EB	4.5 - 4.7	Left wheelpath	1.82	#1 5/16" PME seal coat	C.5
Mon-198	EB	4.7 - 4.9	Inside ETW	1.98	#2 Modified binder seal coat — 3/8" Modified gradation	C.5
Mon-198	EB	4.7 - 4.9	Left wheelpath	1.96	#2 Modified binder seal coat — 3/8" Modified gradation	C.5

Route	Direction	PM (mile)	Location	Avg. MPD (mm)	Treatment	3D Figure in Appendix C
Mon-198	EB	4.9 – 5.1	Inside ETW	2.27	#3 Modified binder seal coat — Utilizing a steel roller	C.5
Mon-198	EB	4.9 – 5.1	Left wheelpath	2.45	#3 Modified binder seal coat — Utilizing a steel roller	C.5
Mon-198	WB	10.2 – 10.4	Inside ETW	0.92	#4 Cinder seal	C.5
Mon-198	WB	10.2 – 10.4	Left wheelpath	0.59	#4 Cinder seal	C.5
Mon-198	WB	10.0 – 10.2	Inside ETW	0.65	#5 Microsurfacing	C.5
Mon-198	WB	10.0 – 10.2	Left wheelpath	0.49	#5 Microsurfacing	C.5
Mon-198	WB	9.8 – 10.0	Inside ETW	1.34	#6 1/4" PME seal coat - Second application of a double chip seal	C.5
Mon-198	WB	9.8 – 10.0	Left wheelpath	1.11	#6 1/4" PME seal coat - Second application of a double chip seal	C.5
Mon-198	WB	9.6 – 9.8	Inside ETW	0.89	#7 Sand seal	C.5
Mon-198	WB	9.6 – 9.8	Left wheelpath	0.57	#7 Sand seal	C.5
Mon-198	WB	9.4 – 9.6	Inside ETW	0.81	#8 Slurry seal	C.5
Mon-198	WB	9.4 – 9.6	Left wheelpath	0.52	#8 Slurry seal	C.5
Mon-198	EB	5.1 – 5.3	Inside ETW	1.00	#9 Old HMA Overlay on Mon-198	C.5
Mon-198	EB	5.1 – 5.3	Left wheelpath	1.22	#9 Old HMA Overlay on Mon-198	C.5
Mon-198	WB	9.2 – 9.4	Inside ETW	1.82	#10 New 2012 chip seal on Mon-198 (Control)	C.5
Mon-198	WB	9.2 – 9.4	Left wheelpath	1.61	#10 New 2012 chip seal on Mon-198 (Control)	C.5

C.1 SLO-41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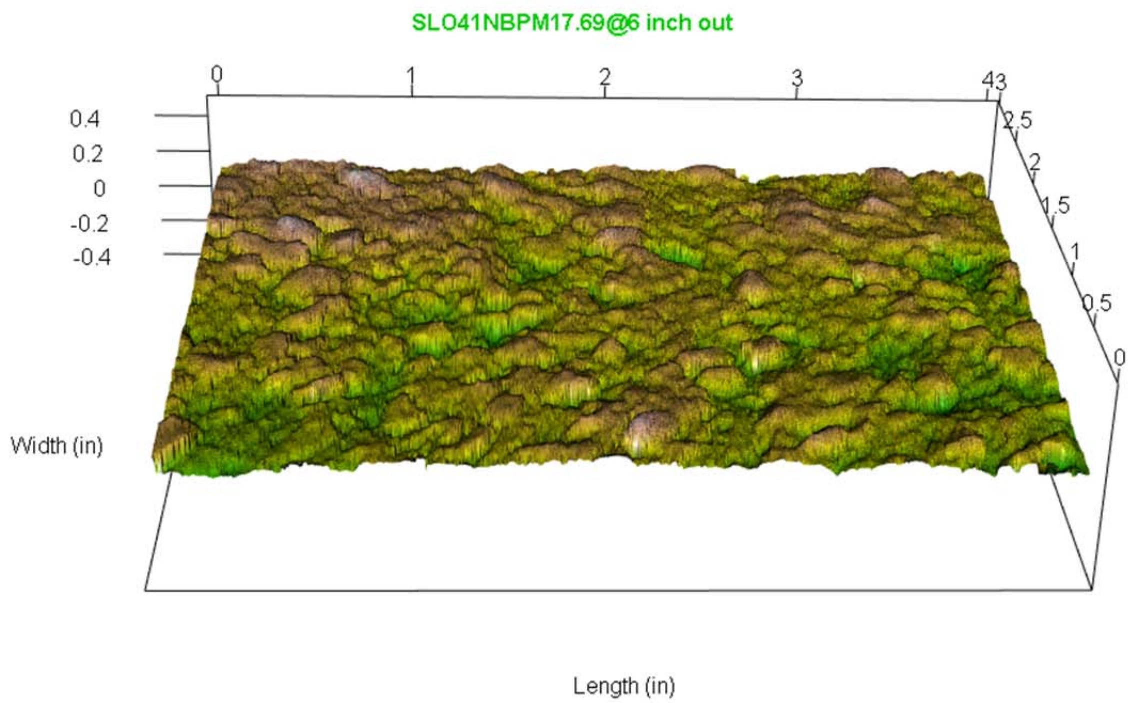
Width (in)
Length (in)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-0.4
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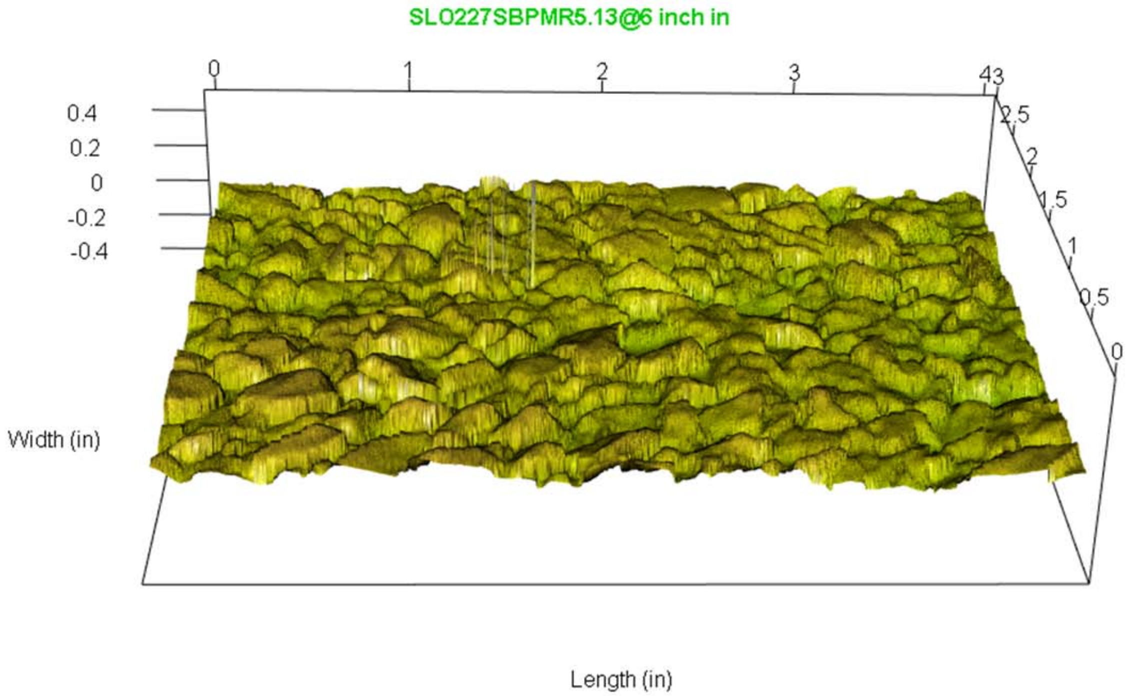
Width (in)
Length (in)

C.2 SLO-227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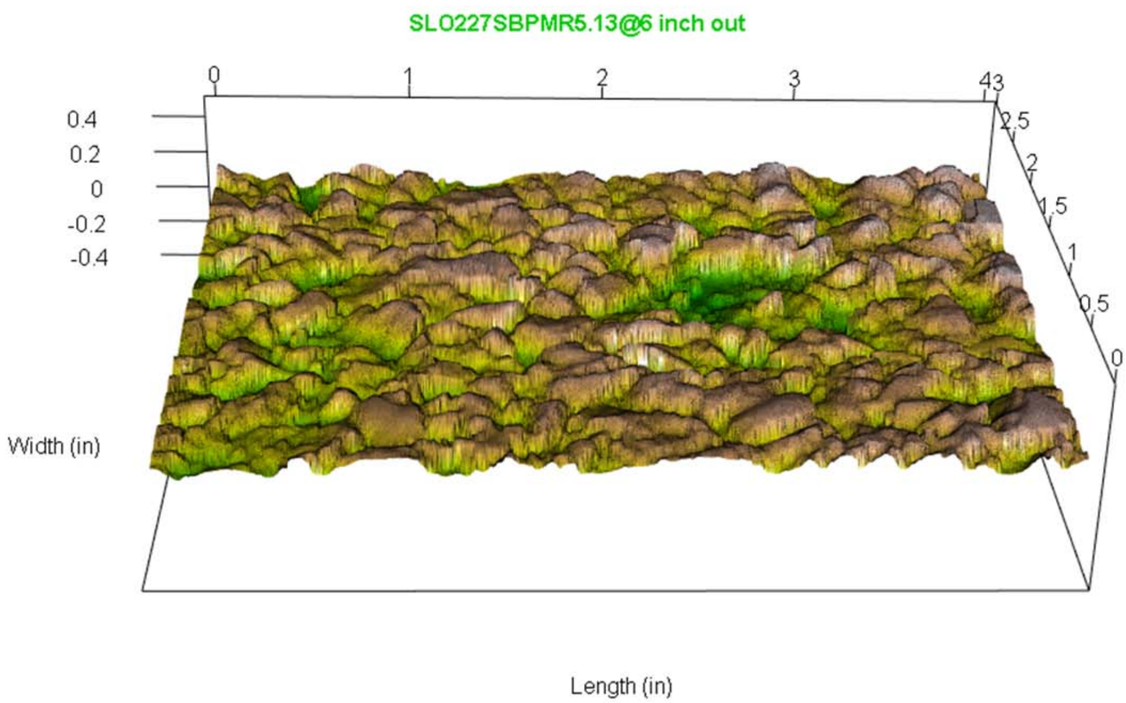
Width (in)
Length (in)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3
43
0.4
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1.5
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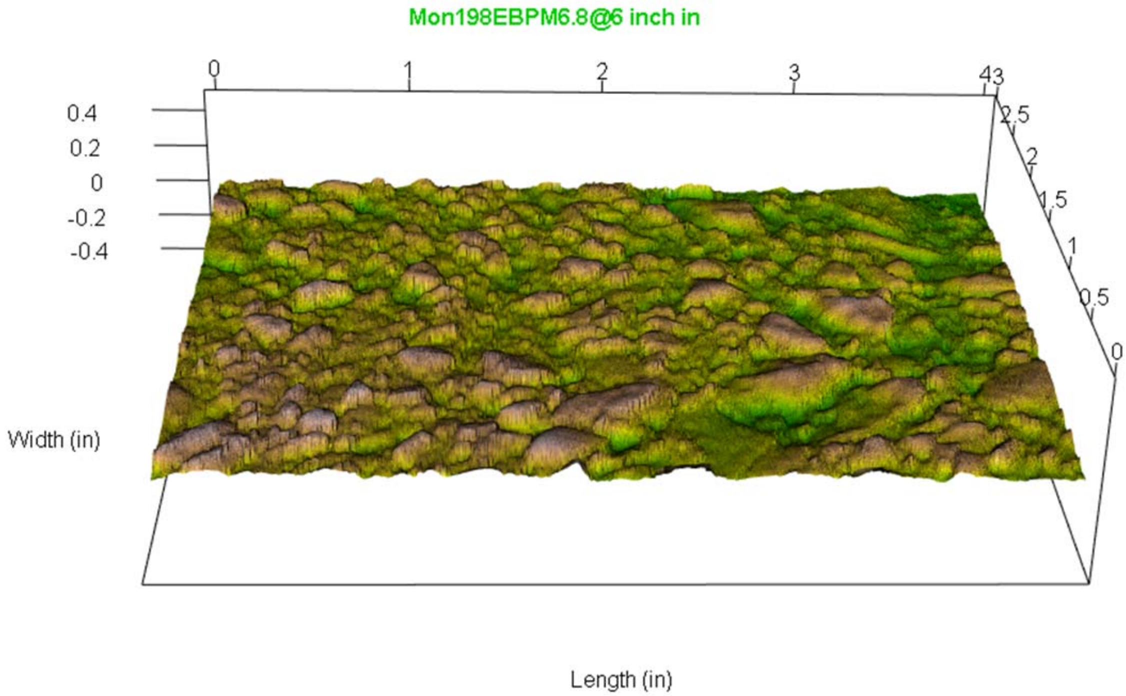
Width (in)
Length (in)

C.3 Mon-198


Mon198EBPM6.8@6 inch in
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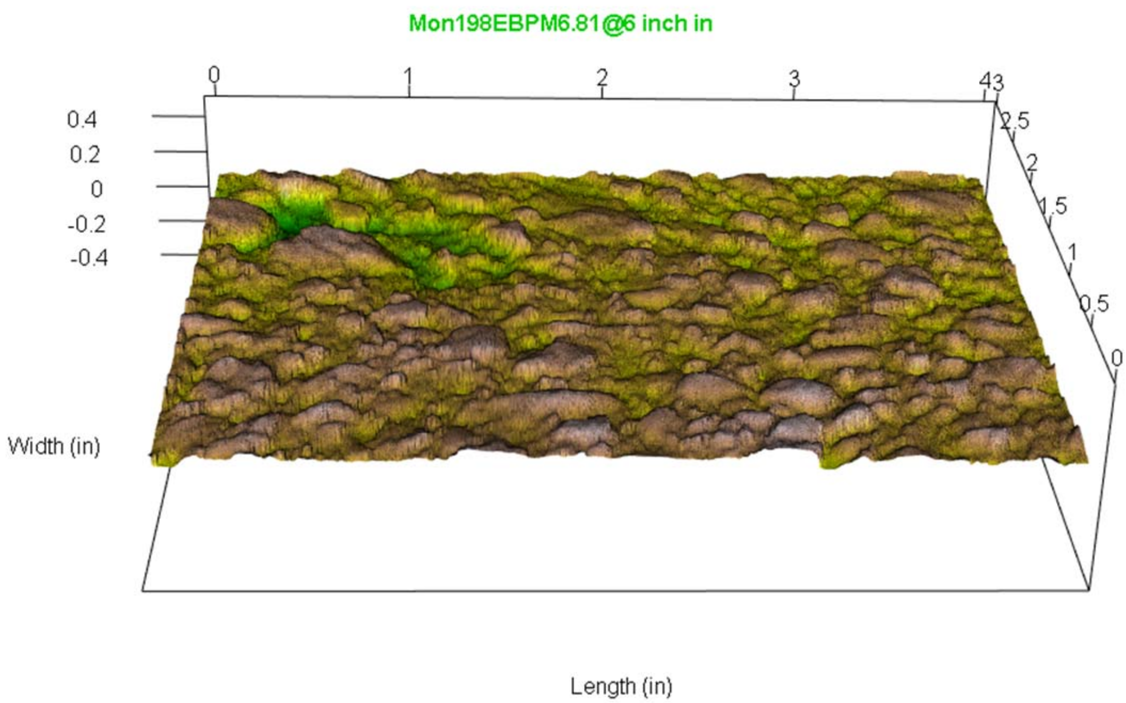
Length (in)


Mon198EBPM6.81@6 inch in
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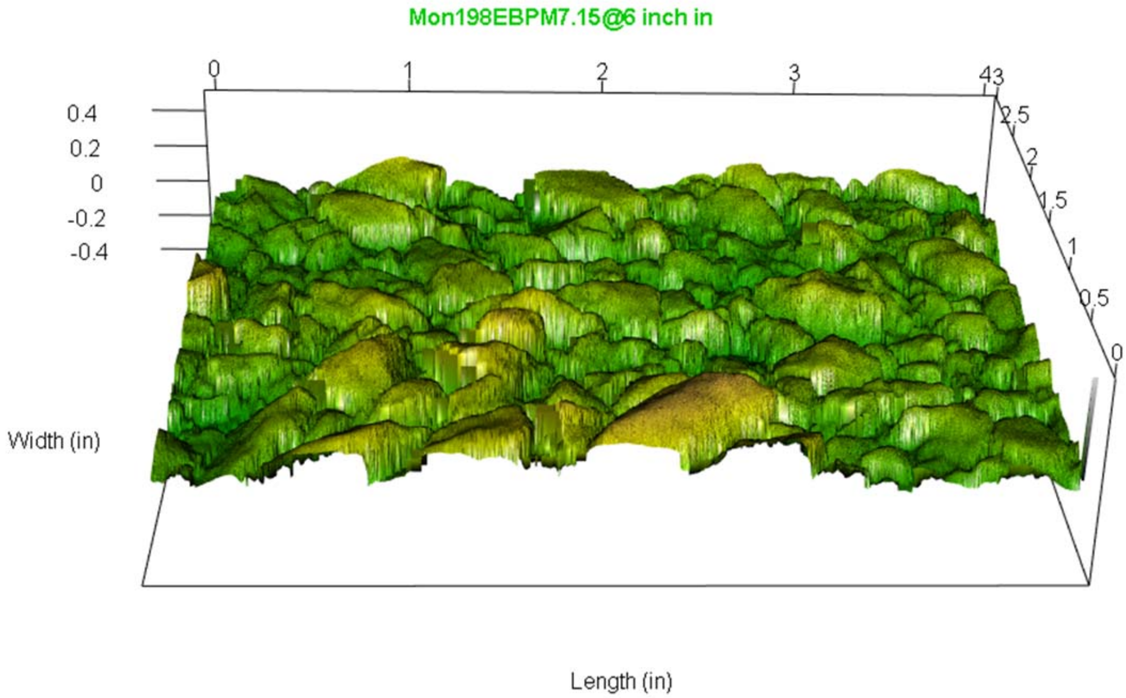
Width (in)
Length (in)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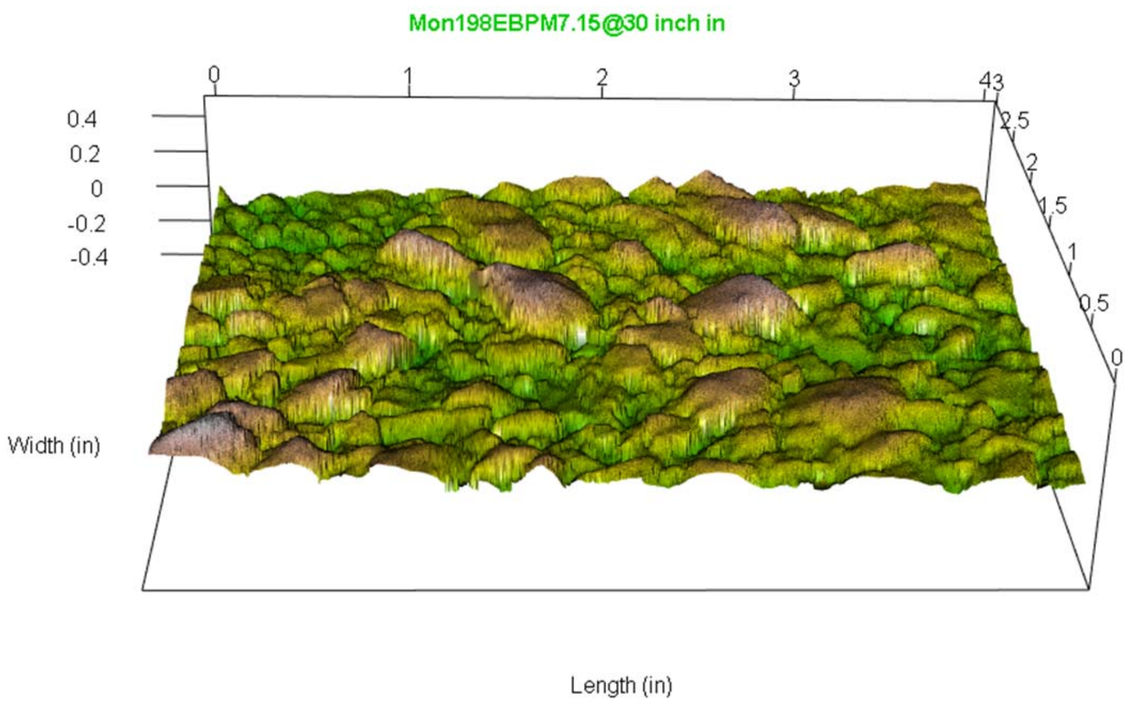
Width (in)
Length (in)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-0.4
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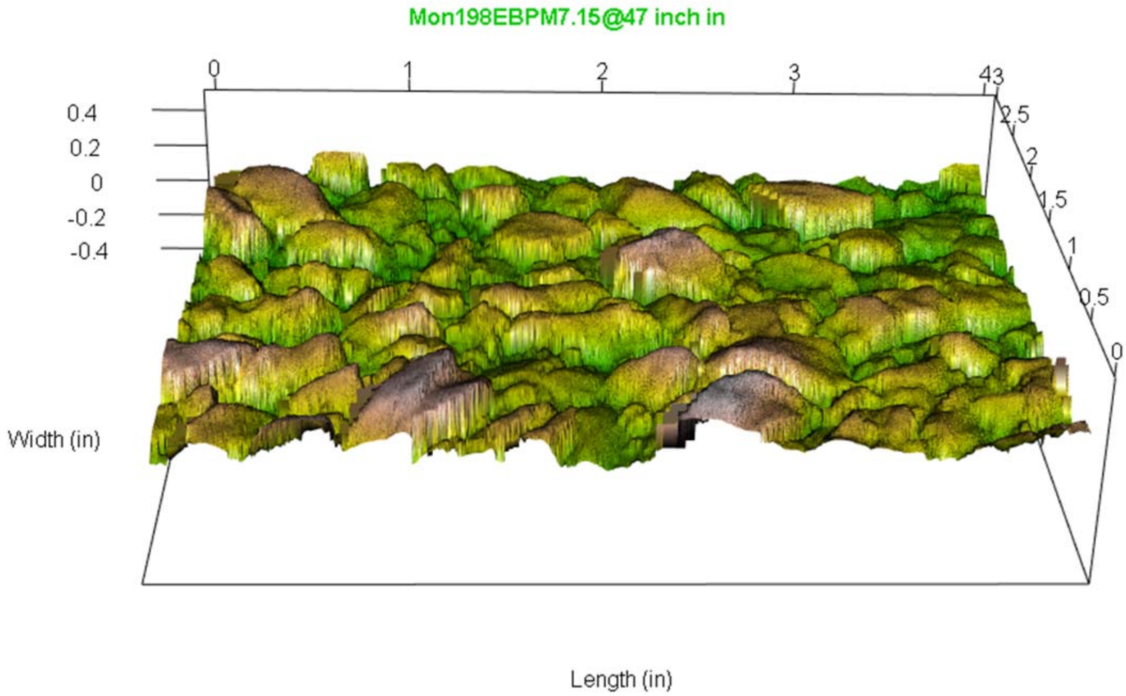
Width (in)
Length (in)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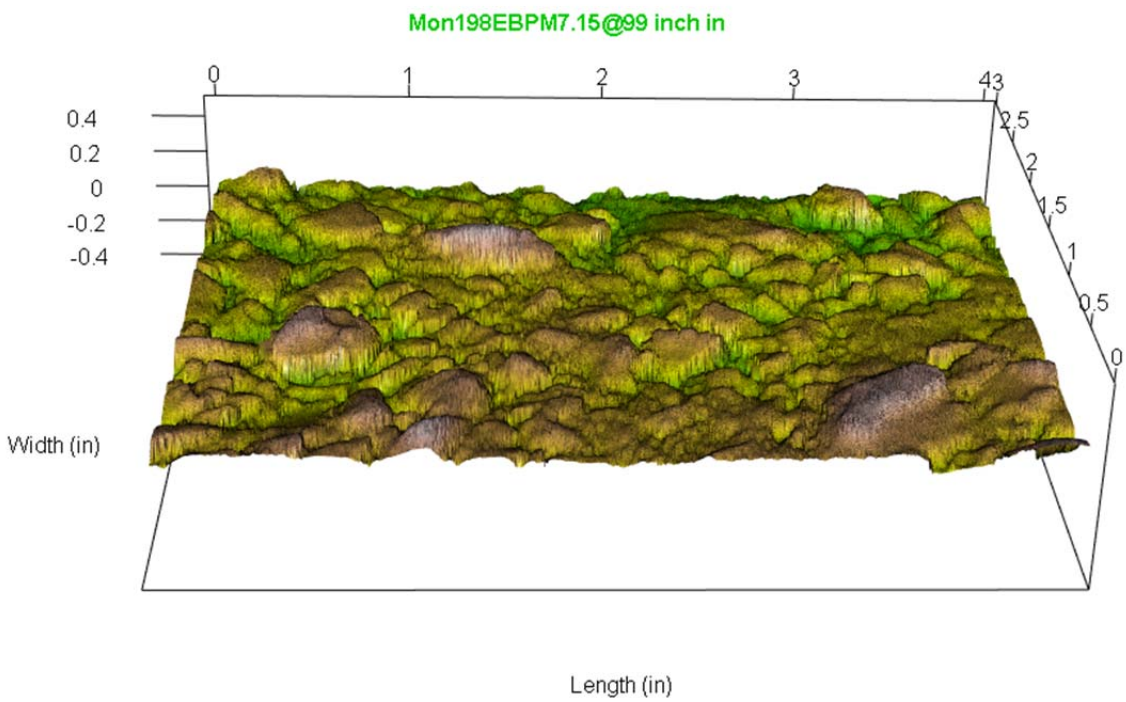
0
Width (in)
Length (in)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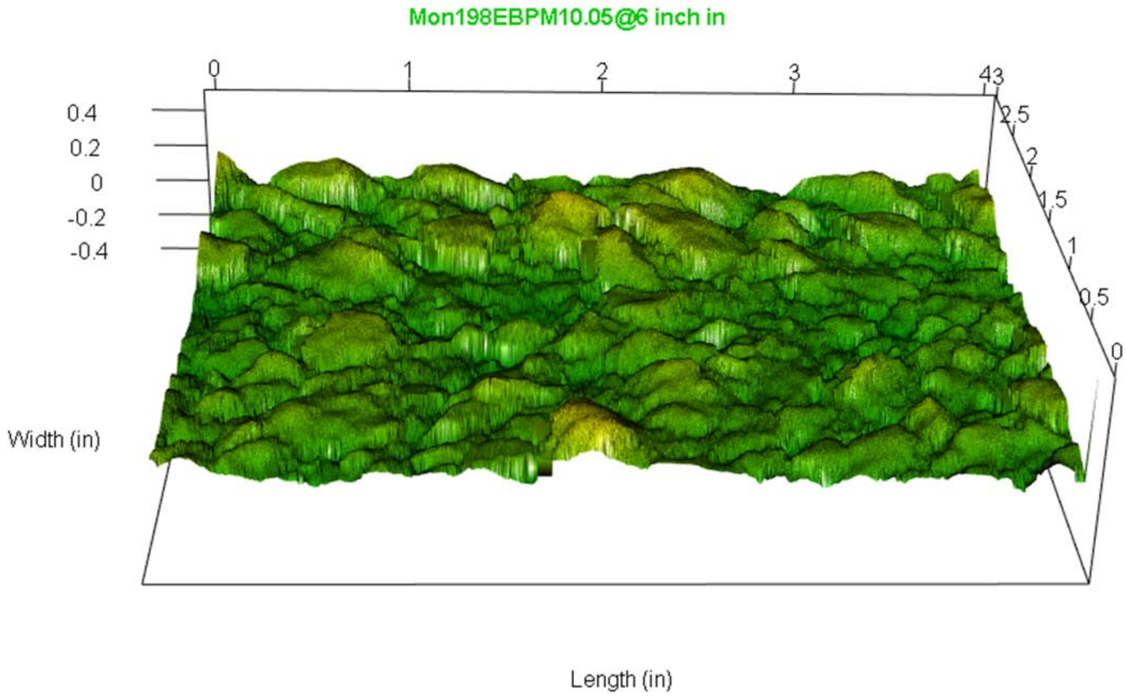
Width (in)
Length (in)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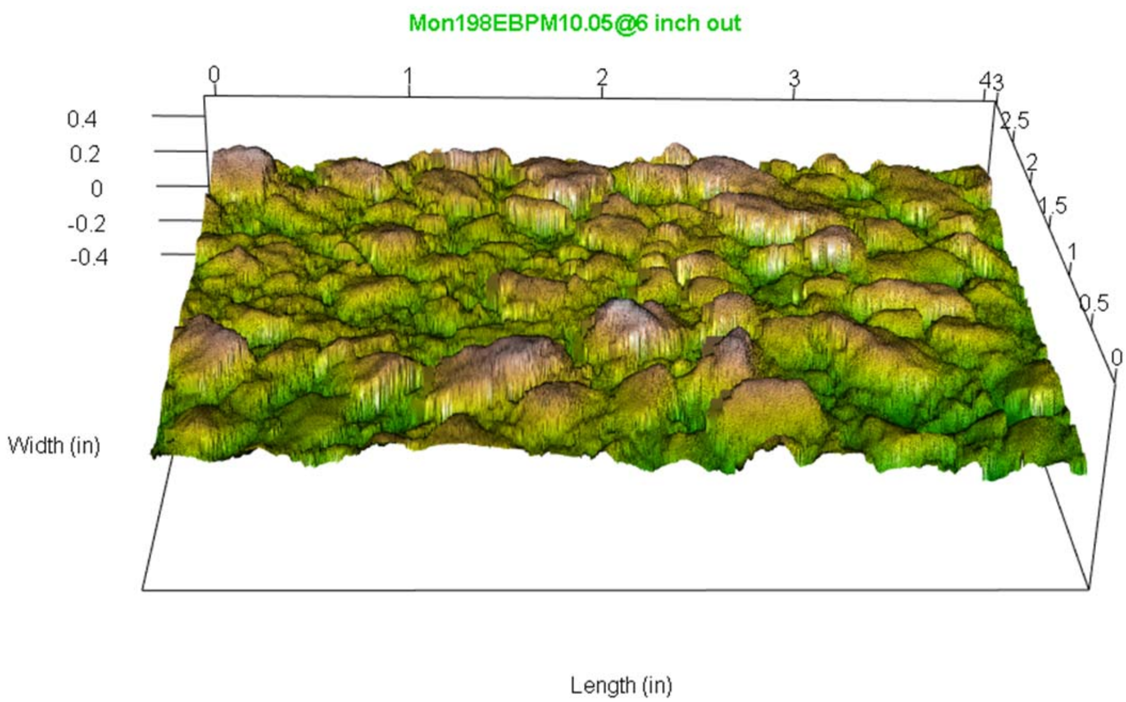
Width (in)
Length (in)


Mon198EBPM10.05@6 inch out
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2
3
4
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2
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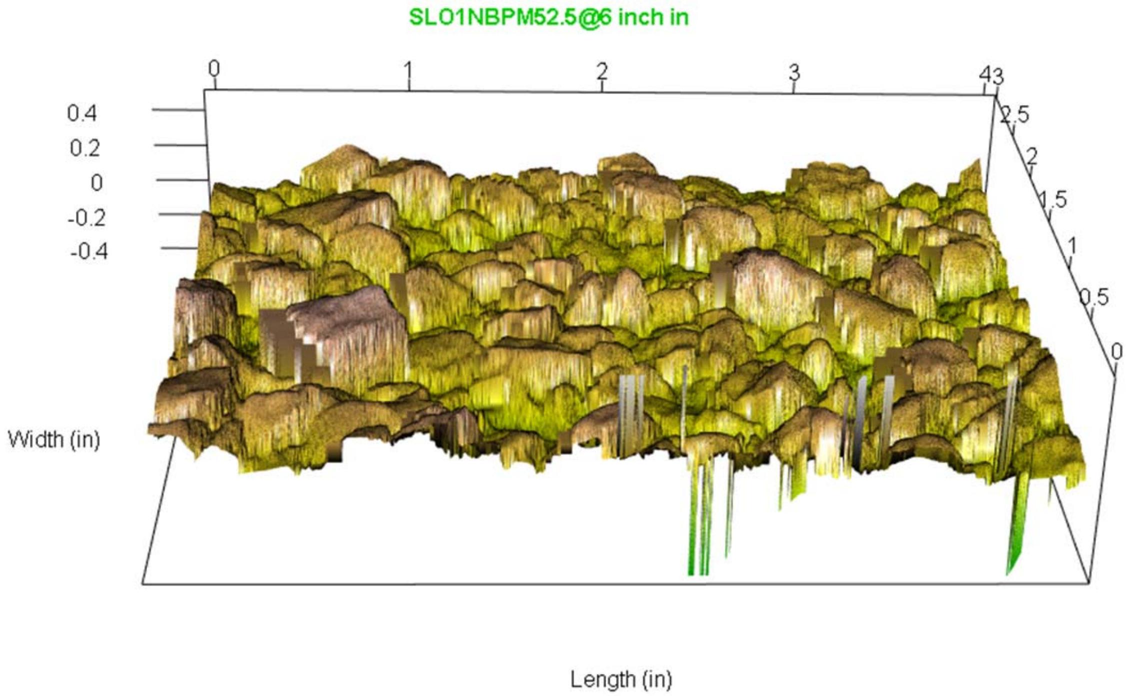
-0.2
-0.4
Width (in)
Length (in)

C.4 SLO-1



SLO1NBPM52.5@6 inch in
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3
4
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0.4
0.2
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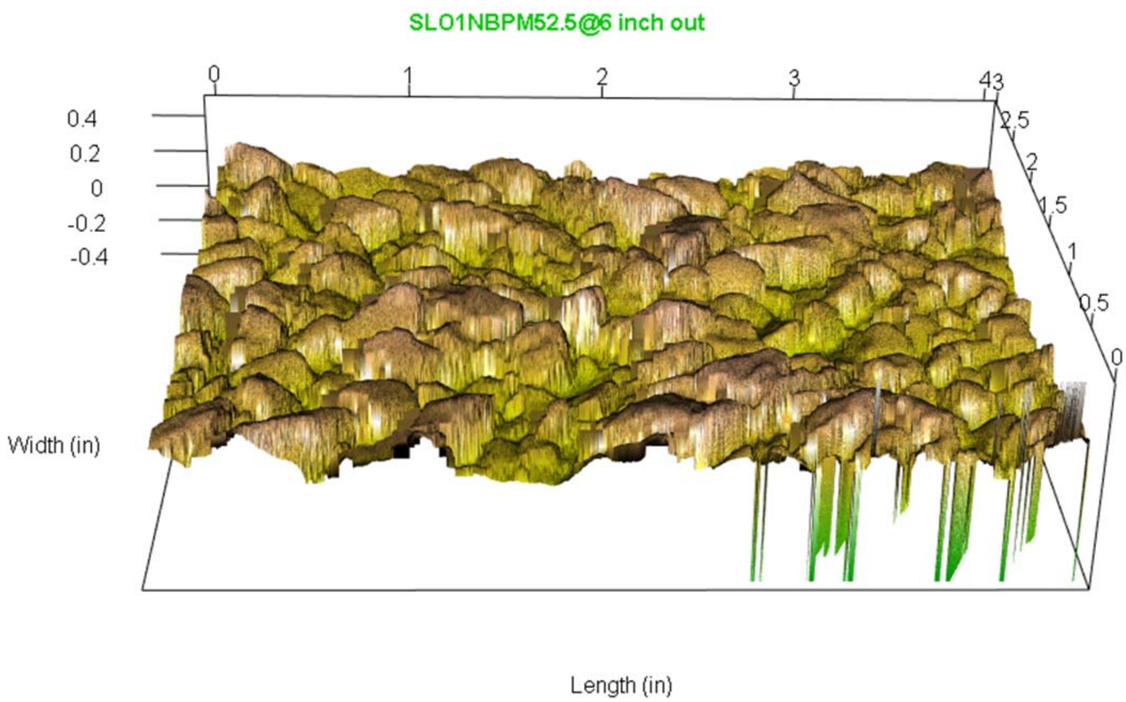
-0.2
-0.4
Width (in)
Length (in)



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1
2
3
4
3
2.5
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1.5
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0.4
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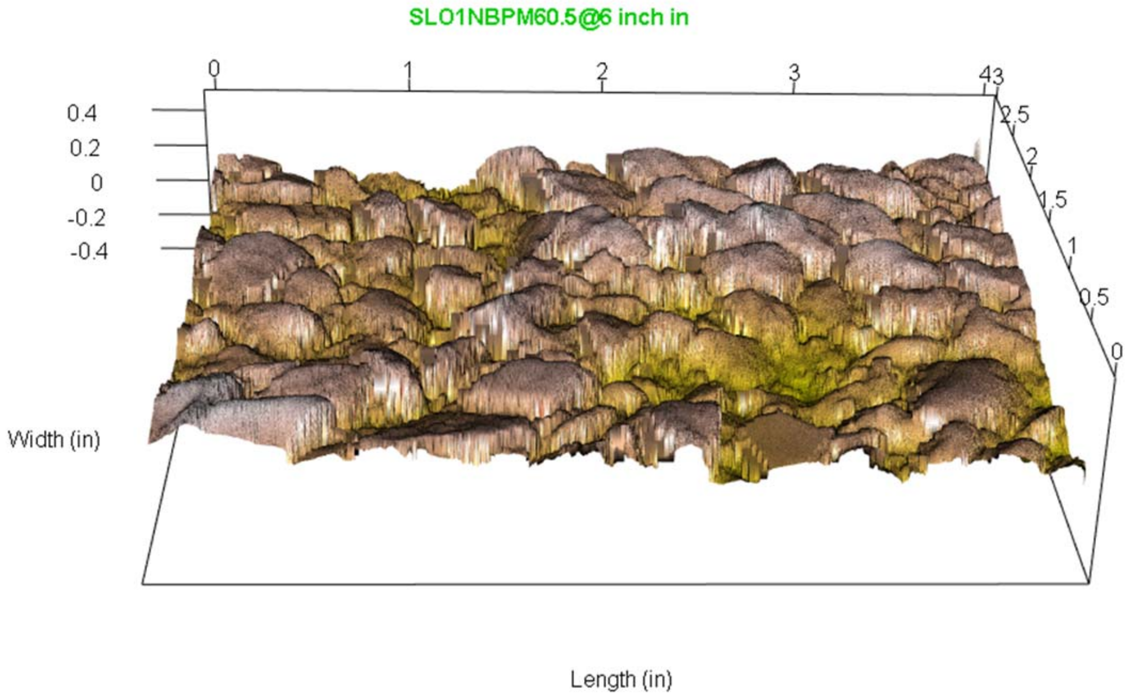
Width (in)
Length (in)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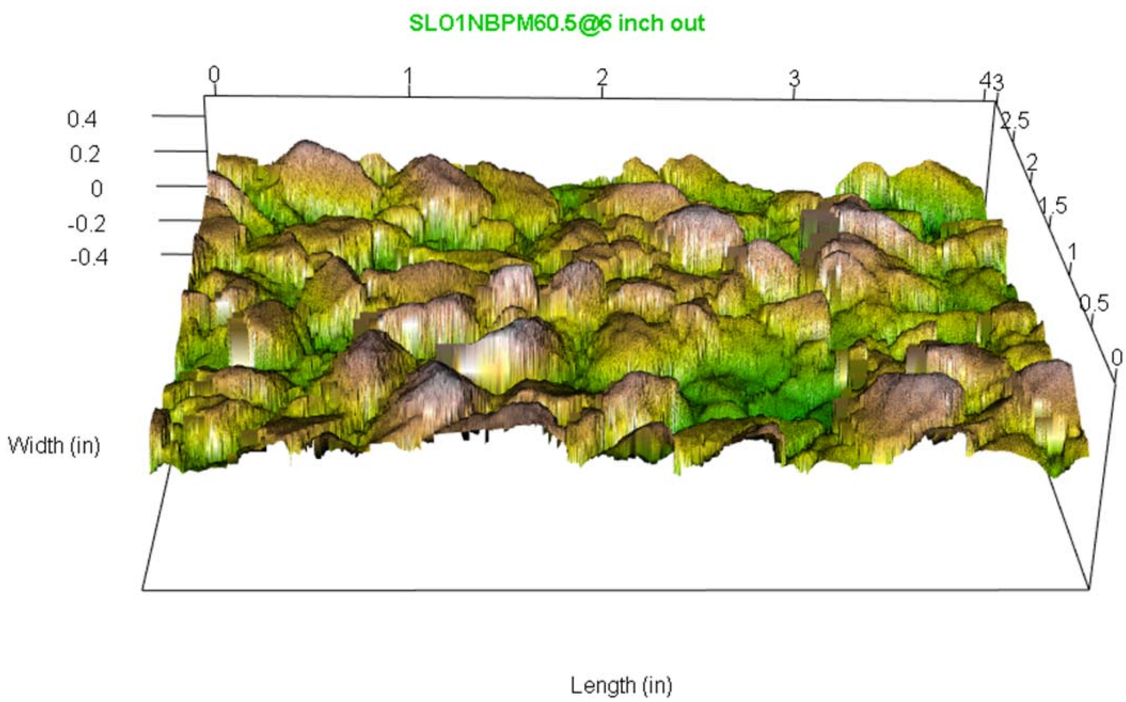
Width (in)
Length (in)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-0.4
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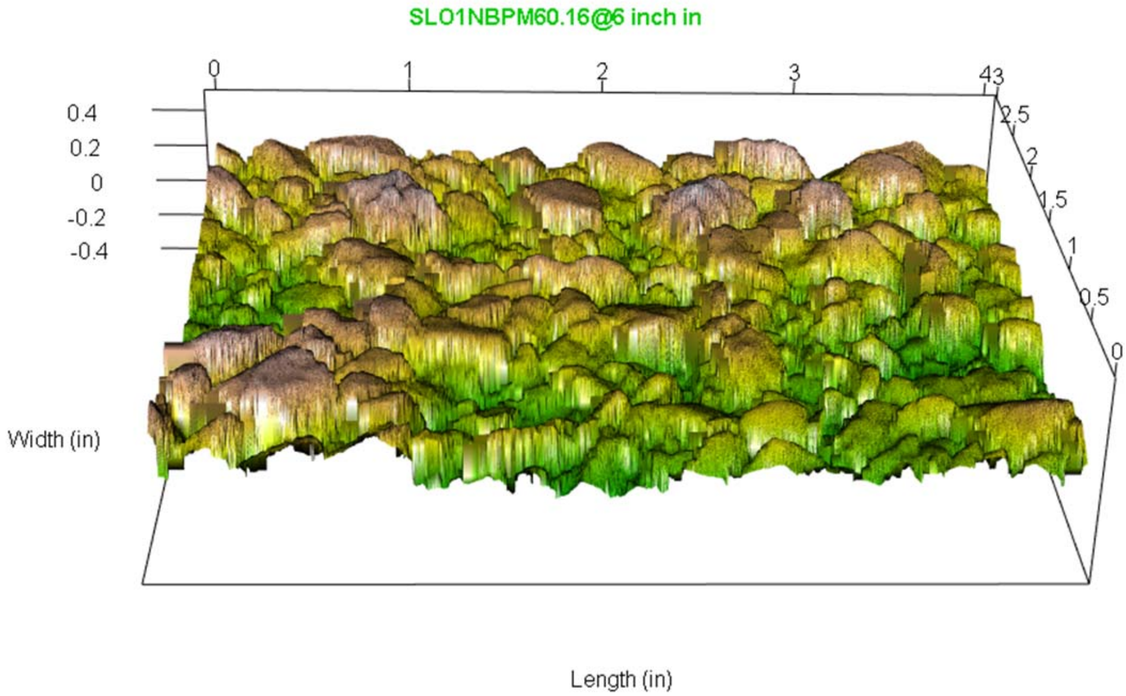
Width (in)
Length (in)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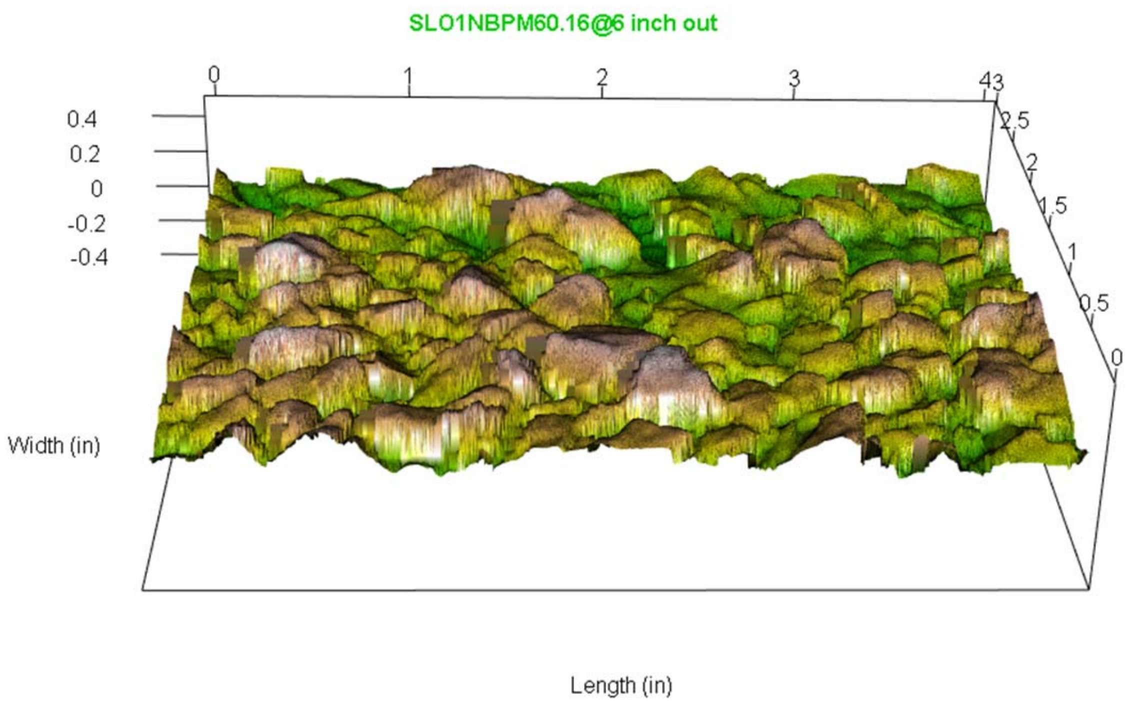
Width (in)
Length (in)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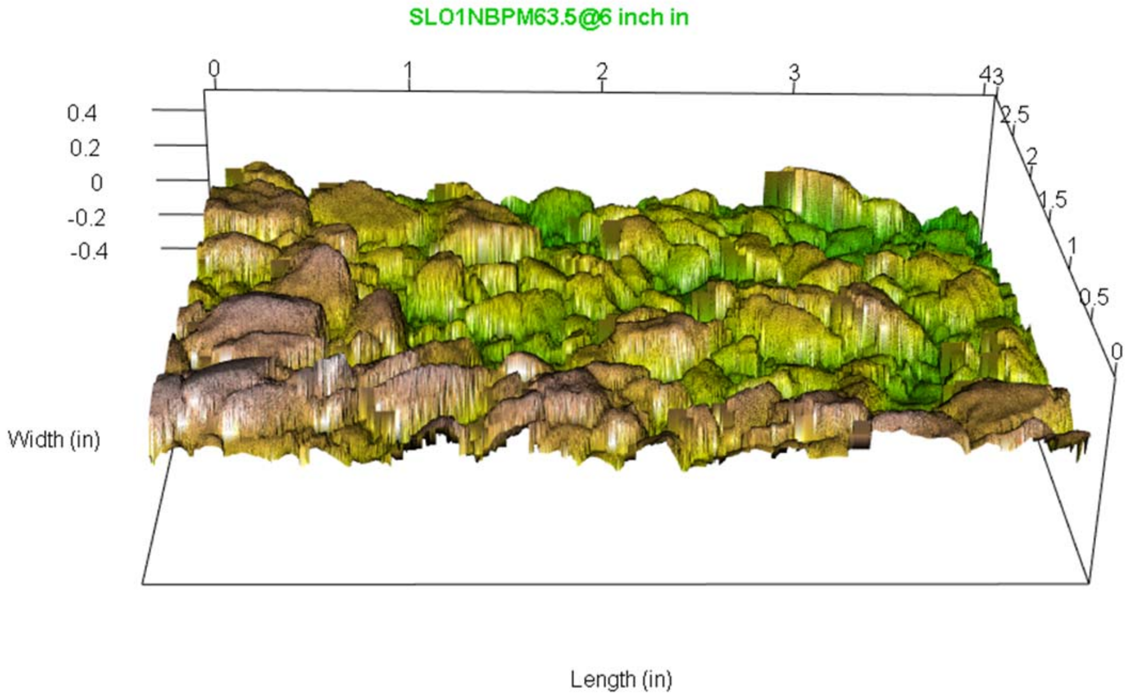
Width (in)
Length (in)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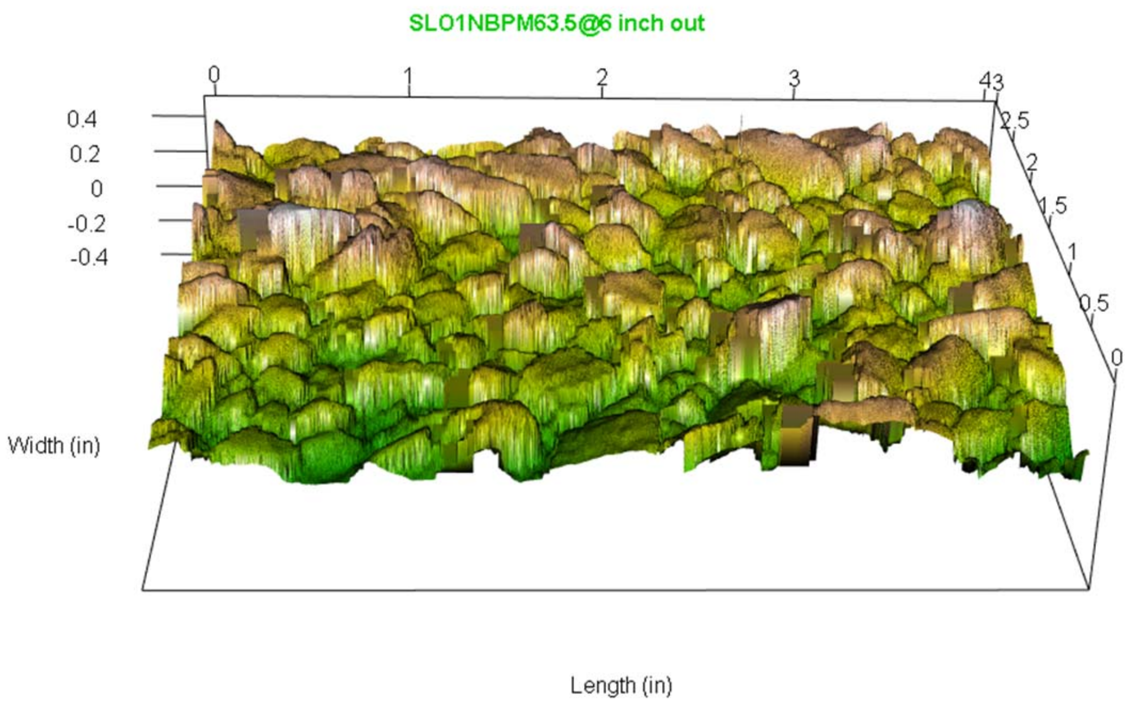
Width (in)
Length (in)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0.4
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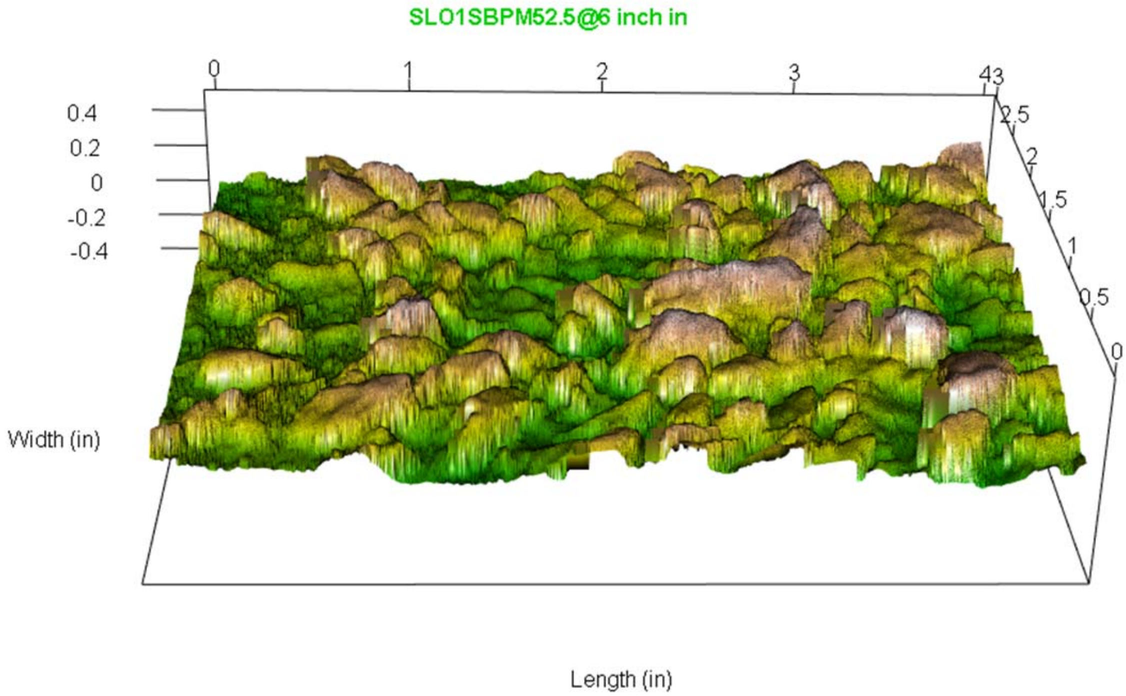
-0.4
Width (in)
Length (in)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1
0.5
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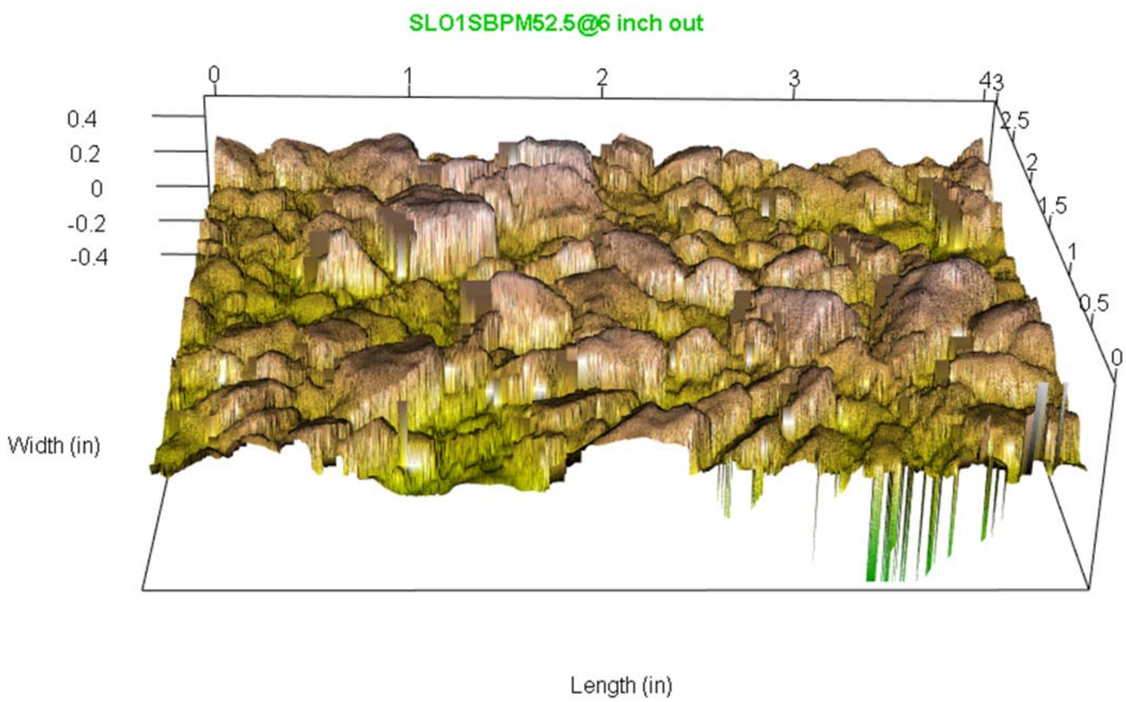
Width (in)
Length (in)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43
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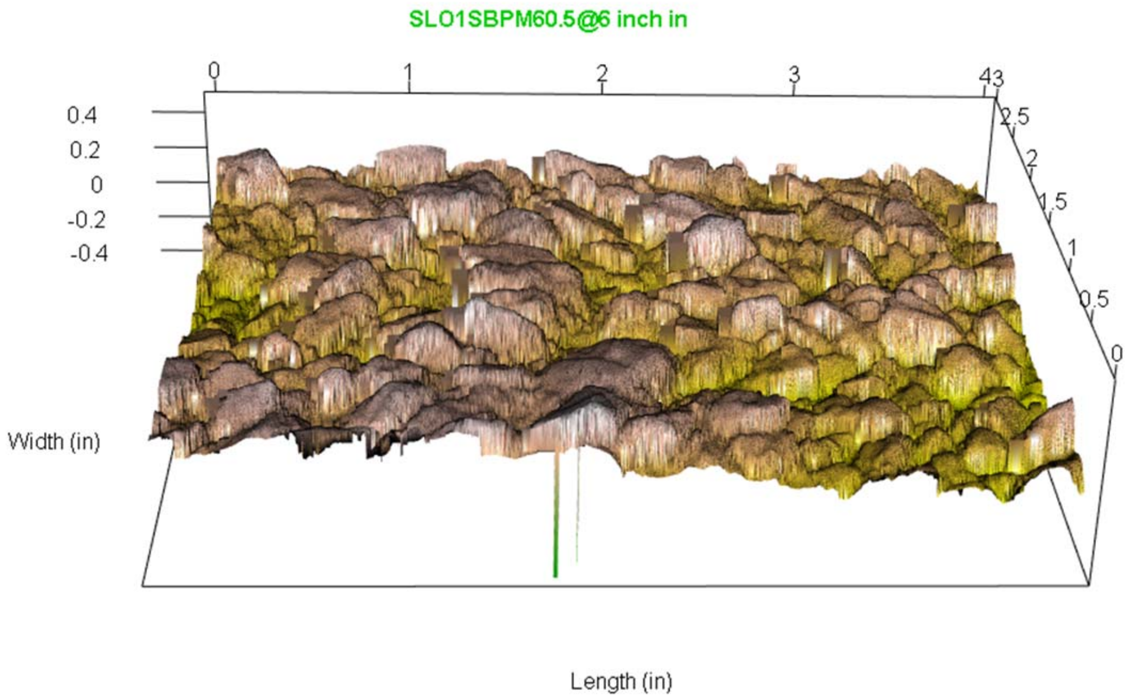
1.5
1
0.5
0
Width (in)
Length (in)


SLO1SBPM60.5@6 inch in
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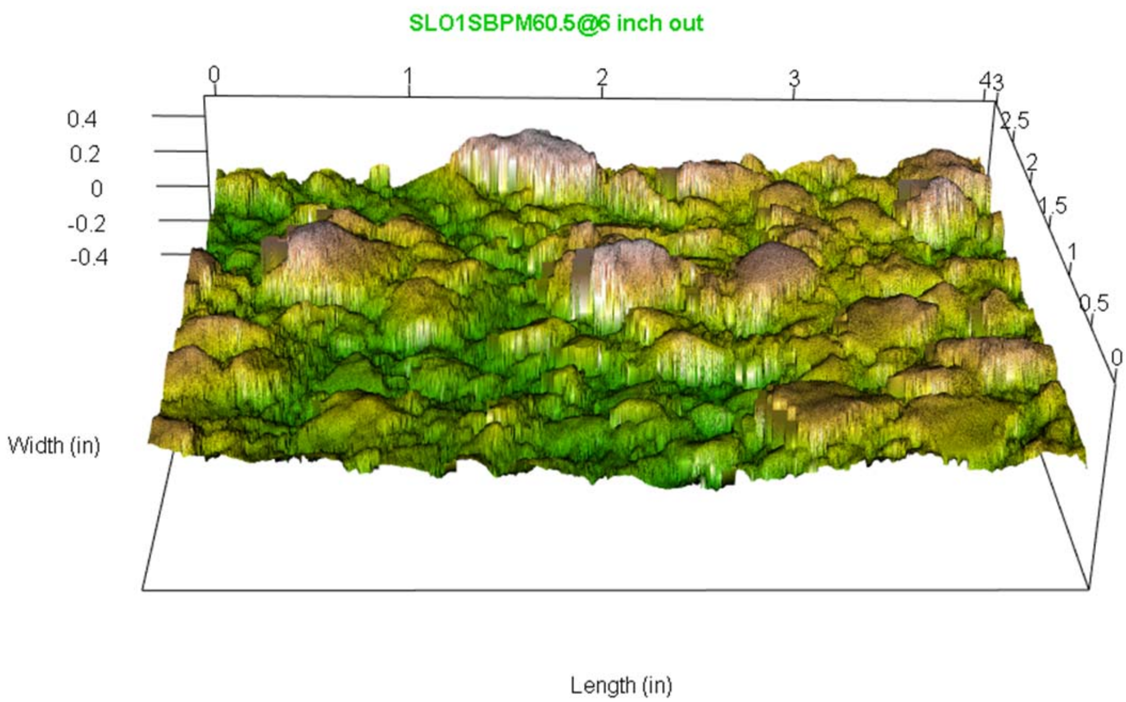
Width (in)
Length (in)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-0.2
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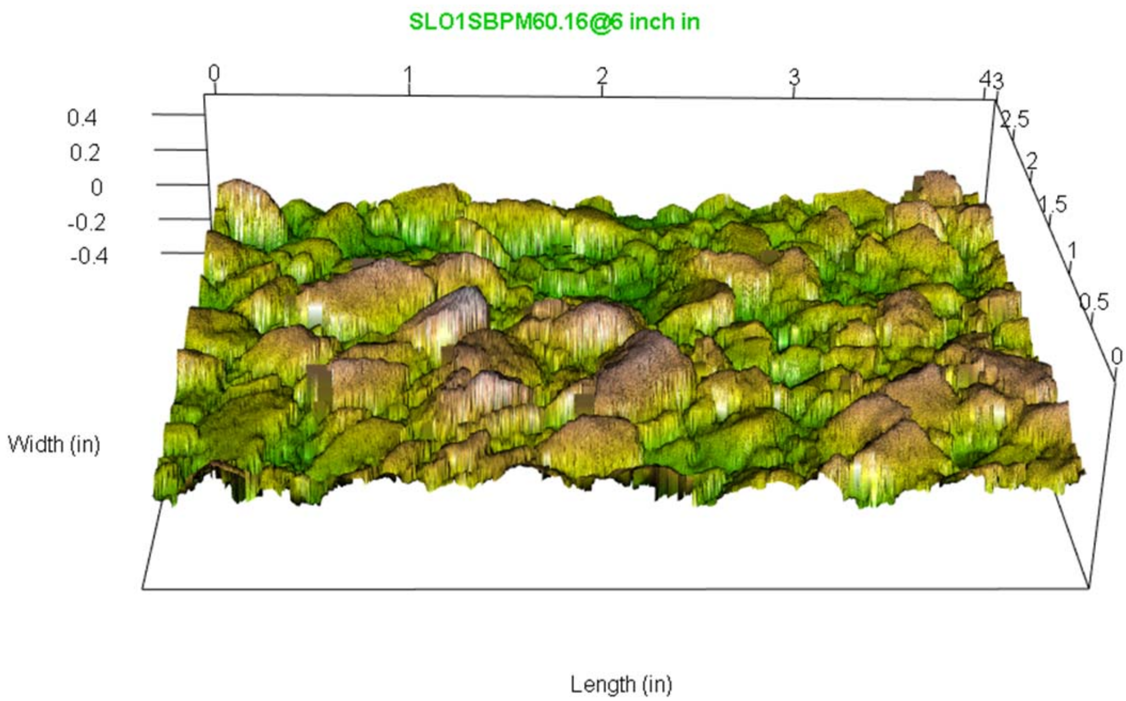
Width (in)
Length (in)


SLO1SBPM60.16@6 inch in
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3
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0.2
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-0.2
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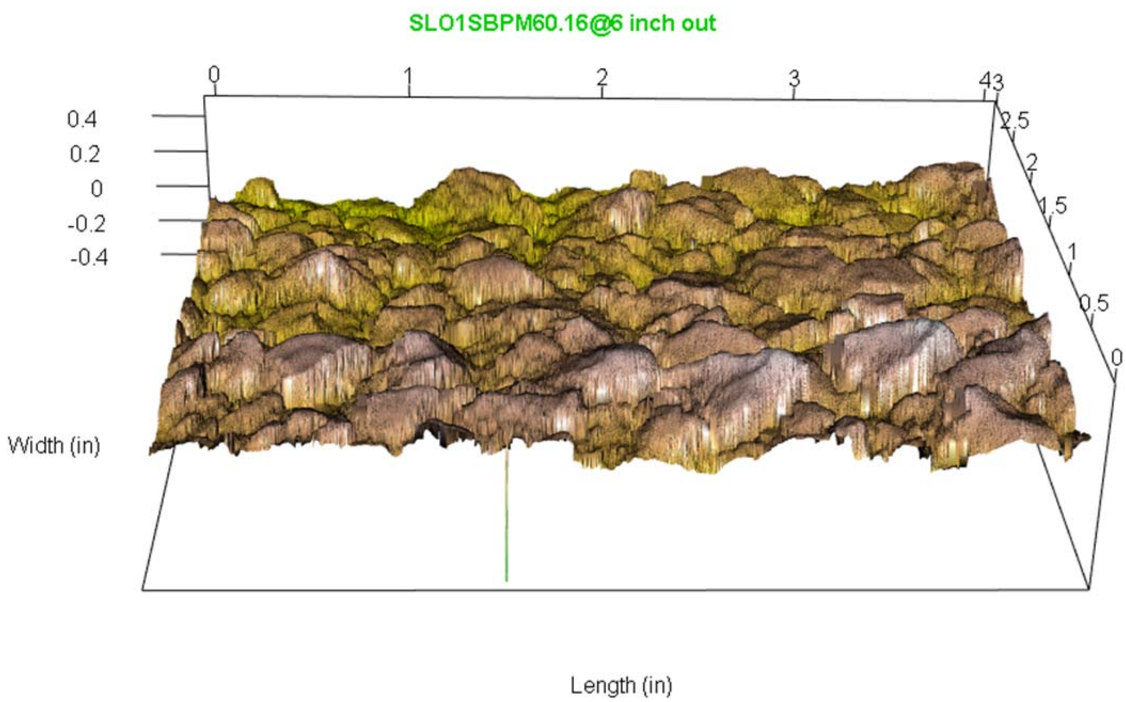
Width (in)
Length (in)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4
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0.4
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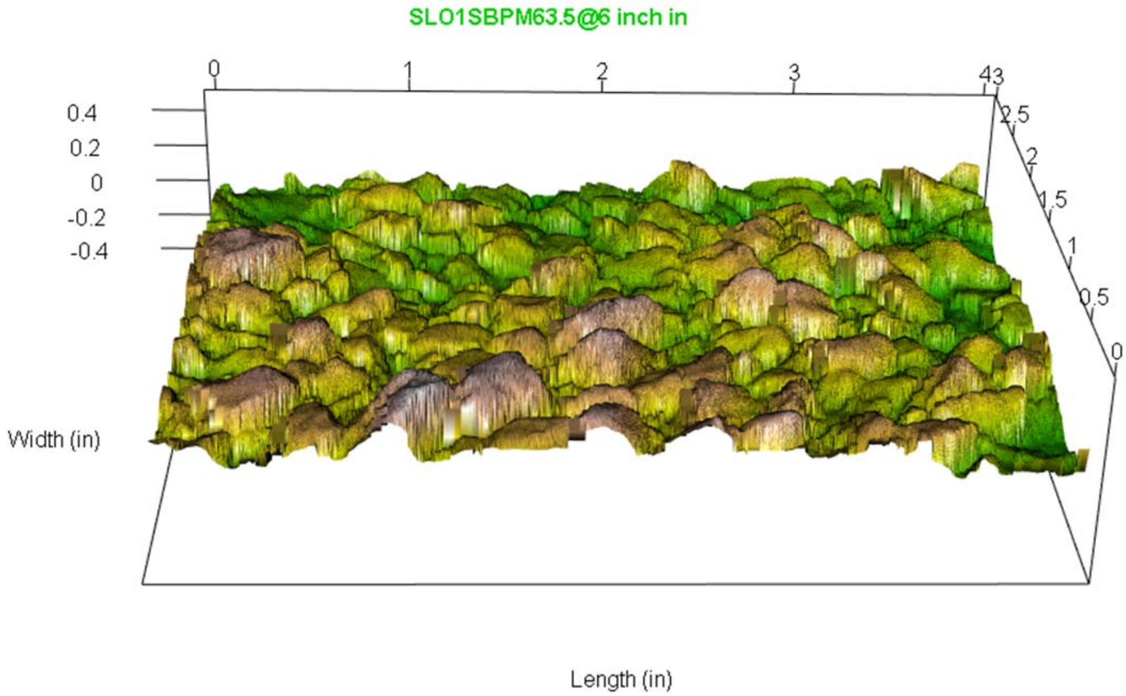
-0.2
-0.4
Width (in)
Length (in)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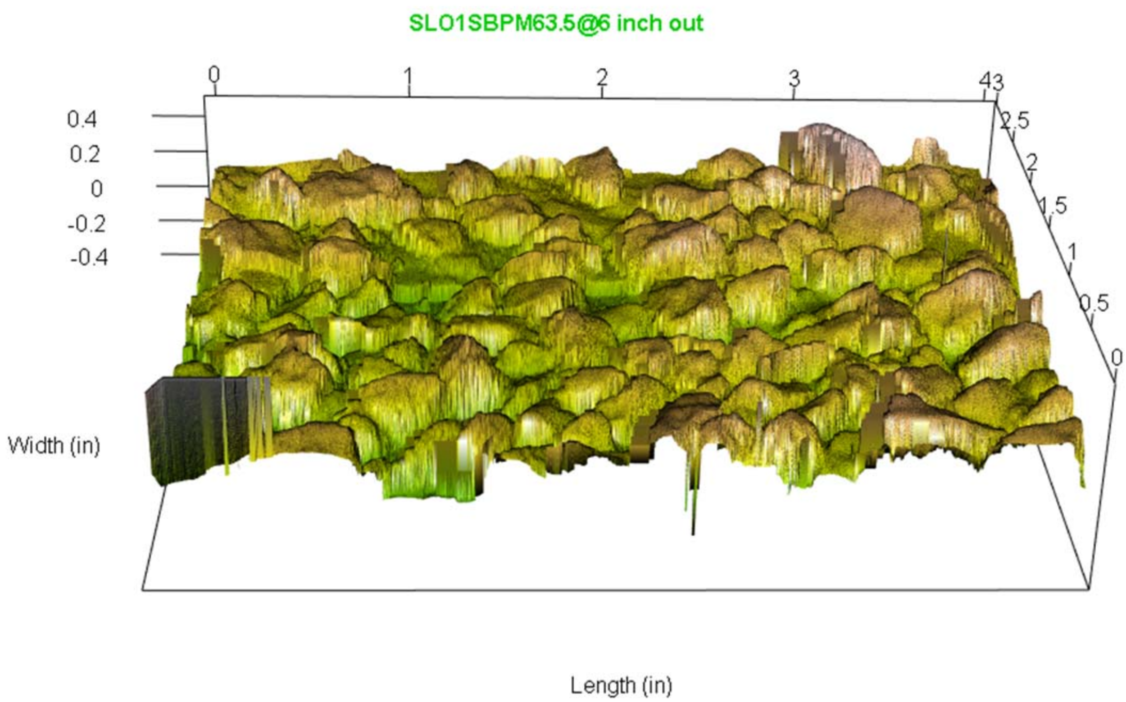
Width (in)
Length (in)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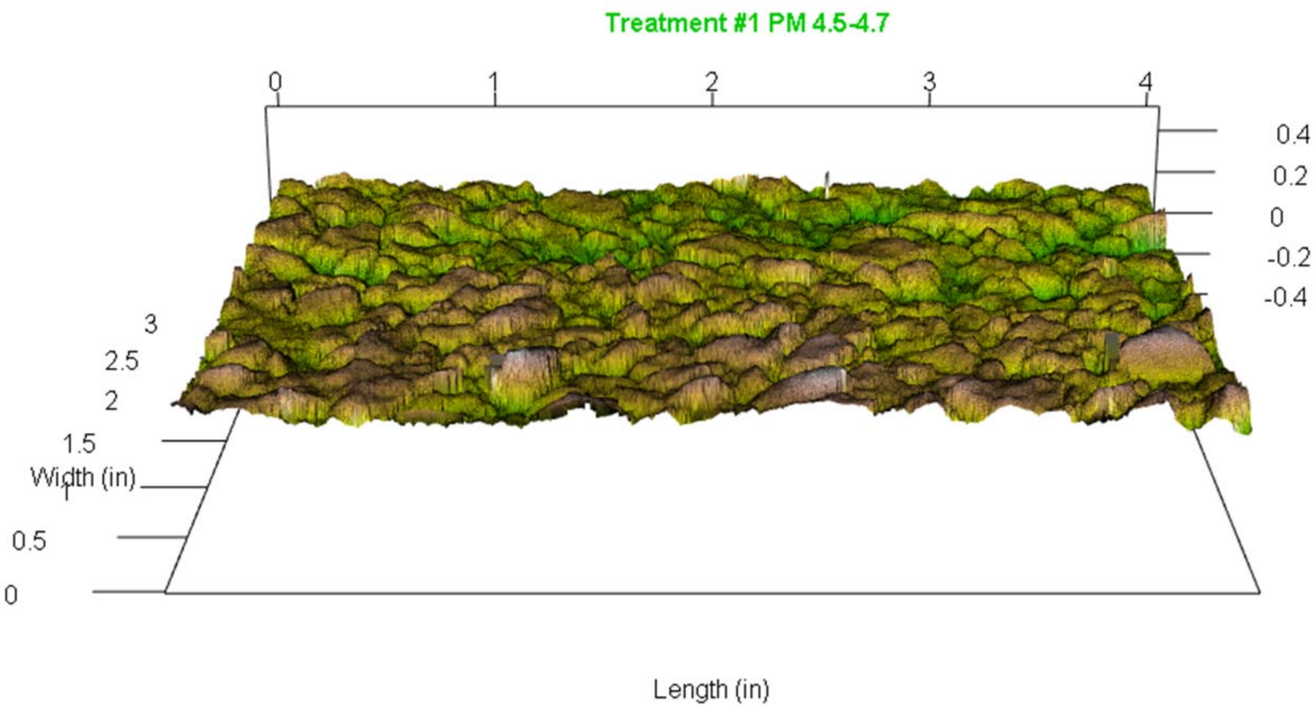
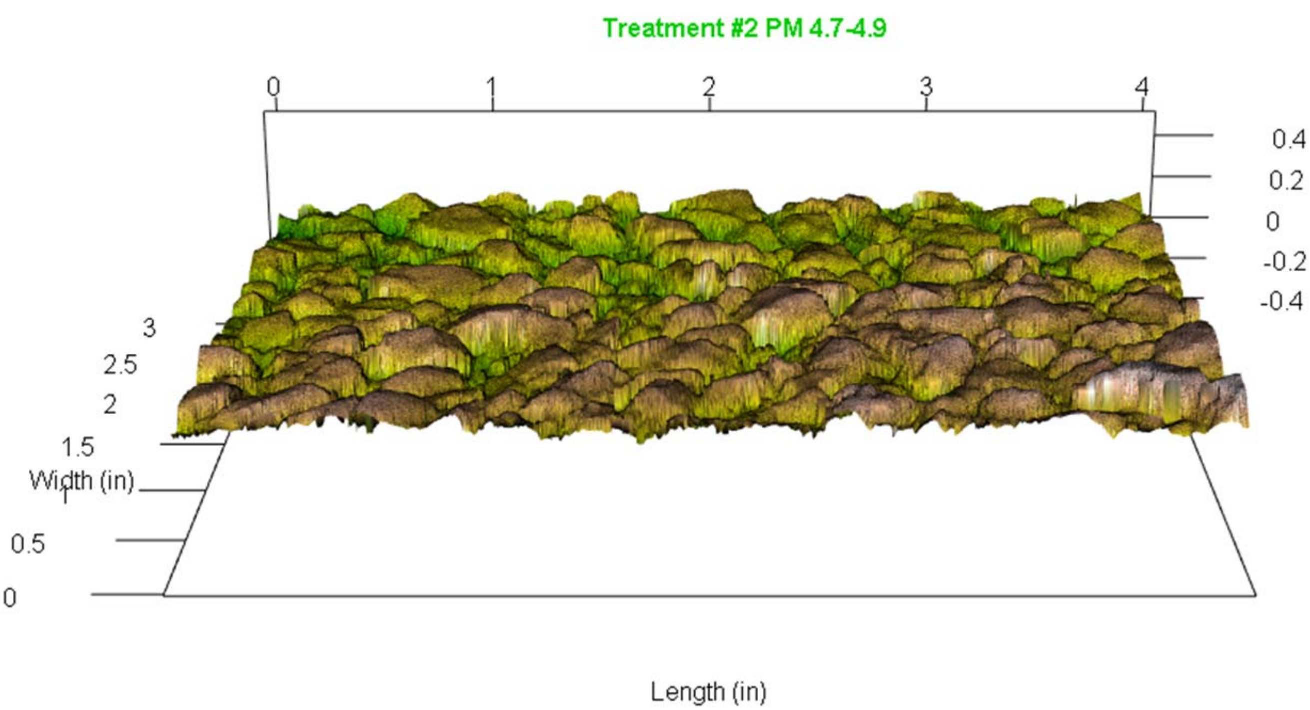
-0.4
Width (in)
Length (in)

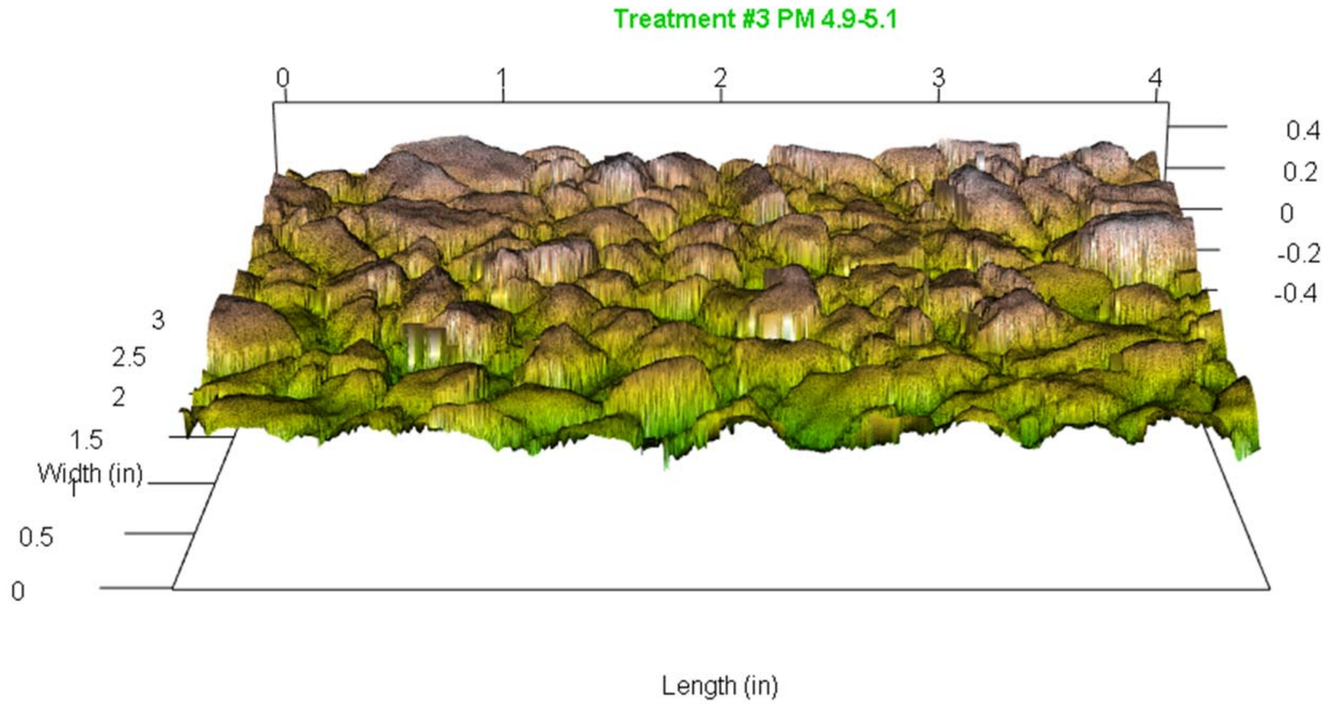
C.5 Test Sections on Mon-198



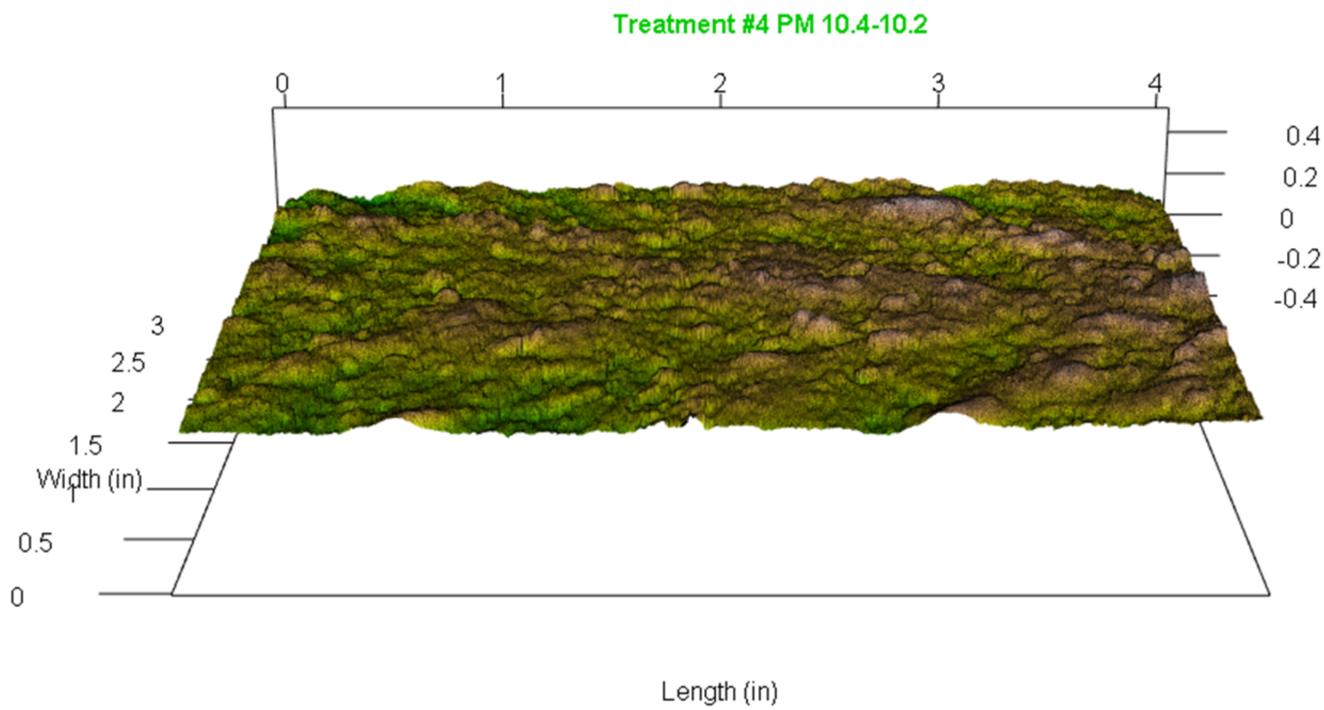
#1 5/16" PME Seal Coat (PM 4.5-4.7)



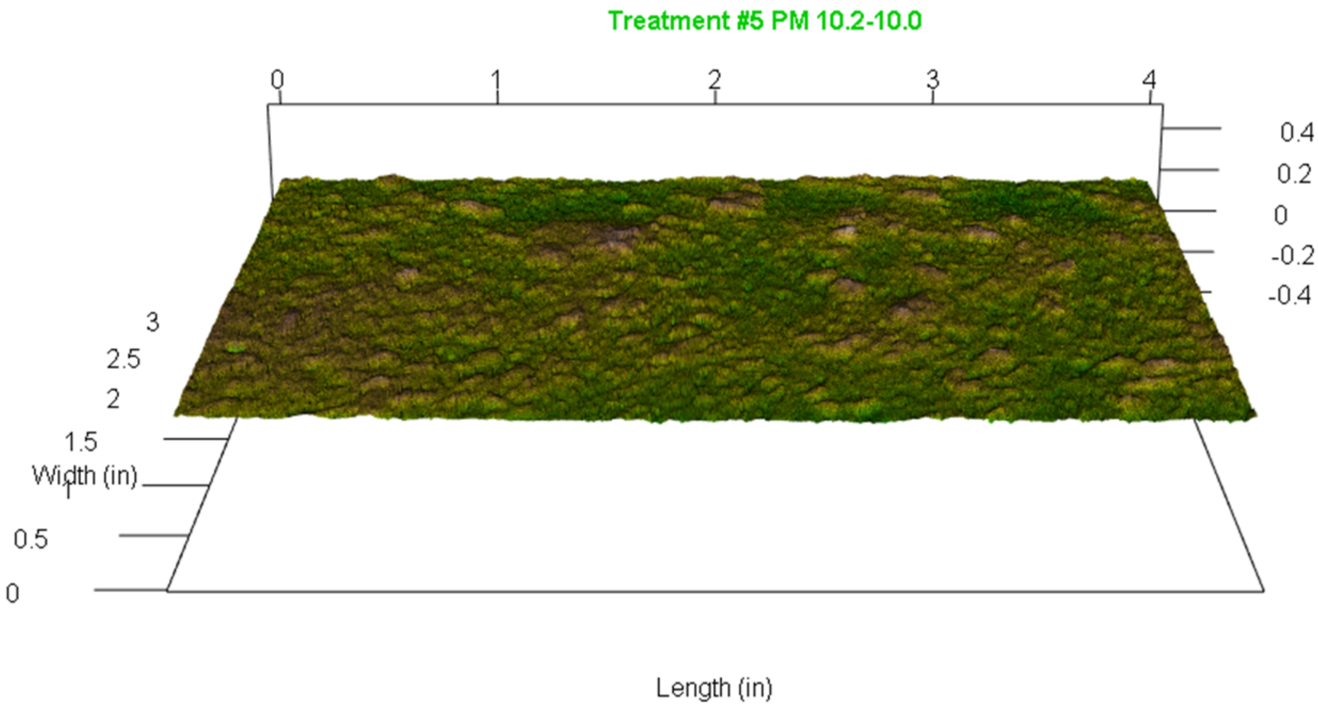
#2 Modified Binder Seal Coat - Modified Gradation (PM 4.7-4.9)



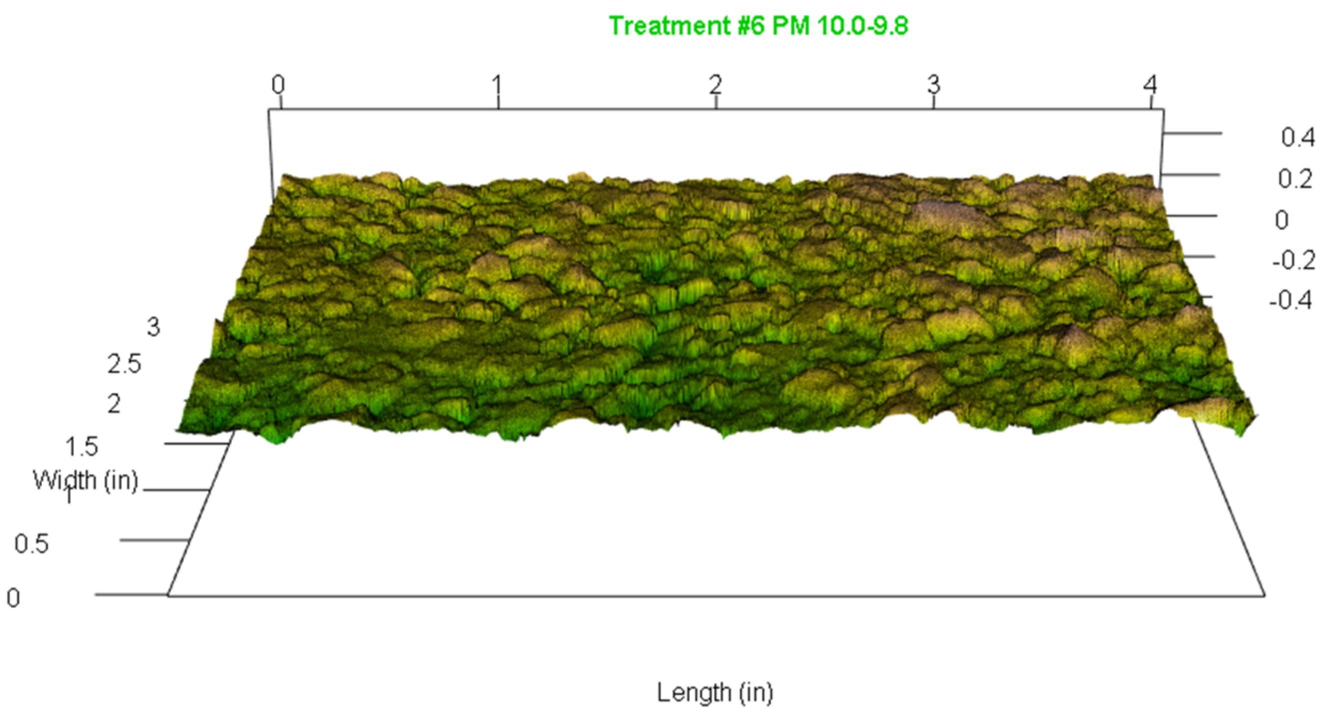
#3 Modified Binder Seal Coat - Utilizing a Steel Roller (PM 4.7-4.9)



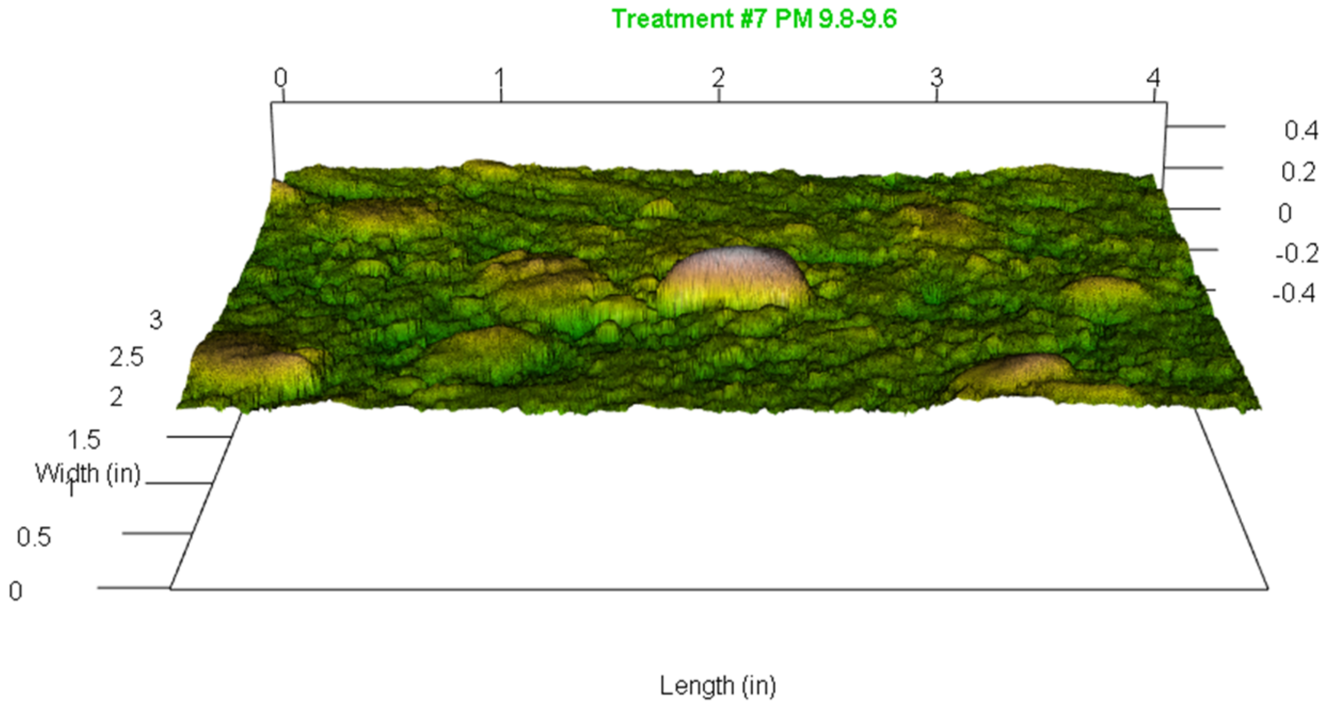
#4 Cinder Seal (PM 10.2-10.4)



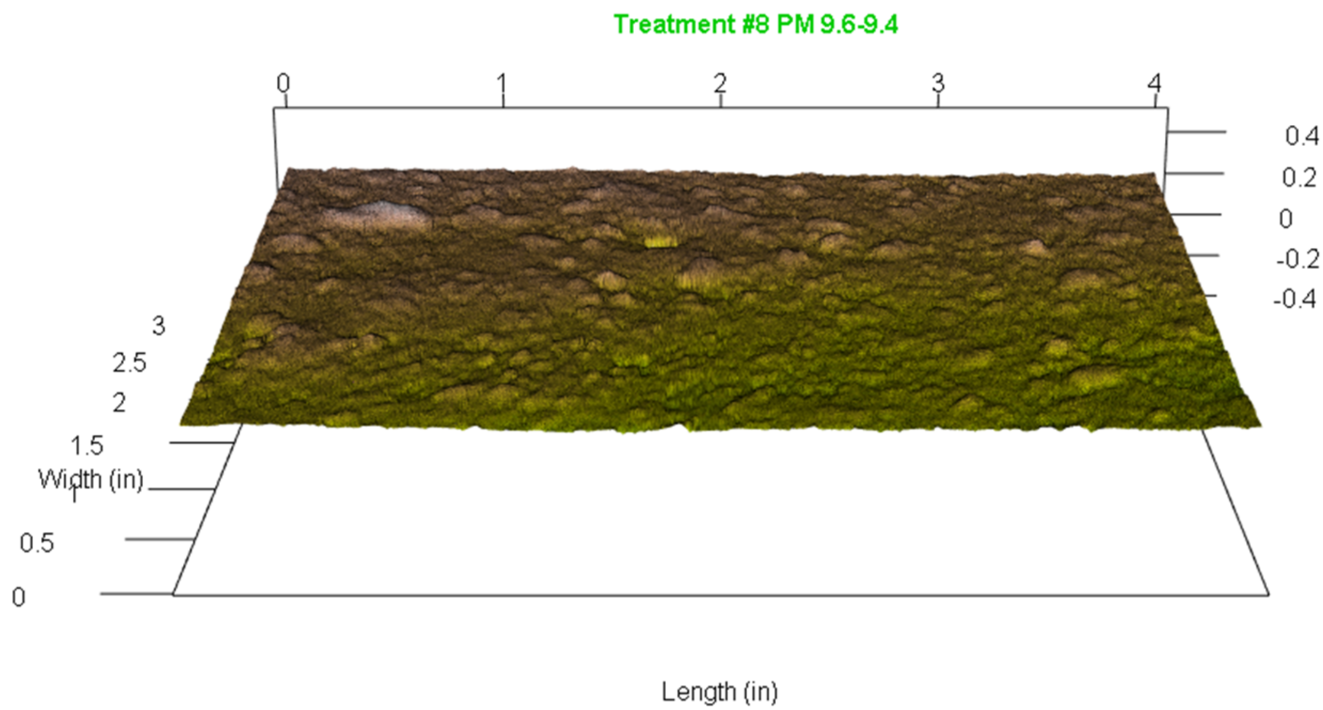
#5 Microsurfacing (PM 10.0-10.2)



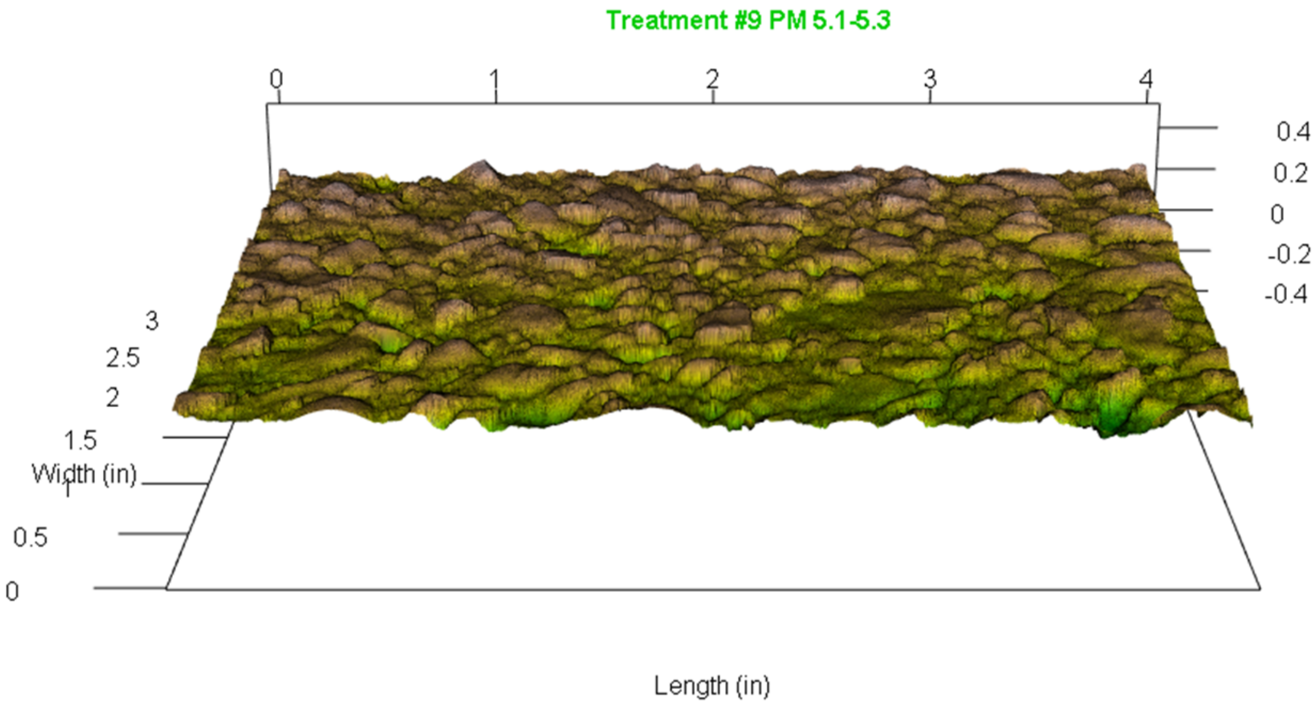
#6 1/4" PME seal coat - 2nd application of a double chip seal (PM 9.8-10.0)



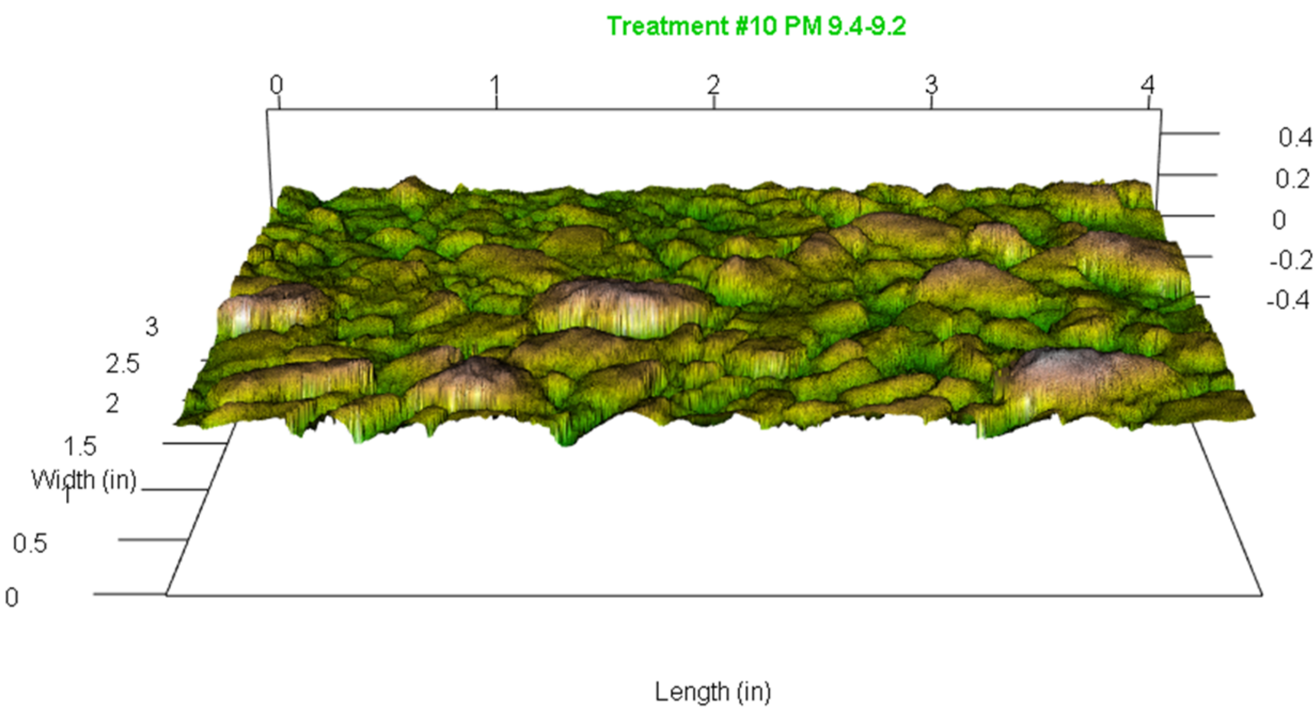
#7 Sand seal (PM 9.6-9.8)



#8 Slurry seal (PM 9.4-9.6)



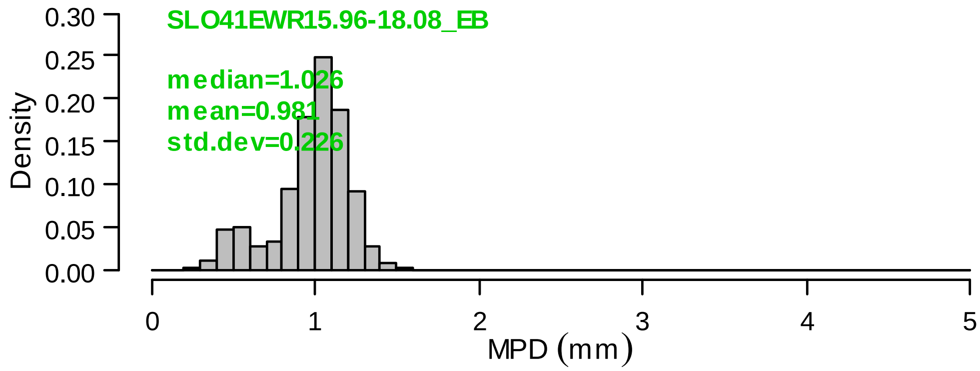
#9 Old HMA overlay on Mon-198 (PM 5.1-5.3)

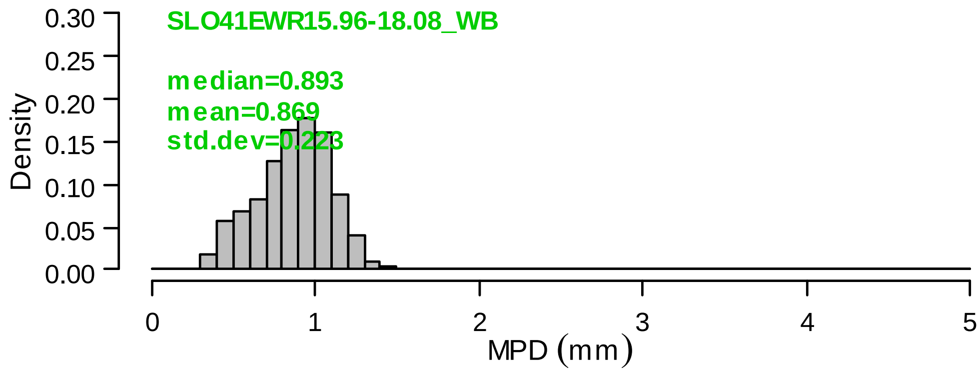


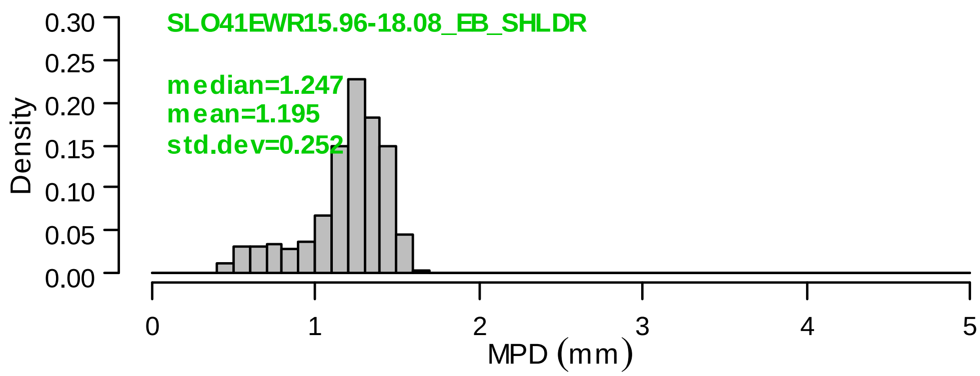
#10 New chip seal on Mon-198 (Control) (PM 9.2-9.4)

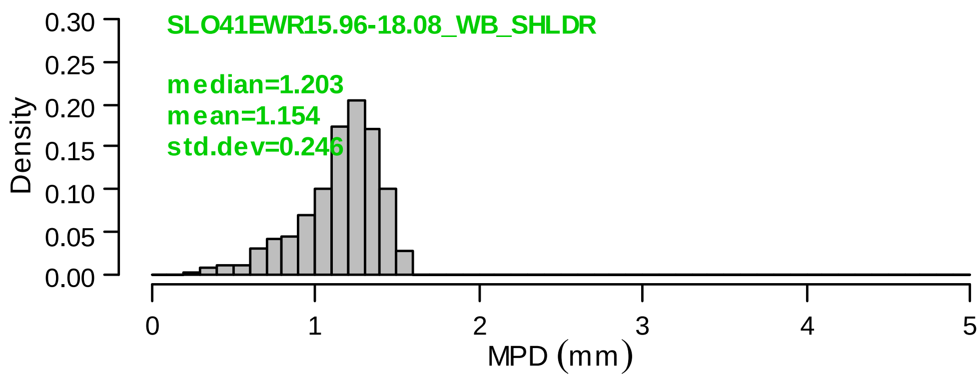
APPENDIX D: DISTRIBUTION OF MPD BY THE INERTIAL PROFILER

D.1 SLO-41, Microsurfacing

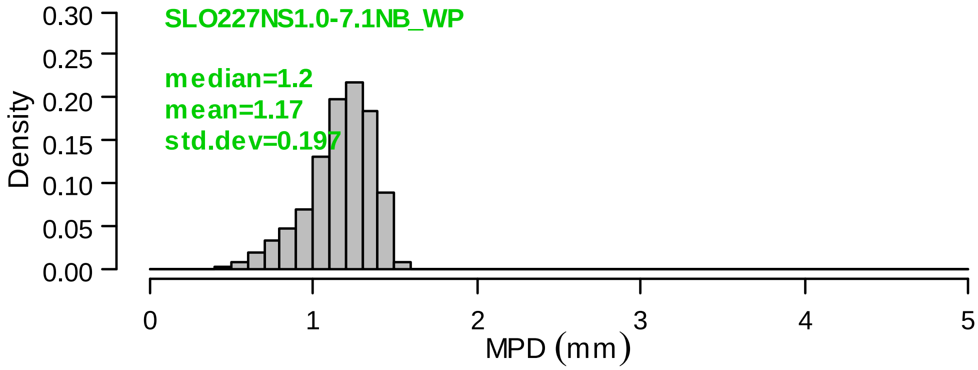


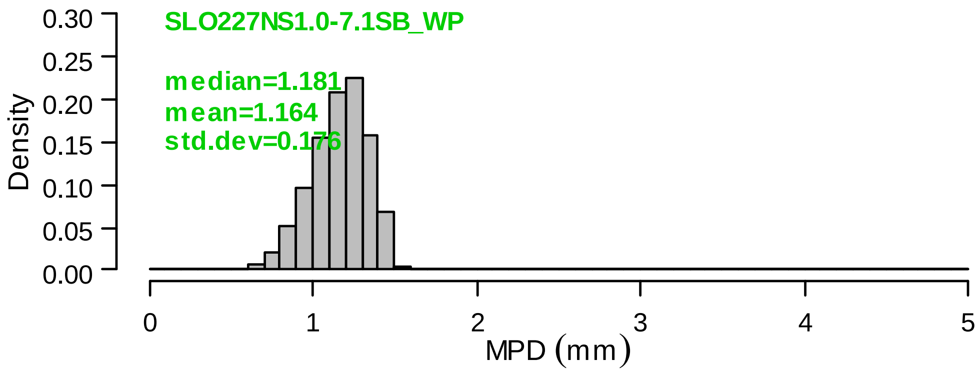




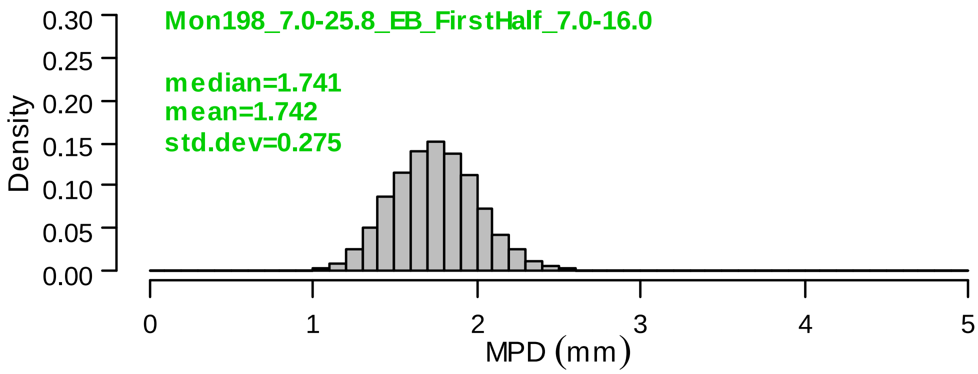


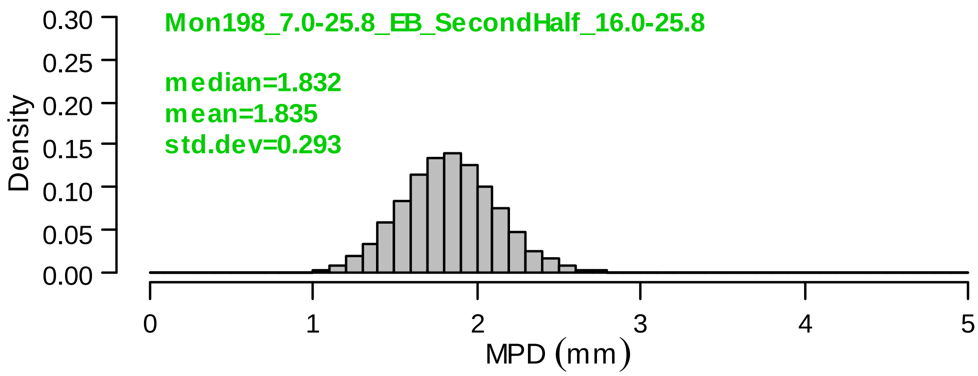
D.2 SLO-227, Chip Seal

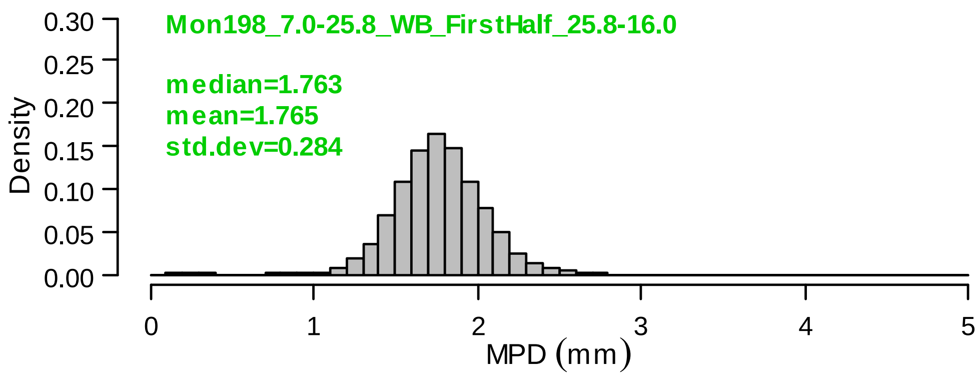


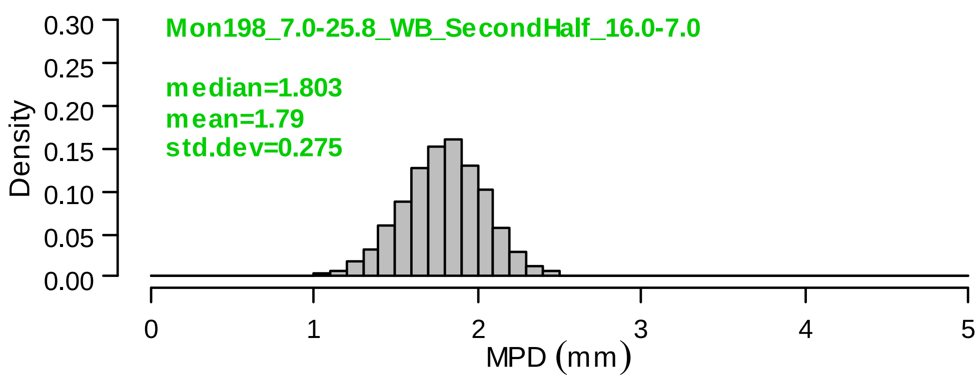


D.3 Mon-198, Chip Seal

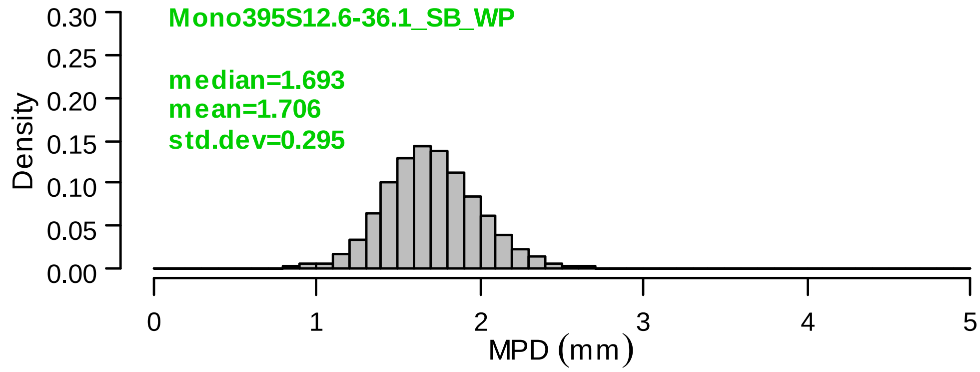


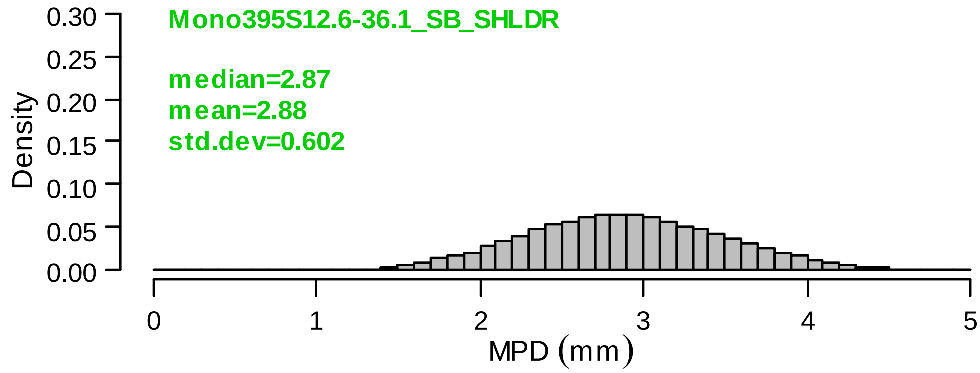


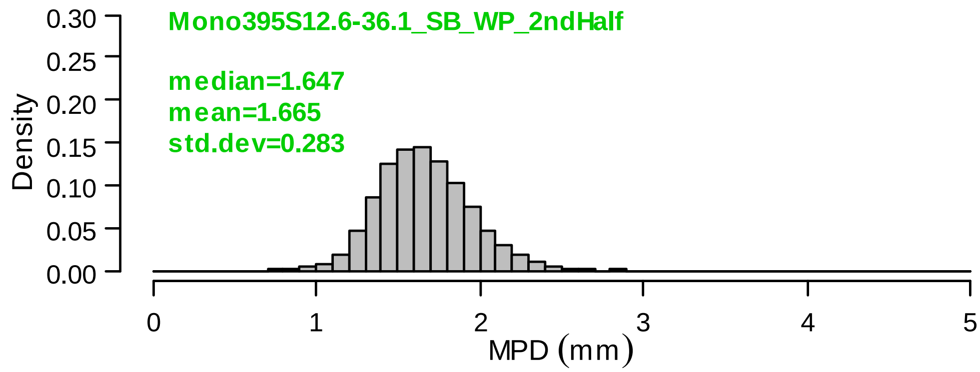


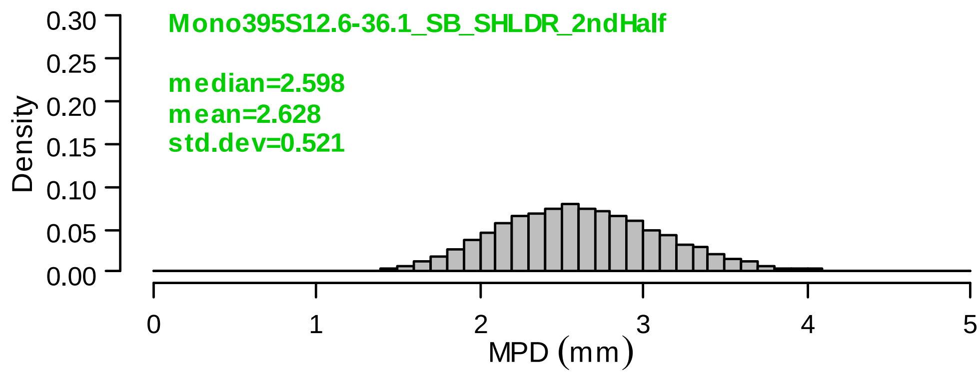


D.4 Mono-395, Chip Seal



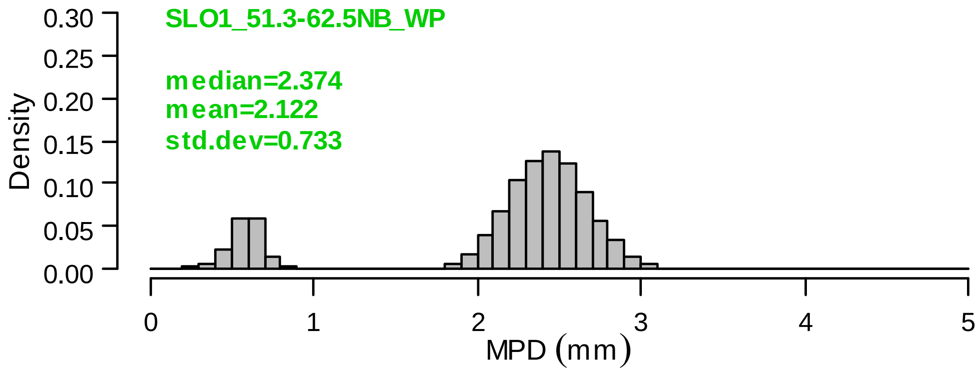


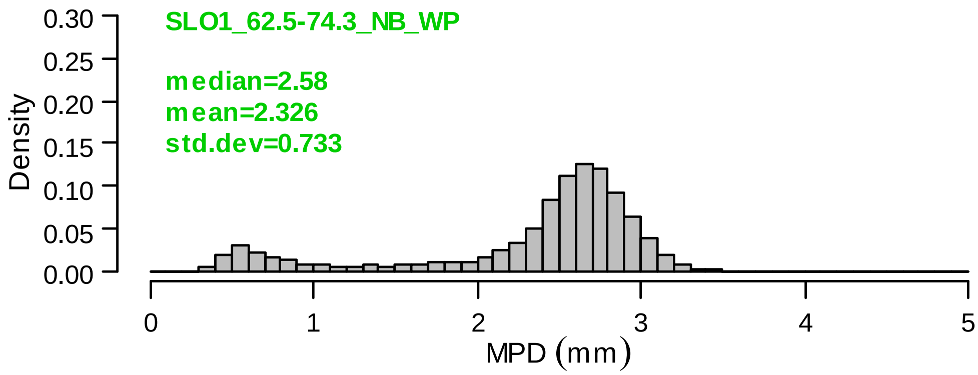


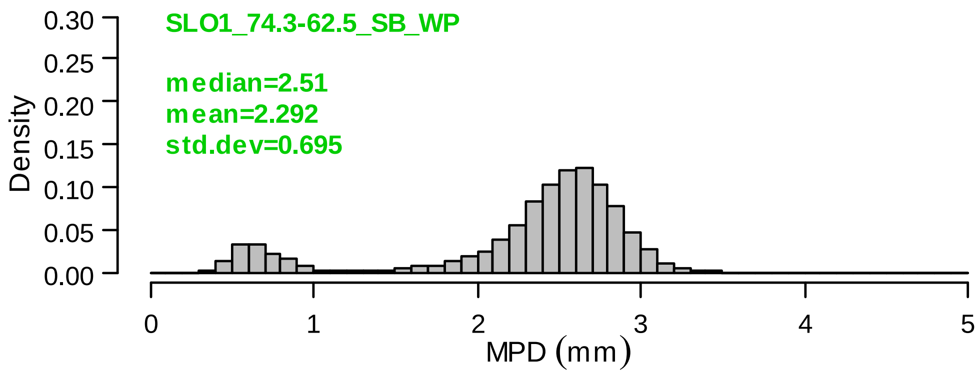


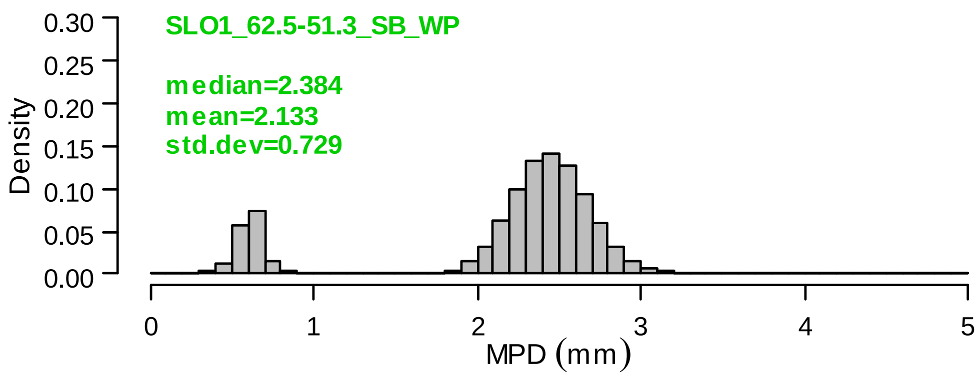
D.5 SLO-1, Chip Seal

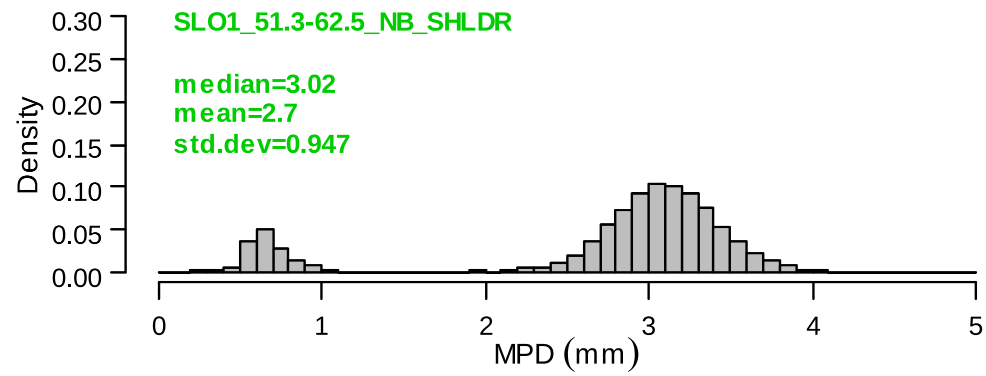
(lower population of values is underlying HMA and bridges)

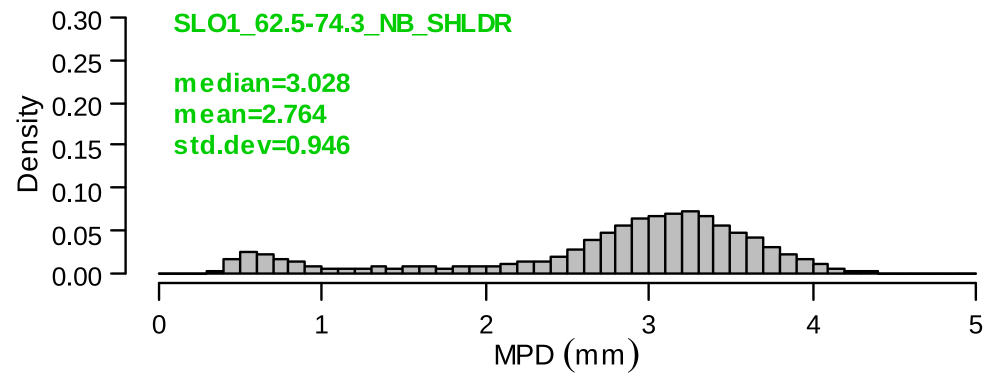


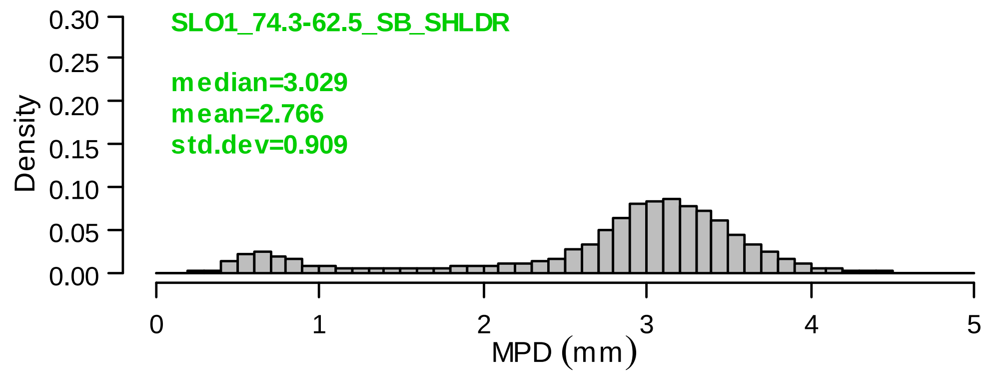


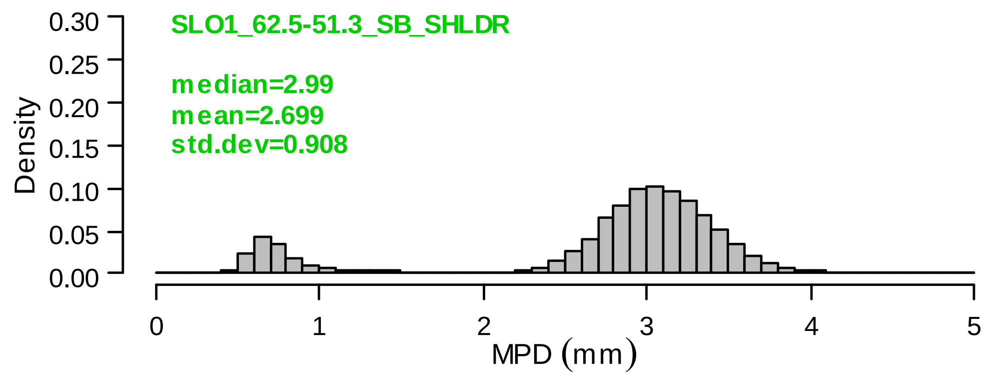




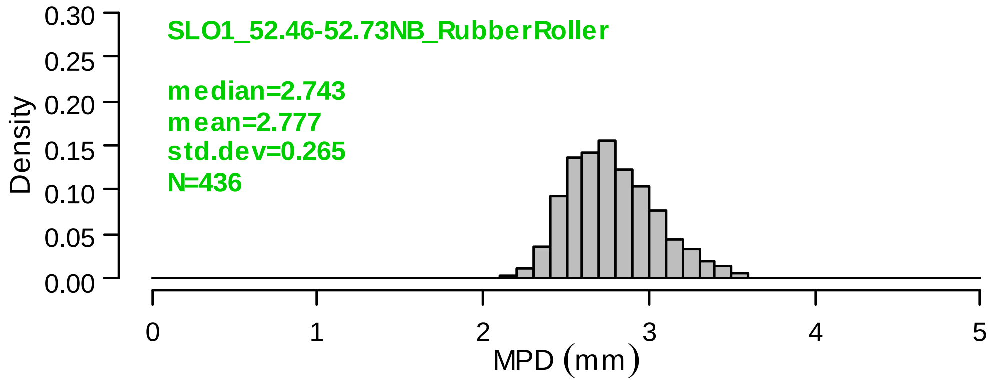

SLO1_51.3-62.5_NB_SHLDR
median=3.02
mean=2.7
std.dev=0.947
Density
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
MPD (mm)

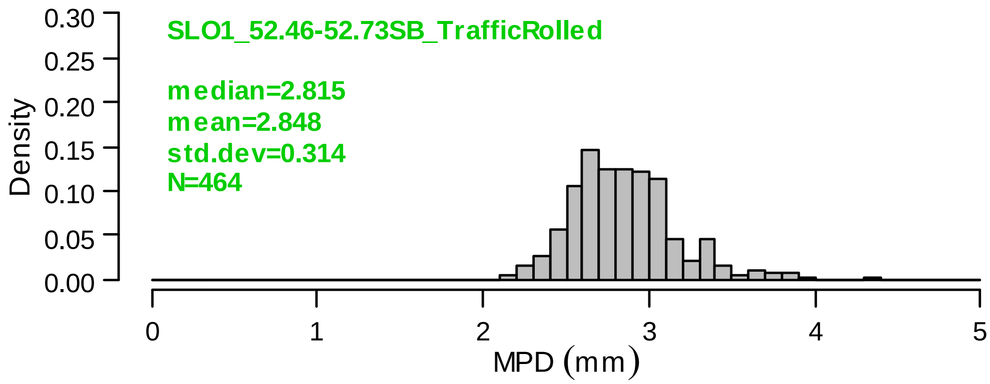

SLO1_62.5-74.3_NB_SHLDR
median=3.028
mean=2.764
std.dev=0.946
Density
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
MPD (mm)


SLO1_74.3-62.5_SB_SHLDR
median=3.029
mean=2.766
std.dev=0.909
Density
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
MPD (mm)


SLO1_62.5-51.3_SB_SHLDR
median=2.99
mean=2.699
std.dev=0.908
Density
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
MPD (mm)

D.6 SLO-1, Additional Rolling Test Section





APPENDIX E: BICYCLIST RIDE QUALITY SURVEY FORMS

E.1 Pre-Ride Survey

Caltrans/UCPRC Bicyclist Comfort Survey

Pre-ride Survey: General Information (*Please fill out and return it **BEFORE** riding*)
Date: 07/13/2013
Participant #:_____________

1. Are you: □ Male □ Female

2. What year were you born? ____________

3. What is your educational background? (Check the highest level attained)
   □ Some grade school or high school □ 4-year college/technical school degree
   □ High school diploma □ Some graduate school
   □ Some college or technical school □ Completed graduate degree(s)

4. What is your current employment status?
   □ Full-time □ Non-employed student □ Homemaker
   □ Part-time □ Unemployed □ Retired

5. Your approximate annual *household* income before taxes:
   □ Less than $15,000 □ $35,000 to $54,999 □ $75,000 to $94,999
   □ $15,000 to $34,999 □ $55,000 to $74,999 □ $95,000 or more

6. What type of bicycle did you ride today?
   □ Road □ Touring □ Mountain
   □ Hybrid □ Cruiser □ Other: _________________

7. What materials are your bicycle frame, fork, and wheels made of and what is the tire pressure?
   A. Frame: □ Aluminum □ Carbon □ Don't know
   □ Titanium □ Steel □ Other: _______________

   B. Fork: □ Aluminum □ Carbon □ Don't know
   □ Titanium □ Steel □ Other: _______________

   C. Wheels: □ Aluminum □ Carbon □ Don’t know
   □ Steel □ Other: _______________

   D. Tire pressure: __________ psi (if known)

8. How often do you ride your bicycle?
   □ Every day □ About once a week □ Once a month or less
   □ About every other day □ About twice a month

*Participant #:*____________

9. How often do you engage in any physical activity of at least 20 minutes?
   - □ Every day
   - □ About once a week
   - □ Once a month or less
   - □ About every other day
   - □ About twice a month

10. For what purposes do you ride your bicycle (check ALL that apply)?
    - □ Recreation or fitness
    - □ Getting to and from work or school
    - □ Visiting friends
    - □ Shopping or running errands
    - □ Competitive sporting events
    - □ Other: ___________________________

11. How many miles did you ride last *week*? _____________ miles

12. How many miles did you ride last *month*? _____________ miles

13. How many miles do you ride *on average every month*? _____________ miles

14. How many paid organized rides did you participate in within the *last 12 months*? __________

15. Based on your experience, what factors influence your enjoyment of a ride the most? Rank the following factors, *from 1 being the 'most influential' to 7 being the 'least influential'*. Write the rank number before each factor.

    __________Scenery
    __________Topography (e.g. hilly, flat)
    __________Road Geometric Design (e.g. straight, bicycle lanes)
    __________Pavement Ride Quality (e.g. bumpy, smooth)
    __________Traffic Conditions
    __________Wind
    __________Companions
    __________Other: ______________________

E.2 In-Ride Survey: Mon-198

Caltrans/UCPRC Bicyclist Comfort Survey

In-ride Survey: Mon-198 (*Please fill out at the end of* ***EACH*** *section*)

Section#: **1** Participant #:_____________

Time __________ - __________ **OR** Avg. speed _________ (mph)

1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:

Best: ___________________________ Worst: ___________________________

Section#: **2** Participant #:_____________

Time __________ - __________ **OR** Avg. speed _________ (mph)

1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:

Best: ___________________________ Worst: ___________________________

Section#: **3** Participant #:_____________

Time __________ - __________ **OR** Avg. speed _________ (mph)

1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:

Best: ___________________________ Worst: ___________________________

Section#: **4** Participant #:_____________

Time __________ - __________ **OR** Avg. speed _________ (mph)

1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:

Best: ___________________________ Worst: ___________________________

Section#: **5** Participant #:_____________

Time __________ - __________ **OR** Avg. speed _________ (mph)

1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:

Best: ___________________________ Worst: ___________________________

Section#: **6** Participant #:______________
Time ___________ - ___________ **OR** Avg. speed _________ (mph)
1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:
Best: _____________________________ Worst: _____________________________

Section#: **7** Participant #:______________
Time ___________ - ___________ **OR** Avg. speed _________ (mph)
1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:
Best: _____________________________ Worst: _____________________________

Section#: **8** Participant #:______________
Time ___________ - ___________ **OR** Avg. speed _________ (mph)
1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:
Best: _____________________________ Worst: _____________________________

Section#: **9** Participant #:______________
Time ___________ - ___________ **OR** Avg. speed _________ (mph)
1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:
Best: _____________________________ Worst: _____________________________

Section#: **10** Participant #:______________
Time ___________ - ___________ **OR** Avg. speed _________ (mph)
1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:
Best: ______________________________ Worst: ______________________________

Section#: **11** Participant #:______________
Time ___________ - ___________ **OR** Avg. speed _________ (mph)
1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:
Best: ______________________________ Worst: ______________________________

Section#: **12** Participant #:______________
Time ___________ - ___________ **OR** Avg. speed _________ (mph)
1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:
Best: ______________________________ Worst: ______________________________

Section#: **13** Participant #:______________
Time ___________ - ___________ **OR** Avg. speed _________ (mph)
1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:
Best: ______________________________ Worst: ______________________________

Section#: **14** Participant #:______________
Time ___________ - ___________ **OR** Avg. speed _________ (mph)
1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:
Best: ______________________________ Worst: ______________________________

Section#: **15** Participant #:______________

Time ___________ - ___________ **OR** Avg. speed _________ (mph)

1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:

Best: _____________________________ Worst: _____________________________

Section#: **16** Participant #:______________

Time ___________ - ___________ **OR** Avg. speed _________ (mph)

1. How do you rate the surface of the road? □ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. Please use one word each to describe the best and worst aspects of this section:

Best: _____________________________ Worst: _____________________________

E.3 Post-Ride Survey: Mon-198

Caltrans/UCPRC Bicyclist Comfort Survey

<u>Post-ride Survey</u> (*please fill out and return it at the end of all Mon-198 sections*)
Date: 07/13/2013
Participant #:_____________

1. Identify your favorite section of road from all the sections you just bicycled on. ________________ (section #)

2. What is the biggest reason that section was your favorite (select one)?
   - □ Scenery
   - □ Topography (e.g. hilly, flat)
   - □ Road Geometric Design (e.g. straight, bicycle lanes)
   - □ Pavement Ride Quality (e.g. bumpy, smooth)
   - □ Traffic Conditions
   - □ Wind
   - □ Companions
   - □ Other: ______________________

3. Identify your least favorite section of road from all the sections you just bicycled on.
________________ (section #)

4. What is the biggest reason that section was your least favorite (select one)?
   - □ Scenery
   - □ Topography (e.g. hilly, flat)
   - □ Road Geometric Design (e.g. straight, bicycle lanes)
   - □ Pavement Ride Quality (e.g. bumpy, smooth)
   - □ Traffic Conditions
   - □ Wind
   - □ Companions
   - □ Other: ______________________

5. Based on your experience, what factors influence your enjoyment of a ride the most? Rank the following factors, *from 1 being the 'most influential' to 7 being the 'least influential'*. Write the rank number before each factor.

__________Scenery
__________Topography (e.g. hilly, flat)
__________Road Geometric Design (e.g. straight, bicycle lanes)
__________Pavement Ride Quality (e.g. bumpy, smooth)
__________Traffic Conditions
__________Wind
__________Companions
__________Other: ______________________

E.4 In-Ride Survey: SLO-1

Caltrans/UCPRC Bicyclist Comfort Survey

In-ride Survey: SLO-1

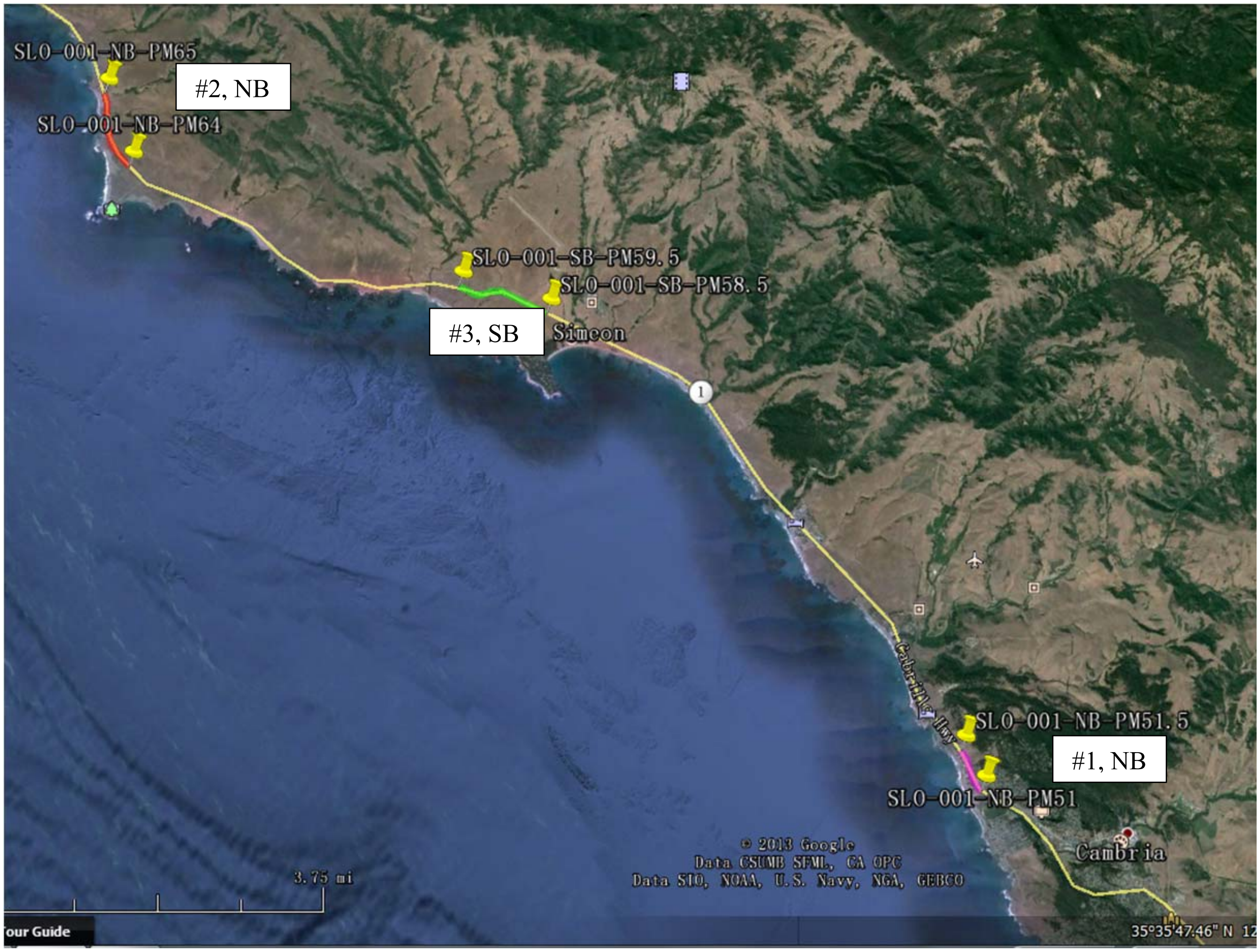
Survey must be returned to David Miller by 8:00 am on 22 July 2013 by email or mail.

By email: davmiller@ucdavis.edu
(can choose to scan or photograph the paper form or use the PDF form sent out to you)

By mail: David Miller (Survey Form)
Dept. of Civil & Environmental Engineering
University of California, Davis
Davis, CA 95616

You are expected to ride and rate three sections on SLO-1. These three specific sections are shown in the following map. The postmiles for them are PM 51.00 – 51.50 (Northbound), PM 64.00 – 65.00(Northbound), and PM 59.50 – 58.50 (Southbound), separately (see the white paddles Caltrans has on the side of the road; example is shown below).

Postmile example showing PM 50.29 on Ventura 33.



Section Locations on SLO-1

Section #1, *Northbound (NB)*, PM 51 (35°34'14.43"N, 121° 6'32.16"W) to PM 52.5 (35°34'42.58"N, 121° 6'48.74"W) (PM 51 is about 0.05 miles south of Weymouth Street in Cambria)

Section #2, *Northbound (NB)*, PM 64 (35°40'21.43"N, 121°16'51.06"W) to PM 65 (35°41'6.19"N, 121°17'11.84"W) (PM 64 is about 0.25 miles north of the driveway to the lighthouse)

Section #3, *Southbound (SB)*, PM 59.5 (35°39'7.64"N, 121°12'33.76"W) to PM 58.5 (35°38'37.17"N, 121°11'8.98"W) (in southbound between section #1 and section #2, north of San Simeon Bay and North in front of the Castle)

Participant #________ (same number as for Mon-198 survey) Date: _________ (mm-dd-yyyy)

#1, Postmile 51.0 – 51.5, Northbound Time ________ - _______ **OR** Avg. speed _________ (mph)

1. Based on this ride on SLO-1, how do you rate the surface of the road?

□ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. How many people were in your group during this section? __________ (1 if riding alone)

4. Please use one word each to describe the best and worst aspects of this section:

Best: ___________________________ Worst: ___________________________

Participant #________ (same number as for Mon-198 survey) Date: _________ (mm-dd-yyyy)

#2, Postmile 64.0 – 65.0, Northbound Time ________ - _______ **OR** Avg. speed _________ (mph)

1. Based on this ride on SLO-1, how do you rate the surface of the road?

□ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. How many people were in your group during this section? __________ (1 if riding alone)

4. Please use one word each to describe the best and worst aspects of this section:

Best: ___________________________ Worst: ___________________________

Participant #________ (same number as for Mon-198 survey) Date: _________ (mm-dd-yyyy)

#3, Postmile 59.5 – 58.5, Southbound Time ________ - _______ **OR** Avg. speed _________ (mph)

1. Based on this ride on SLO-1, how do you rate the surface of the road?

□ Acceptable □ Unacceptable

2. Compared to all of the roads on which you bicycle, please indicate your level of comfort:

Uncomfortable	1	2	3	4	5	Comfortable

3. How many people were in your group during this section? __________ (1 if riding alone)

4. Please use one word each to describe the best and worst aspects of this section:

Best: ___________________________ Worst: ___________________________

APPENDIX F: RAW SURVEY RESULTS

F.1 Raw Survey Results on Mon-198 and SLO-1

F.1.1 Pre-Ride Survey

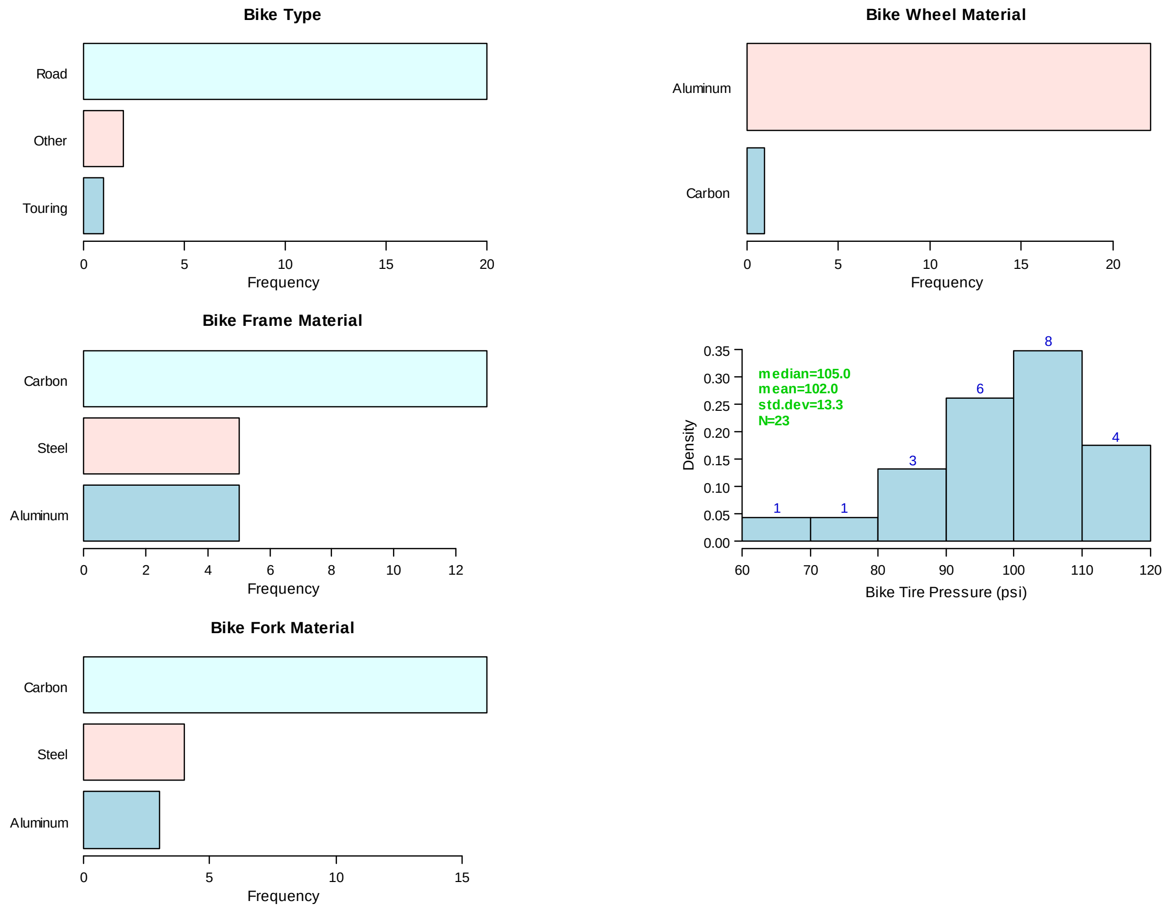


Figure F.1: Survey participants' bicycle information.

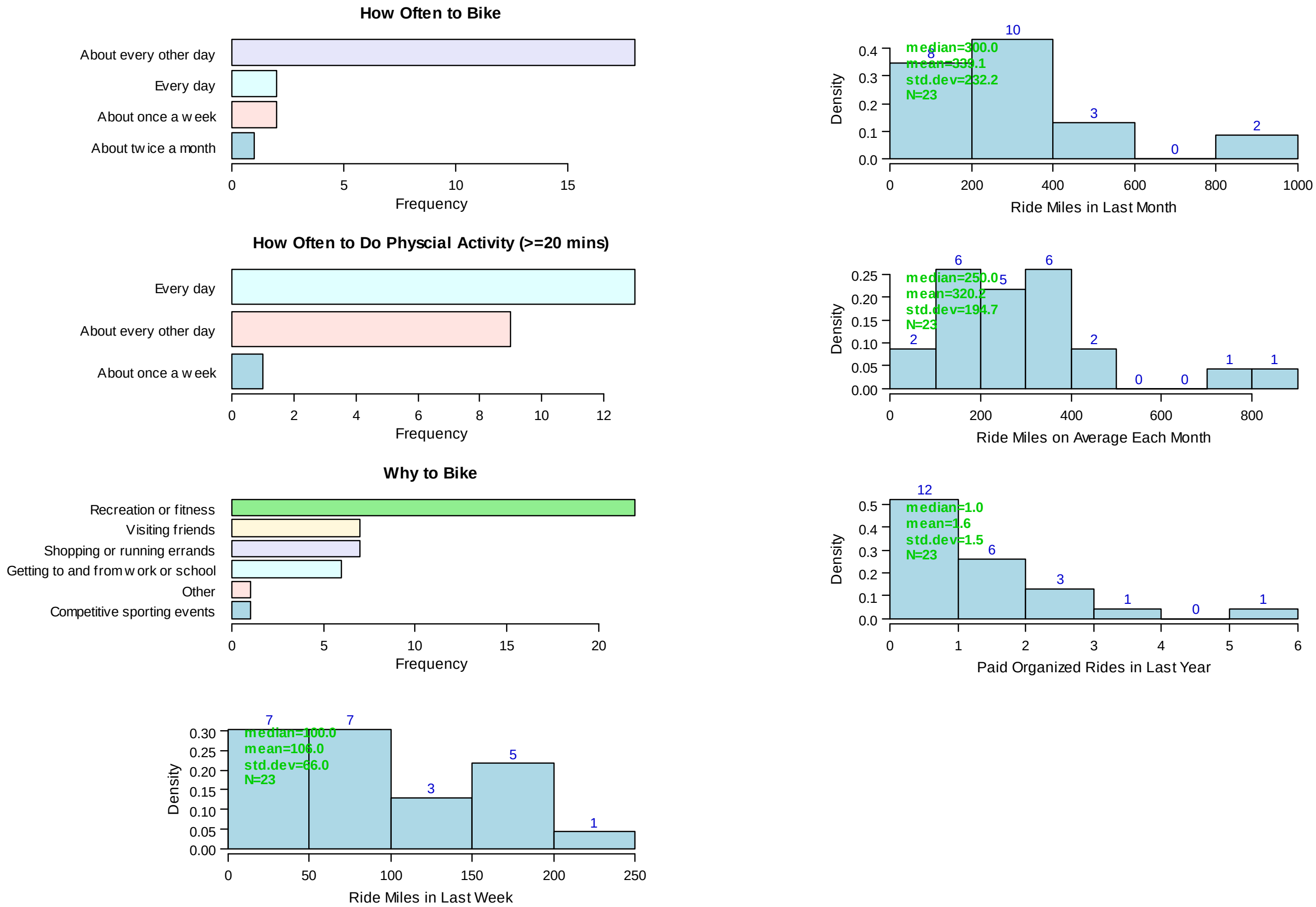


Figure F.2: Survey participants' bicycling information.

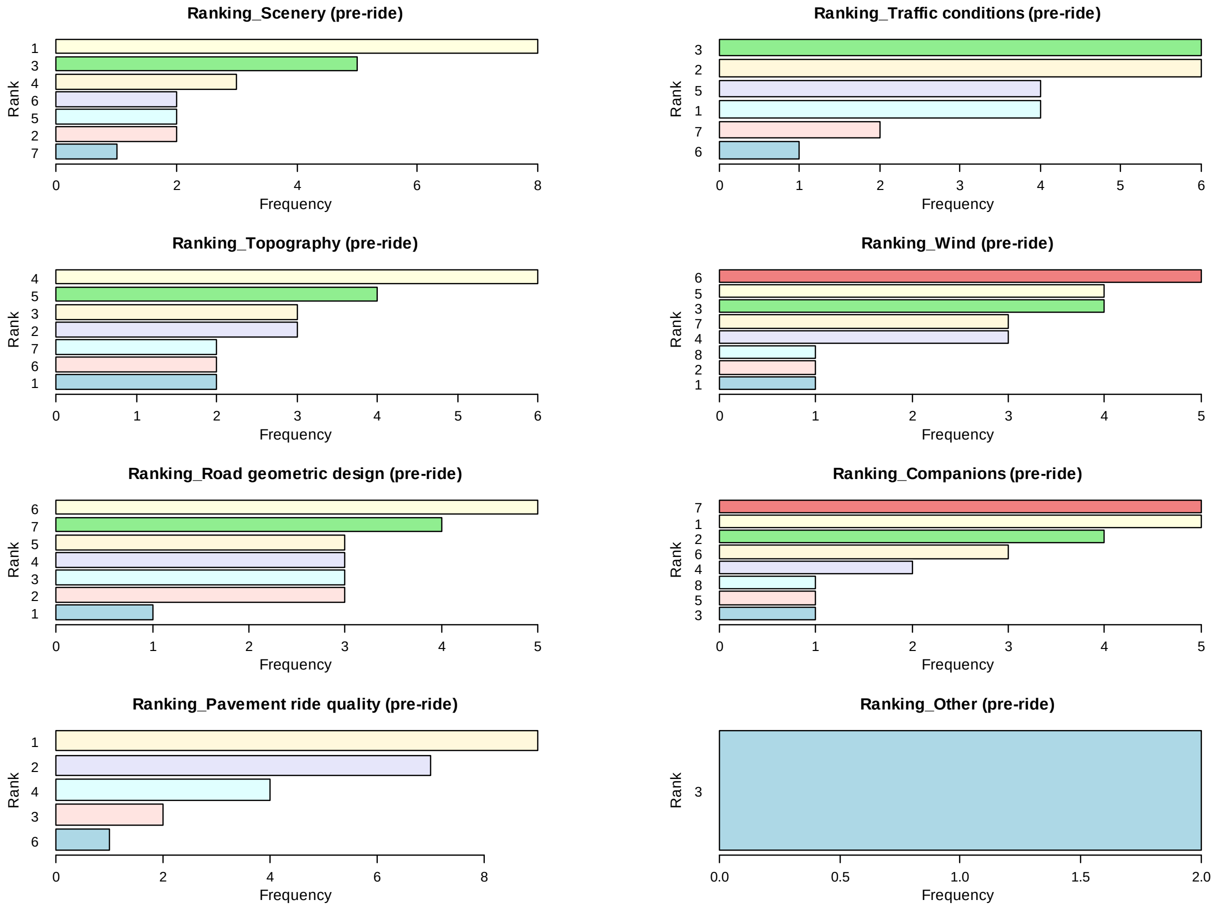


Figure F.3: Survey participants' factor ranking before riding and pre- survey.

F.1.2 In-Ride Survey: Mon-198 and SLO-1

Table F.1: Summary of Ride Quality Survey Results for SLO-1 and Mon-198 Test Sections

Route	Treatment ID	Survey Section ID	Acceptability Rate (0-1)			Ride Quality Level (1-5)		
			Number of Riders in Sample N	Avg.	Std. Dev.	Number of Riders in Sample N	Avg.	Std. Dev.
Mon-198	1	1	23	1.0	0.20	23	3.0	0.69
		6	20	1.0	0.22	23	3.3	0.85
	2	2	23	0.9	0.34	23	3.2	0.78
		5	21	1.0	0.21	23	3.2	1.05
	3	3	22	0.4	0.49	23	2.3	0.92
		4	23	0.4	0.50	23	2.1	0.95
	4	7	23	0.9	0.34	23	3.0	0.87
		16	21	1.0	0.21	22	3.2	0.63
	5	8	22	1.0	0.00	23	4.2	0.97
		15	19	1.0	0.00	22	4.1	0.77
	6	9	22	0.9	0.29	23	3.5	0.82
		14	21	1.0	0.00	23	3.6	0.87
	7	10	23	0.9	0.34	23	3.2	0.88
		13	23	0.9	0.34	23	3.0	0.63
	8	11	22	1.0	0.21	23	3.8	0.98
		12	22	1.0	0.21	22	3.9	0.95
SLO-1	11	21	11	0.1	0.29	11	1.4	0.64
		22	11	0.1	0.29	11	1.2	0.39
		23	11	0.1	0.29	11	1.2	0.39

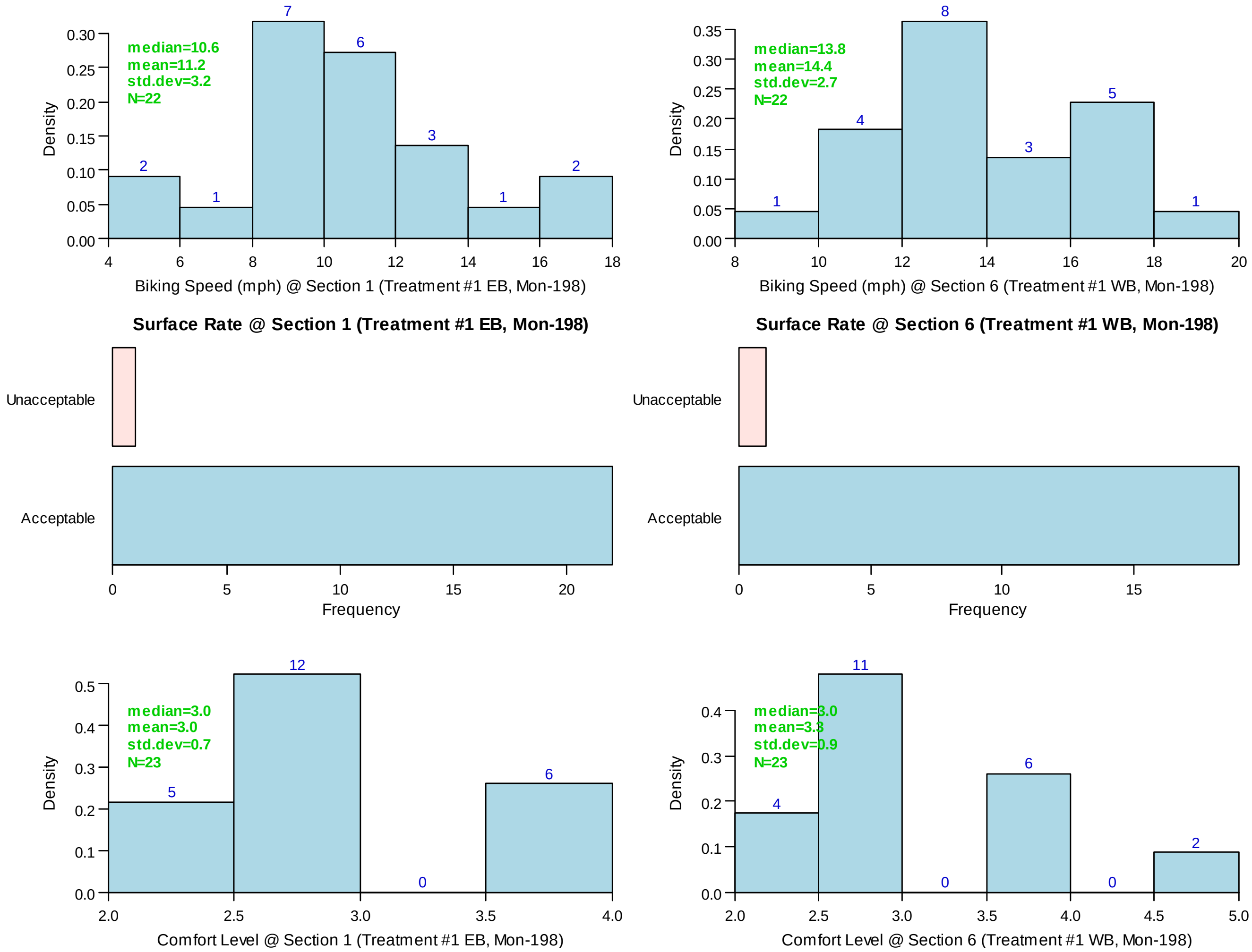


Figure F.4: Raw survey results for treatment #1 (Mon-198).

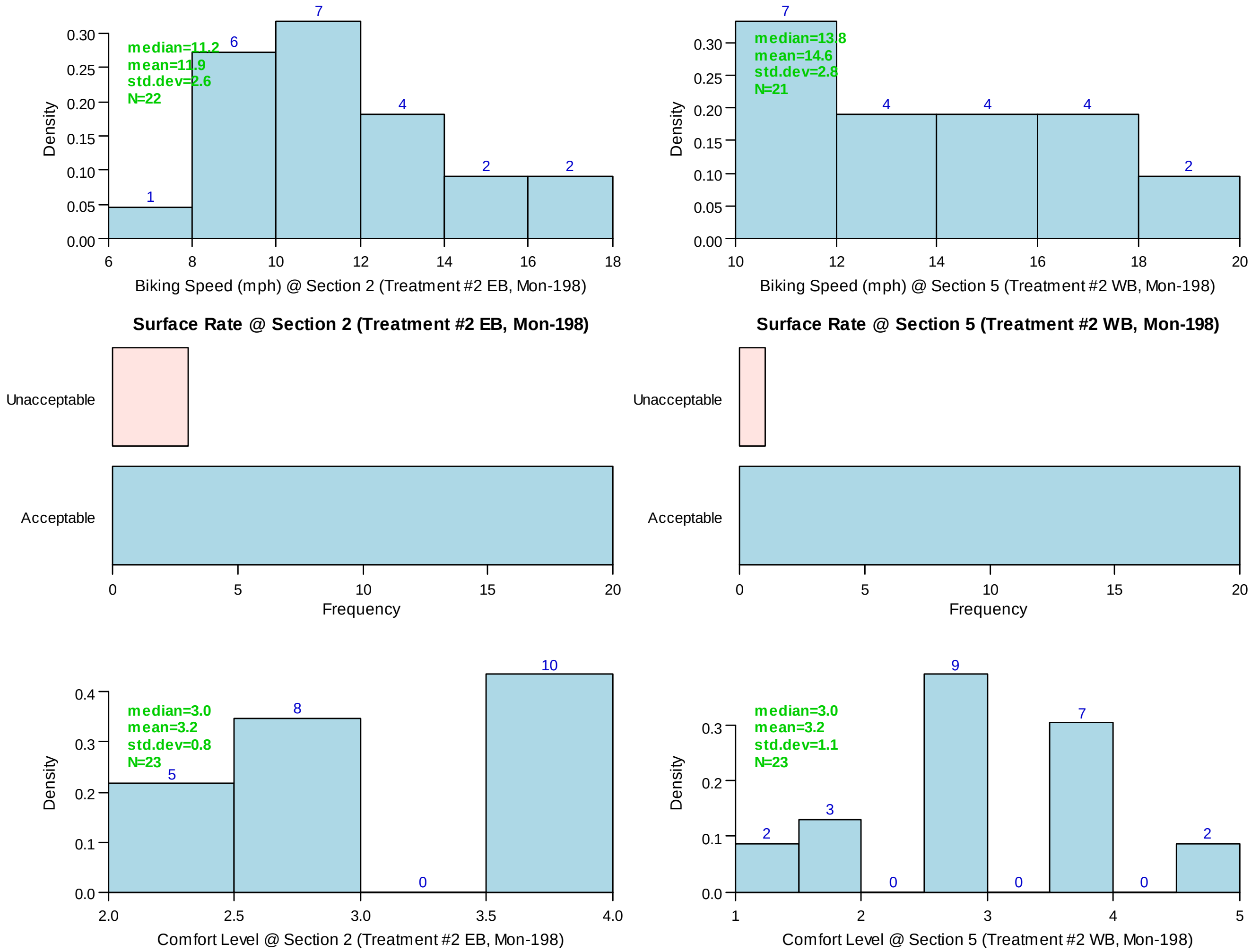


Figure F.5: Raw survey results for treatment #2 (Mon-198).

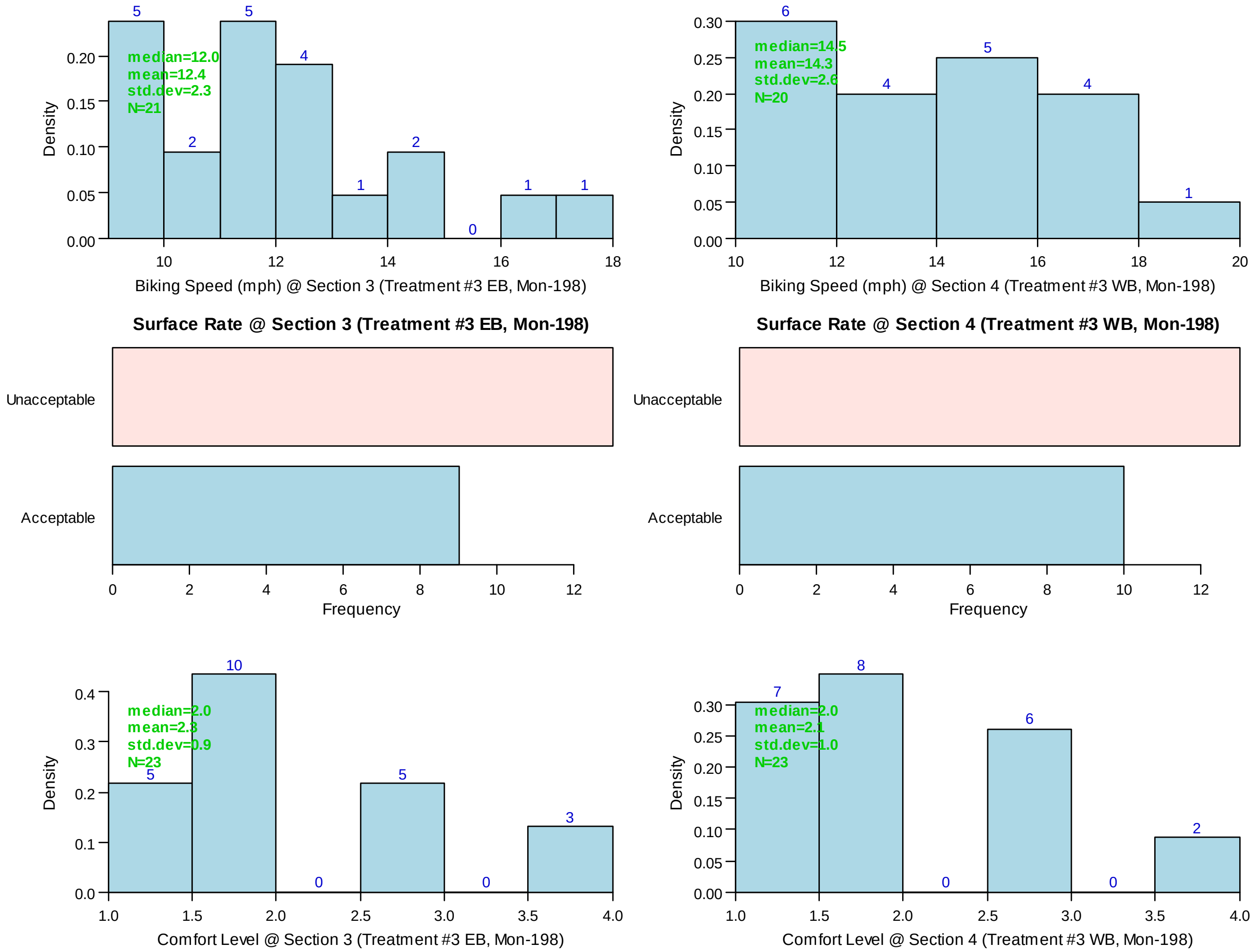


Figure F.6: Raw survey results for treatment #3 (Mon-198).

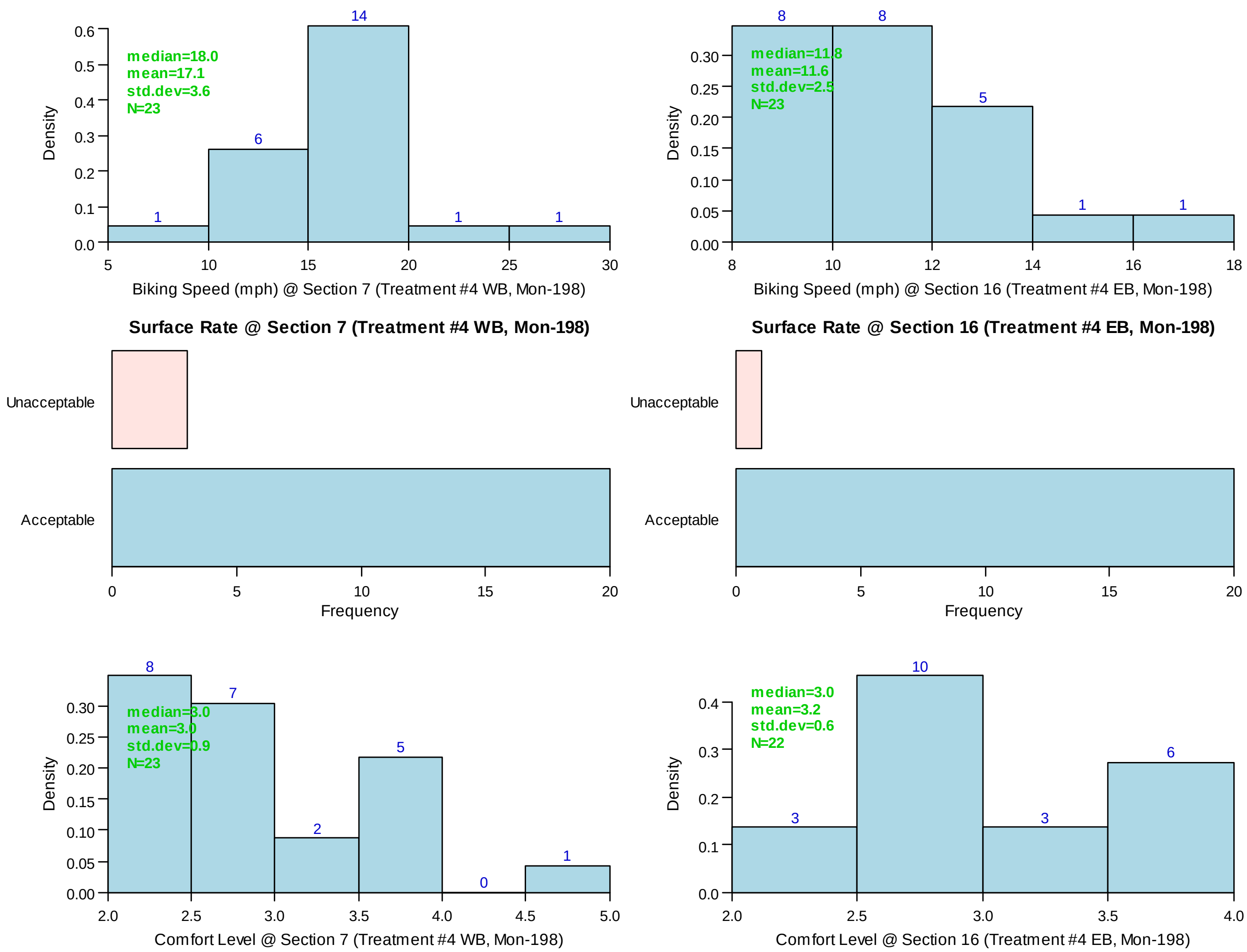


Figure F.7: Raw survey results for treatment #4 (Mon-198).

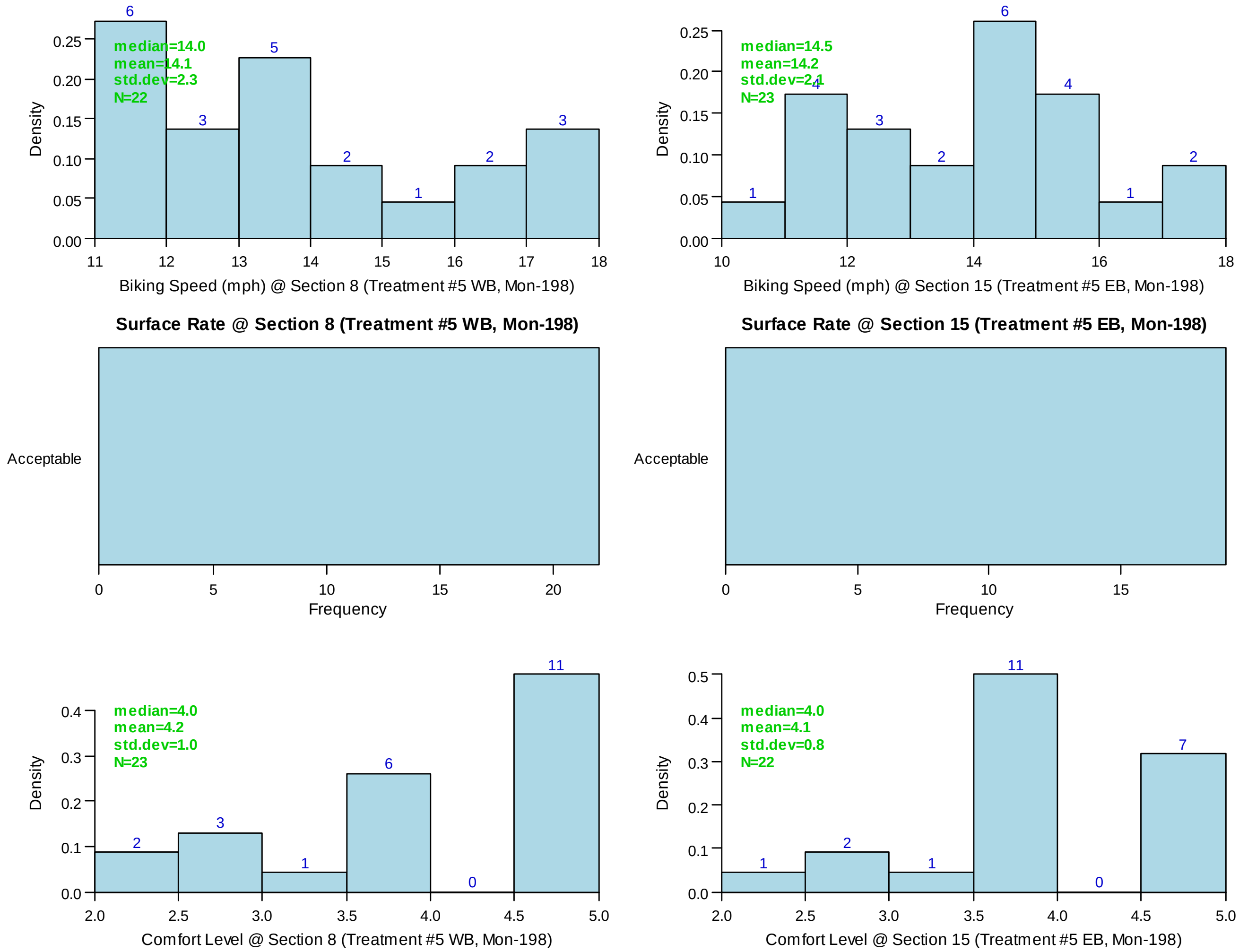


Figure F.8: Raw survey results for treatment #5 (Mon-198).

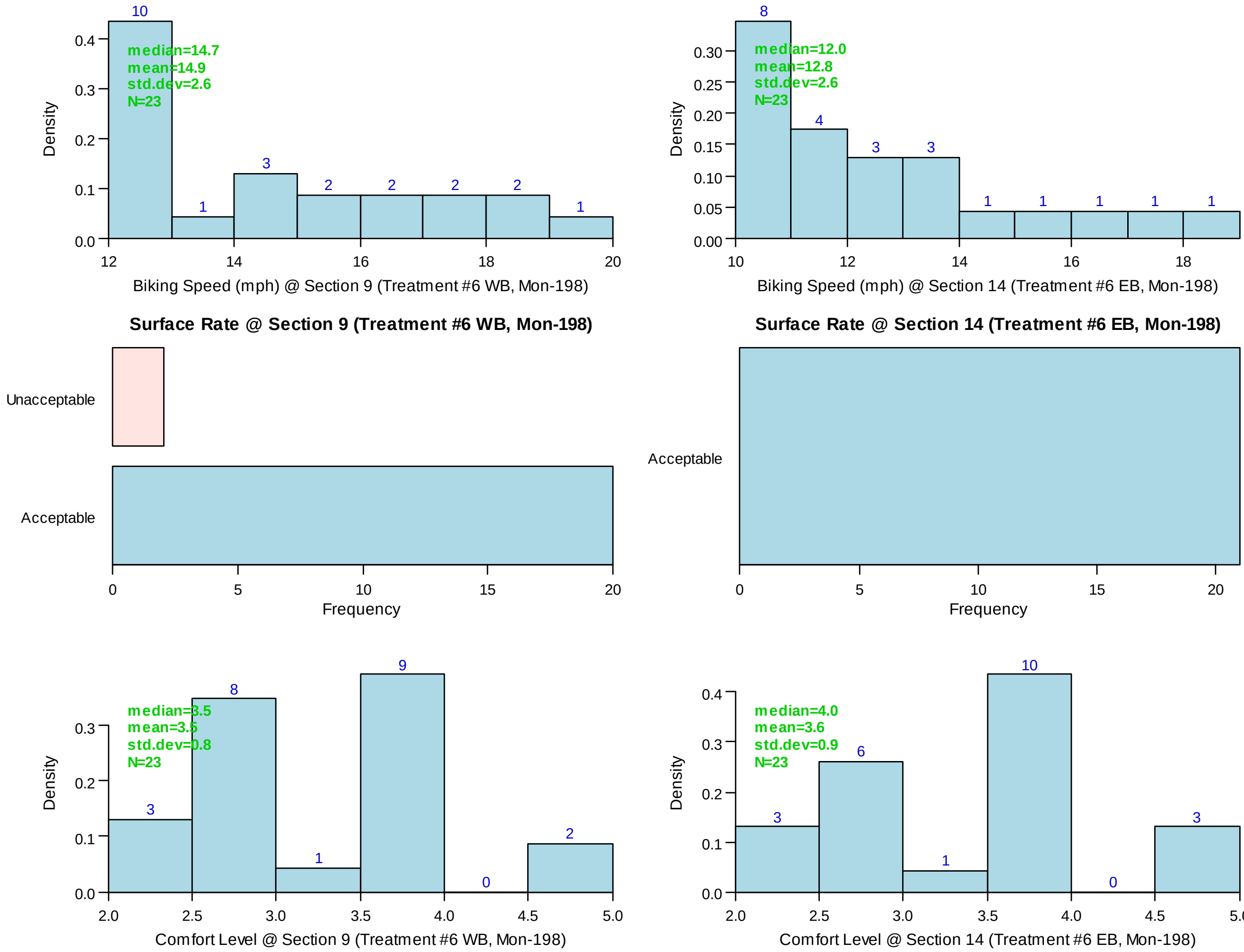


Figure F.9: Raw survey results for treatment #6 (Mon-198).

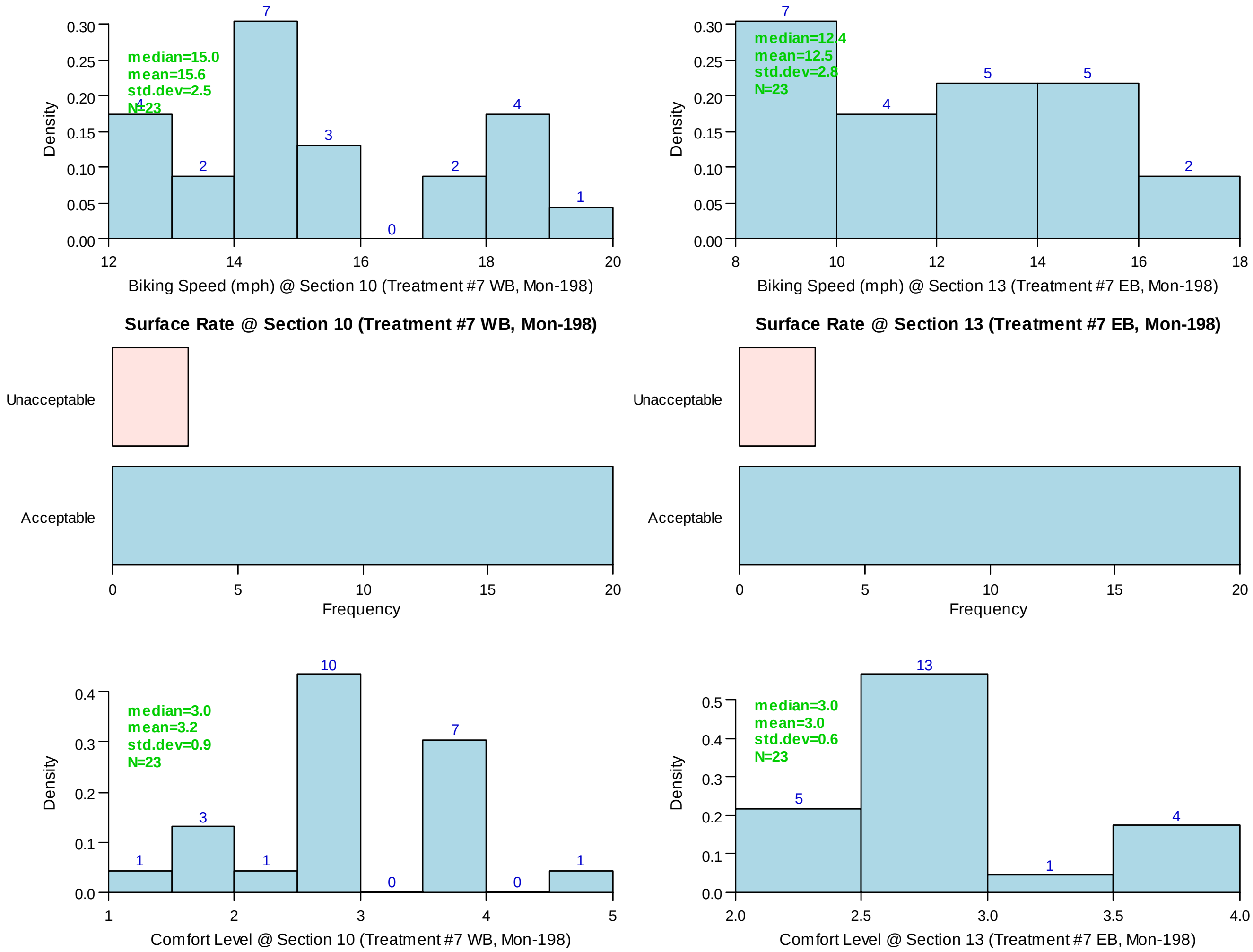


Figure F.10: Raw survey results for treatment #7 (Mon-198).

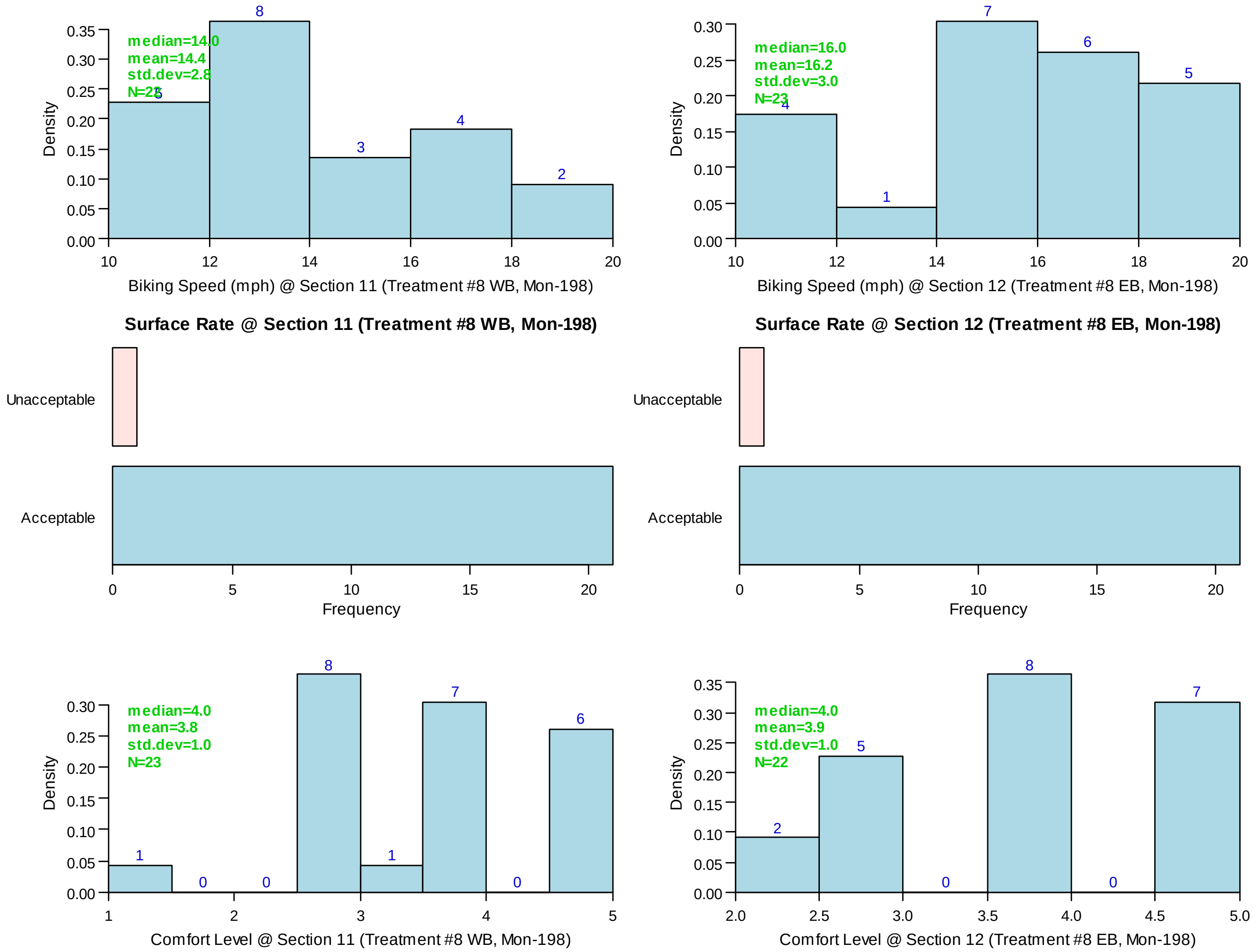


Figure F.11: Raw survey results for treatment #8 (Mon-198).

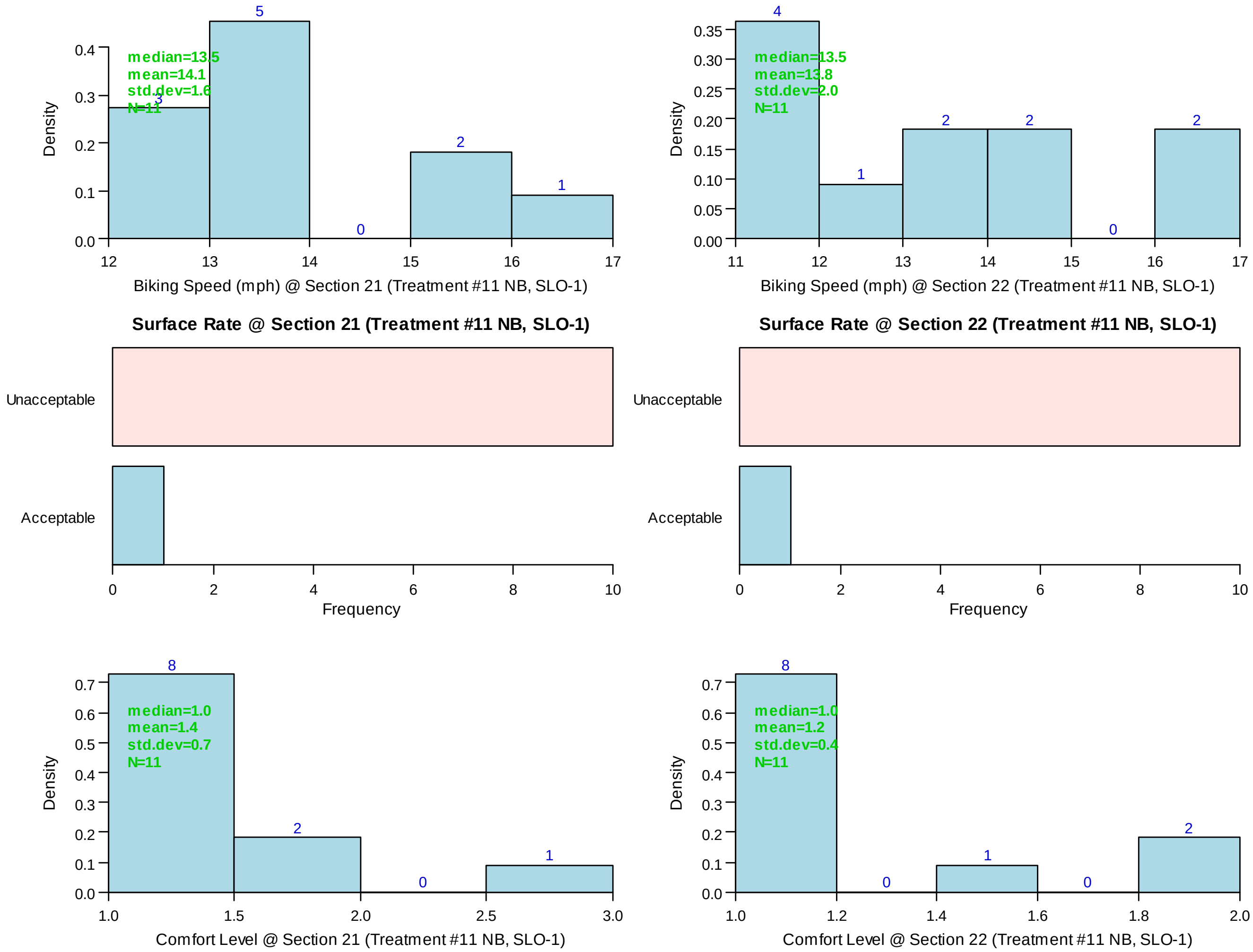
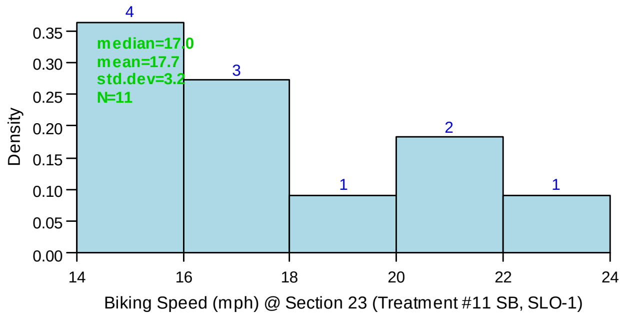
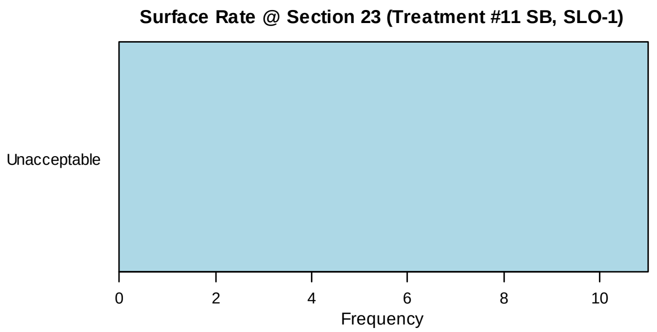


Figure F.12: Raw survey results for treatment #11 (SLO-1).





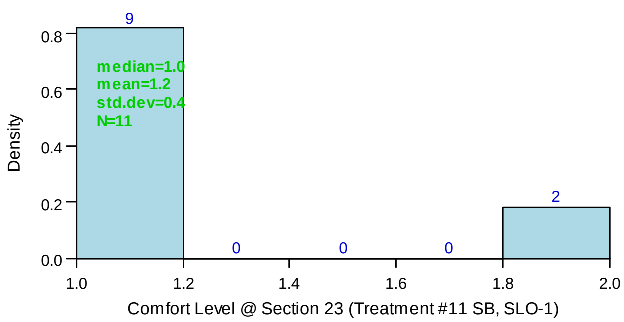


Figure F.12: Raw survey results for treatment #11 (SLO-1) *(continued).*

F.1.3 Post-Ride Survey: Mon-198

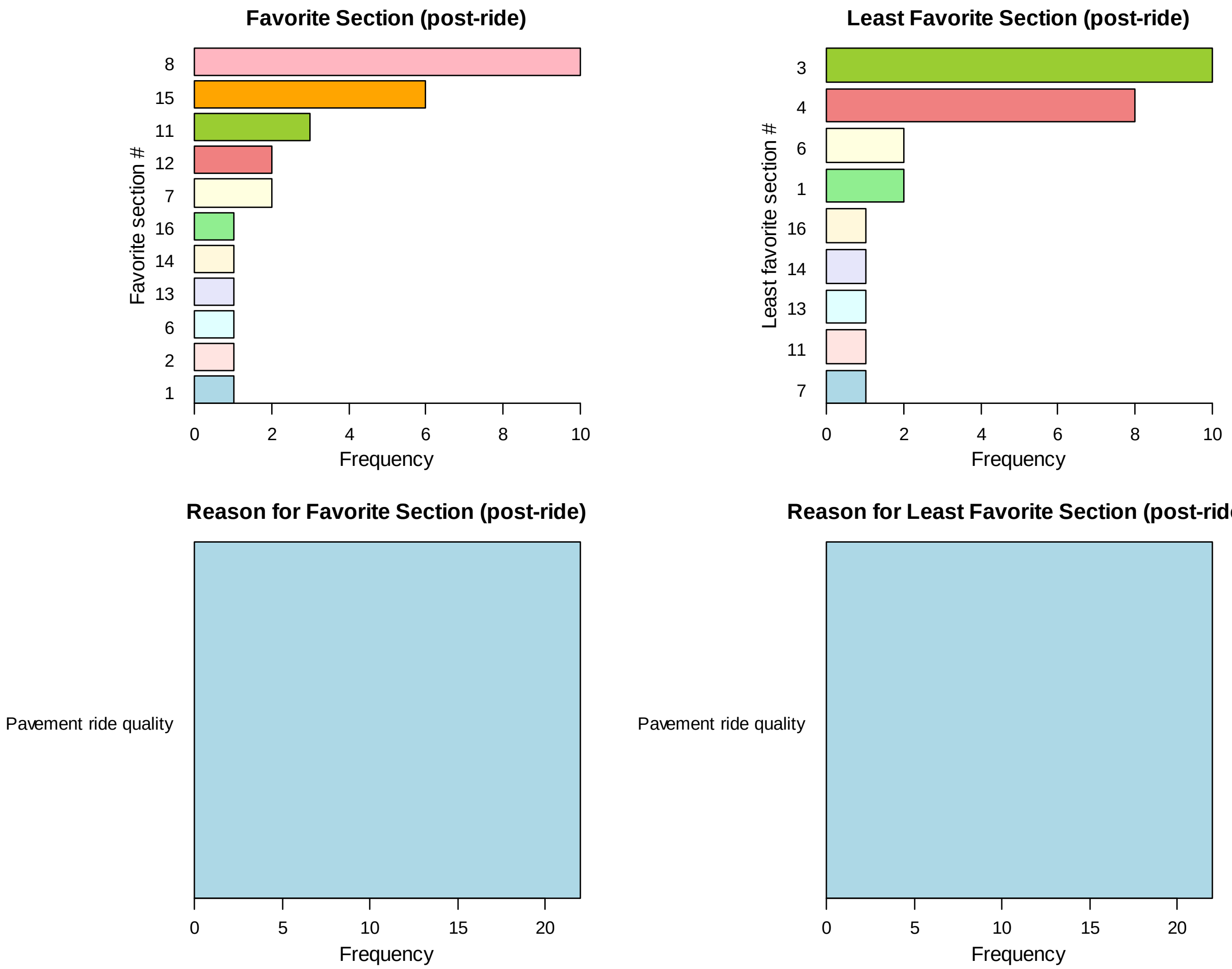


Figure F.13: Raw results for post-ride survey (Mon-198).

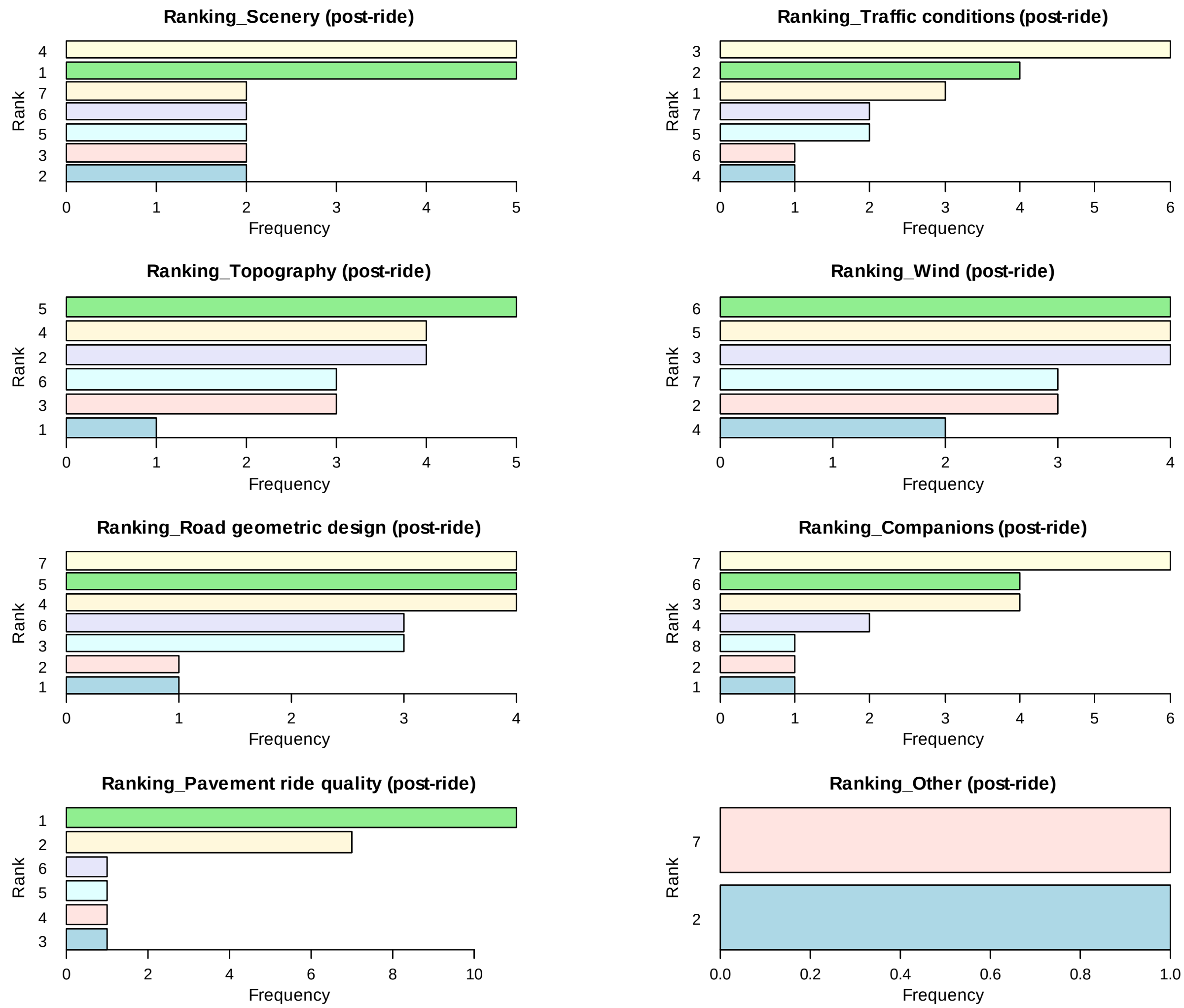


Figure F.14: Survey participants' factor ranking after riding and post-survey (Mon-198).

F.2 Survey Participants' Comments on the Road Sections

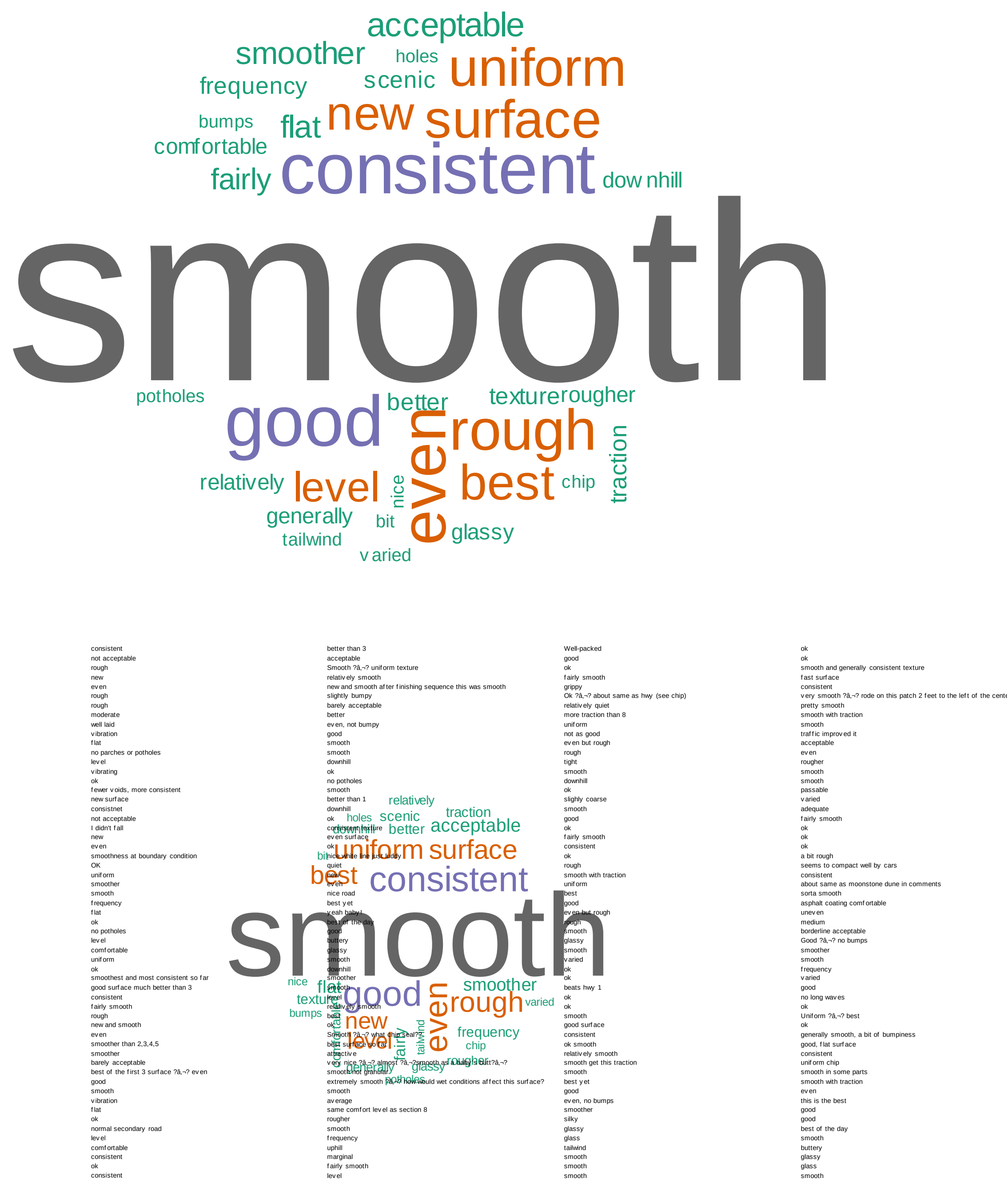


Figure F.15: Word cloud of the words used to describe the best aspect of the sections (Question #3 or 4 of the in-ride survey). (Note: word size is proportional to the frequency of the word).

Figure F.16: Word cloud of the words used to describe the worst aspect of the sections (Question #3 or 4 of the in-ride survey).
(Note: word size is proportional to the frequency of the word.)

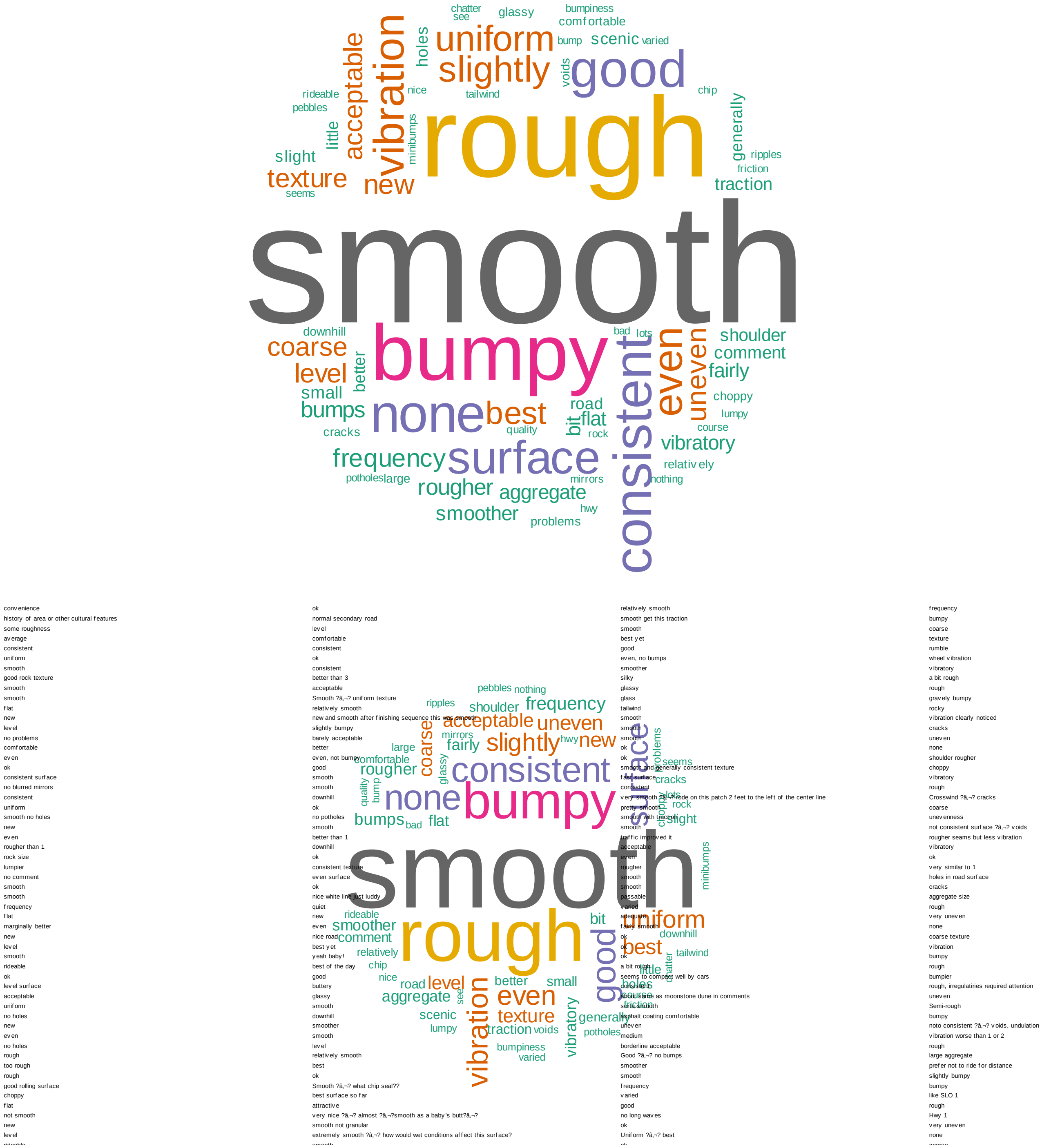


Figure F.17: Word cloud of the words used to describe both best and worst aspects of the sections (Question #3 or 4 of the in-ride survey).
(Note: word size is proportional to the frequency of the word).