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Surface Treatment Macrotexture and Bicycle Ride Quality

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

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Abstract:
This memorandum summarizes the results of measurements of macrotexture on a set of Caltrans and local government pavement surface treatments, and the results of bicycle vibration measurements and a survey of bicycle ride quality on most of those sections. The work was performed to address concerns raised by local bicyclists regarding ride quality after a modified-binder seal coat (chip seal) was placed on State Route 1 in San Luis Obispo County (SLO-1). The test sections that were used for the bicycle vibration and ride quality measurements included various surface treatments on existing chip seals on State Route 198 in Monterey County (Mon-198), several locations on SLO-1, and on other state highway and county road sections in Yolo, Butte, El Dorado, Placer, Sonoma, Marin, and San Mateo counties. 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 statistical correlations between macrotexture, roughness (in terms of International Roughness Index [IRI]), bicycle vibration, and bicycle ride quality for the initial set of treatment sections surveyed, and modeling of the relationships between macrotexture, roughness, 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 a bicycle 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, IRI, bicycle vibration, and bicyclists' perception of ride quality and pavement acceptability for use by bicycles. Recommendations are made regarding a range of MPD values that might be used to select chip seal specifications based on "acceptability" where bicycle ride quality is an issue, selection of remedial treatments for SLO-1 based on the Mon-198 test sections, naming conventions for chip seals, and the use of additional rolling to reduce the texture of chip seals built using the coarser 3/8" aggregate grading.

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

Proposals for implementation:

Select chip seal gradations that will not exceed the recommended MPD where bicycle ride quality is an issue, change naming conventions for chip seal gradations, and perform measurements to provide better guidance to designers regarding the relationship between MPD and chip seal gradations.

Related documents:

H. Li, J. Harvey, R. Wu, C. Thigpen, S. Louw, Z. Chen, J. D. Lea, D. Jones, and A. Rezaie. *Preliminary Results: Measurement of Macrotexture on Surface Treatments and Survey of Bicyclist Ride Quality on Mon-198 and SLO-1 Test Sections.* Univ. of California Pavement Research Center, Davis and Berkeley. 2013. UCPRC-TM-2013-07.

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PROJECT OBJECTIVES

The purpose of this project is to address the impact of surface treatments referred to as *seal coats,* which are often called *chip seals,* on bicyclists. This is to 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 (SLO-1) 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 in those two phases to achieve these objectives:

Phase I

Task A: Evaluate the existing surface textures and alternative ones 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 on other test sections on State Route 198 in Monterey County (Mon-198) 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 examine how they vary with the age of the treatment for different climates and traffic levels.

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

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: As part of Phase II, conduct bicyclist surveys at an extended set of organized ride events, including these:

- Tour of Tahoe event in El Dorado and Placer counties on September 8, 2013
- Smaller rides organized by the following bicycle clubs in August through September 2013
    - Davis Bicycle Club in Solano and Yolo counties (August 10, 2013)
    - Santa Rosa Cycling Club in Sonoma County (September 7, 2013)
    - Chico Velo Cycling Club in Butte County (September 21, 2013)
    - Alto Velo Racing Club and Silicon Valley Bicycle Coalition in San Mateo County (September 28, 2013)
- Texture and roughness measurements were made with the inertial profiler on State Route 2 in Los Angeles County (LA-2) based on a request from Caltrans in late 2013, but no rider survey was conducted.

Task E: Deliver a final report that documents this research effort and includes recommendations for improving the use of chip seal surface treatments for bicyclists.

This research report completes all the deliverables from the project including Phase I and Phase II.

EXECUTIVE SUMMARY

In 2012, the California Department of Transportation (Caltrans) placed a modified-binder seal coat, also commonly called a *chip seal* (the term that will be used primarily in this report) and sometimes called a *surface treatment*, on State Route 1[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.

A hot-applied chip seal had been placed along this entire stretch of highway in 1991, and the chip seal placed in 2012 was intended as a preventive maintenance strategy to extend the service life of the existing pavement and to protect against water intrusion and further oxidation. However, in January 2013, shortly after the chip seal construction, bicyclists using SLO-1 alerted Caltrans about what they perceived as poor ride quality within the project limits.

In response, the Caltrans Division of Maintenance in District 5 contacted the Division of Maintenance Office of Asphalt Pavement and the Division of Research, Innovation, and System Information to address this issue. The Office of Asphalt Pavement and District 5 prepared a scoping document titled “Chip Seal for Highway Including Bicycle Users,” dated 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 prepared a work plan titled “Impact of Chip Seal on Bicyclists” for the evaluation of SLO-1 and treatment test sections which was approved by Caltrans on March 27, 2013. This work plan was updated on July 17, 2013, to include evaluation of additional pavement sections and additional bicyclist surveys.

The purpose of this project was to address the impact of chip seals on bicyclists. This was to 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 (SLO-1) 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] In this research report, this section is referred to as “SLO-1.” References to other state highway sections in this research report follow the same naming convention, using their county abbreviation and route number.

The first phase was intended to obtain preliminary information to make recommendations for SLO-1, and the second phase was intended to obtain more comprehensive data regarding the effects of texture on vibration and bicycle ride quality. The following tasks were performed to achieve the objectives of each phase:

Phase I

Task A: Evaluate the existing surface textures and alternative ones 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 on other test sections on State Route 198 in Monterey County (Mon-198) 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 examine how they vary with the age of the treatment for different climates and traffic levels.

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

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: Conduct bicyclist surveys at an extended set of organized ride events. Texture and roughness measurements were made on State Route 2 in Los Angeles County based on a request from Caltrans in late 2013, but no rider survey was conducted.

Task E: Deliver a final report that documents this research effort and includes recommendations for improving the use of chip seal surface treatments for bicyclists.

A technical memorandum delivered in November 2013 completed the scope of Phase I. Those results are incorporated in this final report along with results from the rest of the project. This research report documents the results from all the tasks in Phase I and Phase II. Recommendations to improve the use of chip seal surface treatments for bicycle users are also included.

Chapter 2 includes the results of a literature review and covers basic pavement surface texture concepts, typical texture characteristics, and the measured texture values for several types of asphalt surfaces built by Caltrans in the past. The chapter also includes a discussion of the available literature regarding pavement surface texture and bicycle ride quality. Chapter 3 describes the test sections and experimental methods used for field measurements on the surface treatments—including the measurement methods for pavement macrotexture and bicycle vibration—and the survey form used to evaluate bicycle ride quality for the initial surveys on SLO-1 and Mon-198. Chapters 4 and 5 present the results and analyses of the pavement surface macrotexture measurements, including the results of the bicycle vibration and bicycle ride quality surveys on Mon-198 and SLO-1, and on the Phase II Task D extended survey sections, respectively. Chapter 6 presents the results of modeling bicycle ride quality using the results from all of the survey sections. Chapter 7 presents the results of the effects of remedial treatment on SLO-1. Chapter 8 presents conclusions and recommendations. The appendixes contain detailed results and statistical analyses of the field measurements and bicycle ride quality surveys.

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. Vehicle ride quality is primarily affected by megatexture (wavelengths of 0.5 mm to 50 mm) and roughness (wavelengths greater than 500 mm). For bicycles, an examination of macrotexture was considered to be more critical as the surface texture in this range of wavelengths is most likely to cause bicycle vibration.

Macrotexture is typically measured in terms of mean profile depth (MPD) or mean texture depth (MTD), two closely related parameters. Ways to measure them include use of the sand patch method (SP, ASTM E965), the outflow meter (OM, ASTM E2380), the laser texture scanner (LTS, ASTM E2157/ASTM E1845), or the inertial profiler (IP, ASTM E1845). In this study, the sand patch, laser texture scanner, and inertial profiler methods were used and then compared with each other and correlated. Good correlations were found.

The sand patch method is a slow process that must be performed manually, and is somewhat subject to user expertise. Use of the laser texture scanner, like the sand patch, follows a stationary method requiring a traffic closure and measurements over a small area (on the order of 40 square inches). Unlike those methods, the inertial profiler is mounted on a vehicle and measures MPD along a line taken by the vehicle operating at highway speeds, which provides a continuous measurement along the section of highway.

MPD values for most hot-mix asphalt (HMA) materials historically used on California state highways typically range from approximately 0.5 mm to 1.5 mm. The macrotexture of some large-stone open-graded materials (F-mixes) that were used for a time on the North Coast are as high as approximately 2.0 mm. These values can be used for reference when looking at the MPD values measured on the different pavement surfaces in this study.

The following table summarizes the testing performed in Phase I. Although a 3/8" chip seal is shown in the table for all the chip seal projects, two gradation specifications were used. The gradation used on SLO-1, Mon-198, and Mno-395 was coarser than that used on SLO-227. The reason for the difference is that 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 Mno-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 the naming of the two gradations used on SLO-227 and on 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 research report as the *finer 3/8" gradation,* and the coarser gradation used on SLO-1, Mon-198, and Mno-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 seal.

Road Sections Used in Phase I of 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 in the report)	July 2013, Cambria to Piedras Blancas	
		Additional rolling subsection	IP, LTS, SP April – May 2013 (Figure 3.2 in the report)		
		Bicycle survey subsections		July 12, 2013, with multiple bicyclists; July 23, 2013, with single bicyclist, multiple speeds, pressures (Figure 3.3 in the report)	July 2013
Mon-198	3/8" modified-binder chip seal		IP, LTS, SP April 2013 (Figure 3.4 in the report)		
		Treatment test sections	LTS July 2013 (Figure 3.5 in the report) IP October 2013	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		
Mno-395	3/8" asphalt rubber (AR) chip seal		IP, LTS, SP April 2013		
West Covell Boulevard, Davis, CA	Chip seal, specification unknown			December 6, 2013, with single bicyclist, multiple bicycles	
Hutchison Drive, Davis, CA	Hot-mix asphalt, specification unknown			December 6, 2013, with single bicyclist, multiple bicycles	

Note: MPD macrotexture measurement method: IP = inertial profiler (ASTM E1845); LTS = laser texture scanner (ASTM 2157/ASTM E1845); SP = sand patch (ASTM E965)

The details of the test sections used for the Phase I bicycle ride quality surveys on Mon-198 and SLO-1 are summarized in the following table. Information is provided in the report regarding the gradations and binders used for the Mon-198 treatments and other surface materials in the Phase I sections.

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[a]	WB or SB[a]
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 [b]	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:
[a.] EB = eastbound direction, WB = westbound direction, SB = southbound direction, NB = northbound direction.
[b.] PME = polymer-modified emulsion

Each bicycle used to measure bicycle vibration on the Phase I and Phase II sections was instrumented with a three-axis accelerometer and a GPS receiver. 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. Some special measurements were taken to isolate the effects of bicycle speed, frame type (steel, aluminum, carbon), and tire pressure on vibration.

The forms used for the bicycle ride quality surveys—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 being 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.

Following the approach decided upon for Phase II Task D, additional surveys of cyclists were conducted at organized riding events in order to obtain a larger sample of riders and pavements, and a broader range of rider demographics and road sections. Using the same methods as in Phase I, pavement macrotexture (smoothness, i.e., MPD) and bicycle vibration were measured to characterize the pavement texture and bicycle dynamic response. Phase II of the study also included the first measurement of pavement roughness (unevenness) in terms of the International Roughness Index (IRI, ASTM E1926-08; see Figure 2.1 in the report for the wavelengths that influence roughness) to investigate whether this pavement surface characteristic influences bicycle ride quality.

The Phase II surveys were performed with different groups of cyclists at different riding events, including:

- The Tour of Tahoe in El Dorado and Placer counties on September 8, 2013, with riders from the Nichols Consulting Engineers cycling team
- Smaller rides organized by the following cycling clubs in August and September 2013
  - Davis Bicycle Club (BC) in Solano and Yolo counties
  - Santa Rosa Cycling Club (CC) in Sonoma County
  - Chico Velo Cycling Club (CC) in Butte County
  - Alto Velo Racing Club (RC) and Silicon Valley Bicycle Coalition (SVBC) in San Mateo County
- Texture and roughness measurements were made with the inertial profiler on State Route 2 in Los Angeles County (LA-2) based on a request from Caltrans in late 2013, but no rider survey was conducted.

The Phase II extended surveys were performed as planned, and the Phase II sections included a mix of county- and state-owned roads. The table below shows the number of riders, the number of road sections, the bike survey date, and the texture measurement date for each of the Phase I and Phase II survey groups. A total of 107 effective participant samples from 7 groups on 42 road sections across Northern and Central California were collected and used for the analysis. There was insufficient time and funding in this project to obtain mix designs, or to sample materials in the field to determine gradation and binder information.

Summary of Phase I and Phase II Surveys

Survey Phase (Set)	Group	No. of Riders	No. of Sections	Bike Survey Date [a]	Texture Measurement Date [b]
Phase I	Mon-198	24	16	Jul 13, 2013	Oct 8 (Jul 23), 2013
	SLO-1	11	3	Jul 22, 2013	Apr 19, 2013
Phase II	Davis BC	6	4	Aug 10, 2013	Nov 15, 2013
	Santa Rosa CC	26	6	Sept 7, 2013	Oct 2, 2013
	Tahoe (Nichols CE)	16	4	Sept 8, 2013	Oct 1, 2013
	Chico Velo CC	8	5	Sept 21, 2013	Sept 25, 2013
	Alto Velo RC + Silicon Valley BC	16	4	Sept 28, 2013	Oct 16, 2013
Total	***7***	***107***	***42***	**-**	**-**

Notes:

[a] Includes bicycle vibration measurement

[b.] Using Inertial Profiler (IP) for most measurements. Laser Texture Scanner (LTS) was also used for Mon-198. Where applicable, the LTS measurement date is in parentheses.

In November 2013, the texture of route LA-2, including the macrotexture in terms of Mean Profile Depth (MPD) and roughness in terms of International Roughness Index (IRI), were measured at the Edge of Traveled Way (ETW) for both directions from PM 26.4 to PM 82.3 using the inertial profiler with a high-speed spot laser mounted on a vehicle operating at highway speed (Figure 5.2 in the report). The texture results of LA-2 are presented in the report along with those of the survey sections.

Correlations between texture, roughness, vibration, bicycle ride quality, and bicyclist rating of the "acceptability" of the ride quality were developed. Models were developed to estimate ride quality and acceptability as functions of texture and bicyclist demographic 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. Regarding the comparison of different chip seals and other surface treatment sections:
    a. The coarser 3/8" aggregate gradation chip seal specification resulted in larger MPD values than other surface treatments. When placed on SLO-1 and Mno-395, it resulted in median values ranging between 1.7 mm and 3.0 mm; when it was used on Mon-198 it resulted in median values ranging between 1.7 mm and 1.8 mm.
    b. The SLO-227 chip seal, which used a finer 3/8" aggregate gradation than the "coarser" ones used on SLO-1, Mon-198, and Mno-395, had median MPD values of about 1.2 mm, which is considerably lower than those of the coarser chip seals. This conclusion stands, even considering the variability

between the latter three chip seals built with the same specification. The variability among those three chip seals is likely due to a combination of different materials and/or construction, and the effects of trafficking in different climates and for different periods of time for the texture measured in the wheelpath. (Details regarding the finer and coarser 3/8" chip seals are presented in Section 3.1 and Table 3.3 of the report.)

   c. 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.
   d. The MPD of the shoulders (outside of the Edge of Traveled Way [ETW]) on all sections was typically somewhat larger than that inside the ETW, and there was 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.
   e. The naming of the different chip seal specifications can be confusing. For example, the terms “fine” and “medium” have little relation to the relative gradation bands.

3. 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 Mno-395 section could not be seen in the MPD values measured along the entire project, although additional information regarding the precise location of the additional rolling was not obtained from District 9.
4. Two alternative chip seals with gradations different from the finer and coarser 3/8" chip seals placed elsewhere were constructed in test sections on Mon-198 (treatments 1 and 2).
   a. 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 mm to 2 mm, which is similar to the roughly 1.7 mm 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 the SLO-1 and Mno-395 pavements built with the same coarser 3/8" chip seal specification.
   b. Treatments 1 and 2 may have had some reduction in MPD after a year of traffic, as occurred on treatment 3, where traffic reduced the MPD in the wheelpath to about 1.6 mm 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.

c. It is uncertain based on this single example whether these two alternatives can consistently produce MPD values lower than those on SLO-1, as they did on Mon-198, although the initial results are promising.

5. 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 coarser 3/8" chip seal were all lower than the MPD of the untreated chip seal section (shown as treatment 10).
6. High correlations were revealed between MPD, vertical bicycle acceleration, what bicyclists considered "acceptable" pavement, and bicycle ride quality level. Medium to weak correlations were revealed between IRI, bicycle vibration, acceptability, and ride quality level. Relatively weak correlation was found between bicycle vibration and bicycle speed. No significant correlation was found between bicyclists' rating of ride quality and acceptability versus bicycle speed, although only a small range of speeds was included in the study.
7. Based on input from cyclists participating in the Phase I Mon-198 and SLO-1 surveys, the range of what bicyclists considered an "acceptable" level of MPD was found to be approximately between 2.0 mm and 2.7 mm, with the percentages for 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.
8. Based on input from cyclists participating in the initial Phase I Mon-198 and SLO-1 surveys and the additional surveys in Phase II, the range of what bicyclists considered an "acceptable" level of MPD was found to be approximately between 1.3 mm and 2.3 mm, with the percentages for that range of MPD values as follows:
    1. 80 percent found 1.3 mm acceptable.
    2. 60 percent found 1.8 mm acceptable.
    3. 50 percent found 2.1 mm acceptable.
    4. 40 percent found 2.3 mm acceptable.
9. The average ride quality level ratings (on a scale of 1 to 5) from the riders participating in the Phase I Mon-198 and SLO-1 surveys and the additional Phase II surveys were approximately:
    1. 3.5 for an MPD of 1.0 mm
    2. 3.0 for an MPD of 1.5 mm
    3. 2.5 for an MPD of 2.0 mm
    4. 1.5 for an MPD of 3.0 mm

10. Models were developed for the ratings of pavement acceptability and bicycle ride quality ratings, with the variables MPD, IRI, and variability of IRI all being significant. When sociodemographic variables representing recent rider mileage and how much a rider considers wind and cycling companionship were added to the model, they were found to be significant. Tire pressure was also significant when added to the model.

Based on the results of this study, the following final recommendations are made regarding pavement macrotexture and its effect on bicycle vibration and ride quality:

1. In order to take bicycle traffic and bicycle ride quality into consideration when applying chip seals, the finer 3/8" chip seal aggregate gradation bands or smaller should be used and the coarser 3/8" gradation bands should not be used.
2. Clear guidance should be provided to designers regarding the potential effects on bicycle ride quality if the coarser chip seal gradation is used. Consider advising designers to select gradations that have MPD below approximately 2.5 mm on freshly placed chip seals when bicycle ride quality is an issue. This will require better information than is currently available regarding the relationship between gradation and MPD for chip seals.
3. A review of chip seal naming conventions is recommended to help reduce the potential for confusion. Any names that include reference to the aggregate gradation should reflect relative differences in coarseness and the aggregate size of the largest chips.
4. Consider performing research to measure macrotexture on existing chip seal projects with different chip seals to provide better information to designers regarding the relationship between gradation and MPD.
5. Mandating the use of a steel roller—as opposed to allowing use of steel or rubber-tired rolling during construction—to reduce MPD is not recommended. The use of additional rolling after initial construction to reduce MPD is not recommended.
6. Long-term monitoring (one or two more years) of the texture changes on the Mon-198 and SLO-1 sections should be considered to determine the effects of traffic on texture.

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
Caltrans	California Department of Transportation
CTM	Circular Texture Meter
EMTD	Estimated Mean Texture Depth
ETD	Estimated Texture Depth
ETW	Edge of Traveled Way
IFI	International Friction Index (IFI)
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 (referenced but not used in this study)
ASTM E2380-09	Standard Test Method for Measuring Pavement Texture Drainage Using an Outflow Meter (referenced but not used in this study)
ASTM E1845-09	Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth
ASTM E1926-08	Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements

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, also commonly called a *chip seal* (the term that will be used primarily in this report) and sometimes called a *surface treatment*, 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.

Note: In this research report, this section is referred to as "SLO-1." References to other state highway sections in this research report follow the same naming convention, using their county abbreviation and route number.

A hot-applied chip seal had been placed along this entire stretch of highway in 1991, and the chip seal placed in 2012 was intended as a preventive maintenance strategy to extend the service life of the existing pavement and to protect against water intrusion and further oxidation. However, in January 2013, shortly after the chip seal construction, bicyclists using SLO-1 alerted Caltrans about what they perceived as poor ride quality within the project limits.

In response, the Caltrans Division of Maintenance in District 5 contacted the Division of Maintenance Office of Asphalt Pavement and the Division of Research, Innovation, and System Information to address this issue. 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 was to address the impact of chip seals on bicyclists. This has been 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 (SLO-1) 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 were performed in two phases to achieve the project objectives:

Phase I

Task A: Evaluate the existing surface textures and alternative ones 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 on other test sections on State Route 198 in Monterey County (Mon-198) 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 examine how they vary with the age of the treatment for different climates and traffic levels.

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

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: As part of Phase II, conduct bicyclist surveys at an extended set of organized ride events, including these:

- 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
    - Davis Bicycle Club in Solano and Yolo counties (August 10, 2013)
    - Santa Rosa Cycling Club in Sonoma County (September 7, 2013)
    - Chico Velo Cycling Club in Butte County (September 21, 2013)
    - Alto Velo Racing Club and Silicon Valley Bicycle Coalition in San Mateo County (September 28, 2013)

- Texture and roughness measurements were made with the inertial profiler on State Route 2 in Los Angeles County (LA-2) based on a request from Caltrans in late 2013, but no rider survey was conducted.

Task E: Deliver a final report that documents this research effort and includes recommendations for improving the use of chip seal surface treatments for bicyclists.

A technical memorandum delivered in November 2013 completed the scope of Phase I (*1*). Those results are incorporated in this final report along with results from the rest of the project.

1.4 Scope of This Report

This research report documents the results from all the tasks in Phase I and Phase II. Recommendations to improve the use of chip seal surface treatment for bicycle users are also included.

Chapter 2 includes the results of a literature review and covers basic pavement surface texture concepts, typical texture characteristics, and the measured texture values for several types of asphalt surfaces built by Caltrans in the past. The chapter also includes a discussion of the available literature regarding pavement surface texture and bicycle ride quality. Chapter 3 describes the test sections and experimental methods used for field measurements on the surface treatments—including the measurement methods for pavement macrotexture and bicycle vibration—and the survey form used to evaluate bicycle ride quality for the initial surveys on SLO-1 and Mon-198. Chapters 4 and 5 present the results and analyses of the pavement surface macrotexture measurements, including the results of the bicycle vibration and bicycle ride quality surveys on Mon-198 and SLO-1, and on the extended survey sections (Phase II Task D), respectively. Chapter 6 presents the results of modeling bicycle ride quality using the results from all of the survey sections. Chapter 7 presents the results of the effects of remedial treatment on SLO-1. Chapter 8 presents conclusions and recommendations. The appendixes contain detailed results and statistical analyses of field measurements and of the bicycle ride quality surveys.

2 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 *(2)*.

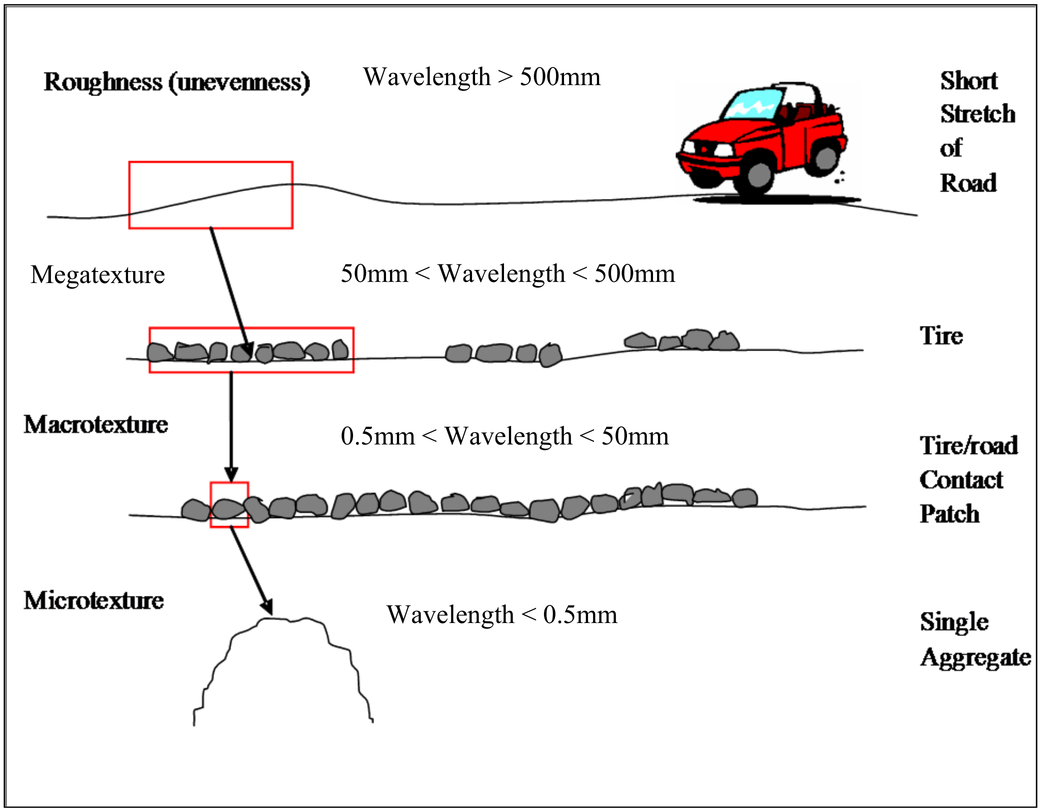

Figure 2.1: Pavement surface texture components and their wavelengths *(2)*.
(Note: **500 mm = 1.64 ft, 50 mm = 0.164 ft or 2.0 in., 0.5 mm = 0.02 in.)**

Figure 2.2 shows the relationship among the four components and their influence on the functional performance of pavement. Although the figure notes that vehicle ride quality is primarily affected by megatexture and roughness *(3-5)*, for bicycles an examination of macrotexture might be more critical as the surface texture in this range of wavelengths is most likely to directly affect ride quality through vibration.

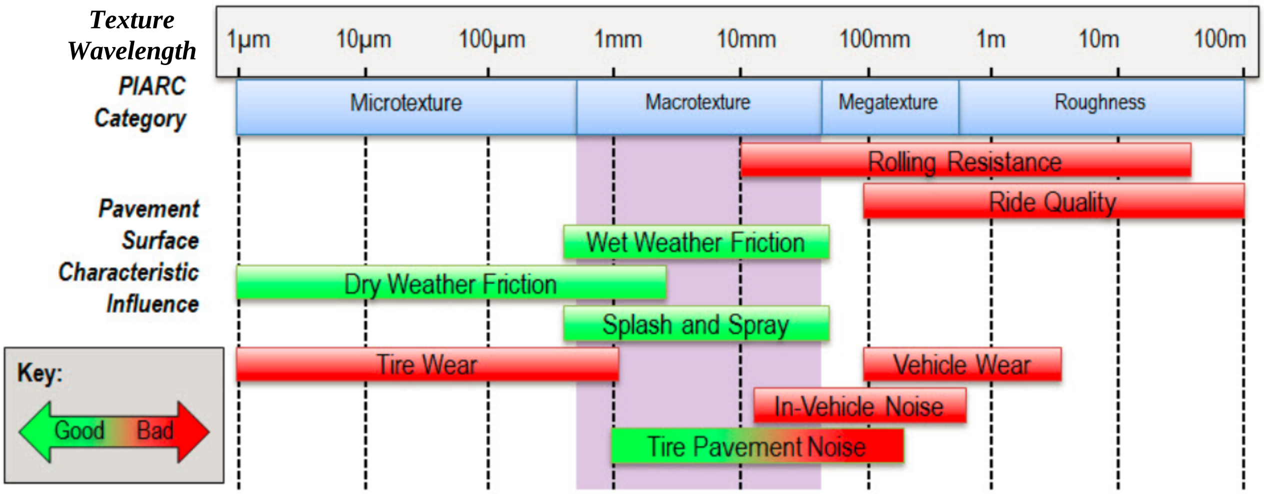

Figure 2.2: Influence of pavement surface texture components on functional performance of motorized vehicles *(2)*.

Macrotexture is typically measured in terms of mean profile depth (MPD) or mean texture depth (MTD), two closely related parameters. Ways to measure them include use of the sand patch method (SP, ASTM E965), the outflow meter (OM, ASTM E2380), the laser texture scanner (LTS, ASTM E2157/ASTM E1845), or the inertial profiler (IP, ASTM E1845).

As is shown in Figure 2.3, MPD values for most hot-mix asphalt (HMA) materials historically used on California state highways typically range from approximately 0.5 mm to 1.5 mm, with the macrotexture of some large-stone open-graded materials (F-mixes) that were used for a time on the North Coast going as high as approximately 2.0 mm *(6)*. Generally, the surface macrotexture of in-service asphalt pavements with hot-mix asphalt surfaces increases with time *(6)* due to raveling (loss of fines around large aggregates) from traffic, oxidation of the asphalt, and rainfall, as shown in Figure 2.4. This figure also shows that for some materials there may be an initial reduction in MPD after construction due to embedment and the polishing of surface aggregates.

To date, no one has measured the MPD values of 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 pavements with surface treatments and have been used in this study to assess bicycle ride quality.

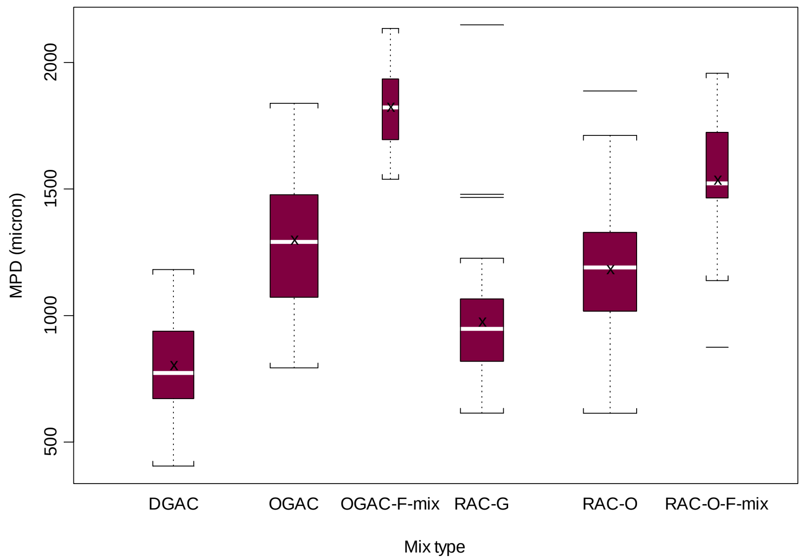

Figure 2.3: Pavement macrotexture (MPD) ranges for different hot-mix asphalt (HMA) mixture types on California highways considering all ages from new to 16 years of service *(6)*.

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 median value, the "x" close to the center line 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 Bicycle Vibration and Bicycle 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 *(7-11)*. No studies were found in the available literature regarding the relationship between bicycle ride quality and bicycle vibration.

2.3 Pavement Macrotexture and Bicycle Ride Quality

Many studies were found that investigated the interactions of human behavior and transportation mode choice (car versus bicycle). These studies indicated that variables affecting mode choice included typical vehicle speeds, vehicle traffic flow, road width, availability of bicycle paths, etc. *(12-14)*. No specific data were found in the literature regarding whether or how pavement macrotexture-related bicycle vibration or other factors related to pavement affected travelers' transportation mode choices.

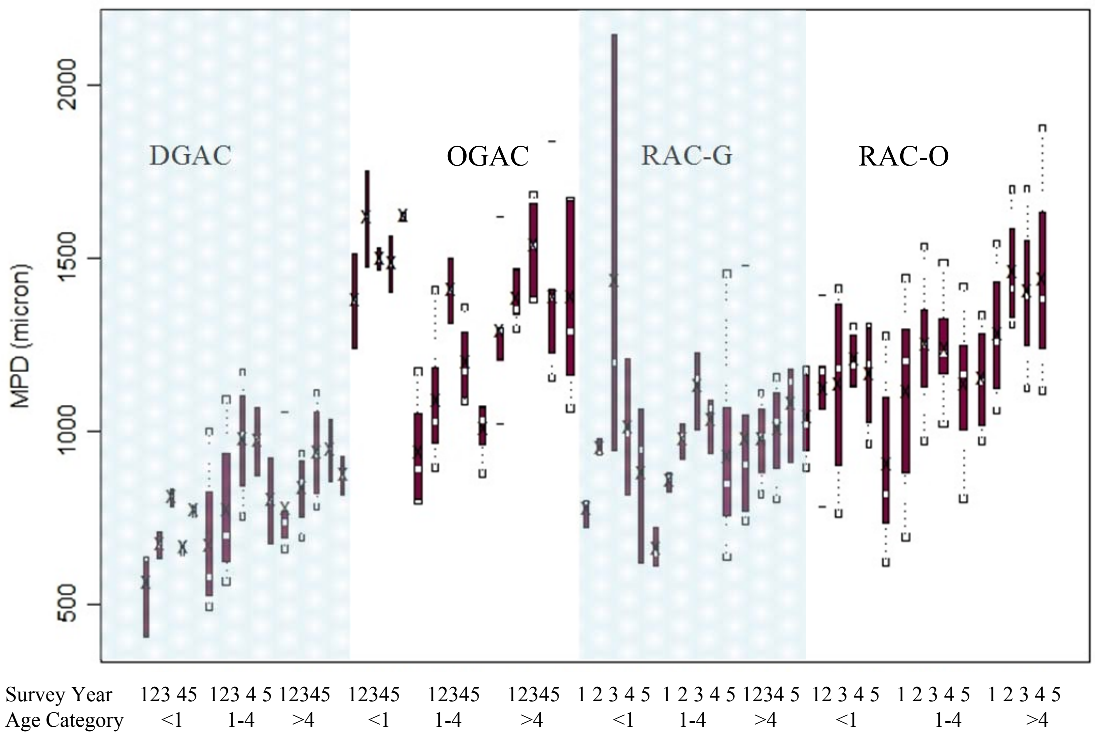

Figure 2.4: Comparison of MPD values for four commonly used asphalt surface mix types in California for different initial age categories (age category, survey years) and for five years of data collection *(6)*.

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 PHASE I SURFACE TEXTURE MEASUREMENTS AND BICYCLIST SURVEYS

3.1 Road Sections Used for Phase I Macrotexture Measurements and Bicyclist Surveys

Table 3.1 shows a list of road sections used for the Phase I macrotexture measurements and/or bicyclist surveys, including the measurement method and the timing of the measurements. The geographic distribution of the Phase I 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 Phase I of 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) IP October 2013	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		
Mno-395	3/8" asphalt rubber (AR) chip seal		IP, LTS, SP April 2013		
West Covell Boulevard, Davis, CA	Chip seal, specification unknown			December 6, 2013, with single bicyclist, multiple bicycles	
Hutchison Drive, Davis, CA	Hot-mix asphalt, specification unknown			December 6, 2013, with single bicyclist, multiple bicycles	

Note: MPD macrotexture measurement method: IP = inertial profiler (ASTM E1845); LTS = laser texture scanner (ASTM 2157/ASTM E1845); SP = sand patch (ASTM E965)

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

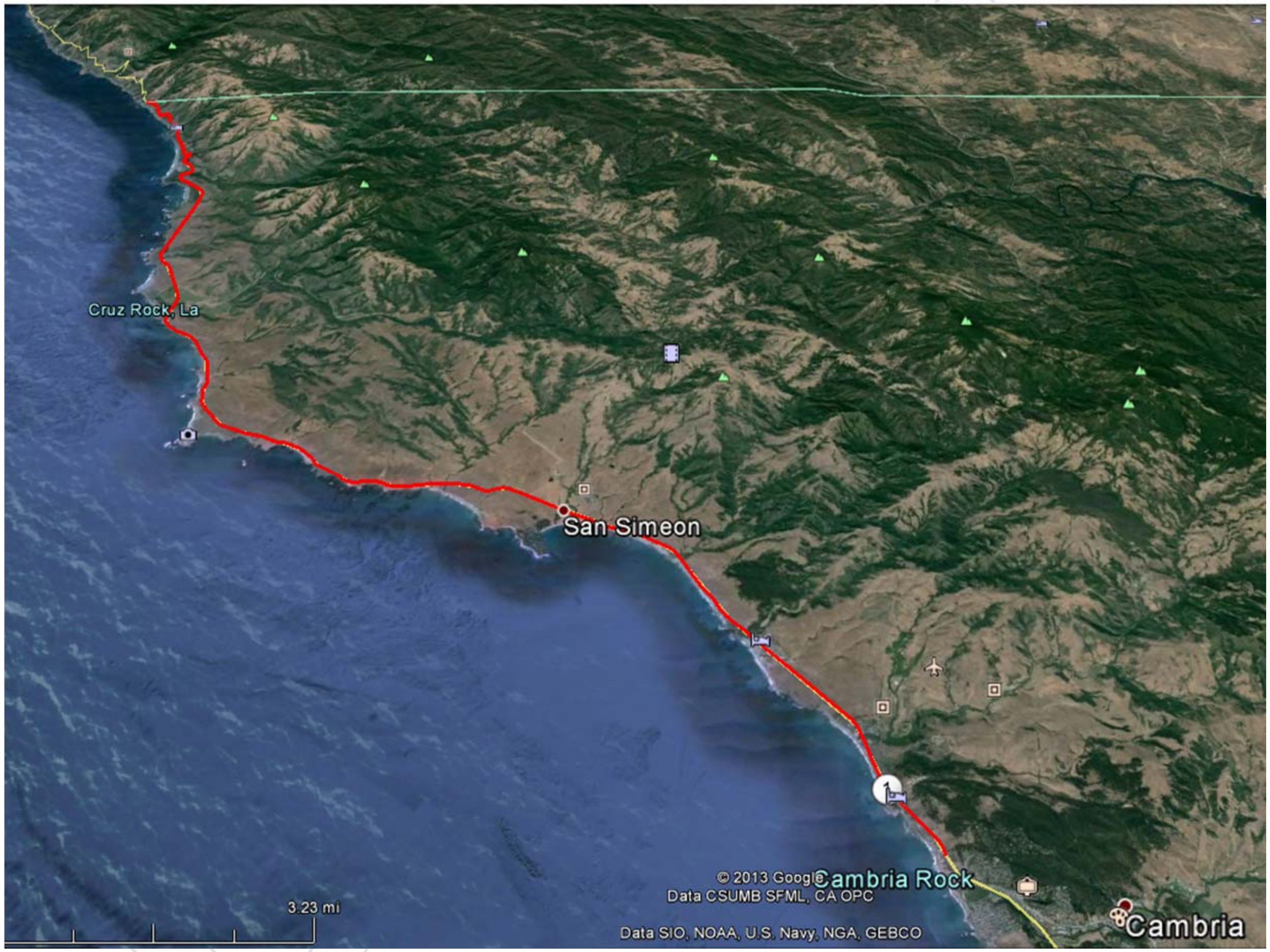

Figure 3.2: Section for MPD measurement with inertial profiler on SLO-1 (PM 51.3 – PM 74.3).

Figure 3.3: Subsections on SLO-1 used for the three bicycle ride quality surveys.
(See Table 3.4 for section details.)

Section #1, *Northbound (NB)*, PM 51 to PM 51.5

(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.)

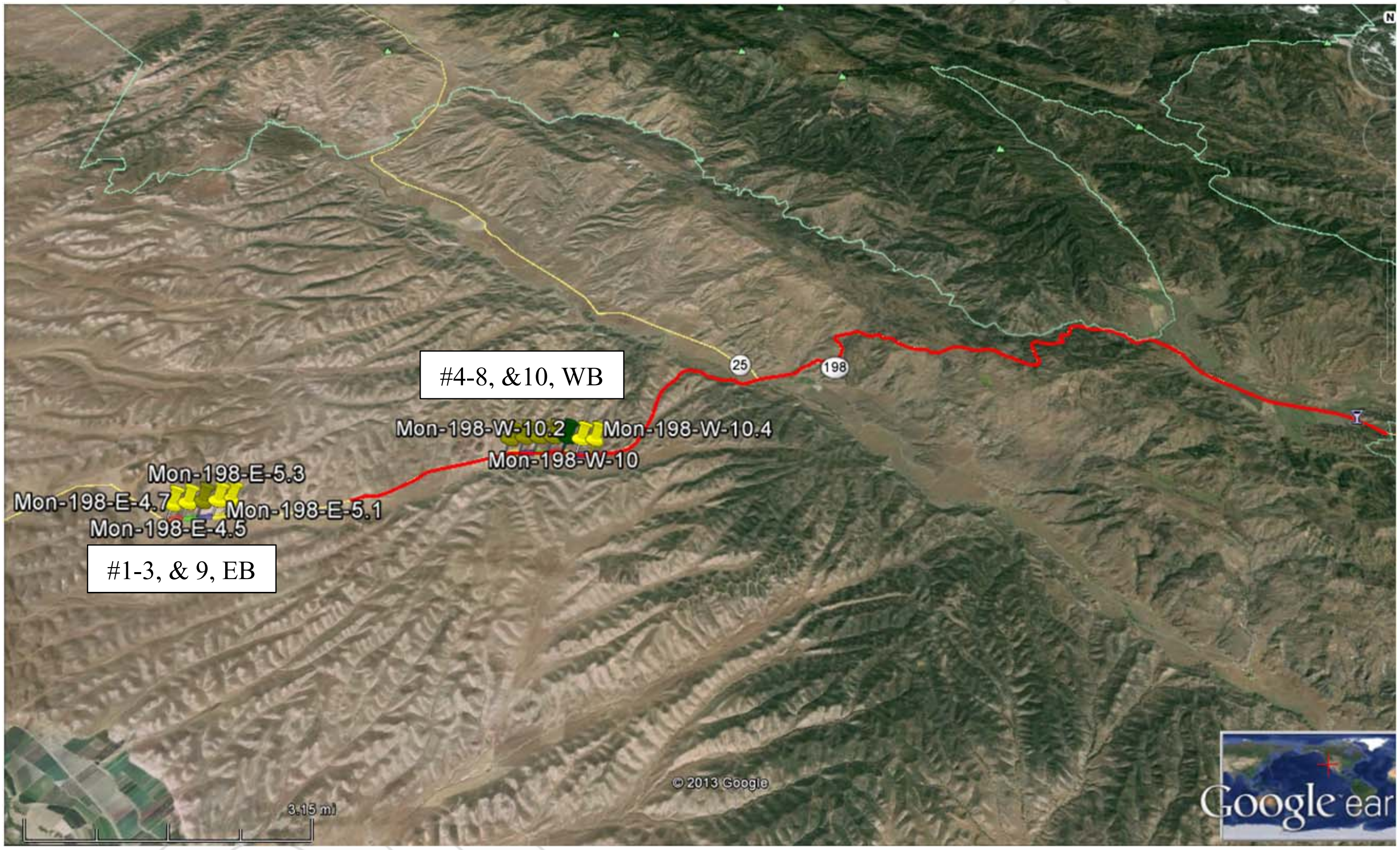

Figure 3.4: Section for MPD measurement with inertial profiler on Mon-198 (PM 7.0 – PM 25.8, in red line), also showing locations of treatment test subsections.
(Note: **see Table 3.4 for section details and Figure 3.5 for more precise locations.)**

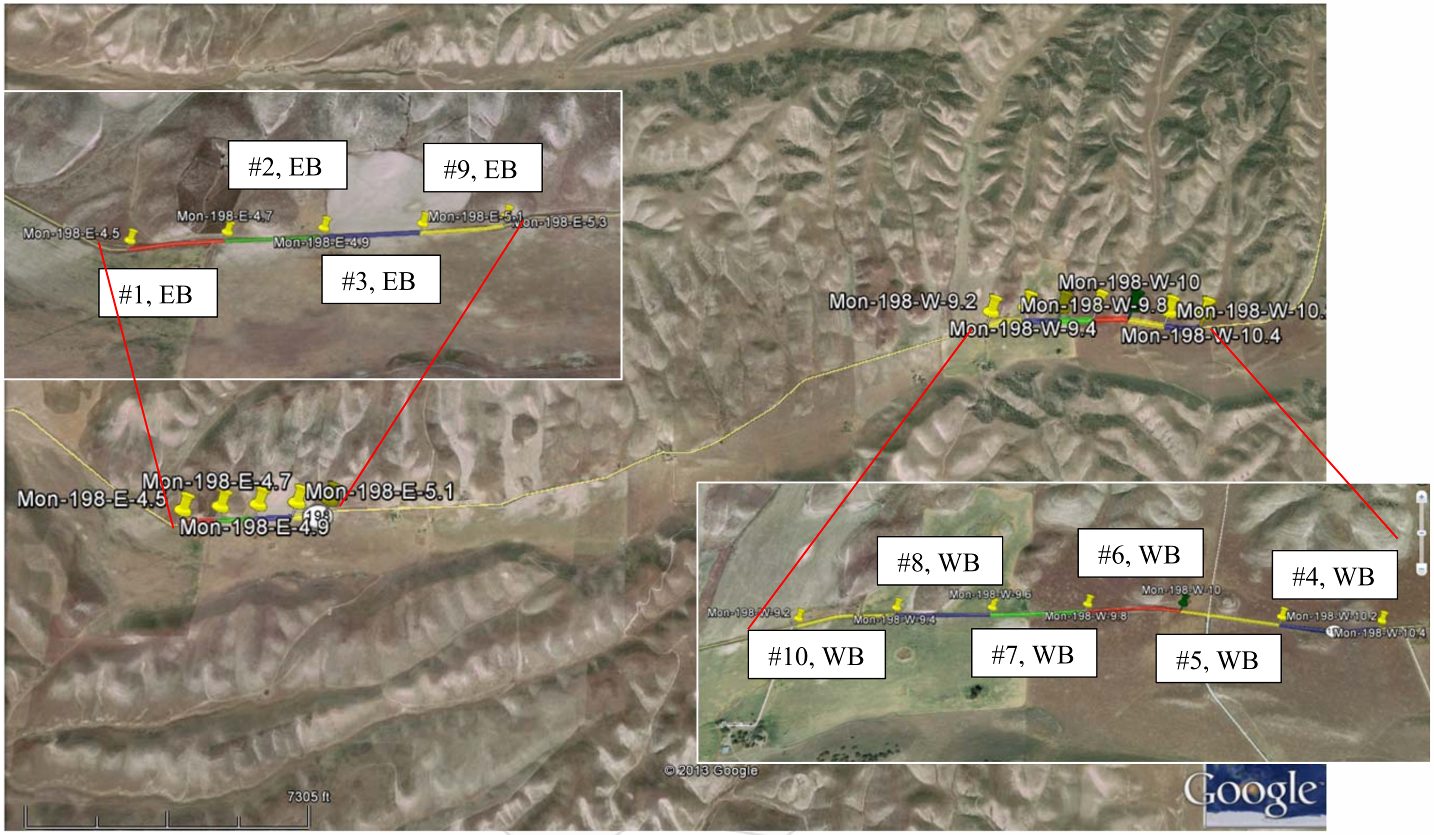

Figure 3.5: Treatment test section locations on Mon-198.
***(Note:* see Table 3.4 for section details.)**

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 10.2 to PM 10.4
Section #5, *Westbound (WB)*, PM 10.0 to PM 10.2
Section #6, *Westbound (WB)*, PM 9.8 to PM 10.0
Section #7, *Westbound (WB)*, PM 9.6 to PM 9.8
Section #8, *Westbound (WB)*, PM 9.4 to PM 9.6
Section #10, *Westbound (WB)*, PM 9.2 to PM 9.4 (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 bands 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 PG 76-22TR and it 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 Mno-395 was an *asphalt rubber binder* with a PG 64-28 base binder. For a binder to be designated as an asphalt rubber binder, it must contain between 18 and 22 percent crumb rubber modifier (CRM), and it is required that the CRM 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 a combination of automobile tires, truck tires, or tire buffings.

Although a 3/8" chip seal is shown for all the chip seal projects shown in Table 3.2, two gradation specifications were used. As Table 3.3 shows, the gradation used on SLO-1, Mon-198, and Mno-395 was coarser than that used on SLO-227. The reason for the difference is that 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 Mno-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 the naming of the two gradations used on SLO-227 and on 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 research report as the "finer 3/8" gradation," and the coarser gradation[2] used on SLO-1, Mon-198, and Mno-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 bicycle 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.

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[2] The coarser gradation used on SLO-1, Mon-198, and Mno-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 Mno-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[c]	Modified binder[d]	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[d]	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, inner wheelpaths	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
Mno-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

Notes:

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. Caltrans, "Notice to Bidders and Special Provisions," Contract No. 05-0T4004, Standard Specifications dated 2006. Bids opened March 2012.

d. Modified-binder suppliers required to certify 10 percent minimum tire rubber modifier in binder.

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.

Table 3.3: Gradation Bands for Various Treatments for Different Projects

Sieve Size		Percentage Passing		
		Chip Seals		Microsurfacing
mm	(in.)	SLO-227 3/8" [a]	SLO-1, Mon-198, Mno-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

Notes:

a. 2006 Standard Specifications "Medium 3/8" max" screenings gradation for polymer-modified emulsion; referred to in this research report 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 research report 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[a]	Survey Section No. WB or SB[a]
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 [b]	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:

a. EB = eastbound direction, WB = westbound direction, SB = southbound direction, NB = northbound direction.

b. PME = polymer-modified emulsion

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

Sieve Size		Percentage Passing							
mm	(in.)	Chip Seals			Cinder seal	Micro-surfacing	Double Chip Seal	Sand Seal	Slurry 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, Mno-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 MTD and MPD are highly correlated with the speed constant of the International Friction Index (IFI) *(15)*, indicating that they produce similar measures of macrotexture. To allow conversions to either of these macrotexture indices, the following relationships were developed *(16)*:

For estimating MTD (referred to as EMTD) 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.

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

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 the bicycle speed (from GPS) and vibration data (from accelerometer) using time stamps, and apply offsets to the time stamps of the vibration data when necessary.
2. Find the start and end times for a given test section using the 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.

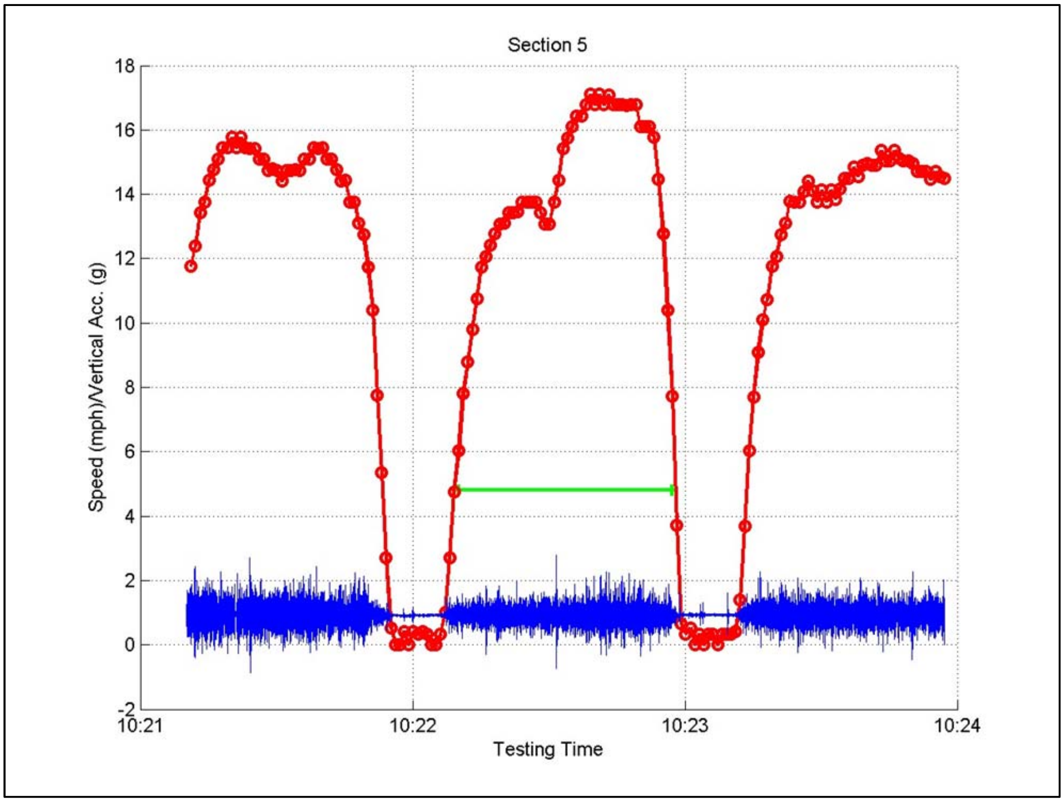

Figure 3.7: Extract of bicycle speed with corresponding acceleration data on Section 5 of Mon-198.
(Note: **the red line with circles shows speed (mph), the blue line shows acceleration (*g*), and the green line shows the test section portion used for analysis where speed > 5 mph.)**

3.3.3 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 I Sections

Date	Route	Bicycles	Testing Description
July 12, 2013	SLO-1 sections north of Cambria, CA	Two aluminum bicycles, one carbon bicycle	Various fixed speeds, normal (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 fixed speeds, normal (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).
December 6, 2013	West Covell Boulevard in Davis, CA	One carbon bicycle and one aluminum bicycle	Combinations of bicycle material and biker weight (with and without a 60 lb backpack).
December 6, 2013	West Covell Boulevard and Hutchison Drive, Davis, CA	One carbon bicycle	Multiple runs on single road sections to evaluate variability in vibration measurement

Note: "normal" speed means speed was not controlled.

3.4 Bicycle 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 being 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 cyclists 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 report, and information regarding the volunteers and survey results are included in Appendix F: Raw Survey Results.

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 counter flow 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 counter flow 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 (verbatim):

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.
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4 PHASE I MEASUREMENT RESULTS AND ANALYSES

As shown in Table 3.1, pavement surface macrotexture measurements were taken using the laser texture scanner (LTS), the inertial profiler (IP), and the sand patch method on all five road sections (SLO-1, Mon-198, SLO-41, SLO-227, and Mno-395) and on eight test sections on Mon-198. The table also indicates that bicycle vibration was measured on these Mon-198 “treatment test sections,” which were further subdivided into “bicycle survey sections” for the shoulder and wheelpath measurements within each treatment test section, and on select “bicycle survey subsections” on SLO-1 (measurements taken near the Edge of Traveled Way [ETW]). The main results of the LTS and IP measurements are summarized in this chapter; the additional results from the sand patch method measurements performed at a few locations as an independent check on the LTS and IP results 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.

4.2 Macrotexture Measured Using Laser Texture Scanner

Pavement macrotexture was measured using the laser texture scanner method at different locations on 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 ETW stripes, where most bicyclists ride when there is traffic. For most sections and locations, measurements were taken in 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) 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.

(a) Mon-198 PM 10.05

(b) SLO-1 PM 60.5

Figure 4.2: Close-up photos of LTS testing on the pavement surface.

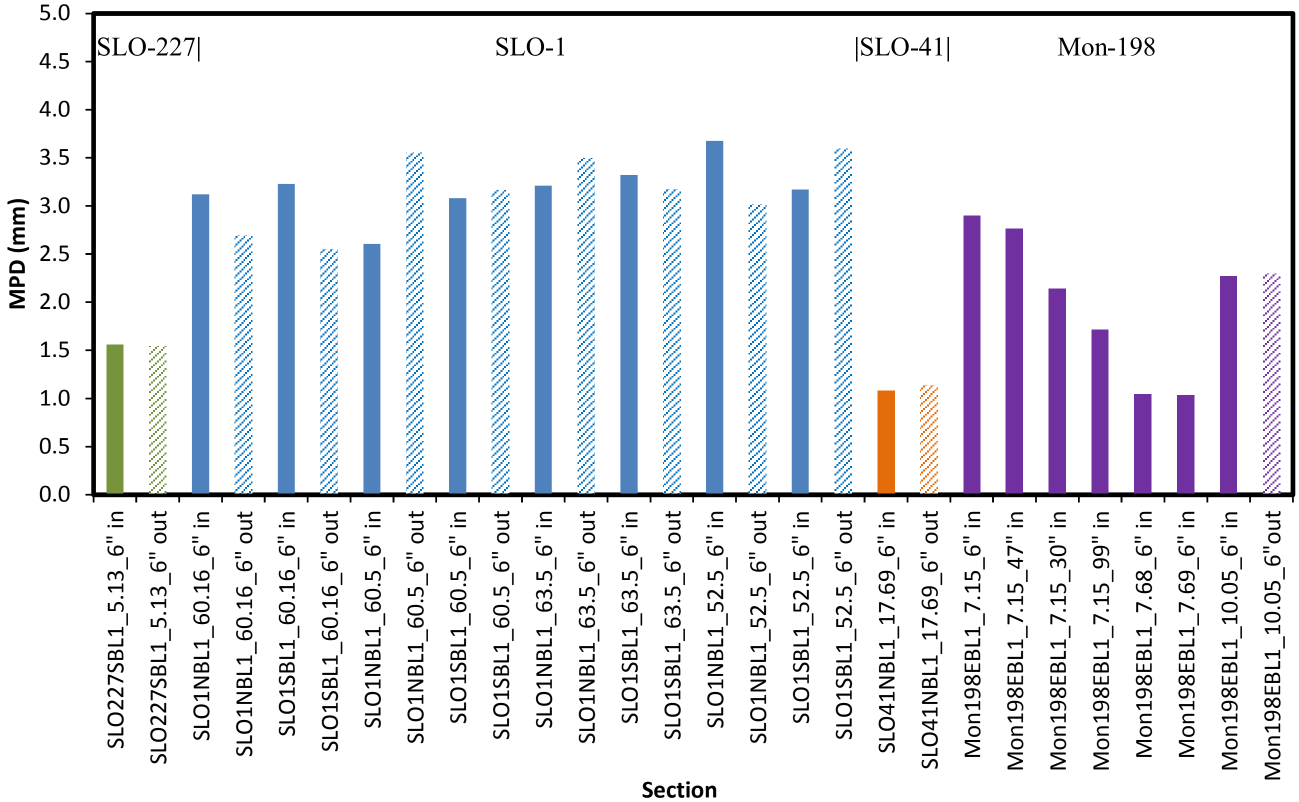


Figure 4.3: MPD from LTS for different road sections (SLO-227, SLO-1, SLO-41, and Mon-198).
(Note: **Inside Edge of Traveled Way [ETW] measurements are shown with solid bars; outside ETW measurements shown with patterned bars.)**

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. These differences in MPD values are most likely due to the differences in aggregate gradation used on these projects, as well as to 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 (referred to as *treatment sections*), which were further broken down into the bicycle *survey sections* for the separate wheelpath and shoulder measurements, and the three locations on SLO-1 used for the bicycle ride quality surveys (also referred to as *survey sections).*

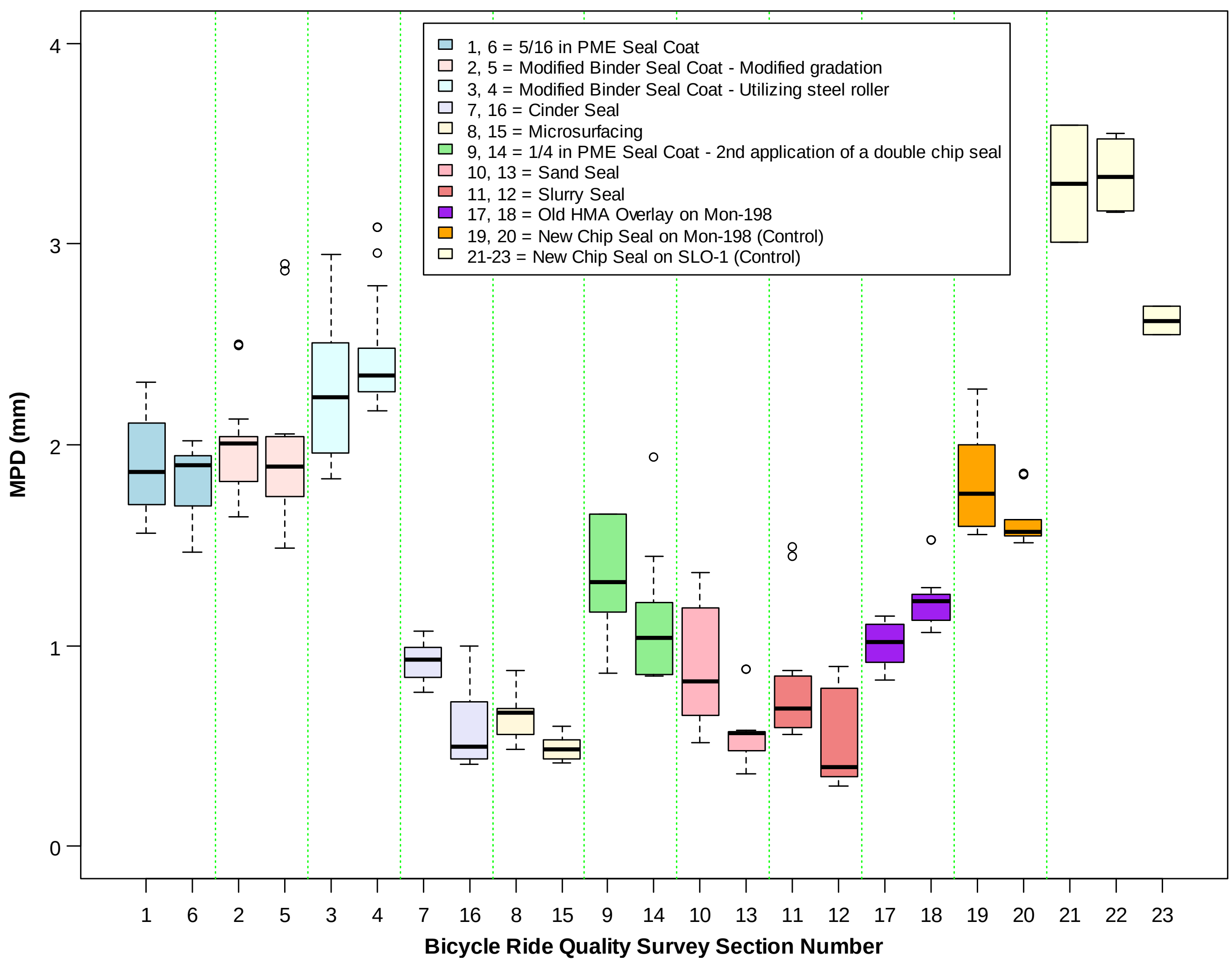


Figure 4.4: MPD from LTS for the inside of the ETW (left) and the left wheelpath (right) for each of the Mon-198 treatment sections and for the single location on each of the three SLO-1 survey sections.
***(Note:* refer to Table 3.4 for treatment descriptions.)**

In Figure 4.4, a pair of measurements appears side by side for each of the eight Mon-198 treatment sections, the inside of the ETW measurement shown on the left and the left wheelpath measurement shown on the right, and for each of the three SLO-1 survey sections (locations shown in Table 3.4) that the cyclists rode on for the ride quality survey.

1. For the Mon-198 sections appearing in Figure 4.4:
    a. The first measurement (the one on the left) shows the average on each test section, taken 6 inches (150 mm) inside the ETW stripe.
    b. The second measurement (the one on the right) shows the average on 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 for each section 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 locations (wheelpath and ETW) in Figure 4.4 for each of the treatment test sections on the Mon-198 treatment sections and the average of the three SLO-1 survey sections. 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 compared to the MPD value from treatment 10, which was 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 had somewhat greater MPD than the control section (treatment 10) even though they had 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 had about the same MPD while the MPD values differed for the shoulder and wheelpath of treatment 10. However, the value for the shoulder of treatment 10 was 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. MPD of treatments 1 and 2 should be 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. It was not known whether similar embedment would occur 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 was 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 initial correlation of MPD, bicycle vibration, and bicycle ride quality in Section 4.6 of this research report based on the Phase I measurements.

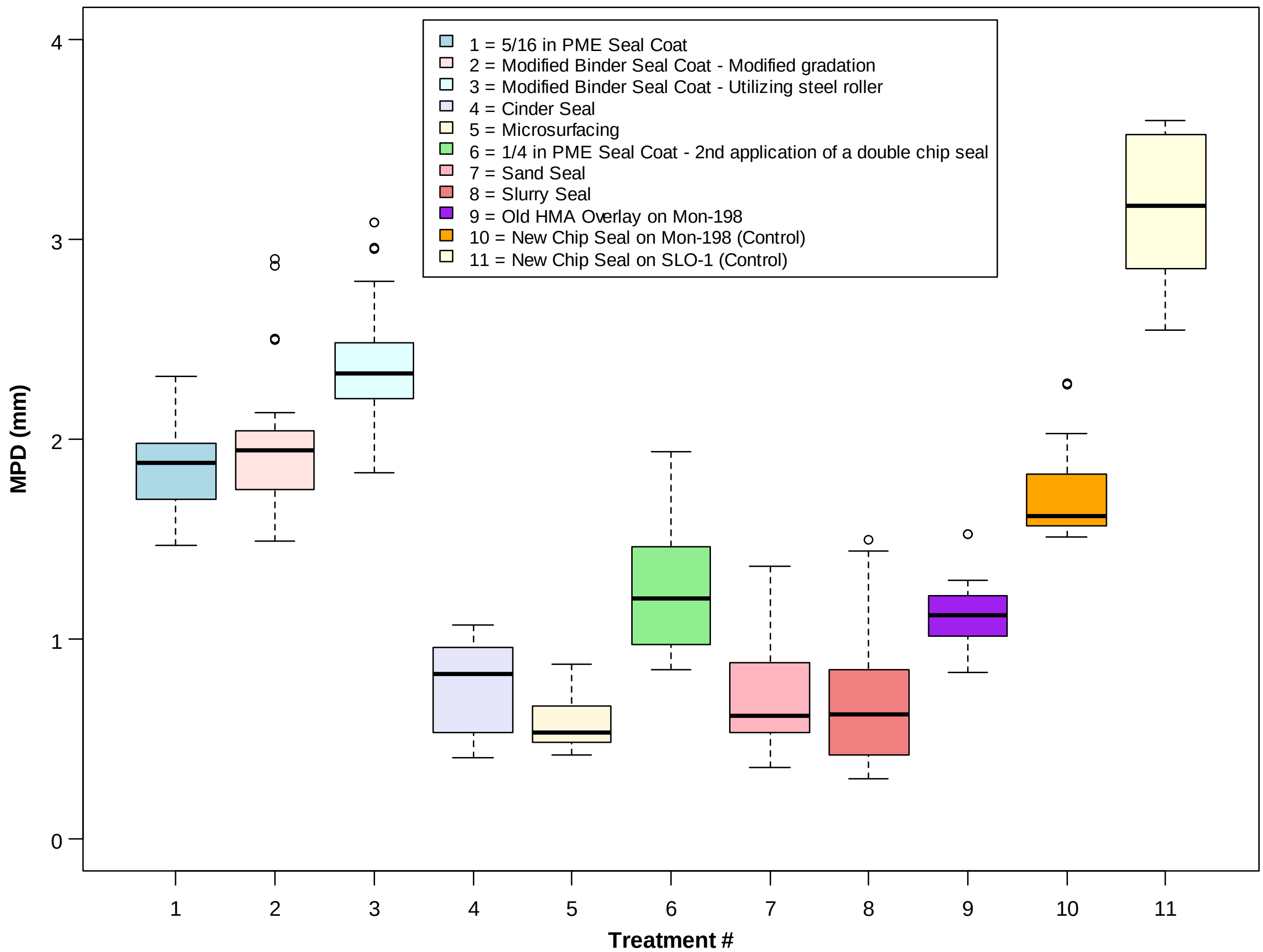
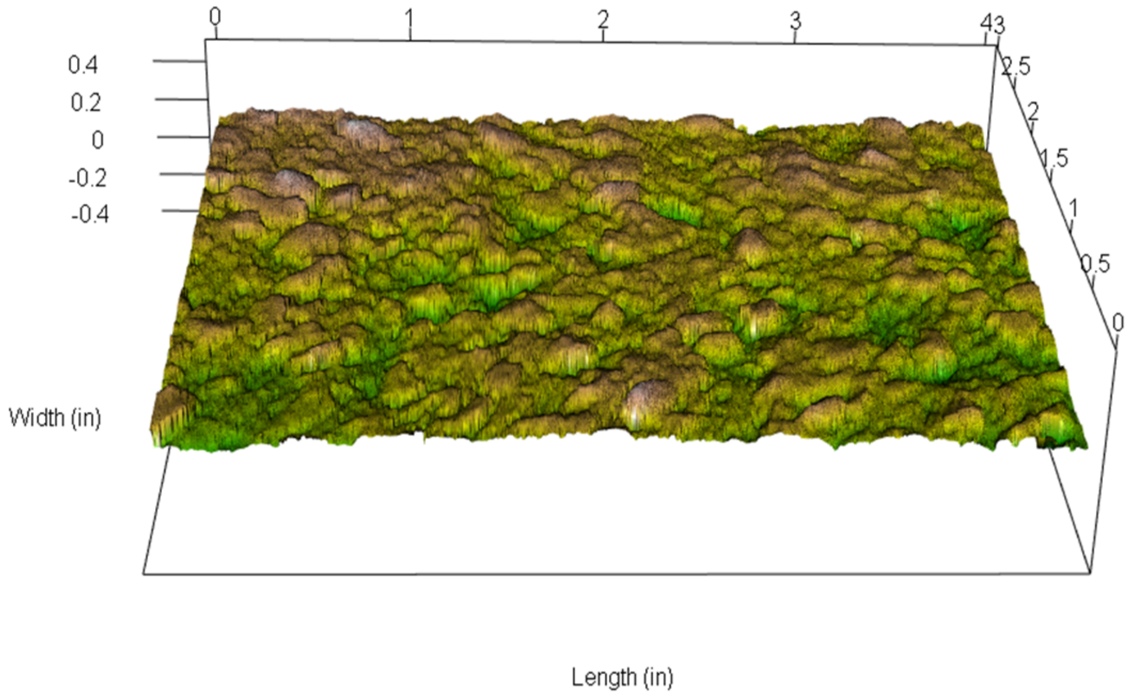


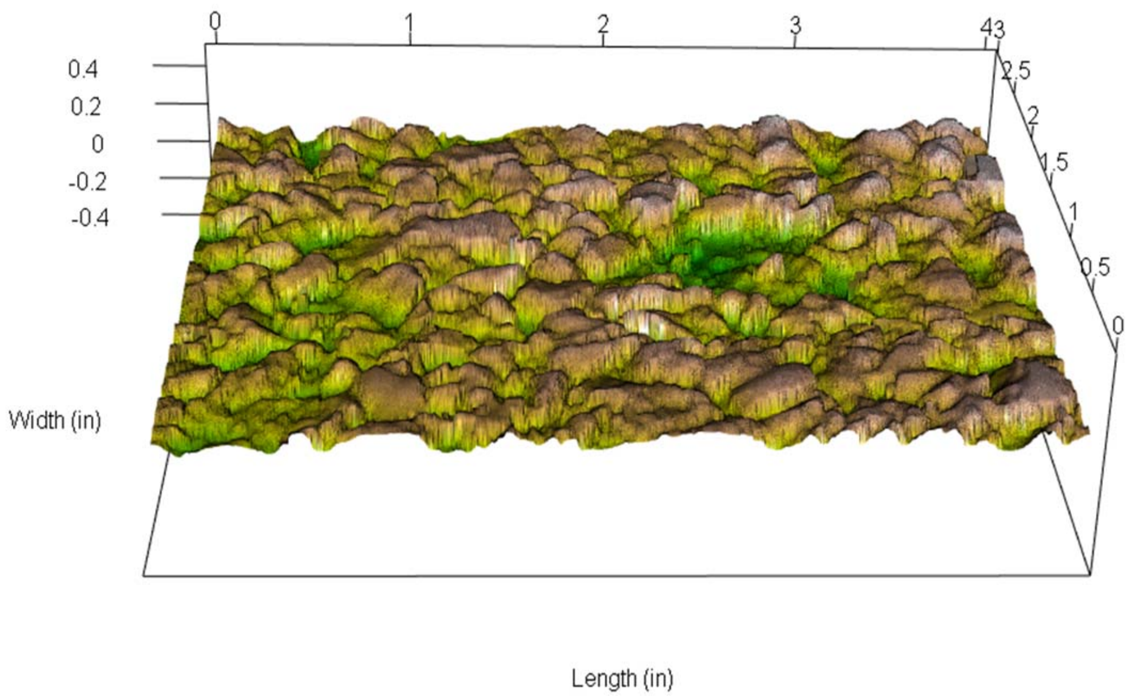
Figure 4.5: Averaged MPD from LTS by treatment type for all test sections covered in the bicycle ride quality surveys on Mon-198 and SLO-1.
(Note: **refer to Table 3.4 for treatment descriptions.)**

4.3 3D Laser Texture Scanner Images of Macrotexture

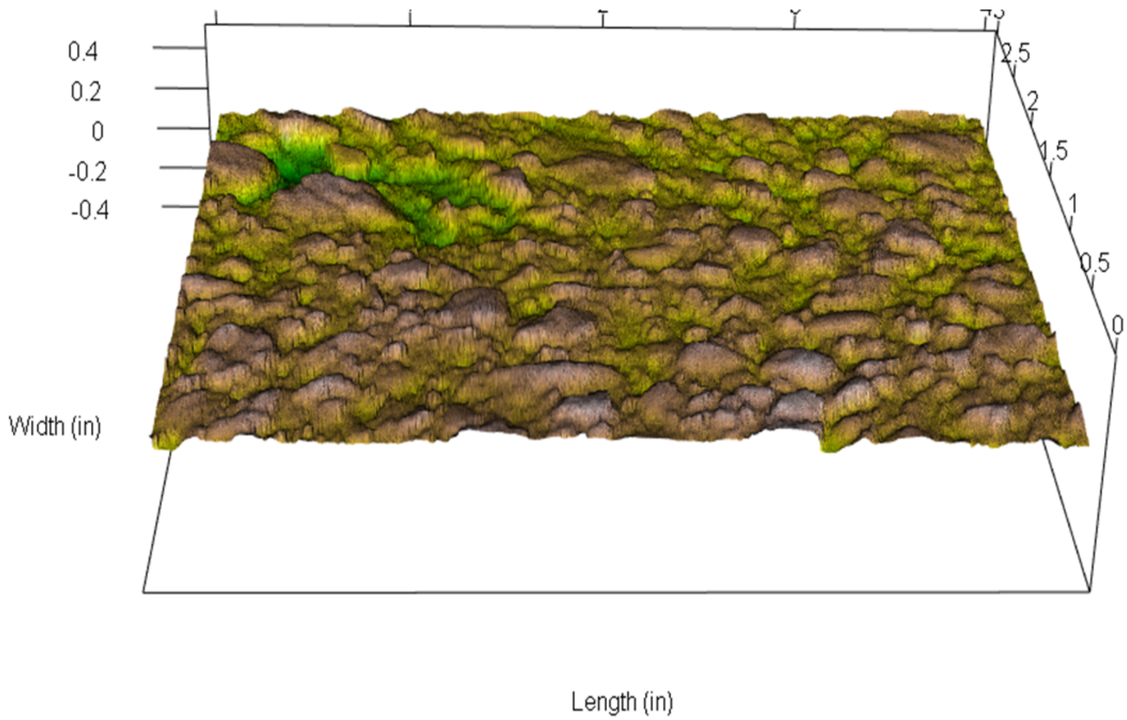
In addition to MPD measurement, the LTS produces 3D images of the pavement surface. Some example 3D macrotexture images from the sections included in this study appear in Figure 4.6. The size of the LTS scanned area is 4 × 3 inches (100 × 75 mm). It can be seen from the figure that the surfaces of SLO-41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



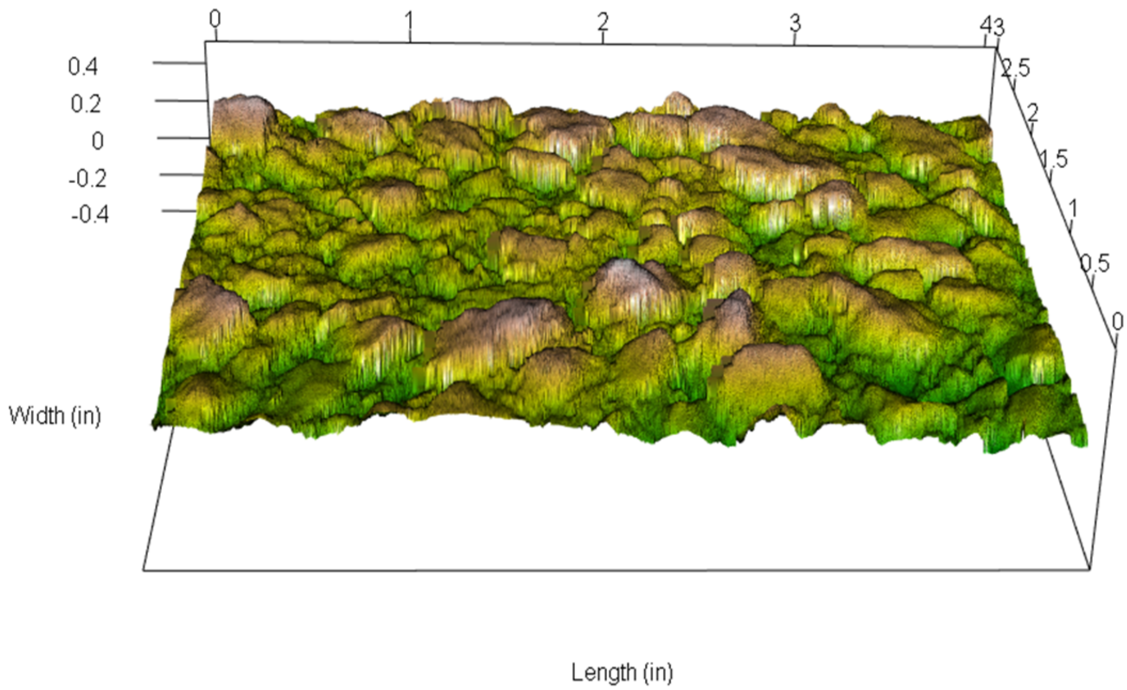
(a) Microsurfacing on SLO-41 NB PM 17.69 placed in 2010



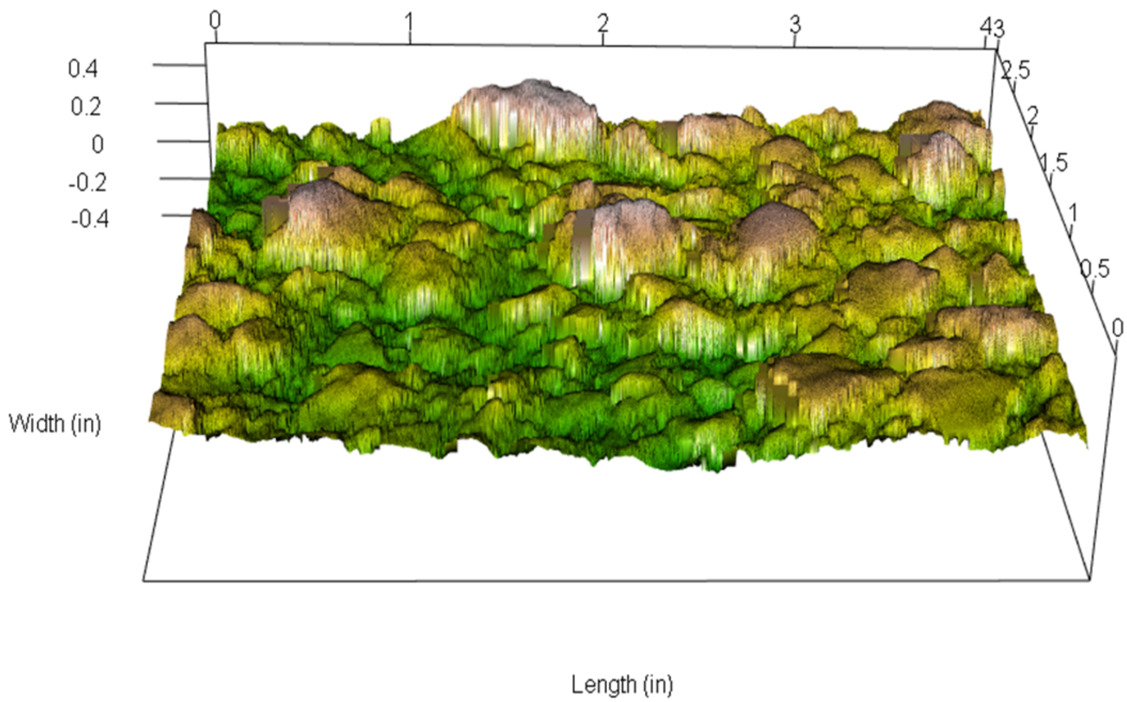
(b) Finer 3/8" gradation chip seal on SLO-227 SB PM R5.13 placed in 2009



(c) Dense-graded asphalt overlay 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

In this part of the study, macrotexture was measured using the vehicle-mounted inertial profiler (IP) shown in Figure 4.7 (measured at highway speed without the need for lane closures, as with the LTS). Measurements taken with the IP followed a continuous line for the entire length of each section included in this study. 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 the Inertial Profiler

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 Mno-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, Mno-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 Mno-395 where MPD values are lower because they have either had dense-graded asphalt concrete surfaces or were concrete bridge decks. An example of this 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) was generally higher than 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 Mno-395, and is due to trafficking on the inside of the ETW.

It was expected that macrotexture under normal traffic would initially decrease after construction. 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 Mno-395 (Figure 4.11). Although the postmile where this was done was not obtained from District 9, it appears that none of those shoulder sections had 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 SLO-1 and Mno-395 had no noticeable effect on macrotexture.

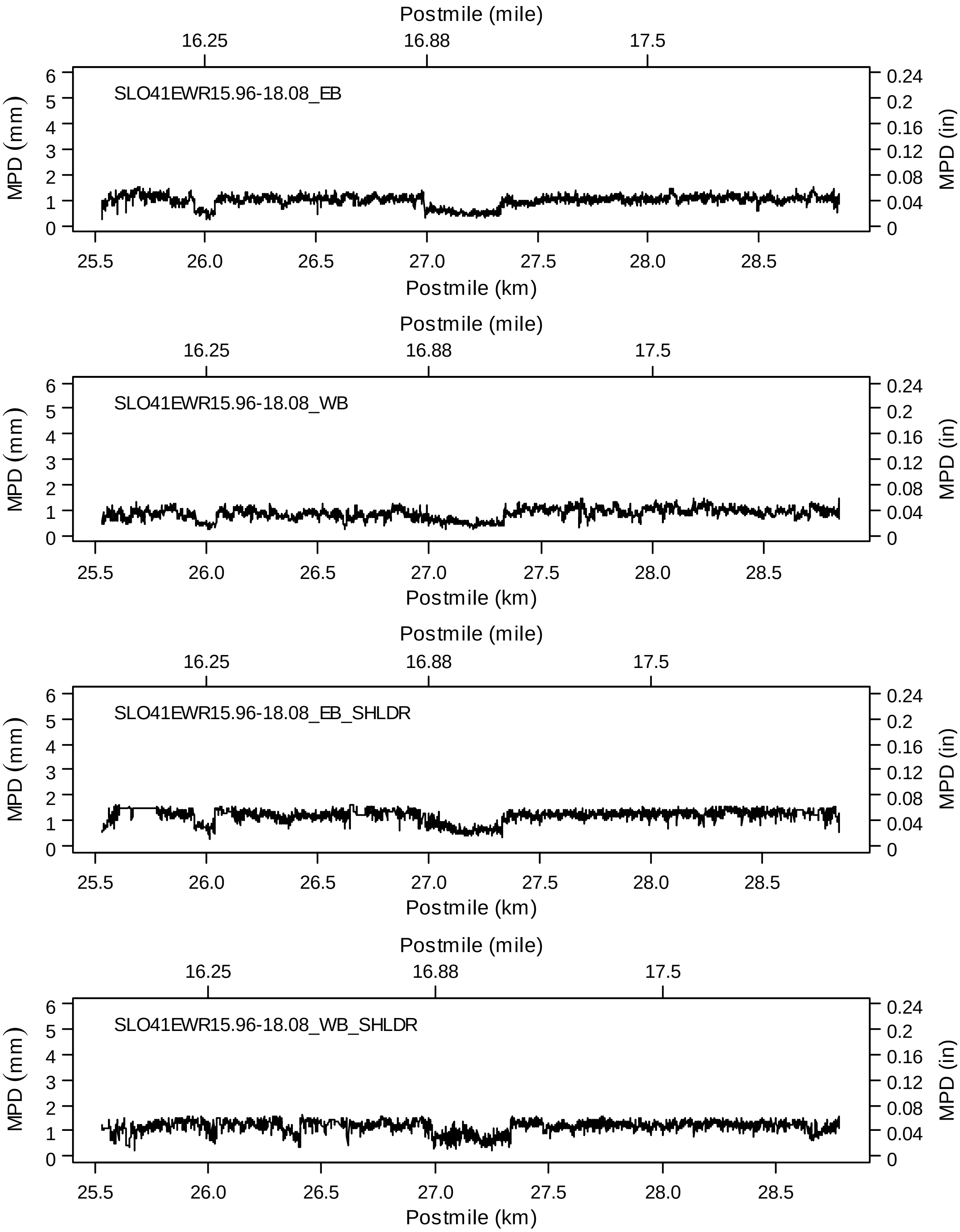


Figure 4.8: Macrotexture measured using IP for SLO-41 (microsurfacing).

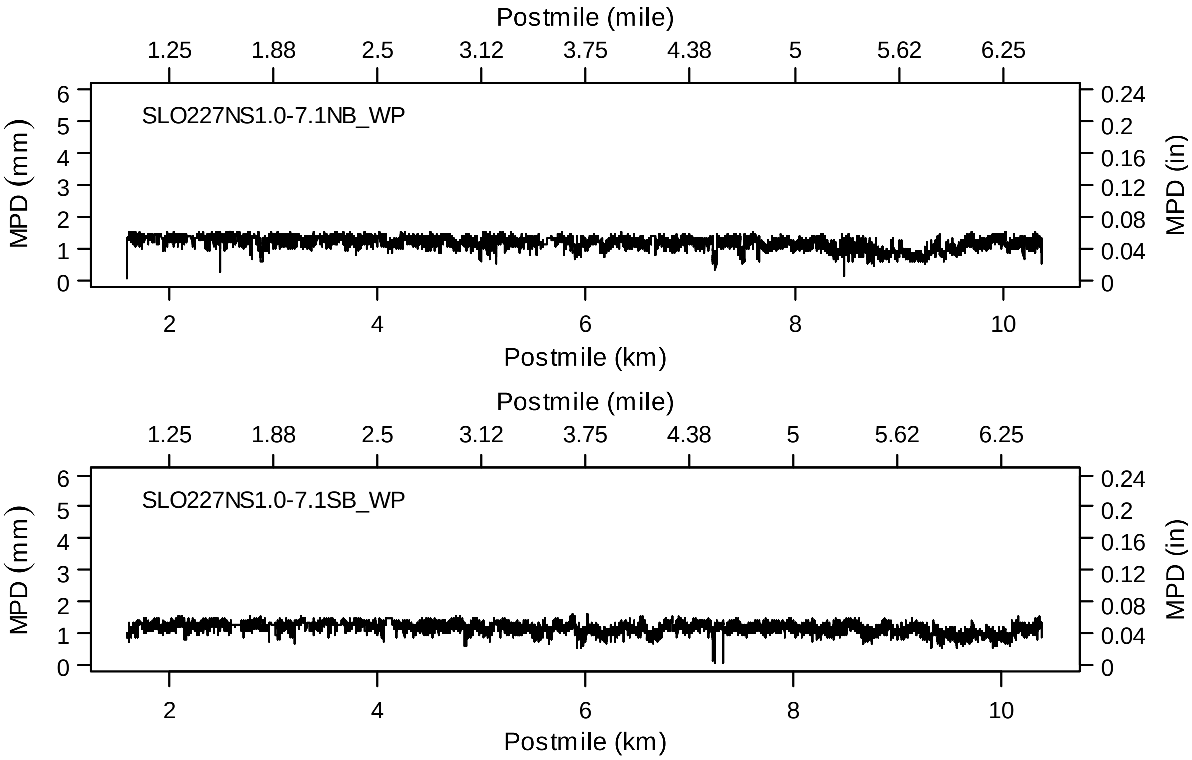


Figure 4.9: Macrotexture measured using IP for SLO-227 (chip seal).

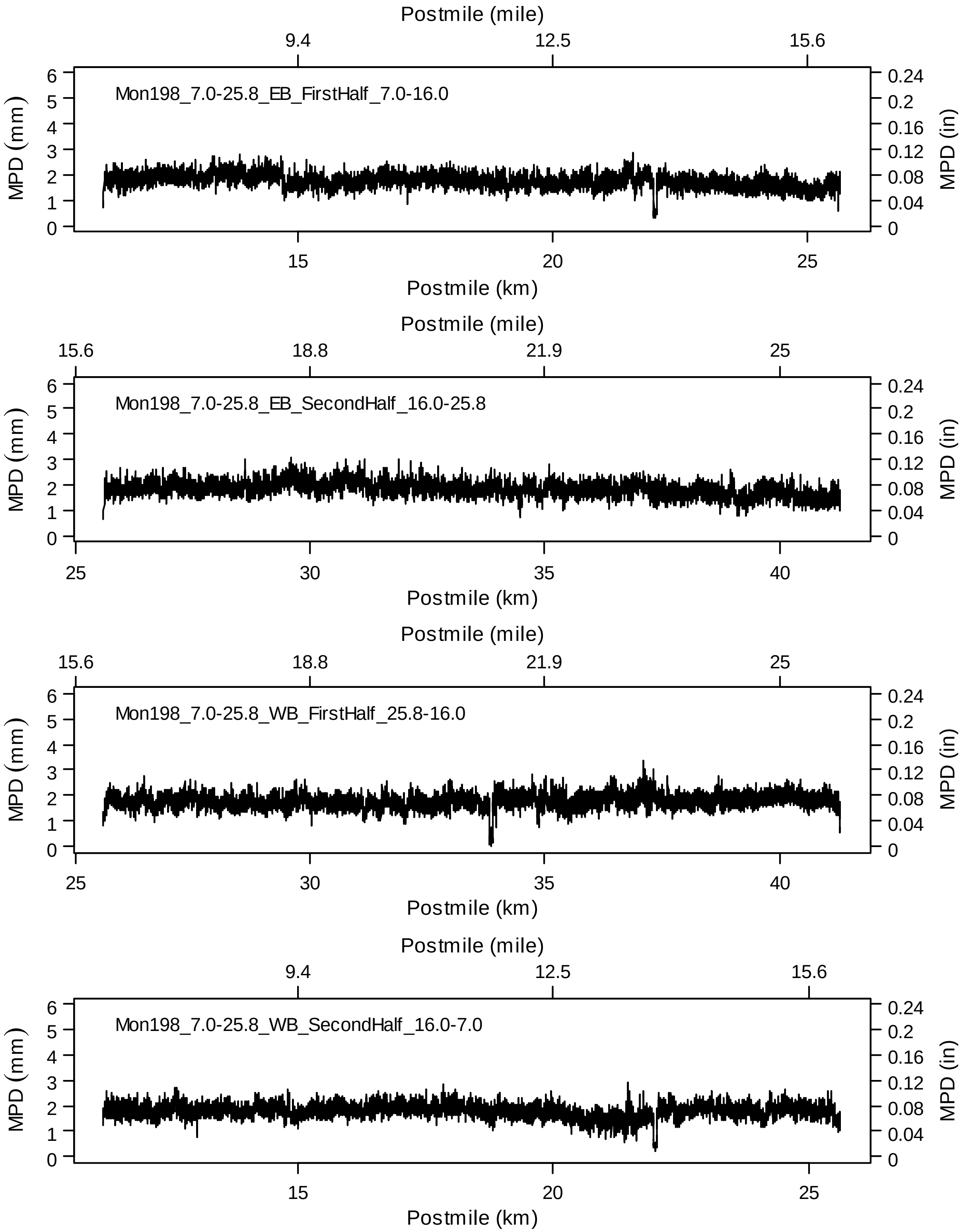


Figure 4.10: Macrotexture measured using IP for Mon-198 (chip seal).

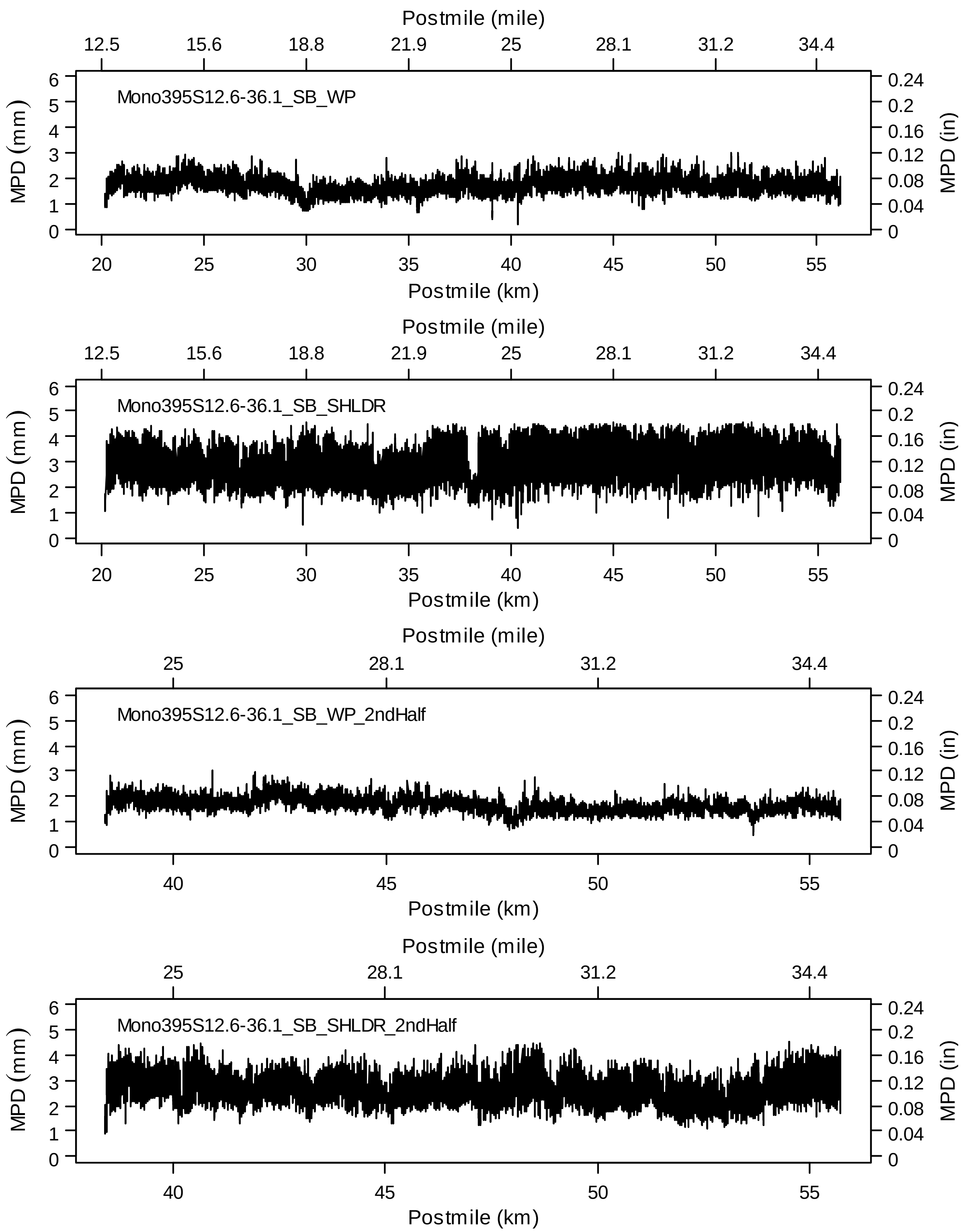


Figure 4.11: Macrotexture measured using IP for Mno-395 (chip seal).

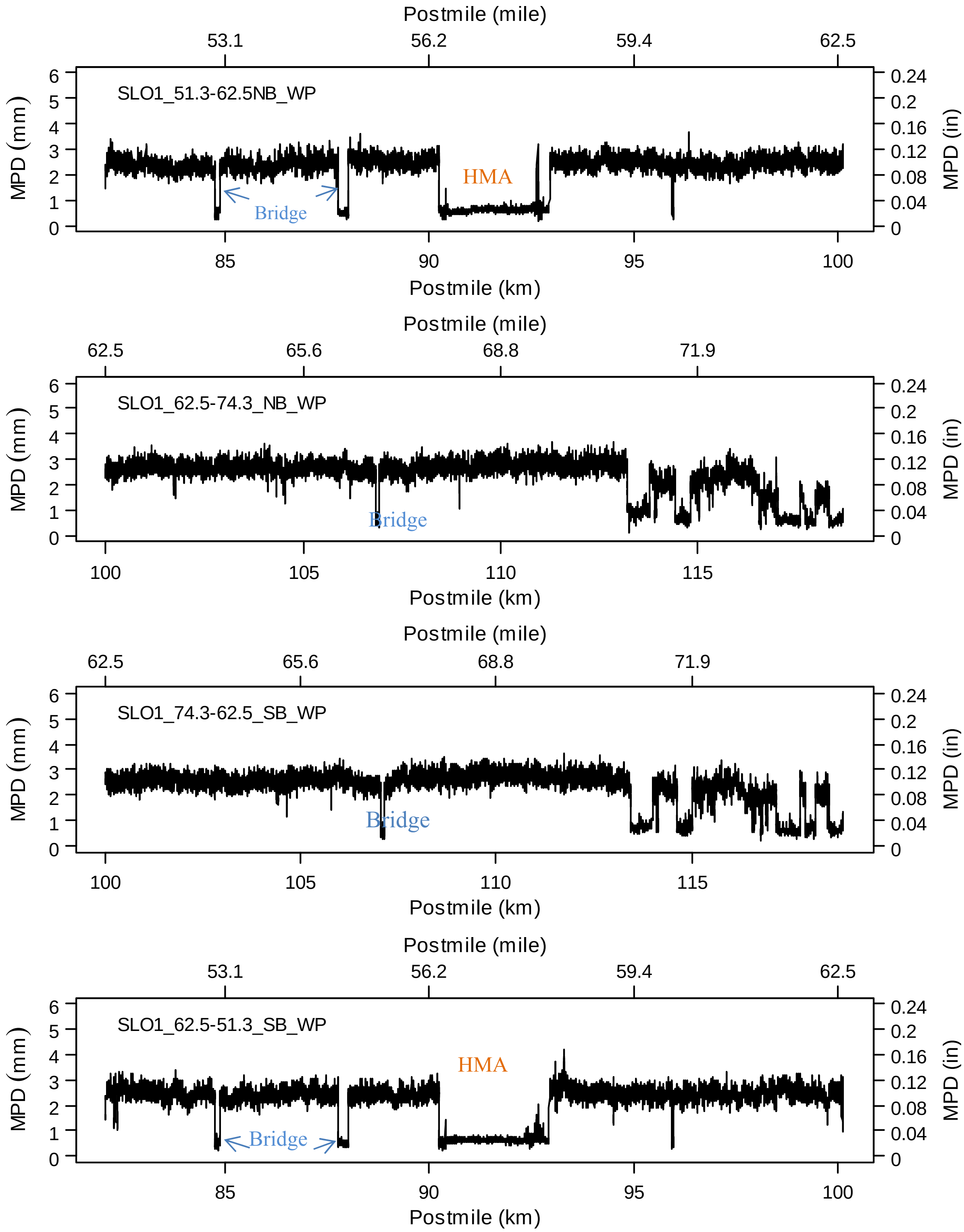
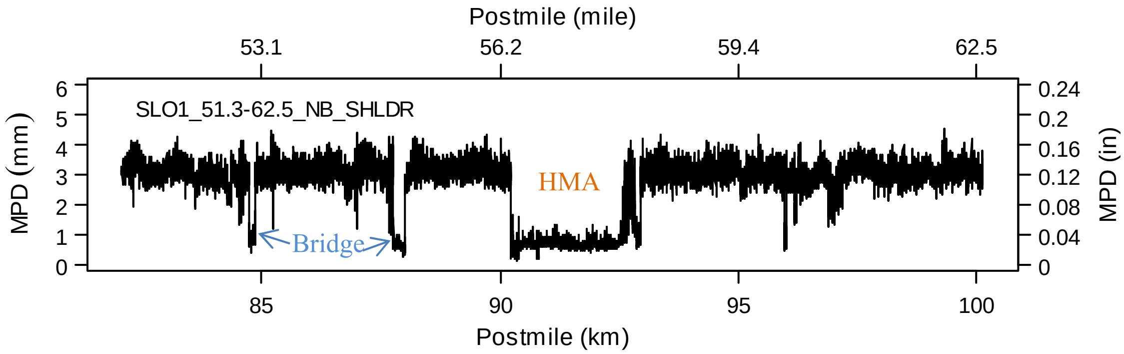
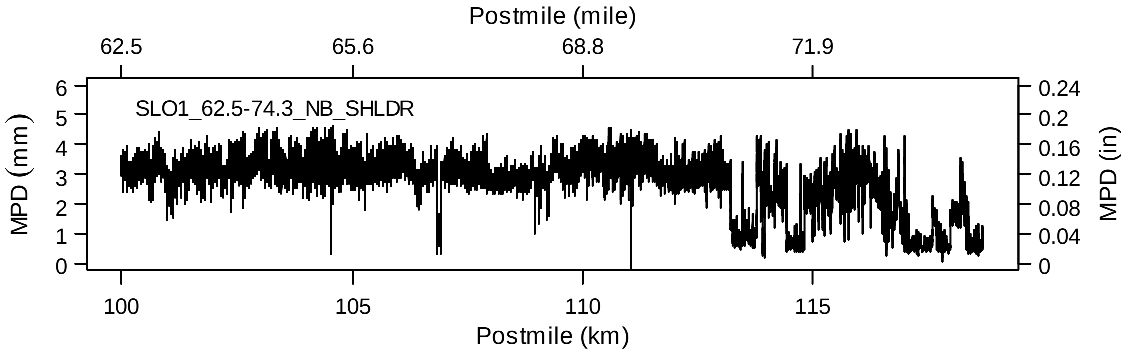
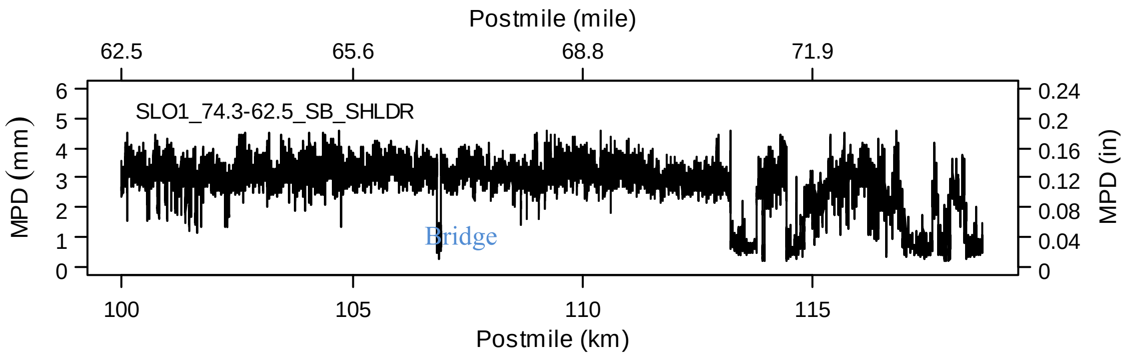


Figure 4.12: Macrotexture measured using IP for SLO-1 in right wheelpath (chip seal).







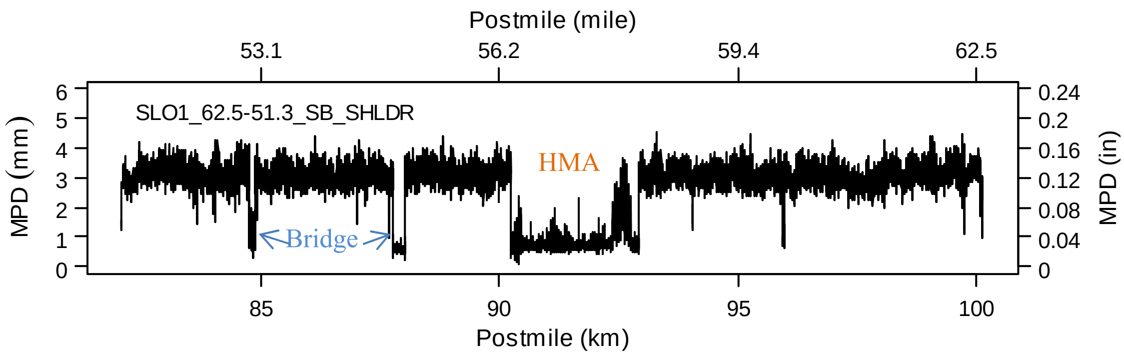


Figure 4.13: Macrotexture measured using IP for SLO-1 on shoulder (chip seal).

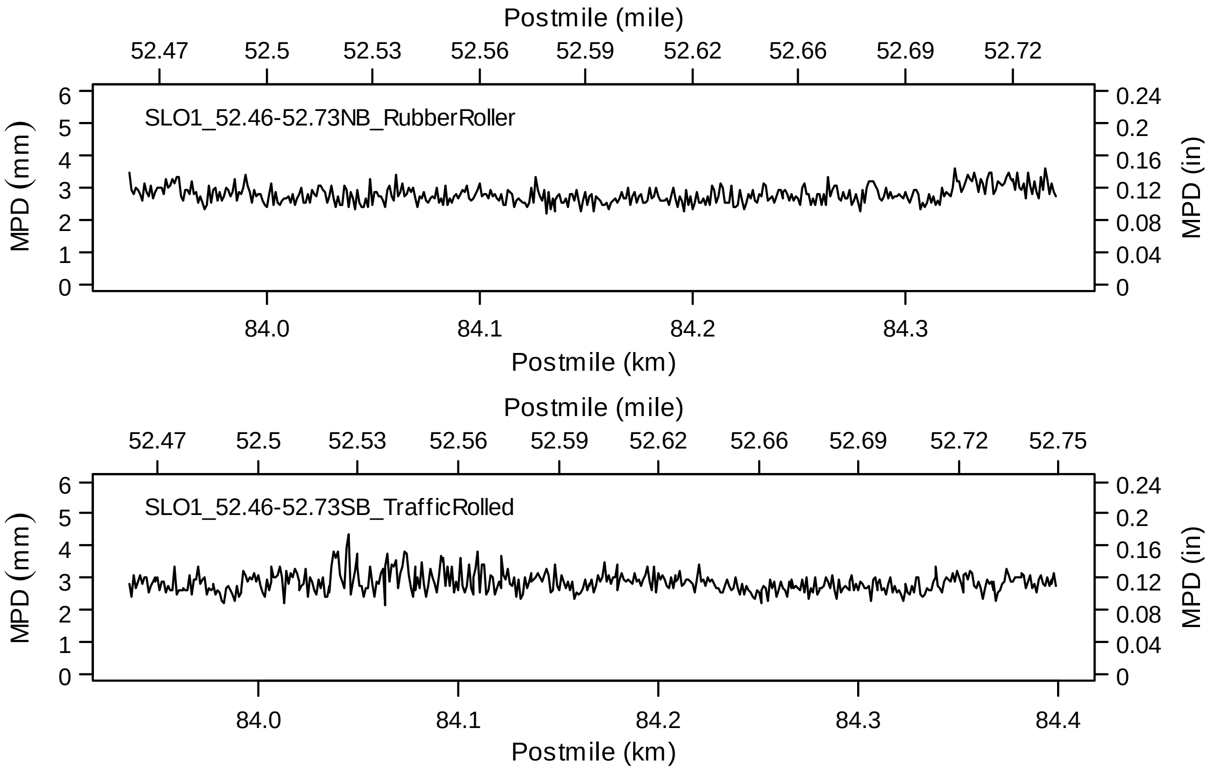


Figure 4.14: Macrotexture measured using IP for the subsection on SLO-1 with additional rolling.

4.4.2 Summary of Phase I Macrotexture Measurements with the Inertial Profiler

The descriptive statistics for MPD measured by the inertial profiler in Phase I 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. Mno-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 [a]	Median	Q3 [a]	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
Mno-395	Mno395S12.6-36.1_SB_WP	36,004	1.71	0.30	0.19	1.51	1.69	1.89	3.02
	Mno395S12.6-36.1_SB_SHLDR	35,964	2.88	0.60	0.37	2.46	2.87	3.30	4.56
	Mno395S12.6-36.1_SB_WP_2ndHalf	17,327	1.67	0.28	0.48	1.47	1.65	1.84	3.01
	Mno395S12.6-36.1_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 [c]	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 [b]	436	2.78	0.27	2.19	2.58	2.74	2.94	3.58
	SLO1_52.46-52.73SB_TrafficRolled [b]	464	2.85	0.31	2.12	2.63	2.82	3.02	4.35

Notes:

[a.] Q1 and Q3 indicate the first and third quartile values.

[b.] The bottom two rows are for the rolling test on SLO-1.

[c.] 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 Mno-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 Mno-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 Mno-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 Mno-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 were collected once the IP equipment was repaired and are presented in the Phase II results in Chapter 5.)

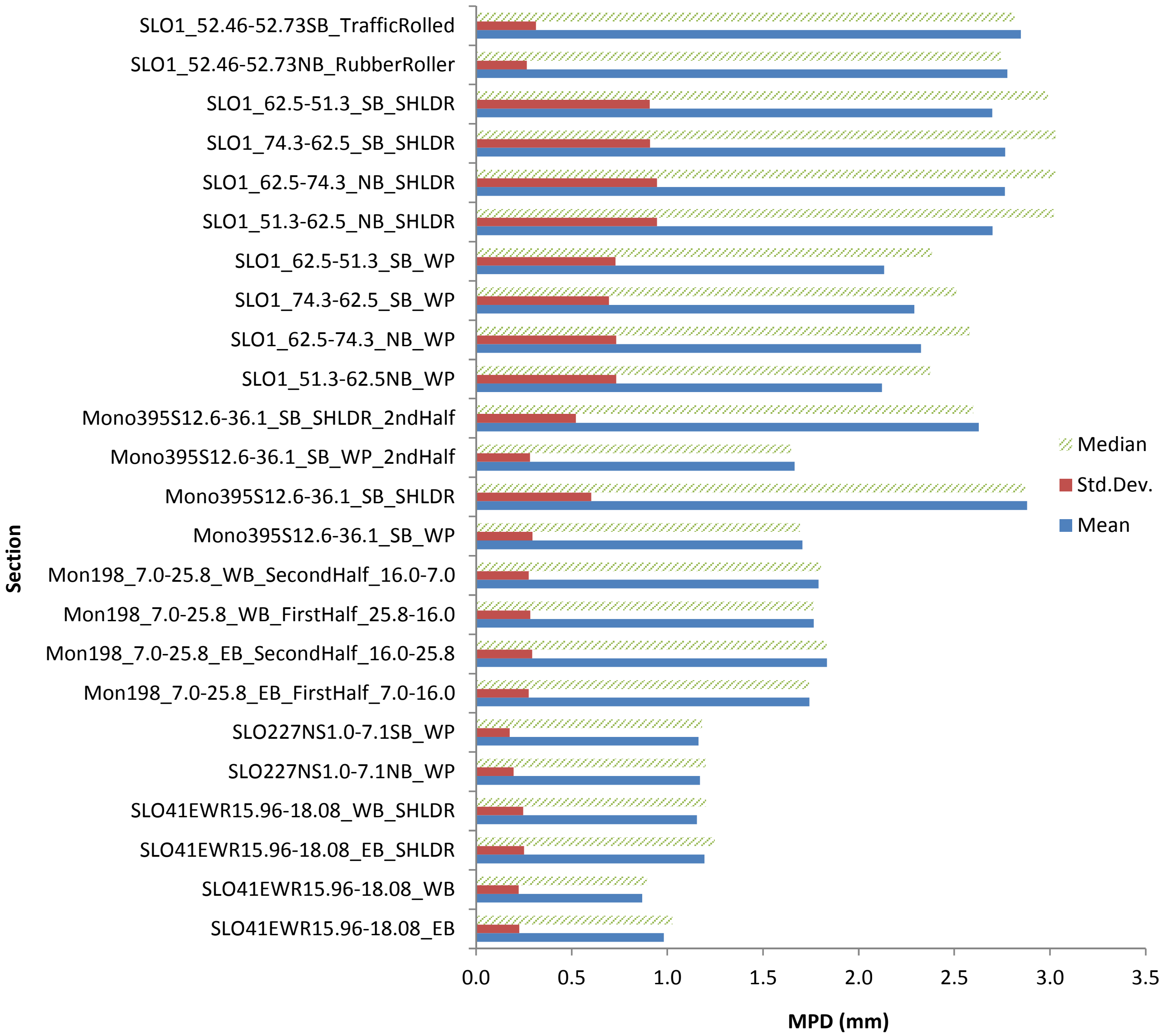


Figure 4.15: Median, mean, and standard deviation of MPD measured from IP for different Phase I sections.
(Note: **SHLDR is for outside of ETW; WP is for inside of ETW.)**

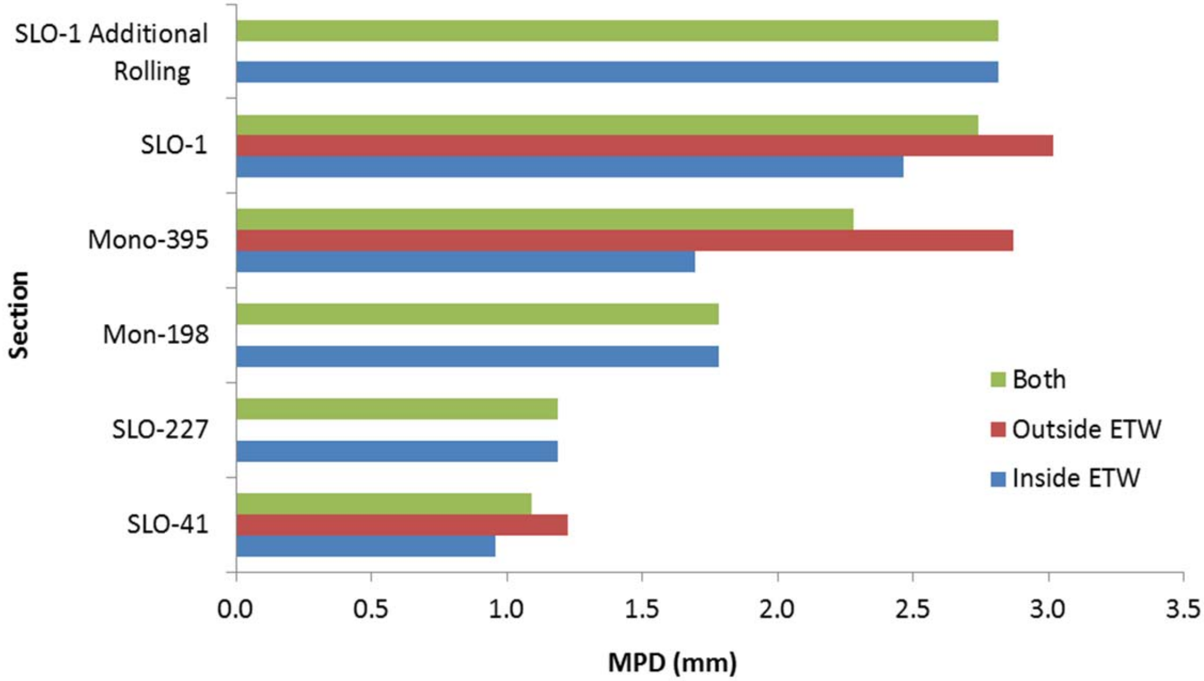


Figure 4.16: Average of median MPD of chip seal measured with IP outside of the ETW, inside of the ETW, and both averaged for each section.

(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 (front position) and two under its seat (rear position), which also permitted evaluation of the effect of sensor-mounting position. The effects of sensor-mounting position with Phase I testing on West Covell Boulevard and Hutchison Drive in Davis, California, are summarized in this section of the 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.

Measurement Variability and Effect of Mounting Position

Data collected on December 6, 2013 (see Table 3.7), on Hutchison Drive and West Covell Boulevard in Davis, California, was used to evaluate the measurement variability and the effect of accelerometer mounting position on bicycle vibration. A carbon bicycle instrumented with two accelerometers was used: one in front (on the fork) and one at the rear (under the seat). Vibrations were measured in both directions on the two test sections. The Hutchison Drive section has an HMA surface and the one on West Covell Boulevard has a chip seal (CS) surface. The measured vibration data are shown in Figure 4.17.

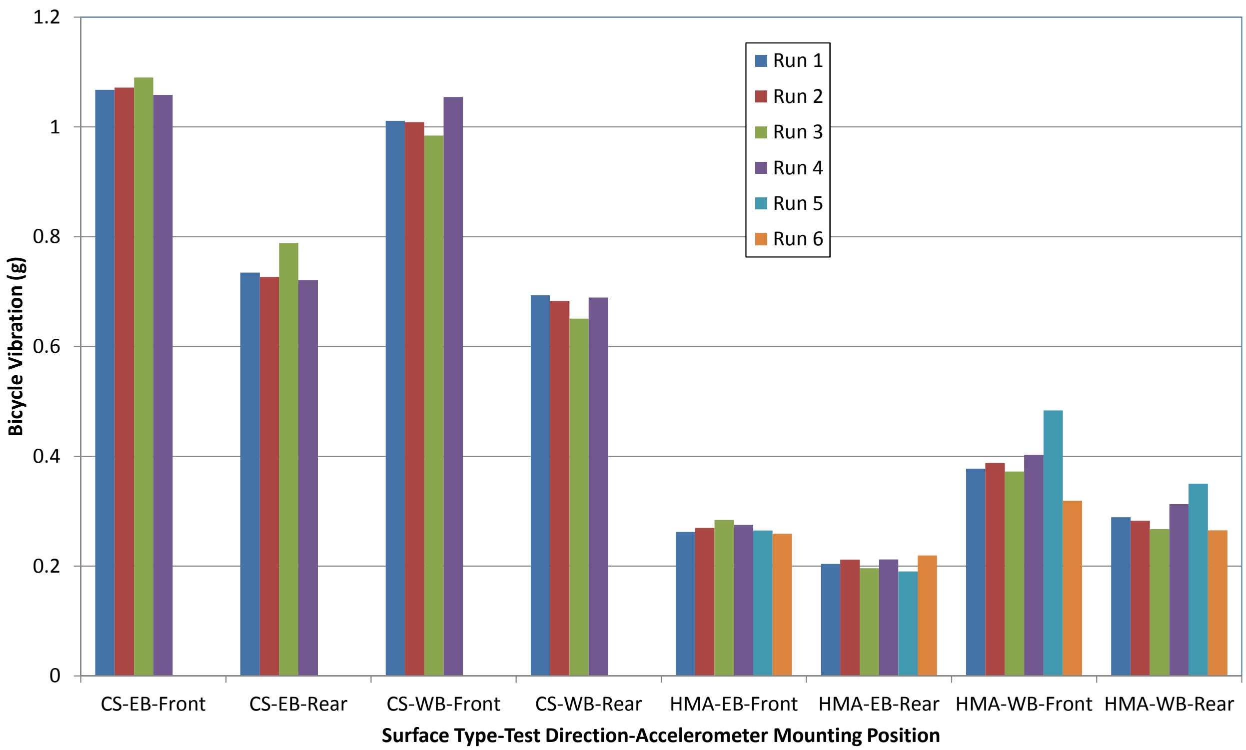


Figure 4.17: Measurement variability and effect of accelerometer mounting position on bicycle vibration. (*Note:* CS = chip seal, EB = eastbound, WB = westbound, HMA = hot-mix asphalt)

Figure 4.17 indicates that in general the differences in measured bicycle vibration between different runs are less than 0.1 *g*. In addition, the vibrations measured at the rear position are consistently lower than the ones measured at the front. A detailed comparison of average bicycle vibrations measured at the front and rear positions are listed in Table 4.2. The table indicates that overall the bicycle vibration measured at the rear position is about 70 percent of the value measured at the front position.

Table 4.2: Comparison of Average Bicycle Vibrations Measured at Front and Rear Positions

Surface Type	Direction	Front (*g*)	Rear (*g*)	Rear-to-Front Ratio
Chip Seal	Eastbound	1.07	0.74	0.69
	Westbound	1.01	0.68	0.67
Chip Seal Average		1.04	0.71	0.68
HMA	Eastbound	0.27	0.21	0.76
	Westbound	0.39	0.29	0.75
HMA Average		0.33	0.25	0.76
Grand Average		0.62	0.43	0.71

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 (30 and 37 km/h), the *medium* controlled speed ranged between 14 and 17 mph (22 and 27 km/h), and the *slow* control speed ranged between 6 and 9 mph (10 and 14 km/h). The *normal* speed was achieved when the individual cyclist rode at a level of moderate exertion.

The bicycle vibrations measured at the different speeds are shown in Figure 4.18 for the different treatments on Mon-198. Note that the bicycle vibrations have already been normalized to 16 mph (26 km/h) as part of the data processing procedure. As shown in Figure 4.18, 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 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.

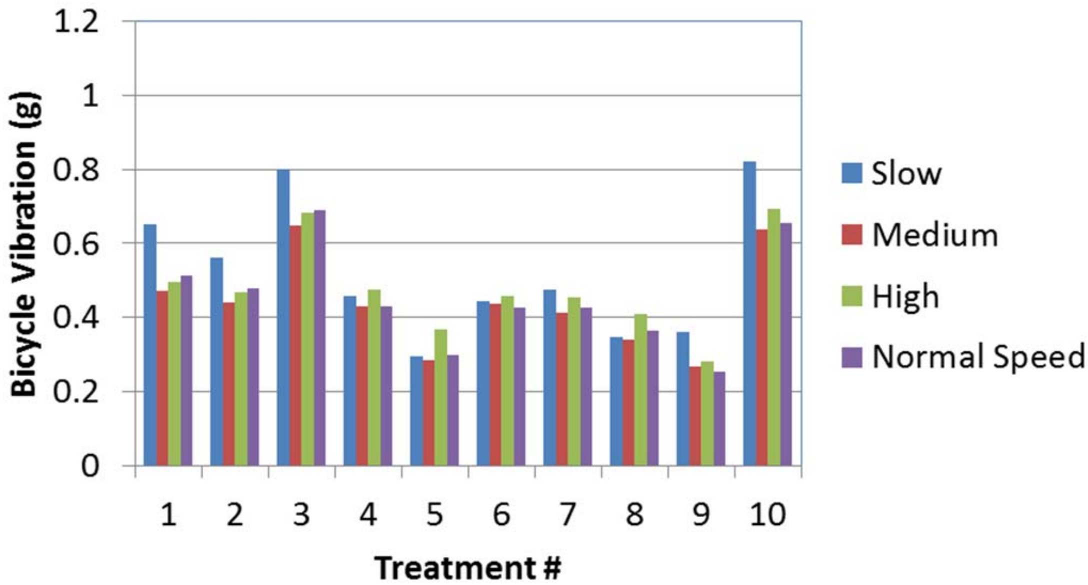


Figure 4.18: Bicycle vibration measured at different speeds on the Mon-198 test sections.
(See Table 3.4 for a description of each treatment #; Normal Speed indicates different speeds for different riders.)

<u>Effect of Tire Pressure on Bicycle Vibration</u>

The data from the aluminum bicycle and single rider that were used to measure vibration on July 23, 2013, on Mon-198 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 4.19 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.

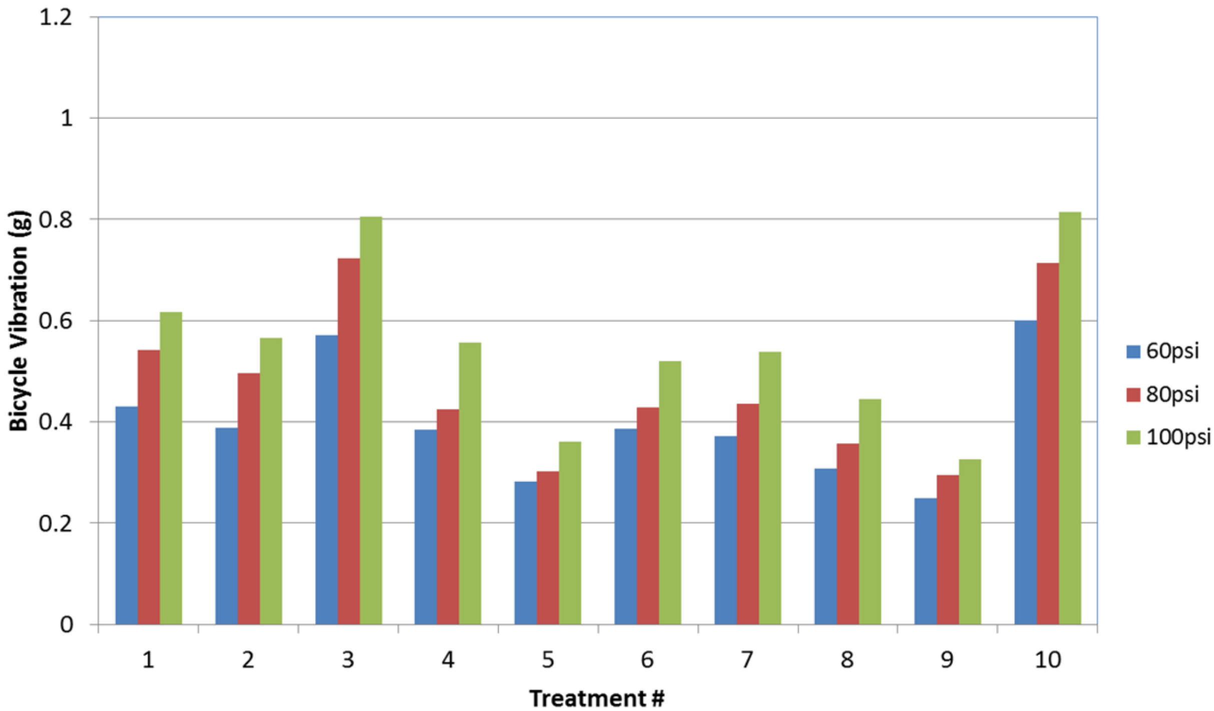


Figure 4.19: Bicycle vibration measured with different tire pressures on Mon-198 sections. (See Table 3.4 for a description of each treatment #.)

Effect of Bicycle Frame Material and Rider Weight on Vertical Acceleration

The data collected on December 6, 2013 (see Table 3.7), on West Covell Boulevard in Davis, California, with two different bicycles and two different rider weights was used to evaluate the effects of bicycle frame materials and rider weight on bicycle vibration. The weight of the rider changed depending on whether or not he wore a 60 lb (27 kg) backpack. Accelerometers were mounted both in the front (on the fork) and at the back (under the seat). The comparison of vibrations measured using bicycles made of different materials is shown in Figure 4.20, while the comparison of data measured with different rider weights is shown in Figure 4.21.

Figure 4.20 indicates that in this particular case, the aluminum bicycle consistently had more vibration than the carbon bicycle. The differences in vibration between these two bicycles were more pronounced when measured at the rear compared to when measured in the front. Figure 4.21 indicates that when the rider is heavier, bicycle vibrations are higher at the rear (i.e., under the seat) position but are either lower or about the same at the front.

Note that no bicycle material or rider weight normalization was included as part of the data processing procedure. Based on Figure 4.20 and Figure 4.21, ignoring the effect of bicycle material or rider weight on bicycle vibration can potentially lead to an error of less than 0.2 g.

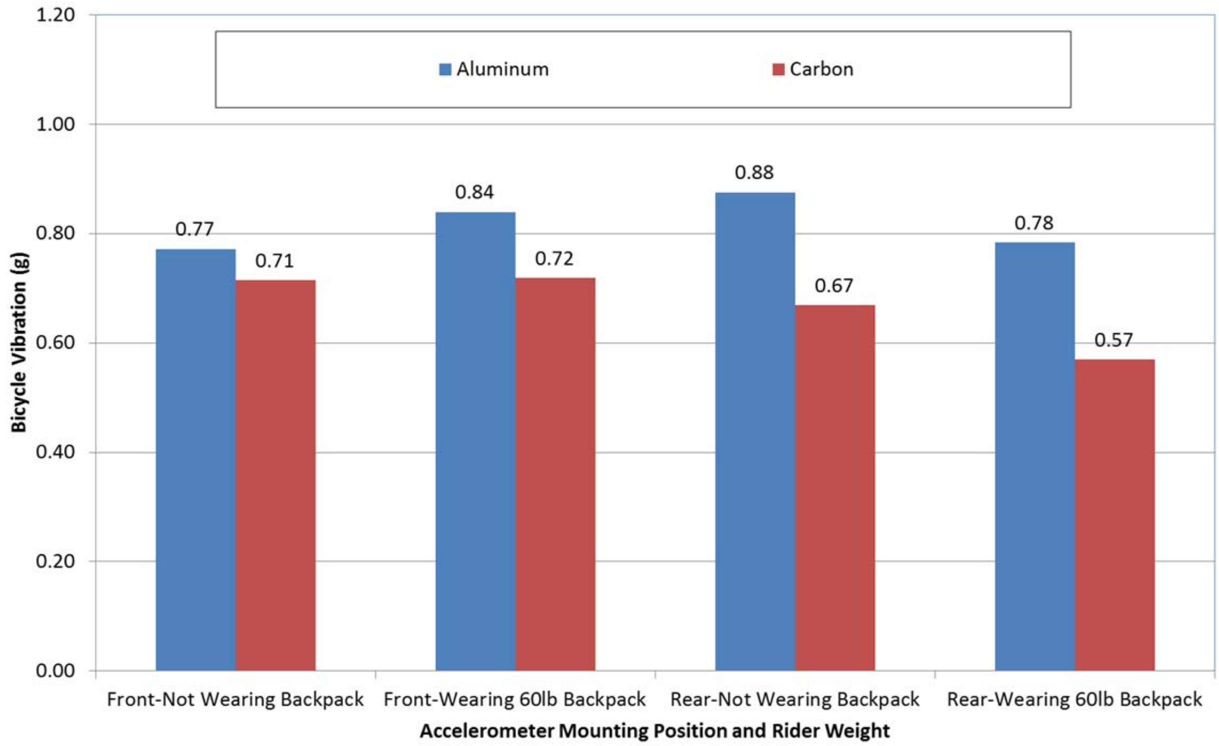


Figure 4.20: Bicycle vibration measured with different frame material on West Covell Boulevard in Davis, California.

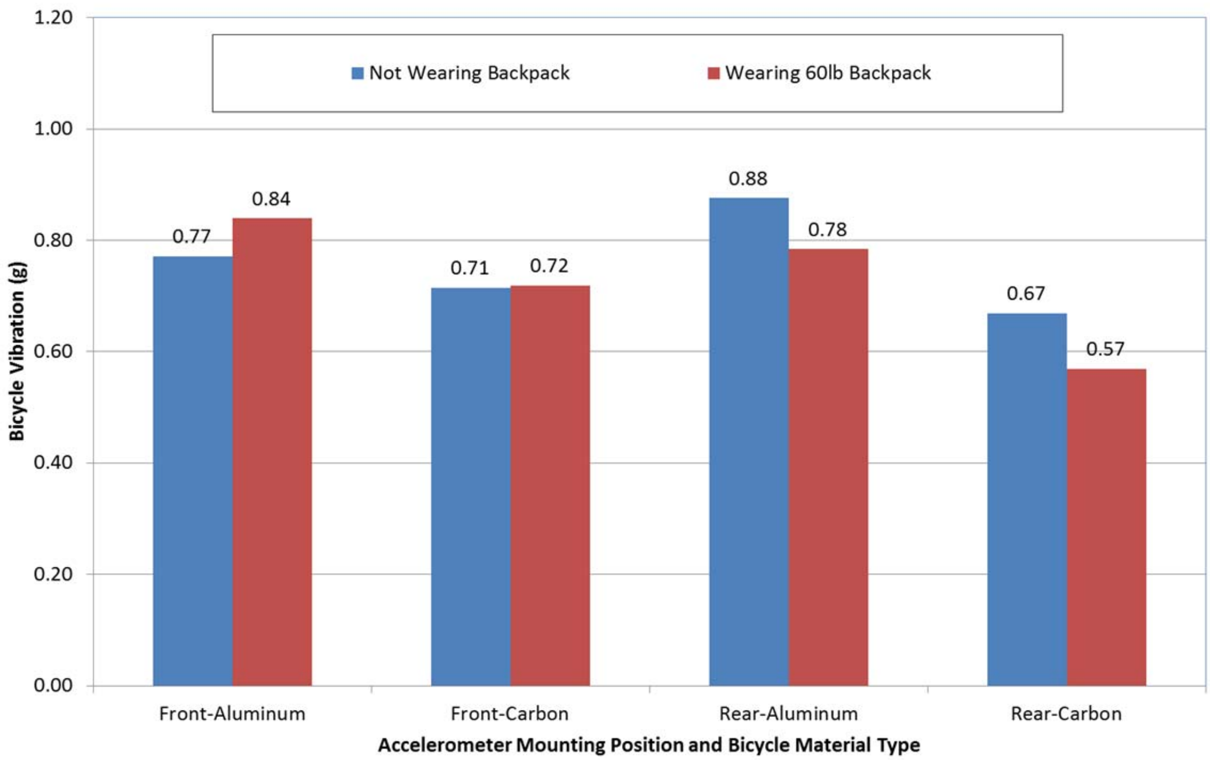


Figure 4.21: Bicycle vibration measured with different rider weights on West Covell Boulevard in Davis, California.

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 4.22 with the results separated into the two lines, and in Figure 4.23 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 significantly lower overall than those on SLO-1, although all the sections were constructed following the same specification.

Figure 4.22 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 4.23) 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).

The control section for Mon-198 (survey sections 19 and 20 in Figure 4.22, and treatment section 10 in Figure 4.23) 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 4.22 and Figure 4.23, respectively) had the lowest vibration: about 0.30 g.

From the results shown in Figure 4.22 and Figure 4.23, 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 4.22 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 4.23 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 compared to the untreated control section on Mon-198. It was 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 4.23), 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 4.23) would be applicable to SLO-1. If the difference in vibration were the result of the treatments instead of the the lower, pre-treatment values seen on Mon-198 versus those on SLO-1, 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 bicycle ride quality in Sections 4.6 and 4.7 of this research report. The answer to the question of the effect of the remedial treatment used on SLO-1 is presented in Chapter 7.

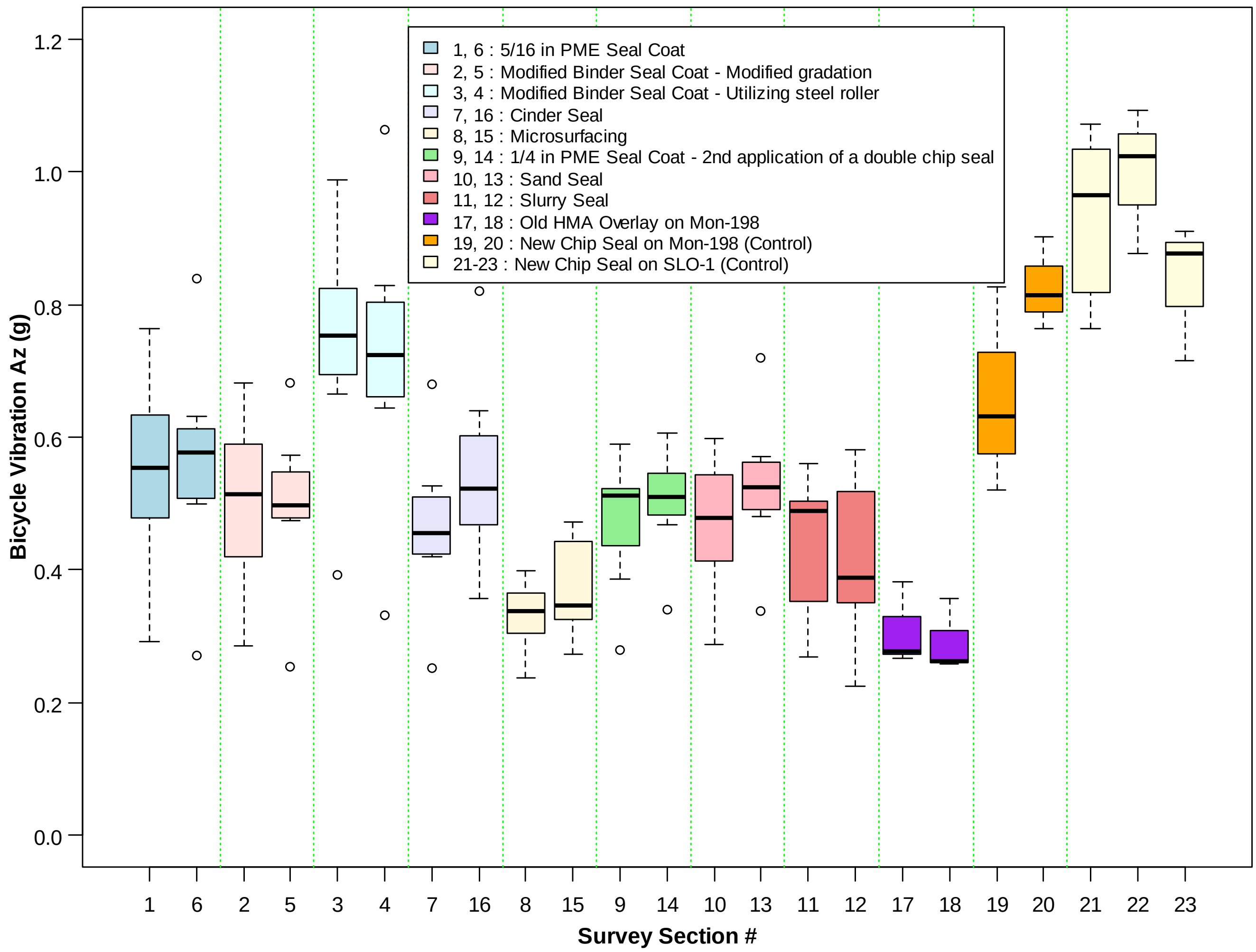


Figure 4.22: Bicycle vibration along the inside of ETW (left) and the left wheelpath (right) for each of the Mon-198 test sections, and along the ETW for three different survey sections on SLO-1.

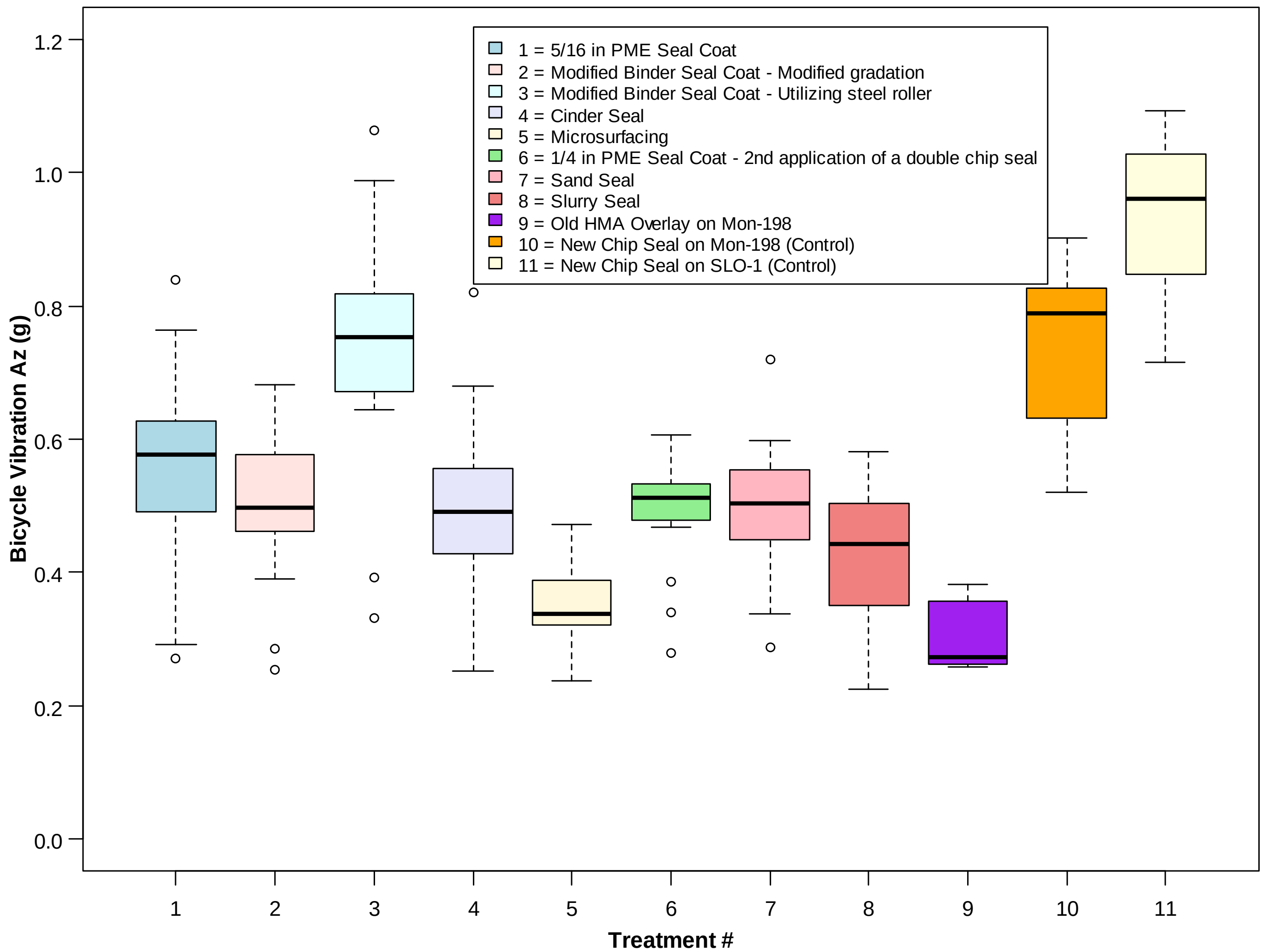


Figure 4.23: Bicycle vibration by treatment type for all Mon-198 and SLO-1 survey sections.

4.6 Correlations between Macrotexture, Vibration, and Ride Quality

The bicycle ride quality survey was conducted on the eight Mon-198 test sections and on three SLO-1 survey sections. 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 initial survey forms (pre-ride, in-ride, and post-ride) and raw survey results appear in Appendix E.1 and Appendix F, respectively.

As shown in Figure 4.24, 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 bicycle 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 (treatment 10 shown in Figure 4.23) 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, acceptability, and ride quality level.
b. No significant correlation was found between other variables and bicycle 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 bicycle ride quality "Acceptability" is based on a straight line interpolation in Figure 4.24 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 was about 2 on the same 1-to-5 scale.

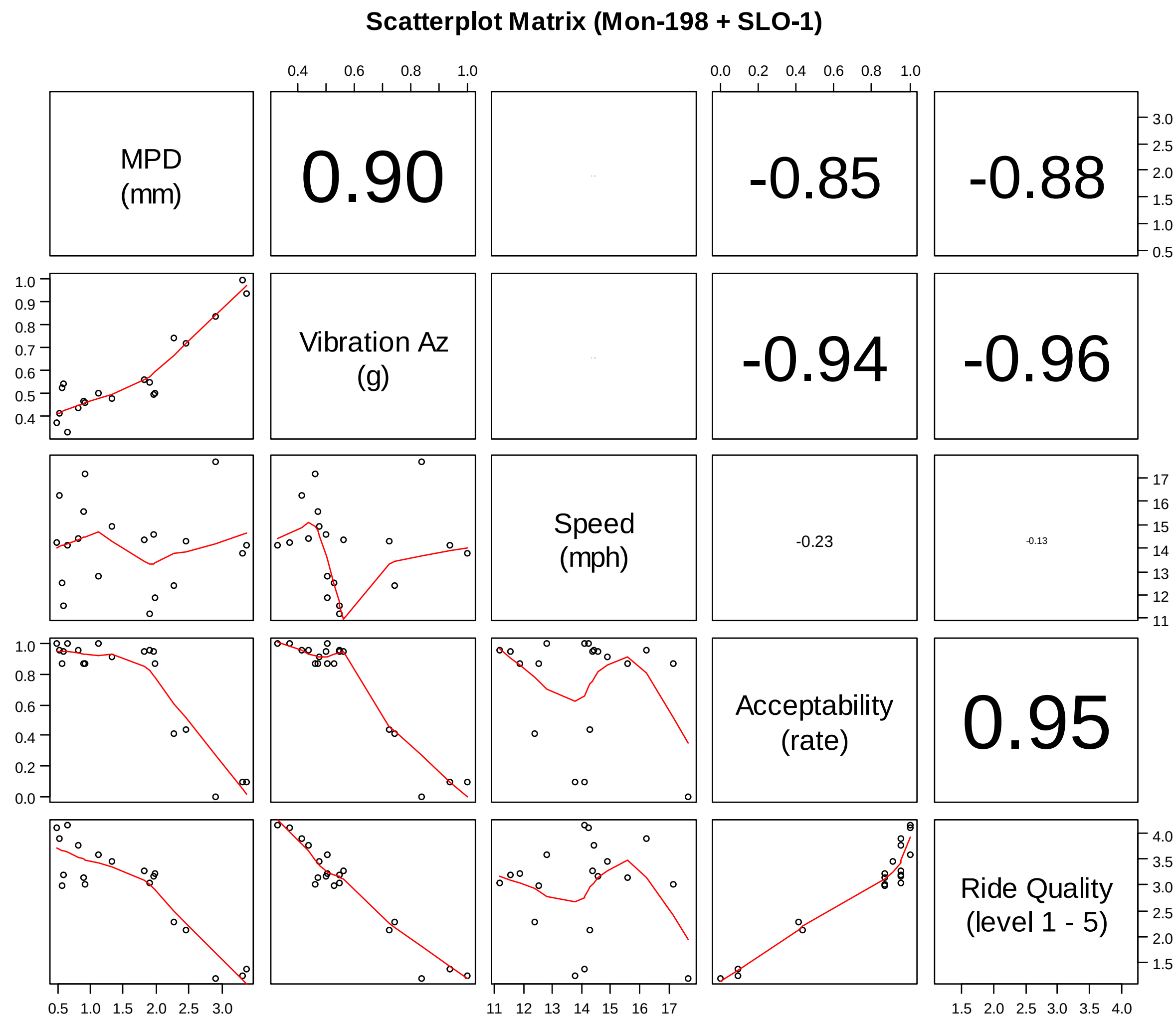


Figure 4.24: Correlations between MPD, acceleration, bicycling speed, acceptability, and ride quality level (Mon-198 test sections).
(Note: **Scatterplots and smooth fitted lines are shown in lower panels. Correlations between variables are shown in upper panels, with the size of the type within the box proportional to absolute correlation.)**

4.7 Initial Modeling Results

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

4.7.1 Vertical Acceleration Assignment

The first step in modeling the relationship between bicycle ride quality level and vertical acceleration was to assign vertical acceleration values to the bicycles that 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 bicycle 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" *(17)*. This describes the Mon-198 data situation well, although 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" *(17)* (emphasis indicated by italic within brackets have been placed by authors of this report).

Nevertheless, a first approximation of the link between bicycle ride quality and vertical acceleration of the bicycle, by using a simple linear regression of average bicycle ride quality rating for each of the eight Mon-198 sections by the average standard deviation of the SDNA at varying bicycle 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 bicycle ride quality ratings.

The first step in multilevel random coefficient modeling is to determine "the levels at which significant variation exist" *(17)*. 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 bicycle ride quality ratings that can be explained by the individual assigning the rating, (2) testing the reliability of the means of the bicycle ride quality ratings by individuals, and (3) testing “whether the variance of the intercept is significantly larger than zero” *(17)*. 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 bicycle 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 bicycle ride quality ratings. The average reliability of the individual bicycle 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 bicycle ride quality ratings among individuals.

A multinomial 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.

$$Comfort\ Rating_{ij} \sim Multinomial(p_{ij}) \quad \textbf{(4.1)}$$

where:
$$\log \frac{p_{ij}}{1-p_{ij}} = a + \beta_{SDNA}(\overline{SDNA}) + \beta_{YOB}(YOB) + \beta_{ICE}(ICE) + \beta_{IWE}(IWE) + \beta_{SBRP}(SBRP) + \beta_{I}(\overline{SDNA})(MRLW) + \beta_{j}(\overline{SDNA})$$

$$\beta_j \sim Normal(0, \sigma)$$

In the final model, the within-individual variation in bicycle 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 bicycle ride quality slope are allowed to randomly vary across individuals and are 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 4.3) indicate that for each individual, higher bicycle vibration (SDNA) values for a particular segment lead to lower bicycle ride quality ratings, as expected. Older individuals gave higher bicycle 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 4.3: 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 4.4 and Table 4.5). 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 4.4: 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 4.5: 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 PHASE II EXTENDED STUDY OF SURFACE MACROTEXTURES AND BICYCLE RIDE QUALITY SURVEYS

Following the approach decided upon for Phase II Task D, additional surveys of cyclists were conducted at organized riding events in order to obtain a larger sample of riders and pavements, and a broader range of rider demographics and road sections. Using the same methods as in Phase I, pavement macrotexture (smoothness, i.e., MPD) and bicycle vibration were measured to characterize the pavement texture and bicycle dynamic response. Phase II of the study also included the first measurement of pavement roughness (unevenness) in terms of the International Roughness Index (IRI, ASTM E1926-08; see Figure 2.1 for the wavelengths that influence roughness) to investigate whether this pavement surface characteristic influences bicycle ride quality.

5.1 Cycling Groups and Road Sections Used in the Phase II Survey

The Phase II surveys were performed with different groups of cyclists at different riding events, including:

- The Tour of Tahoe in El Dorado and Placer counties on September 8, 2013, with riders from the Nichols Consulting Engineers cycling team
- Smaller rides organized by the following cycling clubs in August and September 2013
    - Davis Bicycle Club (BC) in Solano and Yolo counties
    - Santa Rosa Cycling Club (CC) in Sonoma County
    - Chico Velo Cycling Club (CC) in Butte County
    - Alto Velo Racing Club (RC) and Silicon Valley Bicycle Coalition (SVBC) in San Mateo County
- Texture and roughness measurements were made with the inertial profiler on State Route 2 (LA-2) in Los Angeles County, but no rider survey was conducted.

The number of riders, the number of road sections, the bike survey date, and the texture measurement date for each of the Phase II survey groups and the Phase I survey groups are summarized in Table 5.1. A total of 107 effective participant samples from 7 groups on 42 road sections across Northern and Central California were collected and used for the analysis.

The Phase II road sections used for the extended survey along with the Phase I road sections on Mon-198 and SLO-1 are shown in Figure 5.1 and detailed in Table 5.2. Figure 5.2 shows LA-2.

Table 5.1: Summary of Phase I and Phase II Surveys

Survey Phase (Set)	Group	No. of Riders	No. of Sections	Bike Survey Date [a]	Texture Measurement Date [b]
Phase I	Mon-198	24	16	Jul 13, 2013	Oct 8 (Jul 23), 2013
	SLO-1	11	3	Jul 22, 2013	Apr19, 2013
Phase II	Davis BC	6	4	Aug 10, 2013	Nov 15, 2013
	Santa Rosa CC	26	6	Sept 7, 2013	Oct 2, 2013
	Tahoe (Nichols CE)	16	4	Sept 8, 2013	Oct 1, 2013
	Chico Velo CC	8	5	Sept 21, 2013	Sept 25, 2013
	Alto Velo RC + Silicon Valley BC	16	4	Sept 28, 2013	Oct 16, 2013
Total	***7***	***107***	***42***	-	-

a. Includes bicycle vibration measurement
b. Using inertial profiler (IP) for most measurements. Laser texture scanner (LTS) was also used for Mon-198. Where applicable, the LTS measurement date is in parentheses.

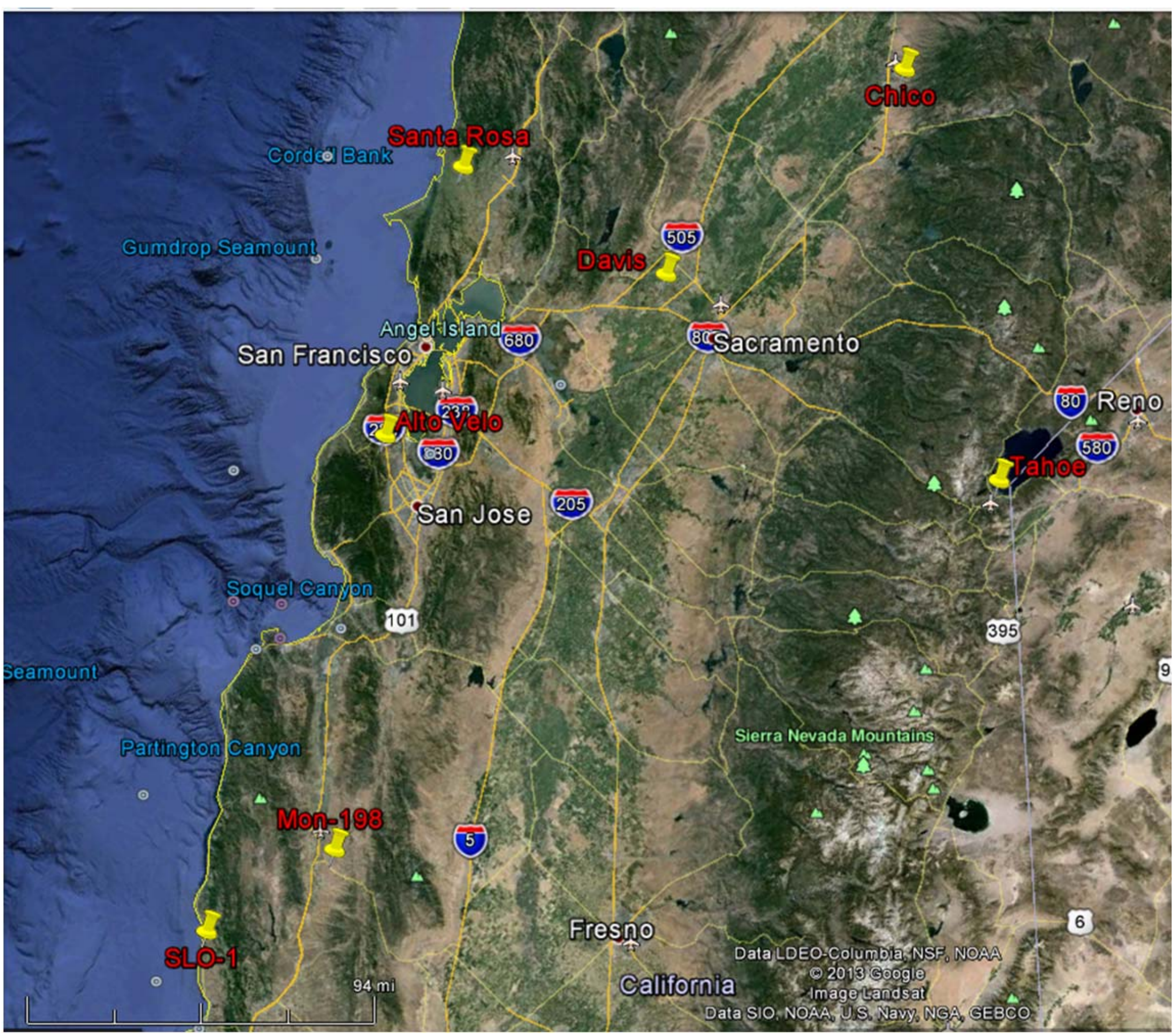


Figure 5.1: Locations of road sections for the Phase I and Phase II surveys.

In November 2013, the texture of route LA-2, including the macrotexture in terms of Mean Profile Depth (MPD) and roughness in terms of International Roughness Index (IRI), were measured at the ETW for both directions from PM 26.4 to PM 82.3 using the inertial profiler with a high-speed spot laser mounted on a vehicle operating at highway speed (Figure 5.2). The texture results of LA-2 are presented along with those of the survey sections.

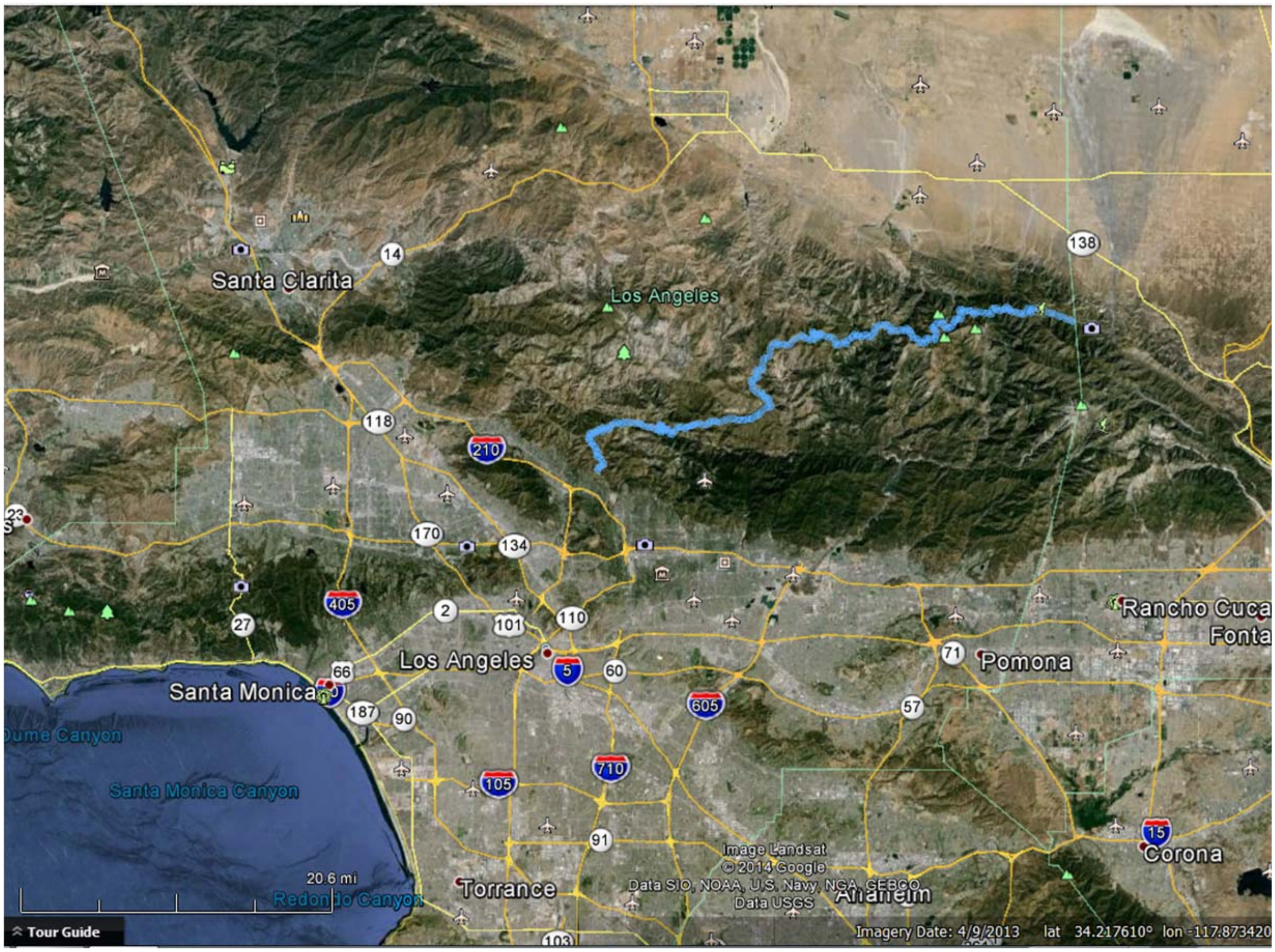


Figure 5.2: Texture measurement on LA-2.
(Note: LA-2 section 1 is PM 26.4 to PM 82.3 EB; LA-2 section 2 is PM 26.4 to PM 82.3 WB.)

Table 5.2: Road Sections Included in the Phase I and Phase II Surveys

Group	Section	County-Route [a]	PM (GPS) [b]	Direction
Mon-198	1, 6	Mon-198 Test Sections	4.5 - 4.7	EB (ETW, LWP)
Mon-198	2, 5	Mon-198 Test Sections	4.7 - 4.9	EB (ETW, LWP)
Mon-198	3, 4	Mon-198 Test Sections	4.9 - 5.1	EB (ETW, LWP)
Mon-198	7, 16	Mon-198 Test Sections	10.2 - 10.4	WB (ETW, LWP)
Mon-198	8, 15	Mon-198 Test Sections	10.0 - 10.2	WB (ETW, LWP)
Mon-198	9, 14	Mon-198 Test Sections	9.8 - 10.0	WB (ETW, LWP)
Mon-198	10, 13	Mon-198 Test Sections	9.6 - 9.8	WB (ETW, LWP)
Mon-198	11, 12	Mon-198 Test Sections	9.4 - 9.6	WB (ETW, LWP)
SLO-1	1	SLO-1	51 - 51.5	NB
SLO-1	2	SLO-1	64 - 65	NB
SLO-1	3	SLO-1	58.5 - 59.5	SB
Davis	1	*Yolo County Road 31* (0.5 miles WB, from CR 31 PM7.5 to CR 96)	(38.56161°, -121.83168°)	WB
Davis	2	*Yolo County Road 96* (1.0 miles NB, from CR 30 to CR 29)	(38.57605°, -121.84016°)	NB
Davis	3	*Yolo County Road 92E* (0.5 miles SB, from CR 29 to CR 29A)	(38.59066°, -121.90442°)	SB
Davis	4	*Yolo County Road 92E* (0.2 mile north of CR 31 to CR 31)	(38.56467°, -121.90442°)	SB
Santa Rosa	1	*Gericke Rd., Petaluma* (0.5 miles SB to Fallon-Two Rock Rd.)	(38.28312°, -122.88778°)	SB
Santa Rosa	2	MRN-1	42.2 - 41.7	SB
Santa Rosa	3	MRN-1	28.7 - 29.9	SB
Santa Rosa	4	*Point Reyes Petaluma Rd., Nicasio* (from dam to north 0.2 miles NB)	(38.07692°, -122.75553°)	NB
Santa Rosa	5	*Point Reyes Petaluma Rd., Nicasio* (0.5 miles NB to Marin French Cheese)	(38.12979°, -122.71318°)	NB
Santa Rosa	6	*Chileno Valley Rd., Petaluma* (0.2 miles WB to the end of Laguna Lake)	(38.20578°, -122.75827°)	WB
Tahoe	1	ED-50	75.5 - 75.7	WB
Tahoe	2	ED-89	21.4 - 21.6	NB
Tahoe	3	PLA-89	2.3 - 2.5	NB
Tahoe	4	PLA-28	9.9 - 10.1	EB
Chico Velo	1	*Humboldt Rd., Chico* (1.1 miles EB)	(39.74578°, -121.75503°)	EB
Chico Velo	2	*Humboldt Rd., Chico* (1.7 miles WB)	(39.74578°, -121.75503°)	WB
Chico Velo	3	BUT-32 (Normal to Orange)	R9.37L - 9.04L	WB
Chico Velo	4	BUT-32 (Orange to Normal)	R9.01R - R9.341R	EB
Chico Velo	5	BUT-32 (Cypress to Bartlett)	9.5R - 10R	EB
Alto Velo	1	*Alpine Rd., Portola Valley* (from Hillbrook Dr. WB 0.25 miles)	(37.37533°, -122.20256°)	WB
Alto Velo	2	*Kings Mountain Rd., Woodside* (0.35 miles NB to Route 35)	(37.42590°, -122.30751°)	NB
Alto Velo	3	SM-35	10.62 - 10.96	SB
Alto Velo	4	SM-35	10.23 - 10.53	NB
None		LA-2 EB	26.4 - 82.3	EB
None		LA-2 WB	26.4 - 82.3	WB

[a.] Refer to *www.dot.ca.gov/hq/tsip/hseb/products/county_name.pdf* for California county abbreviations. County roads and other local roads shown in *italics* and GPS coordinates shown.

[b.] Refer to *earth.dot.ca.gov* for GPS coordinates for PM. (GPS indicates the GPS coordinates of the start point of the section.)

5.2 Texture and Vibration Measurement Methods

Pavement surface characteristics, including macrotexture (MPD) and roughness (IRI), were measured using the vehicle-mounted inertial profiler (IP) shown in Figure 4.7 (which measures at highway speed, eliminating the lane closures needed for LTS). As noted earlier, the IP measures along a continuous line, in this case where the bicyclists rode (on shoulders or at right wheelpaths), for the entire length of each section included in this study. (More details on the IP measurement method appear in Section 3.2.)

As in Phase I, the bicycle vibration was also measured to characterize the bicycle's dynamic response to pavement texture for each road section following the method described in Section 3.3.

5.3 Bicycle Survey Method

Bicycle surveys were performed again for each group and each road section following the method described in Section 3.4, including pre-ride survey, in-ride survey, and post-ride survey. The survey, which was changed slightly from the earlier version, is shown in Appendix E.2.

5.4 Macrotexture Measurement Results

5.4.1 Continuous Macrotexture Results of Different Survey Sections Using IP

The macrotexture measurements taken with the IP along the entire length of each pavement section (see Table 5.2 for details of each section) are presented in Figure 5.3 through Figure 5.15. The figures show that the MPD values for most of the sections of all the groups are approximately around 1.0 mm, while the MPD values for several sections (sections 1 to 6 in the Mon-198 group and sections 3 to 4 in the Alto Velo group) are approximately around 2.0 mm, and only the MPD of sections on SLO-1 are higher at approximately 3.0 mm. The MPD values within most sections show small variations, while Davis section 4, Santa Rosa section 4, and Alto Velo sections 3 and 4 show relatively larger variations within the sections. The MPD of each section for all the groups has been summarized using boxplots in Figure 5.16 and in Table 5.3. The mean MPD values of all the sections are approximately in the range of 0.2 mm to 3.4 mm. Figure 5.17 shows the IP-measured MPD in the area between the right wheelpath and the edge of traveled way (referred to as the ETW) and in the left wheelpath for each of the Mon-198 treatment sections. These measurements, which were taken approximately four months after construction, revealed no significant differences in MPD due to trafficking between the two locations, unlike the MPD values measured with the LTS approximately one month after construction (as seen in Figure 4.4), which showed that for most sections the ETW had higher MPD than the left wheelpath. When these results are compared, it can be seen that the texture difference between the two measurement locations, the ETW and the left wheelpath, is different between the LTS measurements one month after construction (July 2013) and the IP measurements four months after construction (October 2013). One possible explanation is that the traffic in the three months following the first set of measurements resulted in embedment near the ETW similar to that which had occurred earlier in the wheelpath. Measurement differences may also have played a role for a couple of reasons. First, the measurements were taken with different instruments, that is, the LTS versus the IP. Second, there are differences between what the instruments measure. Specifically, the LTS measures a very small discrete location while the IP measures continuously along the entire section. In addition, interpreting the IP measurements is further complicated by the difficulty of maintaining a true line with the IP vehicle between the right wheelpath and the ETW at highway speeds on this mountain road. However, these differences can be evaluated further by long-term monitoring of the texture changes on the Mon-198 and SLO-1 sections in the next step of the investigation, if it is funded.

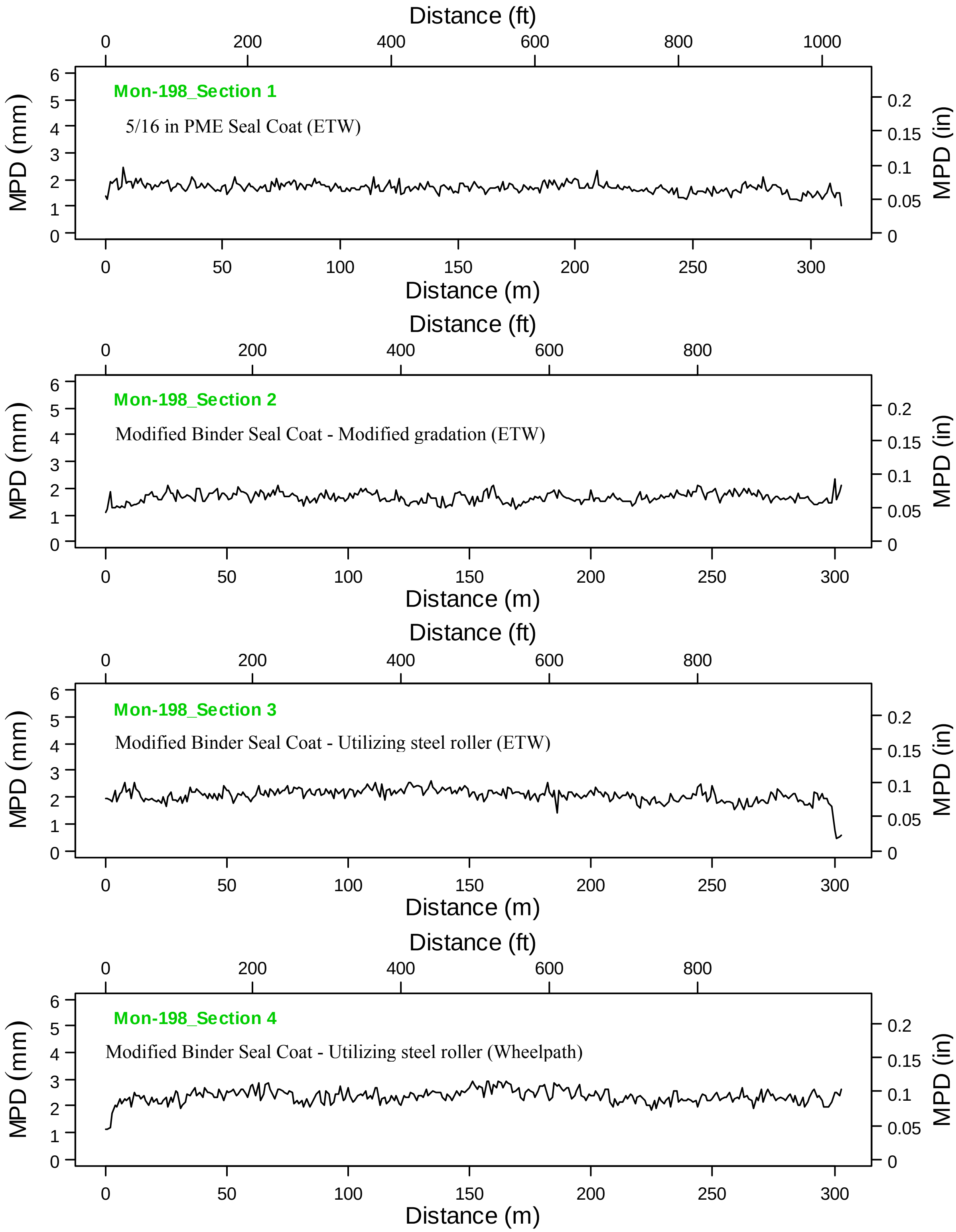


Figure 5.3: Macrotexture measured using IP on the Mon-198 group survey sections 1 to 4.

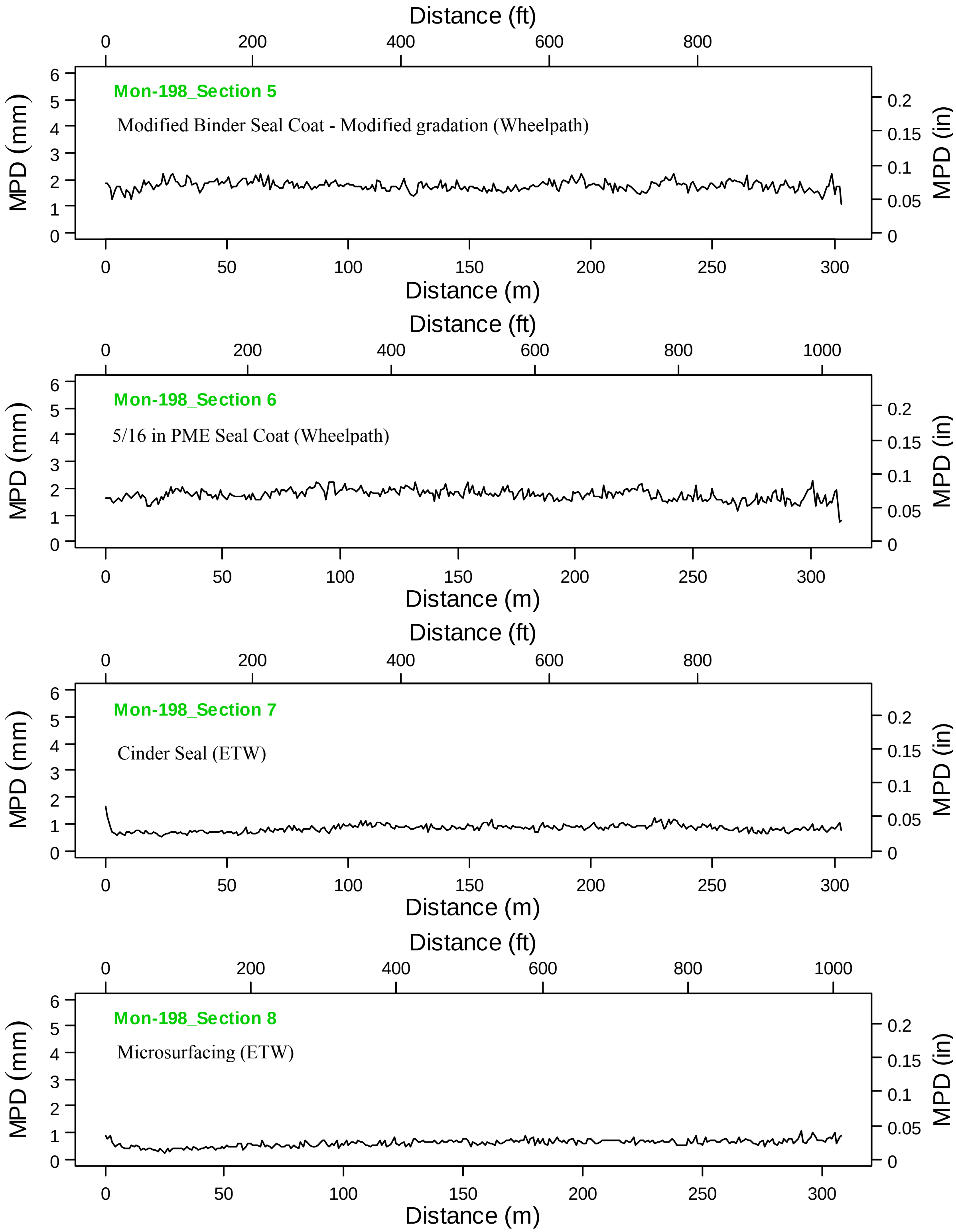


Figure 5.4: Macrotexture measured using IP on the Mon-198 group survey sections 5 to 8.

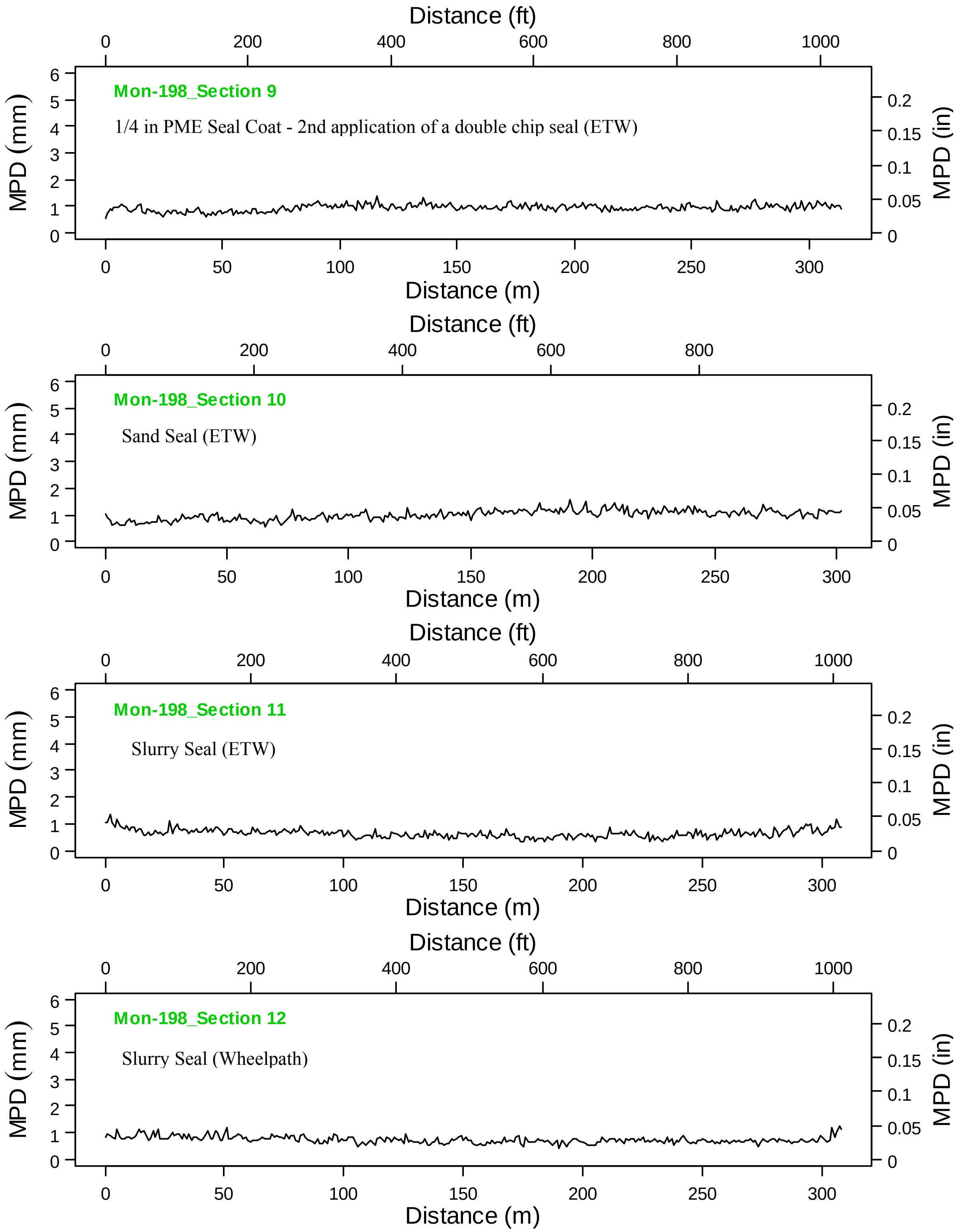


Figure 5.5: Macrotexture measured using IP on the Mon-198 group survey sections 9 to 12.

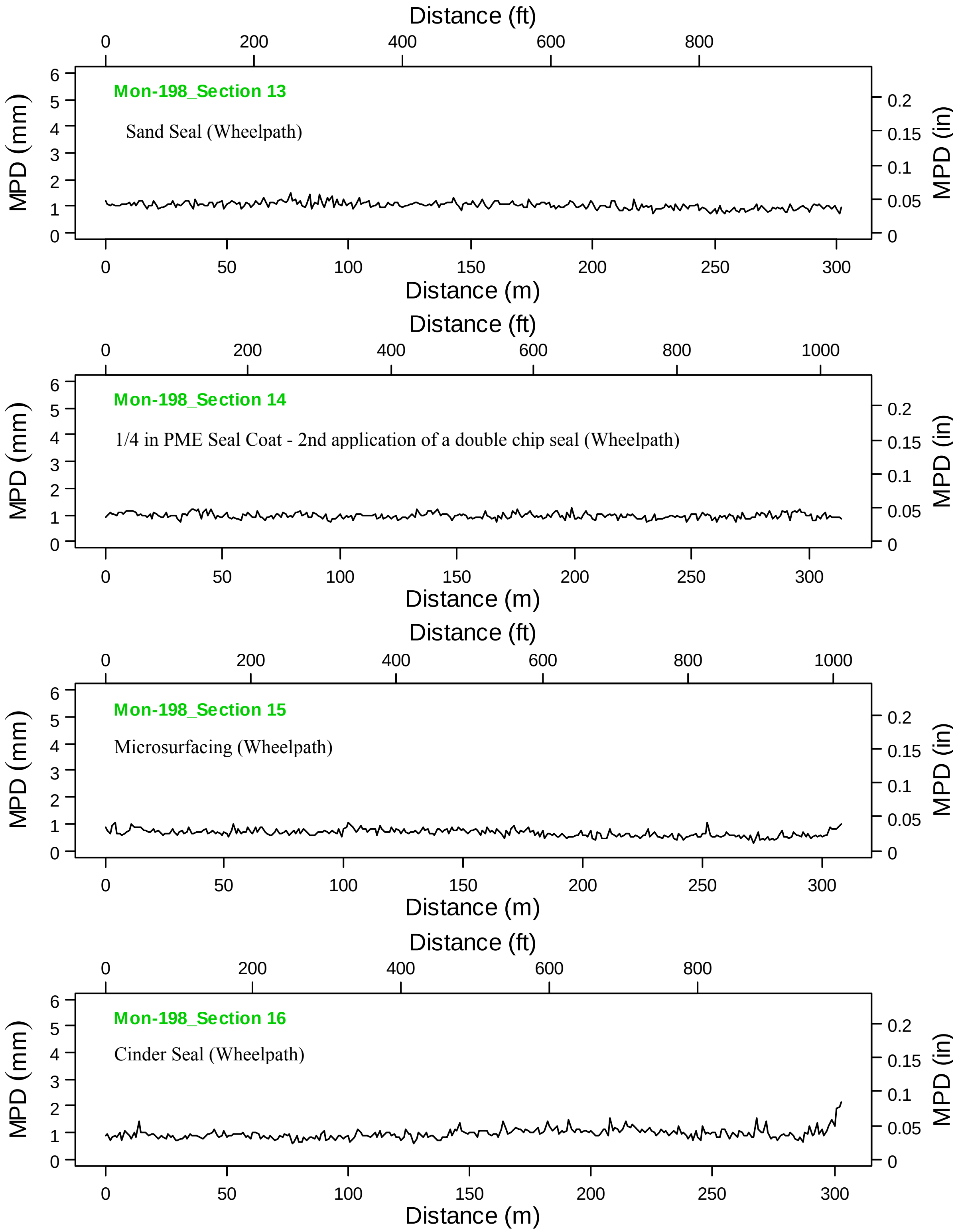


Figure 5.6: Macrotexture measured using IP on the Mon-198 group survey sections 13 to 16.

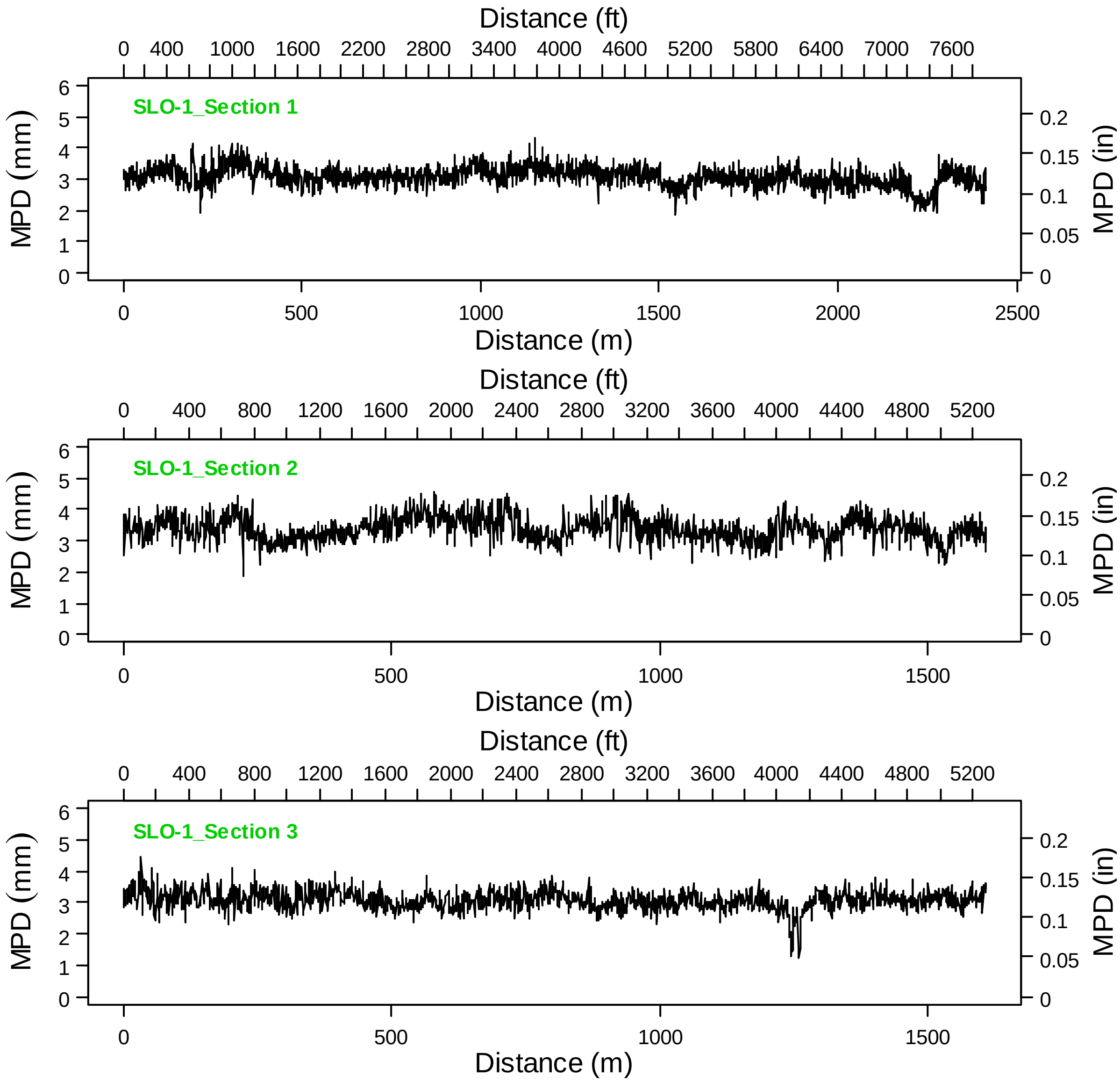


Figure 5.7: Macrotexture measured using IP on the SLO-1 group survey sections 1 to 3, ETW, prior to remedial treatment.

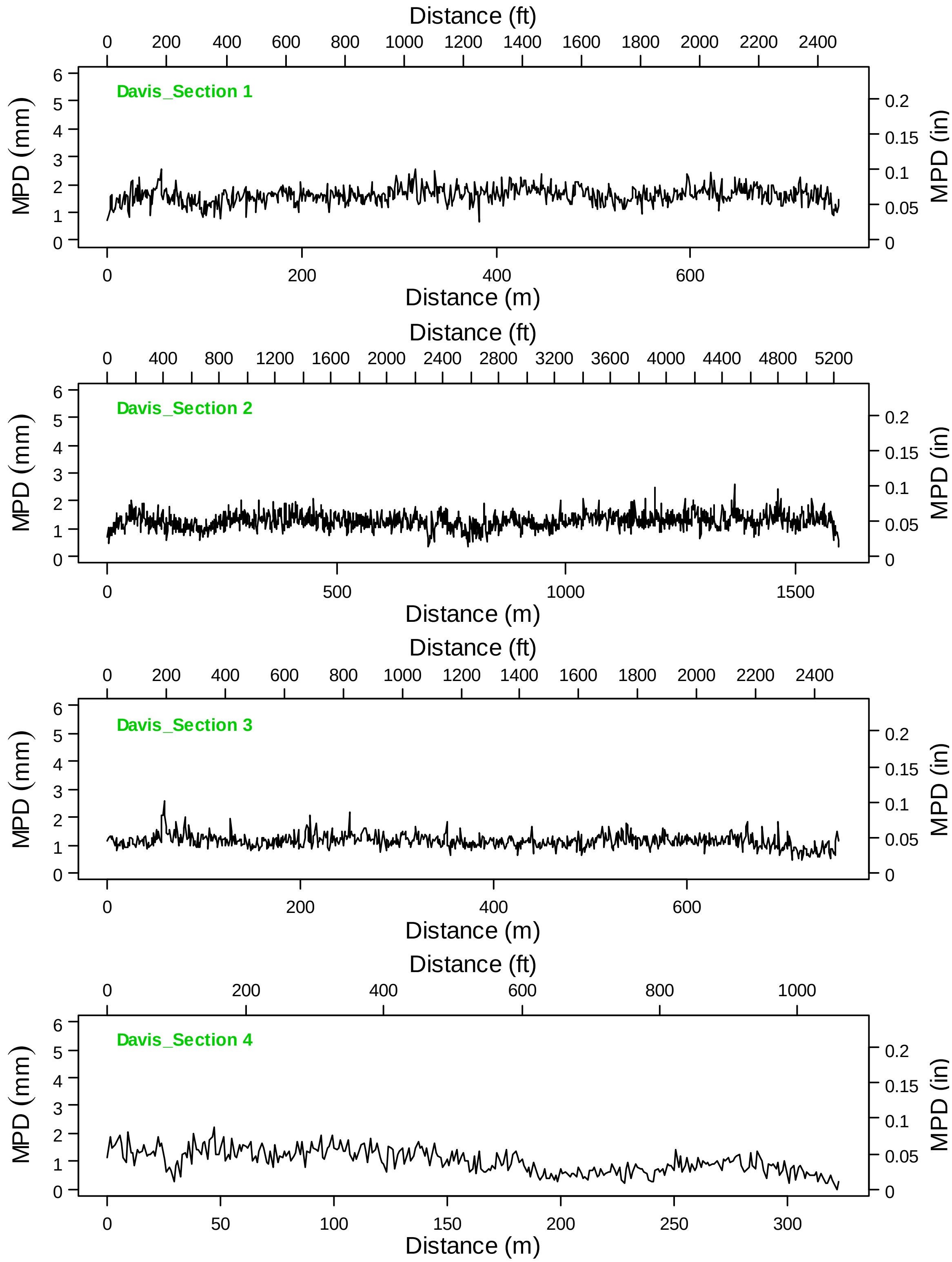


Figure 5.8: Macrotexture measured using IP for the Davis group survey sections 1 to 4, ETW.

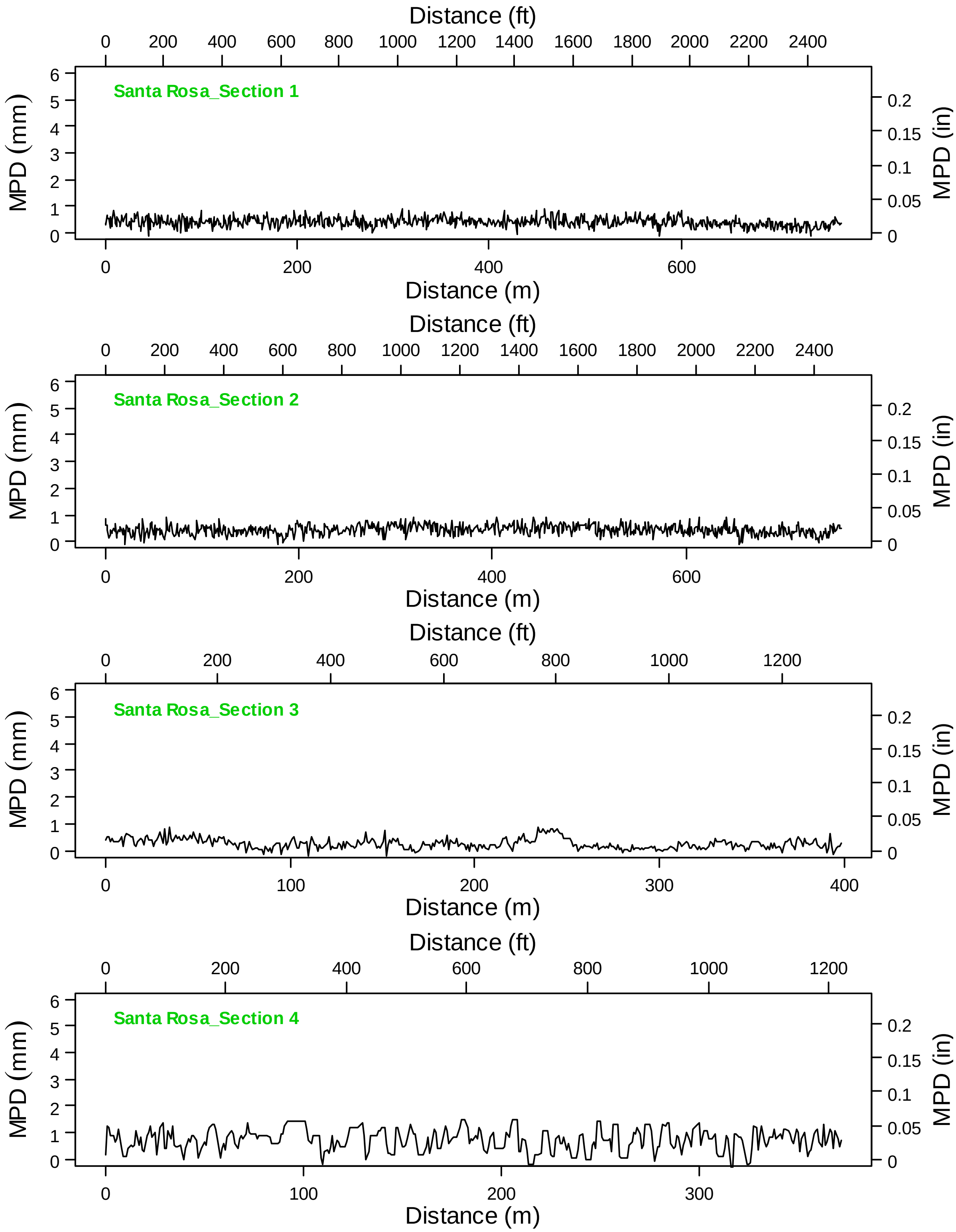
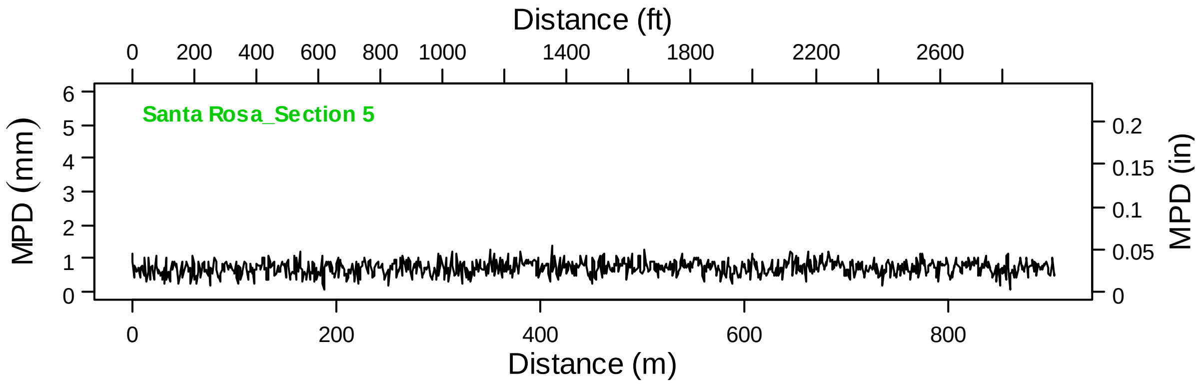


Figure 5.9: Macrotexture measured using IP for the Santa Rosa group survey sections 1 – 4, ETW.



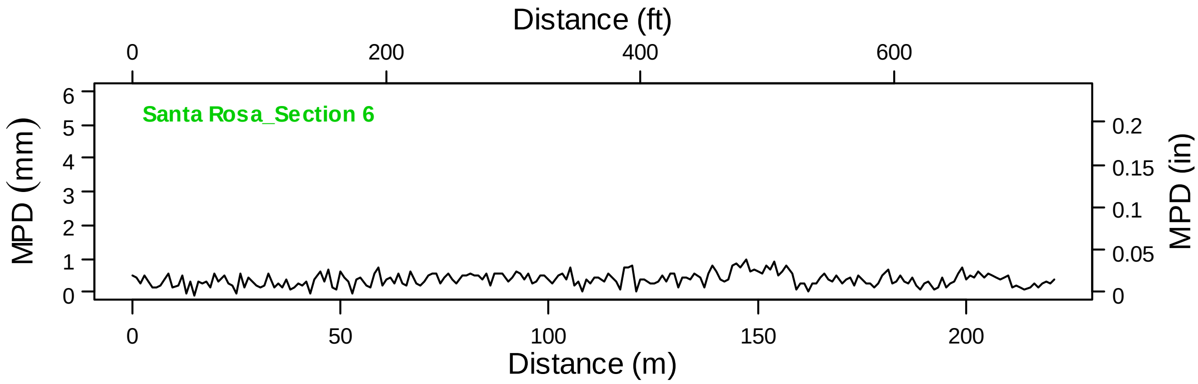


Figure 5.10: Macrotexture measured using IP for the Santa Rosa group survey sections 5 to 6, ETW.

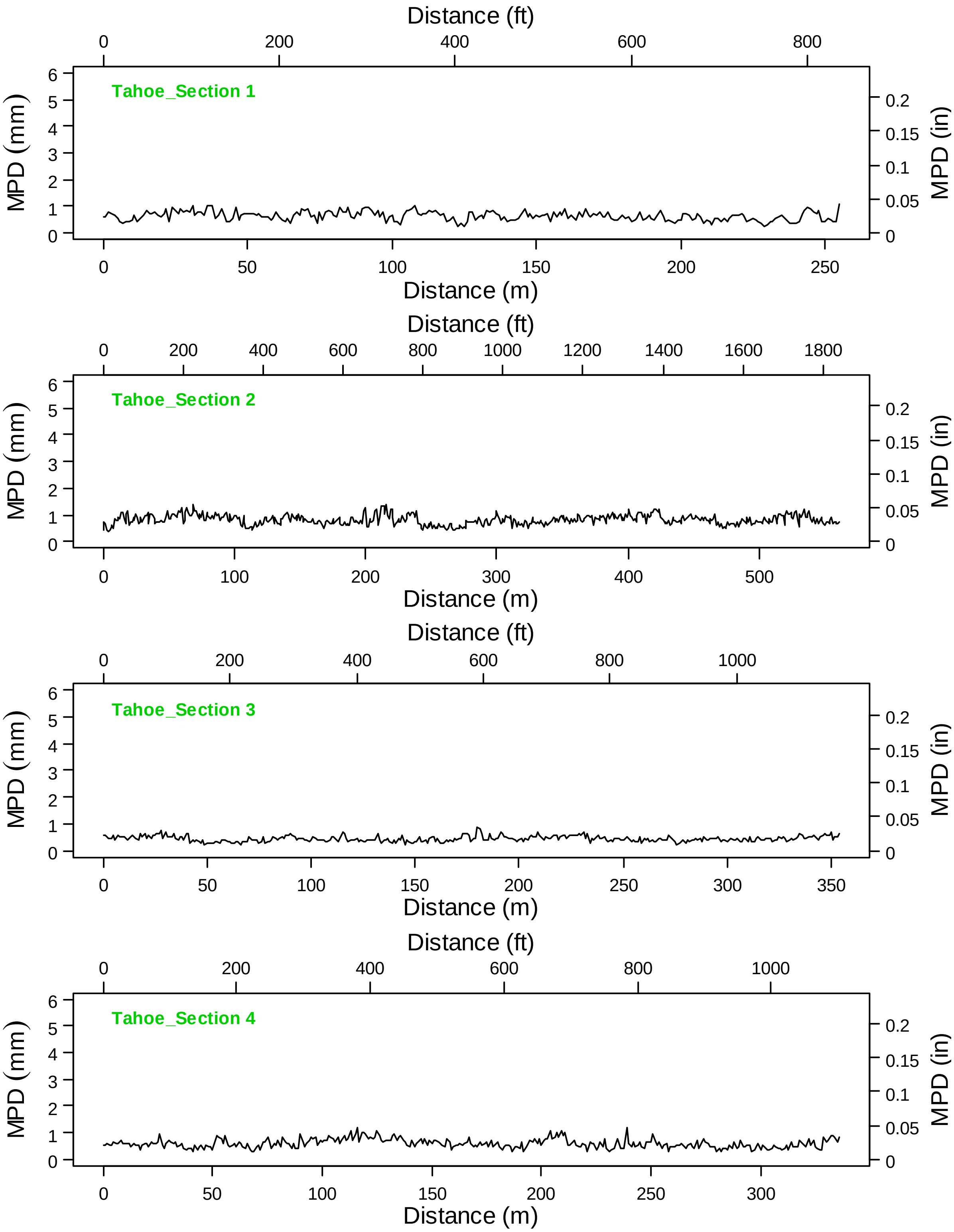


Figure 5.11: Macrotexture measured using IP for the Tahoe group survey sections 1-4, ETW.

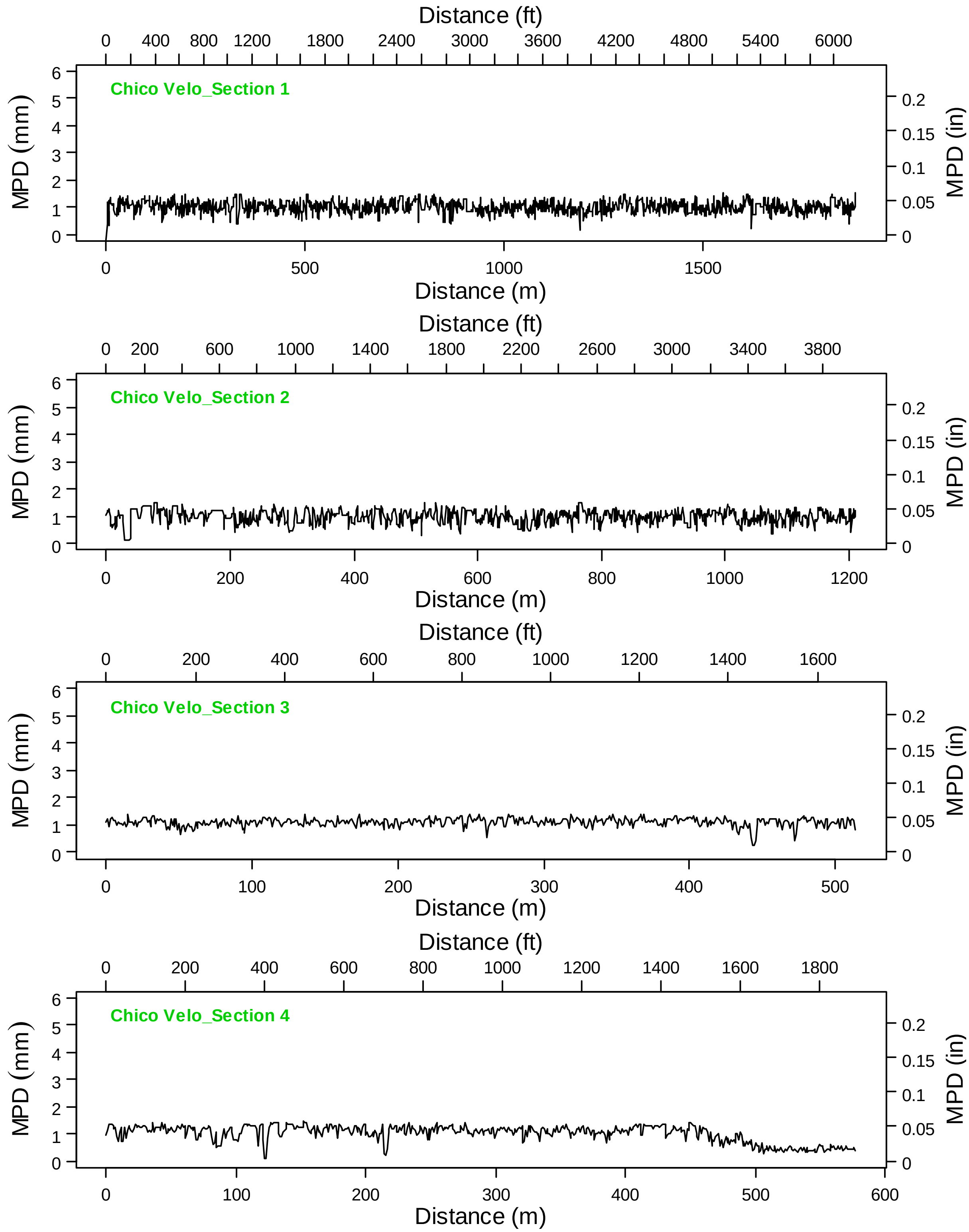


Figure 5.12: Macrotexture measured using IP for the Chico Velo group survey sections 1 to 4, ETW.

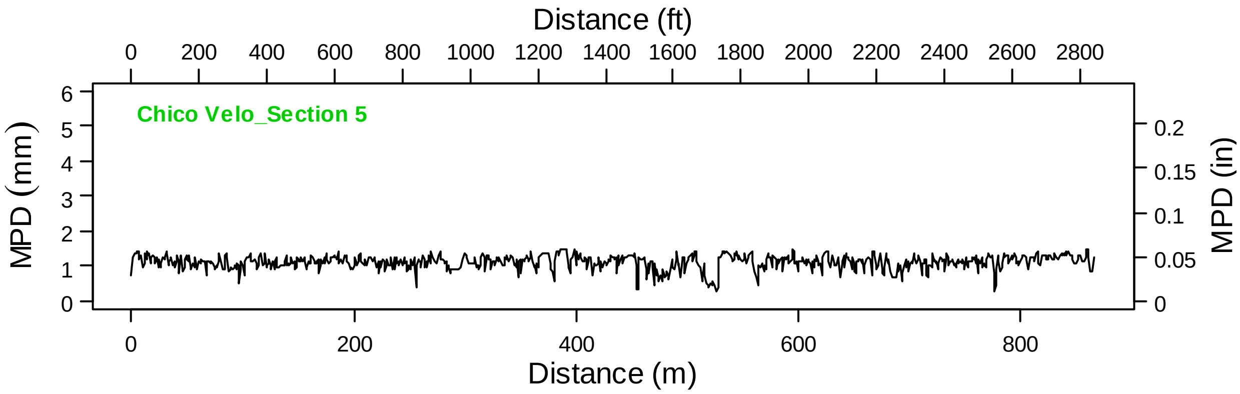


Figure 5.13: Macrotexture measured using IP for Chico Velo group survey section 5, ETW.

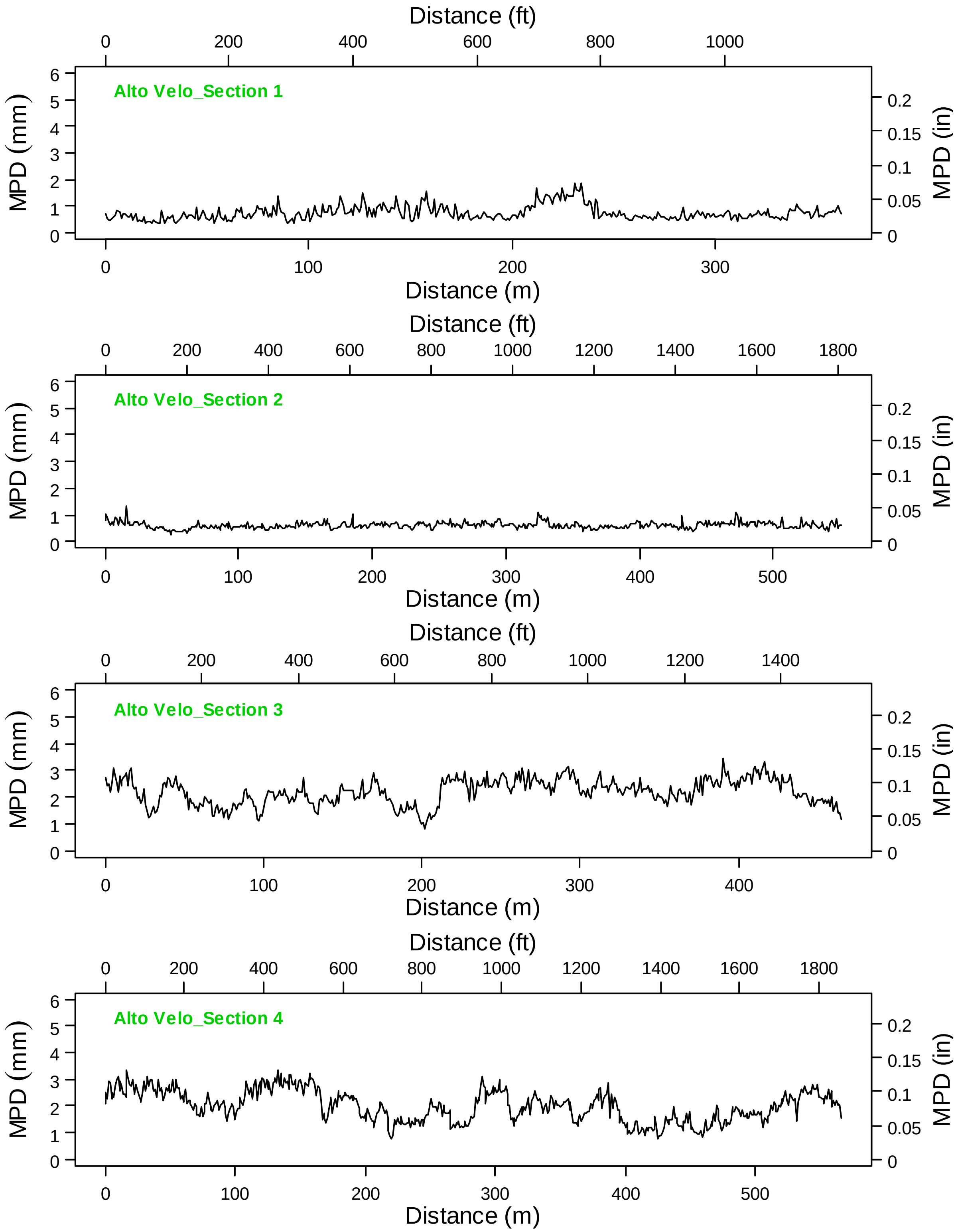


Figure 5.14: Macrotexture measured using IP for the Alto Velo group survey sections 1 to 4, ETW.

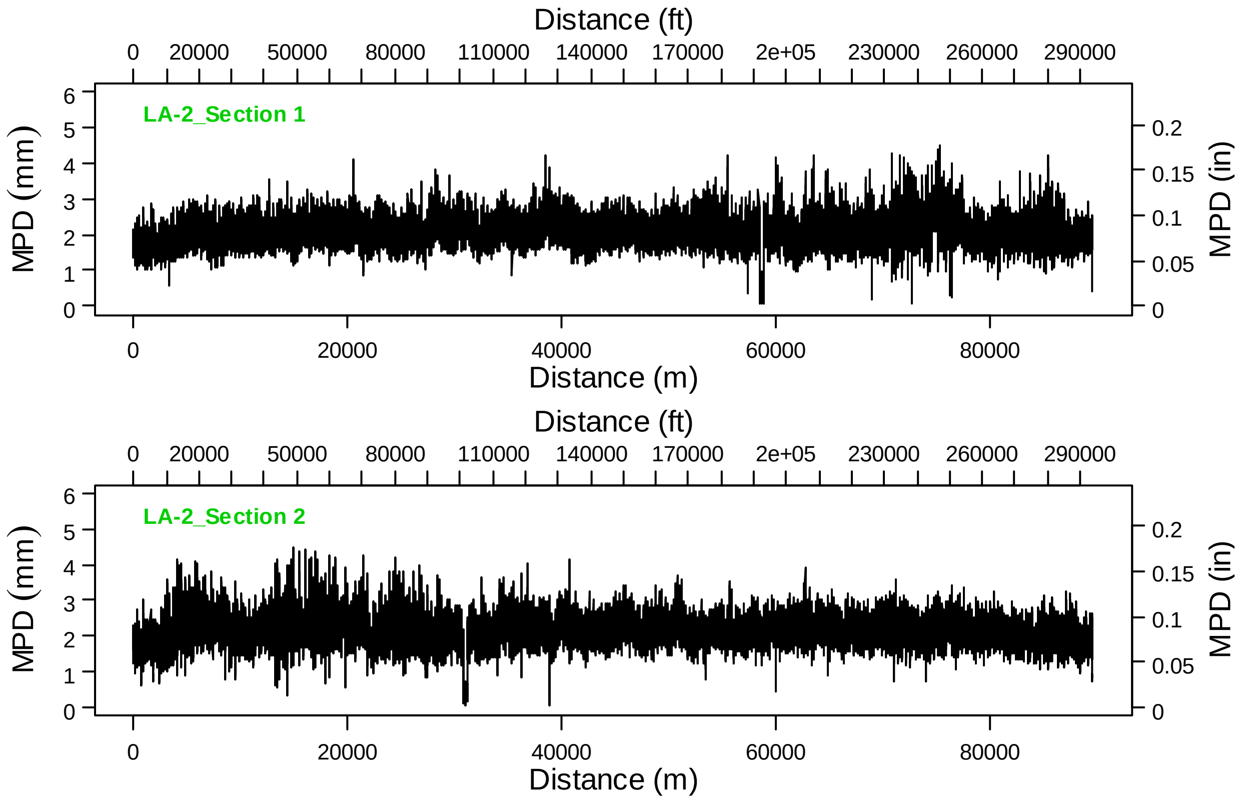


Figure 5.15: Macrotexture measured using IP for the LA-2 sections 1 to 2, ETW.

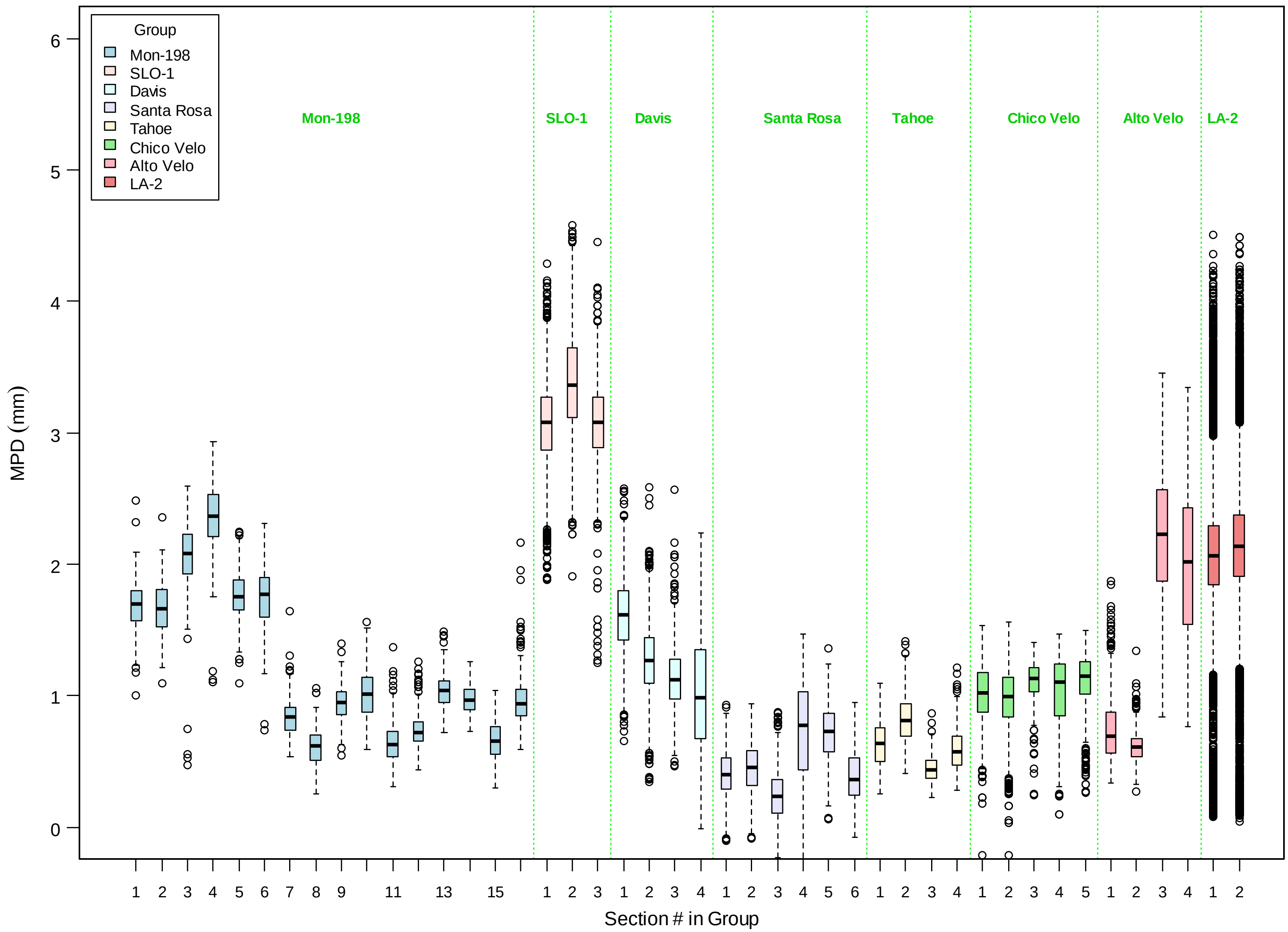


Figure 5.16: Summary boxplot of macrotexture measured using IP for survey sections of all groups (also see Figure 5.32.) *(Note:* the Mon-198 group consists of the Mon-198 *test sections*).

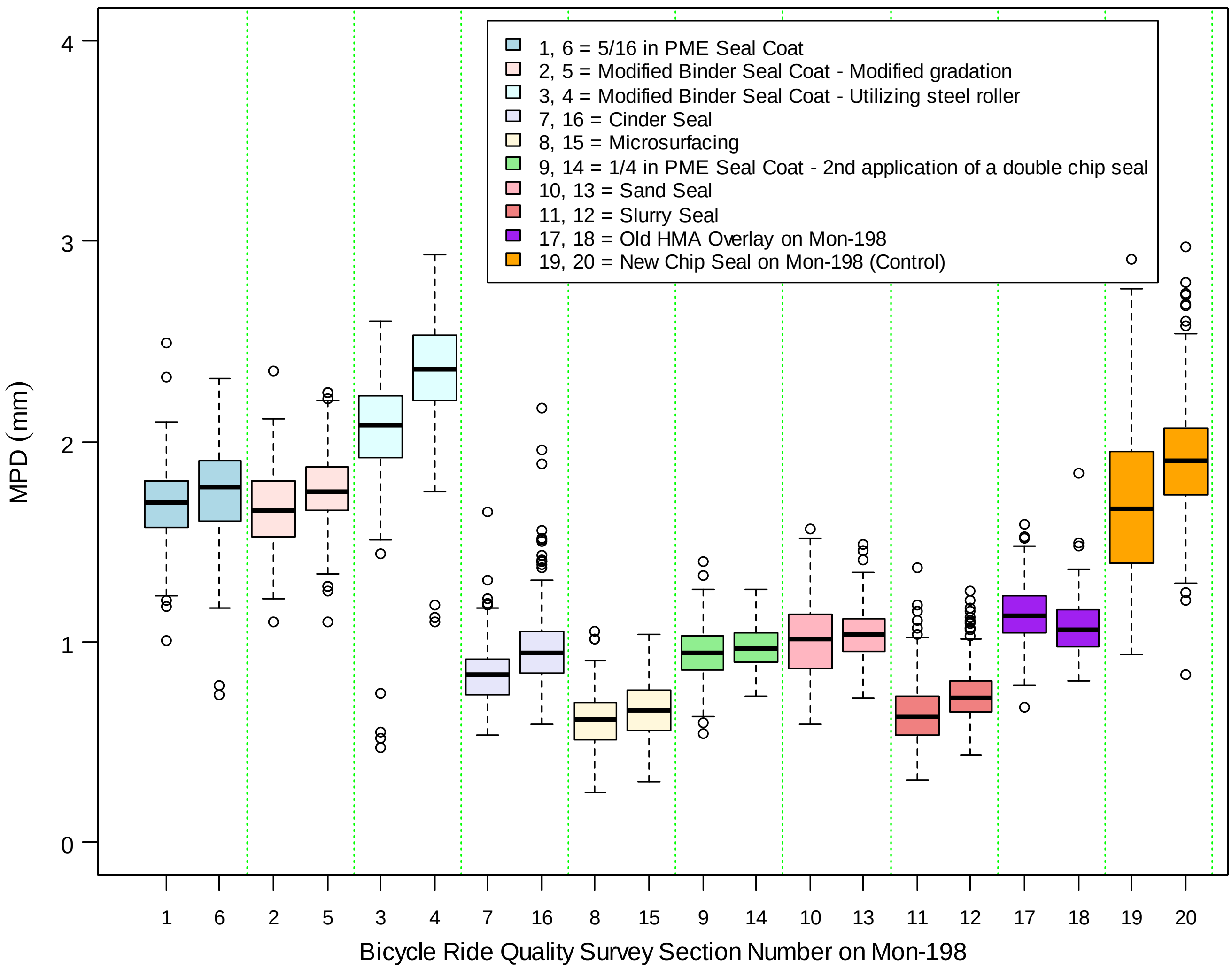


Figure 5.17: MPD measured with IP for the edge of traveled way (ETW, box on the left) and the left wheelpath (box on the right) for each of the Mon-198 treatment sections.
(Note: **see Table 3.4 for treatment descriptions.)**

Table 5.3: Summary Macrotexture Measurements Using IP for Survey Sections for All Groups

Group	Section	N	Mean	Std.Dev.	Min	Q1	Median	Q3	Max
Mon-198 [a]	1	314	1.690	0.188	1.005	1.572	1.696	1.802	2.489
Mon-198	2	304	1.664	0.195	1.097	1.530	1.658	1.804	2.355
Mon-198	3	304	2.060	0.275	0.472	1.924	2.085	2.226	2.598
Mon-198	4	304	2.362	0.263	1.103	2.209	2.362	2.528	2.932
Mon-198	5	304	1.765	0.181	1.097	1.657	1.751	1.877	2.245
Mon-198	6	314	1.756	0.220	0.740	1.603	1.769	1.902	2.311
Mon-198	7	304	0.833	0.139	0.534	0.735	0.835	0.913	1.646
Mon-198	8	309	0.608	0.133	0.252	0.513	0.616	0.701	1.054
Mon-198	9	315	0.944	0.129	0.542	0.859	0.944	1.031	1.401
Mon-198	10	303	1.007	0.182	0.590	0.872	1.014	1.137	1.561
Mon-198	11	309	0.644	0.159	0.308	0.534	0.631	0.732	1.368
Mon-198	12	309	0.737	0.132	0.437	0.653	0.724	0.803	1.255
Mon-198	13	303	1.038	0.131	0.720	0.953	1.038	1.118	1.488
Mon-198	14	315	0.975	0.107	0.729	0.898	0.971	1.045	1.260
Mon-198	15	309	0.663	0.138	0.300	0.558	0.658	0.762	1.041
Mon-198	16	304	0.968	0.196	0.591	0.847	0.944	1.051	2.169
SLO-1	1	2,414	3.070	0.320	1.884	2.871	3.075	3.269	4.288
SLO-1	2	1,609	3.386	0.408	1.904	3.117	3.360	3.649	4.577
SLO-1	3	1,609	3.077	0.317	1.250	2.888	3.077	3.268	4.452
Davis	1	754	1.617	0.298	0.659	1.426	1.617	1.799	2.580
Davis	2	1,596	1.271	0.277	0.346	1.093	1.267	1.444	2.583
Davis	3	758	1.141	0.247	0.465	0.981	1.126	1.275	2.563
Davis	4	324	1.012	0.430	-0.014	0.671	0.981	1.348	2.242
Santa Rosa	1	768	0.410	0.179	-0.100	0.289	0.404	0.529	0.932
Santa Rosa	2	761	0.450	0.189	-0.089	0.321	0.456	0.580	0.940
Santa Rosa	3	399	0.257	0.197	-0.229	0.106	0.236	0.360	0.874
Santa Rosa	4	373	0.723	0.410	-0.303	0.434	0.775	1.030	1.472
Santa Rosa	5	906	0.716	0.210	0.060	0.572	0.725	0.863	1.356
Santa Rosa	6	222	0.381	0.198	-0.080	0.242	0.366	0.527	0.951
Tahoe	1	256	0.635	0.174	0.249	0.501	0.637	0.758	1.097
Tahoe	2	562	0.821	0.182	0.410	0.695	0.811	0.943	1.417
Tahoe	3	355	0.444	0.106	0.227	0.372	0.434	0.510	0.868
Tahoe	4	337	0.591	0.172	0.285	0.474	0.571	0.691	1.215
Chico Velo	1	1,885	1.022	0.216	-0.213	0.878	1.023	1.173	1.533
Chico Velo	2	3,028	0.982	0.225	-0.211	0.839	0.997	1.144	1.564
Chico Velo	3	515	1.110	0.155	0.240	1.029	1.132	1.214	1.408
Chico Velo	4	578	1.012	0.305	0.100	0.848	1.102	1.241	1.467
Chico Velo	5	868	1.116	0.208	0.259	1.013	1.148	1.258	1.494
Alto Velo	1	363	0.759	0.275	0.336	0.568	0.691	0.875	1.870
Alto Velo	2	552	0.616	0.122	0.272	0.536	0.607	0.678	1.346
Alto Velo	3	466	2.201	0.481	0.840	1.873	2.230	2.561	3.455
Alto Velo	4	567	1.999	0.576	0.769	1.544	2.017	2.431	3.343
LA-2 [b]	1	89,572	2.078	0.378	0.076	1.843	2.061	2.296	4.509
LA-2 [b]	2	89,581	2.140	0.387	0.039	1.904	2.134	2.372	4.486

Notes:
Measured at ETW for roads with shoulder, otherwise at wheelpath.
[a.] Mon-198 group is for *test sections* on Mon-198.
[b.] Only texture measurement was performed for LA-2.

5.4.2 *Correlation of Macrotexture Measurements with IP and LTS*

The macrotexture (i.e., MPD) of some sections (20 sections on Mon-198 and 3 sections on SLO-1; refer to Table 3.2 and Table 3.4 for details on the pavement treatment materials) was measured using both the IP and the LTS. The data from both devices was used to establish a correlation between their measurements. The mean MPD data for each of the sections measured with the IP and the LTS are plotted in Figure 5.18 and, as can be seen, a very good linear relationship was found between them. This relationship can be modeled with the following equation:

$$MPD\_IP = 0.97\ MPD\_LTS \quad (R^2 = 0.93) \tag{5.1}$$

where, MPD_IP is the macrotexture MPD value measured with IP, in mm or in. and
MPD_LTS is the macrotexture MPD value measured with LTS, in mm or in.

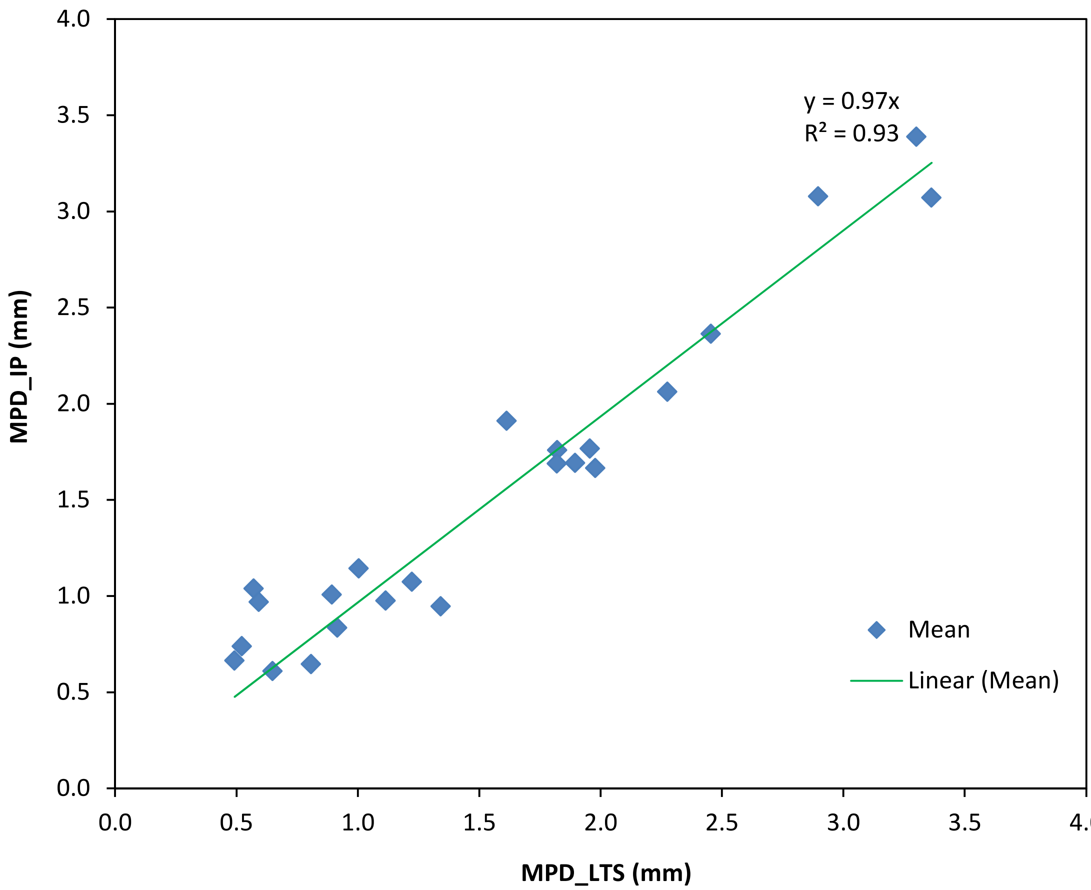


Figure 5.18: Correlation of macrotexture measurements with IP and LTS.

5.5 IRI Measurement Results

IRI measurements (i.e., roughness or unevenness) along the entire length of each pavement section (see Table 5.2 for details on each section) are presented in Figure 5.19 through Figure 5.31. It can be seen from the figures that the IRI values of most sections are in the range of approximately 1.0 m/km to 5.0 m/km (62 in./mile to 310 in./mile), but the IRI values of a few sections (Santa Rosa section 1, Chico Velo sections 1 and 2, and Alto Velo section 2) are larger than 5.0 m/km and show even larger variations within the entire section. The IRI of each section for all the groups are summarized using a boxplot in Figure 5.32 and in Table 5.4. The mean IRI values for all the sections are in the range of approximately 1.5 m/km to 9.3 m/km (93 in./mile to 558 in./mile).

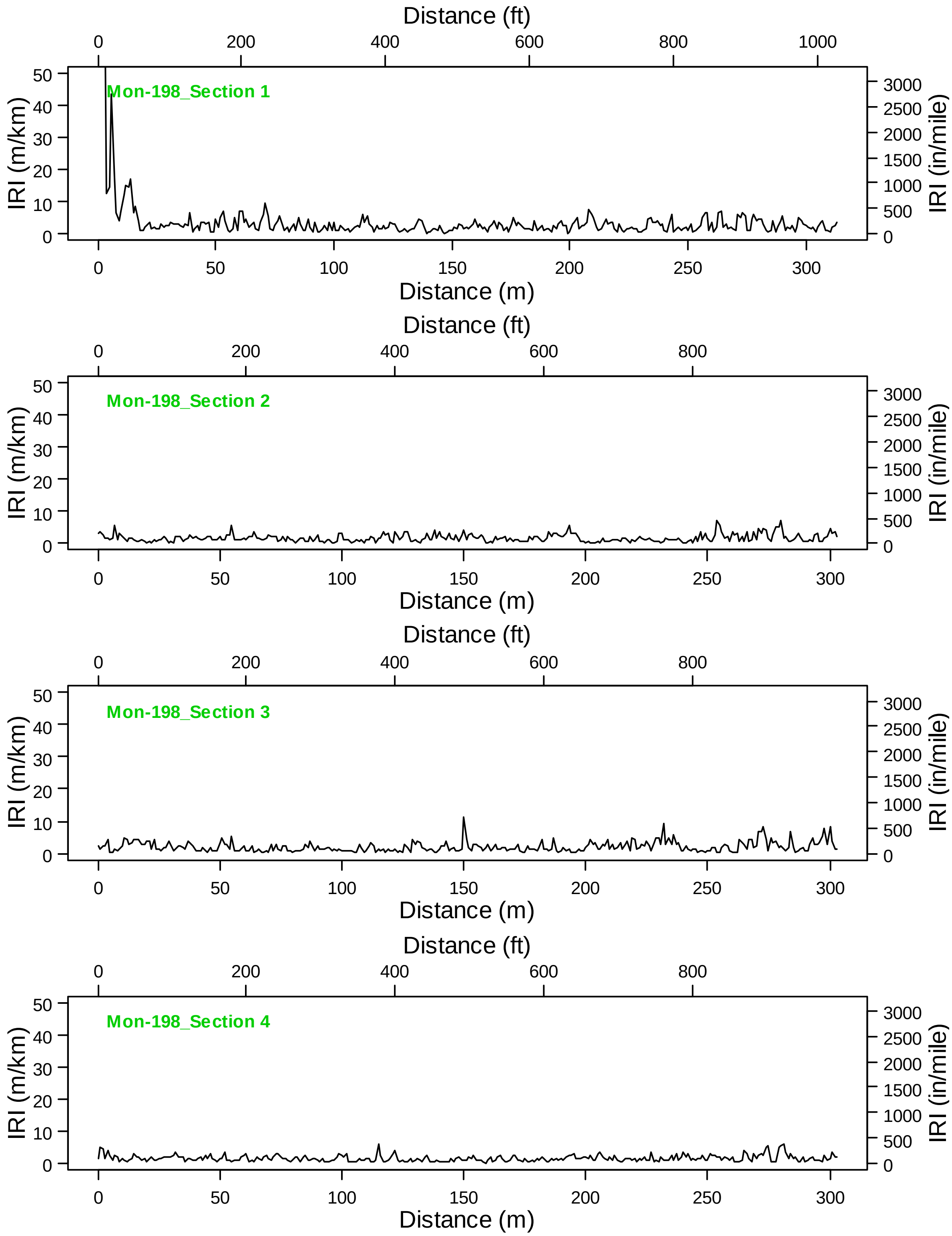


Figure 5.19: IRI of the Mon-198 group survey sections 1 to 4.

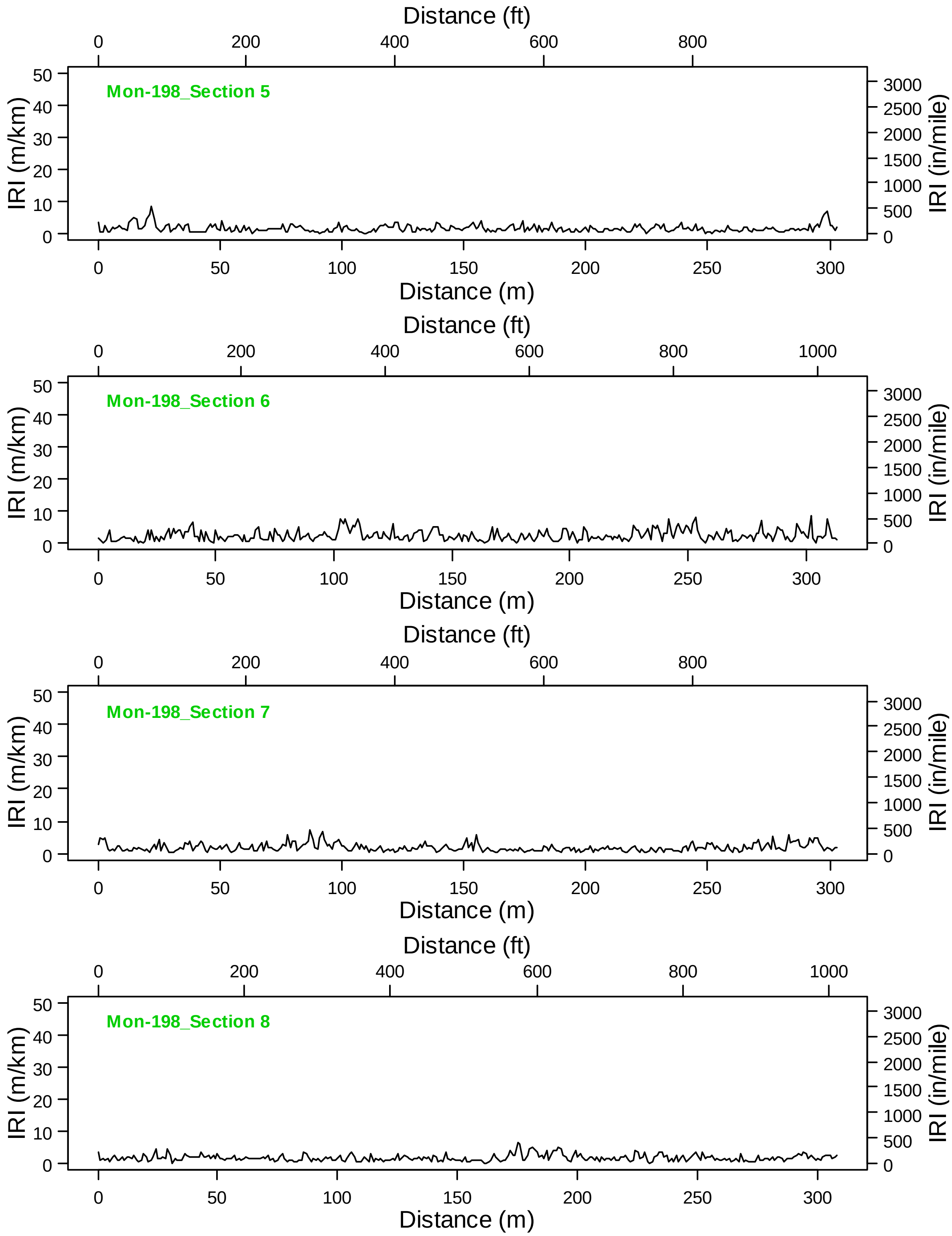


Figure 5.20: IRI of the Mon-198 group survey sections 5 to 8.

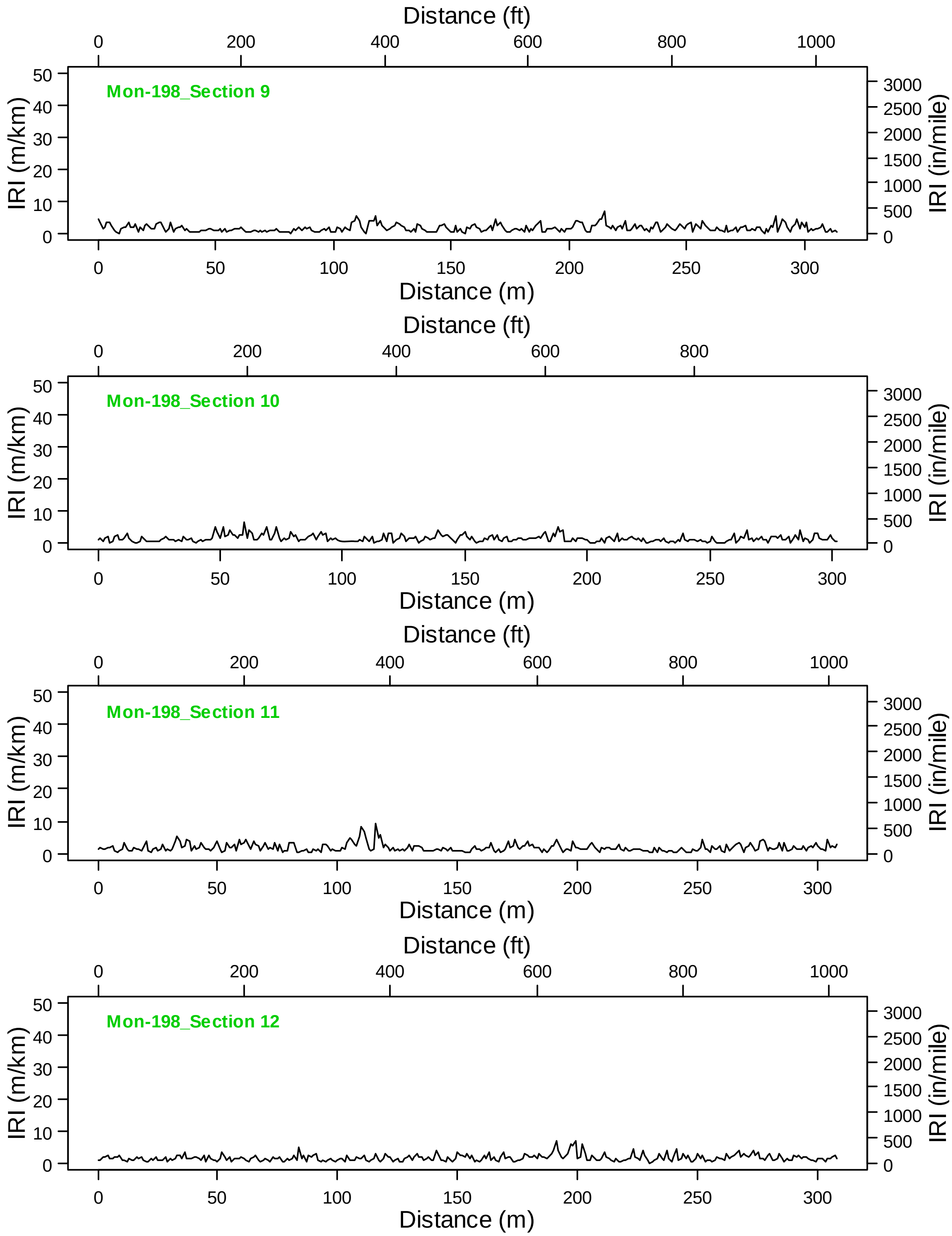


Figure 5.21: IRI of the Mon-198 group survey sections 9 to 12.

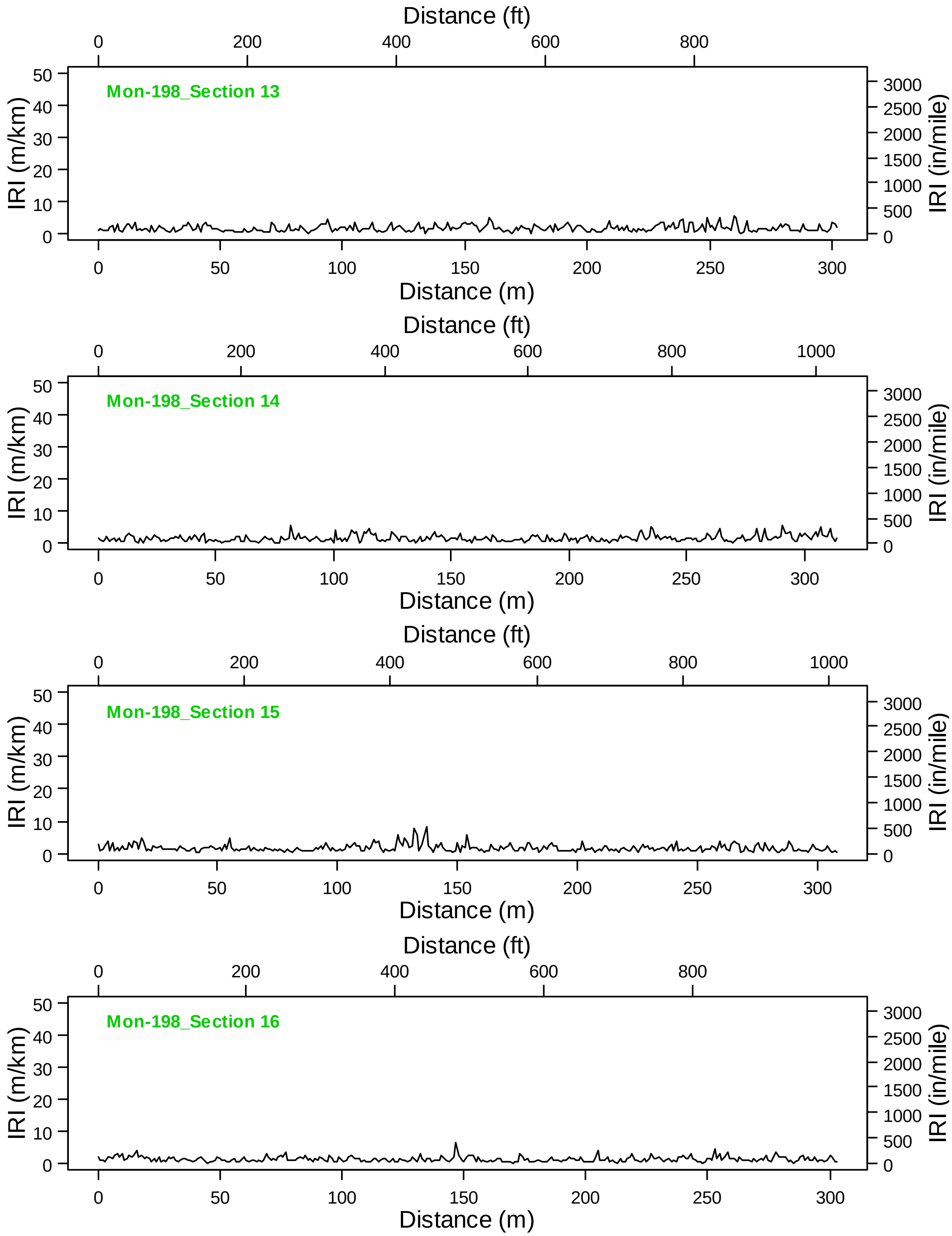


Figure 5.22: IRI of the Mon-198 group survey sections 13 to 16.

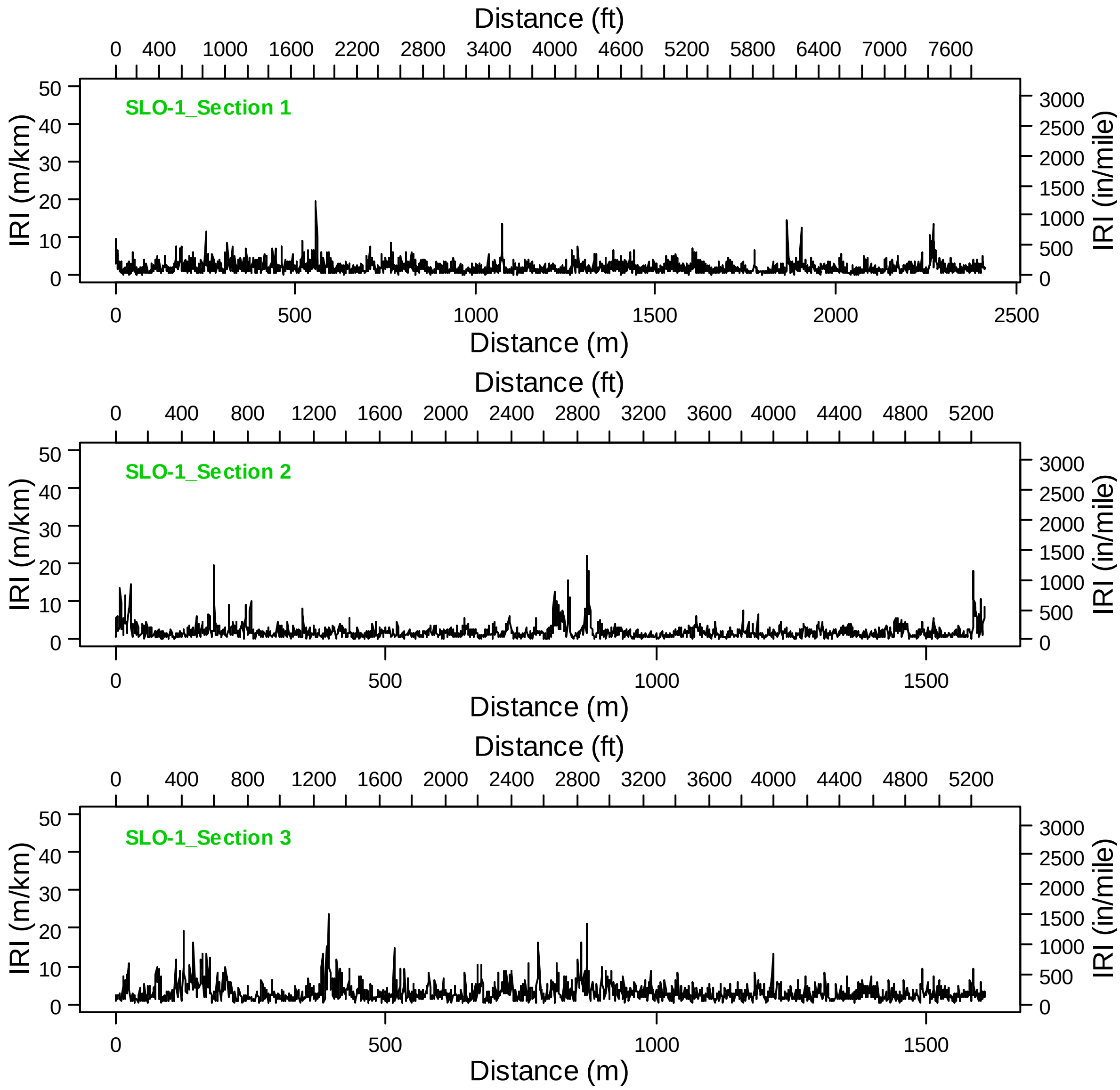


Figure 5.23: IRI of the survey sections in the SLO-1 group, sections 1 to 3.

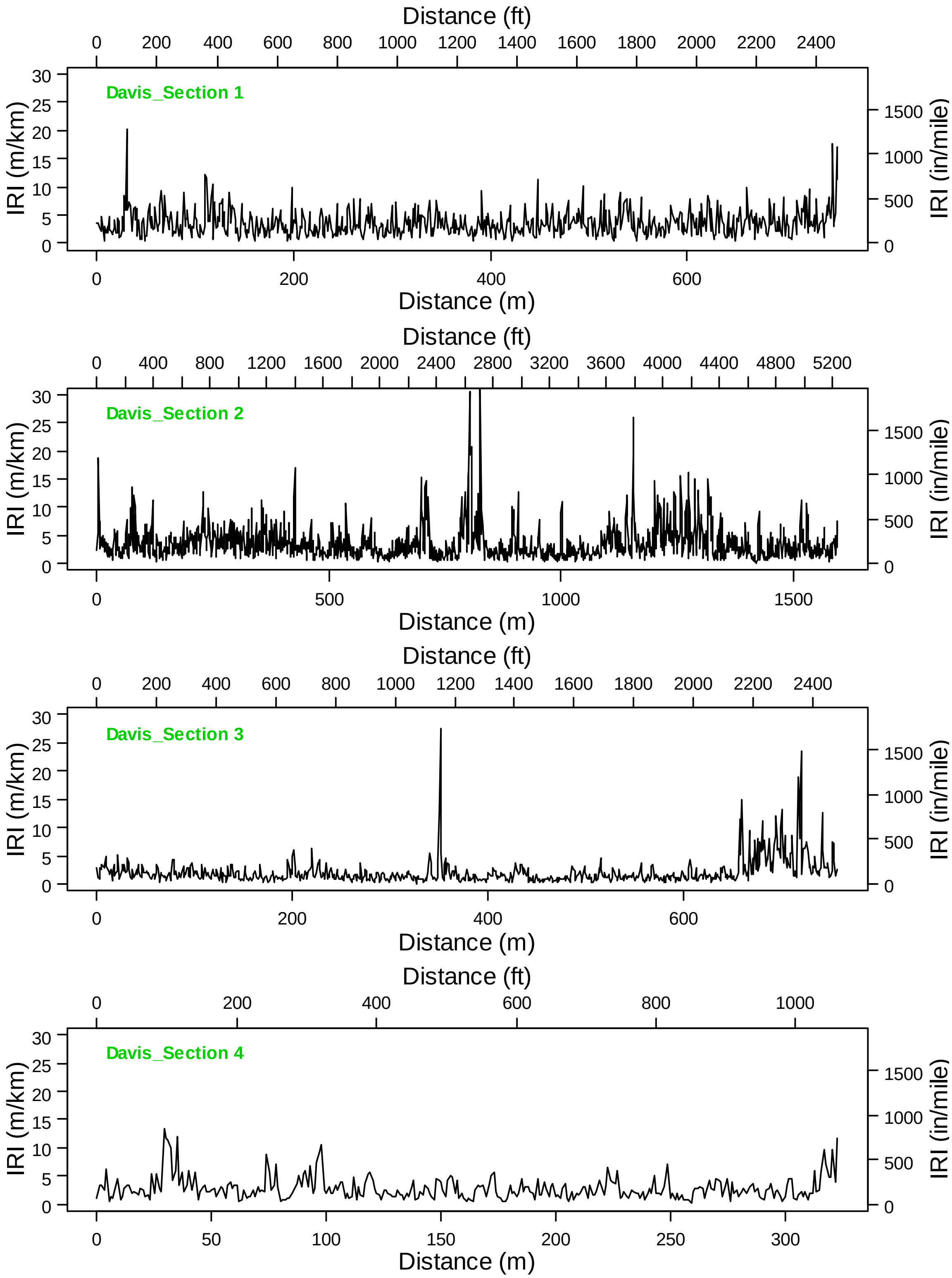


Figure 5.24: IRI of the survey sections in the Davis group, sections 1 to 4.

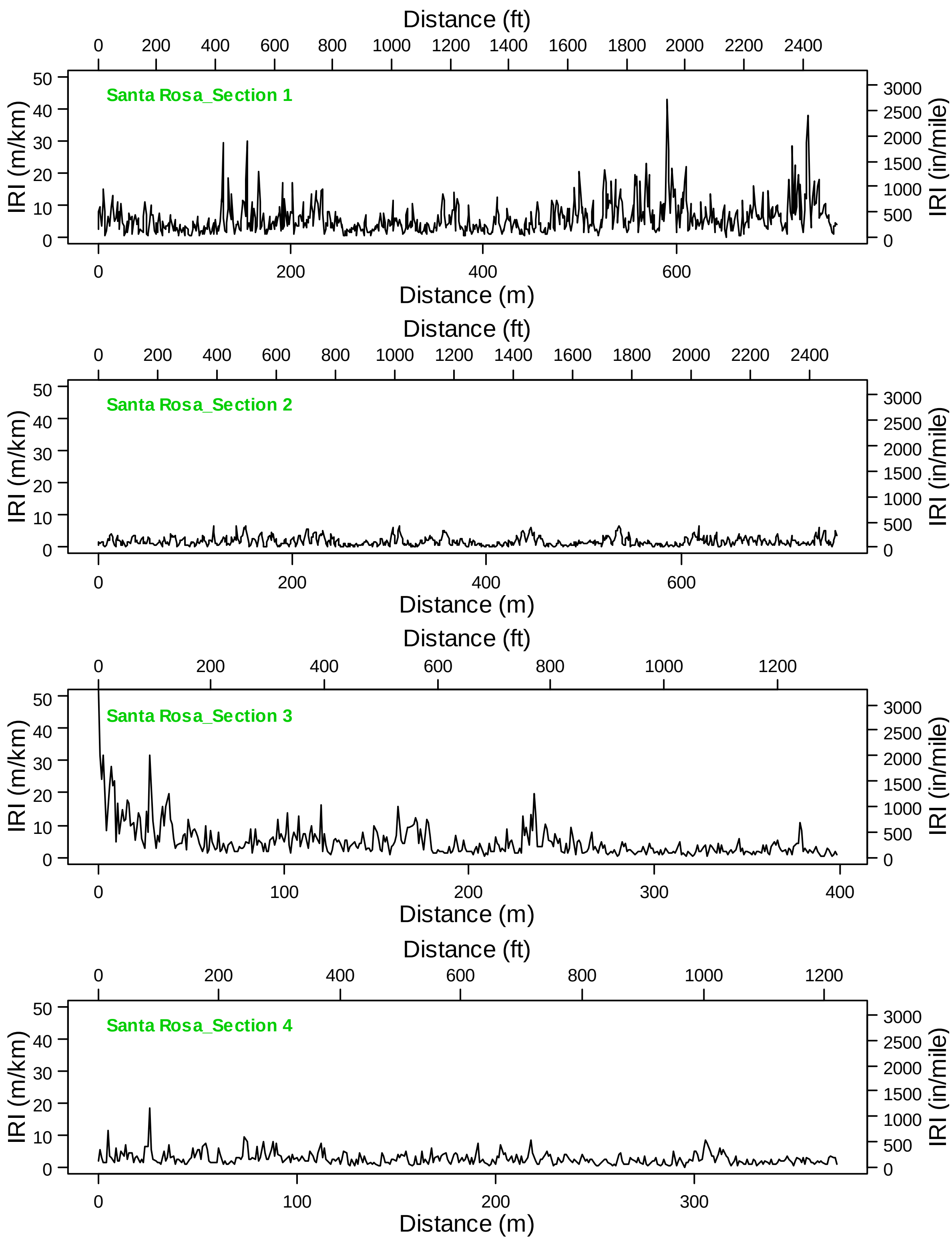


Figure 5.25: IRI of survey sections in the Santa Rosa group, sections 1 to 4.

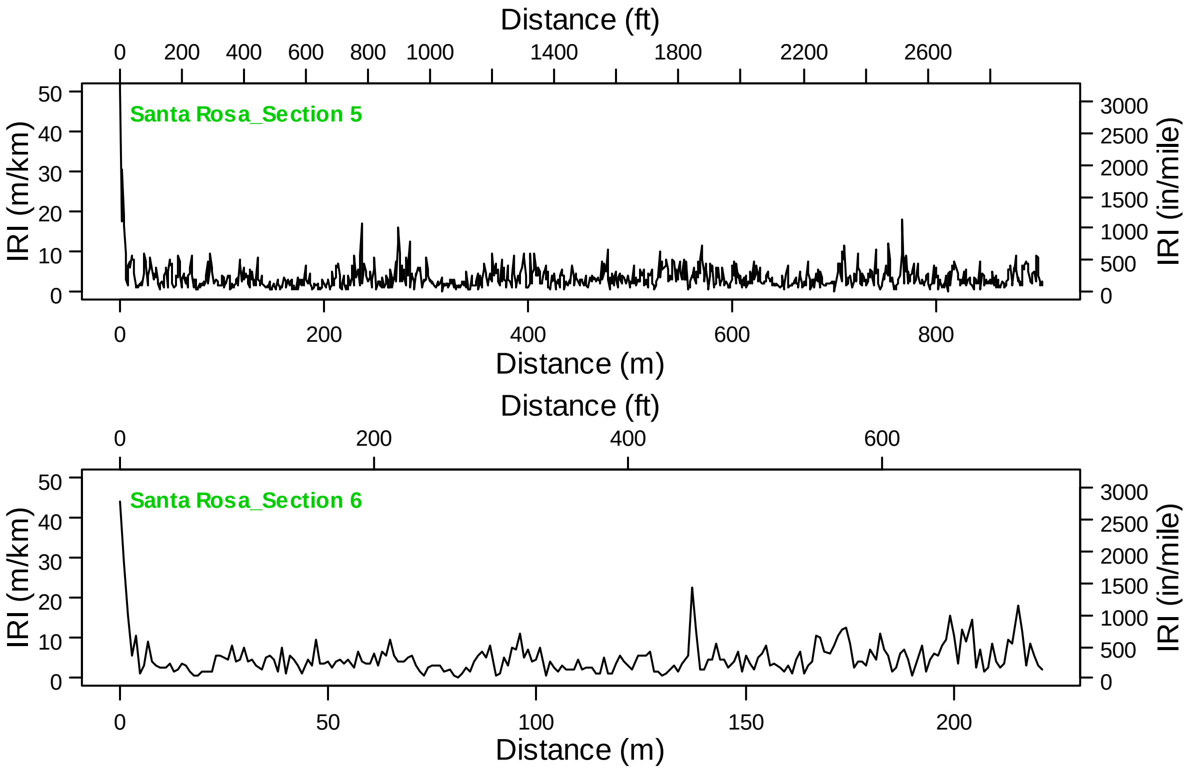


Figure 5.26: IRI of survey sections in the Santa Rosa group, sections 5 to 6.

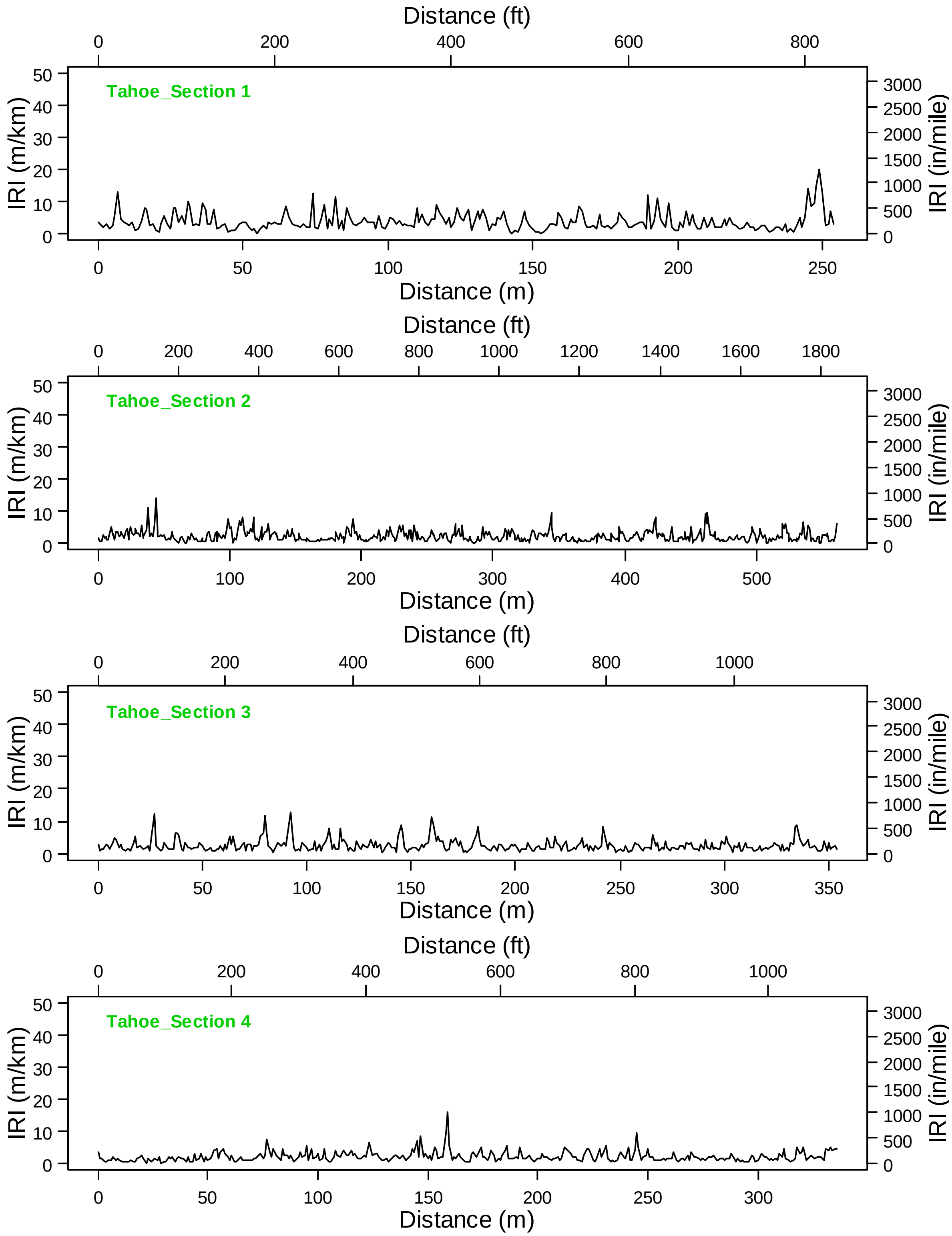


Figure 5.27: IRI of survey sections in the Tahoe group, sections 1 to 4.

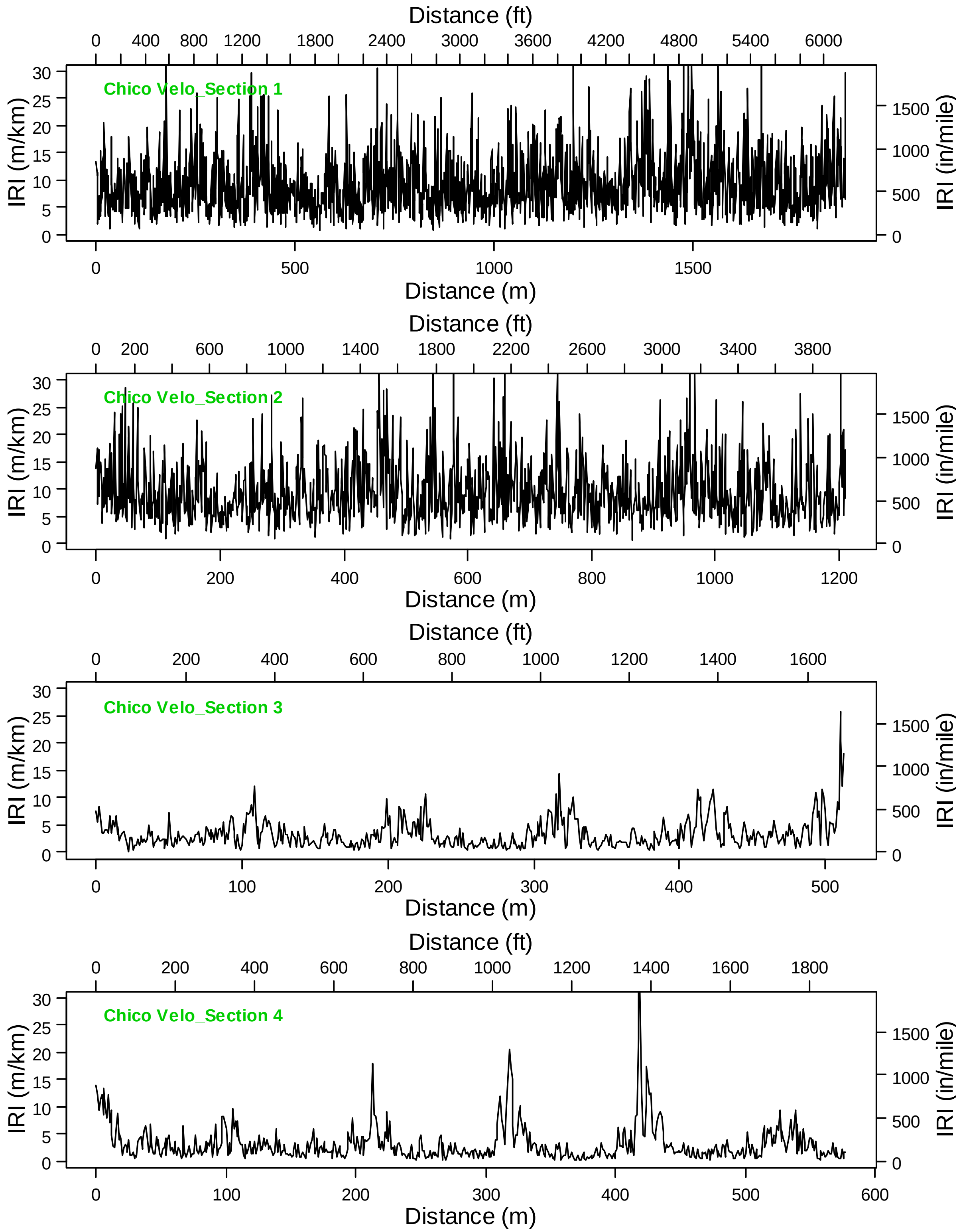


Figure 5.28: IRI of survey sections in the Chico Velo group, sections 1 to 4.

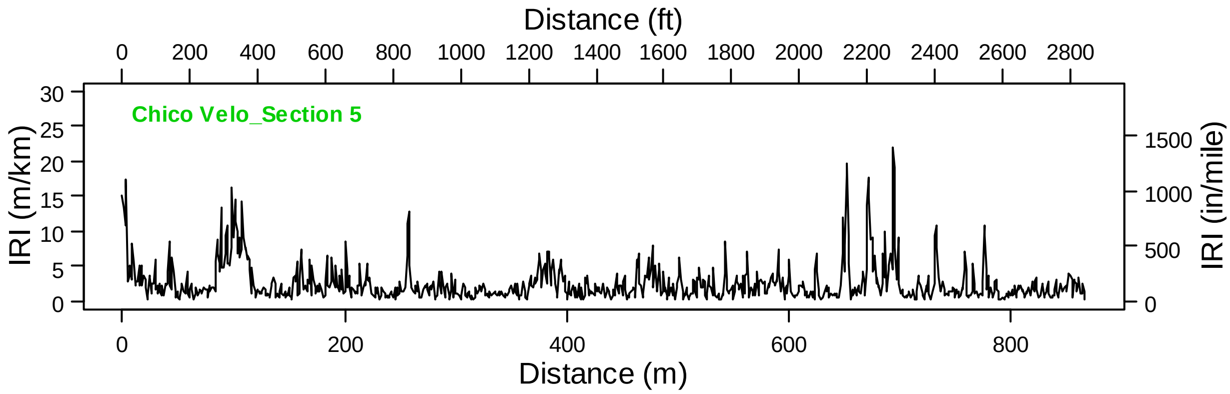


Figure 5.29: IRI of survey sections in the Chico Velo group, section 5.

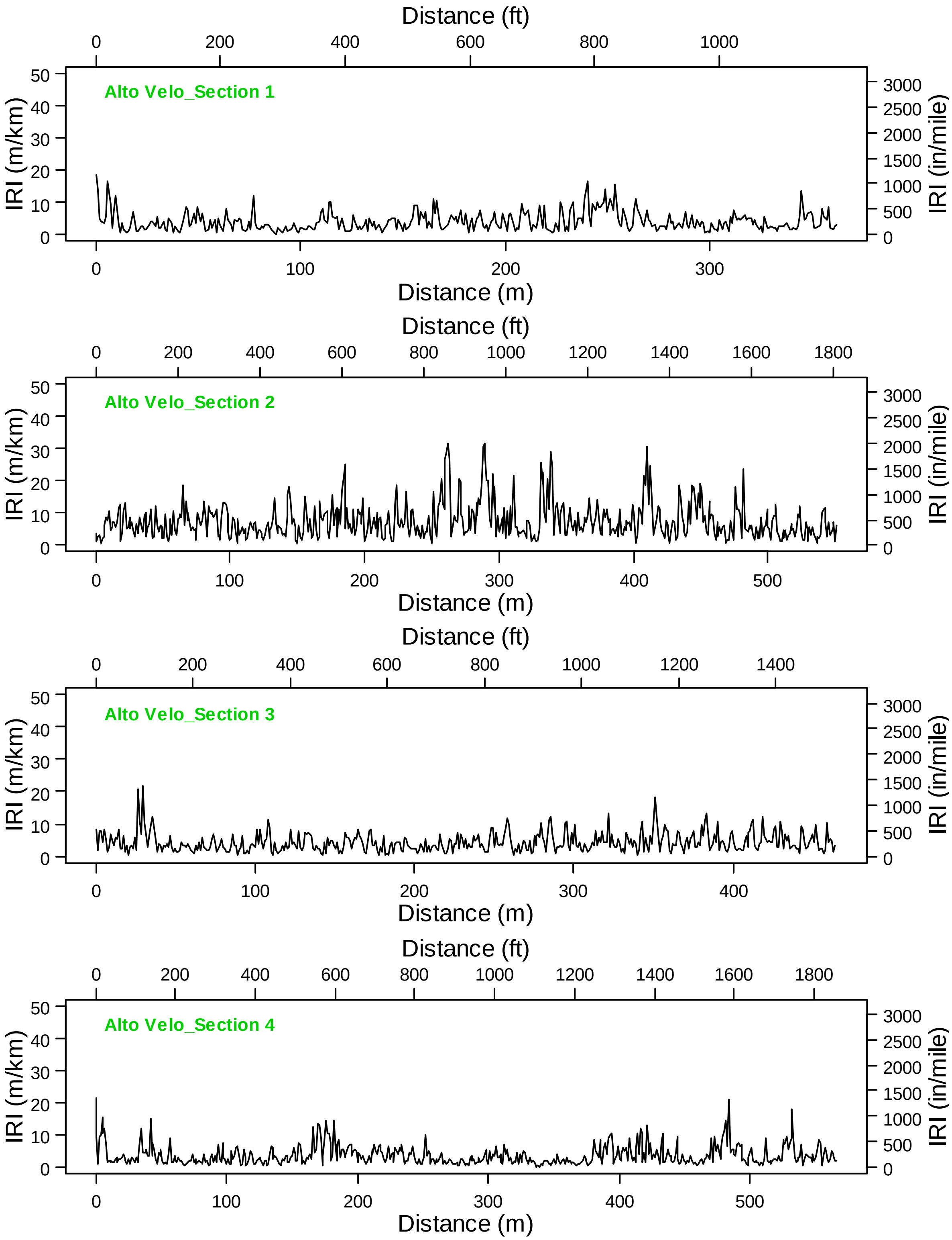


Figure 5.30: IRI of survey sections in the Alto Velo group, sections 1 to 4.

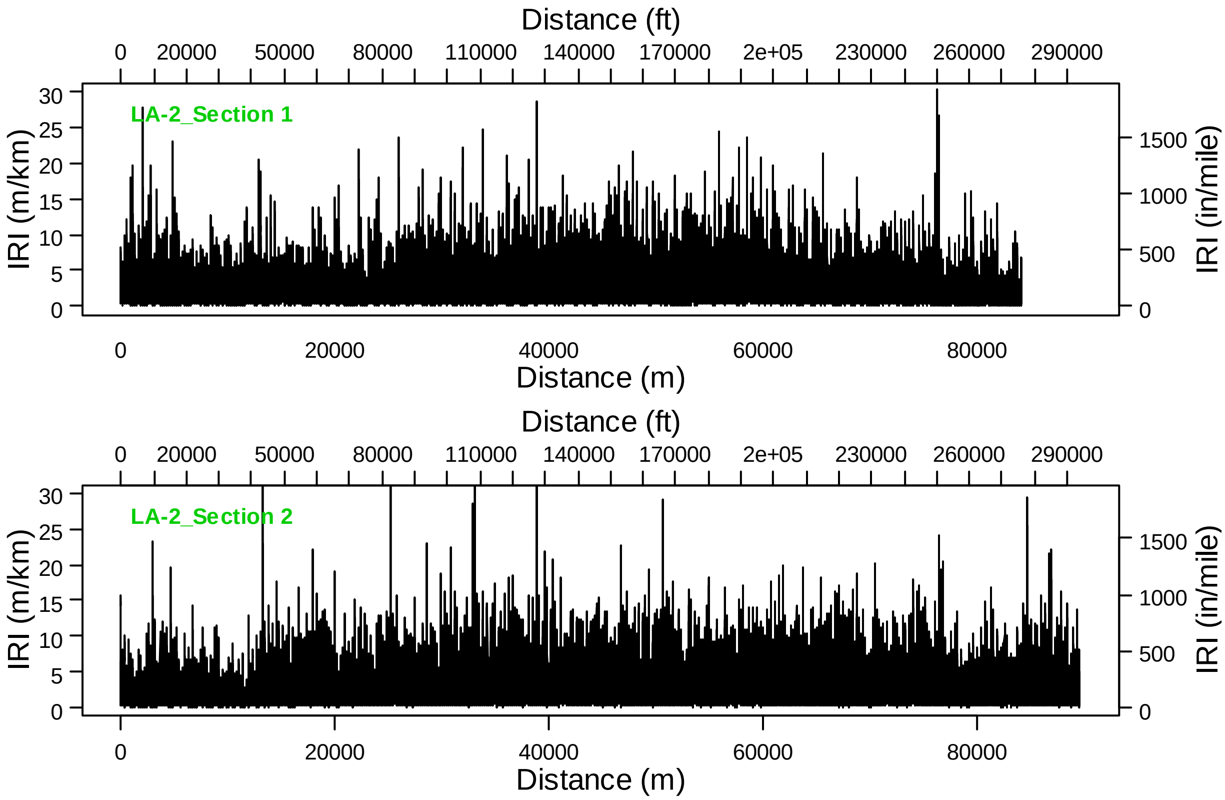


Figure 5.31: IRI of survey sections in the LA-2, sections 1 to 2.

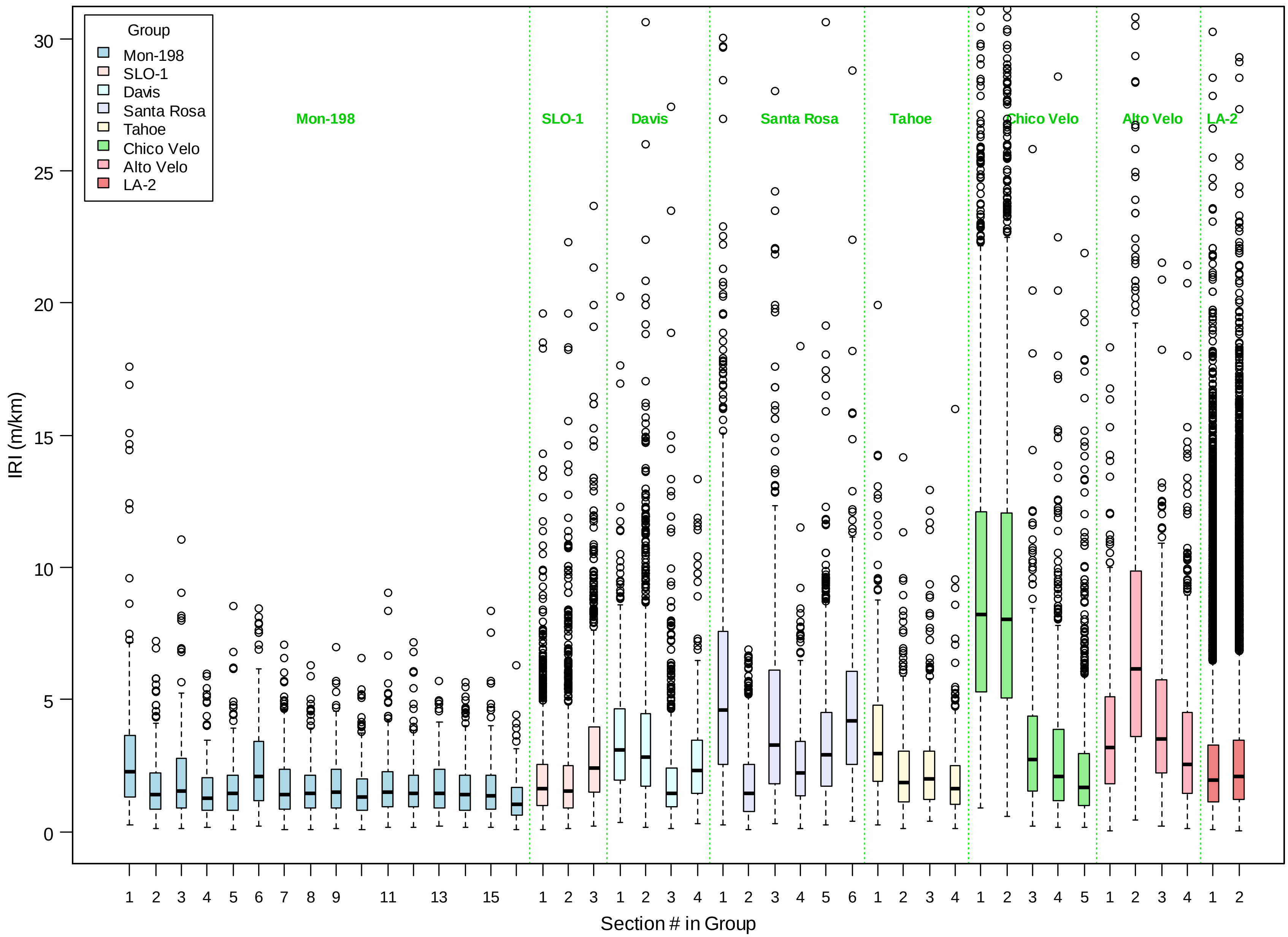


Figure 5.32: Summary boxplot of IRI for all the survey sections in all groups.
(*Note:* the Mon-198 group consists of the Mon-198 *test sections*).

Table 5.4: Summary of IRI for Each Survey Section in All Groups

Group	Section	N	Mean	Std.Dev.	Min	Q1	Median	Q3	Max
Mon-198 [a]	1	314	4.342	12.898	0.270	1.323	2.275	3.660	149.6
Mon-198	2	304	1.714	1.220	0.120	0.870	1.385	2.213	7.220
Mon-198	3	304	2.041	1.622	0.140	0.885	1.535	2.763	11.070
Mon-198	4	304	1.525	1.011	0.160	0.790	1.290	2.030	5.980
Mon-198	5	304	1.667	1.136	0.100	0.828	1.450	2.113	8.520
Mon-198	6	314	2.510	1.695	0.210	1.173	2.105	3.430	8.430
Mon-198	7	304	1.811	1.241	0.070	0.878	1.420	2.378	7.060
Mon-198	8	309	1.661	1.025	0.090	0.880	1.470	2.120	6.280
Mon-198	9	315	1.795	1.164	0.140	0.895	1.490	2.385	6.970
Mon-198	10	303	1.572	1.068	0.070	0.825	1.310	2.005	6.560
Mon-198	11	309	1.791	1.268	0.150	0.930	1.490	2.270	9.030
Mon-198	12	309	1.671	1.063	0.180	0.960	1.440	2.120	7.150
Mon-198	13	303	1.719	1.049	0.230	0.910	1.450	2.355	5.710
Mon-198	14	315	1.638	1.028	0.160	0.830	1.420	2.115	5.670
Mon-198	15	309	1.658	1.140	0.170	0.870	1.380	2.120	8.370
Mon-198	16	304	1.246	0.827	0.100	0.628	1.045	1.673	6.300
SLO-1	1	2,414	2.020	1.607	0.100	1.000	1.655	2.570	19.610
SLO-1	2	1,609	2.048	1.968	0.120	0.900	1.530	2.500	22.300
SLO-1	3	1,609	3.079	2.435	0.200	1.500	2.430	3.970	23.660
Davis	1	754	3.581	2.260	0.360	1.963	3.075	4.650	20.260
Davis	2	1,596	3.623	3.035	0.170	1.718	2.820	4.490	33.140
Davis	3	757	2.085	2.335	0.120	0.930	1.450	2.410	27.410
Davis	4	324	2.844	2.092	0.320	1.438	2.335	3.475	13.320
Santa Rosa	1	768	5.972	5.069	0.270	2.558	4.615	7.590	42.790
Santa Rosa	2	761	1.838	1.380	0.070	0.780	1.430	2.540	6.900
Santa Rosa	3	399	5.053	5.483	0.330	1.810	3.300	6.135	51.930
Santa Rosa	4	373	2.652	1.939	0.130	1.340	2.220	3.430	18.350
Santa Rosa	5	906	3.700	5.118	0.250	1.740	2.895	4.505	127.020
Santa Rosa	6	222	5.110	4.541	0.410	2.570	4.200	6.053	44.120
Tahoe	1	255	3.772	2.854	0.240	1.930	2.970	4.780	19.900
Tahoe	2	562	2.302	1.714	0.140	1.120	1.855	3.048	14.180
Tahoe	3	355	2.471	1.921	0.380	1.240	1.980	3.070	12.920
Tahoe	4	337	2.056	1.652	0.140	1.040	1.650	2.480	15.980
Chico Velo	1	1,885	9.308	5.527	0.910	5.310	8.220	12.100	44.780
Chico Velo	2	3,028	9.299	7.212	0.580	5.080	8.030	12.040	201.030
Chico Velo	3	514	3.429	2.773	0.220	1.543	2.715	4.385	25.800
Chico Velo	4	578	3.208	3.587	0.170	1.190	2.080	3.875	41.820
Chico Velo	5	868	2.573	2.733	0.150	0.978	1.700	2.960	21.880
Alto Velo	1	363	4.026	3.004	0.050	1.830	3.200	5.115	18.300
Alto Velo	2	552	7.577	5.582	0.440	3.610	6.180	9.865	31.610
Alto Velo	3	465	4.299	2.983	0.220	2.220	3.500	5.730	21.500
Alto Velo	4	567	3.522	3.000	0.130	1.460	2.560	4.500	21.440
LA-2 [b]	1	89,572	2.509	2.017	0.060	1.130	1.960	3.270	30.240
LA-2 [b]	2	89,581	2.652	2.102	0.050	1.210	2.090	3.460	40.210

Notes:

[a.] Mon-198 group is for *test sections* on Mon-198.

[b.] Only texture measurement was performed for LA-2.

5.6 Bicycle Vibration Results

Bicycle vibration measurements (i.e., vertical acceleration) taken along the entire length of each pavement section (see Table 5.2 for details on each section) are summarized using a boxplot in Figure 5.33 and presented in Table 5.5. From the figure it can be seen that the vibration values for most of the sections of all the groups were below 1.0 g and centered at approximately 0.5 g, except for a few sections (Chico Velo sections 1 and 2 and Alto Velo sections 3 and 4) where they were larger than 1.0 g and closer to 1.5 g. The higher vibration values on Chico Velo sections 1 and 2 were due to their larger IRI values (see Figure 5.32), while the higher values on Alto Velo sections 3 and 4 were due to their higher MPD values (macrotexture, see Figure 5.16) and possibly to their downhill configuration, which increased the speed of bicycles traveling on them (Figure 5.34). This implies that beside MPD (macrotexture) and IRI (roughness or unevenness) may influence bicycle vibration and consequently bicycle ride quality since unmaintained pavements usually develop greater IRI due to cracking and rutting. The mean vibration values for all the sections measured were in an approximate range of 0.2 g to 1.5 g.

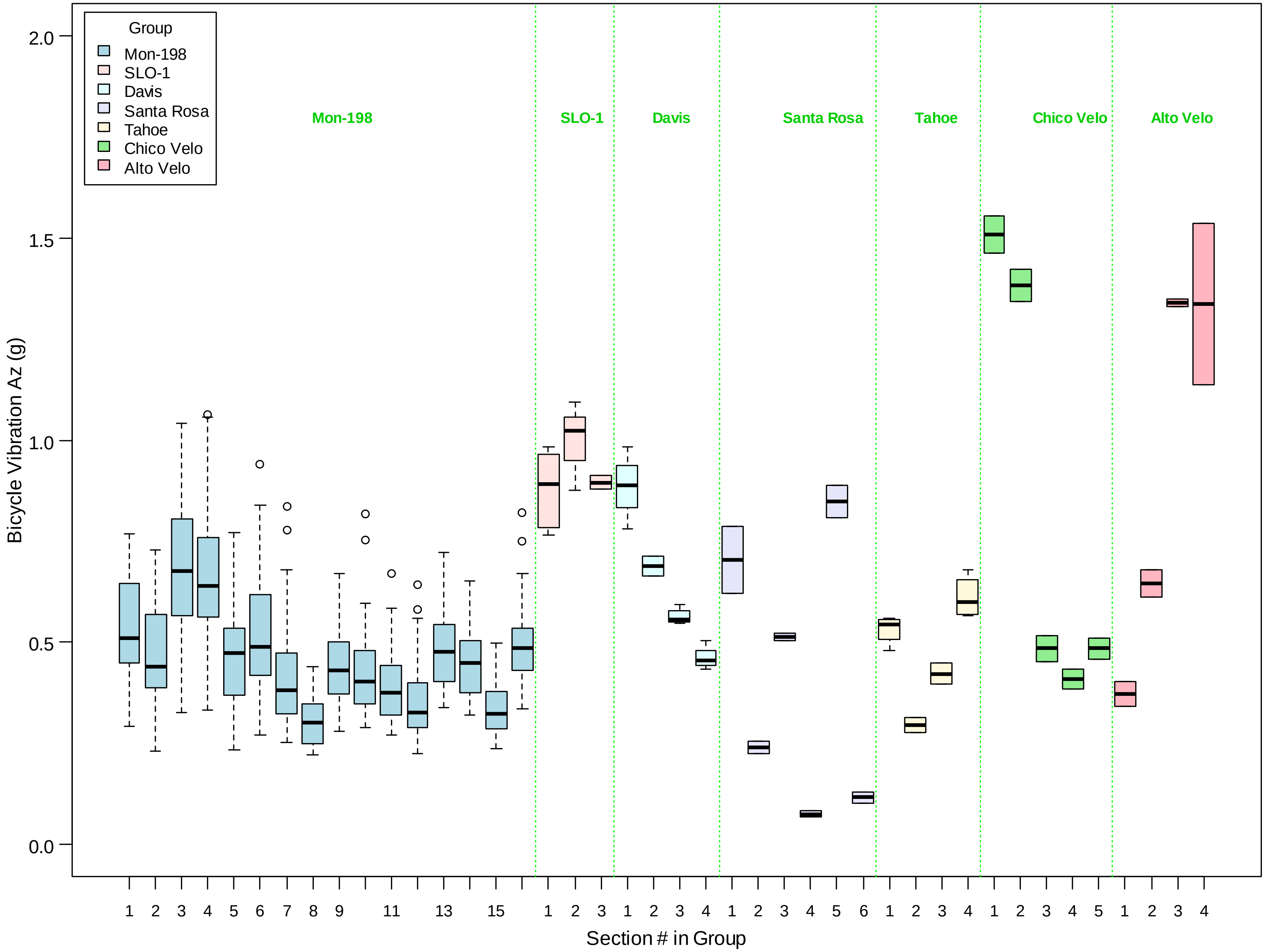


Figure 5.33: Summary boxplot of bicycle vibration for survey sections in all groups.
(Note: **the Mon-198 group is for test sections on Mon-198.)**

Table 5.5: Summary of Bicycle Vibration Data (*g*) for Each Survey Section in All Groups

Group	Section #	N [a]	Mean [b]	Std.Dev.	Min	Q1	Median	Q3	Max
Mon-198 [c]	1	38	0.536	0.131	0.291	0.449	0.509	0.641	0.770
Mon-198	2	43	0.467	0.135	0.230	0.388	0.438	0.567	0.729
Mon-198	3	43	0.676	0.190	0.327	0.565	0.677	0.804	1.043
Mon-198	4	45	0.659	0.189	0.332	0.561	0.641	0.760	1.064
Mon-198	5	45	0.459	0.131	0.233	0.368	0.473	0.536	0.772
Mon-198	6	45	0.519	0.146	0.270	0.417	0.490	0.618	0.941
Mon-198	7	47	0.416	0.133	0.253	0.321	0.381	0.472	0.835
Mon-198	8	47	0.307	0.057	0.220	0.250	0.301	0.348	0.439
Mon-198	9	47	0.444	0.087	0.280	0.372	0.431	0.501	0.670
Mon-198	10	44	0.427	0.112	0.287	0.348	0.404	0.478	0.816
Mon-198	11	44	0.393	0.088	0.269	0.321	0.374	0.440	0.669
Mon-198	12	39	0.357	0.099	0.225	0.289	0.325	0.401	0.644
Mon-198	13	36	0.479	0.094	0.338	0.403	0.476	0.542	0.721
Mon-198	14	34	0.453	0.089	0.320	0.378	0.447	0.502	0.651
Mon-198	15	37	0.334	0.070	0.237	0.286	0.322	0.378	0.498
Mon-198	16	37	0.499	0.105	0.336	0.429	0.486	0.535	0.821
SLO-1	1	6	0.879	0.101	0.764	0.791	0.890	0.964	0.984
SLO-1	2	3	0.998	0.111	0.876	0.950	1.025	1.059	1.093
SLO-1	3	2	0.895	0.024	0.878	0.886	0.895	0.903	0.912
Davis	1	4	0.886	0.083	0.782	0.860	0.889	0.915	0.984
Davis	2	2	0.690	0.034	0.665	0.678	0.690	0.702	0.714
Davis	3	4	0.564	0.021	0.548	0.551	0.556	0.568	0.594
Davis	4	4	0.462	0.030	0.433	0.449	0.455	0.468	0.503
Santa Rosa	1	2	0.703	0.117	0.621	0.662	0.703	0.745	0.786
Santa Rosa	2	4	0.240	0.028	0.208	0.221	0.241	0.259	0.270
Santa Rosa	3	2	0.514	0.013	0.505	0.509	0.514	0.518	0.523
Santa Rosa	4	4	0.201	0.146	0.069	0.078	0.199	0.322	0.338
Santa Rosa	5	2	0.847	0.057	0.807	0.827	0.847	0.868	0.888
Santa Rosa	6	2	0.115	0.019	0.102	0.109	0.115	0.122	0.129
Tahoe	1	4	0.532	0.036	0.480	0.522	0.545	0.556	0.558
Tahoe	2	2	0.296	0.025	0.278	0.287	0.296	0.305	0.314
Tahoe	3	2	0.422	0.038	0.396	0.409	0.422	0.436	0.449
Tahoe	4	4	0.611	0.054	0.564	0.569	0.601	0.643	0.679
Chico Velo	1	2	1.510	0.066	1.464	1.487	1.510	1.533	1.557
Chico Velo	2	2	1.383	0.056	1.344	1.363	1.383	1.403	1.422
Chico Velo	3	2	0.485	0.046	0.453	0.469	0.485	0.501	0.517
Chico Velo	4	2	0.409	0.037	0.383	0.396	0.409	0.422	0.435
Chico Velo	5	2	0.484	0.038	0.457	0.471	0.484	0.498	0.511
Alto Velo	1	2	0.372	0.044	0.341	0.357	0.372	0.387	0.403
Alto Velo	2	2	0.646	0.047	0.613	0.629	0.646	0.663	0.680
Alto Velo	3	2	1.339	0.014	1.330	1.334	1.339	1.344	1.349
Alto Velo	4	2	1.337	0.281	1.138	1.237	1.337	1.436	1.536

Notes:

[a.] The number of processed vibration data, not the number of the initial measurement data.

[b.] Acceleration normalized at the speed of 26 km/h (16 mph), see Section 3.3.2 for details.

[c.] Mon-198 group is for test sections on Mon-198.

5.7 Bicycle Survey Results

As shown in Table 5.1, the bicycle surveys collected data from a total of 107 participants in 7 groups who rode on 42 road sections distributed across Northern and Central California. This section presents the main results, which pertain to ride quality, that were determined from the in-ride survey. Results concerning the surveyed riders' socioeconomic information, bicycle characteristics, and bicycling activities that were gathered in the pre-ride survey can be found in Appendix F.

5.7.1 Bicycling Speed

Riders reported the average bicycle speed on each survey section in the in-ride survey. The speeds on each pavement section have been summarized using a boxplot in Figure 5.34 and in Table 5.6. The figure shows that the bicycle speed values for most of the sections of all groups were in the range of 10 mph to 20 mph (16 to 32 km/h), except for sections 3 and 4 in the Alto Velo group, where median bicycling speed values exceeded 20 mph (32 km/h) and rose as high as nearly 30 mph (48 km/h). The reason for the higher speeds on these two Alto Velo sections is that they run downhill. Thus, as mentioned earlier, the higher bicycling speed may have influenced bicycle vibration and consequently the bicycle ride quality. The mean bicycle speed values for all the sections in this study were the approximate range of 8 mph to 31 mph (13 km/h to 50 km/h; see Table 5.6).

5.7.2 Acceptability

When each rider reached the end of a section, before moving on they filled out their in-ride survey, rating the just-completed section as either "Unacceptable" or "Acceptable." The overall acceptability (a rating of 0 or 1, with 0 = completely unacceptable and 1 = completely acceptable) of each section is either the average rating of all the riders or of the percentage of riders that rated the pavement section "Acceptable." The acceptability values for each pavement section are summarized using a boxplot in Figure 5.35 and in Table 5.7. It can be seen that the acceptability values for most of the sections of all the groups were above 0.8, while only 7 out of 42 sections (SLO-1 sections 1 to 3, Davis section 2, Chico Velo sections 1 and 2, and Alto Velo section 3) obtained median ride quality acceptability values below 0.25. The reason for the lower ride quality acceptability in those sections was higher MPD, higher IRI, or both, with the consequent higher bicycle vibration. The mean ride quality acceptability values for all the sections in this study covered the range 0 (completely unacceptable) to 1 (completely acceptable) (see Table 5.7).

5.7.3 Ride Quality

Riders reported on the bicycle ride quality (on a scale of 1 to 5, with 1 = poor and 5 = excellent) of each survey section through the in-ride survey. The values for each pavement section are summarized using a boxplot in Figure 5.36 and in Table 5.8. It can be seen that bicycle ride quality values for most of the sections of all the groups were above 3, while the mean ride quality values were below 2.0 for only 6 out of 42 sections (SLO-1 sections 1 through 3, Chico Velo sections 1 and 2, and Alto Velo section 3). As with the acceptability ratings, the reason for the lower ride quality rating of those sections is due to either the higher MPD, higher IRI, or both, and the consequent higher bicycle vibration. The mean bicycle ride quality values for all the sections in this study were in the approximate range of 1.1 to 4.7 (see Table 5.8).

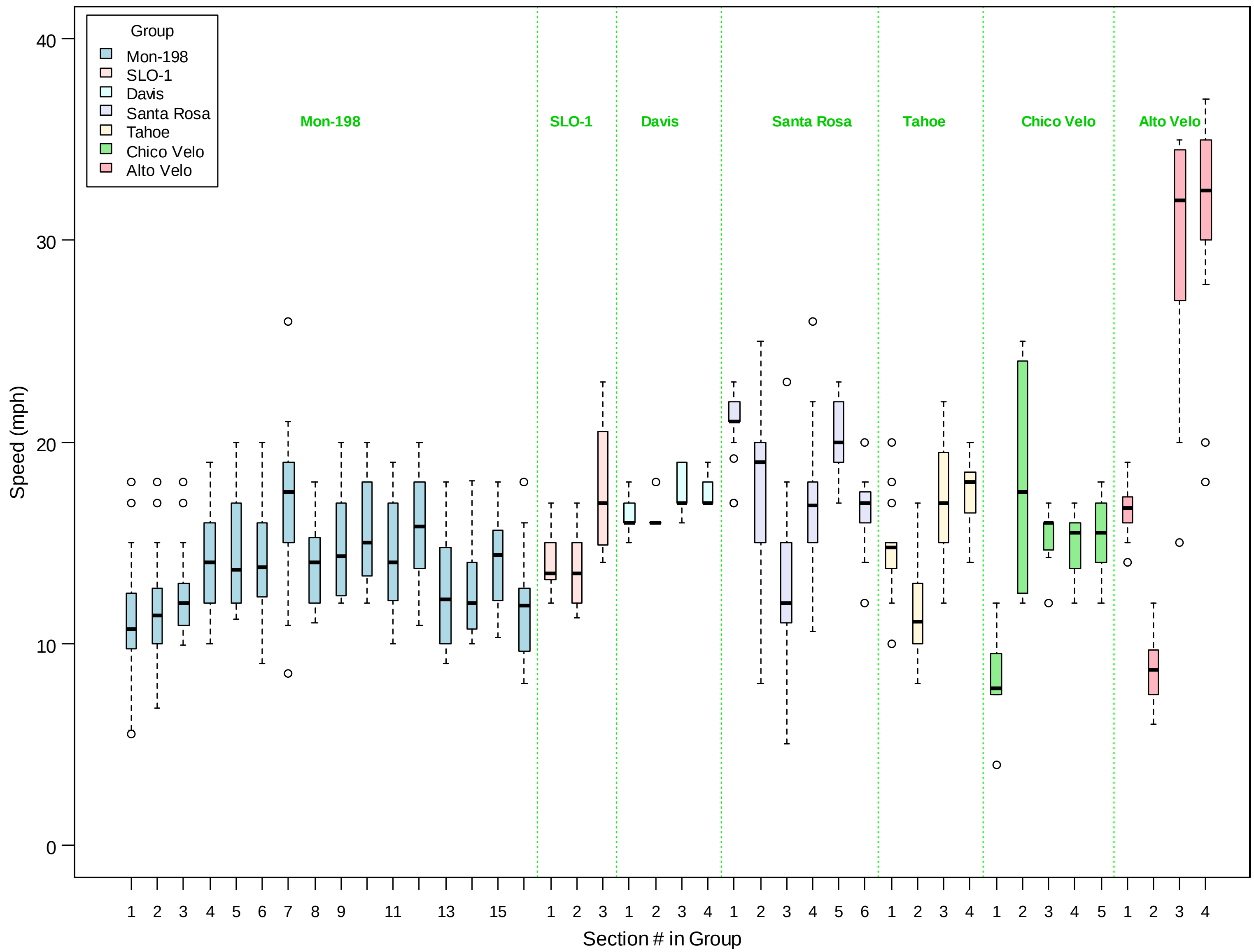


Figure 5.34: Summary boxplot of bicycling speed for each survey section in all groups.
(*Note:* the Mon-198 group is for test sections on Mon-198.)

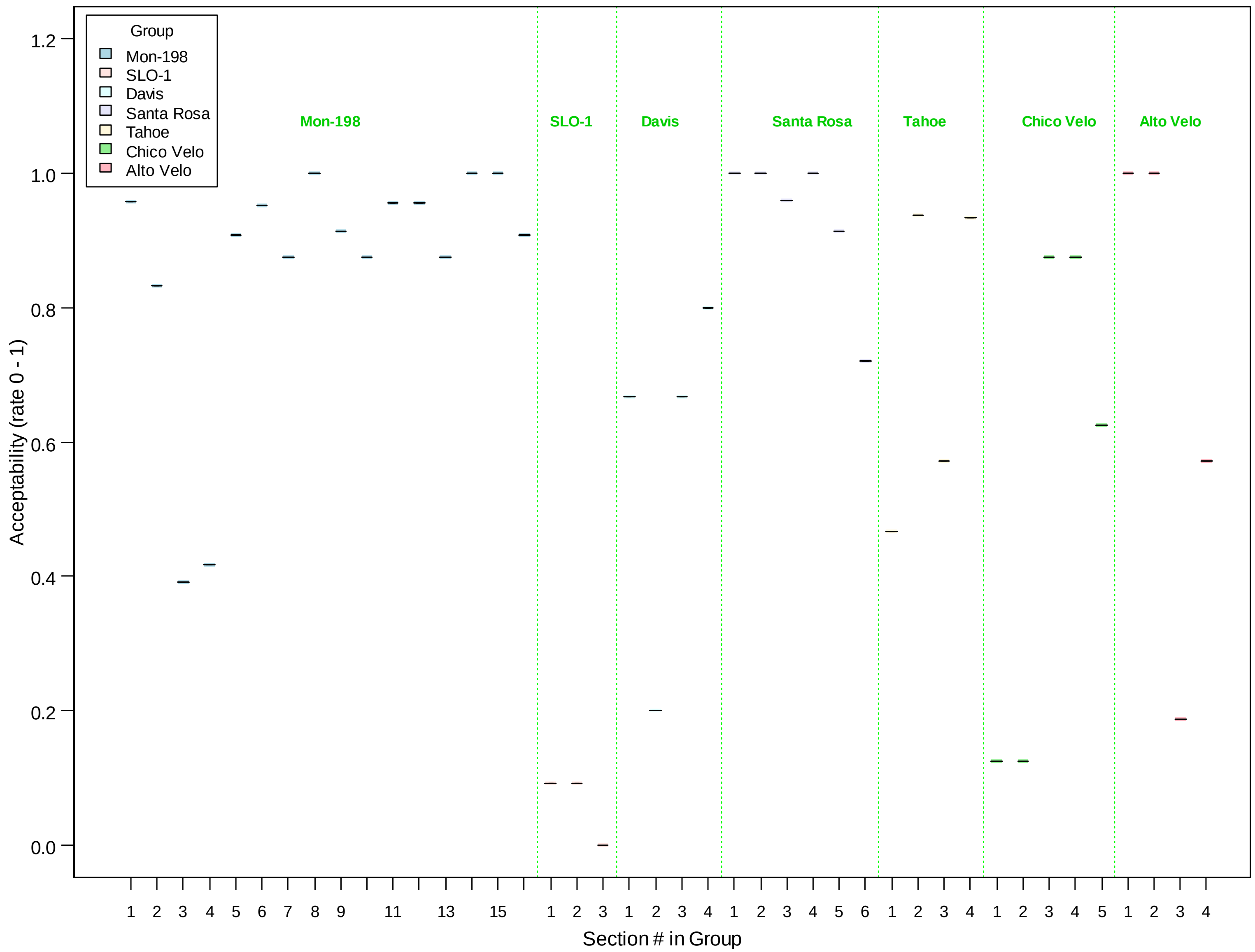


Figure 5.35: Summary plot of acceptability for each survey section in all groups.
(Note: **the Mon-198 group is for test sections on Mon-198.)**

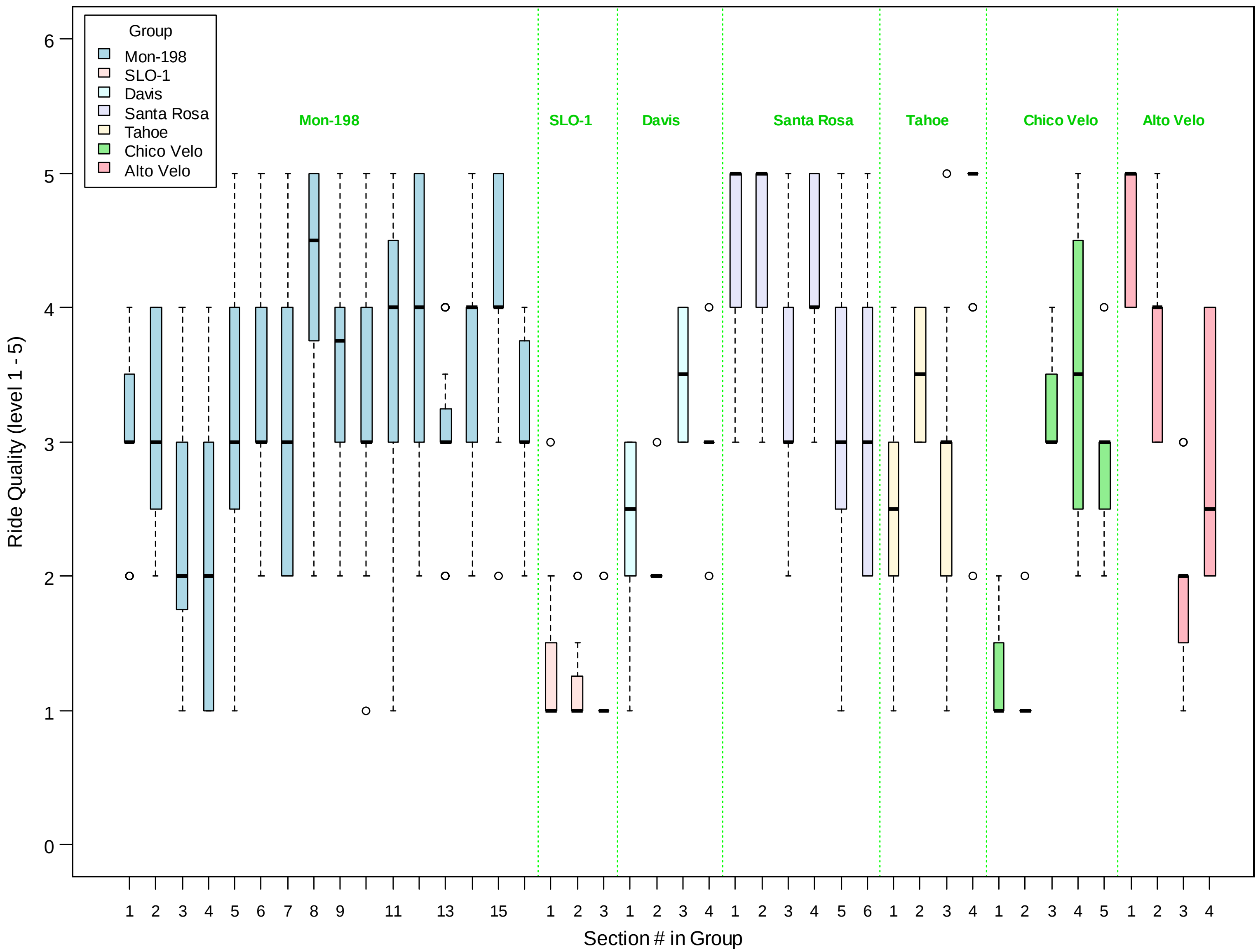


Figure 5.36: Summary boxplot of ride quality for each survey section in all groups.
(*Note:* the Mon-198 group is for test sections on Mon-198.)

Table 5.6: Summary Table of Bicycling Speed (mph) for Each Survey Section in All Groups

Group	Section #	N	Mean	Std.Dev.	Min	Q1	Median	Q3	Max
Mon-198[a]	1	23	11.2	3.1	5.5	9.8	10.7	12.5	18.0
Mon-198	2	23	11.9	2.5	6.8	10.0	11.4	12.8	18.0
Mon-198	3	22	12.4	2.2	9.9	10.9	12.0	13.0	18.0
Mon-198	4	21	14.2	2.6	10.0	12.0	14.0	16.0	19.0
Mon-198	5	22	14.4	2.8	11.2	12.0	13.7	16.8	20.0
Mon-198	6	23	14.3	2.6	9.0	12.3	13.8	16.0	20.0
Mon-198	7	24	16.9	3.6	8.5	15.0	17.6	19.0	26.0
Mon-198	8	23	14.0	2.3	11.0	12.0	14.0	15.3	18.0
Mon-198	9	24	14.8	2.7	12.0	12.5	14.4	17.0	20.0
Mon-198	10	24	15.4	2.6	12.0	13.4	15.0	18.0	20.0
Mon-198	11	23	14.3	2.8	10.0	12.2	14.0	17.0	19.0
Mon-198	12	24	16.1	3.0	10.9	14.3	15.8	18.0	20.0
Mon-198	13	24	12.5	2.7	9.0	10.0	12.2	14.6	18.0
Mon-198	14	24	12.8	2.5	10.0	10.9	12.0	14.0	18.1
Mon-198	15	24	14.2	2.1	10.3	12.2	14.4	15.5	18.0
Mon-198	16	24	11.6	2.5	8.0	9.6	11.9	12.6	18.0
SLO-1	1	11	14.1	1.6	12.0	13.2	13.5	15.0	17.0
SLO-1	2	11	13.8	2.0	11.3	12.0	13.5	15.0	17.0
SLO-1	3	11	17.7	3.2	14.0	14.9	17.0	20.5	23.0
Davis	1	6	16.3	1.0	15.0	16.0	16.0	16.8	18.0
Davis	2	6	16.3	0.8	16.0	16.0	16.0	16.0	18.0
Davis	3	6	17.5	1.2	16.0	17.0	17.0	18.5	19.0
Davis	4	5	17.6	0.9	17.0	17.0	17.0	18.0	19.0
Santa Rosa	1	25	21.0	1.6	17.0	21.0	21.0	22.0	23.0
Santa Rosa	2	26	17.8	4.4	8.0	15.0	19.0	20.0	25.0
Santa Rosa	3	25	12.4	3.9	5.0	11.0	12.0	15.0	23.0
Santa Rosa	4	24	16.9	2.9	10.6	15.0	16.9	18.0	26.0
Santa Rosa	5	23	20.3	1.8	17.0	19.0	20.0	22.0	23.0
Santa Rosa	6	25	16.5	1.6	12.0	16.0	17.0	17.5	20.0
Tahoe	1	16	14.7	2.3	10.0	13.8	14.8	15.0	20.0
Tahoe	2	16	11.6	2.5	8.0	10.0	11.1	12.5	17.0
Tahoe	3	15	17.2	2.6	12.0	15.0	17.0	19.5	22.0
Tahoe	4	15	17.5	1.9	14.0	16.5	18.0	18.5	20.0
Chico Velo	1	8	8.2	2.3	4.0	7.5	7.8	9.3	12.0
Chico Velo	2	8	18.1	5.8	12.0	12.8	17.5	23.5	25.0
Chico Velo	3	8	15.3	1.6	12.0	14.8	16.0	16.0	17.0
Chico Velo	4	8	14.9	1.7	12.0	13.9	15.5	16.0	17.0
Chico Velo	5	8	15.4	2.1	12.0	14.0	15.5	16.5	18.0
Alto Velo	1	14	16.6	1.2	14.0	16.0	16.8	17.3	19.0
Alto Velo	2	15	8.8	2.0	6.0	7.5	8.7	9.7	12.0
Alto Velo	3	15	29.4	6.2	15.0	27.0	32.0	34.5	35.0
Alto Velo	4	13	30.5	5.7	18.0	30.0	32.5	35.0	37.0

Note:
[a.] Mon-198 group is for test sections on Mon-198.

Table 5.7: Summary of Ride Quality Acceptability (0 or 1) for Each Survey Section in All Groups

Group	Section #	N	Mean	Std.Dev.	Min	Q1	Median	Q3	Max
Mon-198 [a]	1	24	1.0	0.2	0.0	1.0	1.0	1.0	1.0
Mon-198	2	24	0.8	0.4	0.0	1.0	1.0	1.0	1.0
Mon-198	3	23	0.4	0.5	0.0	0.0	0.0	1.0	1.0
Mon-198	4	24	0.4	0.5	0.0	0.0	0.0	1.0	1.0
Mon-198	5	22	0.9	0.3	0.0	1.0	1.0	1.0	1.0
Mon-198	6	21	1.0	0.2	0.0	1.0	1.0	1.0	1.0
Mon-198	7	24	0.9	0.3	0.0	1.0	1.0	1.0	1.0
Mon-198	8	23	1.0	0.0	1.0	1.0	1.0	1.0	1.0
Mon-198	9	23	0.9	0.3	0.0	1.0	1.0	1.0	1.0
Mon-198	10	24	0.9	0.3	0.0	1.0	1.0	1.0	1.0
Mon-198	11	23	1.0	0.2	0.0	1.0	1.0	1.0	1.0
Mon-198	12	23	1.0	0.2	0.0	1.0	1.0	1.0	1.0
Mon-198	13	24	0.9	0.3	0.0	1.0	1.0	1.0	1.0
Mon-198	14	22	1.0	0.0	1.0	1.0	1.0	1.0	1.0
Mon-198	15	20	1.0	0.0	1.0	1.0	1.0	1.0	1.0
Mon-198	16	22	0.9	0.3	0.0	1.0	1.0	1.0	1.0
SLO-1	1	11	0.1	0.3	0.0	0.0	0.0	0.0	1.0
SLO-1	2	11	0.1	0.3	0.0	0.0	0.0	0.0	1.0
SLO-1	3	11	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Davis	1	6	0.7	0.5	0.0	0.3	1.0	1.0	1.0
Davis	2	5	0.2	0.4	0.0	0.0	0.0	0.0	1.0
Davis	3	6	0.7	0.5	0.0	0.3	1.0	1.0	1.0
Davis	4	5	0.8	0.4	0.0	1.0	1.0	1.0	1.0
Santa Rosa	1	25	1.0	0.0	1.0	1.0	1.0	1.0	1.0
Santa Rosa	2	26	1.0	0.0	1.0	1.0	1.0	1.0	1.0
Santa Rosa	3	25	1.0	0.2	0.0	1.0	1.0	1.0	1.0
Santa Rosa	4	25	1.0	0.0	1.0	1.0	1.0	1.0	1.0
Santa Rosa	5	23	0.9	0.3	0.0	1.0	1.0	1.0	1.0
Santa Rosa	6	25	0.7	0.5	0.0	0.0	1.0	1.0	1.0
Tahoe	1	15	0.5	0.5	0.0	0.0	0.0	1.0	1.0
Tahoe	2	16	0.9	0.3	0.0	1.0	1.0	1.0	1.0
Tahoe	3	14	0.6	0.5	0.0	0.0	1.0	1.0	1.0
Tahoe	4	15	0.9	0.3	0.0	1.0	1.0	1.0	1.0
Chico Velo	1	8	0.1	0.4	0.0	0.0	0.0	0.0	1.0
Chico Velo	2	8	0.1	0.4	0.0	0.0	0.0	0.0	1.0
Chico Velo	3	8	0.9	0.4	0.0	1.0	1.0	1.0	1.0
Chico Velo	4	8	0.9	0.4	0.0	1.0	1.0	1.0	1.0
Chico Velo	5	8	0.6	0.5	0.0	0.0	1.0	1.0	1.0
Alto Velo	1	16	1.0	0.0	1.0	1.0	1.0	1.0	1.0
Alto Velo	2	15	1.0	0.0	1.0	1.0	1.0	1.0	1.0
Alto Velo	3	16	0.2	0.4	0.0	0.0	0.0	0.0	1.0
Alto Velo	4	14	0.6	0.5	0.0	0.0	1.0	1.0	1.0

Note:
[a.] Mon-198 group is for test sections on Mon-198.

Table 5.8: Summary of Ride Quality (1 to 5) for Each Survey Section in All Groups

Group	Section #	N	Mean	Std.Dev.	Min	Q1	Median	Q3	Max
Mon-198[a]	1	24	3.0	0.7	2.0	3.0	3.0	3.3	4.0
Mon-198	2	24	3.2	0.8	2.0	2.8	3.0	4.0	4.0
Mon-198	3	24	2.2	1.0	1.0	1.9	2.0	3.0	4.0
Mon-198	4	24	2.1	1.0	1.0	1.0	2.0	3.0	4.0
Mon-198	5	24	3.1	1.1	1.0	2.8	3.0	4.0	5.0
Mon-198	6	24	3.3	0.9	2.0	3.0	3.0	4.0	5.0
Mon-198	7	24	3.0	0.9	2.0	2.0	3.0	4.0	5.0
Mon-198	8	24	4.2	1.0	2.0	3.9	4.5	5.0	5.0
Mon-198	9	24	3.5	0.8	2.0	3.0	3.8	4.0	5.0
Mon-198	10	24	3.2	0.9	1.0	3.0	3.0	4.0	5.0
Mon-198	11	24	3.8	1.0	1.0	3.0	4.0	4.3	5.0
Mon-198	12	23	3.9	0.9	2.0	3.0	4.0	5.0	5.0
Mon-198	13	24	3.0	0.7	2.0	3.0	3.0	3.1	4.0
Mon-198	14	24	3.6	0.9	2.0	3.0	4.0	4.0	5.0
Mon-198	15	23	4.2	0.8	2.0	4.0	4.0	5.0	5.0
Mon-198	16	23	3.2	0.6	2.0	3.0	3.0	3.8	4.0
SLO-1	1	11	1.4	0.7	1.0	1.0	1.0	1.5	3.0
SLO-1	2	11	1.2	0.4	1.0	1.0	1.0	1.3	2.0
SLO-1	3	11	1.2	0.4	1.0	1.0	1.0	1.0	2.0
Davis	1	6	2.3	0.8	1.0	2.0	2.5	3.0	3.0
Davis	2	6	2.2	0.4	2.0	2.0	2.0	2.0	3.0
Davis	3	6	3.5	0.5	3.0	3.0	3.5	4.0	4.0
Davis	4	6	3.0	0.6	2.0	3.0	3.0	3.0	4.0
Santa Rosa	1	25	4.4	0.7	3.0	4.0	5.0	5.0	5.0
Santa Rosa	2	26	4.7	0.6	3.0	4.0	5.0	5.0	5.0
Santa Rosa	3	25	3.4	0.8	2.0	3.0	3.0	4.0	5.0
Santa Rosa	4	25	4.4	0.6	3.0	4.0	4.0	5.0	5.0
Santa Rosa	5	23	3.3	1.1	1.0	2.5	3.0	4.0	5.0
Santa Rosa	6	25	3.0	0.9	2.0	2.0	3.0	4.0	5.0
Tahoe	1	16	2.5	0.9	1.0	2.0	2.5	3.0	4.0
Tahoe	2	16	3.5	0.5	3.0	3.0	3.5	4.0	4.0
Tahoe	3	15	2.8	1.1	1.0	2.0	3.0	3.0	5.0
Tahoe	4	15	4.7	0.8	2.0	5.0	5.0	5.0	5.0
Chico Velo	1	8	1.3	0.5	1.0	1.0	1.0	1.3	2.0
Chico Velo	2	8	1.1	0.4	1.0	1.0	1.0	1.0	2.0
Chico Velo	3	8	3.3	0.5	3.0	3.0	3.0	3.3	4.0
Chico Velo	4	8	3.5	1.2	2.0	2.8	3.5	4.3	5.0
Chico Velo	5	8	2.9	0.6	2.0	2.8	3.0	3.0	4.0
Alto Velo	1	16	4.6	0.5	4.0	4.0	5.0	5.0	5.0
Alto Velo	2	16	3.9	0.7	3.0	3.0	4.0	4.0	5.0
Alto Velo	3	16	1.9	0.6	1.0	1.8	2.0	2.0	3.0
Alto Velo	4	14	2.8	0.9	2.0	2.0	2.5	3.8	4.0

Note:
[a.] Mon-198 group is for test sections on Mon-198.

5.8 Correlations between Texture, Vibration, and Ride Quality

The bicycle ride quality survey was conducted on all 42 road sections and included 107 participants divided among 7 groups (see Table 5.1). On Mon-198, the eight controlled test sections were divided into 16 survey sections, reflecting the two survey paths taken by the bicyclists on each test section: one along the ETW and one in the left wheelpath. A total of 107 effective participant samples from the survey were used for the correlation 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 5.37, the correlation analysis included the average macrotexture (MPD, in mm) of each survey section measured using the IP, the average IRI (in m/km) of each survey section, the average normalized vibration (vertical acceleration Az, in *g*) of each survey section measured using accelerometers on all the instrumented bicycles, the average reported bicycling speed (Speed in mph), the ride quality level rated on a 1-to-5 scale (Ride Quality, level 1 to 5) on each survey section, and the percentage of survey participants who rated the pavement “acceptable” (Acceptability, rating 0 to 1).

The main observations from the correlation include the following:

a. Strong correlations were revealed between MPD, bicycle vibration, acceptability, and ride quality level.
b. Medium to weak correlations were revealed between IRI, bicycle vibration, acceptability, and ride quality level.
c. Relatively weak correlation (0.35) was found between bicycle vibration and bicycle speed. No significant correlation was found between other variables and bicycle speed (small set of speeds).
d. Vibration appears to be somewhat more sensitive to MPD when MPD values are above 2 mm.
e. Vibration appears to be somewhat more sensitive to IRI when IRI values are above 4 m/km (248 in./mile).
f. The relationship between MPD and ride quality is approximately linear.
g. The approximate range of MPD for bicycle ride quality “Acceptability” is based on a straight line interpolation in Figure 5.37 for the percentage of participants who rated sections as “Acceptable”:
    - 80 percent found 1.3 mm acceptable.
    - 60 percent found 1.8 mm acceptable.
    - 50 percent found 2.1 mm acceptable.
    - 40 percent found 2.3 mm acceptable.

h. The average ride quality level rating (on a scale of 1 to 5) is approximately:
    - 3.5 for an MPD of 1.0 mm
    - 3.0 for an MPD of 1.5 mm
    - 2.5 for an MPD of 2.0 mm
    - 1.5 for an MPD of 3.0 mm

i. Most riders rated a pavement as “Acceptable” when the ride quality rating was 3.0 or greater, and the percentage of riders finding a pavement “Acceptable” decreased approximately linearly for ride quality ratings below 3.0 to a point where almost no one found a pavement acceptable when its ride quality rating was about 1.0.

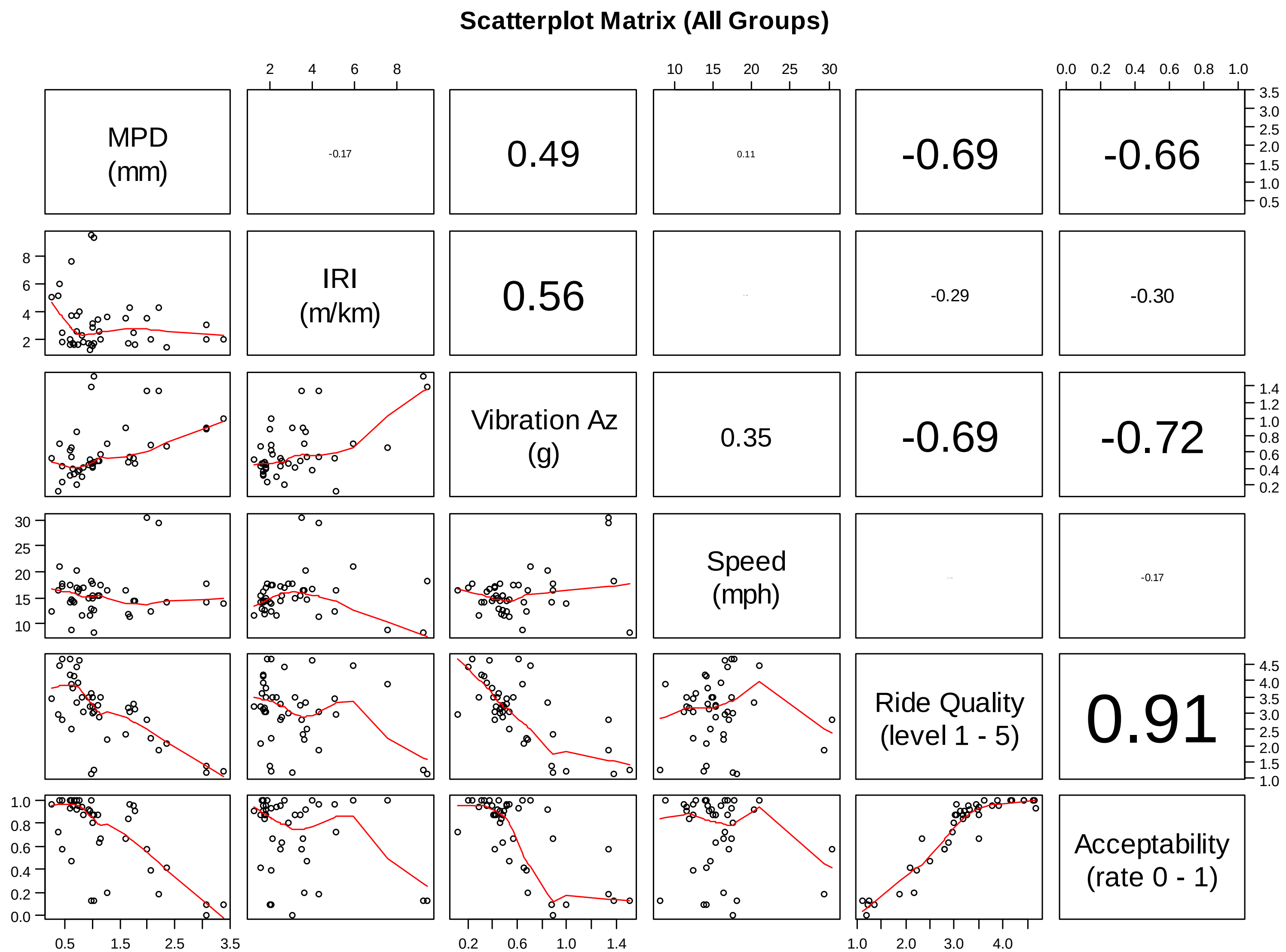


Figure 5.37: Correlations between MPD, IRI, vibration, speed, ride quality level, and acceptability level (all groups).
(Note: **scatterplots and smooth fitted lines are shown in lower panels. Correlations between variables are shown in upper panels, with the size of the type within the box proportional to absolute correlation.)**

6 MODELS FOR BICYCLE RIDE QUALITY

6.1 Data Exploration

Before beginning the modeling process, it can be worthwhile to explore the data using a more informal graphical tool like the scatterplot matrix shown in Figure 6.1. A matrix of this type can help to identify potentially important explanatory variables, as well as to suggest where multicollinearity problems may occur in the future. In this case, the absolute coefficient for the pavement rating and comfort rating is 0.61—which indicates that as a whole, the participants in this study were consistent in giving a high comfort rating to sections they had also rated as "acceptable."

The correlations between the potential pavement index explanatory variables are also of interest—for both measures, the mean and standard deviation are highly correlated. This might suggest that including both the mean and the standard deviation for a given pavement index (MPD or IRI) might cause multicollinearity problems in the model, but informal statistical rules suggest that correlations less than about 0.9 should not be cause for too much concern in the regression model.

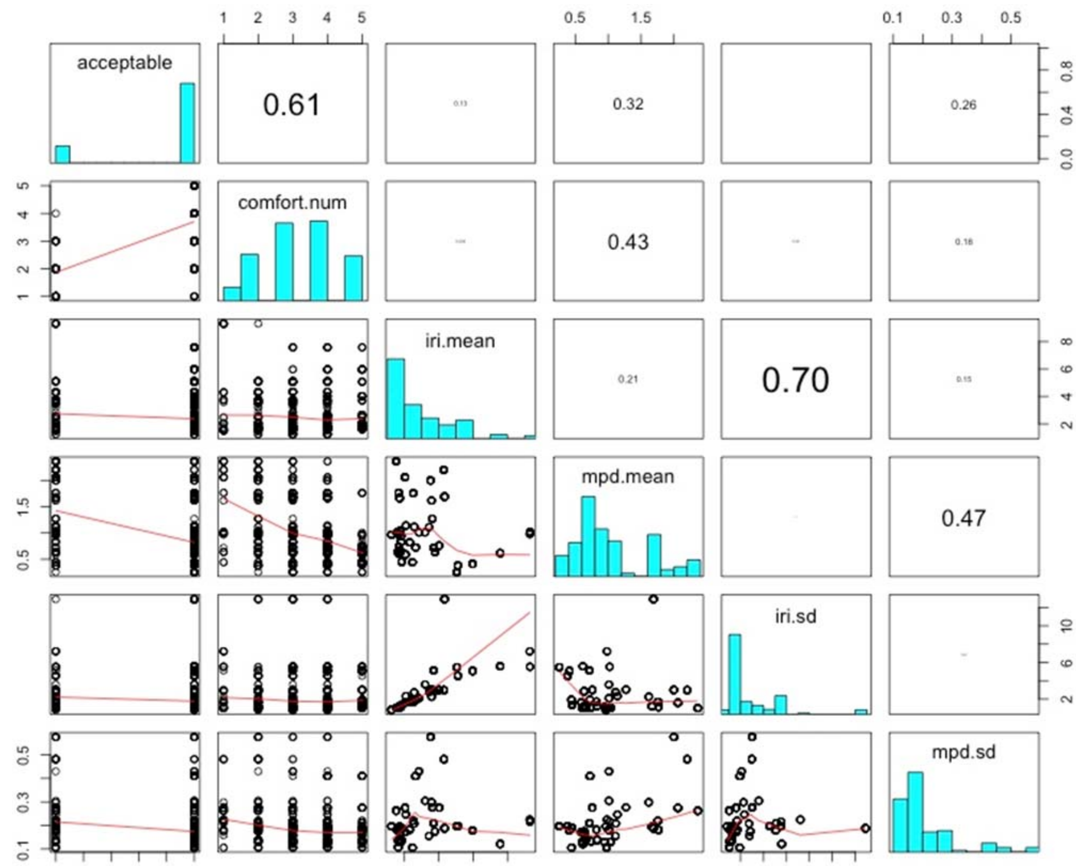


Figure 6.1: Correlations between mean MPD, mean IRI, standard deviation of MPD, standard deviation of IRI, acceptability, and ride quality level (on a 5-point Likert scale from "Worst Ride Quality" to "Best Ride Quality") (Mon-198 test sections).

(Note on Figure 6.1: Scatterplots and smooth fitted lines are shown in lower panels. A histogram of the variable values are plotted on the diagonal. Correlations between variables are shown in the upper panels, with the size of the type within the box proportional to absolute correlation.)

6.2 Modeling the Acceptability of Pavement

The open-source graphical and statistical computing language *R* was used to analyze the data. The *R* script uses the packages 'lme4,' 'boot,' 'car,' 'geepack,' 'multgee,' 'MASS,' and 'nlme,' and is available upon request.

The study's repeated measures sampling scheme (also called "longitudinal" or "clustered" data) resulted in a hierarchical data structure—observations were "nested" within individuals, who were further nested within bicycle clubs. One of the central assumptions of generalized linear regression models (GLMs) is the independence of observations; repeated measures sampling can potentially violate this tenet, as several measurements are taken for any given individual and this can lead to correlated observations within the individual and, consequently, to biased coefficient and standard error estimates.

To address this assumption violation, over the past several decades statisticians developed two main modeling approaches: generalized linear mixed effects (ME) models and generalized estimating equations models (GEEs). ME models accommodate the hierarchical nature of the data by introducing "random effect" terms that explicitly model the variation in individuals' rating scales by allowing individuals' intercept or slope estimates to vary randomly (as opposed to the fixed effect terms that are fixed for each individual, as is found in typical GLMs). GEEs are a semi-parametric approach to repeated measures data; a working variance-covariance matrix is estimated to account for within-subject correlated observations. Further, ME models' coefficients are subject-specific, while GEE coefficients are population-averaged. A population-averaged approach is appropriate in the current study's context, which ultimately should serve as a basis for appropriate pavement types for a broad cross section of California road-riding bicyclists. In this study, a GEE model was estimated to explain the acceptability ratings by the pavement roughness measurements: mean profile depth (MPD) and the International Roughness Index (IRI).

Having measured MPD and IRI for the entirety of each test section in this study, the summary statistics of the mean and standard deviation of MPD and IRI were available as independent variables in the GEE to explain acceptability ratings. Results from using the Wald's *t*-test of the regression coefficients as well as the quasi-Akaike information criterion (QIC, a semi-parametric analogue to the Akaike information criterion, or AIC, which is used to estimate the out-of-sample predictive power of a model) *(18)*, the mean of MPD and IRI as well as the standard deviation of IRI were clearly all significant explanatory variables, while the standard deviation of MPD was not.

As a nonparametric approach to statistical inference, stratified bootstrapping was used to estimate the sampling distribution of the GLM coefficients. Bootstrapped regression entails repeated resampling, with replacement, of the independent variables from the sample and subsequent estimation of the GLM. This results in a sampling distribution of the regression coefficients that can then be used to estimate more accurate standard errors. The study also utilized stratified bootstrapping, which samples repeatedly from within clusters (in this case, individuals), which mimics the study's actual sampling approach.

Four different models—the naïve GEE (the GLM), the full GEE with exchangeable variance-covariance matrix, and the unstratified and stratified bootstrap GLMs—are compared in Table 6.1, which shows that the different model structures result in nearly identical coefficient estimates. This suggests that the simplest model, the naïve GEE/GLM, amply explains the variation in the acceptability ratings. Further, the model that includes the standard deviation of IRI is a clear improvement upon the model with only the means of IRI and MPD, as evidenced by the decrease in the information criteria AIC and QIC, and the increase in the pseudo-R^2 measures.

A similar analysis that investigated the role of pavement texture on ride quality ratings produced similar results (see Table 6.2). Increasing the average IRI or average MPD results in a higher probability of low ride quality ratings, while increasing the variation in IRI or MPD for a given segment results instead in higher probability of high ride quality ratings. This mirrors the findings for the acceptability model—it appears that increasing average pavement roughness, on both the macro and micro levels, leads to lower ratings, an intuitive result. Interestingly, though, the coefficients for the standard deviation of IRI and MPD indicate that higher variability in pavement roughness is at the very least acceptable, if not desirable. Perhaps this indicates that relatively smooth roads, with potholes or short sections of particularly rough pavement, are preferred over uniformly rough roads. The AIC score preferred the model with all four pavement texture explanatory variables over the model with only the average MPD and IRI.

Table 6.1: Pavement Acceptability Models with Pavement Roughness Index Dependent Variables (No. of Observations = 681)

	Model 1				Model 2			
	GEE		Bootstrap		GEE		Bootstrap	
Variables	Naïve (independence)	Full (exchangeable)	Unstratified	Stratified	Naïve (independence)	Full (exchangeable)	Unstratified	Stratified
Intercept	**4.334** (0.363)	**4.329** (0.362)	**4.351** (0.367)	**4.343** (0.322)	**4.521** (0.373)	**4.519** (0.363)	**4.542** (0.367)	**4.532** (0.323)
MPD mean	**-1.543** (0.179)	**-1.542** (0.182)	**-1.551** (0.183)	**-1.547** (0.163)	**-1.643** (0.184)	**-1.643** (0.186)	**-1.650** (0.188)	**-1.646** (0.167)
IRI mean	**-0.325** (0.061)	**-0.325** (0.053)	**-0.325** (0.055)	**-0.325** (0.048)	**-0.585** (0.095)	**-0.585** (0.075)	**-0.599** (0.080)	**-0.598** (0.073)
IRI s.d.	-	-	-	-	**0.264** (0.080)	**0.263** (0.065)	**0.279** (0.073)	**0.279** (0.070)
ρ^2_{EL}	0.42	-			0.44	-		
ρ^2_{MS}	0.14	-			0.17	-		
AIC	549.5	-			532.6	-		
QIC	-	548.8			-	531.0		

Note: The dependent variable is Pavement Acceptability (0 = "Unacceptable"; 1 = "Acceptable"). The coefficient estimate is in bold and its standard error is in parentheses. AIC was calculated only for the GLM models and QIC only for the GEE models.

Table 6.2: Ride Quality Rating Models with Pavement Roughness Index Dependent Variables (No. of Observations = 681)

	Model 1			Model 2		
	GEE	Bootstrap		GEE	Bootstrap	
Variables	Naïve (independence)	Unstratified	Stratified	Naïve (independence)	Unstratified	Stratified
ASC 1	**5.8** (0.78)	**5.9** (0.99)	**5.9** (0.88)	**5.8** (0.9)	**6.0** (1.3)	**6.0** (1.3)
ASC 2	**6.3** (0.78)	**6.4** (0.99)	**6.4** (0.88)	**6.4** (0.9)	**6.6** (1.3)	**6.6** (1.3)
ASC 3	**6.3** (0.78)	**6.4** (0.99)	**6.4** (0.88)	**6.4** (0.9)	**6.6** (1.3)	**6.6** (1.3)
ASC 4	**5.7** (0.78)	**5.9** (0.99)	**5.9** (0.88)	**5.8** (0.9)	**6.0** (1.3)	**6.0** (1.3)
MPD mean	**-2.0** (0.33)	**-2.1** (0.40)	**-2.1** (0.36)	**-2.9** (0.5)	**-3.0** (0.7)	**-3.0** (0.7)
IRI mean	**-0.6** (0.06)	**-0.6** (0.11)	**-0.6** (0.10)	**-1.0** (0.2)	**-1.1** (0.2)	**-1.1** (0.2)
MPD s.d.	-	-	-	**5.7** (2.4)	**6.0** (2.3)	**6.0** (2.3)
IRI s.d.	-	-	-	**0.4** (0.2)	**0.5** (0.3)	**0.5** (0.3)
ρ^2_{EL}	0.11			0.11		
ρ^2_{MS}	0.03			0.04		
AIC	2028			2015		
BIC	2055			2051		

Note: The dependent variable is Pavement Ride quality (1 = "Worst Ride Quality"; 5 = "Best Ride Quality"). The coefficient estimate is in bold and its standard error is in parentheses. "ASC" stands for the alternative-specific constants in this model.

6.3 Exploratory Model

Three mixed effects models were estimated to investigate the role of sociodemographic characteristics as well as bicycle features on individuals' pavement acceptability ratings. A base model, which included the three significant roughness index variables (the mean MPD and IRI of the segment as well as the standard deviation of IRI), was estimated for comparison with the two other models, which included sociodemographic variables and then added the attributes of bicycles (see Table 6.3).

6.3.1 Base Model

In the base model, increases in the mean MPD and mean IRI resulted in a lower probability of an "acceptable" rating, while increasing the standard deviation of the IRI resulted in a higher probability of an acceptable rating. While the direction of the MPD mean and IRI mean coefficients are intuitive—higher average roughness leads to more vibrations experienced by the bicyclist—the direction of the coefficient for the standard deviation of IRI is surprising. Perhaps higher variability in the IRI for a segment simply indicates a relatively smooth road interspersed with large potholes or other rough patches, and this may be more appealing to a bicyclist than a ride on a uniformly rough road. Or the counterintuitive direction of this coefficient could reflect the nature of the IRI index, which was designed to simulate ride quality for passengers in a car rather than on a bicycle. Further, the constant term in the base model is significant, suggesting that much of the variation in pavement acceptability remains unexplained by the three roughness index independent variables and that including sociodemographic traits and bicycle attributes could improve the model's fit.

6.3.2 Sociodemographic Model

Building upon the base model foundation, the sociodemographic model included individual level characteristics: gender, age, educational attainment, and bicycling habits. The addition of these explanatory variables only marginally changed the coefficient values for the roughness index variables while the constant term changed substantially and was no longer significant. Although many of the added sociodemographic variables were insignificant according to the Wald test for regression coefficients, they were retained for hypothesis testing and in order to illustrate their magnitude and direction. These estimates must be viewed with caution—the interplay between different variables is quite complex, and removing one variable can cause other variable's coefficients to shift, sometimes substantially.

The gender coefficient suggested that women tend to have less forgiving pavement comfort scales than men—although this insignificant conclusion is in even further doubt, given the small proportion of women in the study sample. Younger riders also gave harsher pavement acceptability ratings, as did people with higher levels of education, although neither coefficient estimate is significant. This suggests, nevertheless, that increased life experience, either on the bike or off, plays a role in softening an individual's pavement acceptability scale, while increased education levels perhaps indicates that such individuals, who may be more likely to work in white collar jobs, may be less exposed to discomfort on a daily basis than their peers.

Bicyclists who reported riding more often and riding many miles in the past month tended to have more lenient acceptability ratings. It is likely that these bicyclists were exposed to a variety of different pavements on recent rides and remembered them well enough to compare them against the test segments. Although insignificant, the estimated coefficient for the number of organized rides a year that an individual participated in was negative, so more active cyclists seemed to rate the pavement more harshly in this case.

Each individual was asked about a set of ride enjoyment factors ("What factors influence your enjoyment of a ride the most?") and these were included in the sociodemographic model. While the topography, scenery, traffic conditions, pavement ride quality, and road geometric design factors were all insignificant, the wind and companion factors were positive and significant. This indicates that those who ranked wind and the presence of companions high on their list of influential ride enjoyment factors were more likely to rate a given test segment as acceptable, suggesting that these individuals may focus on their ride companions or on the presence of wind more than the pavement quality, and are thus more likely to find the pavement to be acceptable.

6.3.3 Bicycle Attributes Model

The addition of bicycle attributes to the sociodemographic model resulted in a "full" model, which included all potentially relevant variables. The inclusion of new variables did not change the direction of the constant, roughness indices, or sociodemographic terms. Dummy variables for bicycle type as well as bicycle frame material were included in the model to try to take into account the potential for different ride quality experiences across different bicycle types and frames. Further, tire pressure, a commonly acknowledged source of ride quality, was included as well.

The hybrid and folding bicycle type dummy variable coefficients were insignificant, while the touring and mountain bicycle type dummy variable coefficients were negative and statistically significant. Somewhat counterintuitively, this suggests that these two bicycle types, which are designed for ride quality, were tied to a higher probability of unacceptable pavement condition. Surprisingly, the coefficients for the frame material dummy variables were all insignificant—which would be surprising news for bicycle manufacturers. This could be attributed to the fact there were very few titanium or steel frames, with most participants riding aluminum (the base alternative) or carbon frame bicycles, which are similar in ride quality. The tire pressure coefficient was statistically significant and negative, suggesting that tires ridden at a higher pressure produced poorer ride quality and therefore led to increased unacceptable pavement acceptability.

6.4 Random Effects

Mixed effects models included random effects in addition to the more common “fixed” effects in order to accommodate a nested/clustered/longitudinal data structure. All three models included a random intercept term as well as a term that randomly varied an individual’s slope by the mean MPD value. In effect, this allowed individuals to have different rating “scales.” For example, some individuals might have had higher thresholds for an acceptable rating, a difference accommodated by the random intercept and slope terms. The random intercept term decreased from the base model to the full bicycle attributes model, suggesting that the additional independent variables served to explain the variation that was previously accounted for in the intercept. In contrast, the MPD mean random slope term’s variance remained high across all three models, suggesting that it sufficiently accounted for individuals’ differing rating scales.

$$Comfort\ Rating_{ij} \sim Multinomial(p_{ij}) \qquad \textbf{(6.1)}$$

where $log\frac{p_{ij}}{1-p_{ij}} = a + a_j + \vec{\beta}_{roughness}[Roughness] + \vec{\beta}_{sociodemo}[Sociodemo] + \vec{\beta}_{bicycle\_attributes}[Bicycle\_Attributes] + \beta_{MPDj}(\overline{MPD})$

$$\begin{pmatrix} a_j \\ \beta_{MPDj} \end{pmatrix} \sim MVNormal\left(\begin{pmatrix} 0 \\ 0 \end{pmatrix}, SRS\right)$$

$$R \sim LKJCorr(2)$$

Table 6.3: Pavement Acceptability Multinomial Mixed Effects Models for Hypothesis Testing

	Roughness Model		Sociodemographic Model		Bicycle Attributes Model	
Fixed Effects	**Coefficient Estimate**	**p-value**	**Coefficient Estimate**	**p-value**	**Coefficient Estimate**	**p-value**
Constant	**8.1**	<0.001	73.0	0.13	23.0	0.58
MPD mean	**-3.2**	<0.001	**-3.0**	<0.001	**-2.8**	<0.001
IRI mean	**-0.8**	<0.001	**-0.8**	<0.001	**-0.7**	<0.001
IRI s.d.	**0.4**	<0.001	**0.4**	0.003	**0.4**	0.007
Gender (female = 1)	-	-	-0.3	0.74	-0.2	0.79
Age (year born)	-	-	-0.03	0.16	-0.006	0.79
Education	-	-	-0.3	0.23	**-0.5**	0.04
Bicycling Frequency	-	-	0.2	0.62	0.7	0.13
Miles Ridden Last Month	-	-	**0.003**	0.04	**0.003**	0.03
Organized Rides per Year	-	-	-0.05	0.49	-0.07	0.18
Scenery Ranking	-	-	0.3	0.09	0.1	0.36
Topography Ranking	-	-	-0.2	0.28	-0.2	0.13
Road Design Ranking	-	-	-0.05	0.75	-0.1	0.47
Pavement Ranking	-	-	-0.04	0.83	0.001	0.99
Traffic Ranking	-	-	0.03	0.86	-0.003	0.98
Wind Ranking	-	-	**0.3**	0.03	**0.5**	<0.001
Companion Ranking	-	-	**0.3**	0.04	**0.4**	<0.001
Hybrid Bike Dummy	-	-	-	-	0.2	0.99
Touring Bike Dummy	-	-	-	-	**-2.6**	0.04
Mountain Bike Dummy	-	-	-	-	**-8.2**	<0.001
Folding Bike Dummy	-	-	-	-	2.2	0.33
Titanium Frame Dummy	-	-	-	-	-0.5	0.74
Carbon Frame Dummy	-	-	-	-	0.05	0.94
Steel Frame Dummy	-	-	-	-	2.0	0.09
Tire Pressure (psi)	-	-	-	-	**-0.08**	0.002
Random Effects:	Variance		Variance		Variance	
Intercept	13.57		3.50		0.63	
MPD mean	2.13		1.44		2.34	
Model Statistics						
Number of observations	681		573		565	
AIC	472.23		392.40		382.99	
BIC	503.89		479.42		504.42	

Note: The dependent variable is Pavement Acceptability (0 = "Unacceptable"; 1 = "Acceptable"). The coefficient estimates with p-values lower than $\alpha = 0.05$ are in bold.

7 EFFECT OF REMEDIAL TREATMENT ON SLO-1

In October 2013, Caltrans District 5 applied a sand seal treatment on the top of the 2012 chip seal to improve the macrotexture (that is, to lower the MPD) of the chip seal on SLO-1 in order to enhance bicycle ride quality. To determine the effectiveness of the treatment, this study examined the differences between the MPD of the chip seal placed in December 2012 (and measured in April 2013) and the MPD of the sand seal treatment (measured in November 2013). Data was gathered from the treated sections using the inertial profiler (IP). The results appear below.

7.1 MPD of Chip Seal and Sand Seal on SLO-1

The MPD-measured values of the 2012 chip seal and the 2013 remedial sand seal applied on the top of the 2012 chip seal along the entire length of SLO-1 for the shoulders and right wheelpaths in both directions are presented in Figure 7.1 through Figure 7.4. Due to data storage limitations, sections longer than about 20 km (12 mi.) were divided into smaller subsections for measurement. It can be seen from the figures that the MPD values for the SLO-1 chip seal were approximately within the range of 2.0 mm to 4.0 mm, while the MPD range for the SLO-1 sand seal was approximately 0.5 mm to 3.0 mm. There are subsections within the sections on SLO-1 where MPD values were lower because they either have dense-graded asphalt concrete surfaces or are concrete bridge decks (examples are shown in Figure 7.1). It can also be seen that the MPD on the shoulders (that is, outside the ETW) was generally higher than in the wheelpath due to the trafficking in the wheelpath.

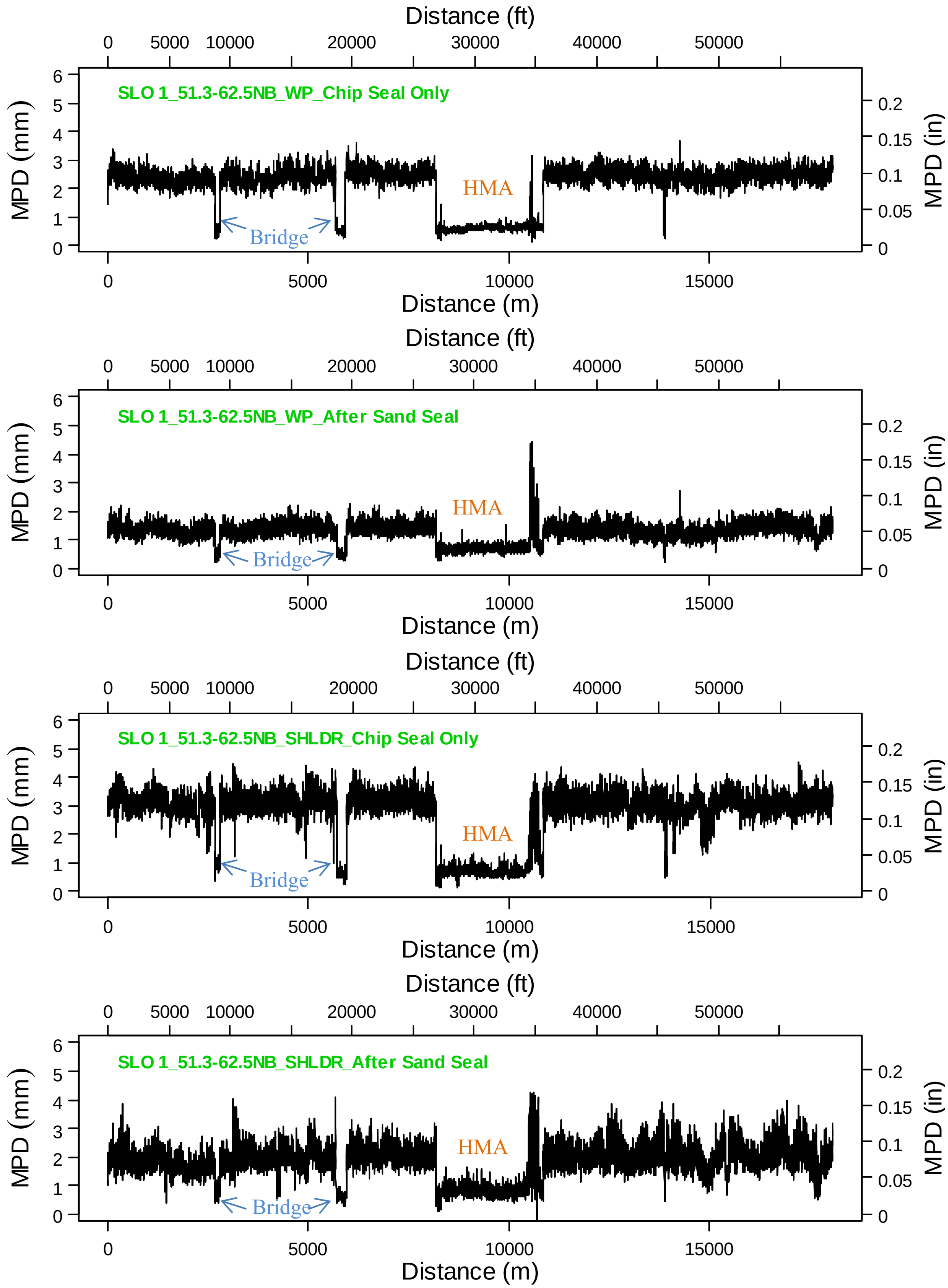


Figure 7.1: MPD of SLO-1 with chip seal only and after sand seal, wheelpath and shoulder (ETW) at PM 51.3-62.5 northbound.

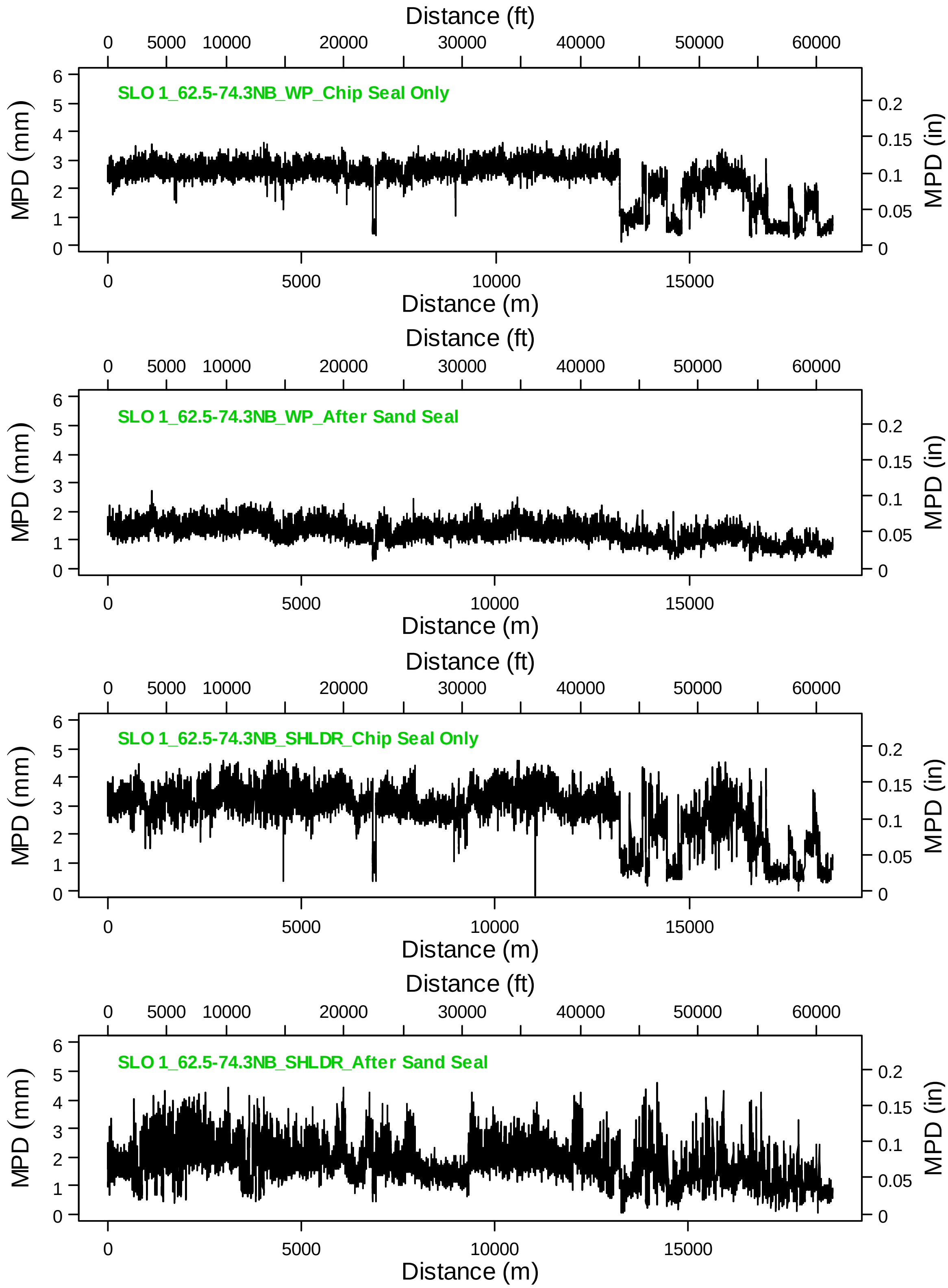


Figure 7.2: MPD of SLO-1 with chip seal only and after sand seal, wheelpath and shoulder (ETW) at PM 62.5-74.3 northbound.

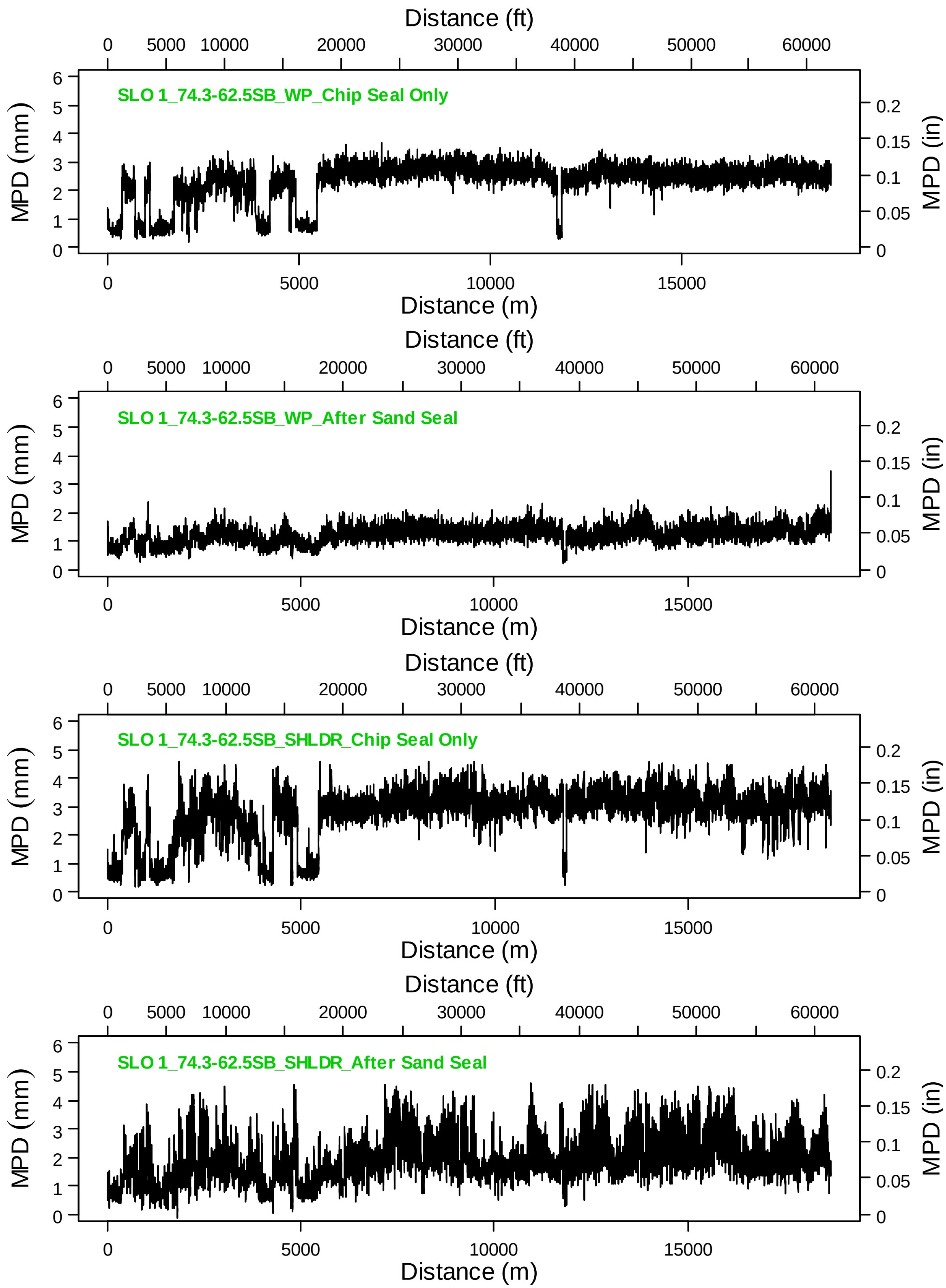


Figure 7.3: MPD of SLO-1 with chip seal only and after sand seal, wheelpath and shoulder (ETW) at PM 62.5-74.3 southbound.

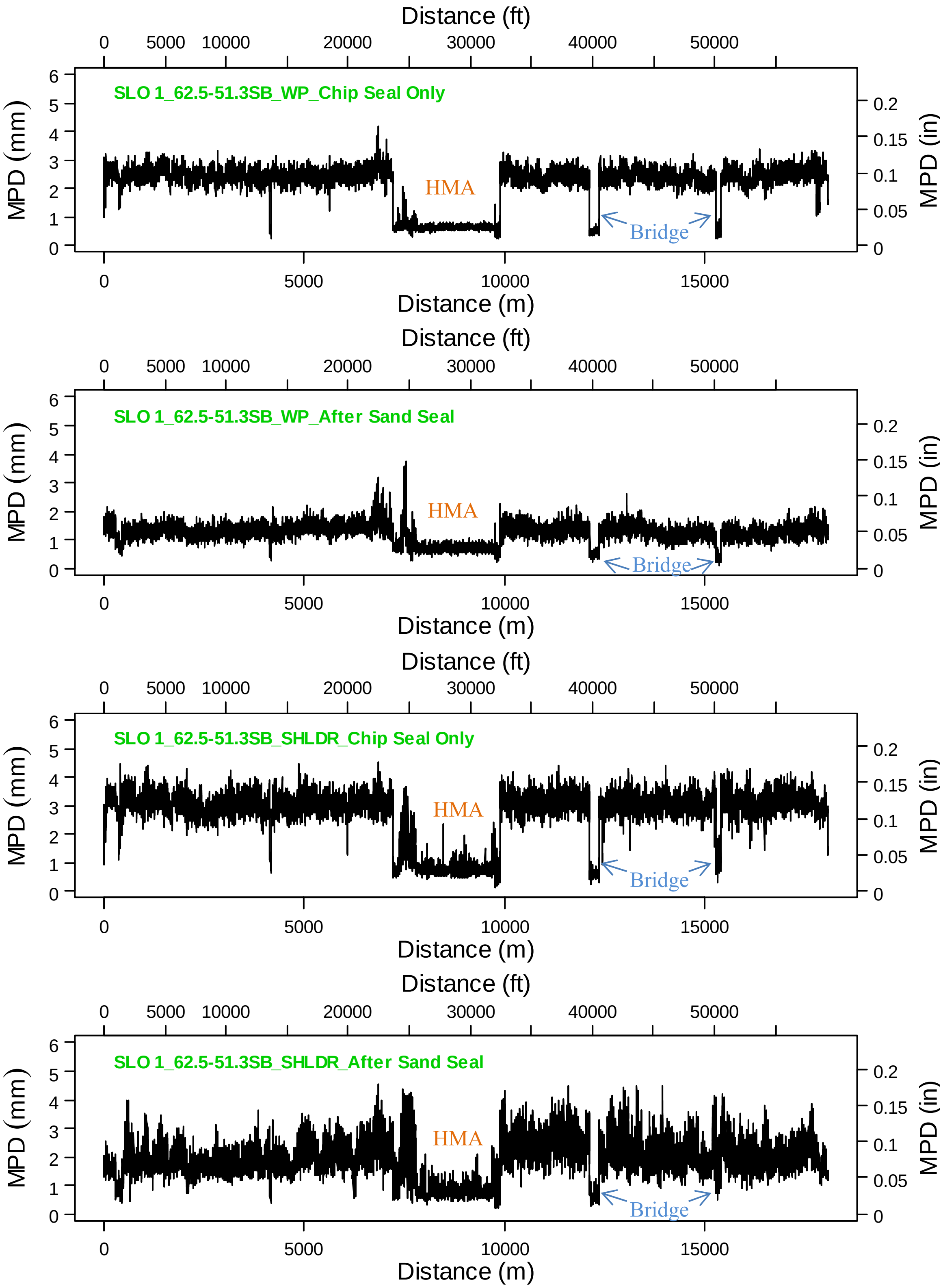
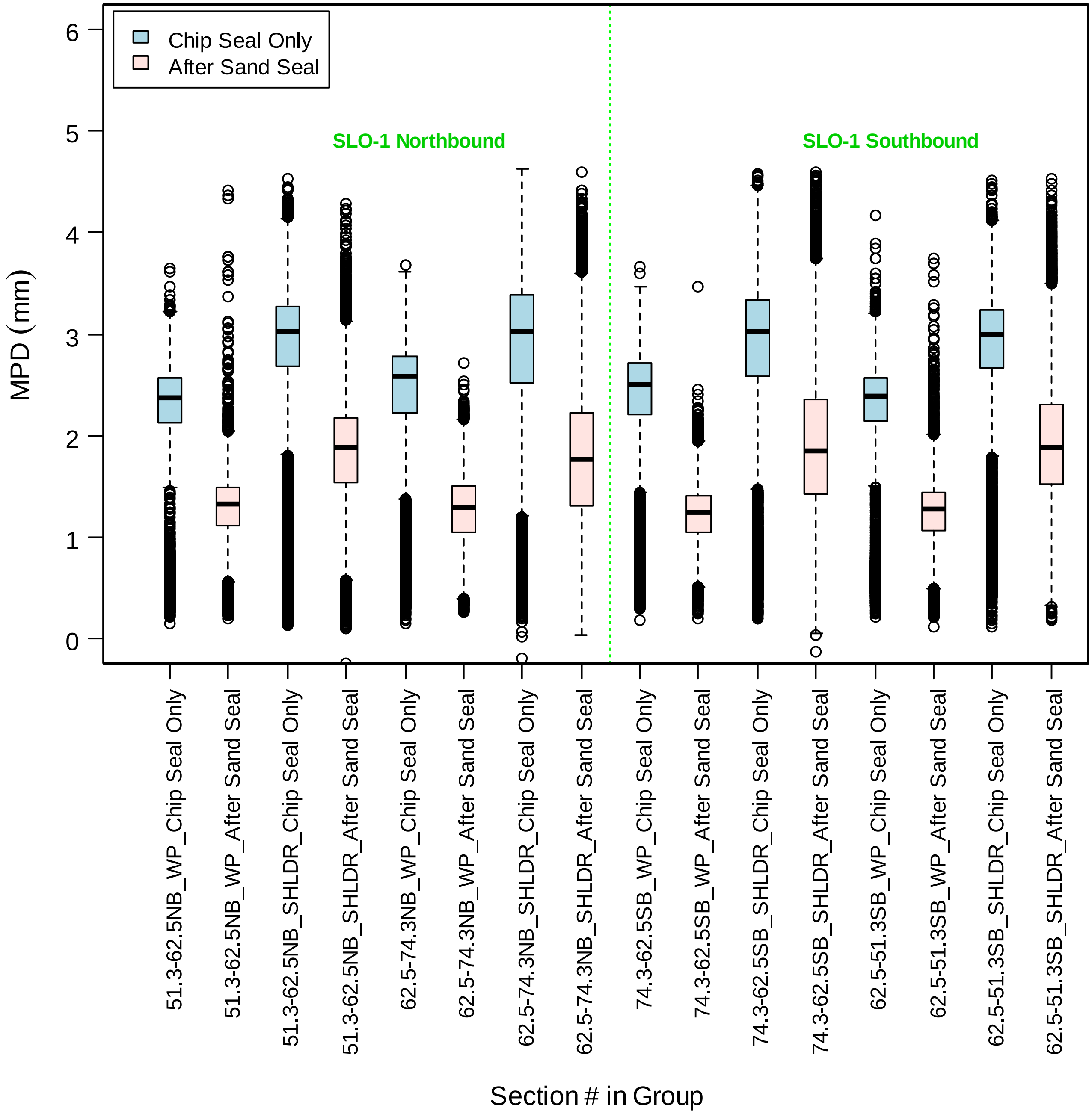


Figure 7.4: MPD of SLO-1 with chip seal only and after sand seal, wheelpath and shoulder (ETW) at PM 51.3-62.5 southbound.

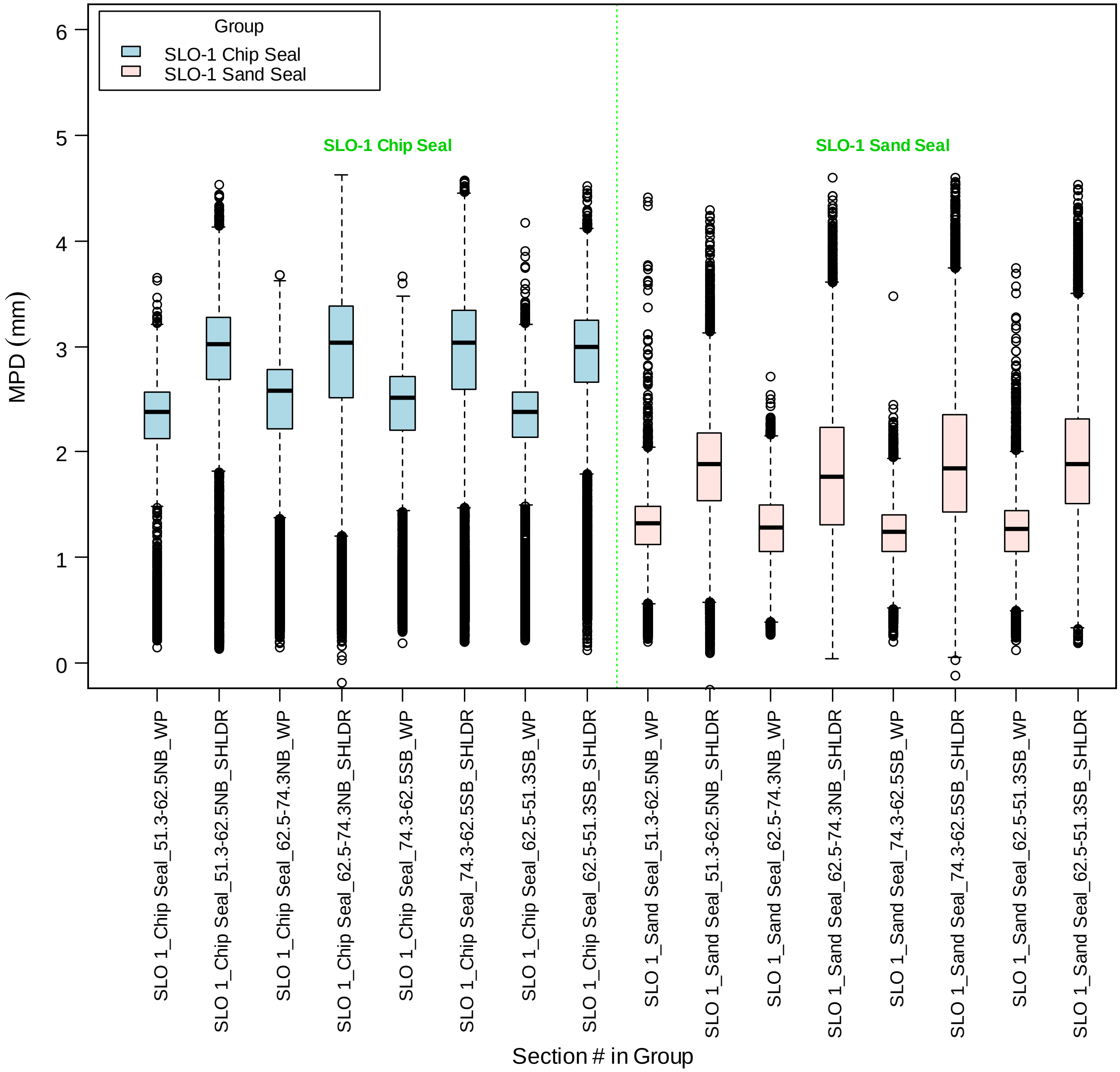
7.2 MPD Summary and Comparison

The MPD of the chip seal and the sand seal on SLO-1 for the shoulders and wheelpaths in both directions are summarized using boxplots in Figure 7.5. It can be clearly seen that the median MPD of sand seal is lower than that of chip seal for both shoulders and wheelpaths. The median MPD for the chip seal on the shoulders is approximately 3.0 mm and approximately 2.5 mm in the wheelpaths, while for the sand seal it is approximately 1.8 mm on the shoulders and 1.3 mm in the wheelpaths. Thus, the remedial treatment of sand seal applied on the chip seal on SLO-1 reduced the median MPD value by approximately 1.2 mm.

Also, as mentioned above, the median MPD in the wheelpath is generally 0.5 mm lower than that on the shoulders (outside of ETW) due to embedment as well as to surface wear from traffic in the wheelpath.



(a) Comparison grouped by treatment type (chip seal versus sand seal on chip seal)



(b) Comparison grouped by location (wheelpath versus ETW [shoulder])

Figure 7.5: MPD summary for SLO-1 with chip seal and after sand seal.
(Note: **the 2013 remedial sand seal was applied on the top of the 2012 chip seal.)**

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

This research report summarizes the macrotexture characterization—in terms of mean profile depth (MPD)—of different pavement surface treatments using three measurement methods. The report also presents the results of measurements of bicycle vibration on many of those test sections, as well as the results of surveys to assess bicycle ride quality and perception of the "acceptability" of pavement test sections. Lastly, this report presents final correlations of macrotexture, bicycle vibration, and bicycle ride quality, and final efforts to develop models that explain how ride quality and the perception of pavement acceptability are 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. Regarding the comparison of different chip seals and other surface treatment sections:
    a. The coarser 3/8" aggregate gradation chip seal specification resulted in larger MPD values than other surface treatments. When placed on SLO-1 and Mno-395, it resulted in median values ranging between 1.7 mm and 3.0 mm; when it was used on Mon-198 it resulted in median values ranging between 1.7 mm and 1.8 mm.
    b. The SLO-227 chip seal, which used a finer 3/8" aggregate gradation than the "coarser" ones used on SLO-1, Mon-198, and Mno-395, had median MPD values of about 1.2 mm, which is considerably lower than those of the coarser chip seals. This conclusion stands, even considering the variability between the latter three chip seals built with the same specification. The variability among those three chip seals is likely due to a combination of different materials and/or 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.)
    c. 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.
    d. The MPD of the shoulders (outside of the Edge of Traveled Way [ETW]) on all sections was typically somewhat larger than that inside the ETW, and there was 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.

e. The naming of the different chip seal specifications can be confusing. For example, the terms "fine" and "medium" have little relation to the relative gradation bands.

3. 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 Mno-395 section could not be seen in the MPD values measured along the entire project, although additional information regarding the precise location of the additional rolling was not obtained from District 9.
4. 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 (treatments 1 and 2).
   a. 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 mm to 2.0 mm, which is similar to the roughly 1.7 mm 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 the SLO-1 and Mno-395 pavements built with the same coarser 3/8" chip seal specification.
   b. Treatments 1 and 2 may have had some reduction in MPD after a year of traffic, as occurred on treatment 3, where traffic reduced the MPD in the wheelpath to about 1.6 mm 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.
   c. It is uncertain based on this single example whether these two alternatives can consistently produce MPD values lower than those on SLO-1, as they did on Mon-198, although the initial results are promising.
5. 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 coarser 3/8" chip seal were all lower than the MPD of the untreated chip seal section (shown as treatment 10).
6. High correlations were revealed between MPD, vertical bicycle acceleration, what bicyclists considered "acceptable" pavement, and bicycle ride quality level. Medium to weak correlations were revealed between IRI, bicycle vibration, acceptability, and ride quality level. Relatively weak correlation was found between bicycle vibration and bicycle speed. No significant correlation was found between bicyclists' rating of ride quality and acceptability versus bicycle speed, although only a small range of speeds was included in the study.

7. Based on input from cyclists participating in the initial Mon-198 and SLO-1 surveys, the range of what bicyclists considered an “acceptable” level of MPD was found to be approximately between 2.0 mm and 2.7 mm, with the percentages for 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.
8. Based on input from cyclists participating in the initial Phase I Mon-198 and SLO-1 surveys and the additional surveys in Phase II, the range of what bicyclists considered an “acceptable” level of MPD was found to be approximately between 1.3 mm and 2.3 mm, with the percentages for that range of MPD values as follows:
    1. 80 percent found 1.3 mm acceptable.
    2. 60 percent found 1.8 mm acceptable.
    3. 50 percent found 2.1 mm acceptable.
    4. 40 percent found 2.3 mm acceptable.
9. The average ride quality level ratings (on a scale of 1 to 5) from the riders participating in the Phase I Mon-198 and SLO-1 surveys and the additional Phase II surveys were approximately:
    1. 3.5 for an MPD of 1.0 mm
    2. 3.0 for an MPD of 1.5 mm
    3. 2.5 for an MPD of 2.0 mm
    4. 1.5 for an MPD of 3.0 mm
10. Models were developed for the ratings of pavement acceptability and bicycle ride quality, with the variables MPD, IRI, and variability of IRI all being significant. When sociodemographic variables representing recent rider mileage and how much a rider considers wind and cycling companionship were added to the model, they were found to be significant. Tire pressure was also significant when added to the model.

8.2 Recommendations

Based on the results of this study, the following final recommendations are made regarding pavement macrotexture and its effect on bicycle vibration and ride quality:

1. In order to take bicycle traffic and bicycle ride quality into consideration when applying chip seals, the finer 3/8" chip seal aggregate gradation bands or smaller should be used and the coarser 3/8" gradation bands should not be used.
2. Clear guidance should be provided to designers regarding the potential effects on bicycle ride quality if the coarser chip seal gradation is used. Consider advising designers to select gradations that have MPD below approximately 2.5 mm on freshly placed chip seals when bicycle ride quality is an issue. This will require better information than is currently available regarding the relationship between gradation and MPD for chip seals.
3. A review of chip seal naming conventions is recommended to help reduce the potential for confusion. Any names that include reference to the aggregate gradation should reflect relative differences in coarseness and the aggregate size of the largest chips.
4. Consider performing research to measure macrotexture on existing chip seal projects with different chip seals to provide better information to designers regarding the relationship between gradation and MPD.
5. Mandating the use of a steel roller—as opposed to allowing use of steel or rubber-tired rolling during construction—to reduce MPD is not recommended. The use of additional rolling after initial construction to reduce MPD is not recommended.
6. Long-term monitoring (one or two more years) of the texture changes on the Mon-198 and SLO-1 sections should be considered to determine the effects of traffic on texture.

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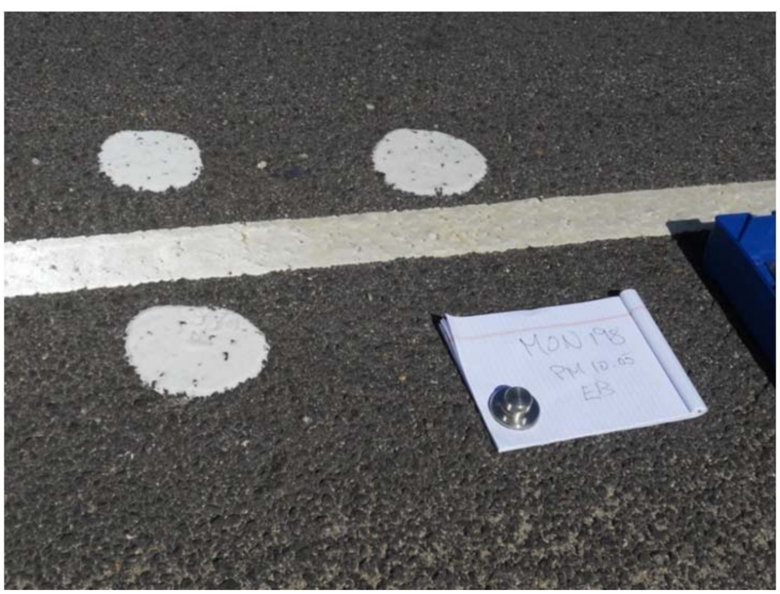
APPENDIX A: MACROTEXTURE MEASURED USING SAND PATCH (SP) METHOD

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 cyclists 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: Examples of sand patch testing on the pavement surface.

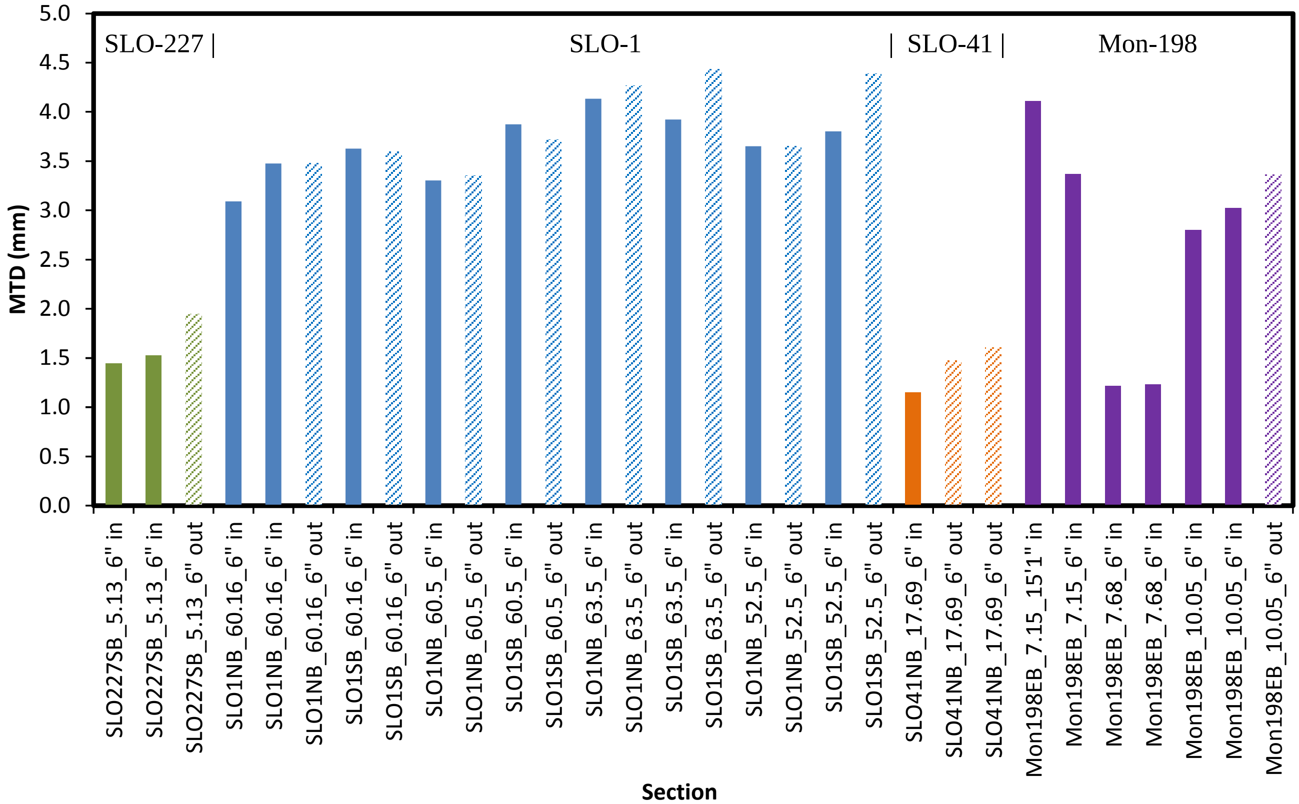


Figure A.2: MTD from sand patch testing for different road sections.
(*Note:* inside ETW measurements are shown with solid bars; outside ETW measurements shown with patterned bars.)

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:

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

The ETD-calculated values using this equation and the MPD values from the LTS measurements are presented in Figure A.3. The LTS device uses the ASTM equation (A.1) to calculate MTD (called ETD when calculated using a laser device). The MPD from the sand patch is calculated using the same equation in reverse [i.e., MPD_SP = (MTD_SP – 0.2)/0.8]. Results measured with the sand patch and LTS are compared along with the values calculated using Equation A.1 in Figure A.4. These results show that MPD calculated from sand patch measurements is larger than those measured using the LTS for the same locations in this study.

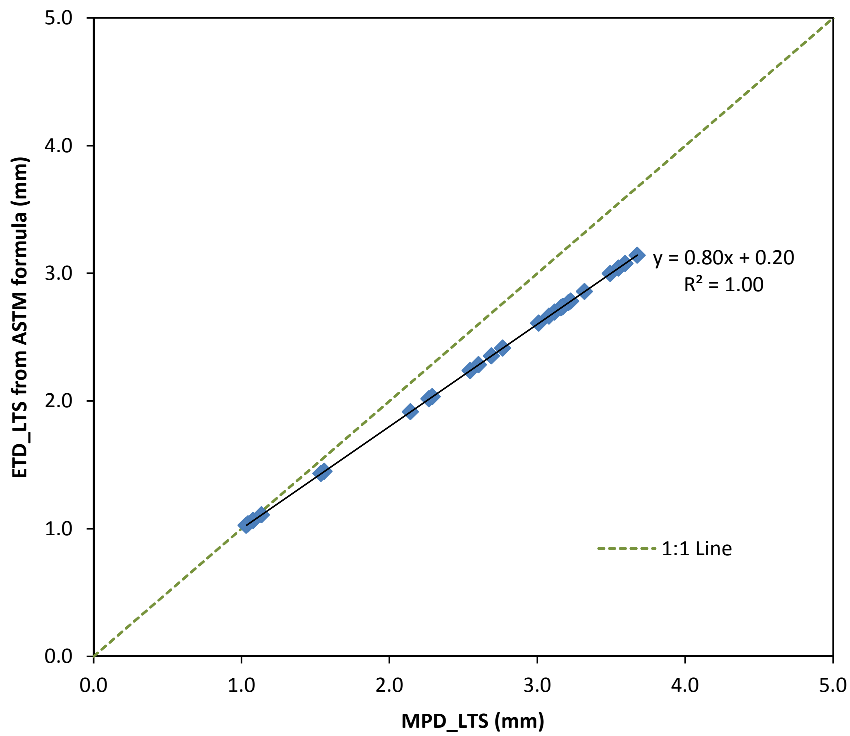


Figure A.3: Estimated Texture Depth (ETD, same as Mean Texture Depth) from MPD measured using LTS.

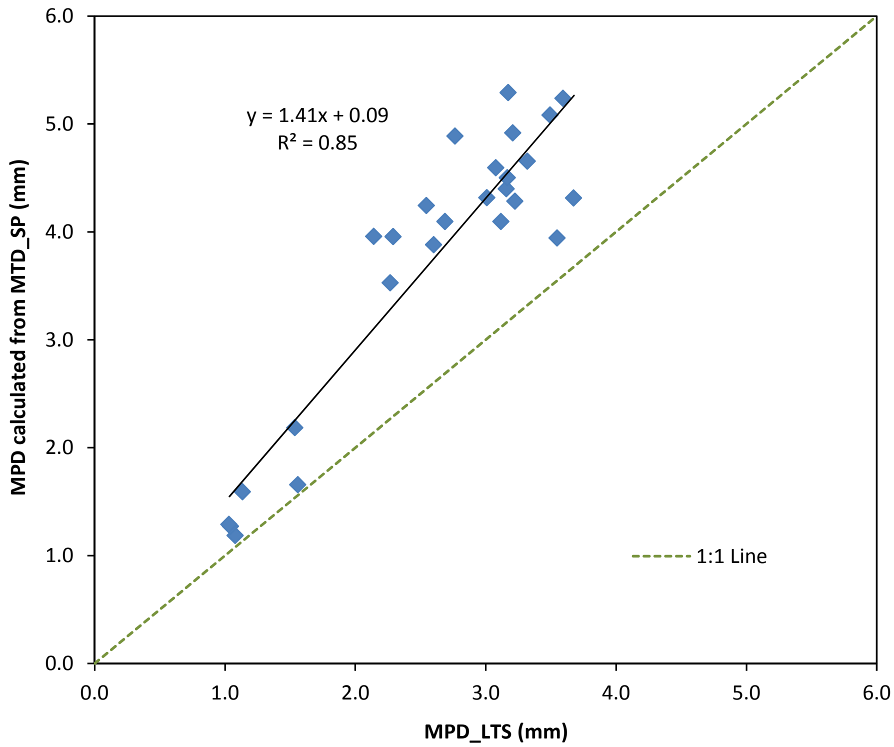


Figure A.4: Correlation between macrotexture parameters measured by sand patch (SP) and LTS.
(Note: **MPD_SP is calculated from MTD_SP using the ASTM equation in reverse.)**

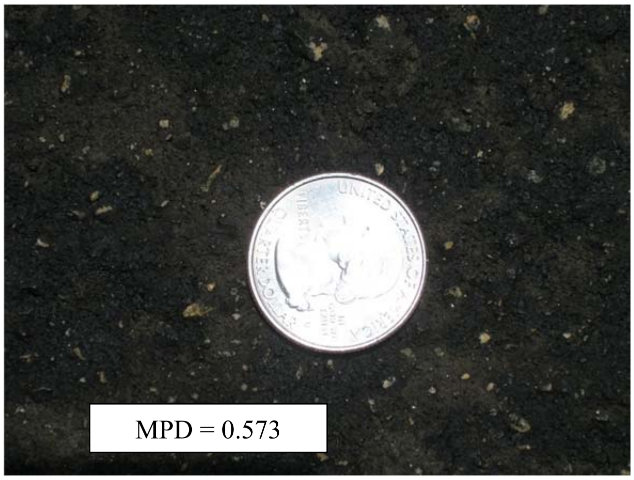
APPENDIX B: PHOTOS AND MPD FROM LTS FOR TEST SECTIONS ON MON-198

#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)



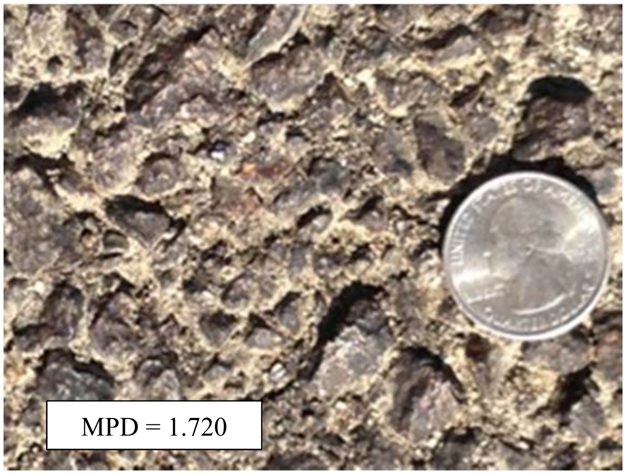
#5 Microsurfacing (PM 10.2-10.0)

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

#7 Sand seal (PM 9.6-9.8)

#8 Slurry seal (PM 9.4-9.6)

#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

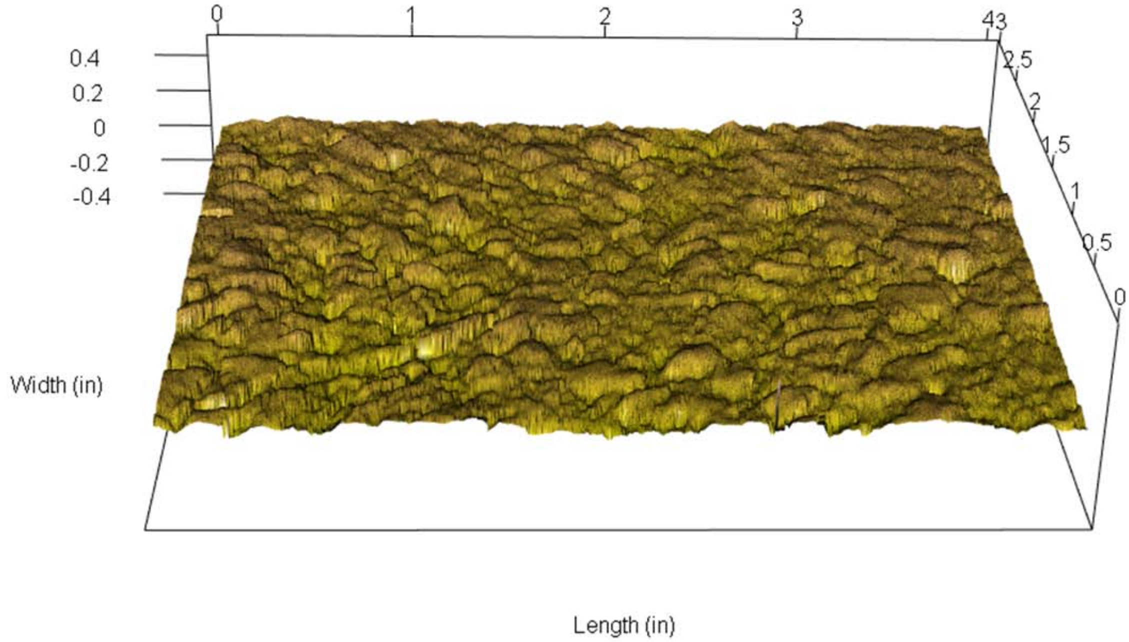
Table C.1: Summary of MPD Measured by LTS for All Road Sections

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	6.8	6" inside ETW	1.046	Coarser 3/8" chip seal	C.3
Mon-198	EB	6.81	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	-
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	-

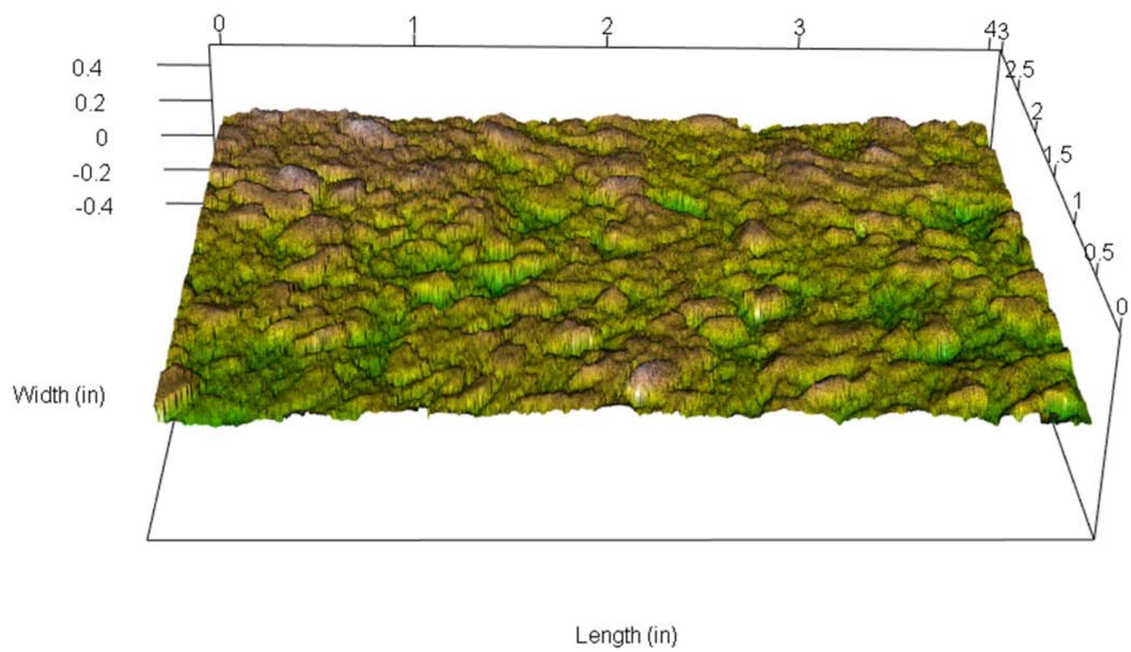
Route	Direction	PM (mile)	Location	Avg. MPD (mm)	Treatment	3D Figure in Appendix C
Mon-198	EB	4.9 – 5.1	Inside ETW	2.27	#3 Modified binder seal coat — Utilizing a steel roller	C.5
Mon-198	EB	4.9 – 5.1	Left wheelpath	2.45	#3 Modified binder seal coat — Utilizing a steel roller	-
Mon-198	WB	10.2 – 10.4	Inside ETW	0.92	#4 Cinder seal	C.5
Mon-198	WB	10.2 – 10.4	Left wheelpath	0.59	#4 Cinder seal	-
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	-
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	-
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	-
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	-
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	-
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.1: SLO-41

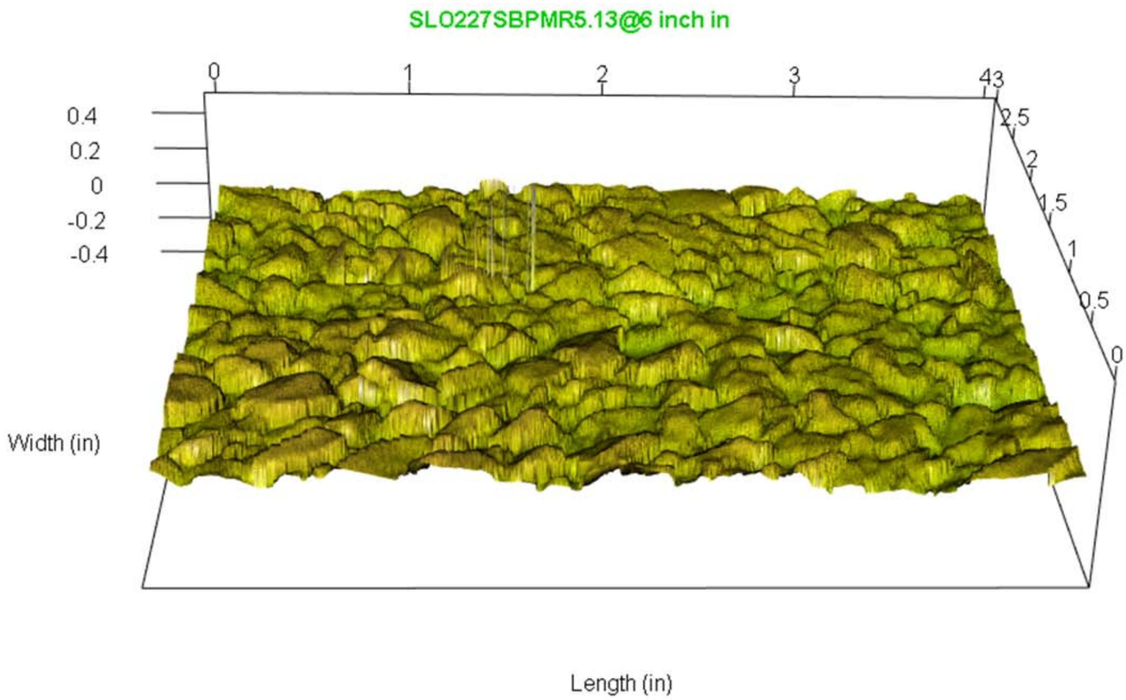
SLO41NBPM17.69@6 inch in



SLO41NBPM17.69@6 inch out



C.2: SLO-227


SLO227SBPMR5.13@6 inch in
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Width (in)
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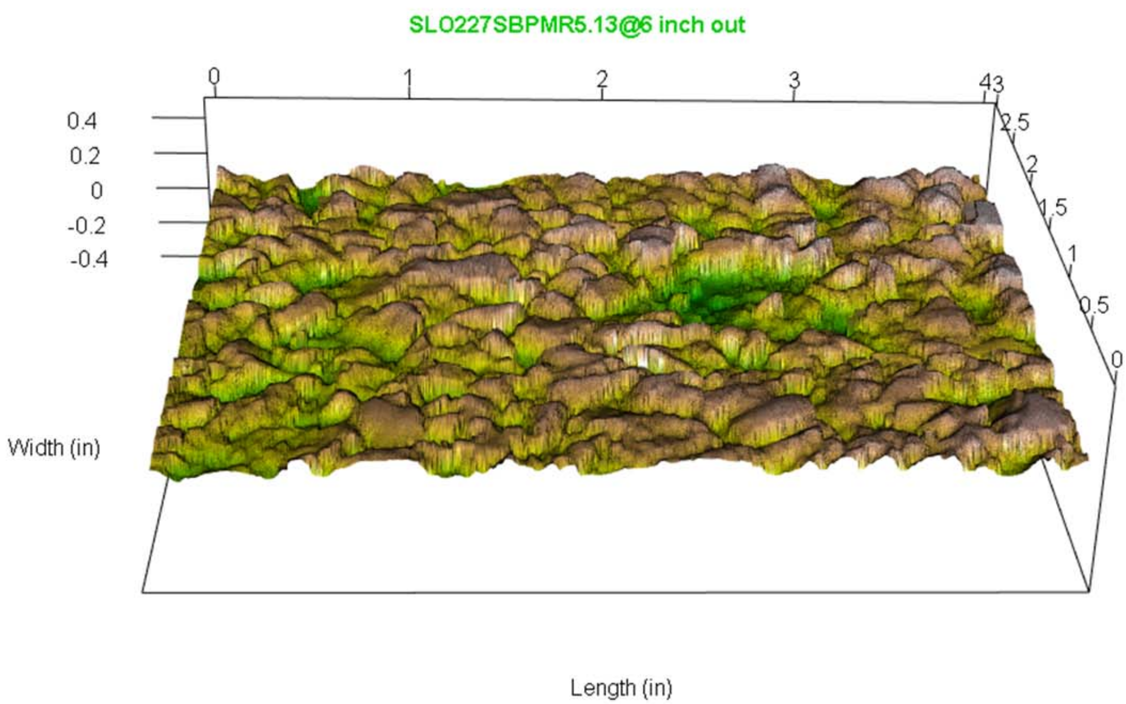
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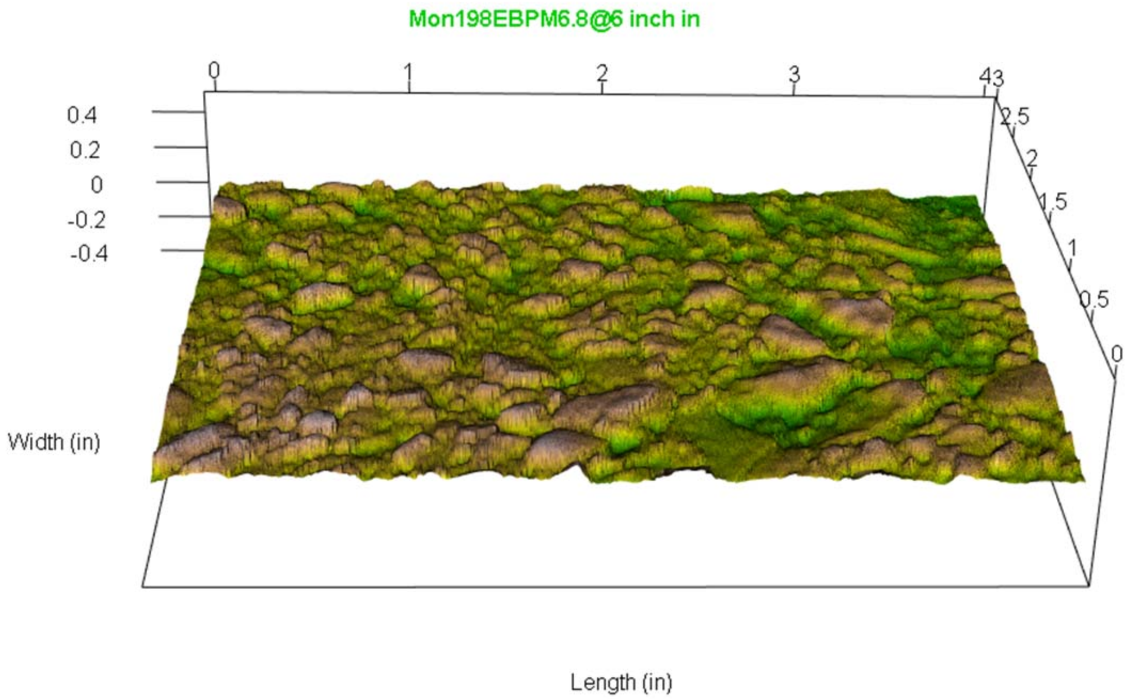
Width (in)
Length (in)

C.3: Mon-198



Mon198EBPM6.8@6 inch in
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4
0.4
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Width (in)
Length (in)

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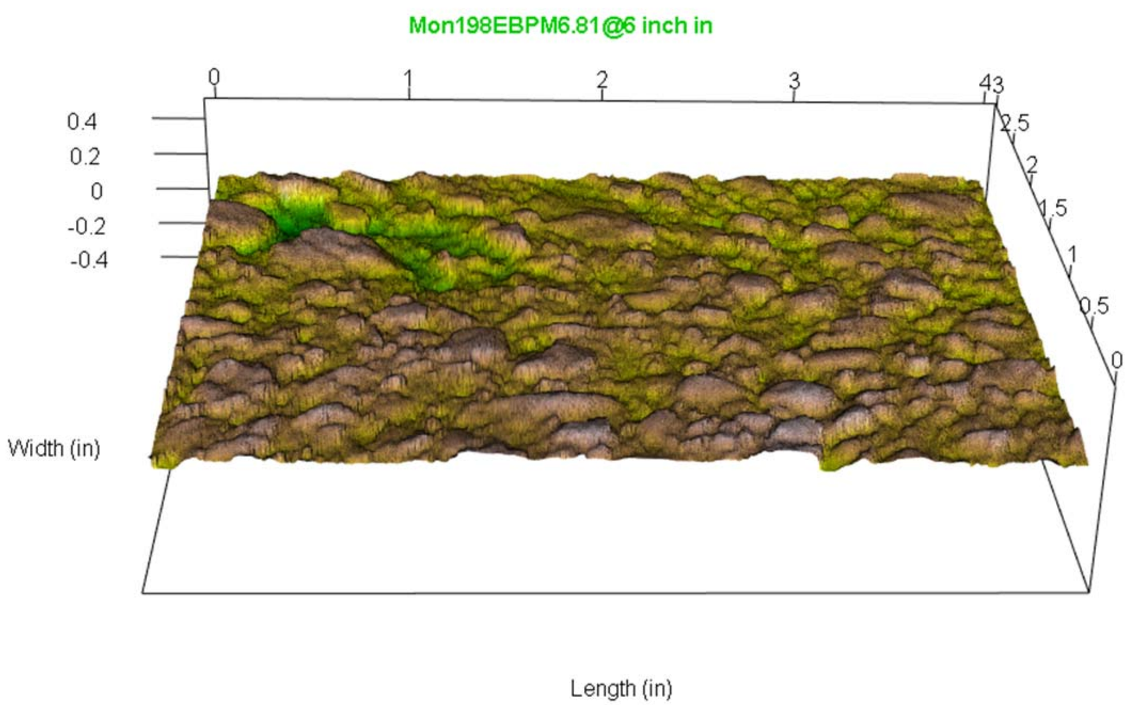

Mon198EBPM6.81@6 inch in
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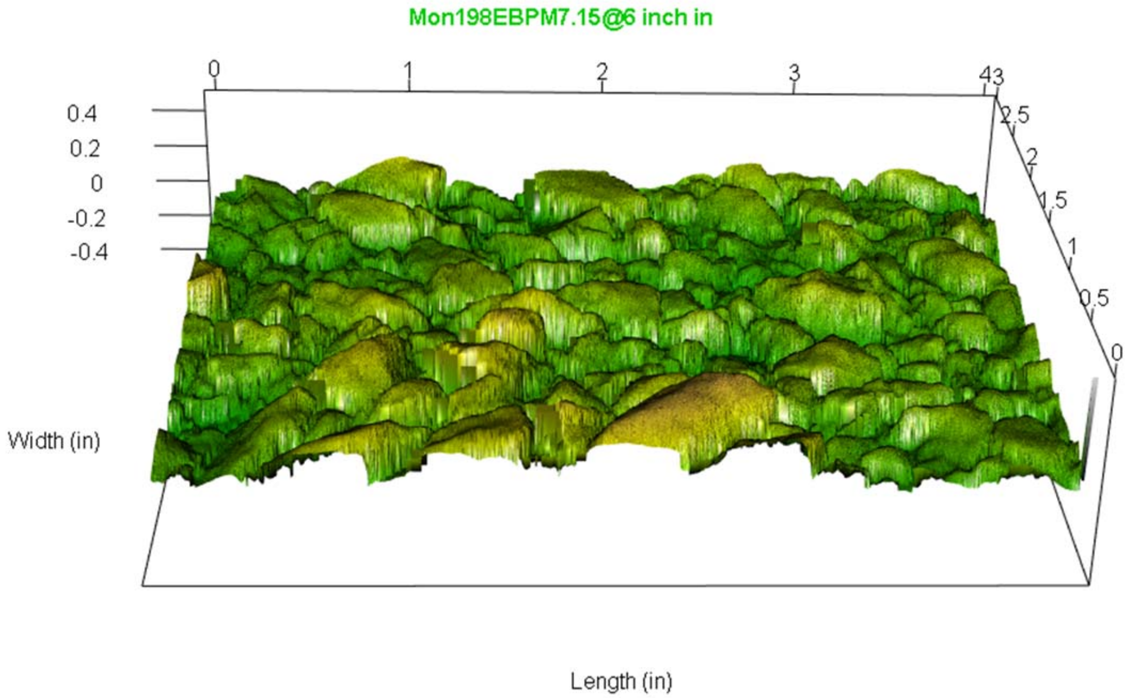

Mon198EBPM7.15@6 inch in
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1
2
3
43
0.4
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-0.4
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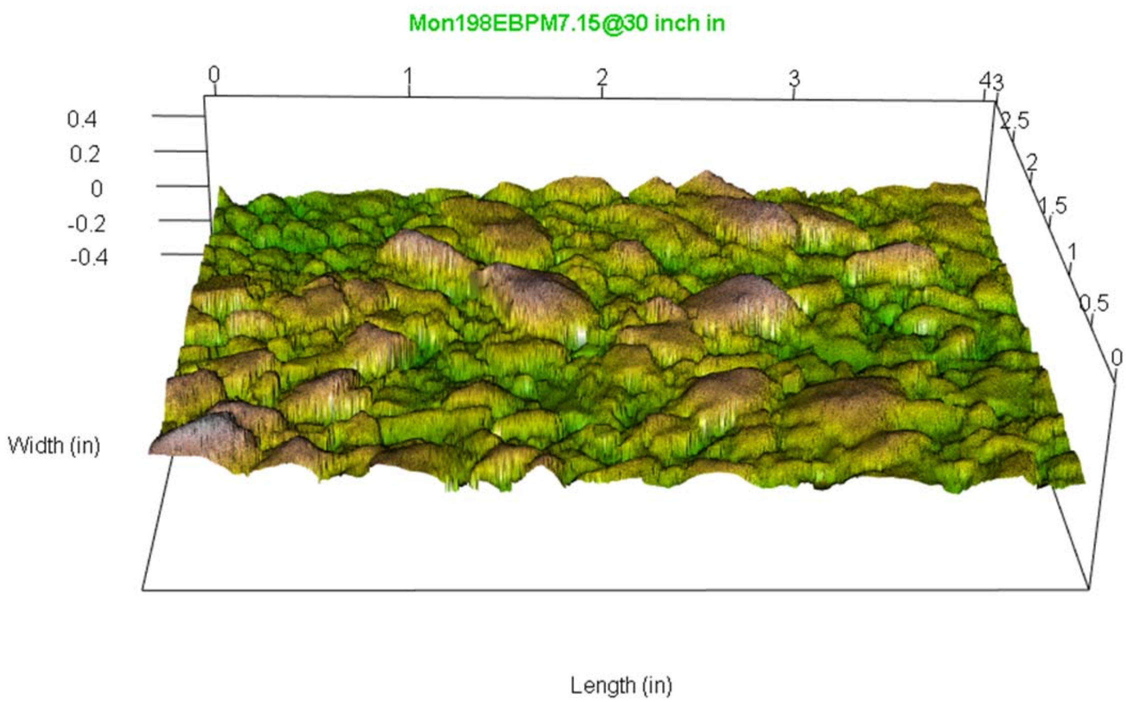
Width (in)
Length (in)



Mon198EBPM7.15@30 inch in
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1
2
3
43
0.4
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-0.4
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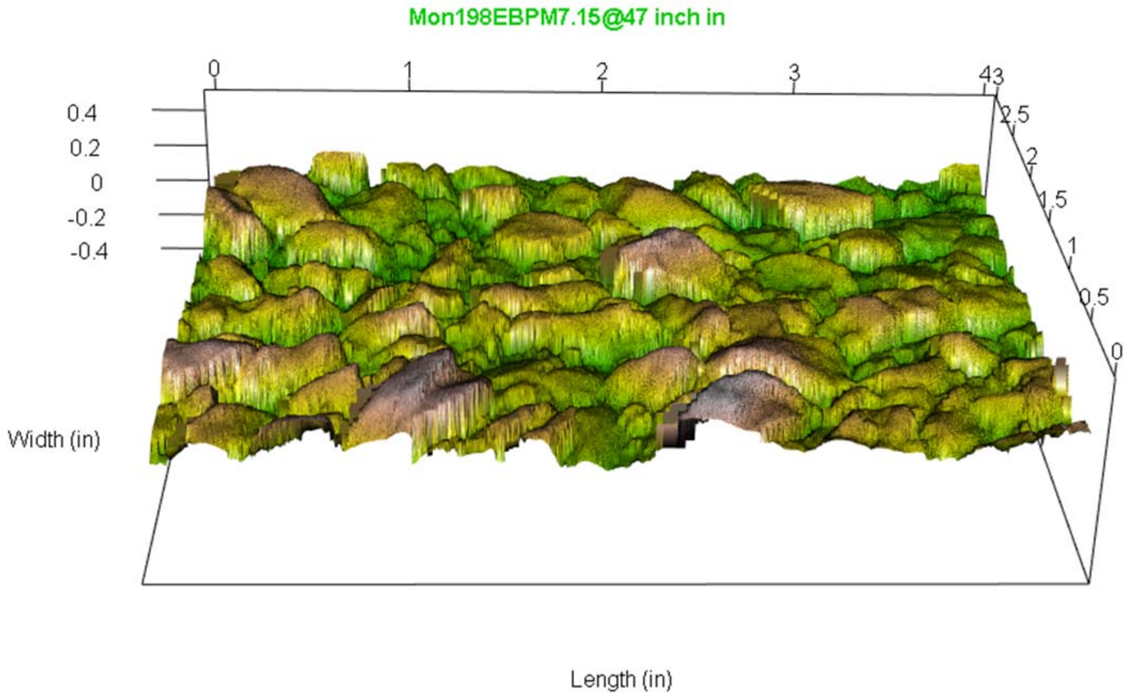
Width (in)
Length (in)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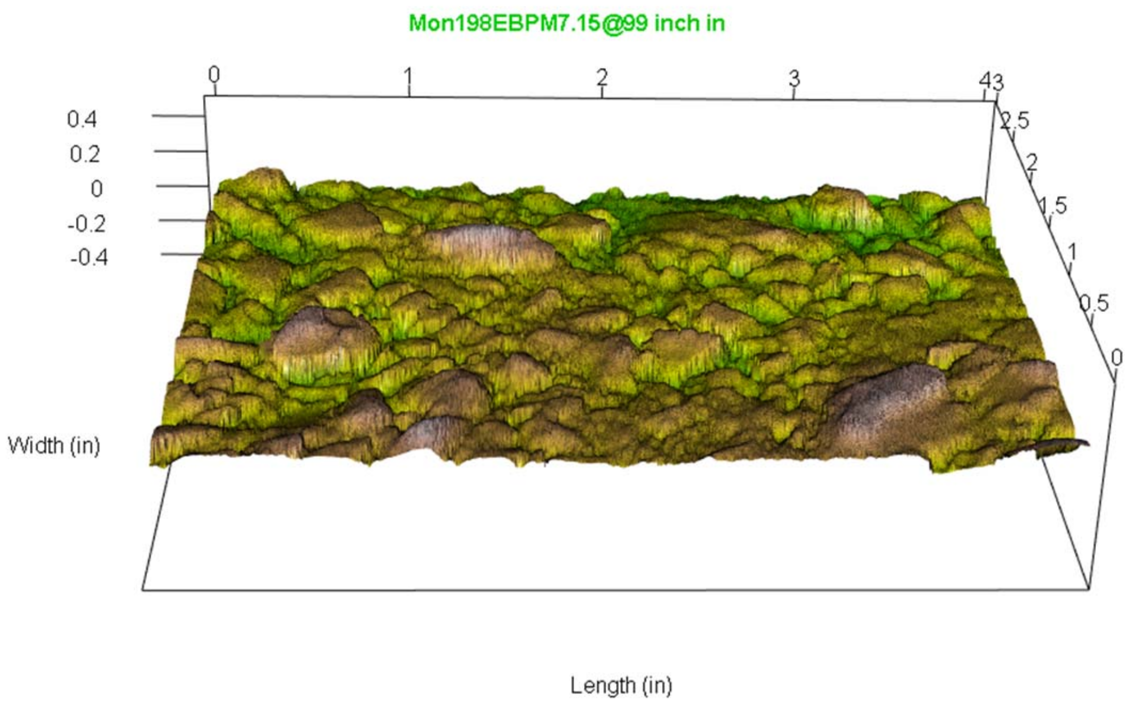
Width (in)
Length (in)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4
3
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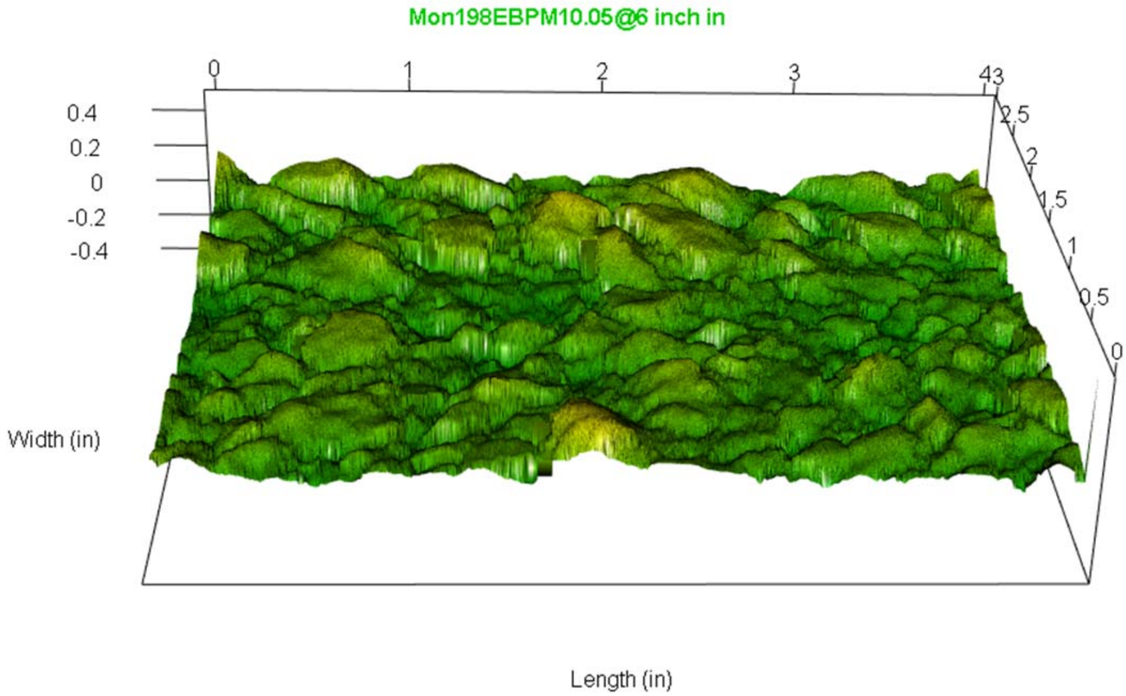
Width (in)
Length (in)


Mon198EBPM10.05@6 inch in
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Width (in)
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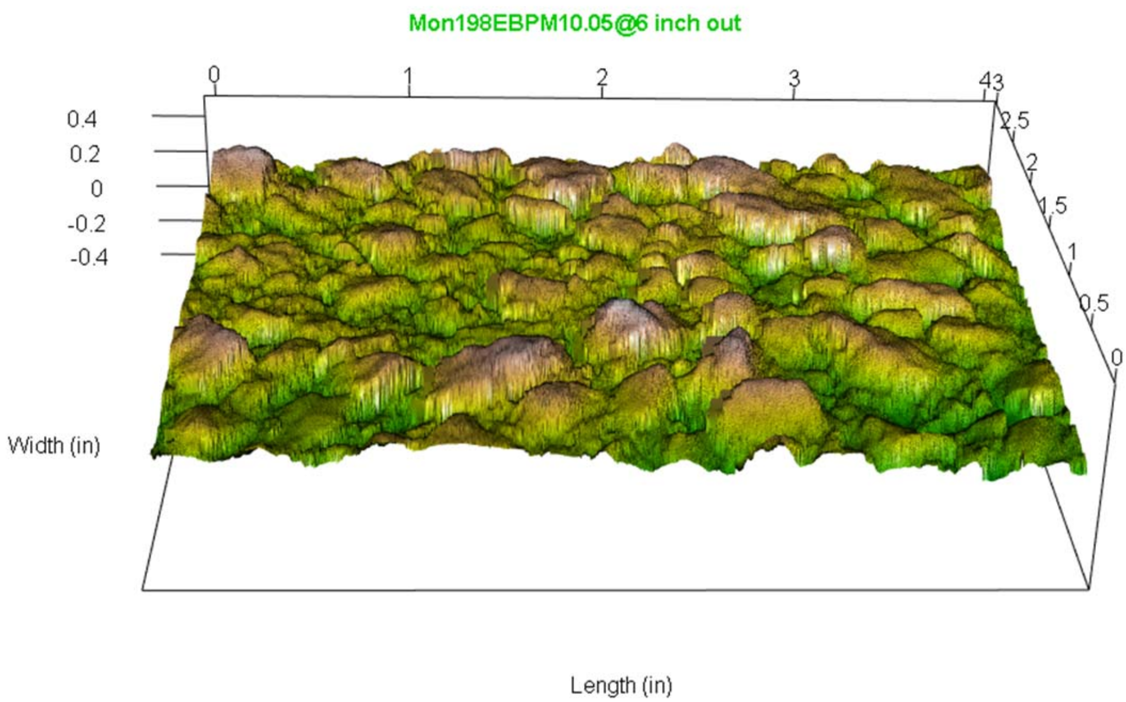
Mon198EBPM10.05@6 inch out
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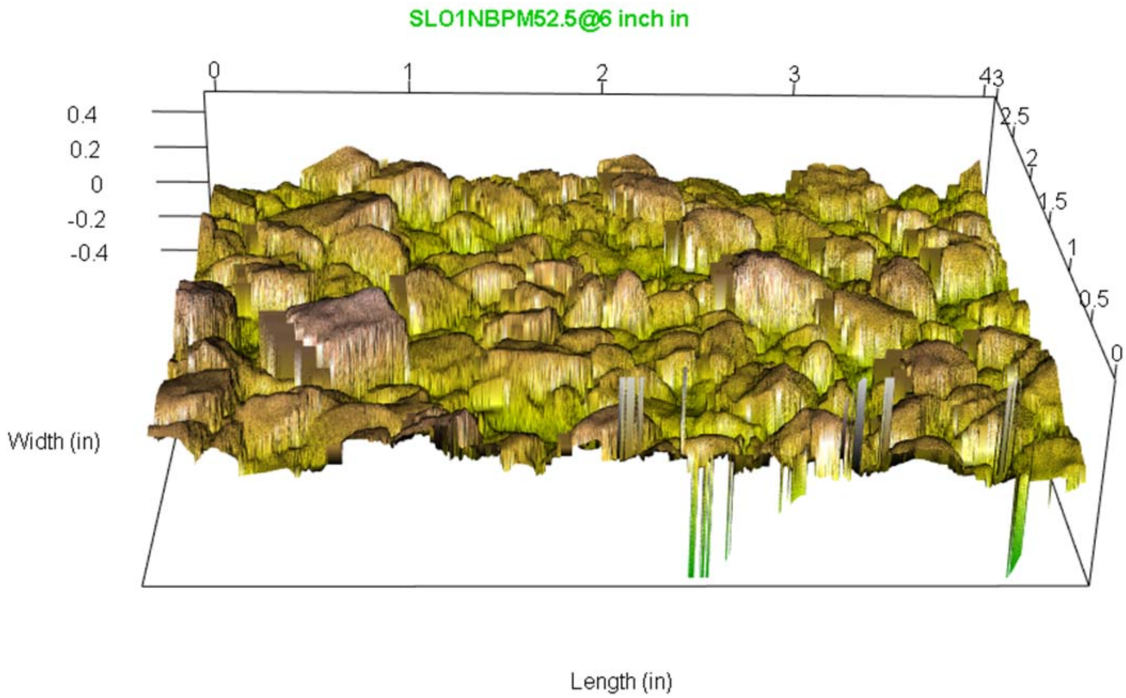
Width (in)
Length (in)

C.4: SLO-1



SLO1NBPM52.5@6 inch in
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2
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4
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Width (in)
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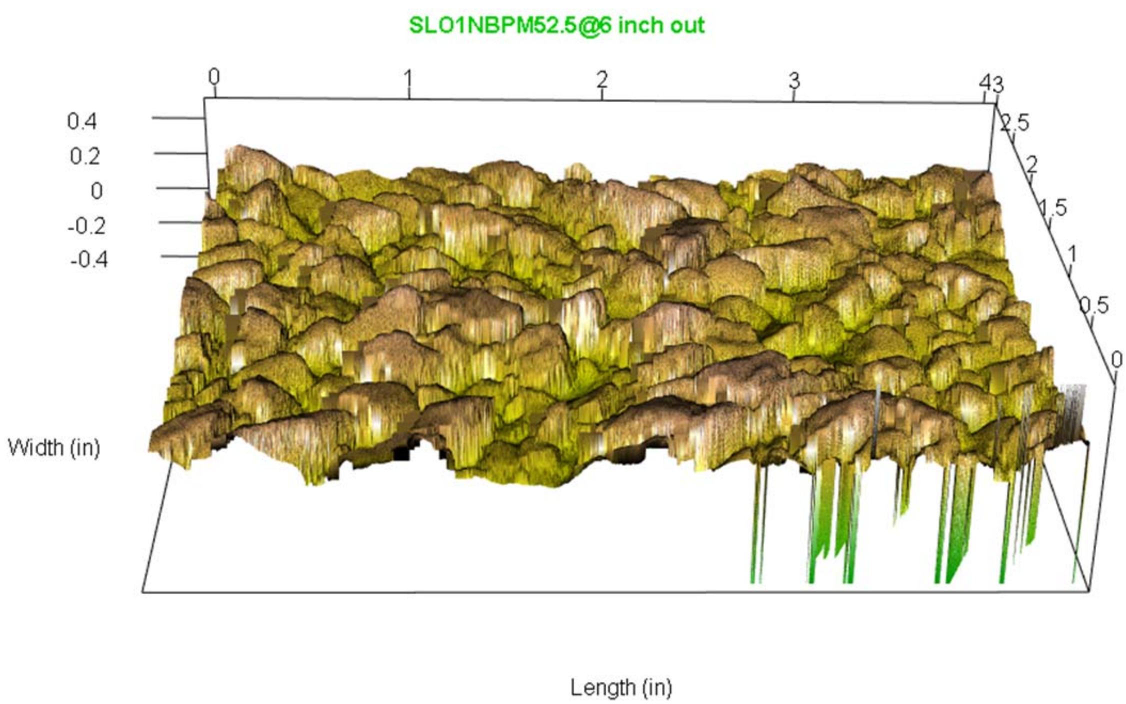

SLO1NBPM52.5@6 inch out
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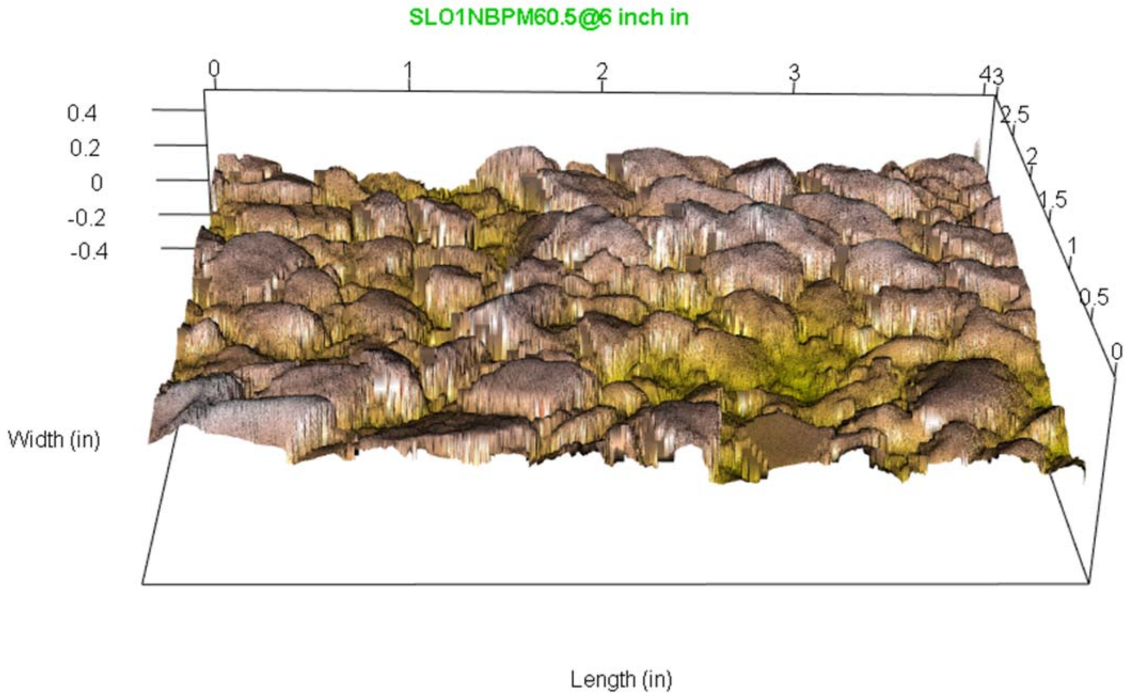
Width (in)
Length (in)


SLO1NBPM60.5@6 inch in
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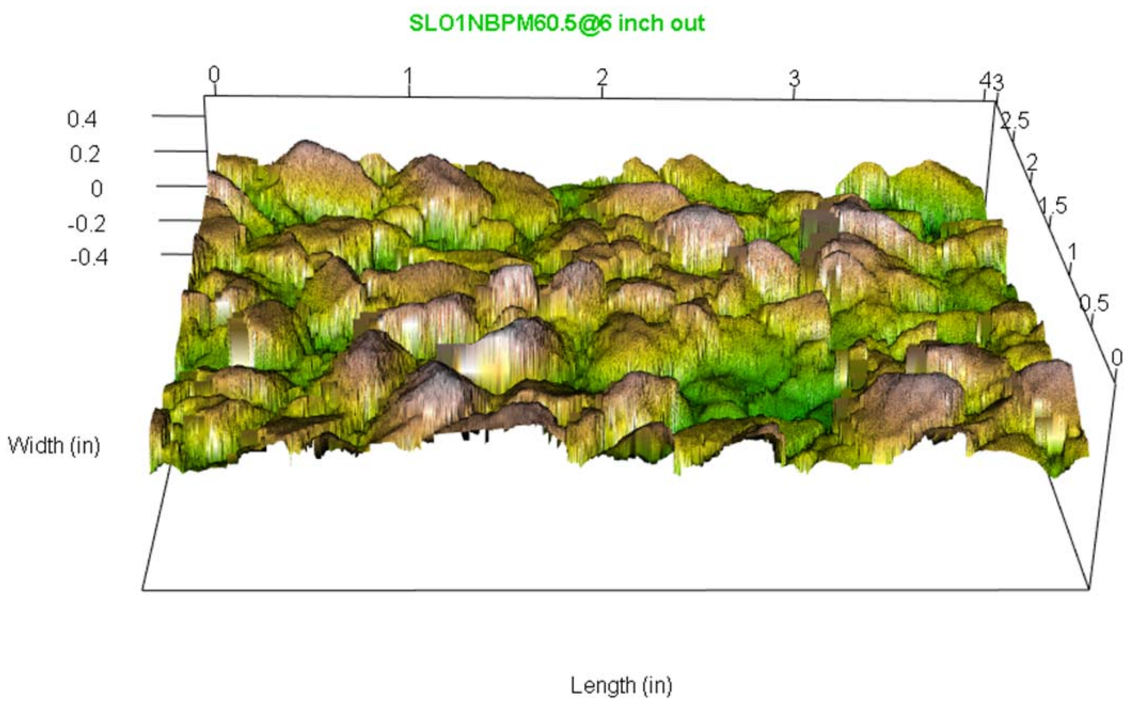
Width (in)
Length (in)


SLO1NBPM60.5@6 inch out
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2
1.5
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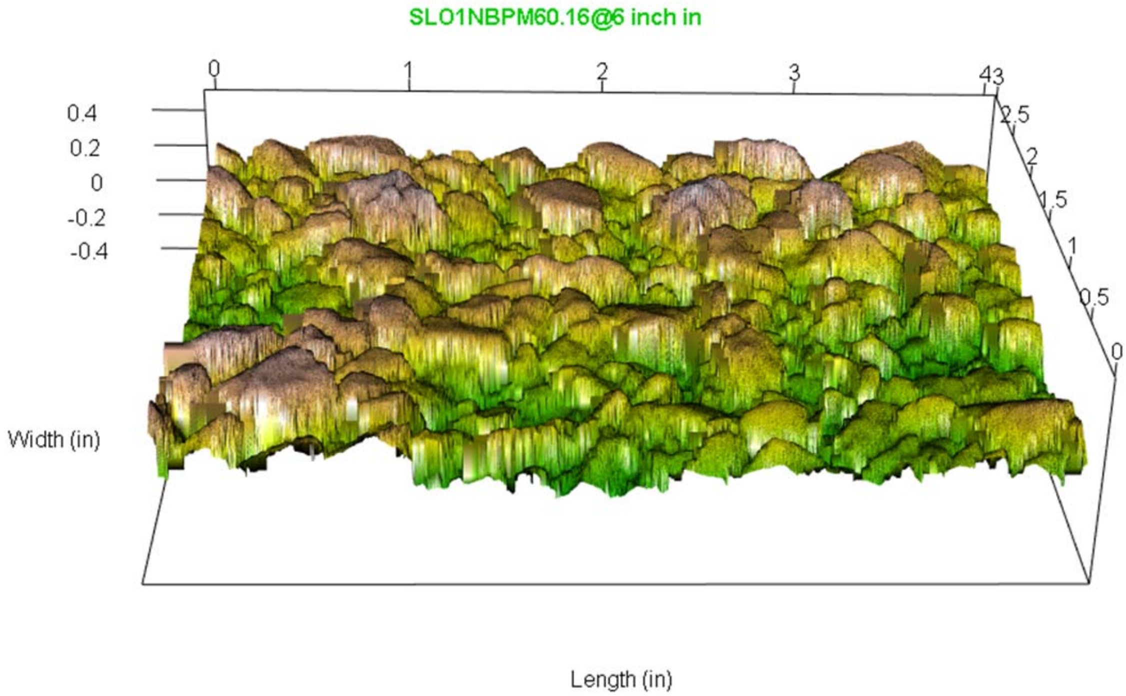
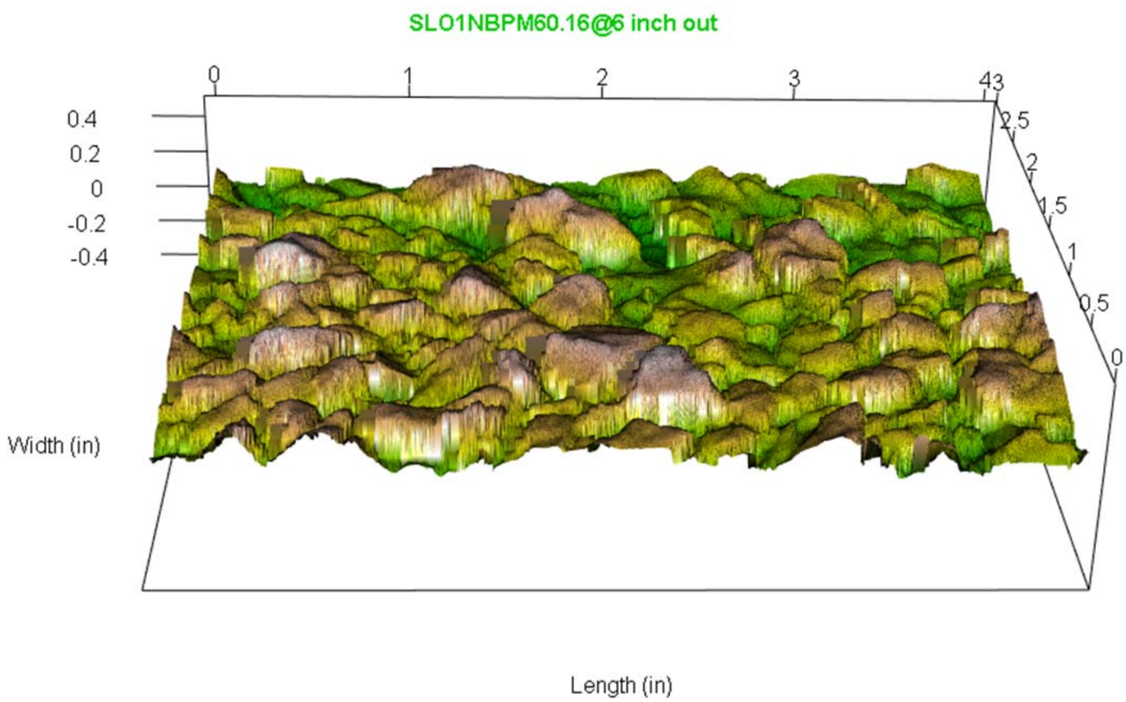
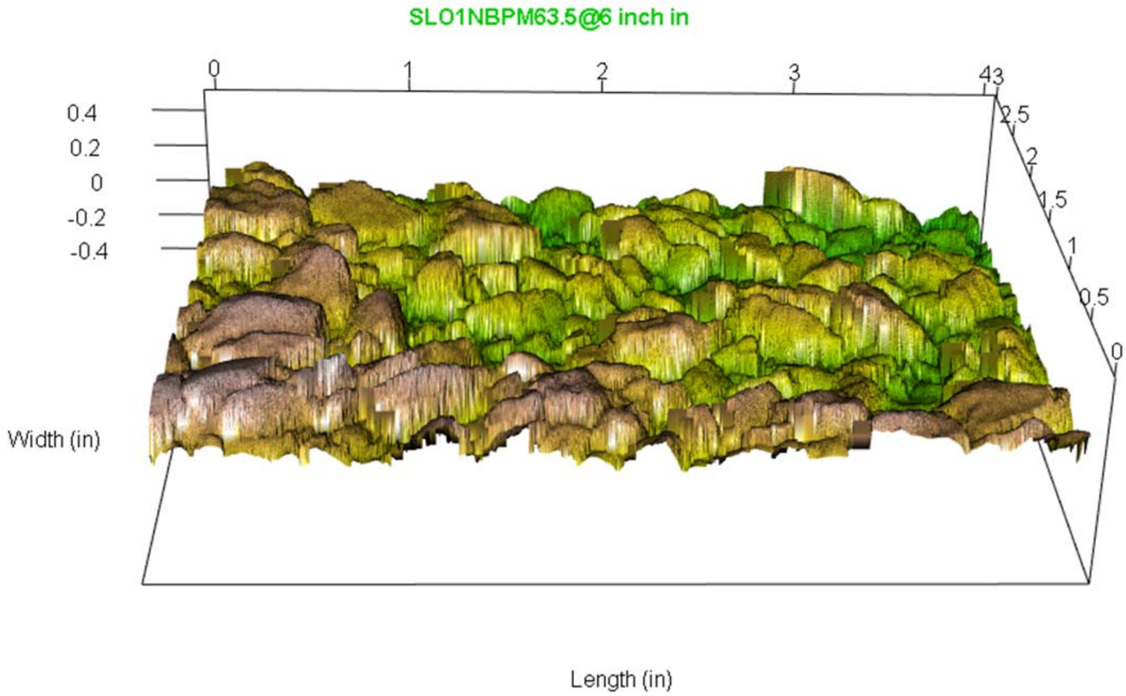
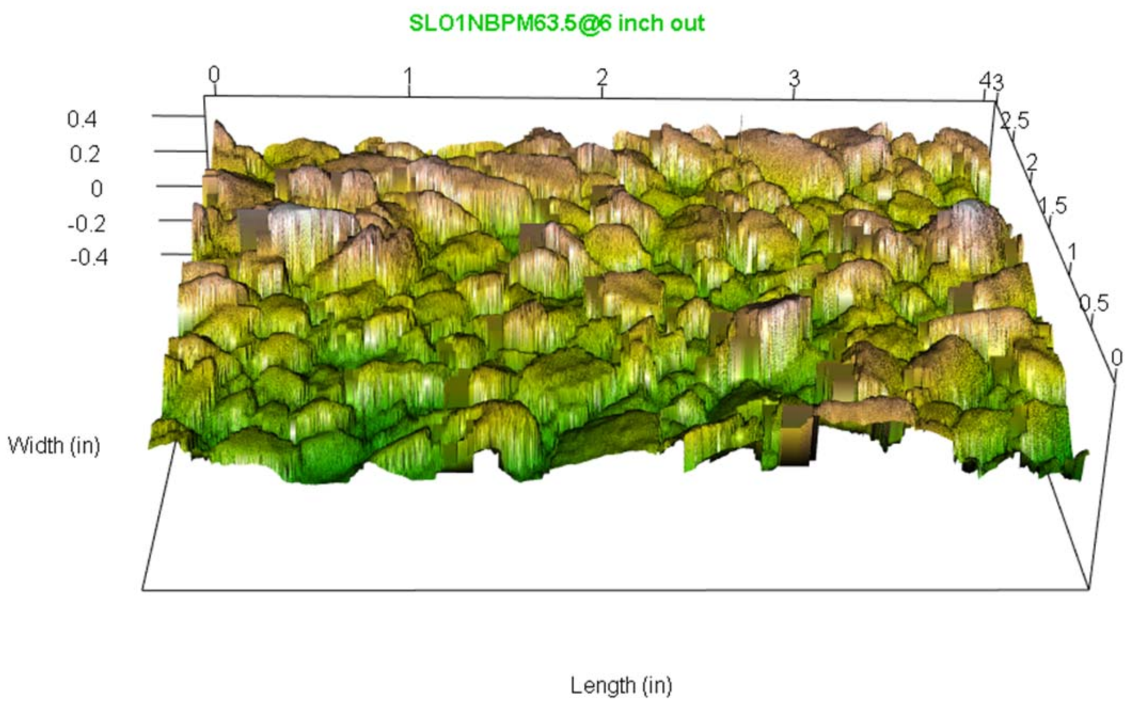
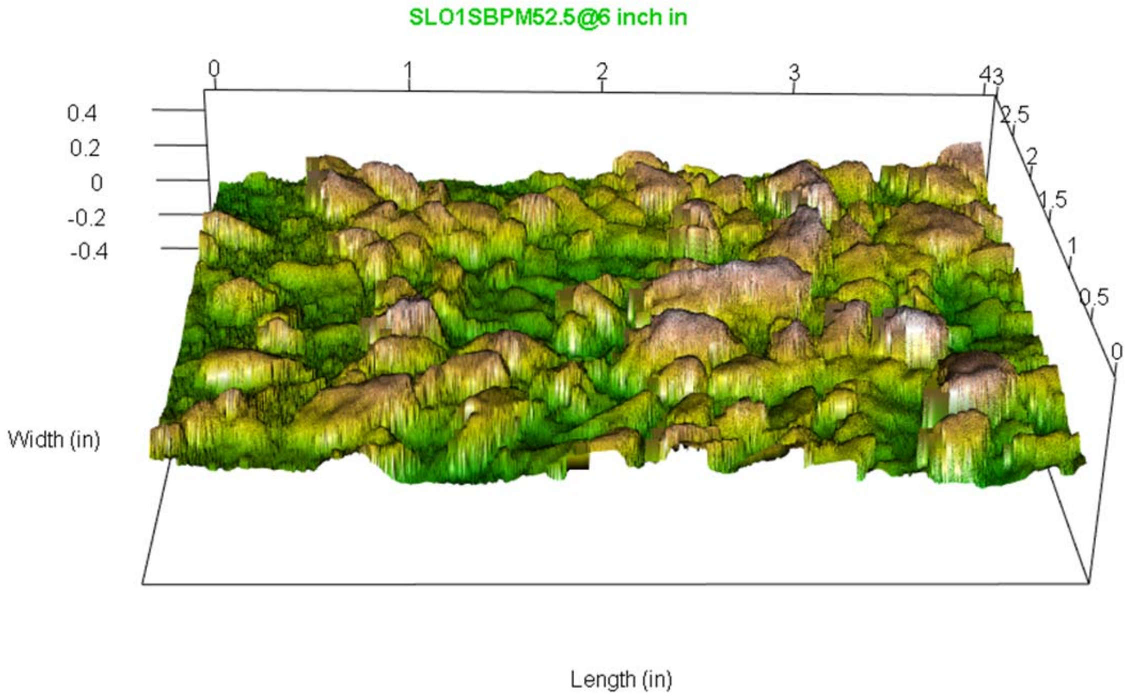
0.5
0
Width (in)
Length (in)

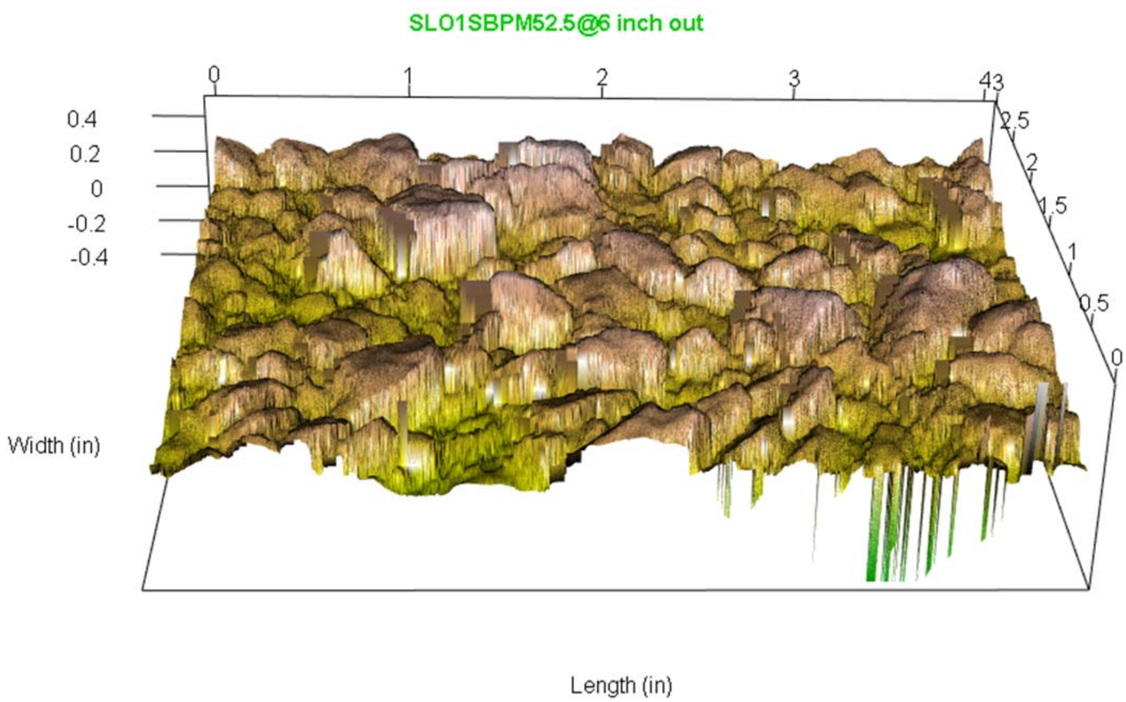

SLO1NBPM60.16@6 inch in
0
1
2
3
4
3
2.5
2
1.5
1
0.5
0
0.4
0.2
0
-0.2
-0.4
Width (in)
Length (in)

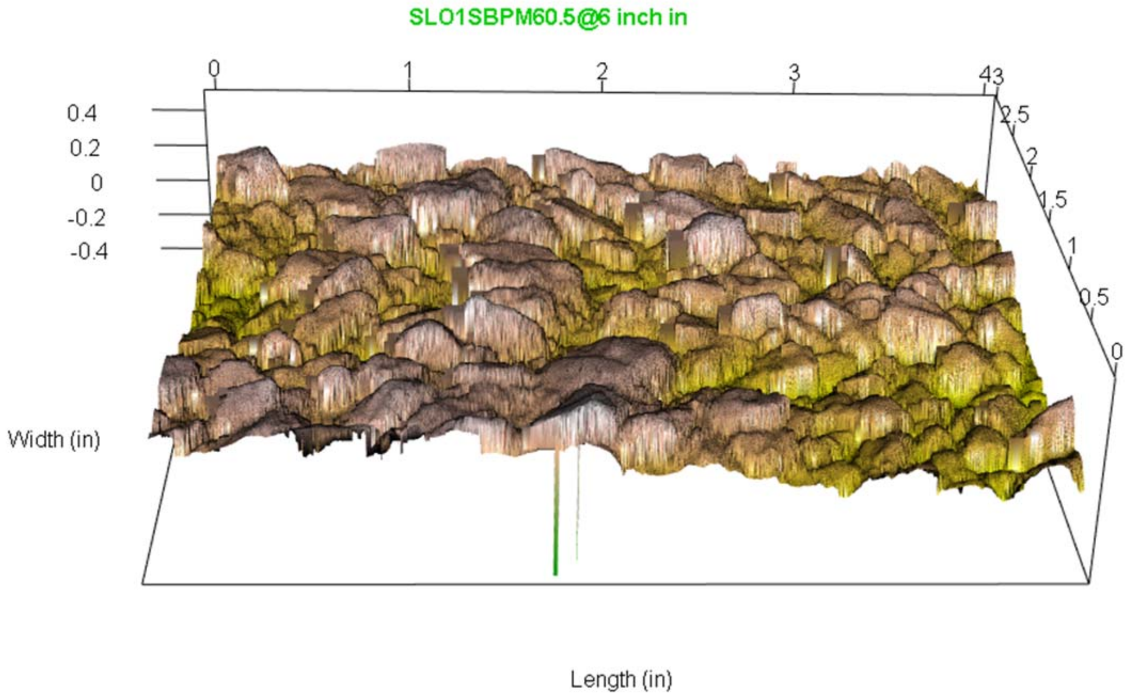

SLO1NBPM60.16@6 inch out
0
1
2
3
4
3
2.5
2
1.5
1
0.5
0
0.4
0.2
0
-0.2
-0.4
Width (in)
Length (in)

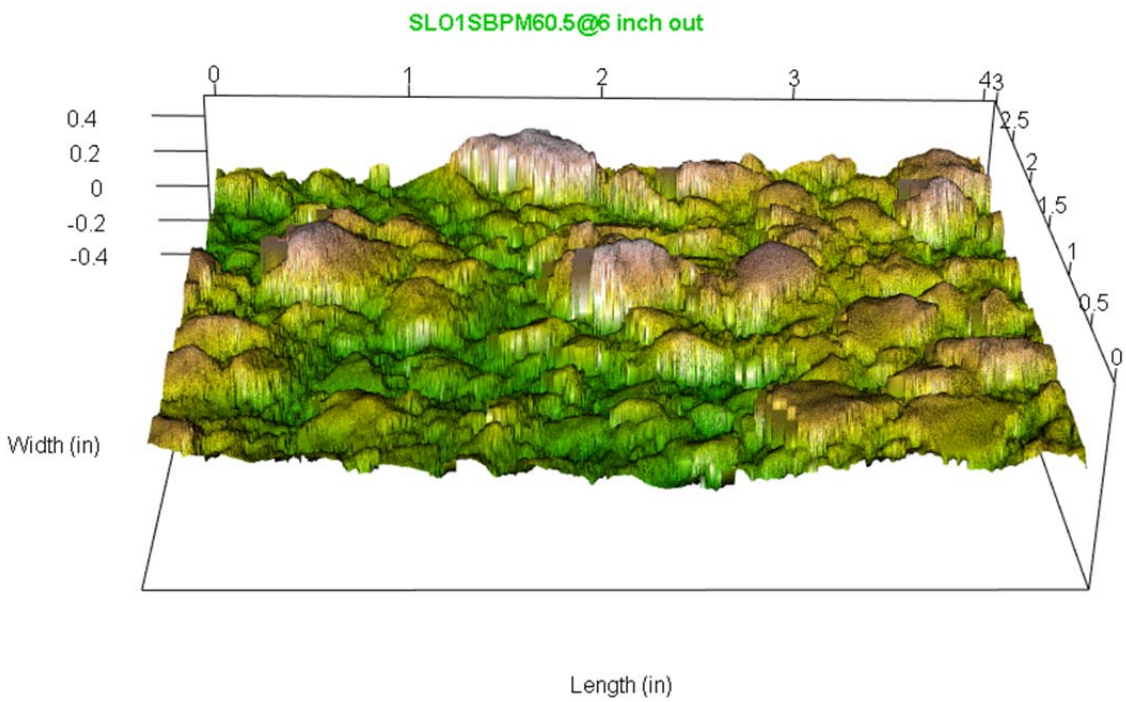

SLO1NBPM63.5@6 inch in
0
1
2
3
4
3
2.5
2
1.5
1
0.5
0
0.4
0.2
0
-0.2
-0.4
Width (in)
Length (in)

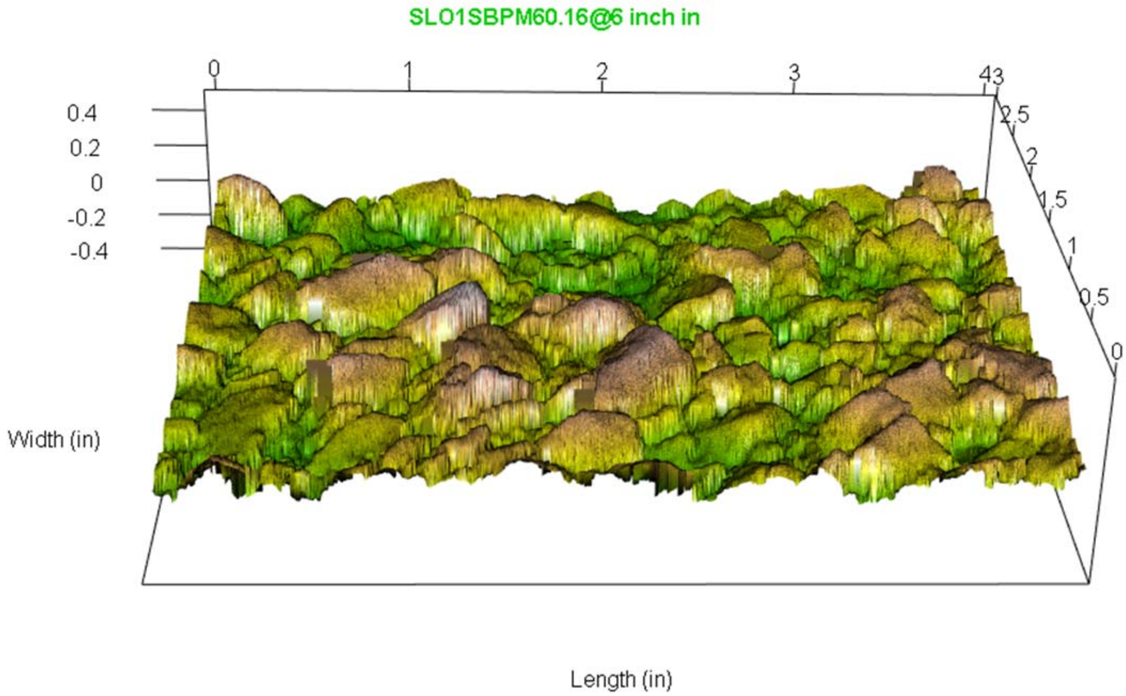

SLO1NBPM63.5@6 inch out
0
1
2
3
4
3
2.5
2
1.5
1
0.5
0
0.4
0.2
0
-0.2
-0.4
Width (in)
Length (in)

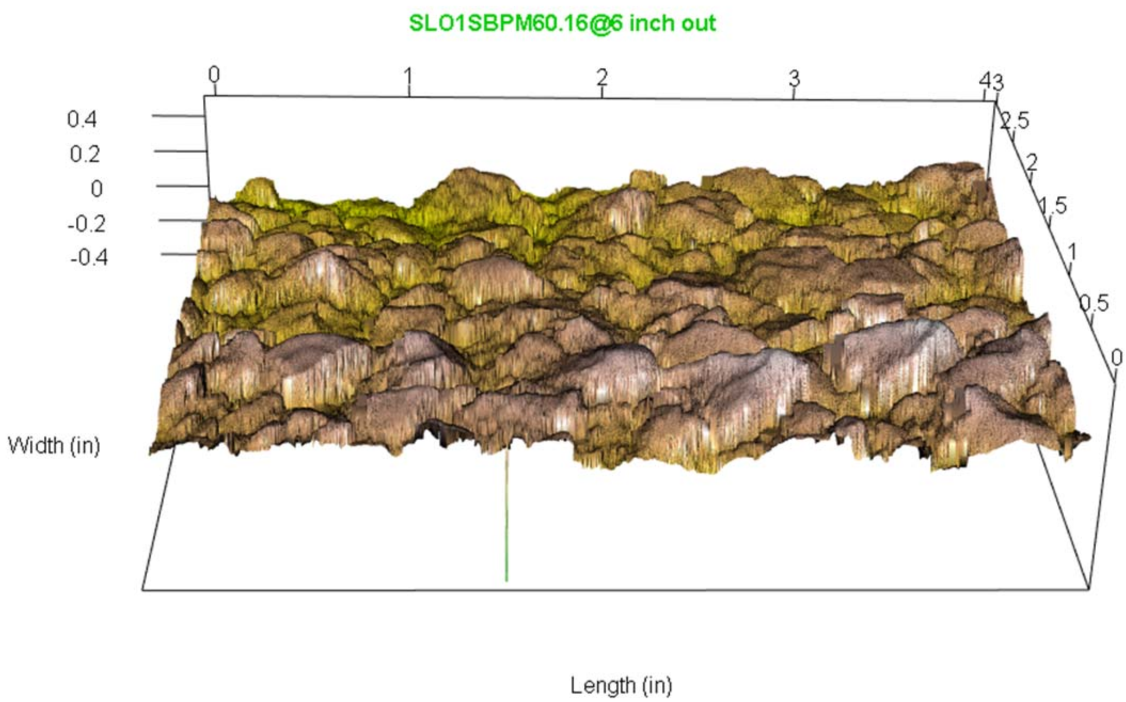

SLO1SBPM52.5@6 inch in
0
1
2
3
4
3
2.5
2
1.5
1
0.5
0
0.4
0.2
0
-0.2
-0.4
Width (in)
Length (in)

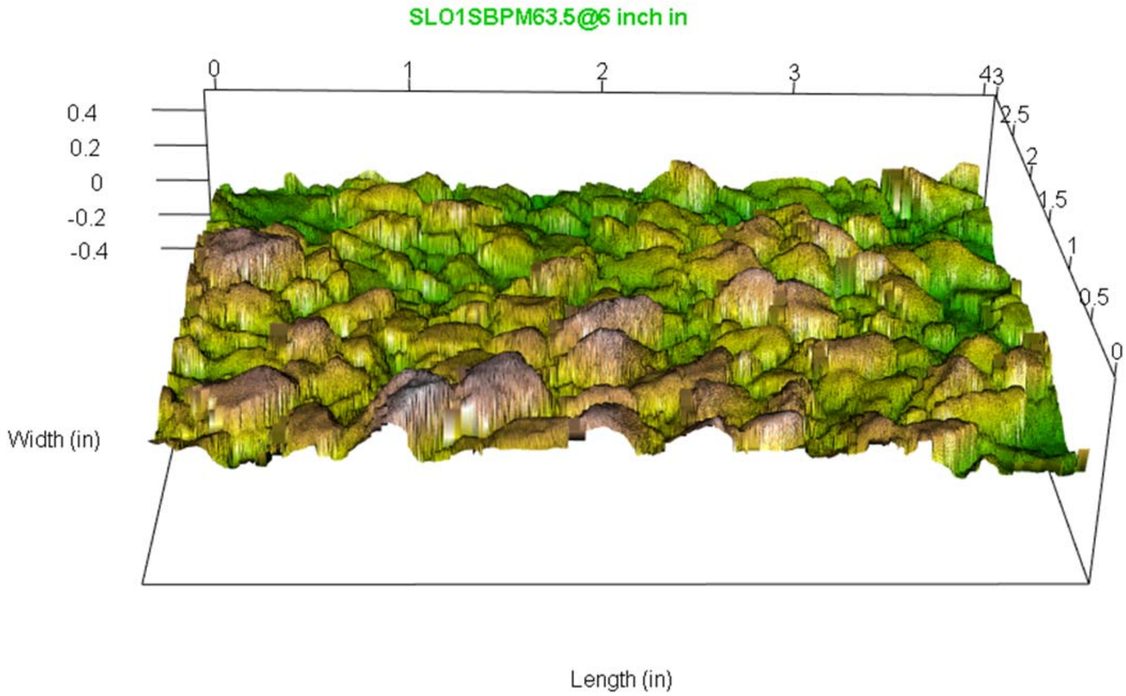

SLO1SBPM52.5@6 inch out
0
1
2
3
4
3
2.5
2
1.5
1
0.5
0
0.4
0.2
0
-0.2
-0.4
Width (in)
Length (in)

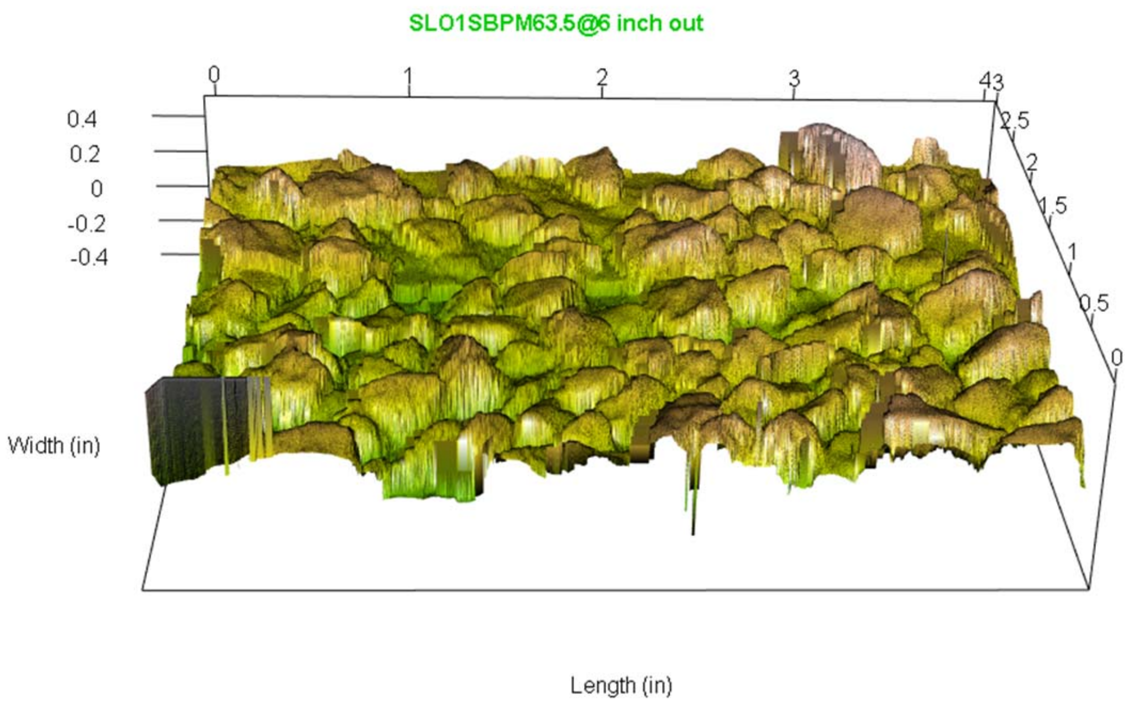

SLO1SBPM60.5@6 inch in
0
1
2
3
4
3
2.5
2
1.5
1
0.5
0
0.4
0.2
0
-0.2
-0.4
Width (in)
Length (in)


SLO1SBPM60.5@6 inch out
0
1
2
3
4
3
2.5
2
1.5
1
0.5
0
0.4
0.2
0
-0.2
-0.4
Width (in)
Length (in)

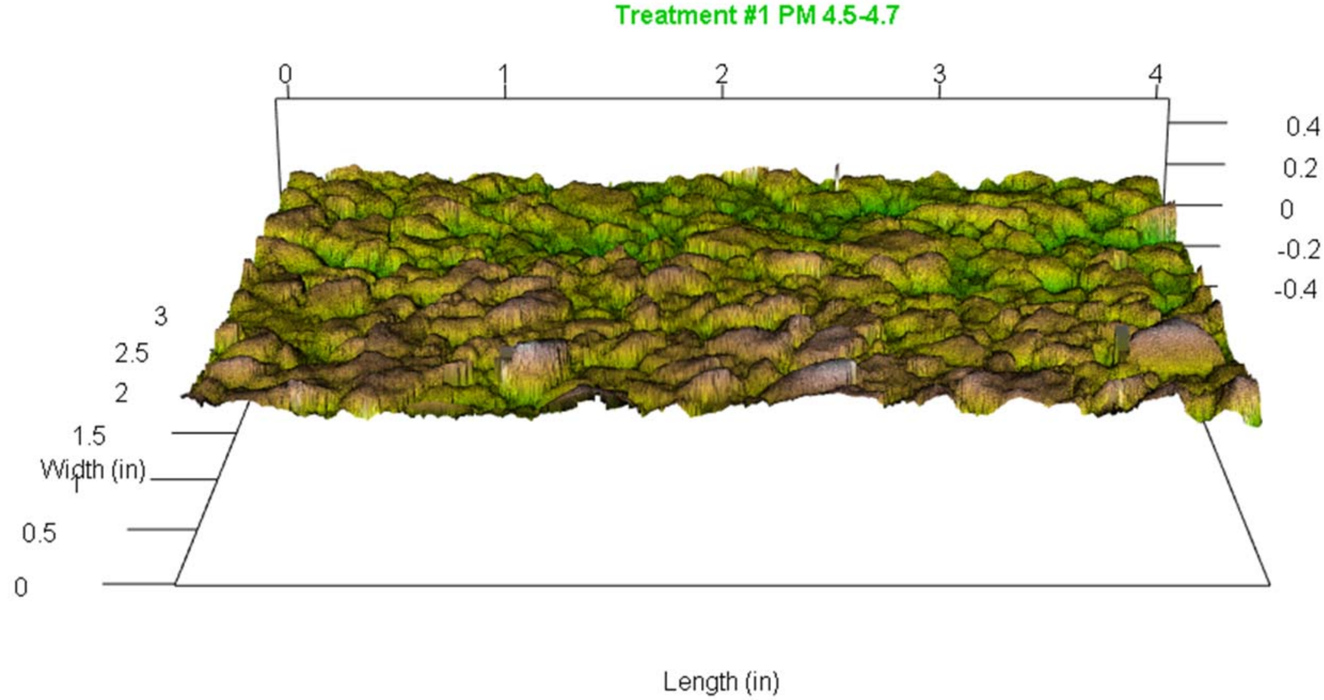

SLO1SBPM60.16@6 inch in
0
1
2
3
4
3
2.5
2
1.5
1
0.5
0
0.4
0.2
0
-0.2
-0.4
Width (in)
Length (in)


SLO1SBPM60.16@6 inch out
0
1
2
3
4
3
2.5
2
1.5
1
0.5
0
0.4
0.2
0
-0.2
-0.4
Width (in)
Length (in)

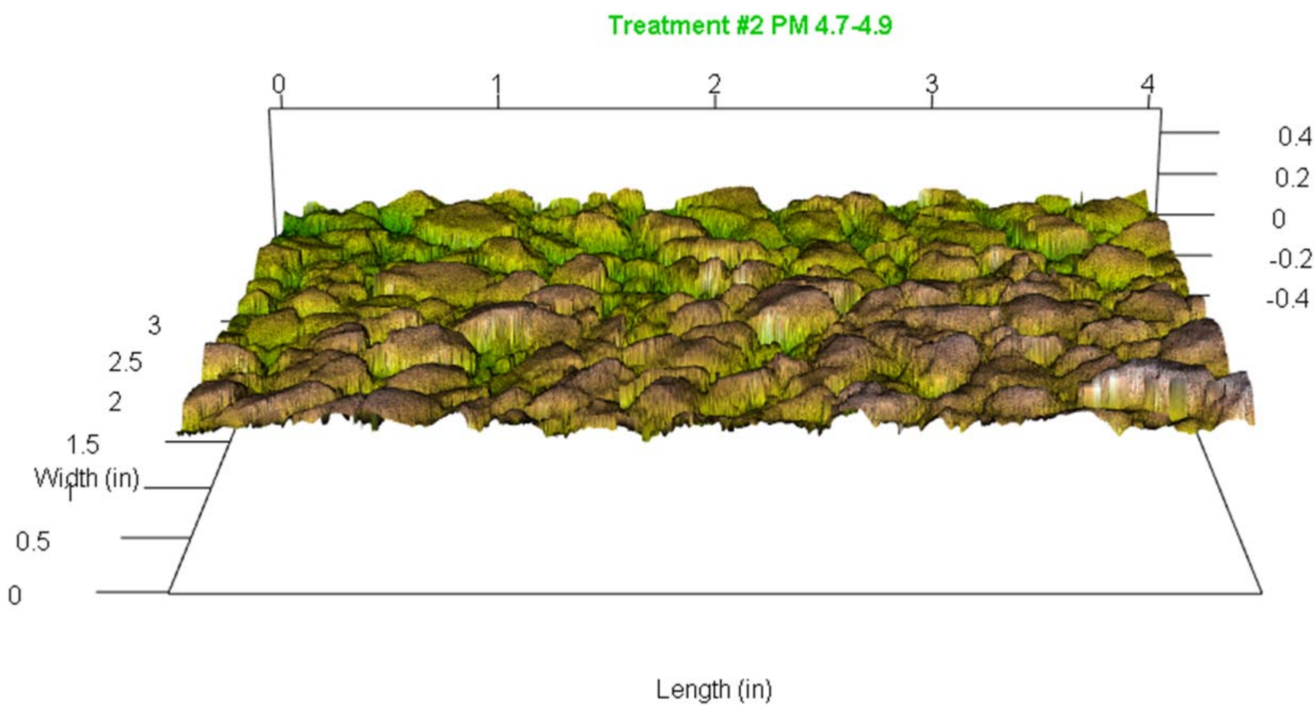

SLO1SBPM63.5@6 inch in
0
1
2
3
4
3
2.5
2
1.5
1
0.5
0
0.4
0.2
0
-0.2
-0.4
Width (in)
Length (in)


SLO1SBPM63.5@6 inch out
0
1
2
3
4
3
2.5
2
1.5
1
0.5
0
0.4
0.2
0
-0.2
-0.4
Width (in)
Length (in)

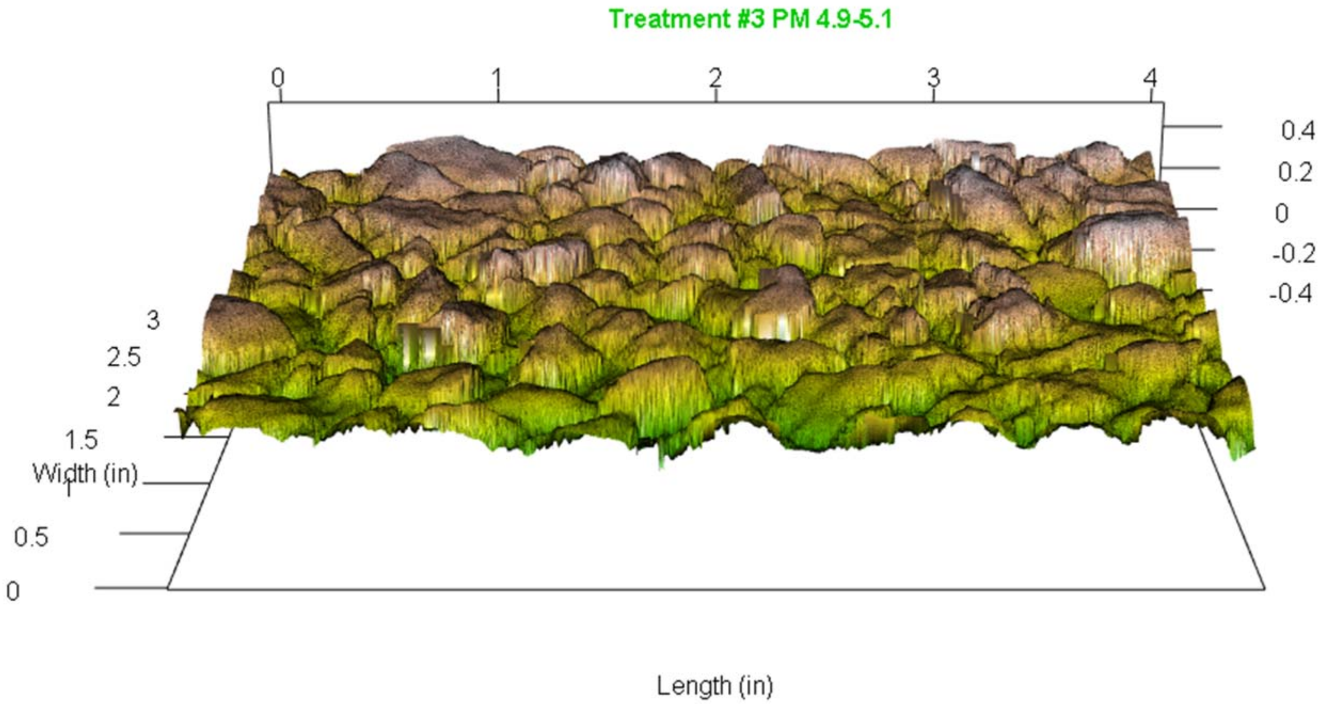
C.5: Test Sections on Mon-198 (Inside ETW)



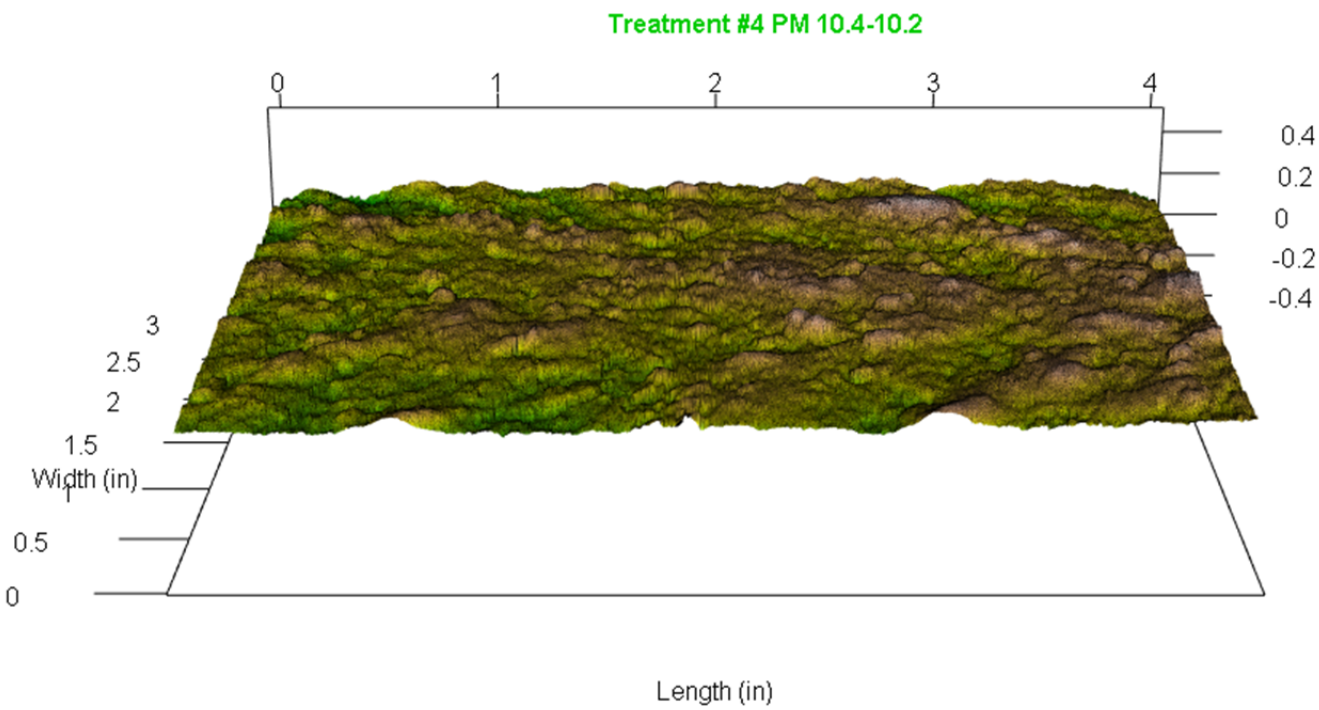
#1 5/16" PME Seal Coat (PM 4.5-4.7)



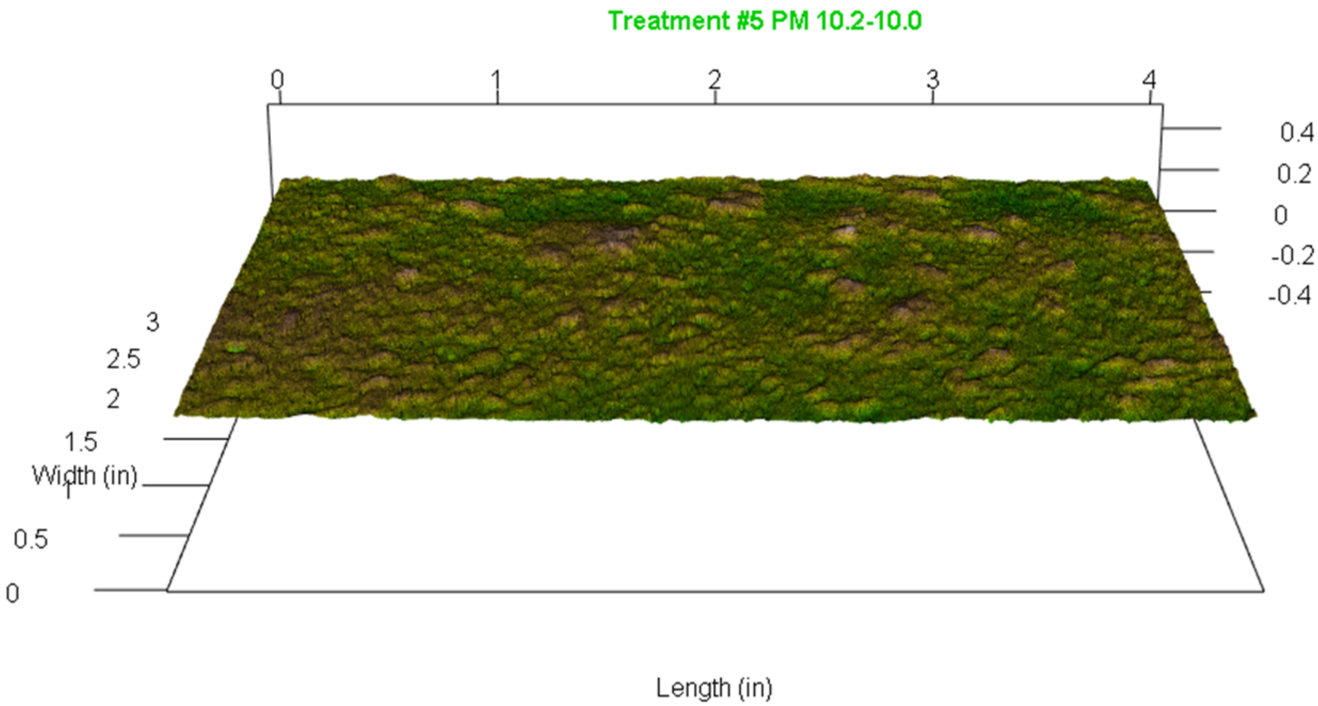
#2 Modified Binder Seal Coat - Modified Gradation (PM 4.7-4.9)



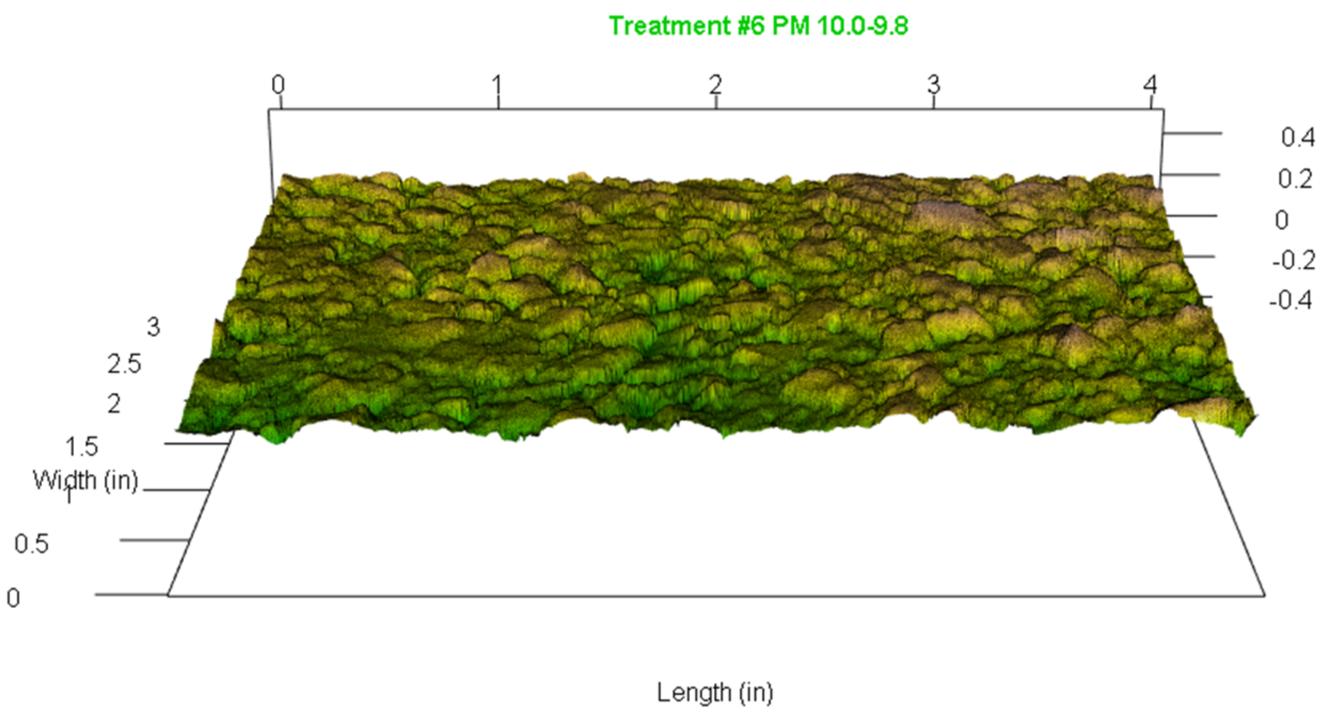
#3 Modified Binder Seal Coat - Utilizing a Steel Roller (PM 4.9-5.1)



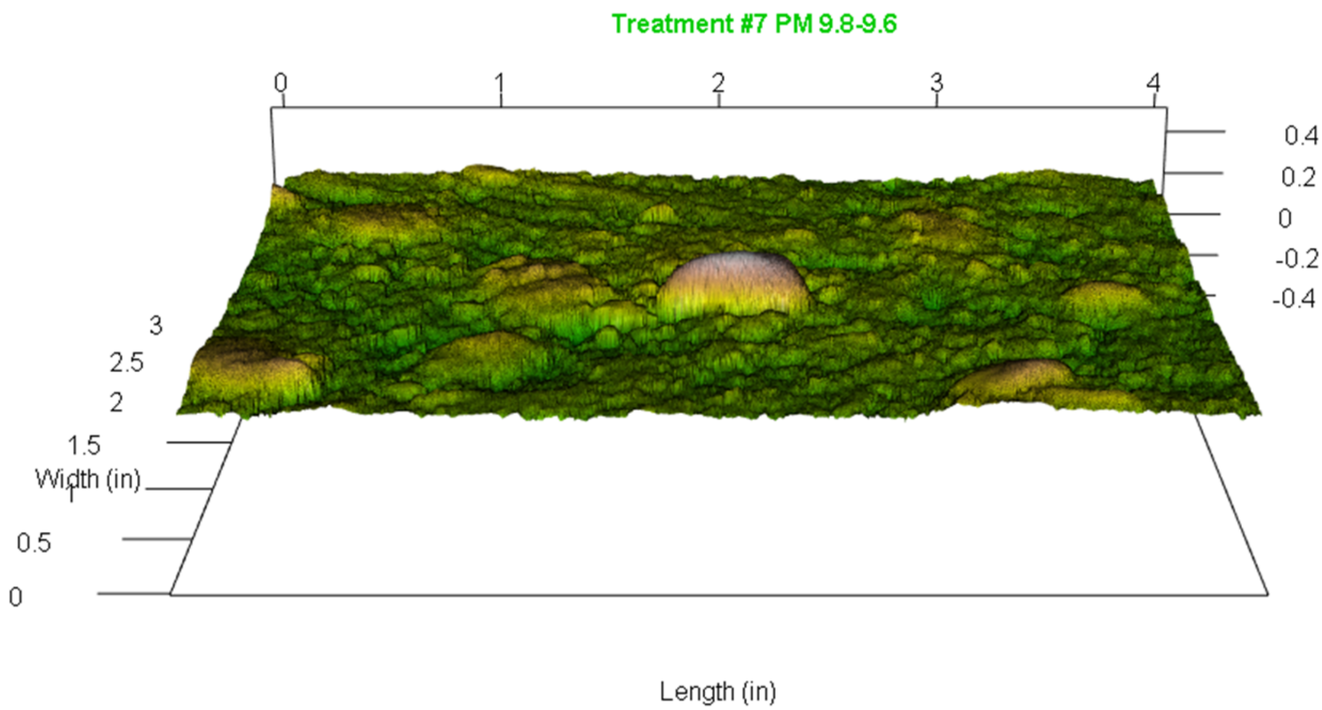
#4 Cinder Seal (PM 10.2-10.4)



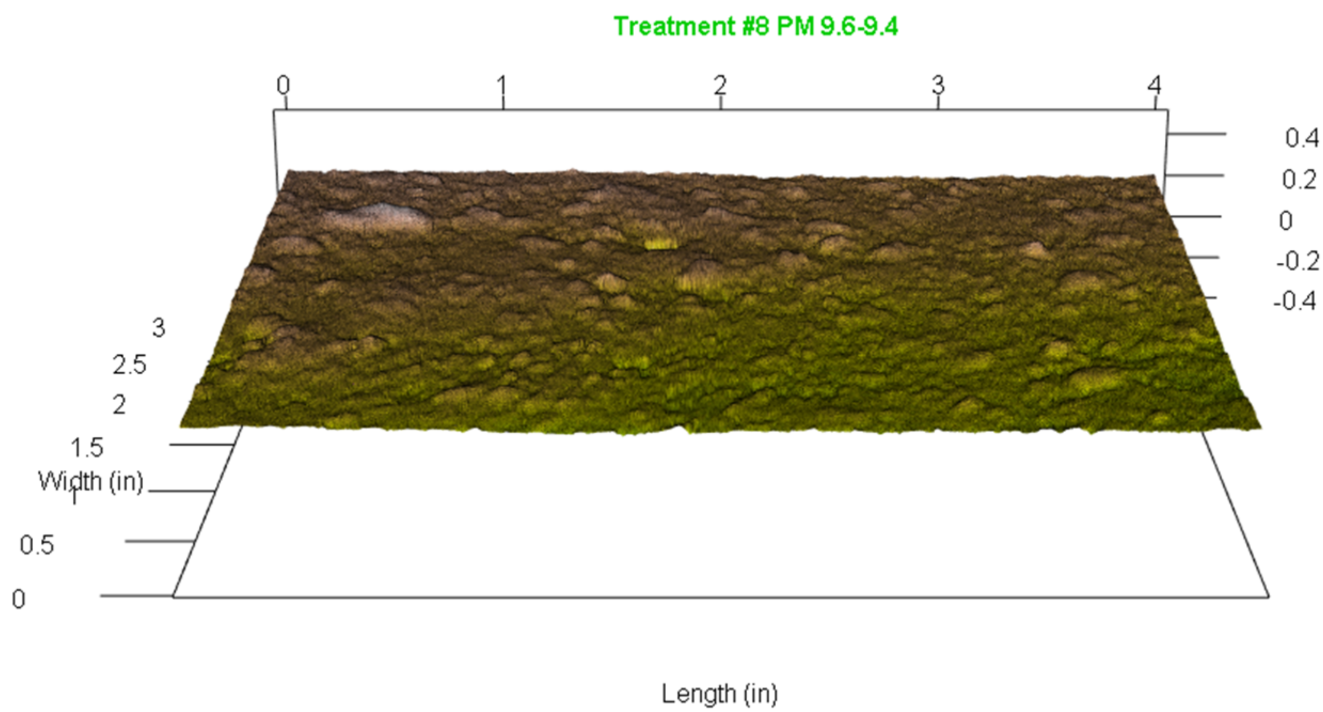
#5 Microsurfacing (PM 10.0-10.2)



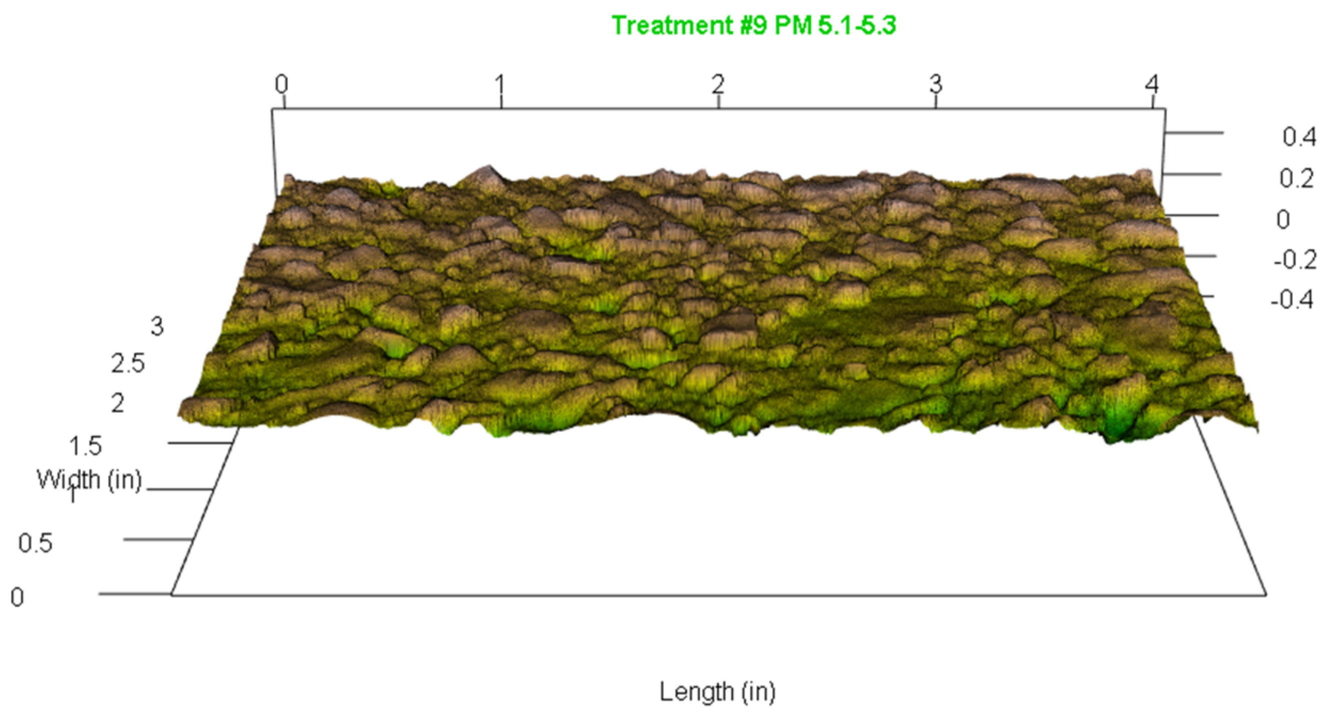
#6 1/4" PME seal coat — 2nd application of a double chip seal (PM 9.8-10.0)



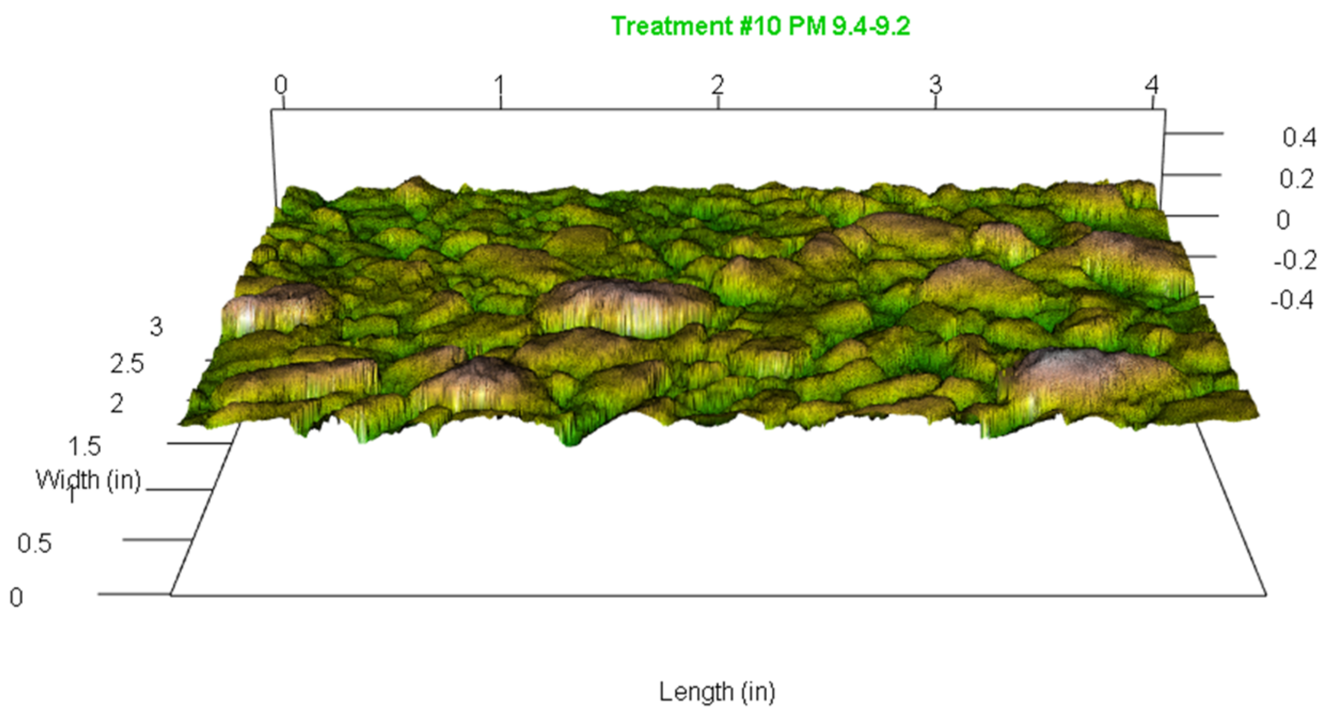
#7 Sand seal (PM 9.6-9.8)



#8 Slurry seal (PM 9.4-9.6)



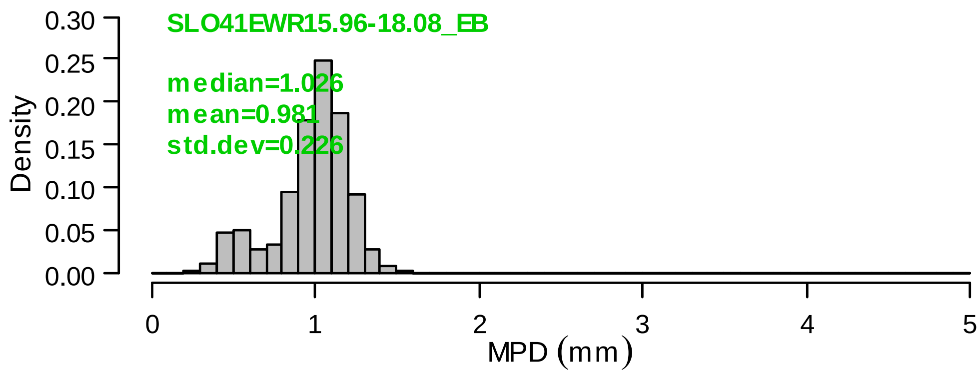
#9 Old HMA overlay on Mon-198 (PM 5.1-5.3)

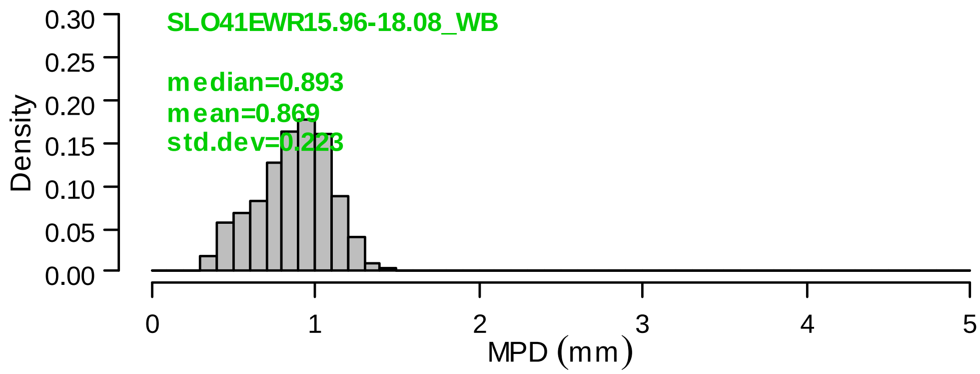


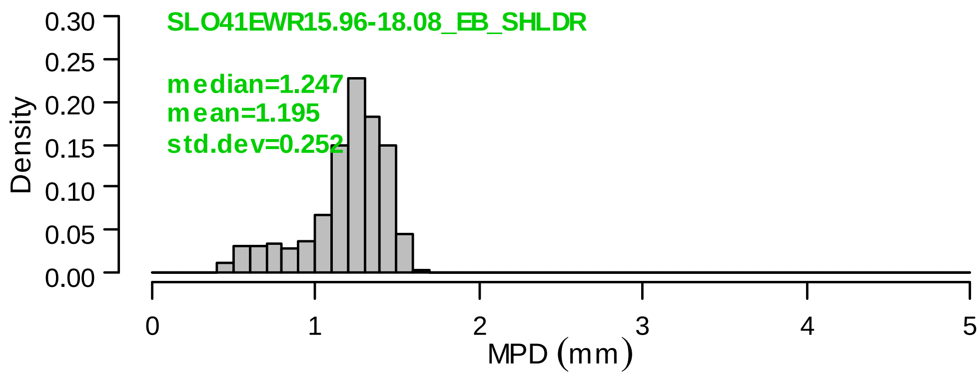
#10 New chip seal on Mon-198 (Control) (PM 9.2-9.4)

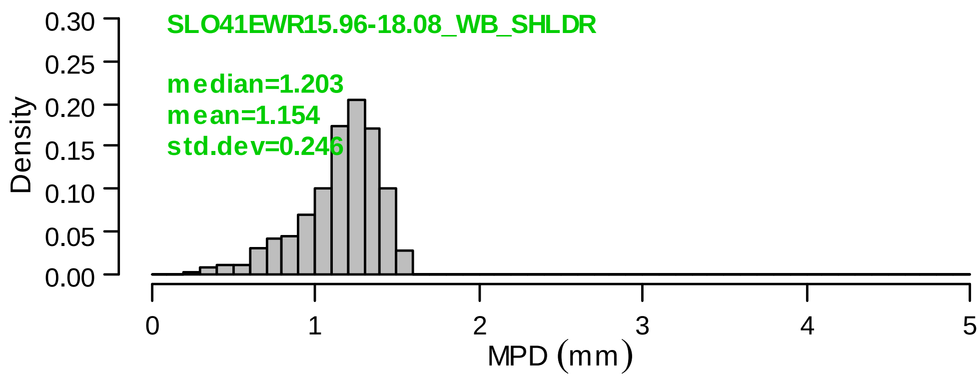
APPENDIX D: DISTRIBUTION OF MPD BY THE INERTIAL PROFILER ON SLO-1 AND MON-198 SECTIONS

D.1: SLO-41, Microsurfacing

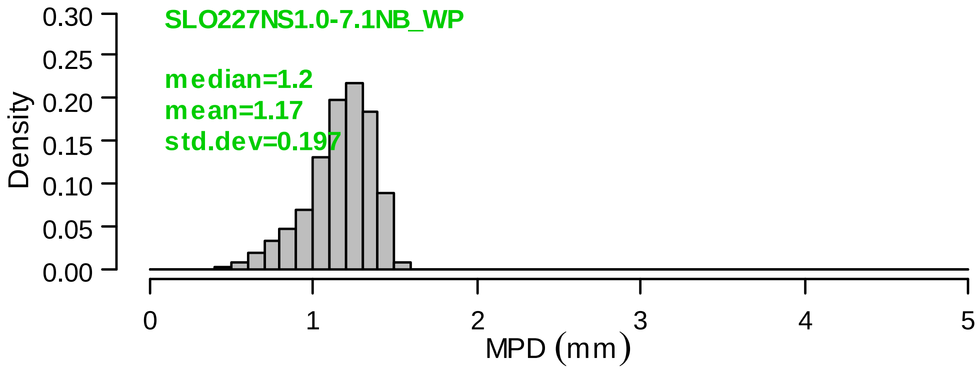


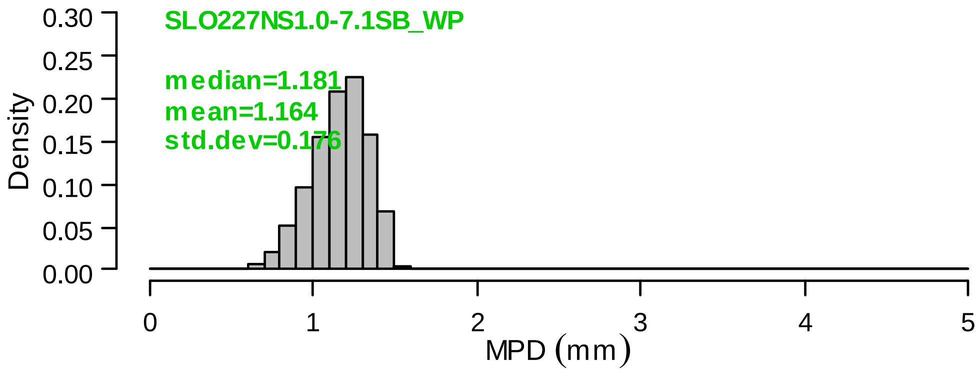




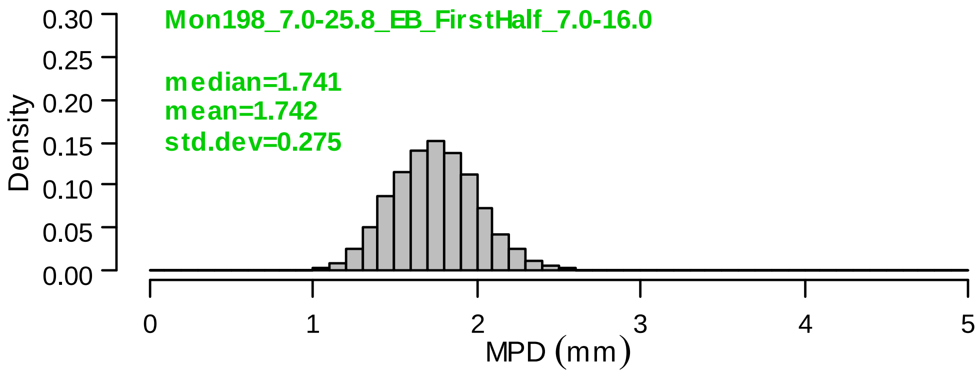


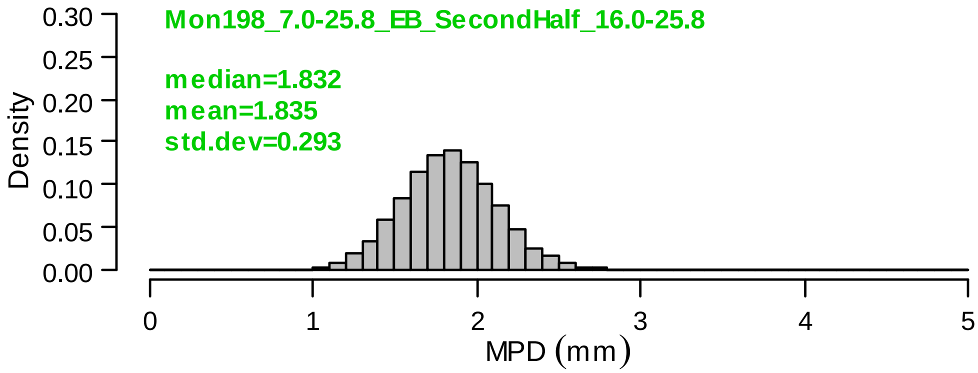
D.2: SLO-227, Chip Seal

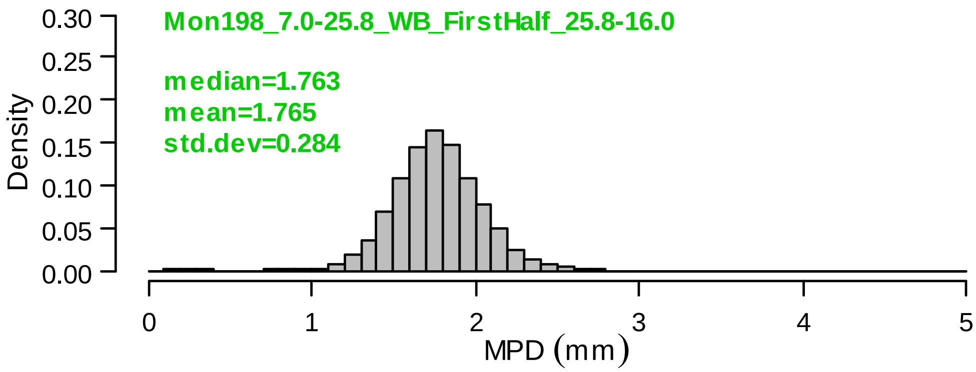


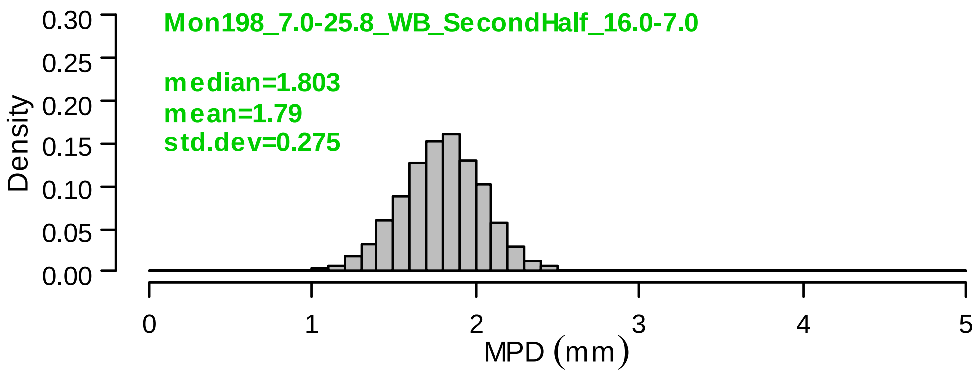


D.3: Mon-198, Chip Seal

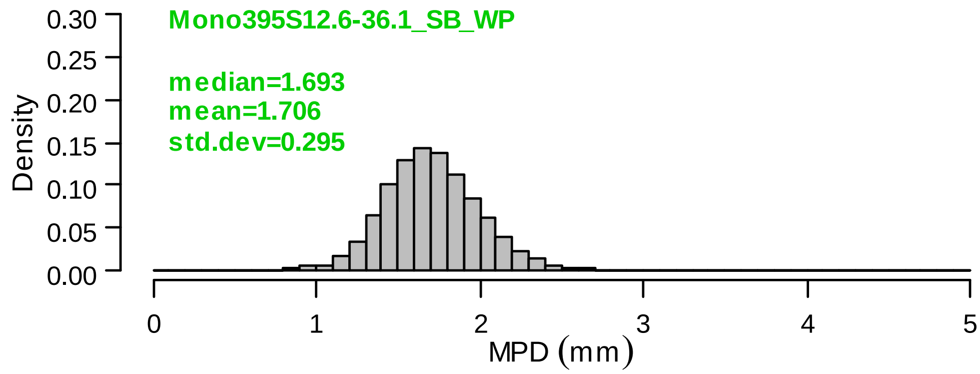


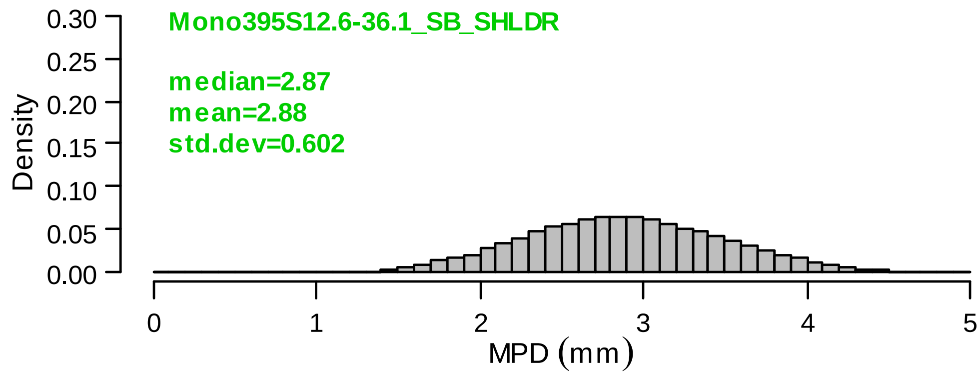


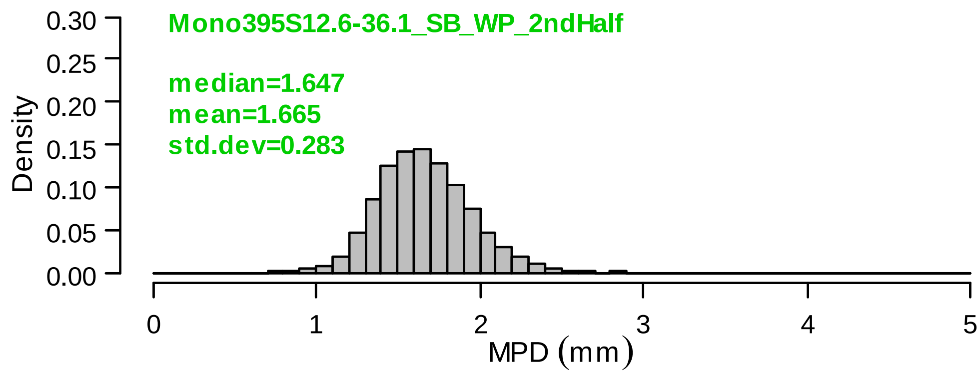


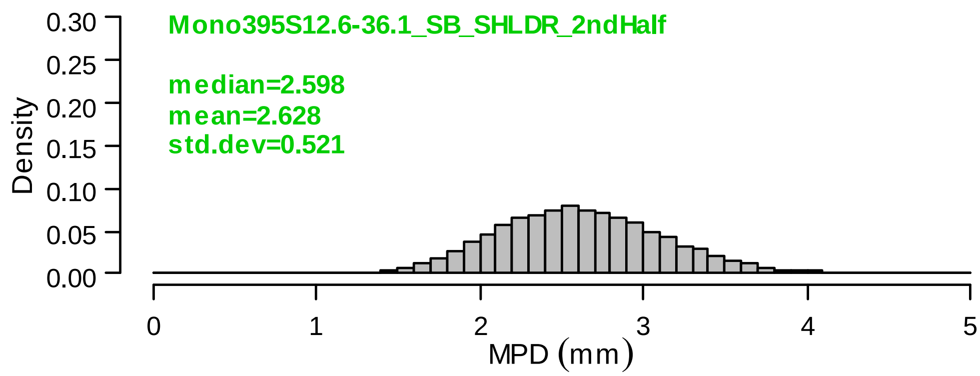


D.4: Mno-395, Chip Seal



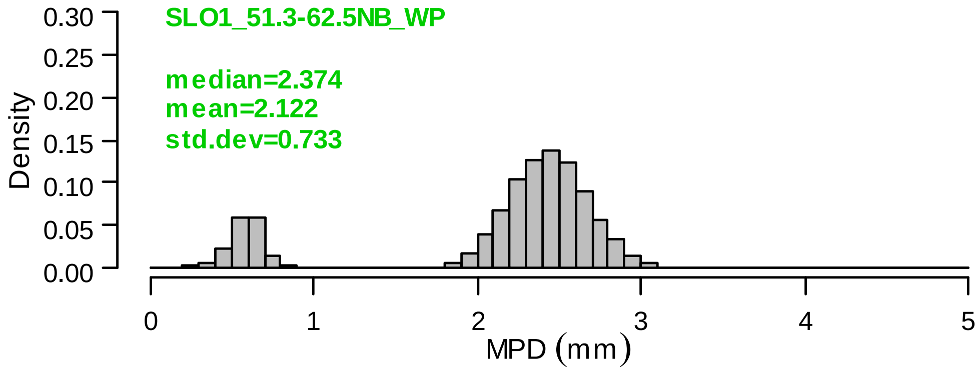


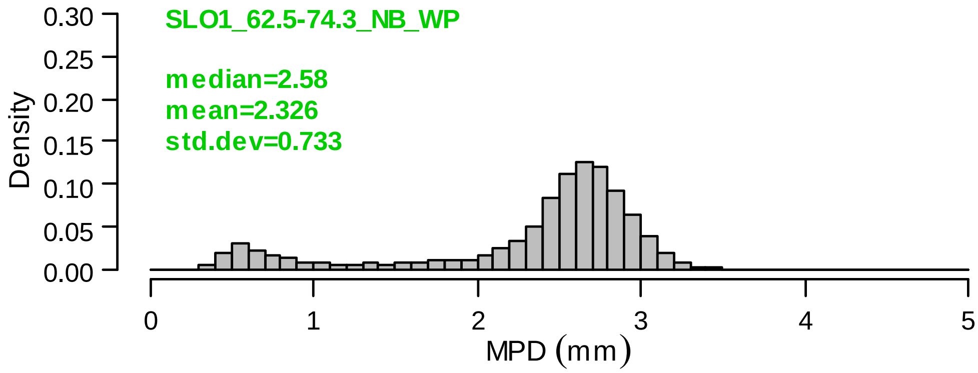


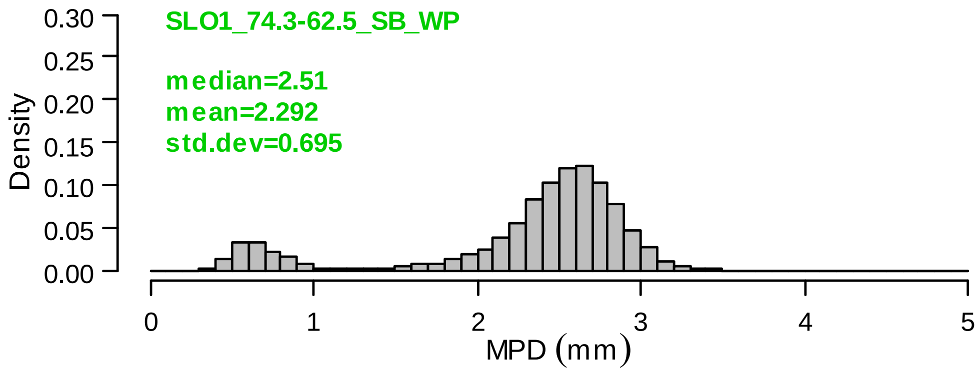


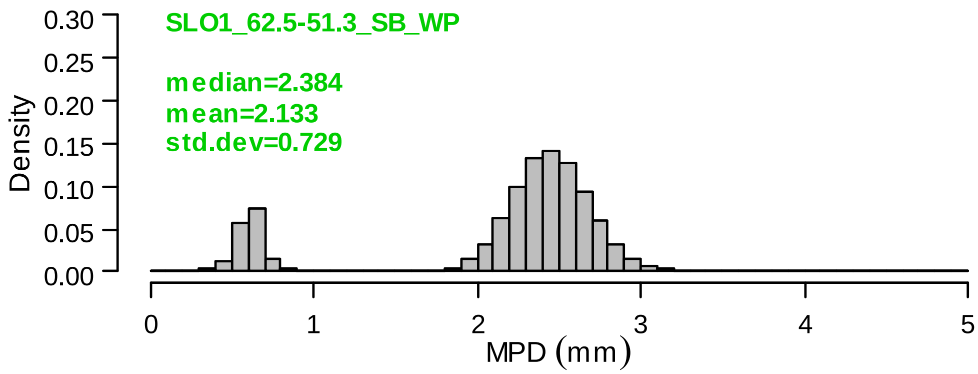
D.5: SLO-1, Chip Seal

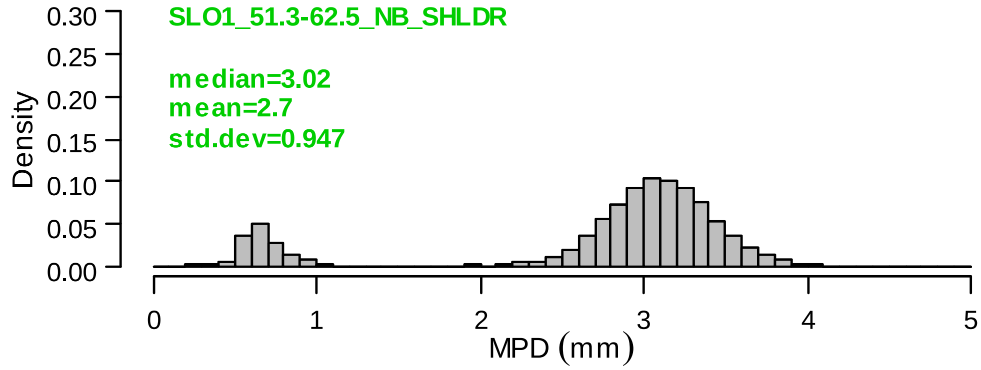
(The populations of lower values indicate the presence of underlying HMA or of a bridge.)

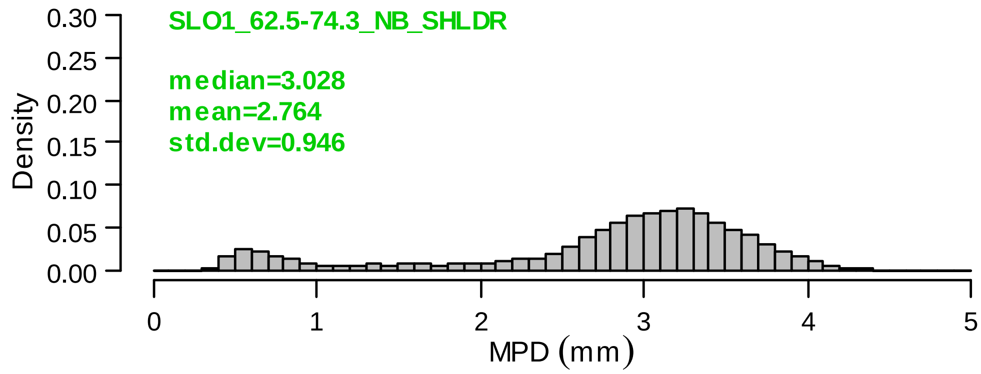


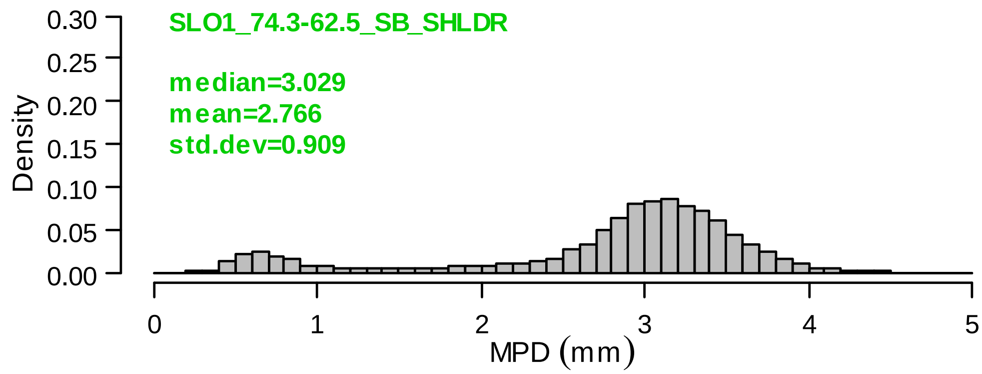


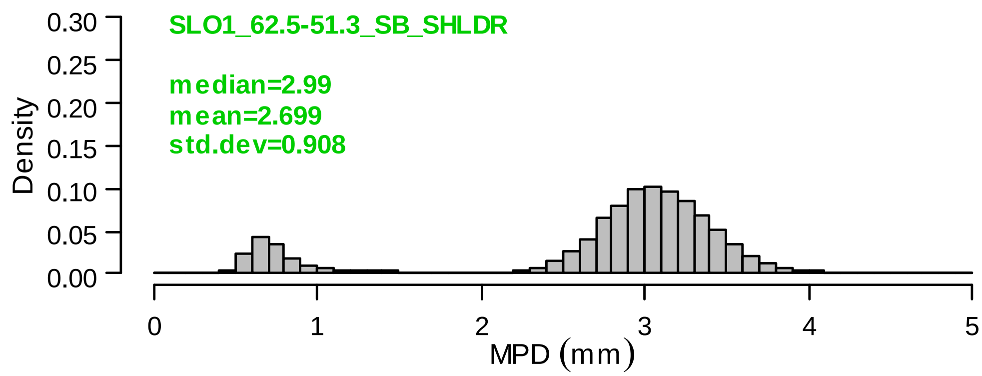




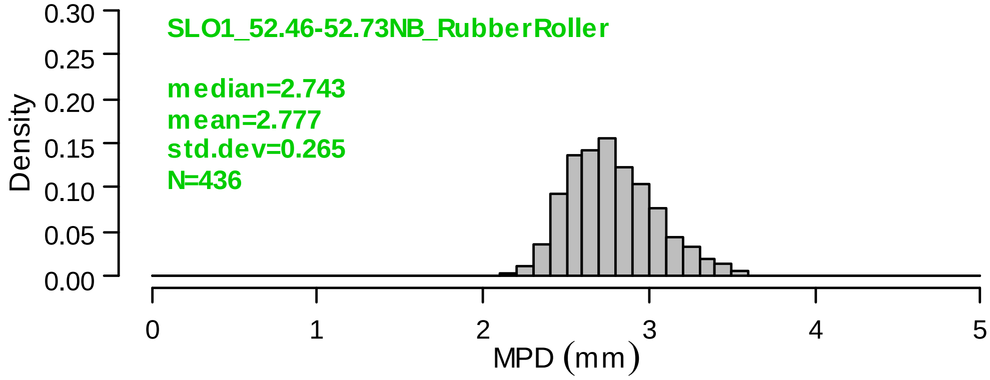

SLO1_51.3-62.5_NB_SHLDR
median=3.02
mean=2.7
std.dev=0.947
Density
MPD (mm)

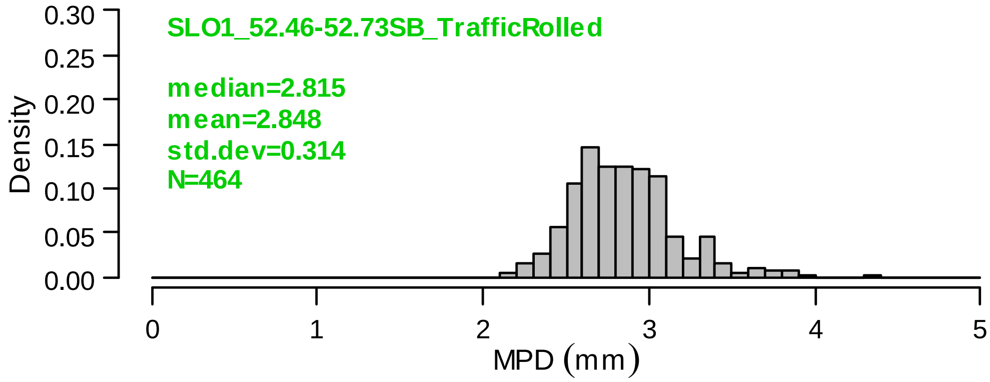

SLO1_62.5-74.3_NB_SHLDR
median=3.028
mean=2.764
std.dev=0.946
Density
MPD (mm)


SLO1_74.3-62.5_SB_SHLDR
median=3.029
mean=2.766
std.dev=0.909
Density
MPD (mm)


SLO1_62.5-51.3_SB_SHLDR
median=2.99
mean=2.699
std.dev=0.908
Density
MPD (mm)

D.6: SLO-1, Test Section with Additional Rolling





APPENDIX E: EXAMPLE BICYCLE RIDE QUALITY SURVEY FORMS

E.1. Example Survey Forms for Initial Survey

E.1.1 Pre-Ride Survey: Mon-198

Caltrans/UCPRC Bicycle Ride Quality 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.1.2 In-Ride Survey: Mon-198

Caltrans/UCPRC Bicycle Ride Quality 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.1.3 Post-Ride Survey: Mon-198

Caltrans/UCPRC Bicycle Ride Quality 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.1.4 In-Ride Survey: SLO-1

Caltrans/UCPRC Bicycle Ride Quality Survey

<u>In-ride Survey: SLO-1</u>

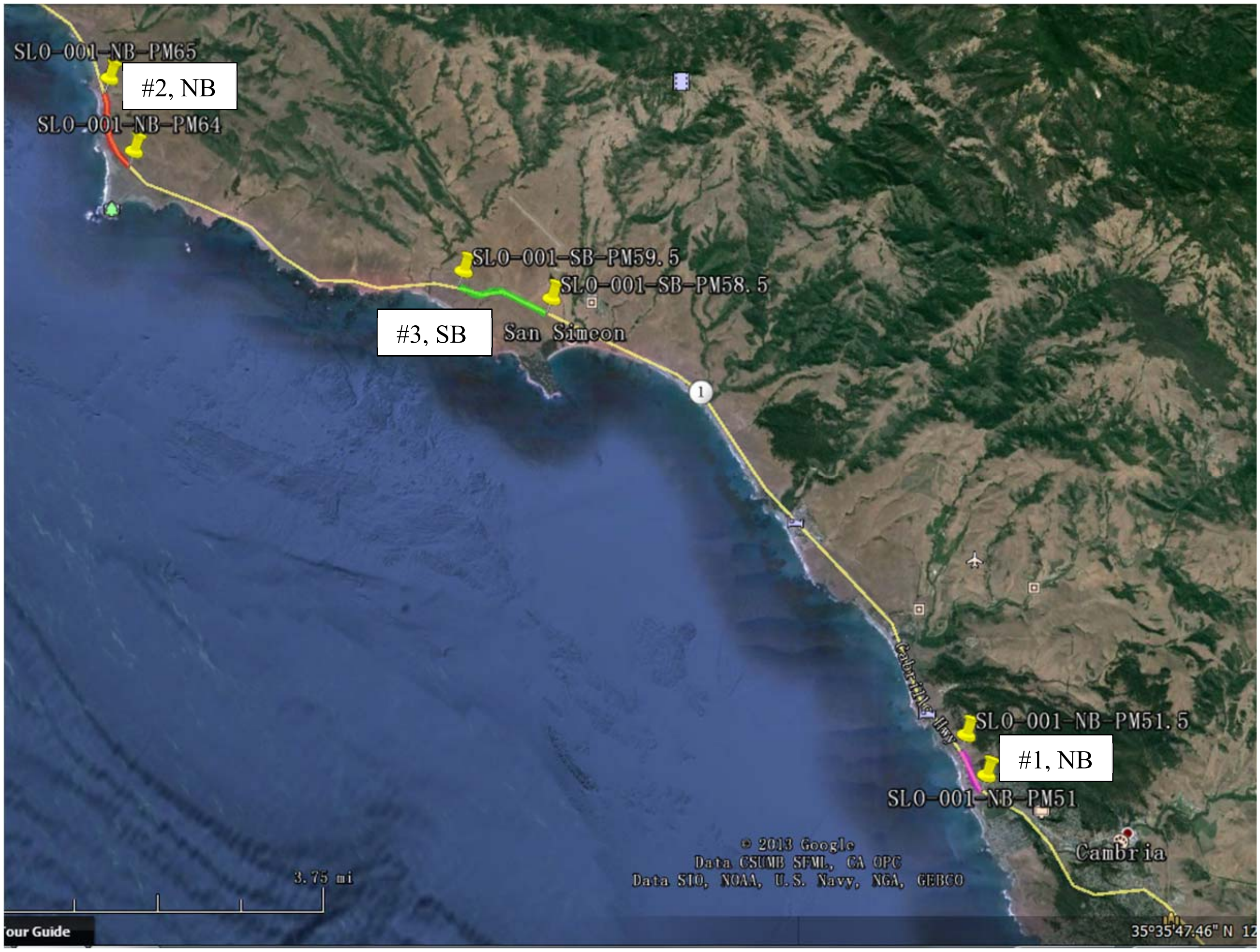
Survey must be returned to David Miller by 8:00 am on 22 July 2013 by email or mail.

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 51.5 (35°34'38.31"N, 121° 6'47.17"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: ___________________________

E.2. Example Survey Forms for Extended Survey

E.2.1 Pre-Ride Survey: Tahoe

Caltrans/UCPRC Bicycle Ride Quality Survey (Tour of Tahoe)

Instruction

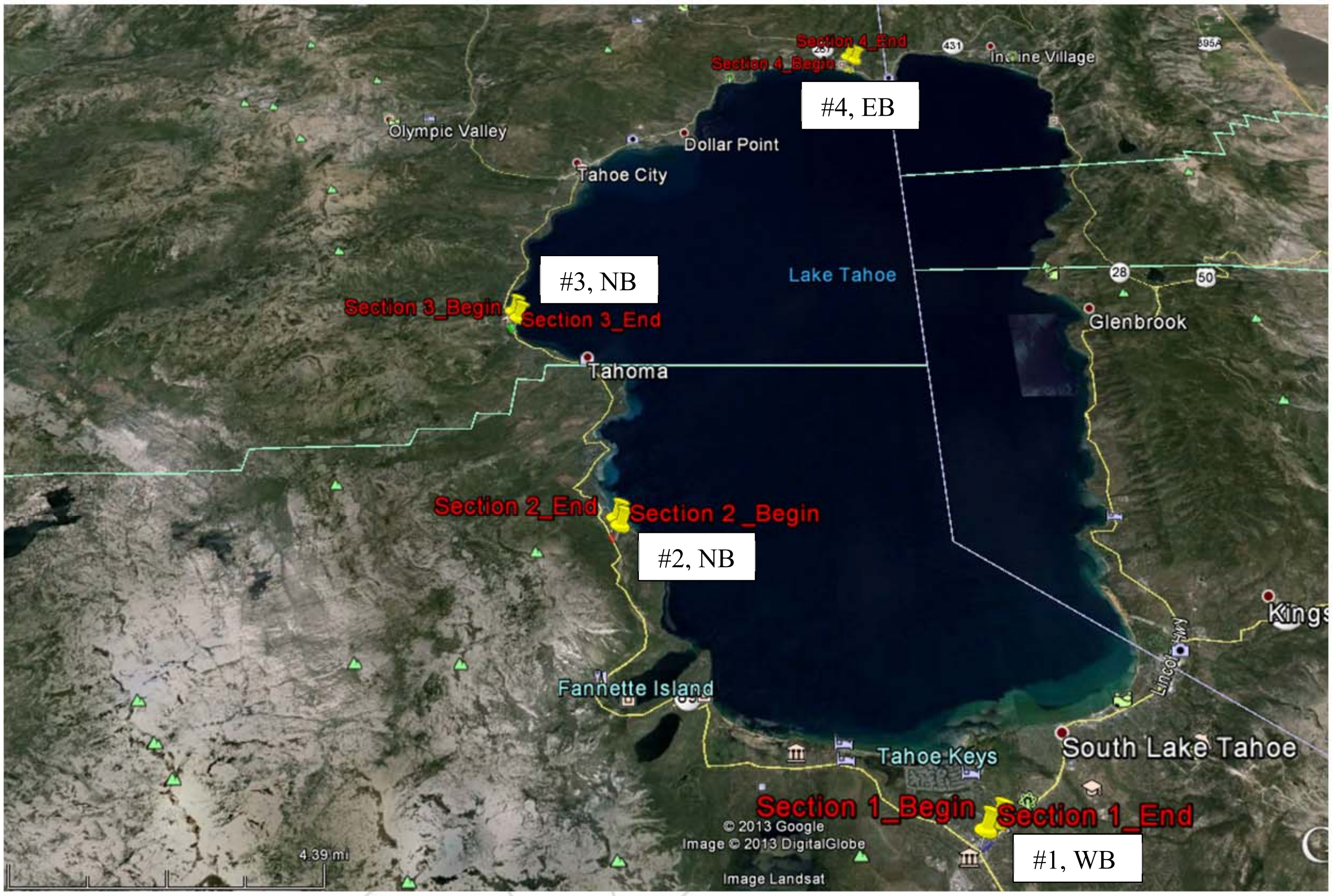
1. *Fill in* **Pre-ride Survey: General Information** (two pages) *and return it in* ***BEFORE*** *riding.*
2. *Fill in* **In-ride Survey** (one page) *at the end of EACH section.*
3. *Fill in* **Post-ride Survey** (one page) *at the end of ALL sections and return the in-ride and post-ride survey in.*

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 FOUR sections in Tour of Tahoe ride. These four specific sections are shown in the following map. The postmiles for them are listed below the map (see the white paddles Caltrans has on the side of the road for postmiles; example is shown below).

Postmile example showing PM 50.29 on Ventura 33.



Section Locations at Tahoe

Section #1, *Westbound (WB)*, ED-50, PM 75.3 to PM 75.5;
Section #2, *Southbound (SB)*, ED-89, PM 21.2 to PM 21.4;
Section #3, *Southbound (SB)*, PLA-89, PM 2.1 to PM 2.3;
Section #4, *Southbound (SB)*, PLA-28, PM 9.7 to PM 9.9.

Caltrans/UCPRC Bicycle Ride Quality Survey (Tour of Tahoe)

<u>Pre-ride Survey: General Information</u> (*Please fill it out **BEFORE** riding*)
Date:__9/8/2013__ (mm/dd/yyyy)

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 □ Recumbent
   □ Hybrid □ Cruiser □ Folding □ 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 □ Other: _______________
   □ Steel □ Don't know

   D. Tire pressure: __________ psi E. Tire width: __________ mm

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 every other day
   - □ About once a week
   - □ About twice a month
   - □ Once a month or less

10. For what purposes do you ride your bike (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, bike lanes)
    __________Pavement Ride Quality (e.g. bumpy, smooth)
    __________Traffic Conditions
    __________Wind
    __________Companions
    __________Other: _______________________

16. How would you rate your *favorite local* recreational bicycle ride on the following factors?

	Very Poor	Poor	Neutral	Good	Very Good
Scenery	□1	□2	□3	□4	□5
Topography	□1	□2	□3	□4	□5
Road Geometric Design	□1	□2	□3	□4	□5
Pavement Ride Quality	□1	□2	□3	□4	□5
Traffic Conditions	□1	□2	□3	□4	□5
Wind	□1	□2	□3	□4	□5
Companions	□1	□2	□3	□4	□5

E.2.2 In-Ride Survey: Tahoe

Caltrans/UCPRC Bicycle Ride Quality Survey (Tour of Tahoe)

In-ride Survey: (*Please fill out at the end of* ***EACH*** *section*)
Date: __9/8/2013__ (mm/dd/yyyy)

Participant #:____________

Section#: **1**

1. Avg. biking speed on this section _________ (mph).
2. How do you rate the surface of the road? □ Unacceptable □ Acceptable
3. Compared to all of the roads on which you bicycle, please indicate your level of comfort (1-5):

Uncomfortable → Comfortable

1	2	3	4	5

Section#: **3**

1. Avg. biking speed on this section _________ (mph).
2. How do you rate the surface of the road? □ Unacceptable □ Acceptable
3. Compared to all of the roads on which you bicycle, please indicate your level of comfort (1-5):

Uncomfortable → Comfortable

1	2	3	4	5

Caltrans/UCPRC Bicycle Ride Quality Survey (Tour of Tahoe)

<u>In-ride Survey:</u> (*Please fill out at the end of **EACH** section*)
Date:__9/8/2013__ (mm/dd/yyyy)

Participant #:_____________

Section#: **2**

1. Avg. biking speed on this section _________ (mph).
2. How do you rate the surface of the road? □ Unacceptable □ Acceptable
3. Compared to all of the roads on which you bicycle, please indicate your level of comfort (1-5):

Uncomfortable → Comfortable

1	2	3	4	5

Section#: **4**

1. Avg. biking speed on this section _________ (mph).
2. How do you rate the surface of the road? □ Unacceptable □ Acceptable
3. Compared to all of the roads on which you bicycle, please indicate your level of comfort (1-5):

Uncomfortable → Comfortable

1	2	3	4	5

E.2.3 Post In-Ride Survey: Tahoe

Caltrans/UCPRC Bicycle Ride Quality Survey (Tour of Tahoe)

Post-ride Survey (*please fill out at the end of **ALL** sections*)
Date: 9/8/2013 (mm/dd/yyyy)
Participant #:_____________

1. Identify your favorite section of road from all the sections you just biked 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, bike 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 biked 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, bike 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, bike lanes)
   __________Pavement Ride Quality (e.g. bumpy, smooth)
   __________Traffic Conditions
   __________Wind
   __________Companions
   __________Other: ______________________

APPENDIX F: RAW SURVEY RESULTS

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

F.1.1: Pre-Ride Survey: Mon-198 and SLO-1

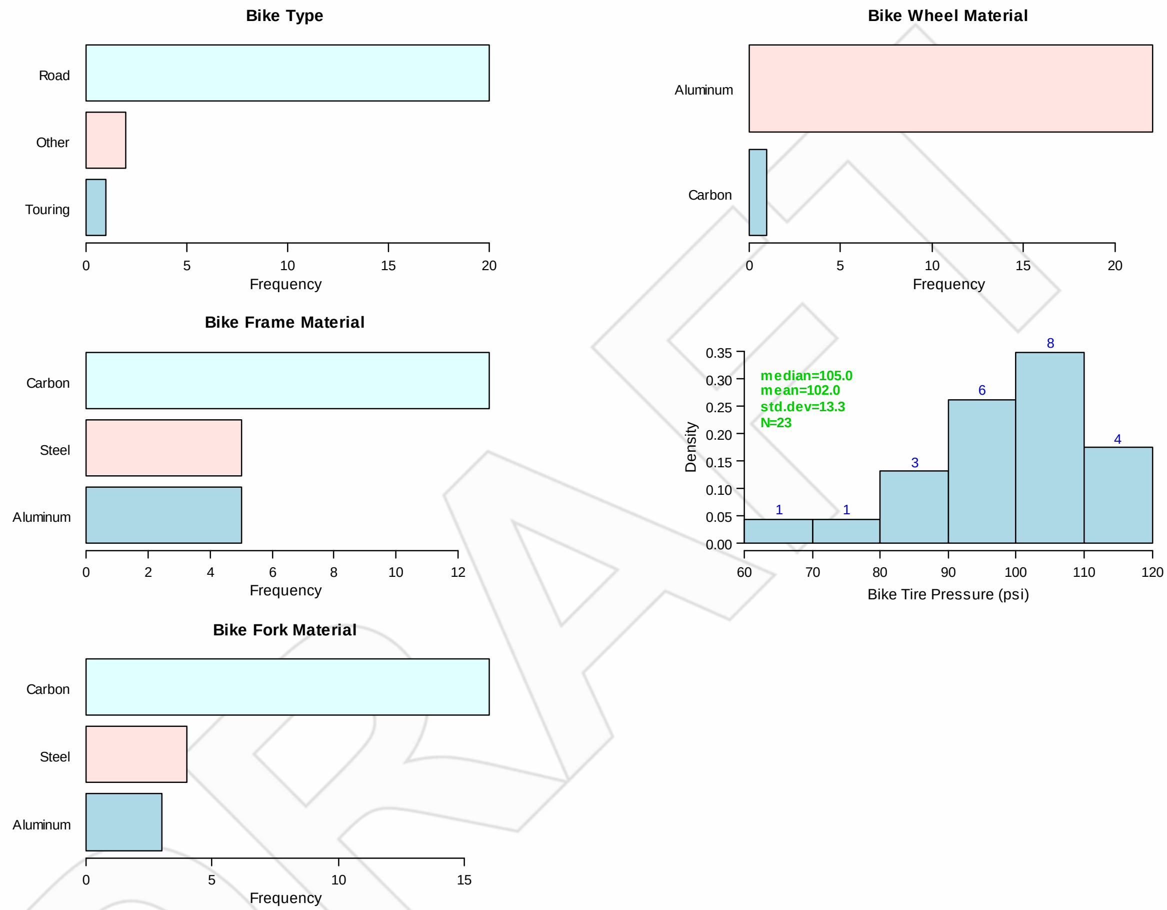


Figure F.1: Survey participants' bicycle information.

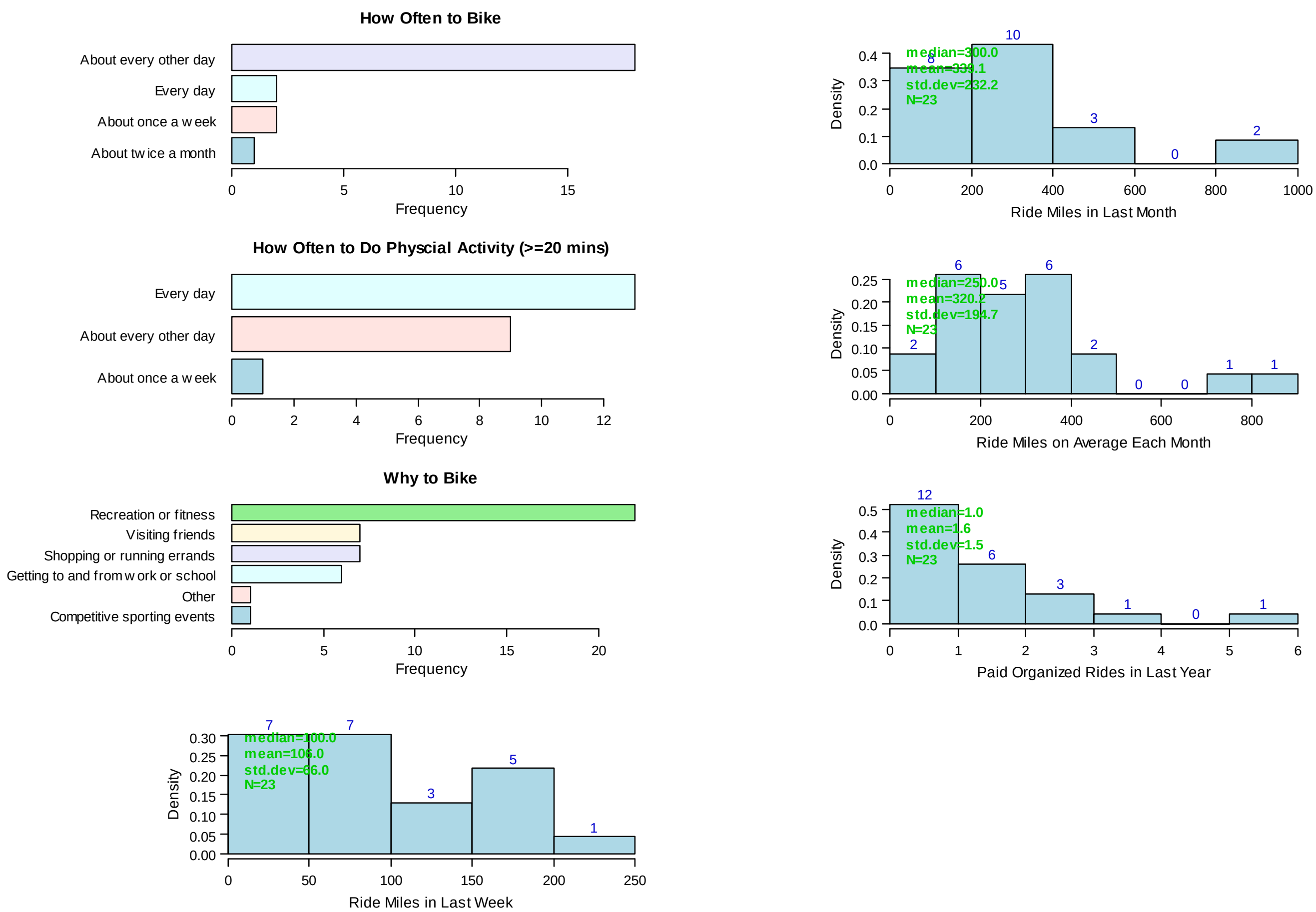


Figure F.2: Survey participants' bicycling activity information.

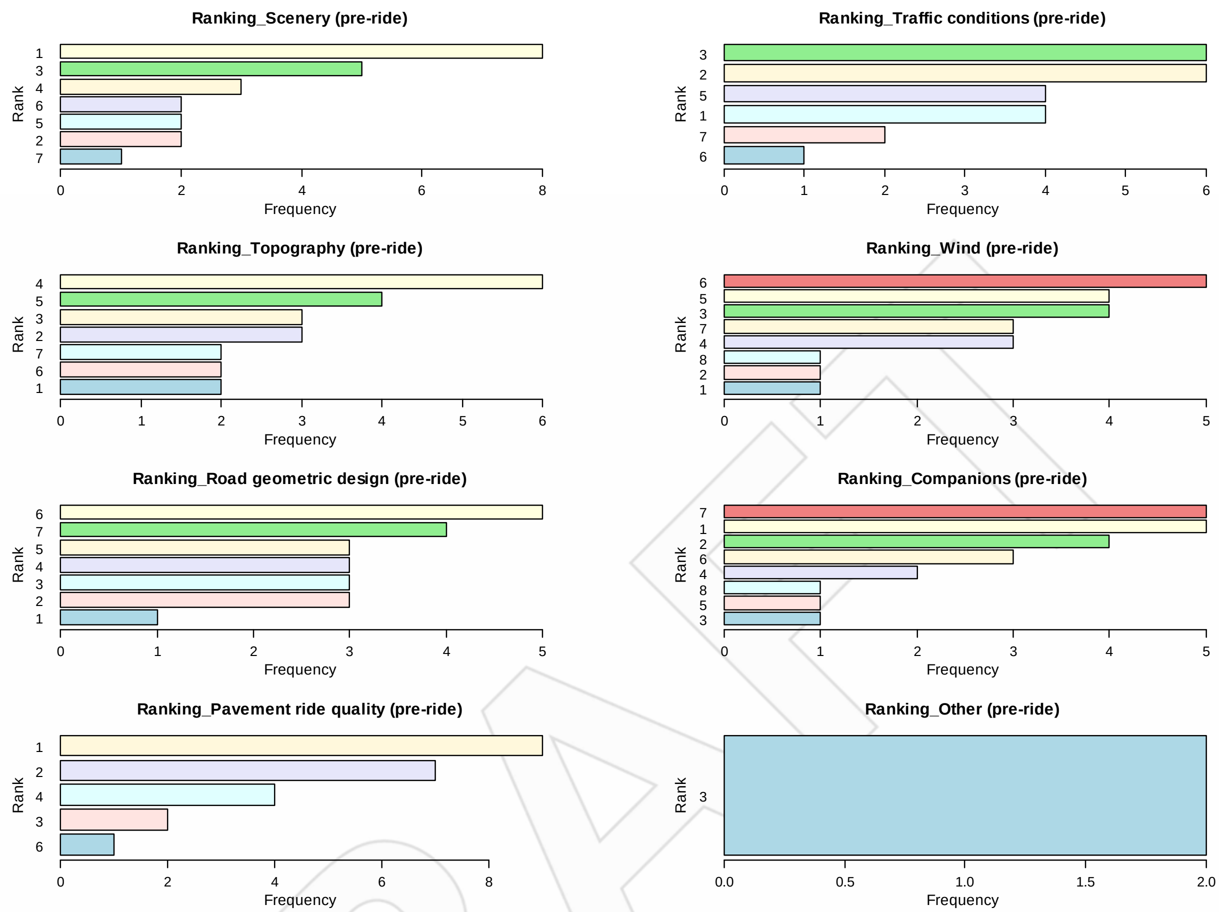


Figure F.3: Survey participants' factor ranking before riding (pre-ride survey).

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 (no survey for treatment 9 and 10)	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

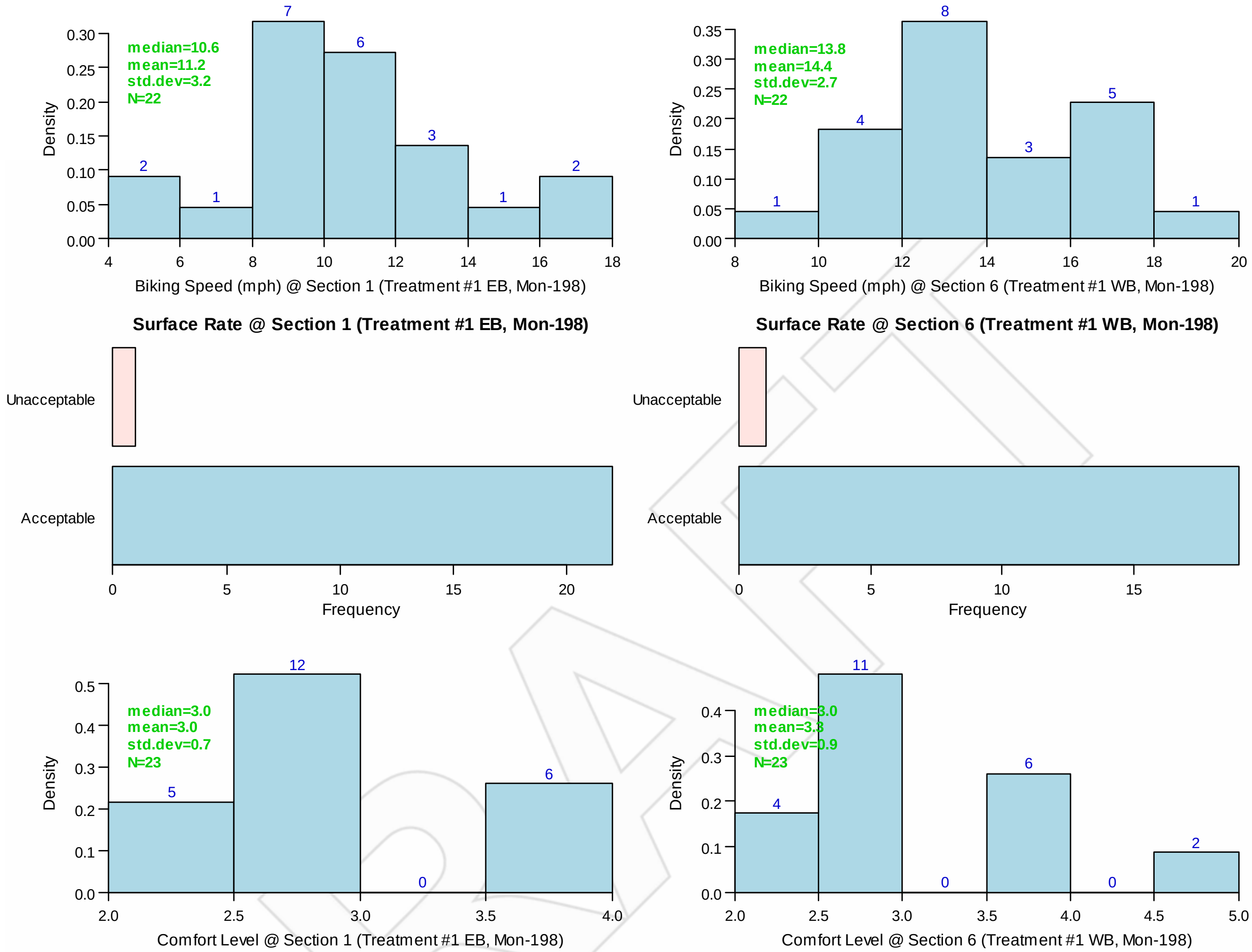


Figure F.4: Raw survey results for treatment #1 (Mon-198).

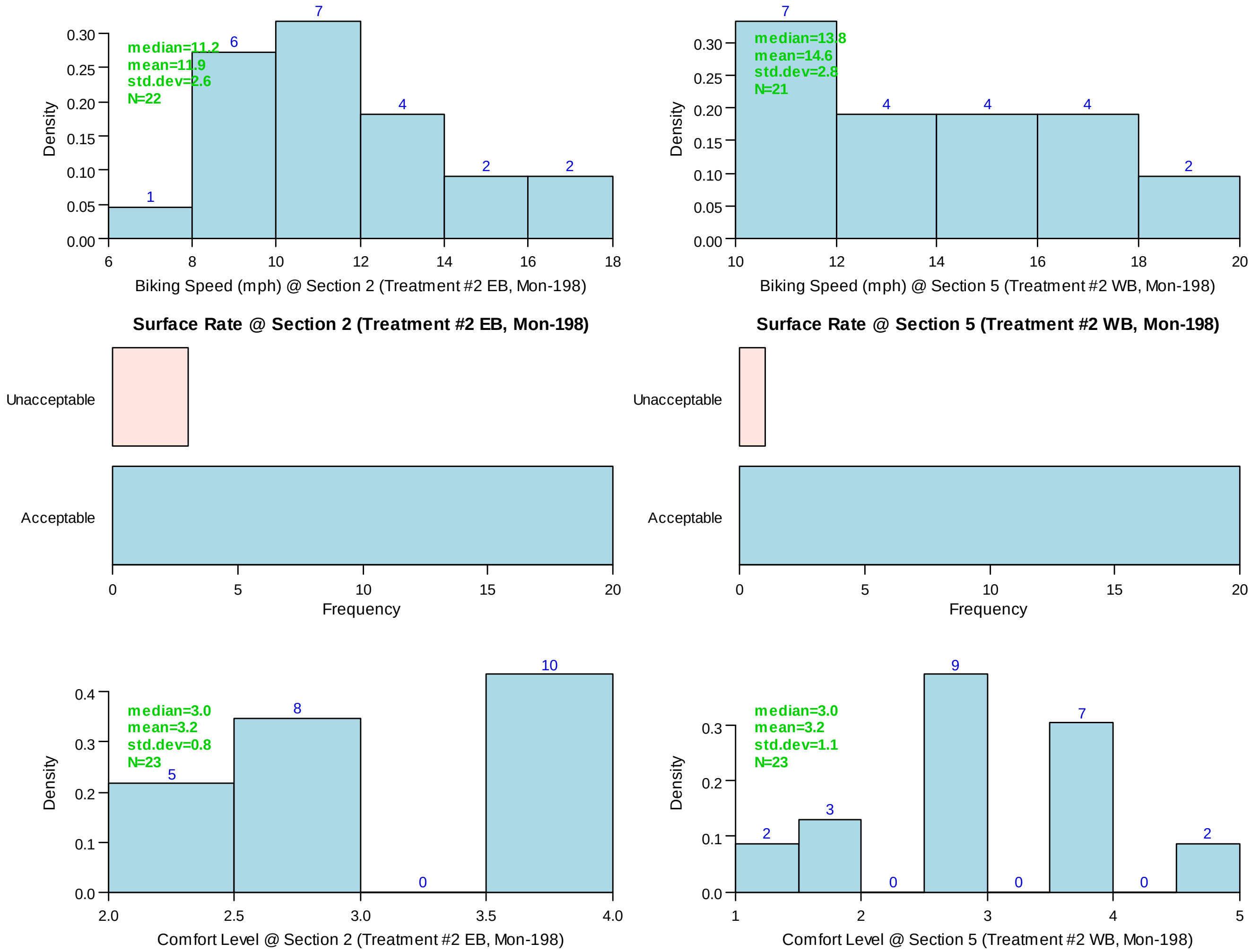


Figure F.5: Raw survey results for treatment #2 (Mon-198).

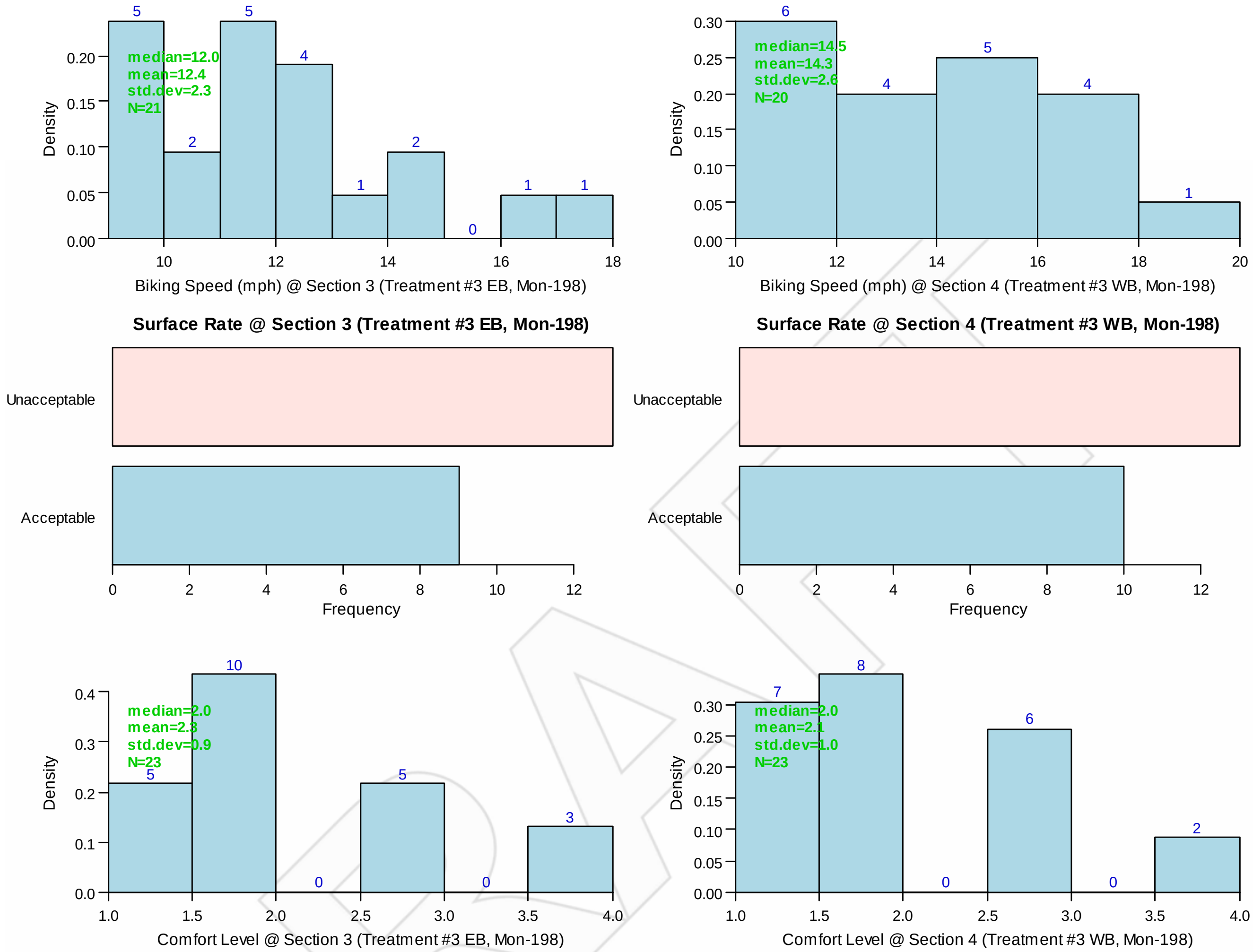


Figure F.6: Raw survey results for treatment #3 (Mon-198).

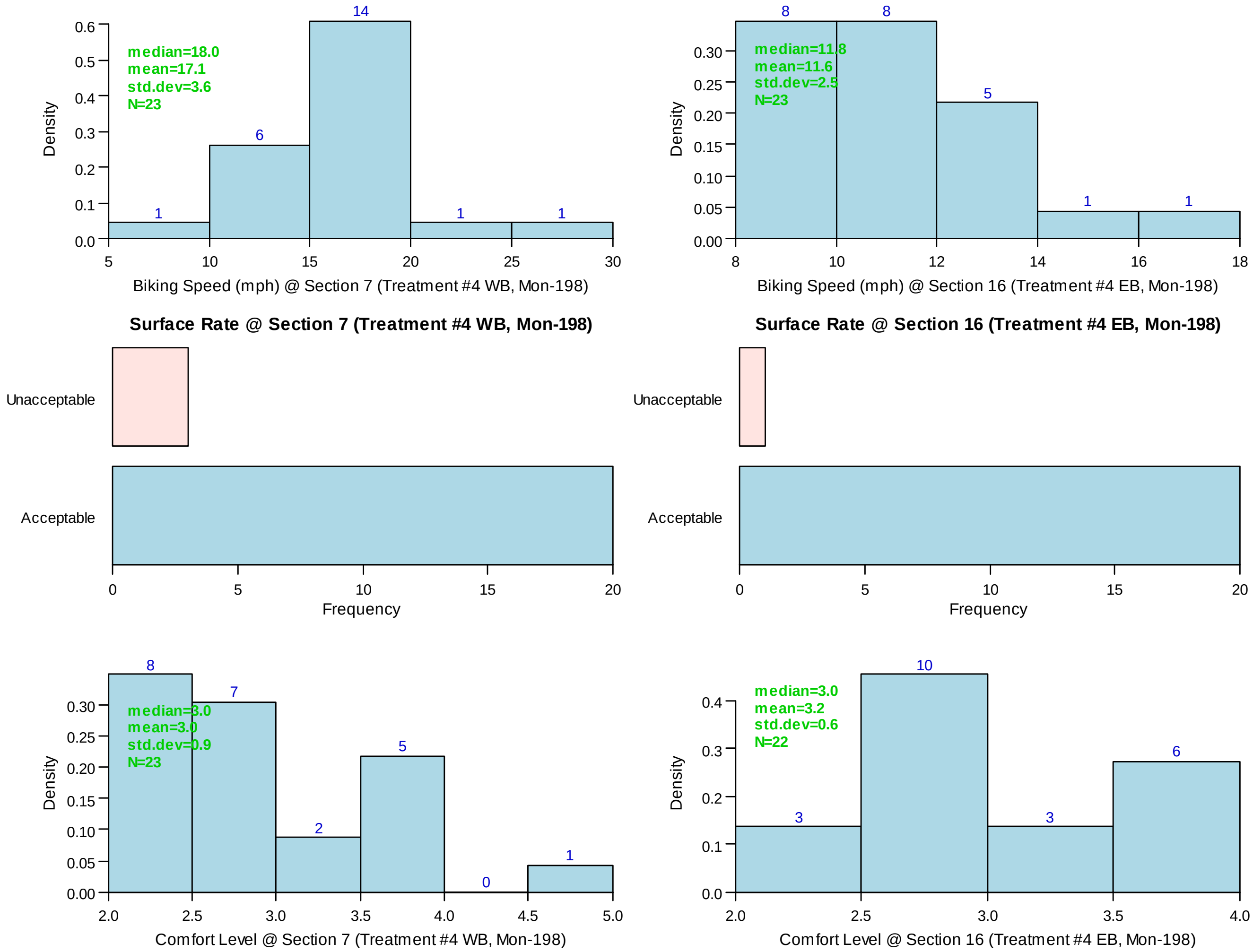


Figure F.7: Raw survey results for treatment #4 (Mon-198).

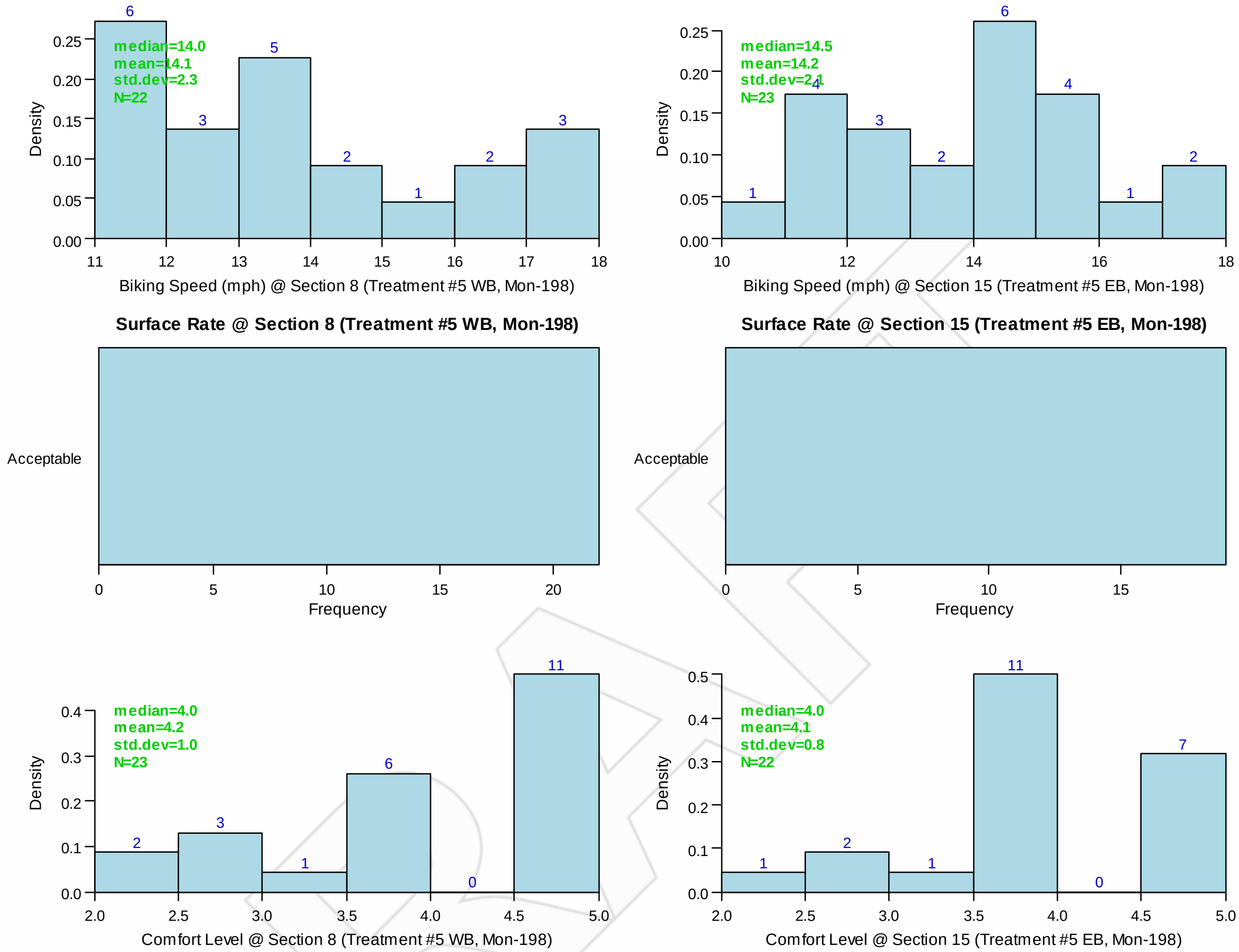


Figure F.8: Raw survey results for treatment #5 (Mon-198).

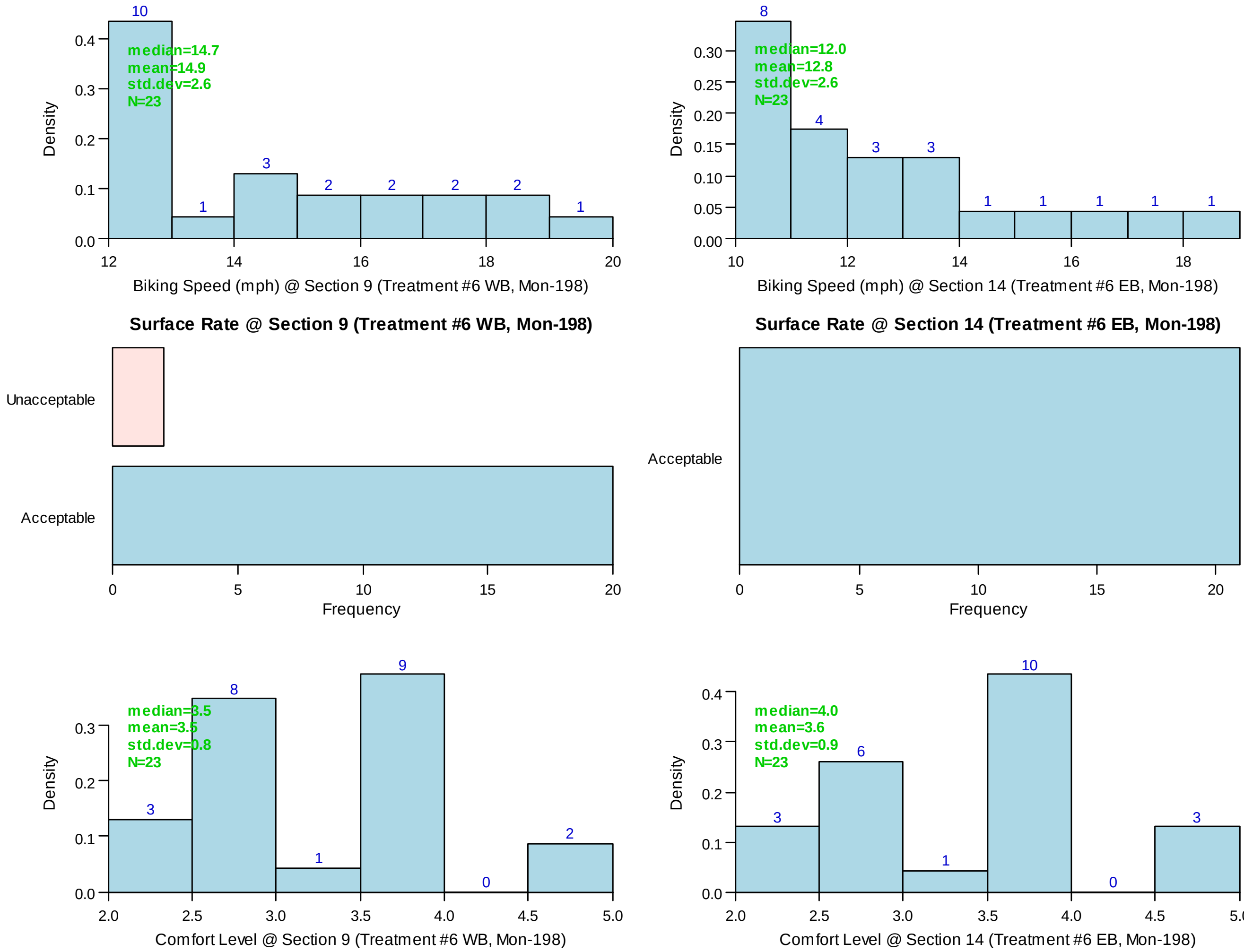


Figure F.9: Raw survey results for treatment #6 (Mon-198).

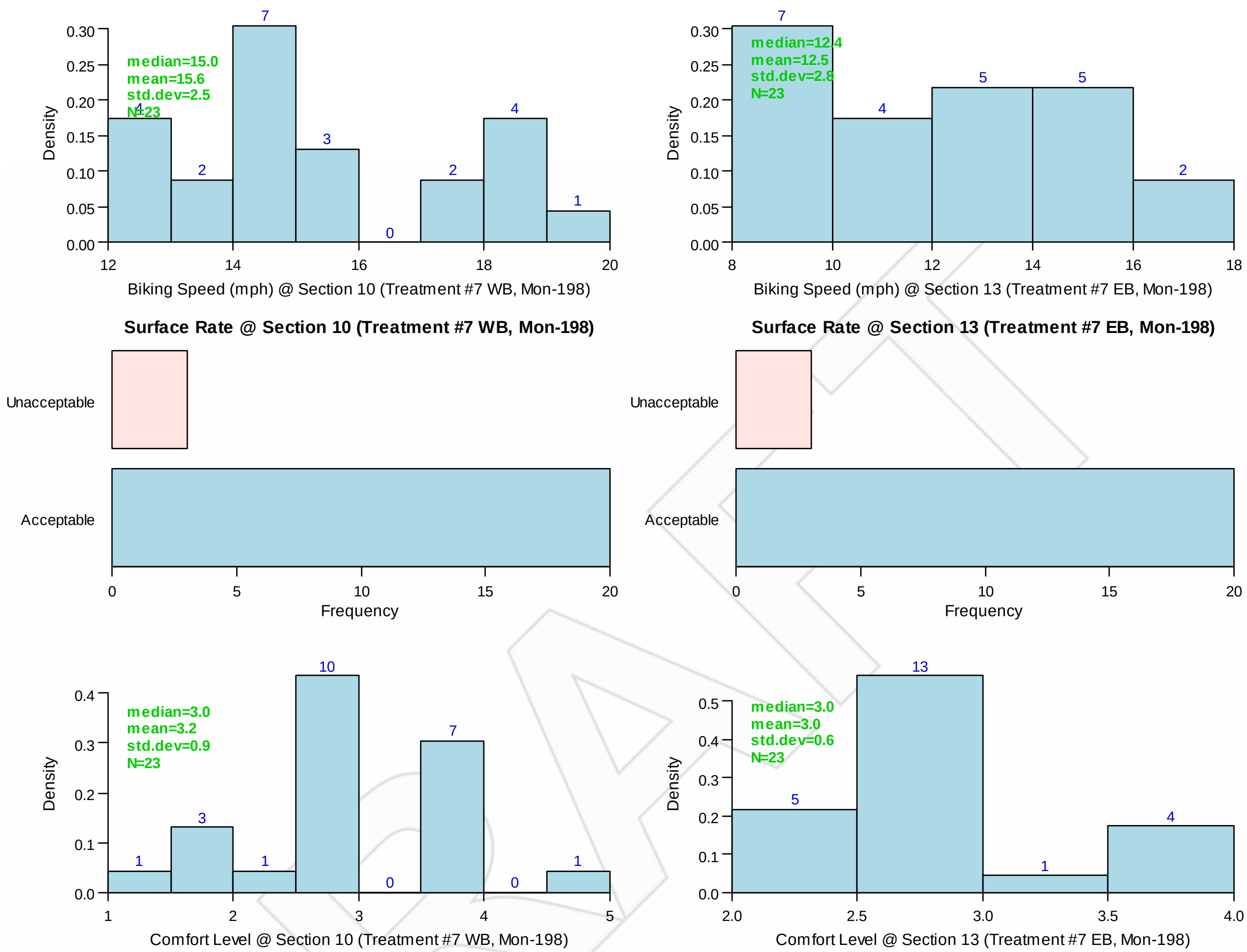


Figure F.10: Raw survey results for treatment #7 (Mon-198).

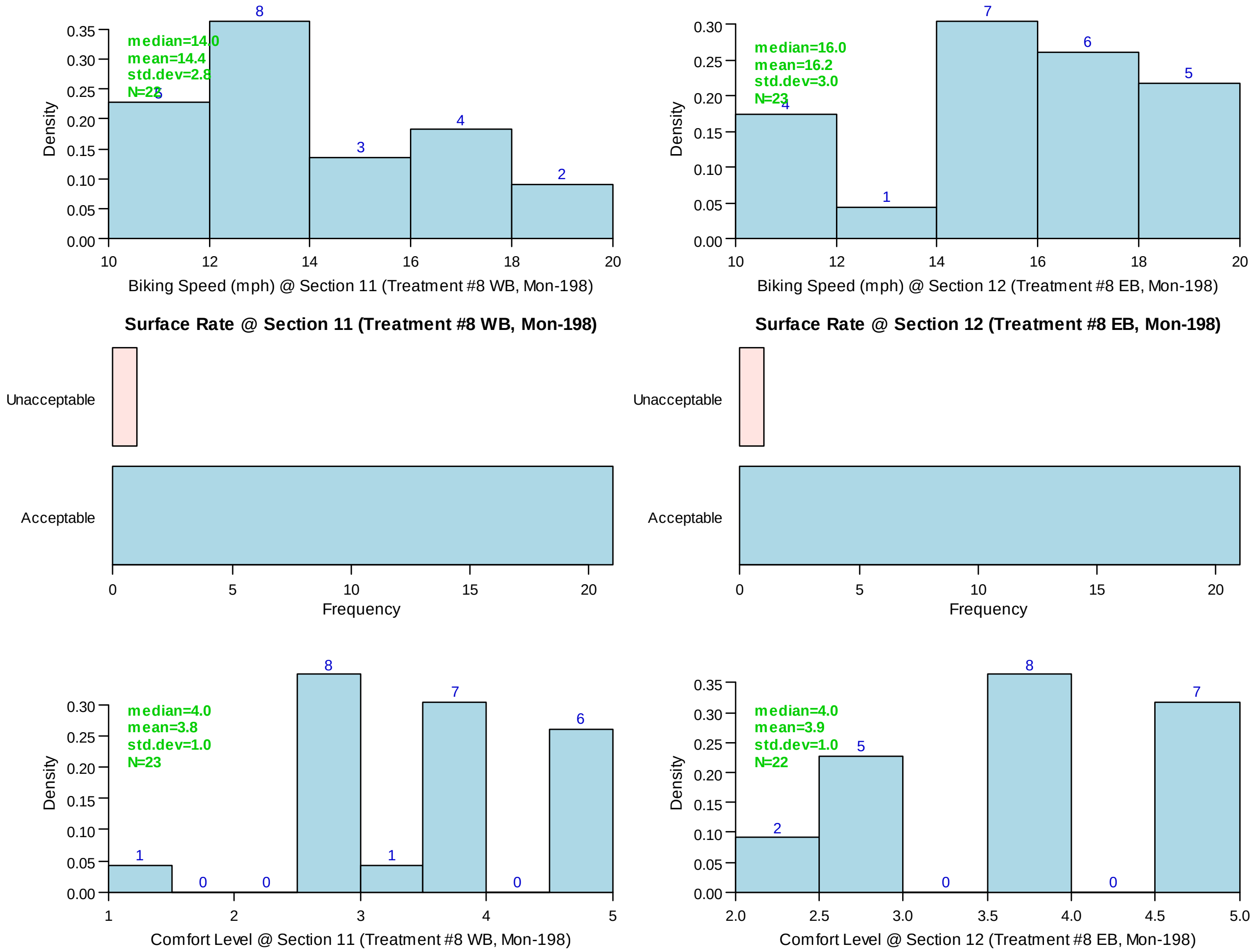


Figure F.11: Raw survey results for treatment #8 (Mon-198).

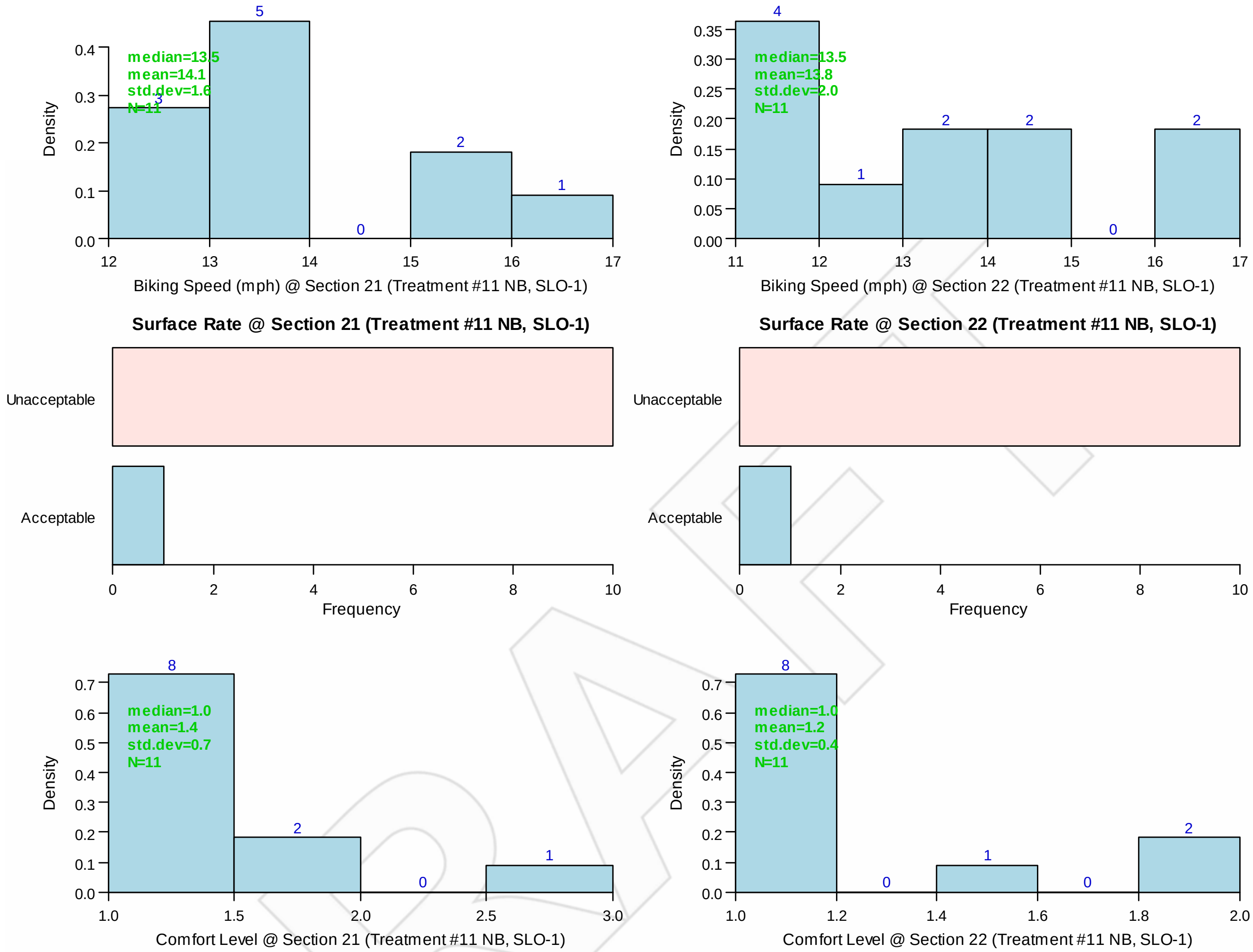
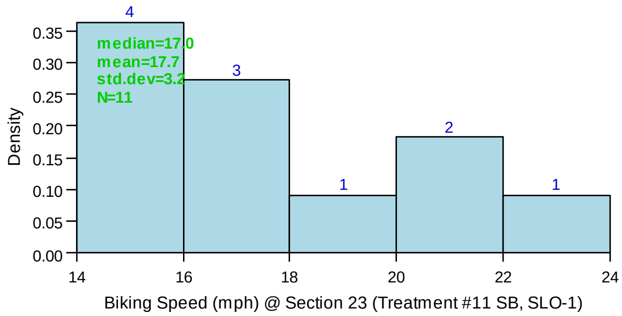
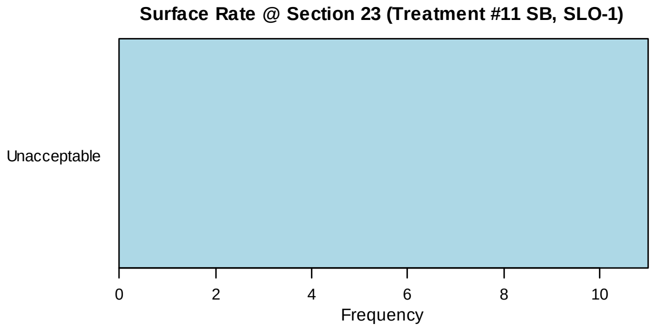


Figure F.12: Raw survey results for treatment #11 (SLO-1).





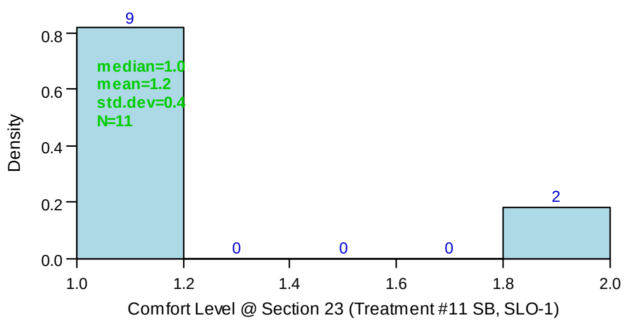


Figure F.12: Raw survey results for treatment #11 (SLO-1) *(continued)*.

F.1.3: Post-Ride Survey: Mon-198

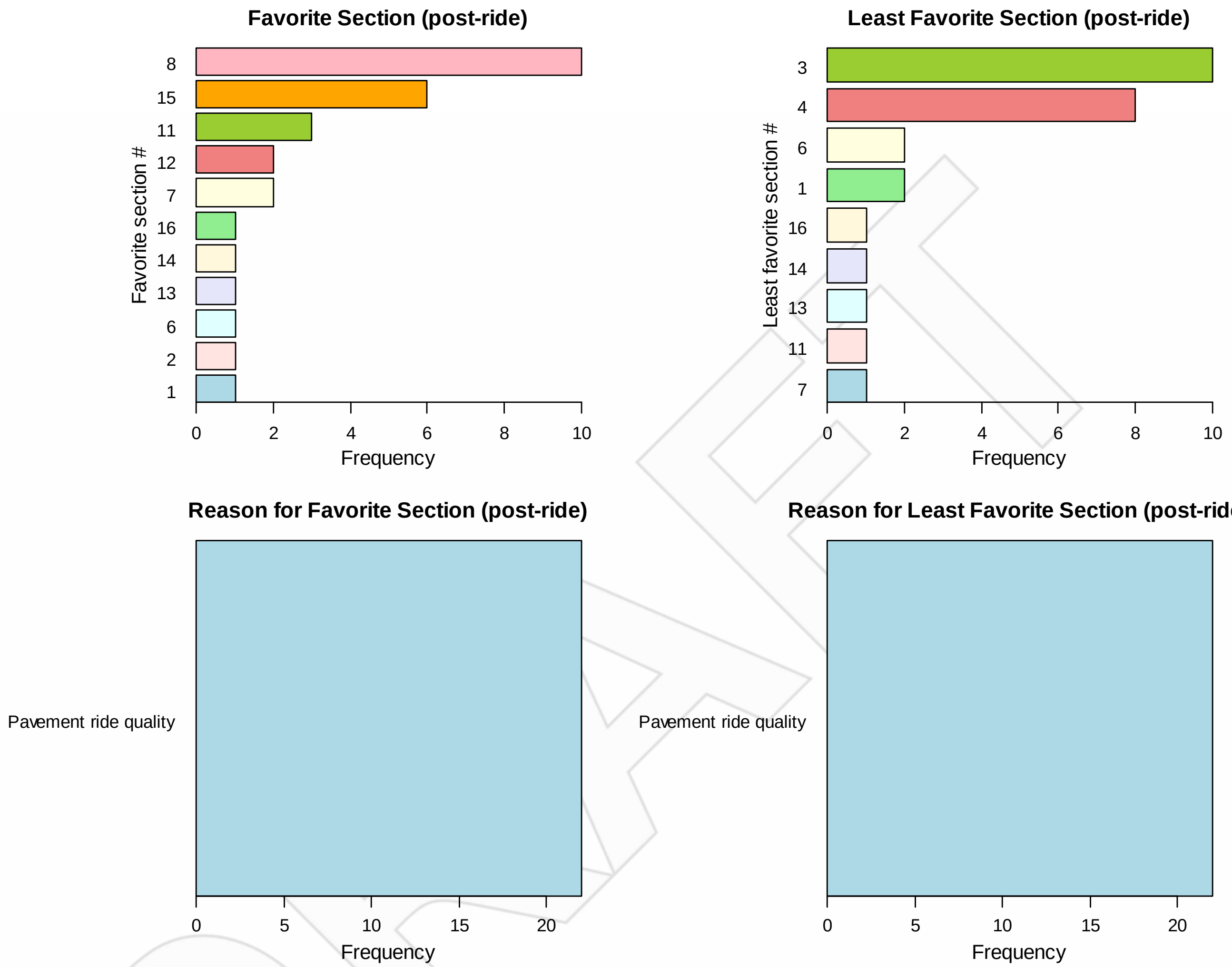


Figure F.13: Raw results of post-ride surveys (Mon-198).

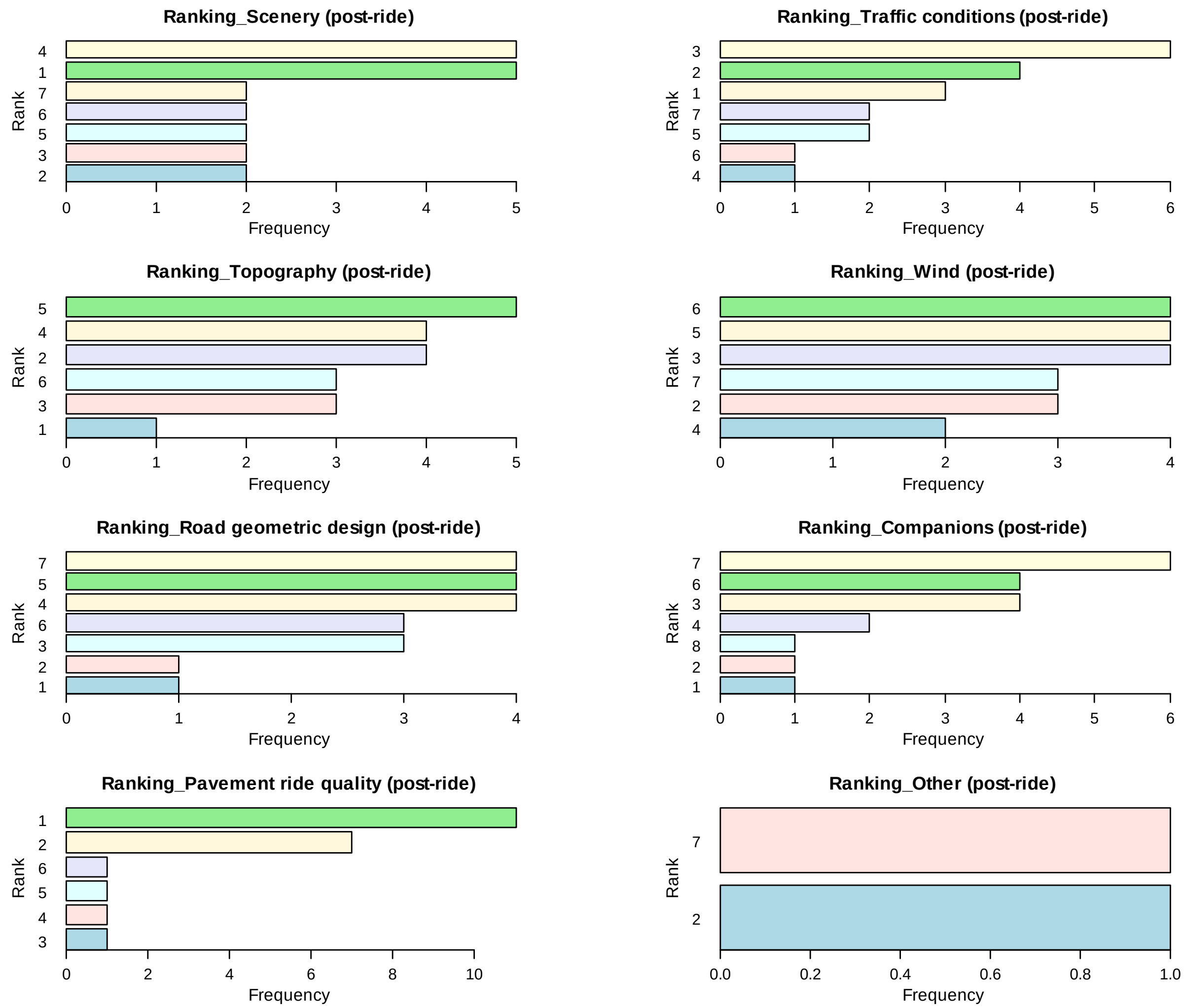


Figure F.14: Survey participants' factor rankings after riding and post-survey (Mon-198).

F.2 Raw Survey Results across All Survey Groups including SLO-1, Mon-198, and Phase II Extended Survey Sections

F.2.1: Background Information of the Survey Participants (Pre-Ride Survey)

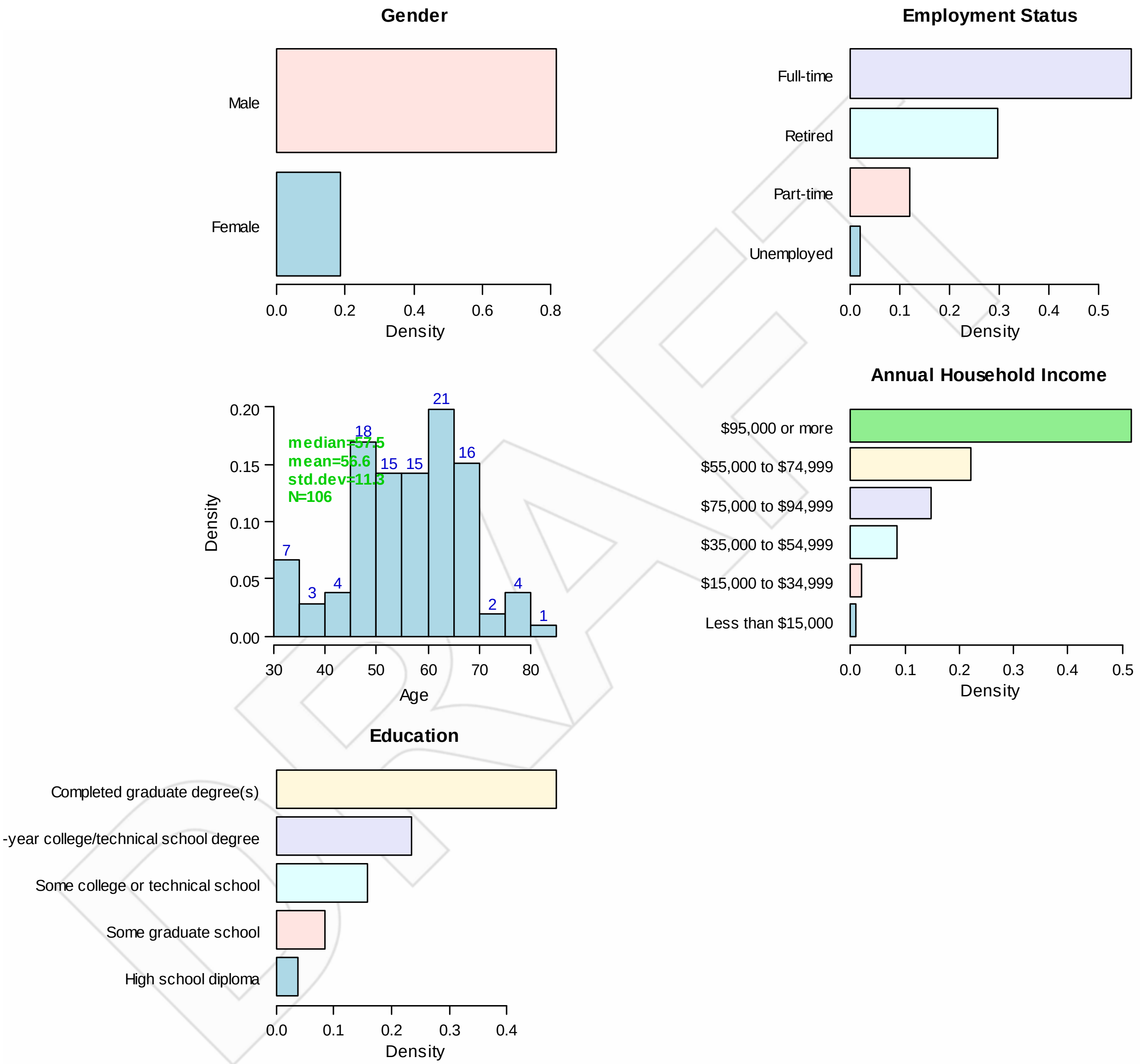


Figure F.15: Survey participants' socioeconomic information.

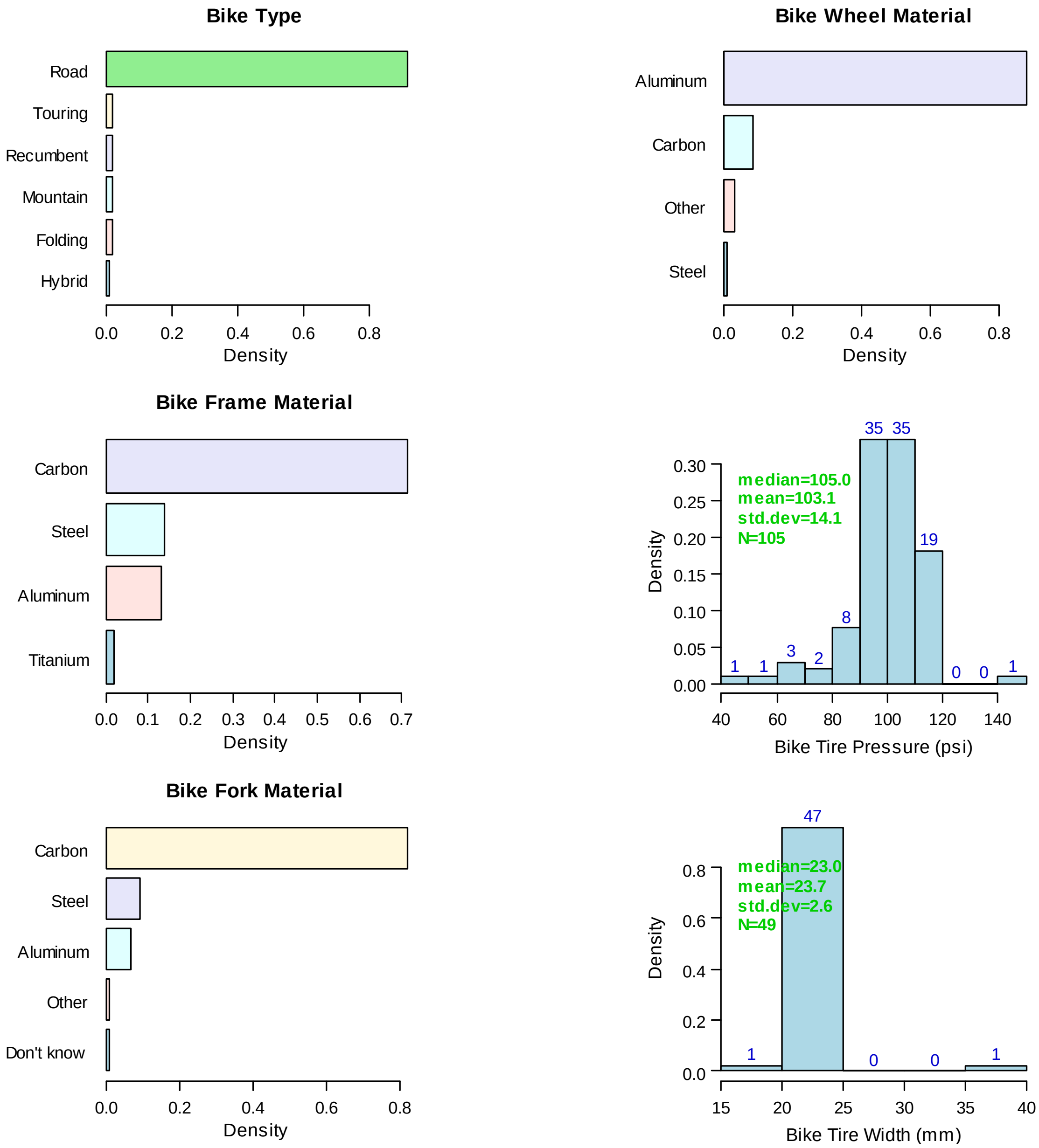


Figure F.16: Survey participants' bicycle information.

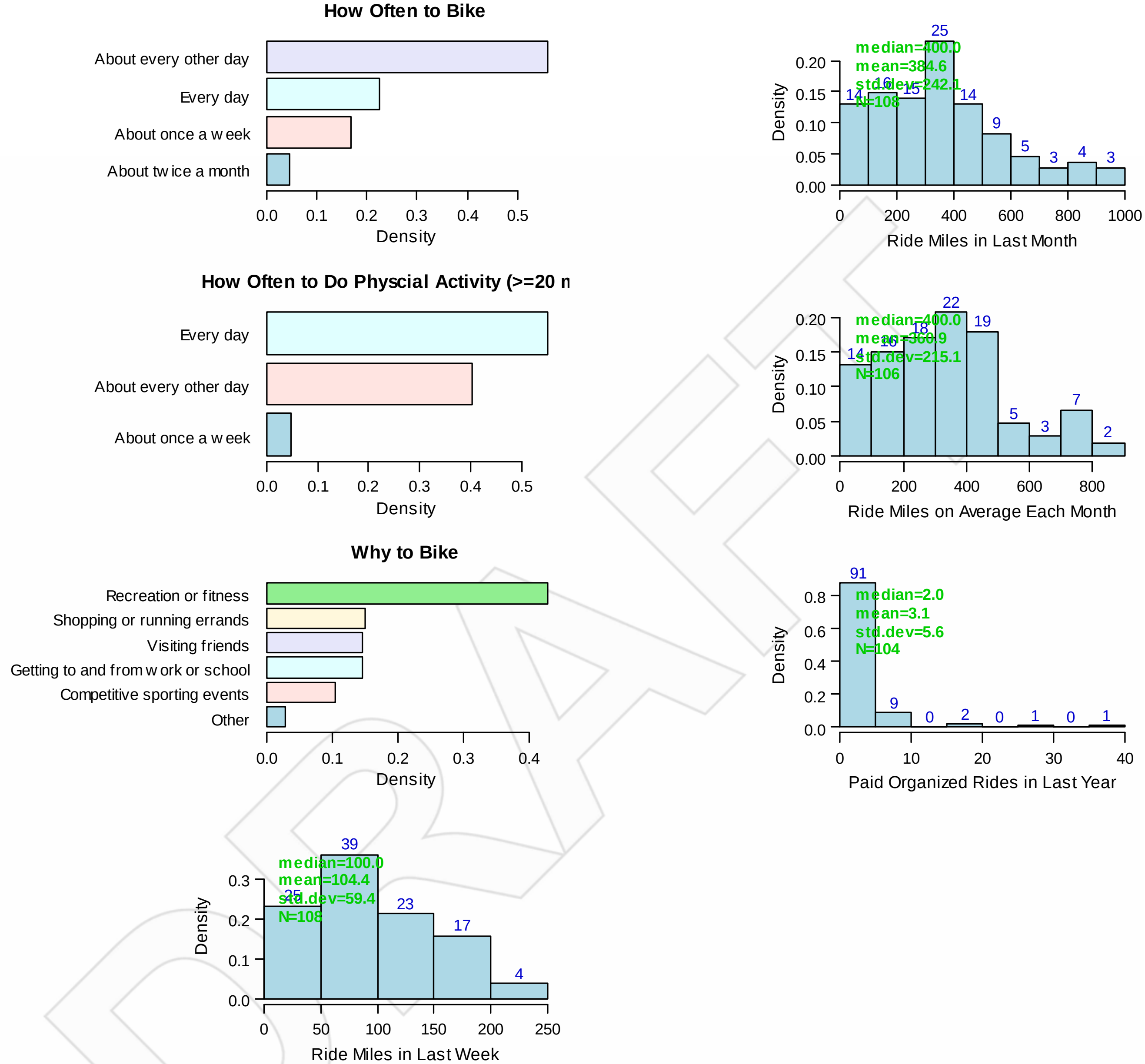


Figure F.17: Survey participants' bicycling activity information.

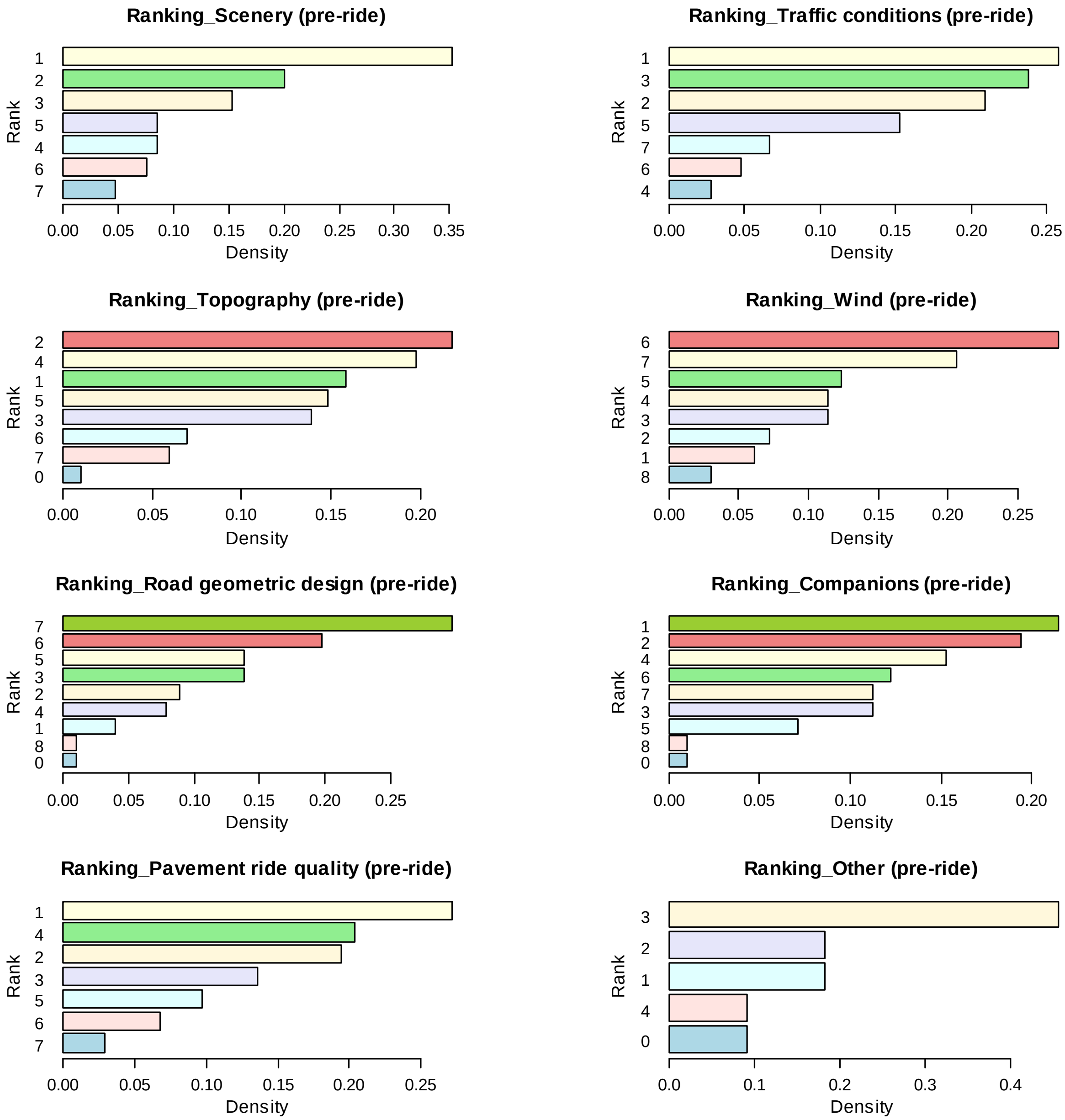


Figure F.18: Survey participants' factor rankings before riding (pre-ride survey).

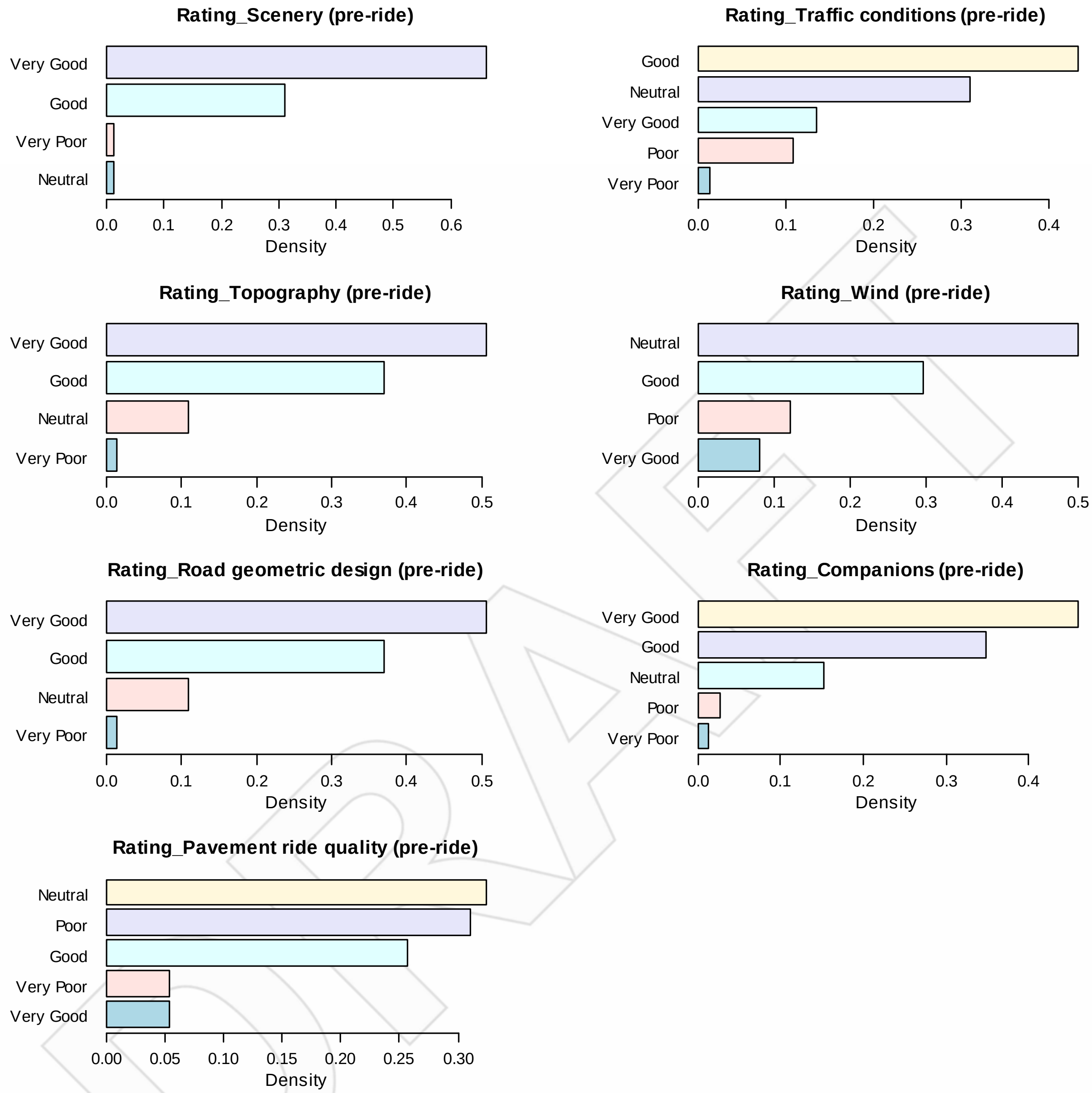


Figure F.19: Survey participants' factor ratings for favorite local recreational bicycle ride (pre-ride survey).

F.3 Survey Participants' Comments on the Road Sections (Mon-198 and SLO-1)

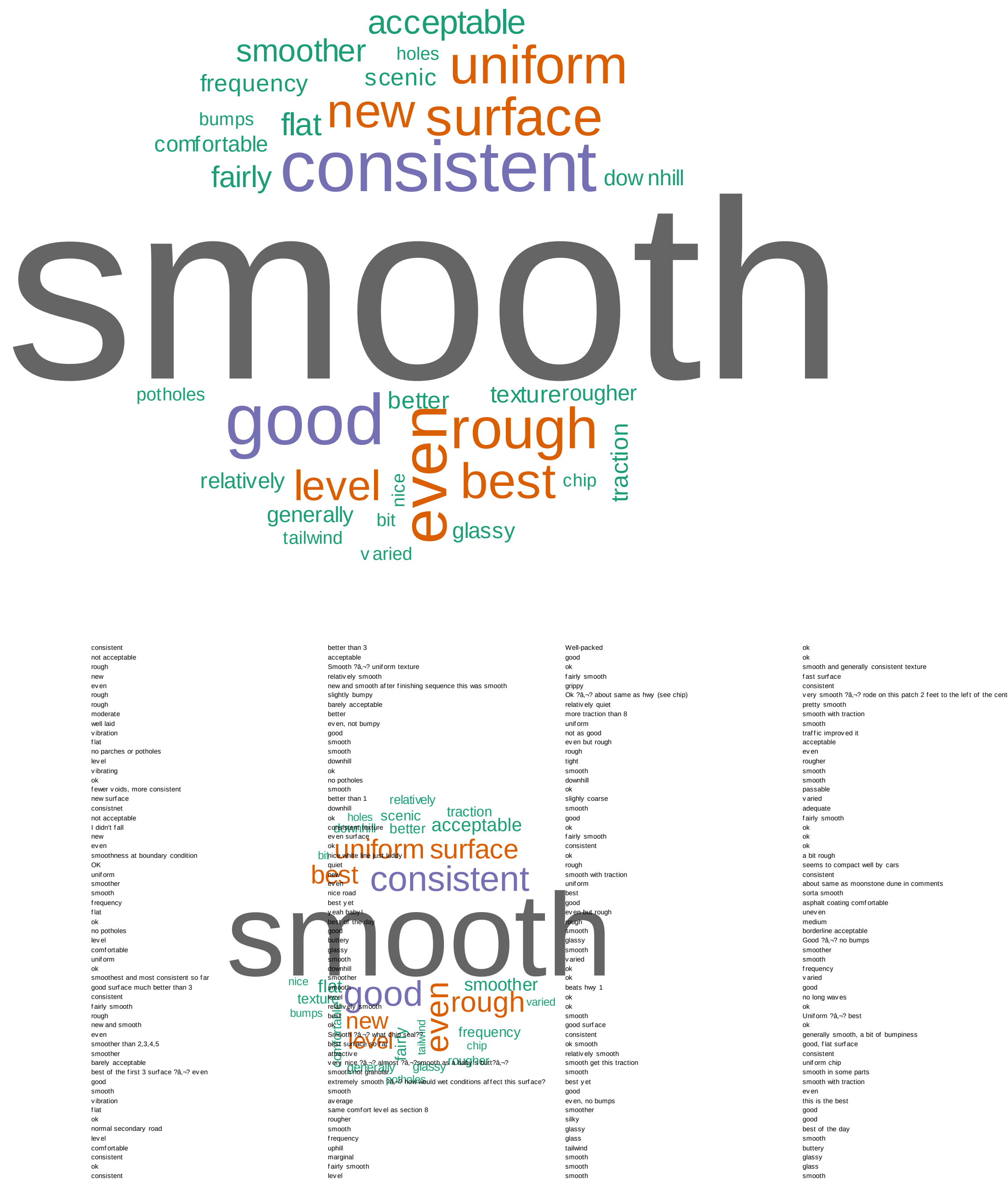


Figure F.20: Word cloud of the words used to describe the best aspect of the sections (Question #3 or #4 of the in-ride survey).
(*Note:* the size of the word is proportional to the frequency with which it was used.)

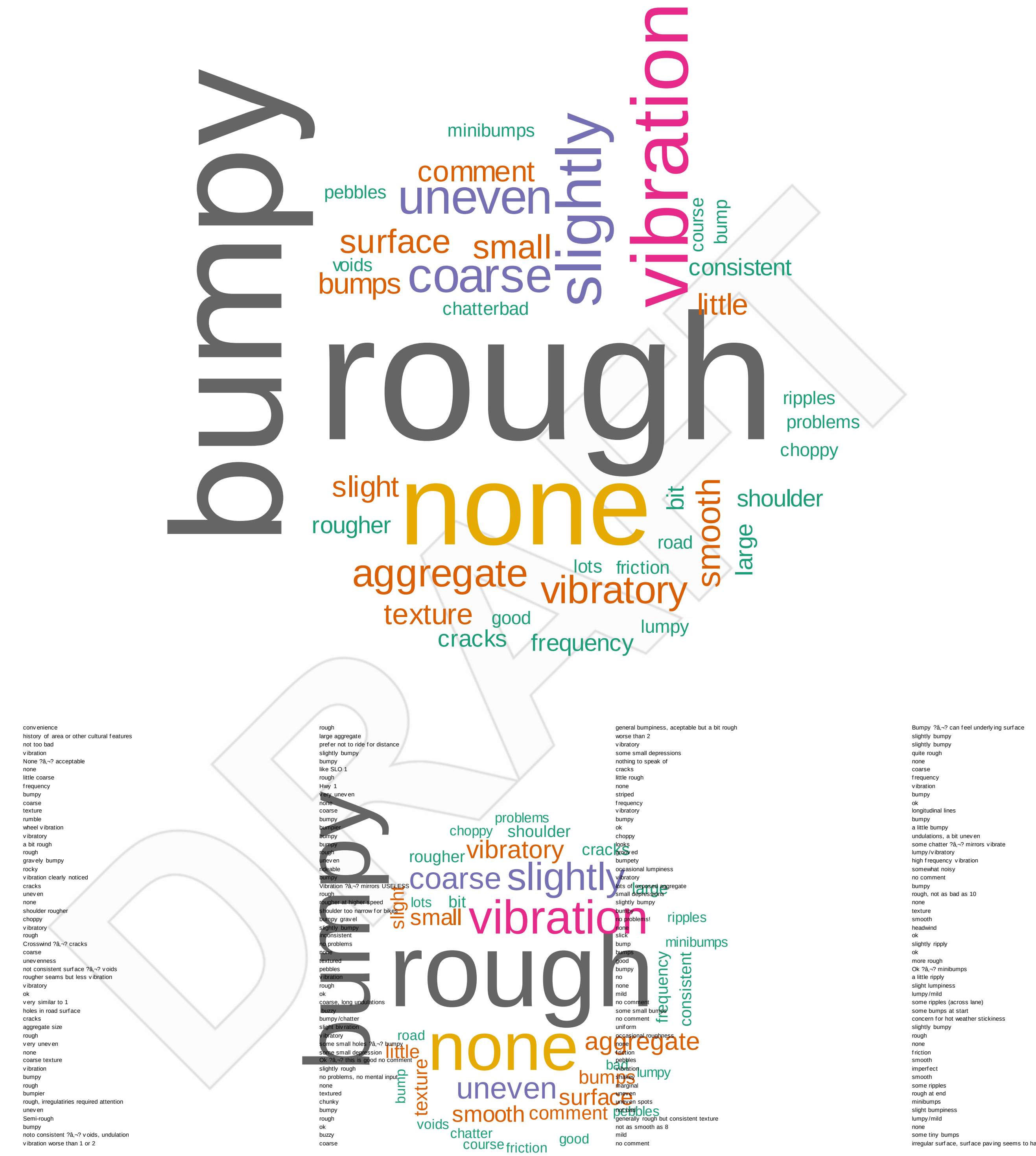


Figure F.21: Word cloud of the words used to describe the worst aspect of the sections (Question #3 or #4 of the in-ride survey).
(Note: **the size of the word is proportional to the frequency with which it was used.)**

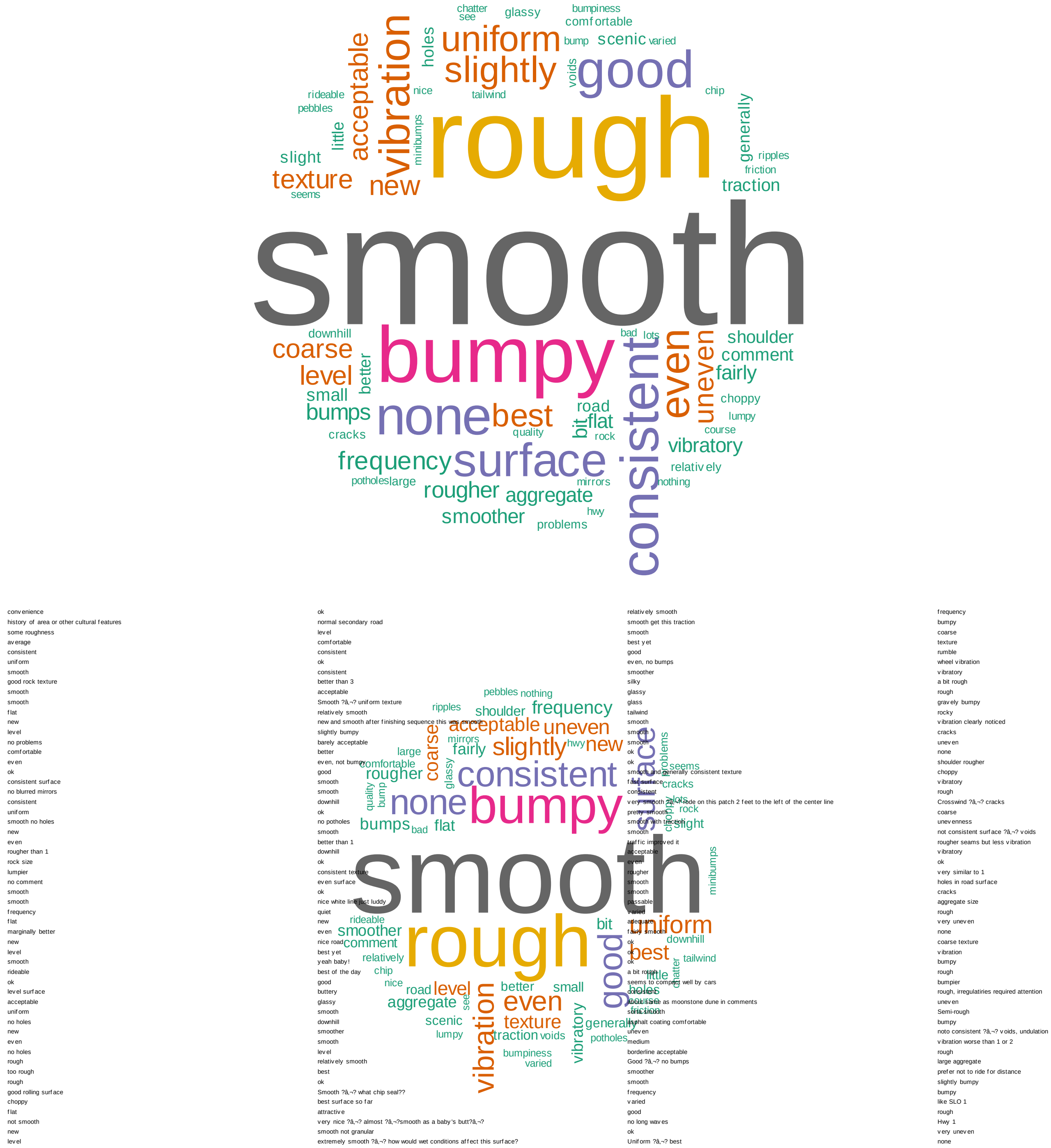


Figure F.22: Word cloud of the words used to describe both best and worst aspects of the sections (Question #3 or #4 of the in-ride survey).
(Note: **the size of the word is proportional to the frequency with which it was used.)**