Louisiana Transportation Research Center

Technical Assistance Report 14-01 TA-P

Joor Road Noise Level Assessment

by

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16. Abstract

Joor Road (LA 946) is an Urban 5-lane Portland cement concrete roadway with an annual daily traffic (ADT) of approximately 13,500 with 7 percent trucks and posted speed of 55 mph. Since being opened to traffic in 2009, residents have been complaining about the high noise levels emanating from the roadway.

A comprehensive experiment was developed. The experiment consisted of randomly selecting six PCC slabs, three northbound and three southbound, in the noisy areas. An additional PCC slab was selected in the southbound direction outside of the noisy area to use as a control. In order to determine if there were any significant differences between this project and another project constructed under the 2006 specifications, four PCC slabs were randomly selected for evaluation on O'Neal Lane, which was constructed approximately two years after this section of Joor Road. The parameters assessed from each of eleven slabs were tine depth, tine width, spacing between tines, and randomness of spacing between tines.

Sound level measurements based on the pass by method indicated the sound levels were excessive (82 dBA) when compared to the Louisiana Department of Transportation and Development's (DOTD) Highway Traffic Noise Policy of 66 dBA for residential areas. Sound level measurements from the OBSI assessment also indicated that sound levels generated by the tire/road contact were excessive with values as high as 110.6 dBA.

Tine parameter analysis implied that the sources of excessive noise level emissions were due to excessive tine widths, non-randomness of spacing between tines, and the spacing intervals between the tines.

Pavement macrotexture values for the north and southbound lanes were generally within the range of 0.5 to 0.8 mm as recommended by Federal Highway Administration (FHWA).

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ABSTRACT

Joor Road (LA 946) is an urban 5-lane Portland cement concrete (PCC) roadway with an annual daily traffic (ADT) of approximately 13,500 with 7 percent trucks and posted speed of 55 mph. Since being opened to traffic in 2009, residents have been complaining about the high noise levels emanating from the roadway.

A comprehensive experiment was developed. The experiment consisted of randomly selecting six PCC slabs, three northbound and three southbound, in the noisy areas. An additional PCC slab was selected in the southbound direction outside of the noisy area to use as a control. In order to determine if there were any significant differences between this project and another project constructed under the 2006 specifications, four PCC slabs were randomly selected for evaluation on O'Neal Lane, which was constructed approximately two years after this section of Joor Road. The parameters assessed from each of eleven slabs were tine depth, tine width, spacing between tines, and randomness of spacing between tines.

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Tine parameter analysis implied that the sources of excessive noise level emissions were due to excessive tine widths, non-randomness of spacing between tines, and the spacing intervals between the tines.

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INTRODUCTION

Joor Road (LA 946) is an Urban 5-lane Portland cement concrete roadway with 10 ft. concrete shoulders, see Appendix A. It has a current average daily traffic (ADT) of approximately 13,500 with 7 percent trucks. The length of the project under detailed investigation for noise level emissions is approximately 3.12 miles (CSLM 1.91 to 5.05).

Since being opened to traffic in 2009, residents have been complaining about the high noise levels emanating from the roadway. In February 2014, Secretary Sherri Lebas requested that the Louisiana Transportation Research Center (LTRC) conduct a detailed investigation on this section of Joor Road to determine the source(s) of the high noise levels as well as develop abatement methods for senior Louisiana Department of Transportation and Development (DOTD) executives to review.

Literature Review

Noise generated by vehicles on roadways has been studied extensively internationally *[1-20]*. As presented in Table 1, there are many sources of noise generated by light and heavy vehicles *[1, 2]*. There are noises generated by the vehicle itself (air intake, exhaust outlet, engine block, transmission, and cooling fan) as well as the tire-road surface contact. The amount of noise varies depending on vehicle type and its travel speed. In higher speed situations, the tire-road contact may account for as much as 80 percent of the noise being generated.

Table 1
Vehicle noise *[1] [2]*

	Light vehicles %		Heavy vehicles %	
Source of noise (dBA)	Town	Open road	Town	Open road
Air intake inlet, exhaust outlet	15 to 35		15 to 60	
Exhaust pipe assembly	15 to 30			40 to 80
Engine block	20 to 30	20 to 70		
Gear box and transmission	5 to 30		30 to 80	
Cooling fan	-		10 to 50	
Tire-road surface contact	5 to 10	30 to 80	5	20 to 60

Note: Town-lower speeds and Open road- higher speeds

Since the type of vehicles traveling on Joor Road cannot be altered and the travel speed (55 mph) is unlikely to be lowered, both of which could reduce the magnitude of the noise, the authors focused on the tire-road noise component in this study.

Unpleasant sounds are generally described as noise. Though subjective, depending upon the individual, generalizations have been developed regarding noise as presented in Table 2 *[3, 4, 5]*. Equation (1) presents the relationship between sound pressure (μPA) and sound noise level (dBA).

Table 2
Facts about sound intensity *[3, 4, 5]*

EFFECTS:	TYPICAL SOUND SOURCE	SOUND PRESSURE (μPA)	SOUND NOISE LEVEL (dBA)
Serious hearing damage	Space rocket launch, in the vicinity of the launch pad	200,000,000	140
Hearing damage and pain	Jet engine (25 m/82 ft. distance)	63,245,555	130
Hearing damage after short exposure	Air-raid alarm (5 m/16 ft. distance)	20,000,000	120
Serious hearing damaged hazard	Rock music concert, close to stage	6,324,555	110
Hearing hazard	Jet plane take-off (300 m/984 ft.)	2,000,000	100
Some hearing hazard	Noisy industrial hall	632,456	90
Health effects	Heavy truck, 70 km/h; 44 mph (10 m/32.8 ft. distance)	200,000	80
Some health effects Severe annoyance	Car, 60 km/h; 37 mph (10 m/32.8 ft. distance)	63,246	70
Annoyance	Normal conversation (1 m/3.3 ft. distance)	20,000	60
Some annoyance	Quiet conversation (1 m/3.3 ft. distance)	6,325	50
Good environment	Subdued radio music	2,000	40
	Whispering	632	30
	Quiet bedroom	200	20
	Rustling leave	63	10
Uncomfortably “quiet”	Anechoic room for sound measurements	20	0

$$\text{Sound pressure } (\mu\text{PA}) = 17.808 * e^{0.1151x \text{ (dBA)}} \quad (1)$$

Tire-road surface contact generates sound through a multitude of mechanisms some of which are not fully understood as presented in Figures 1 and 2 and Table 3 *[5, 6, 7]*. Additional noise generation is developed by the tire block protruding into the tine which creates a “pipe resonance effect” as presented in Figure 3*[5]*. Specific to PCC pavements, depth of tine, width of tine, spacing between tines, and randomness of spacing between tines affects sound generation, which is discussed in detail later *[8-10]*.

Two main groups are generally used to describe sound generation: structure-borne and air-borne. Structure-borne refers to the mechanical vibrations of the tire such as impact, shock, and adhesion mechanisms all of which varies based upon tire type, pavement surface, and vehicle speed as presented in Figure 1 and Table 3 *[3, 4, 11-17]*. Impacts and shocks occur by the tire block making contact and losing contact with the pavement surface as the tire rolls along the highway. This generates vibrations which in turn creates sound pressure waves propagating away from the tire. Adhesion mechanisms emerge due to frictional losses in the contact area between the tire and pavement *[3, 4]*.

Air-borne noise is generated by the pumping of air through the tire tread as it contacts and loses contact with the pavement, as presented in Figure 2 with additional specifics in Table 3. Air is drawn in (compressed) as the grooves between the tread block makes contact with the pavement surface and is pumped out (decompressed) when the grooves between the tread block loses contact with the pavement *[3, 4, 11-17]*.

When the pavement is tined (grooved), another mechanism exists for air to be compressed, decompressed, and jetted (pipe resonance) when the tread block protrudes into the pavement groove, as presented in Figure 3. The wider the pavement groove, the more volume of air can be displaced resulting in increased sound generation (noise) *[5]*.

Sound emissions are also influenced by the macrotexture of the pavement, pavement chemical properties, surface geometry, porosity, elastic properties within the pavement structure, and surface roughness as presented in Table 4 *[1]*.

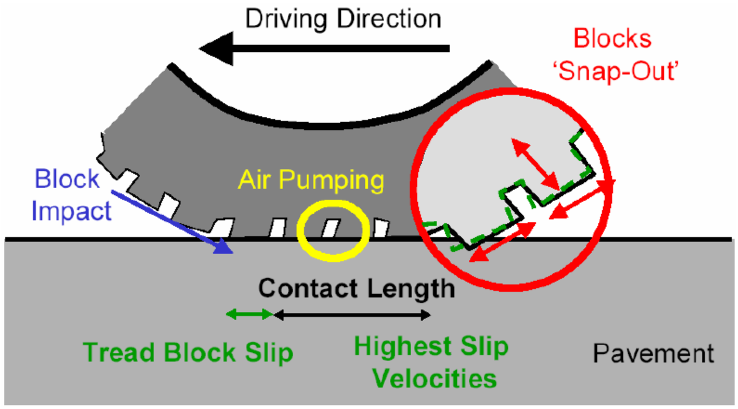

Figure 1
Noise generation mechanisms *[5, 7, 11, 17]*

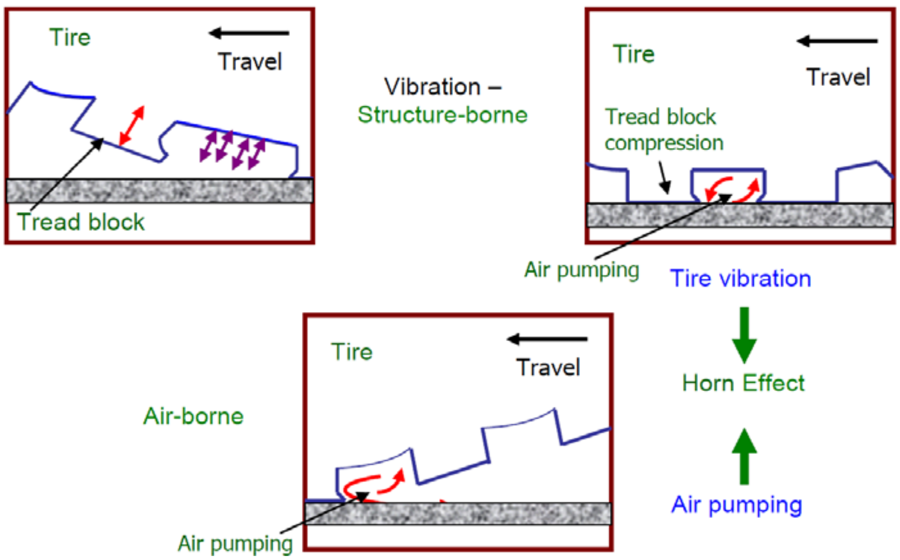

Figure 2
Structure-borne and air-borne emission *[5, 7, 11, 17]*

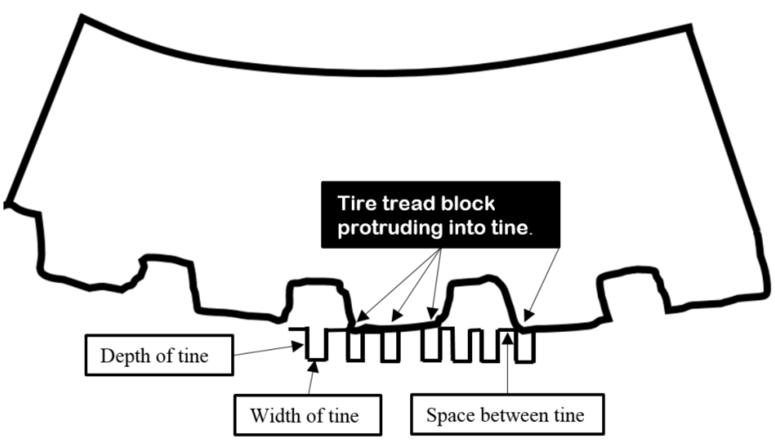

Figure 3
Tread block into pavement surface tine *[5]*

Table 3
Mechanisms of noise emission *[5,6]*

Generation Mechanisms	
Mechanism	Comments
Radial Vibration Mechanism	Impact of tire tread blocks or other pattern elements on road surfaces. Impact of road surface texture on the tire treads.
Air Resonance Mechanism	Pipe resonance. Helmholtz resonance. Pocket air-pumping.
Adhesion Mechanism	Stick/slip motions causing tangential tire vibrations. Rubber-to-road stick/release (adhesive effect).
Special amplification or reduction mechanisms	
Mechanism	Comments
The Horn effect	The curved volume between the tire leading and trailing edges and the pavement constitute something similar to an exponential horn used to amplify sound.
The Acoustical Impedance effect	Communicating voids in porous surfaces act like sound absorbing material, affecting the source strength. Same, affecting sound propagation to far-field receiver.
The Mechanical Impedance effect	Pavement gives more or less reaction to tire block impacts depending on dynamic tire/road stiffness proportions. Some tire vibrations may be transferred to the pavement, possibly radiating as sound (speculation).

Table 4
Noise due to tire-road contact *[1]*

	Phenomenon	**Road surface parameter**
I.	Vertical excitation and radiation of noise from the tire casing	Longitudinal profile (macrotexture) Mechanical impedance at the point of contact (elastic properties of the Road)
II.	Tangential excitation as a result of stick and slip action	Physico-chemical properties and longitudinal profile
III.	Suction and expulsion of air (air pumping and air pocket resonance)	Geometry and porosity
IV.	Aerodynamic action and air turbulence	None
V.	Radiation of noise from the Road itself	Elastic properties of the different layers making up the Road structure
VI.	Radiation of noise from the vehicle body or the load being carried	Profile (surface evenness)

According to a Federal Highway Administration (FHWA) sponsored study, the major PCC pavement surface parameters that influence sound production are, the depth of tines, the width of tines, the spacing between tines, and the randomness of spacing between tines *[8]*. All four of these factors were investigated in this study. Regarding transverse tinning, FWHA states, "When using random transverse tine spacing (minimum spacing of 10 mm and a maximum spacing of 40 mm with no more than 50 percent of the spaces exceeding 25 mm) should be specified pending the results of further research. The actual tine width should be 3 mm (+/-) 0.5 mm (2.5 to 3.5 mm), and the tined depth should be a minimum of 3 mm and a maximum of 6 mm (provided minimum dislodging of the aggregate particles results.) Narrow (less that 4 mm width), deep grooves are considered better than wider, shallow grooves for minimizing noise. The average texture depth as measured by the sand patch test (ASTM E 965) should be 0.8 mm with a minimum of 0.5 mm for individual tests. Measurements of random spacing's at two locations in Wisconsin that generate low-noise levels and no tire/pavement whine are as follows *[8, 9, 10]*.

1. 32/19/22/25/35/22/22/22/22/25/35/13/38 mm
2. 16/25/22/16/32/19/25/25/25/25/19/22/25/22/10/25/25/25/32/38/22/25/22/25 mm"

Joor Road was constructed under the 2006 DOTD specification guidelines *[18]*. Section 601, of the 2006 DOTD Specifications book that pertains to tinning states that "tines shall be steel flat wire, 4 to 5 inches (100 to 125 mm) in length, randomly spaced, with a minimum spacing of 3/8 inch (10 mm) and a maximum spacing of 1 1/2 inch (40 mm). No more than 50 percent of the spaces shall exceed 1 inch (25 mm). The width of tines shall be 1/8 ± 1/64 inch (3.0 ± 0.5 mm). The depth of groove produced in the concrete shall be 3/16 inch (5 mm) maximum and 1/8 inch (3 mm) minimum, measured in accordance with DOTD TR 229. Pavement, which does not meet the above requirements, shall be corrected by regrooving." DOTD tinning specifications mirrors FHWA guidelines with the exception that the maximum tine depth allowed by DOTD is 5 mm instead of 6 mm recommended by FHWA *[8]*.

METHODOLOGY

Experiment Design

In order to determine the pavement surface characteristics on Joor Road, a comprehensive experiment was developed. The experiment consisted of randomly selecting six PCC slabs, 3 northbound and 3 southbound, in the noisy areas. An additional PCC slab was selected in the southbound direction outside of the noisy area to use as a control. In order to determine if there were any significant differences between this project and another project constructed under the 2006 specifications, four PCC slabs were randomly selected for evaluation on O'Neal Lane, which was constructed approximately two years after this section of Joor Road. The parameters assessed from each of eleven slabs were tine depth, tine width, spacing between tines, and randomness of spacing between tines as presented in Figures 4 to 7. Additional testing on Joor Road included noise assessments using the Pass-by-noise analysis, On-board surface intensity (OBSI) noise analysis method, pavement roughness (IRI) and macrotexture using LTRC's high speed profiler. Details of each is as follows.

PCC Tining Measurements

Grids were laid out on the selected PCC slabs and tine depth measurements were taken in accordance with DOTD TR 229M/229-97 from the edge of the slab to the centerline at one foot intervals as presented in Figures 4 and 5. The field data were transferred from field notes into an excel sheet. The collected data were used in statistical analyses (described later) as well as to determine if the tine depths were within the range (3 mm to 5 mm) specified in DOTD Section 601 *[18]*.

Spacing between tines and tine widths were determined by examining photographs taken of the slabs as presented in Figures 4, 6, and 7. A tape with metric units was placed on the pavement slab (approximately 20 ft. in length) from joint to joint and photographed with a 16.1 megapixel camera as presented in Figure 6. The spacing between each tine was recorded into an excel sheet and used in the statistical analyses, which in this case included a statistical test for randomness *[19, 20, 21]*. Tine widths were tabulated by recording the width of the first tine from the joint and measuring the tine nearest each foot mark on the tape as it progressed along the slab, which generally produced about 20 tine width measurements per slab. Both the spacing between tines and test for randomness were conducted to determine if DOTD section 601 specifications were met. Since DOTD does not specify a specific tine spacing sequence such as "32/19/22/25/35/22/22/22/22/25/35/13/38 mm," an assessment for that could not be conducted. The researchers did attempt to identify if any pattern of tining intervals was present.

Figure 4
PCC tine measurements

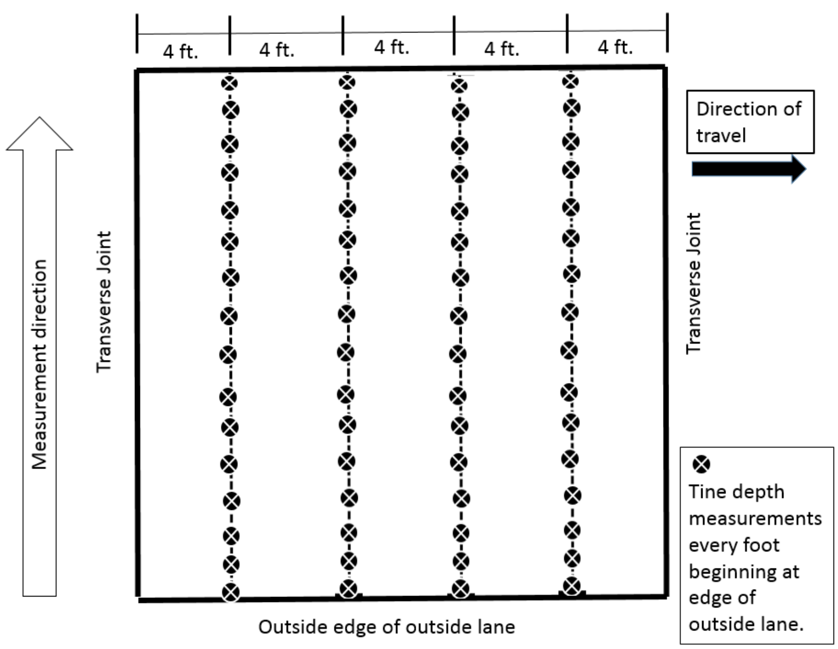

Figure 5
PCC tine depth measurement

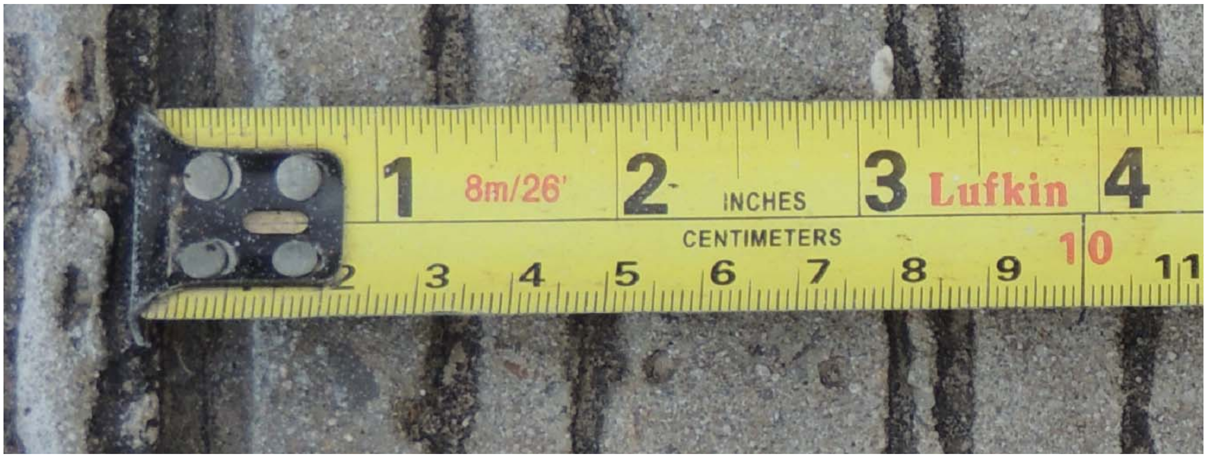

Figure 6
Photo of tape measurement used for tine width and spacing measurements

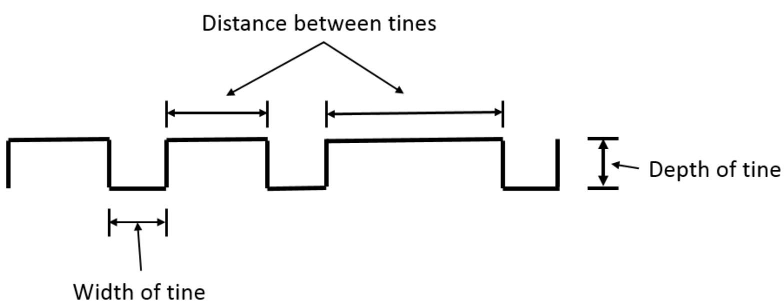

Figure 7
Schemata of tine depth, width, and distance between tines

Statistical Analyses of Tine Data

The statistical method using Tukey groups was used to determine if statistical differences existed between the slabs measured for the parameters of tine depths and widths *[19]*. Since uniform spacing between tines is not part of DOTD Section 601 specifications, checking for statistical differences would have value only to determine if the averages were similar. However, random spacing between tines is part of the DOTD 601 specification, so a non-parametric test for randomness (Runs Test) was employed for each measured slab or site *[20]*. All parameters were evaluated to determine if DOTD 601 specifications were met.

Noise Analyses

Pass-By Noise Measurements

Pass by noise measurements "a weighted dBA" were conducted by setting up a microphone at a distance of 50 ft. from the right wheel path of the outside the lane in accordance with DOTD, FHWA, and AASHTO guide lines *[22, 23, 24]*. The sound noise level (Leq) in dBA was reported using 15 minute moving averages. Sound readings were taken in the morning (≈ 6 am to 9 pm) and afternoon (≈ 4 pm to 6 pm) in the noisy area and in the morning (≈ 6 am to 9 am) outside the noisy area on Joor Road. Since the posted speeds on Joor Road (55 mph) were significantly different than the posted speed (35 mph) on O'Neal Lane, and speed has a huge impact on sound emission, sound measurements were not taken on O'Neal Lane. In accord with the noise measurement standards, 15 minute moving averages were calculated throughout the measurement time and the peak 15 minute Leq in dB(a) from the peak hour was used to determine whether or not it was in compliance with the noise levels presented in Table 5 *[22, 23]*. Joor Road fits into activity Category B based upon FHWA guidelines as presented in Table 5.

Table 5
FHWA noise abatement criteria

Activity Category	Activity Leq (h)	Evaluation Location	Activity Description	In Louisiana, Impact occurs when Noise Level ***is equal to or greater than*** the values below*
A	57	Exterior	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.	**56**
B	67	Exterior	Residential (includes undeveloped lands permitted for residential).	**66**
C	67	Exterior	Active sport areas, amphitheaters, auditoriums, campgrounds, cemeteries, day care centers, hospitals, libraries, medical facilities, parks, picnic areas, places of worship, playgrounds, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, recreation areas, Section 4(f) sites, schools, television studios, trails, and trail crossings. (Includes undeveloped lands permitted for these activities).	**66**
D	52	Interior	Auditoriums, day care centers, hospitals, libraries, medical facilities, places of worship, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, schools, and television studios.	**51**
E	72	Exterior	Hotels, motels, offices, restaurants/bars, and other developed lands, properties or activities not included in A-D or F. (Includes undeveloped lands permitted for these activities).	**71**
F	------	------	Agriculture, airports, bus yards, emergency services, industrial, logging, maintenance facilities, manufacturing, mining, rail yards, retail facilities, shipyards, utilities (water resources, water treatment, electrical), and warehousing.	**n/a**
G	------	------	Undeveloped lands that are not permitted.	**n/a**

*These values are consistent with the FHWA's requirement for consideration of traffic noise impacts 1 dBA below their noise abatement criteria.

OBSI Noise Measurements

OBSI noise measuring devices provide a consistent way to determine the noise emission from the tire-pavement contact. OBSI measurements were conducted in accordance with AASHTO TP 76-09 as presented in Figure 8 *[25]*. OBSI measurements were taken in both directions and in the inside and outside travel lanes within the noisy areas. Measurements were also taken in the outside lanes of the quieter areas for comparison purposes.

Figure 8
OBSI system

In a publication by the National Concrete Pavement Technology Center, OBSI noise based measurements were divided into three categories, (low, middle, and high) as presented in Table 6 *[26, 27]*. Figure 9 presents the OBSI data set with rankings used for transverse tined PCC pavement for informational purposes only. These rankings will be used as a benchmark to evaluate the OBSI noise measurements taken on Joor Road.

Table 6
OBSI noise ranking

Zone	Ranking	Decibels (dBA)
1	Low noise level or "Innovation" Zone	< 99/100
2	Middle noise level or "Quality" Zone	99/100 to 104/105
3	High noise level or "Avoid" Zone	> 104/105

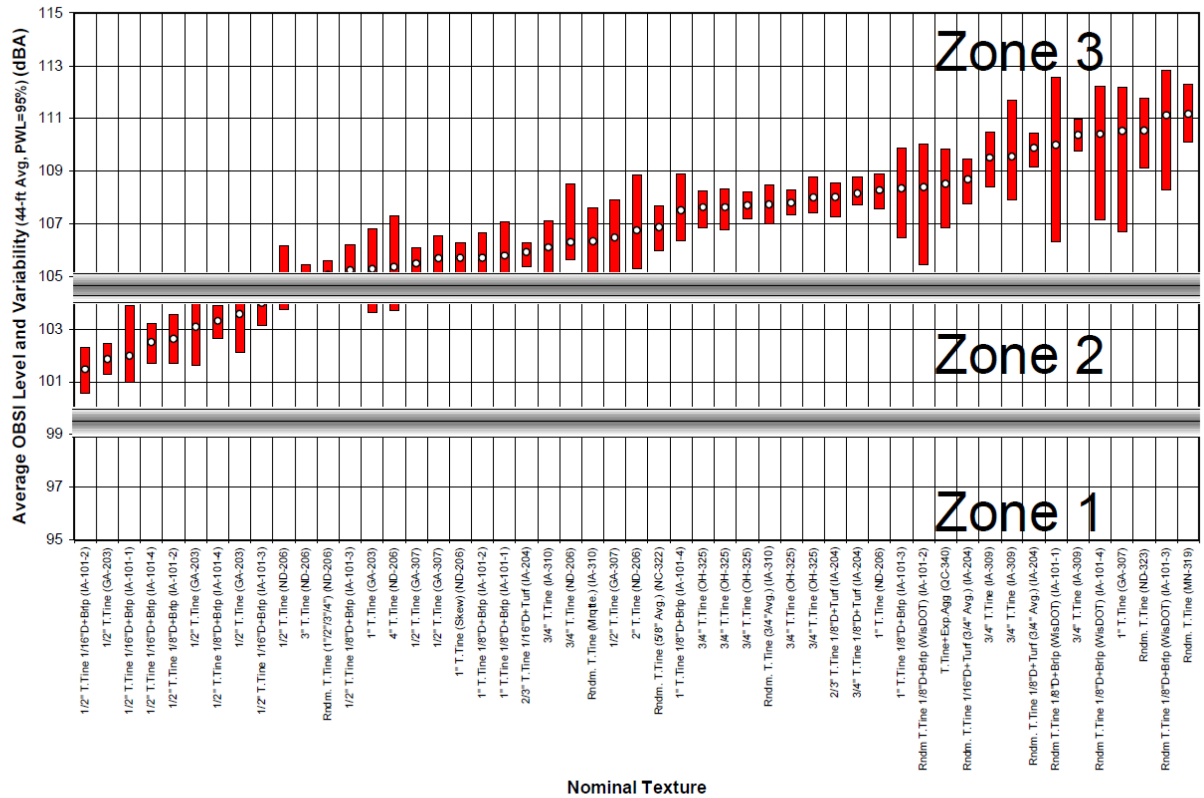

Figure 9
OBSI measurements on transverse tinned pavements

Profile and Macrotexture Data

The high speed profiler was used to collect roughness data (IRI) and macrotexture using a texturing laser both inside and outside of the noisy areas. The IRI data was evaluated in accordance with FHWA guidelines for smoothness as presented in Table 7 *[28]*. Macrotexture values were evaluated based on FHWA criteria that states macrotexture values should be between 0.5 mm to 0.8 mm *[8]*.

Table 7
FHWA ride quality guide

Ride Quality	IRI (in./mile)
Smooth	≤ 80
Moderate	81 to 130
Rough	≥ 131

DISCUSSION OF RESULTS

Pavement Tining Parameters

Tine Depth Analyses

Tine depth measurements were taken at seven sites on Joor Road with sites 1 to 6 in the noisy area and Site 7 outside the noisy area. Four sites were assessed on O'Neal Lane (Sites 8 to 11). Table 8 presents the descriptive statistics (average and standard deviation) for all eleven sites along with the results from the statistical analysis (Tukey grouping) *[19]*. The Tukey method assigns a letter to each site. Sites with similar letters means that no statistical difference existed while sites with different letters indicate that statistical differences exist. Figures 10 and 11 present boxplots and histograms, respectively, for all 11 sites and Appendix B contains histograms for each individual site. Table 9 presents the results of the specification check.

Regarding sites (1 to 7) associated with Joor Road, the statistical analysis indicated that with the exception of Site 2, the tine depths for the sites in the noisy area were significantly different from Site 7 (quiet area) with Site 7 having the least tine depth. The tine depths were similar between Sites 1,3, 5, and 6 and similar between Sites 3 and 4. Sites 2 and 4 were similar to Site 8 on O'Neal Lane. Sites 1 to 7 were evaluated to determine if they conformed to DOTD Section 601 specifications as presented in Table 10 *[18]*. The results indicated that all seven sites did not conform to DOTD specifications. All seven sites had tine depths less than 3 mm with only a few having tine depths greater than 5 mm. Though shallow depths can reduce noise emissions, tine depths greater than 6 mm are generally associated with excessive noise emissions. Based on that, it is the authors' opinion that tine depth was not the source of excessive noise on Joor Road *[8]*.

Regarding O'Neal Lane (Sites 8 to 11), the results indicated that Sites 8 and 11, Sites 10 and 11, and Sites 9 and ll are similar. Relating Joor Road to O'Neal Lane, Sites 2 and 7 have something in common to Sites 8, 10, and 11. As with Joor Road all sites had tine depths less than 3 mm and did not conform to DOTD specifications as presented in Table 10 *[8]*.

There is one issue of concern regarding the shallow tine depths on these projects: potential hydroplaning issues. One of the purposes of tining concrete pavement is to provide an avenue for water displacement during the braking process in wet weather as well as reducing hydroplaning. As the tine depths become shallower or non-existent from wear due to traffic, hydroplaning issues may emerge.

Table 8
Tine depth metrics and statistical results

Roadway	Site No.	Average (mm)	STDEV. (mm)	Tukey grouping					
Joor Road	1	3.41	1.1915	A					
Joor Road	5	3.28	1.1747	A					
Joor Road	6	3.22	1.1194	A					
Joor Road	3	2.88	0.9840	A	B				
Joor Road	4	2.38	0.9344		B	C			
Oneal Lane	8	2.08	0.7945			C	D		
Joor Road	2	1.95	0.5471			C	D	E	
Oneal Lane	10	1.84	0.7587			C	D	E	
Joor Road	7	1.81	0.9063				D	E	
Oneal Lane	11	1.45	0.7360					E	F
Oneal Lane	9	1.05	0.8926						F

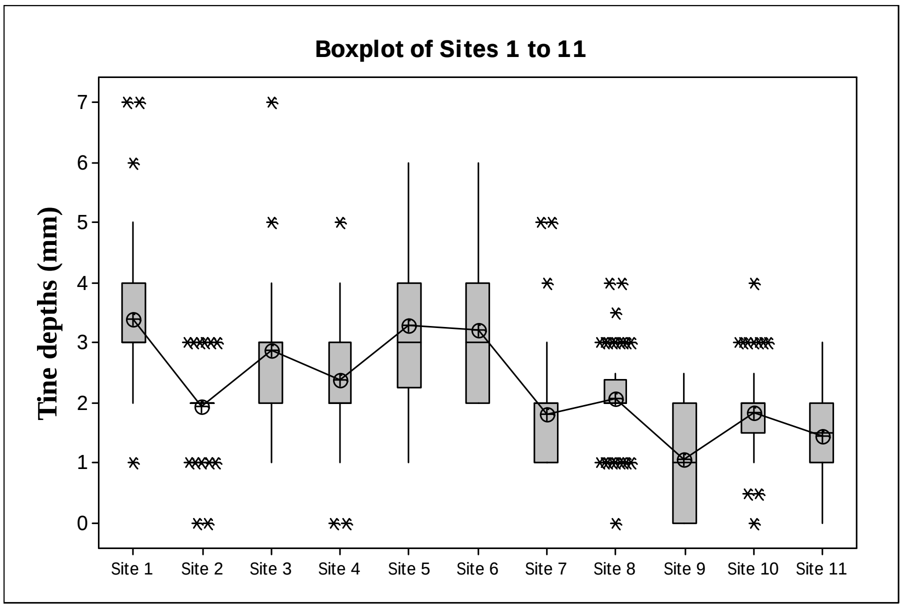

Figure 10
Box plot of tine depth data

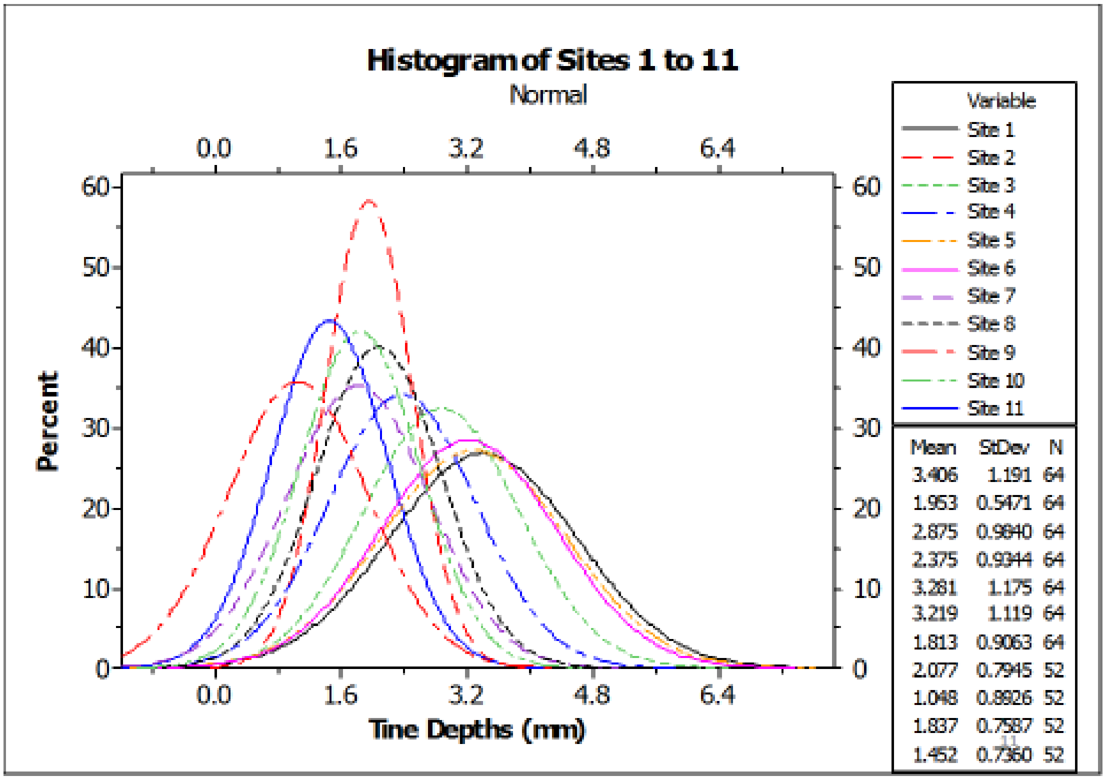

Figure 11
Histograms of tine depths

Table 9
Tine depths

Site	Road	No. of points	D < 3 mm (%)	3 mm ≤ D ≤ 5 mm (%)	D > 5 mm (%)	Meets Specification
1	Joor	64	20.3	75.0	4.7	No - Exceeds 5 mm and less than 3 mm
2	Joor	64	90.6	9.4	0.0	No - Less than 3 mm
3	Joor	64	37.5	60.9	1.6	No - Exceeds 5 mm and less than 3 mm
4	Joor	64	64.1	35.9	0.0	No - Less than 3 mm
5	Joor	64	25.0	68.8	6.3	No - Exceeds 5 mm and less than 3 mm
6	Joor	64	29.7	62.5	7.8	No - Exceeds 5 mm and less than 3 mm
7	Joor	64	85.9	14.1	0.0	No - Less than 3 mm
8	O'Neal	52	75.0	25.0	0.0	No - Less than 3 mm
9	O'Neal	52	96.0	4.0	0.0	No - Less than 3 mm
10	O'Neal	52	83.0	17.0	0.0	No - Less than 3 mm
11	O'Neal	52	92.0	8.0	0.0	No - Less than 3 mm

Tine Width Analyses

Tine width measurements were taken at seven sites on Joor Road with Sites 1 to 6 in the noisy area and Site 7 outside the noisy area. Four sites were assessed on O'Neal Lane (Sites 8 to 11). As previously mentioned, measurements were taken by examining photographs as presented in Figure 6. Table 10 presents the descriptive statistics (average and standard deviation) for all eleven sites along with the results from the statistical analysis (Tukey grouping) *[19]*. The Tukey method assigns a letter to each site. Sites with similar letters means that no statistical difference existed while sites with different letters indicate that statistical differences exist. Figures 12 and 13 present boxplots and histograms, respectively, for all 11 sites and Appendix C contains histograms for each individual site. Table 11 presents the results of the specification check.

On the Joor Road sites, Sites 1 and 5, Sites 2, 3, 4, and 6, and Sites 2, 3, 6, and 7 are similar. There were many similar grouping overlaps between Joor Road and O'Neal Lane, with Sites 1,5, and 9, Sites 1, 8, and 9, Sites 2, 3, 8, 9, and 11, Sites 2, 3, 4, 6, 8, 10, and 11, and Sites 2, 3, 4, 6, 7, 10, and 11 having statistical similarities. There was a broader range of sites statistically grouped together than with the tine depth data sets.

As presented in Table 11, all sites had tine widths greater than the 3.5 mm maximum specified in DOTD Section 601 and therefore did not meet that specification. Cumulative distribution functions (CDF) were created for Joor Road alone and Joor Road in combination with O'Neal Lane data, both yielding similar CDF's. With that being the case, the CDF (Sites 1 to 11) presented in Figure 14 was used to illustrate the fact that 60 percent of the tines were over the 3.5 mm maximum specified by DOTD and recommended by FHWA *[8, 18]*. It has been demonstrated that as tine width increases so does sound emission *[5]*. The authors postulate that the excessive tine widths are one of three pavement surface parameters contributing to the excessive noise on this project, discussed in detail later.

Table 10
Tine width metrics and statistics

Roadway	Site No.	Average (mm)	STDEV. (mm)	Tukey grouping				
Joor Road	5	4.50	0.5477	A				
Joor Road	1	4.38	0.7891	A	B			
Oneal Lane	9	4.07	0.5542	A	B	C		
Oneal Lane	8	3.90	0.7003		B	C	D	
Joor Road	3	3.74	0.4364			C	D	E
Joor Road	2	3.64	0.4781			C	D	E
Oneal Lane	11	3.53	0.4993			C	D	E
Joor Road	4	3.48	0.5356				D	E
Oneal Lane	10	3.40	0.4757				D	E
Joor Road	6	3.38	0.4976				D	E
Joor Road	7	3.31	0.5585					E

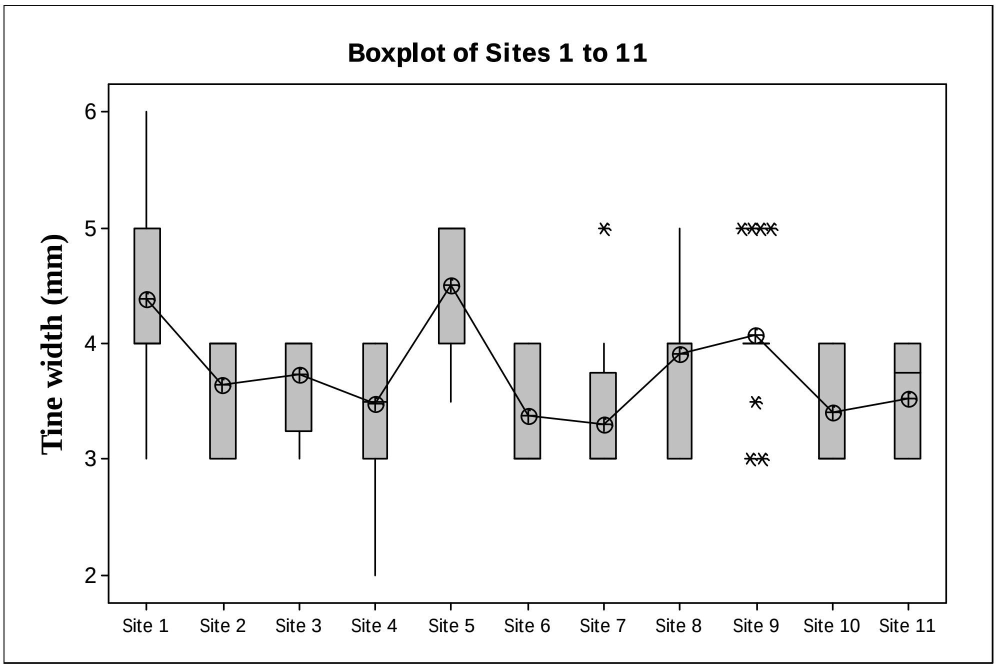

Figure 12
Tine width box plots

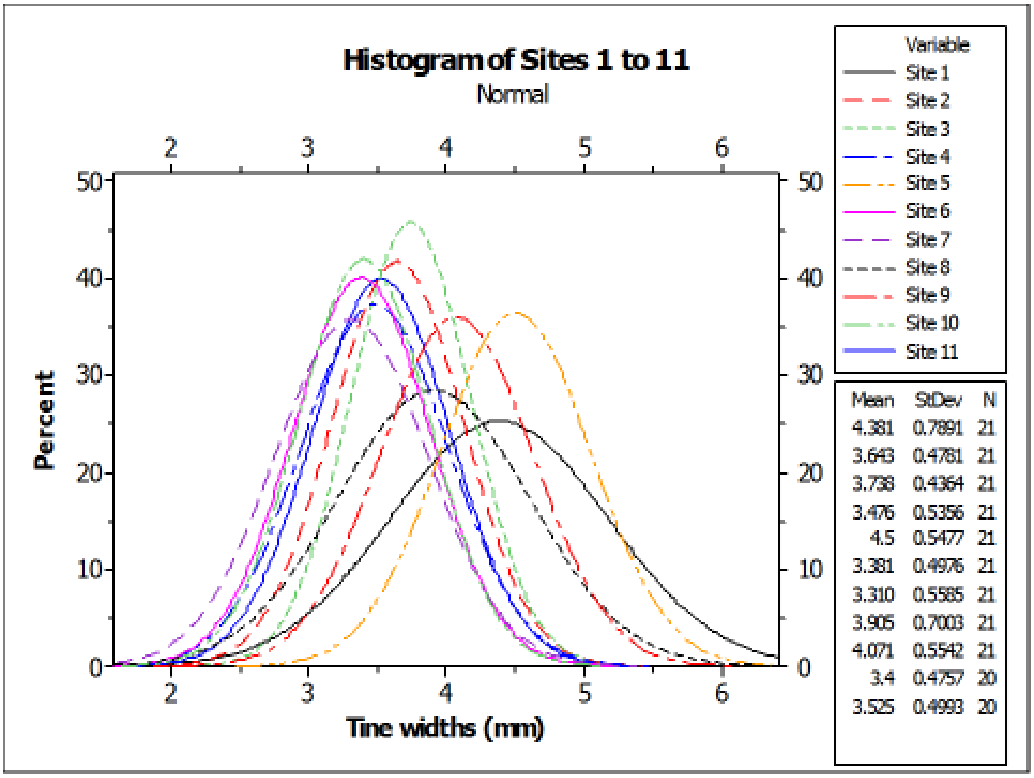

Figure 13
Tine width histogram

Table 11
Tine width specification check

Site	Road	No. of points	W < 2.5 mm (%)	2.5 mm ≤ W ≤ 3.5 mm (%)	W > 3.5 mm (%)	Meets Specification
1	Joor	21	0.0	9.5	90.5	No - Exceeds 3.5 mm
2	Joor	21	0.0	38.1	61.9	No - Exceeds 3.5 mm
3	Joor	21	0.0	28.6	71.4	No - Exceeds 3.5 mm
4	Joor	21	4.8	57.1	38.1	No - Exceeds 3.5 mm and less than 2.5 mm
5	Joor	21	0.0	4.8	95.2	No - Exceeds 3.5 mm
6	Joor	21	0.0	61.9	38.1	No - Exceeds 3.5 mm
7	Joor	21	0.0	76.2	23.8	No - Exceeds 3.5 mm
8	O'Neal	21	0.0	28.6	71.4	No - Exceeds 3.5 mm
9	O'Neal	21	0.0	14.3	85.7	No - Exceeds 3.5 mm
10	O'Neal	20	0.0	65.0	35.0	No - Exceeds 3.5 mm
11	O'Neal	20	0.0	50.0	50.0	No - Exceeds 3.5 mm

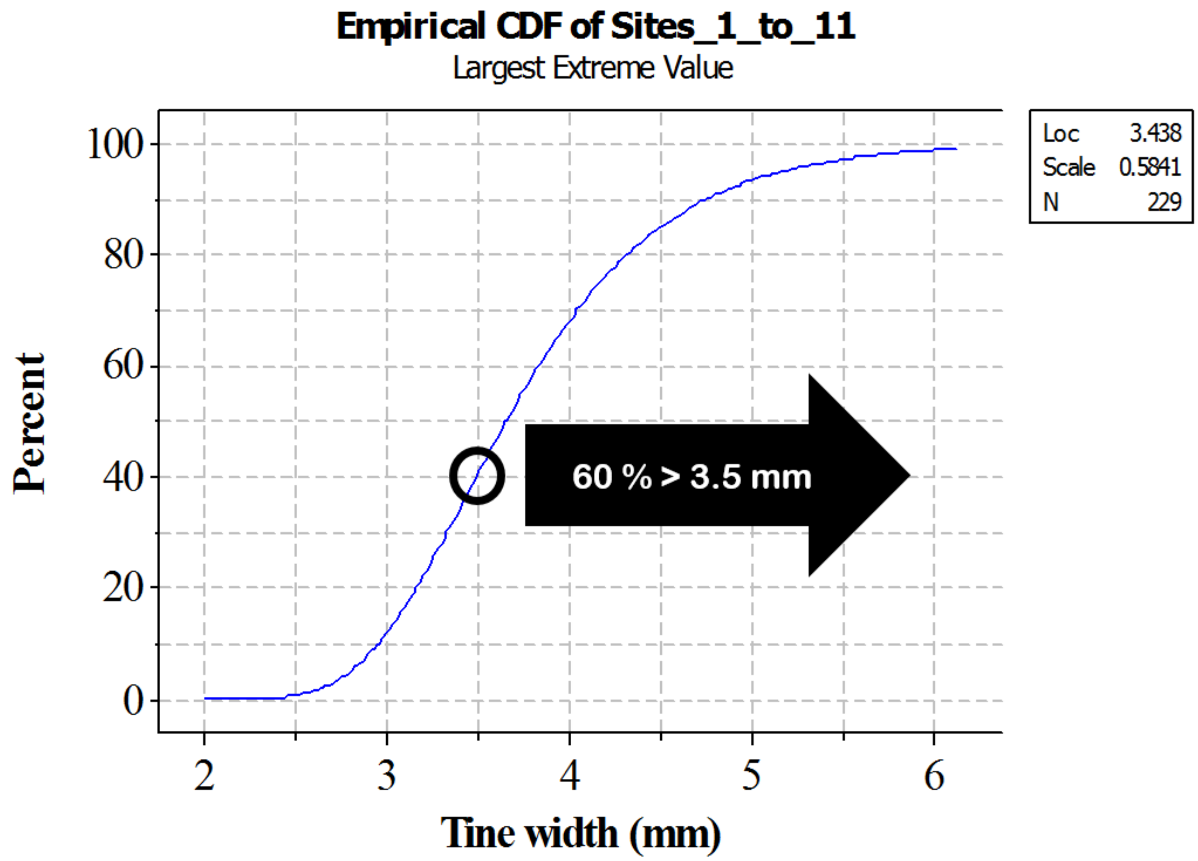

Figure 14
Cumulative distribution function of tine widths (mm)

Spacing between Tines and Randomness of Spacing between Tines Analyses

Spacing between tine measurements were taken at seven sites on Joor Road with Sites 1 to 6 in the noisy area and Site 7 outside the noisy area. Four sites were assessed on O'Neal Lane (Sites 8 to 11). As previously mentioned, measurements were taken by examining photographs as presented in Figure 6. Table 12 presents the descriptive statistics (average and standard deviation) for all eleven sites along with the results from the statistical analysis (Tukey grouping) *[19]*. The Tukey method assigns a letter to each site. Sites with similar letters means that no statistical difference existed while sites with different letters indicate that statistical differences exist. Figures 15 and 16 present boxplots and histograms, respectively, for all 11 sites and Appendix D contains histograms for each individual site. Table 13 presents the results of the specification check.

The analysis of this parameter differs from the parameters of tine depth and width in that a specific spacing interval between tines is not defined in the DOTD Section 601 specifications. Instead the specifications state "tines shall be steel flat wire, 4 to 5 inches (100 to 125 mm) in length, randomly spaced, with a minimum spacing of 3/8 inch (10 mm) and a maximum spacing of 1 1/2 inch (40 mm). No more than 50 percent of the spaces shall exceed 1 inch (25 mm)." However, it is possible to compare the average spacing between tines to determine if similar spacing patterns exist between sites as well as exam the magnitudes of the average spacing at each site. The specification check listed above will be discussed later. Referring to Table 13, it can be seen that the average spacing in sites ranged from approximately 24.9 mm to 12.7 mm. It has been shown that wider spacing between tines can contribute to increased noise emissions *[8, 9, 10]*. Also, the quieter area on Joor Road (Site 7) has an average spacing of 12.7 mm while 5 out of 6 sites measured have average spacing's greater than 22.6 mm, almost twice the magnitude. Additionally, none of Sites 1 to 6 on Joor Road were statistically similar to Site 7. The specifications check, presented in Table 13, shows that all of the 11 sites evaluated did not conform to DOTD Section 601 specifications.

The randomness of spacing between tines was evaluated using a non-parametric statistics test called the "Runs Test" and the results are presented in Table 14 *[21,22]*. The results indicated that approximately 72 percent of the sites on Joor Road do not meet the requirement for randomness while 25 percent of the sites on O'Neal do not meet the requirement for randomness. This implies that randomness between tines can be achieved as measured on O'Neal Lane and it is unknown why Joor Road did not meet that criteria. It has been demonstrated that non-random spacing between tines as well as large spaces between tines will increase sound emissions *[8, 9, 10, 26]*. It is the authors' opinion that the spacing interval between tines and the non-randomness of spacing between tines are two of three parameters contributing the high noise emissions on Joor Road.

Table 12
Spacing between tines metrics and statistical analysis

Roadway	Site No.	Average (mm)	STDEV. (mm)	Tukey grouping					
Joor Road	5	24.889	1.414	A					
Joor Road	6	24.266	10.097	A	B				
Joor Road	2	23.046	5.971	A	B				
Joor Road	4	22.617	6.323		B	C			
Joor Road	1	22.574	10.431		B	C			
Oneal Lane	8	21.111	7.336			C	D		
Oneal Lane	10	21.109	8.464			C	D		
Oneal Lane	11	20.123	8.468				D		
Joor Road	3	17.551	8.995					E	
Oneal Lane	9	12.776	1.222						F
Joor Road	7	12.672	2.163						F

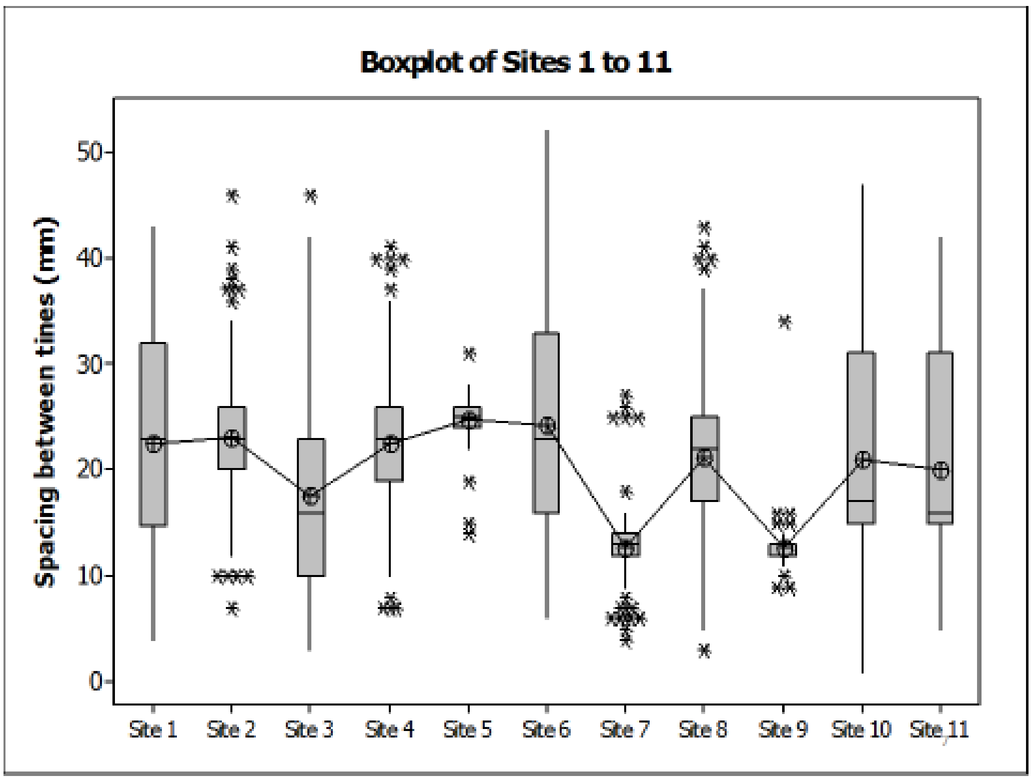

Figure 15
Box plot of spacing between tines

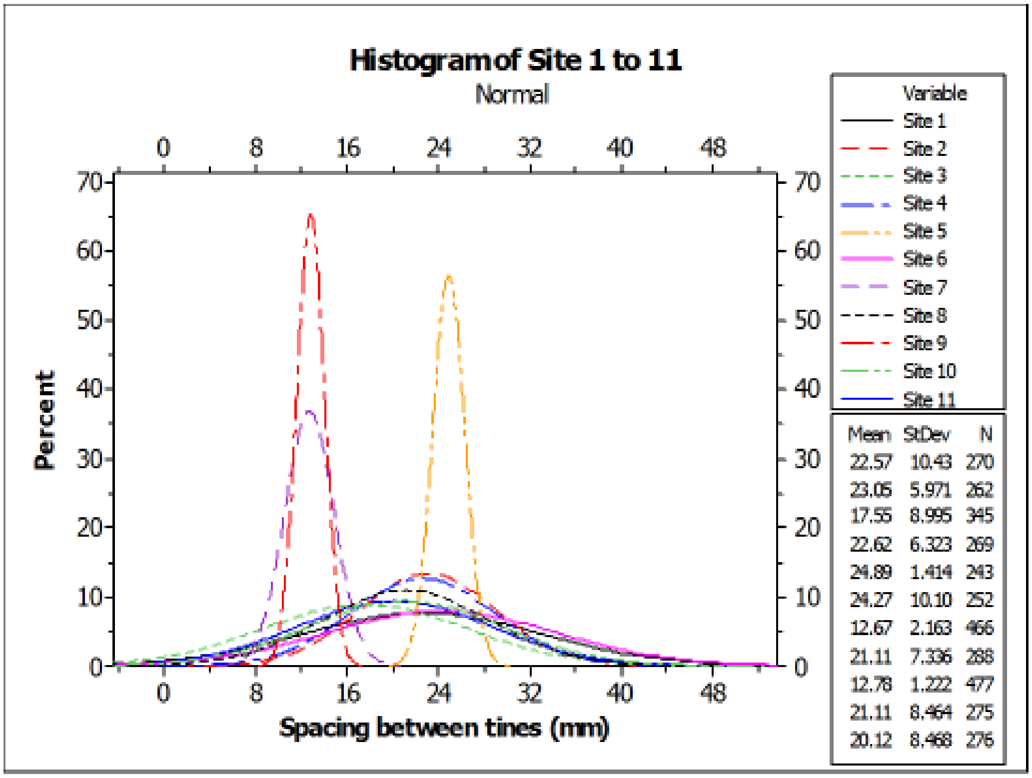

Figure 16
Histograms of tine spacing

Table 13
Spacing between tines

Site	Road	No. of points	S < 10 mm (%)	10 mm ≤ S ≤ 25 mm (%)	25 < S ≤ 40 (%)	S > 40 mm (%)	Meets Specification
1	Joor	270	15.2	45.9	37.0	1.9	No - Exceeds 40 mm and less than 10 mm
2	Joor	262	0.4	71.8	27.1	0.8	No - Exceeds 40 mm and less than 10 mm
3	Joor	345	21.2	60.0	18.0	0.9	No - Exceeds 40 mm and less than 10 mm
4	Joor	269	1.9	71.0	26.8	0.4	No - Exceeds 40 mm and less than 10 mm
5	Joor	243	0.0	73.3	26.7	0.0	Meets Specification
6	Joor	252	7.5	48.4	40.9	3.2	No - Exceeds 40 mm and less than 10 mm
7	Joor	466	3.0	96.6	0.4	0.0	No - Less than 10 mm
8	O'Neal	288	8.7	67.4	23.3	0.7	No - Exceeds 40 mm and less than 10 mm
9	O'Neal	477	0.4	99.4	0.2	0.0	No - Less than 10 mm
10	O'Neal	275	5.8	59.3	34.5	0.4	No - Exceeds 40 mm and less than 10 mm
11	O'Neal	276	8.0	60.5	31.2	0.4	No - Exceeds 40 mm and less than 10 mm

Table 14
Random spacing between tines

Roadway	Site Number	Tine spacing Random "Runs Test"	Tine spacing Not Random "Runs Test"
Joor Road	1		X
Joor Road	2	X	
Joor Road	3	X	
Joor Road	4		X
Joor Road	5		X
Joor Road	6		X
Joor Road (*)	7		X
Oneal Lane	8	X	
Oneal Lane	9		X
Oneal Lane	10	X	
Oneal Lane	11	X	
(*) Located outside of Noisy Area			

Noise Emission Measurements

Pass-by Noise Measurements

Pass by noise measurements were taken between the hours of 6 am to 9 am and 4 pm to 6 pm in the noisy area and between 6 am and 9 am in the quieter area *[22, 23, 24]*. In accordance with FHWA guidelines, 15 minute running averages from the peak hour were calculated for the noise parameter Leq (dBA) and the highest Leq value from those readings should be used as the Leq for that location. Figure 17 presents the results from noise testing on Joor Road. The peak noise value for the noisy area on Joor Road is 82 dBA while the peak noise value in the quieter area is 74 dBA. Both areas exceed DOTD and FHWA noise level guidelines for residential areas, but there is a considerable difference in magnitude between 82 and 74 dBA, 251 percent to be exact in terms of sound pressure. Additionally no complaints about noise levels have been reported regarding noise levels outside the "noisy area" on Joor Road.

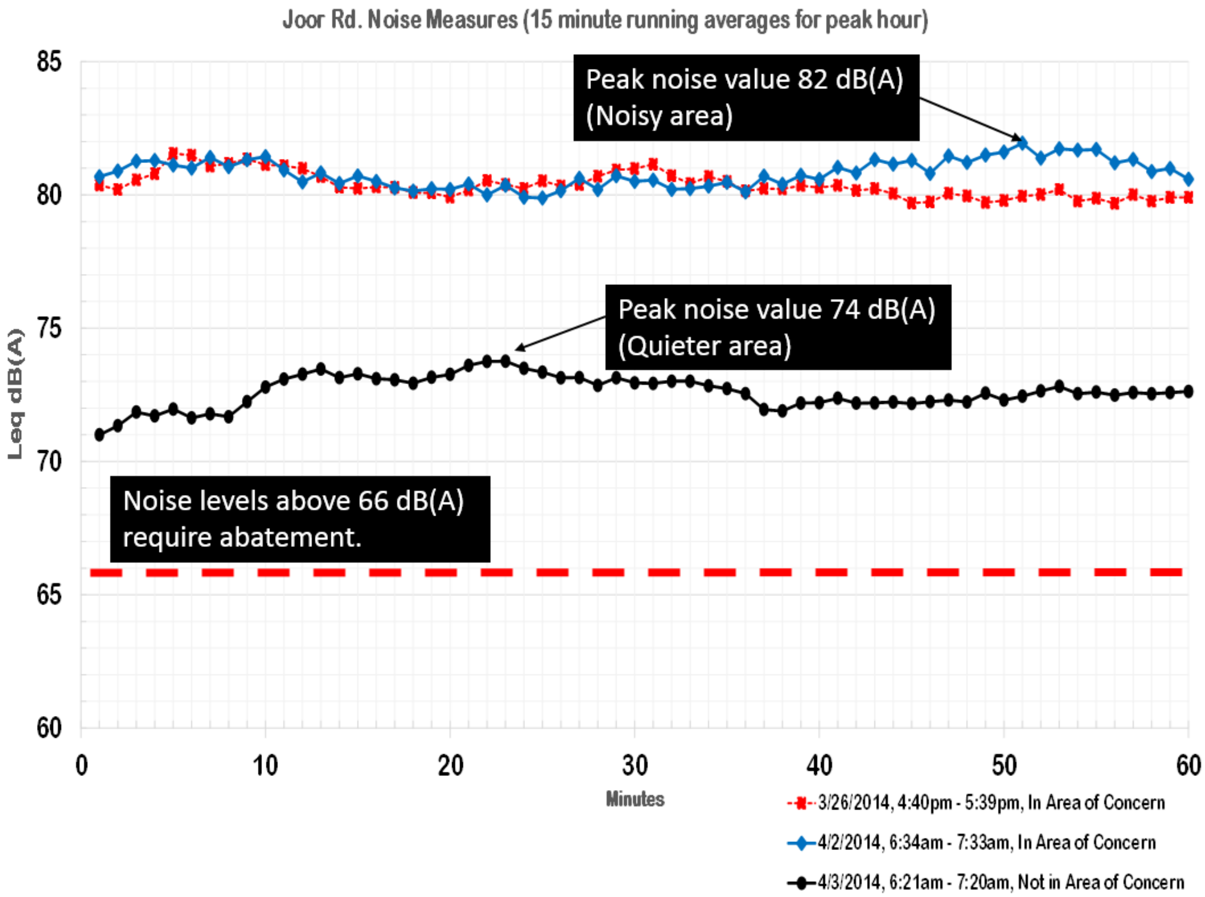

Figure 17
Pass by noise measurements

OBSI Noise Measurements

OBSI noise measurements were conducted in accordance with AASHTO TP 76-09 standards both inside and outside of the noisy area as presented in Figure 18. The results presented in Figure 18 represent the average value of triplicate tests. The zone regions shown in Figure 18 represent the regions outlined in Table 6 with Zone 1 considered the low noise level region, Zone 2 the middle noise level region or quality noise level zone, and Zone 3 considered the high noise level region or “avoid” noise level zone *[26]*. As shown in Figure 18, the quieter area on Joor Road is within the bounds of the quality noise level region and the majority of the test results on the noisy section of Joor Road are in the “avoid” noise level zone.

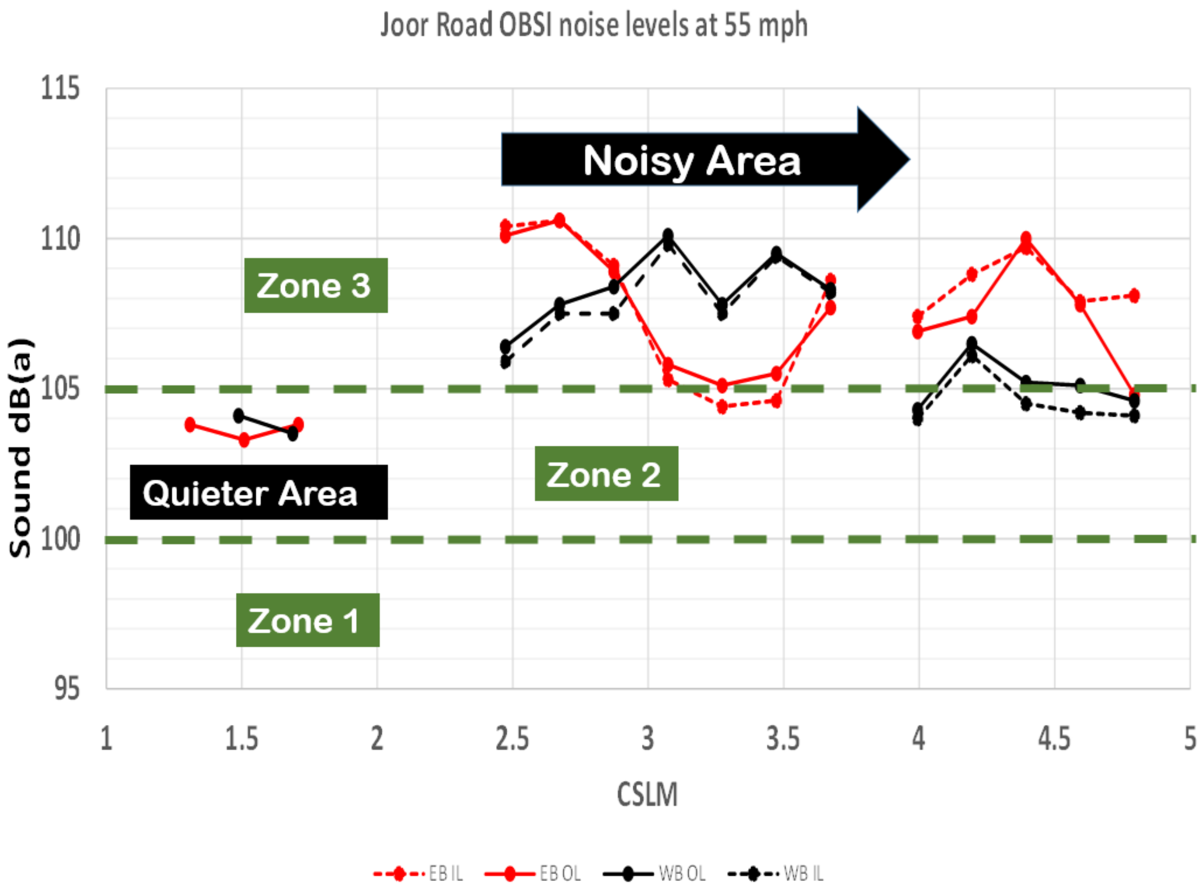

Figure 18
OBSI noise measurements

Pavement Roughness and Macrotexture

Joor Road was assessed with a high speed profiler to obtain IRI values and macrotexture (mean texture depth, MTD) as presented in Figures 19 to 21. The IRI in the quieter area (CSLM 1 to 1.9) was quite rough with an average IRI of 168 and 196 in the north and southbound lanes, respectively *[28]*. In the noisy areas (CSLM 1.91 to 5.05), the IRI can be considered moderate with the northbound lane having an average IRI of 117 and the southbound lane having an IRI of 109.

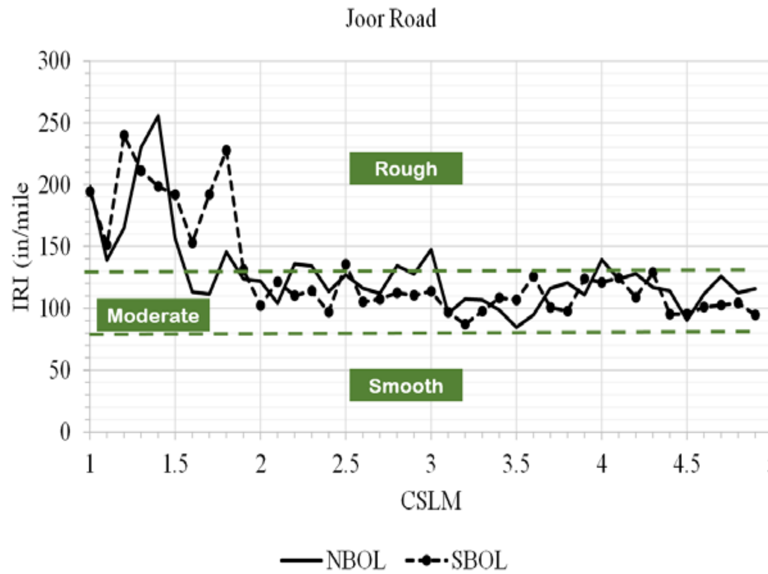

Figure 19
IRI values

Pavement macrotexture readings are presented in Figures 20 and 21. Using the FHWA recommended ranges of 0.5 to 0.8 mm for MTD as a guide, the macrotexture in both the noisy and quieter areas generally fits within the range recommended by FHWA *[8]*. Macrotexture above 0.8 can cause excessive noise emissions while macrotexture below 0.5 may cause hydroplaning when the pavement is wet.

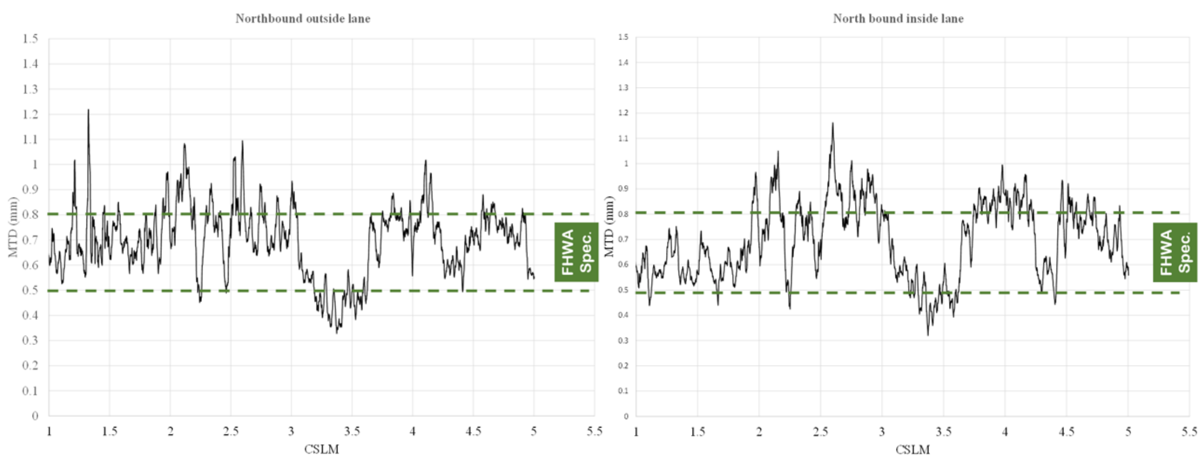

Figure 20
Northbound macrotexture values

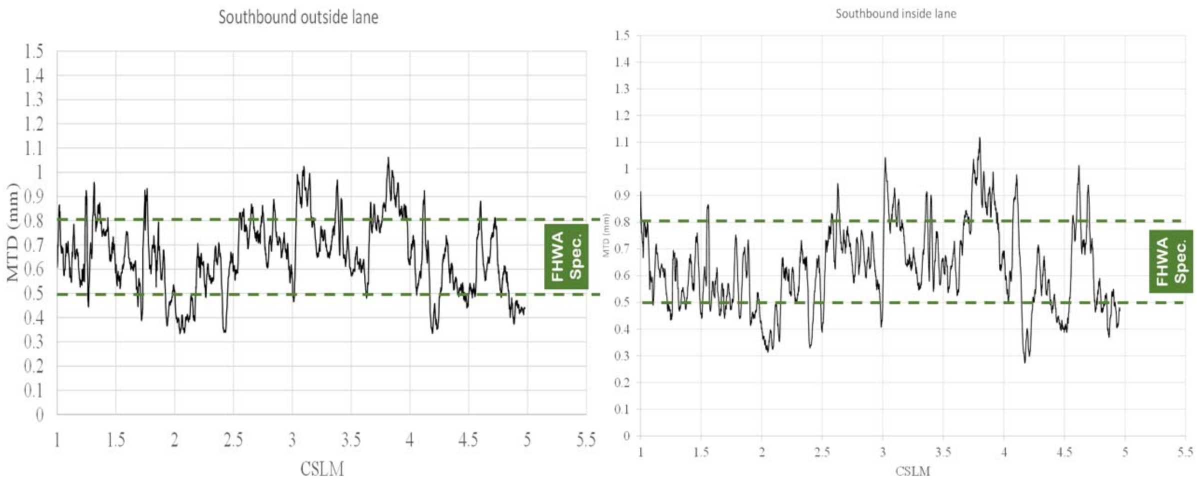

Figure 21
Southbound macrotexture values

Noise level mitigation alternates

The noise levels on this project may be reduced by either overlaying the existing PCC with AC or removing the existing tines by diamond grinding followed by longitudinal grooving.

The length of this project is 3.12 miles. It is an urban 5-lane roadway with 10 ft. concrete shoulders. The lane widths are as follows:

Outside lanes – 15 ft. wide
Inside lanes – 12 ft. wide
Center turn lane – 14 ft.
Outside shoulders – 7 ft.

Asphaltic concrete alternates: If the AC alternate is chosen then a total of 68 ft. will need to be overlaid: Two 15 ft. outside lanes, Two 12 ft. inside lanes, and center turn lane (14 ft.).

Table 15
AC alternates

AC Alternate	DOTD Item No:	Square yards	Tons	Cost ($)	Total Cost ($)
OGFC	501-01-00006	124,467	6,223.4	746,803	
Tack coat	501-02-00001	124,467	N/A	69,826	
					816,629 (1)
Coarse Mix	501-01-00005	124,467	6,846	1,244,672	
Tack coat	501-02-00001	124,467	N/A	69,826	
					1,314,498 (1)
(1) Total cost = Cost of AC + Cost of Tack coat					

Grinding and longitudinal grooving alternate: If the Grinding and grooving alternate is chosen, then a total of 68 ft. will need to be ground: Two 15 ft. outside lanes, Two 12 ft. inside lanes, and two 7 ft. shoulders.

Table 16
Grind and groove alternate

DOTD Item	Square yards	Cost ($) per square yard	Total cost ($)
S- XXXX	124,467	10.00	1,244,672

CONCLUSIONS

The objective of this study was to identify the source(s) of excessive noise levels on Joor Road. This was accomplished through sound level measurements as well as a comprehensive assessment of the PCC surface. Sound levels (Leq (dBA)) were measured using the pass by and OBSI methods. The PCC surface analysis included measuring four tine parameters which were tine depths, tine widths, spacing between tines, and random spacing between tines. Pavement roughness (IRI), macrotexture, and friction numbers were also measured.

Sound level measurements based on the pass by method indicated the sound levels were excessive (82 dBA) when compared to DOTD's Highway Traffic Noise Policy of 66 dBA for residential areas. Sound level measurements from the OBSI assessment also indicated that sound levels generated by the tire/road contact were excessive with values as high as 110.6 dBA.

Tine parameter analysis implied that the sources of excessive noise level emissions were due to excessive tine widths, non-randomness of spacing between tines, and the spacing intervals between the tines.

Pavement roughness analysis indicated that the pavement was in moderate condition with average IRI's values of 117 and 109 in the northbound and soundbound lanes, respectively. The macrotexture values for the north and southbound lanes were generally within the range of 0.5 to 0.8 mm as recommended by FHWA.

RECOMMENDATIONS

As a result of the analysis conducted in this study, it was determined that excessive sound levels are present on Joor Road. There are several methods to mitigate the excessive sound levels such as an asphaltic concrete overlay and removal of the existing transverse tines with grinding followed by sawing longitudinal grooves.

Estimates were developed for the AC overlay and Grinding and Grooving options. For the AC options, overlaying the existing PCC would cost approximately $817,000 if OGFC were specified and $1.3 million if dense graded AC were specified. Grinding and Grooving was estimated to cost approximately $1.2 million.

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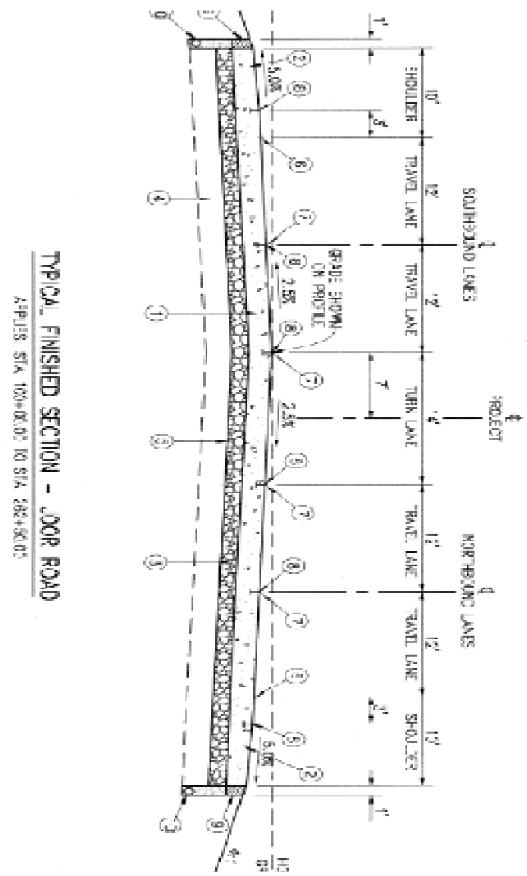
APPENDIX A

Joor Road Typical Section

Outside lanes – 15 ft. wide (striped at 12 ft)
Inside lanes – 12 ft. wide
Center turn lane – 14 ft.
Outside shoulders – 7 ft.



APPENDIX B

Tine depths

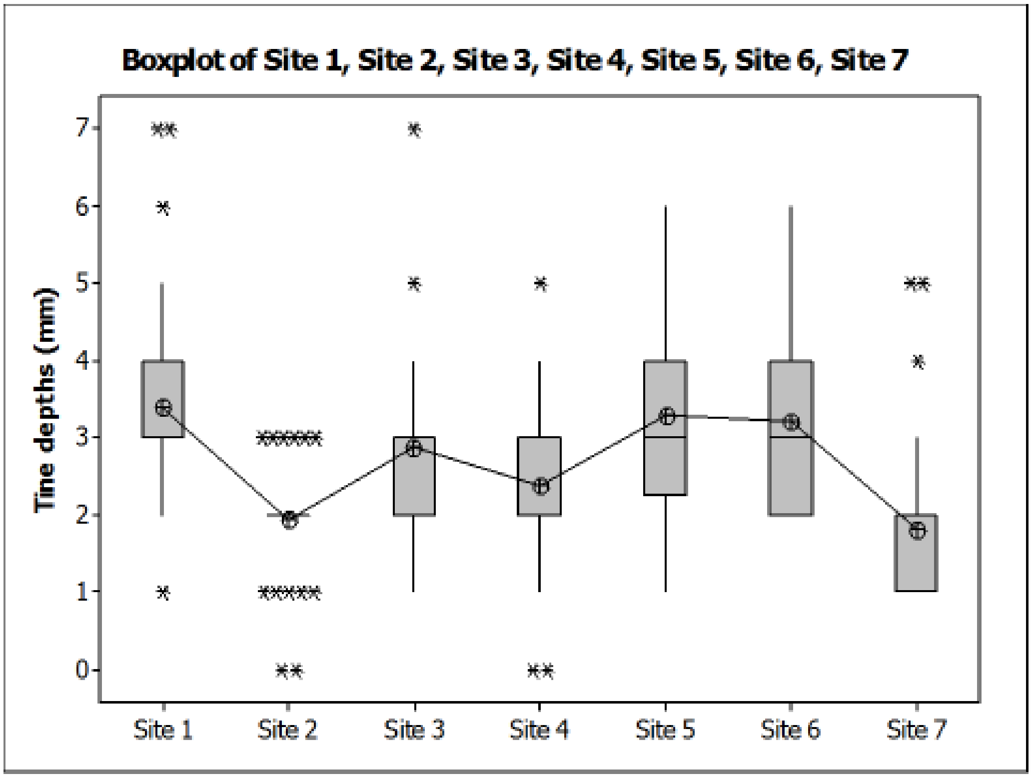


Figure 22
Boxplot of tine depths for Joor Road

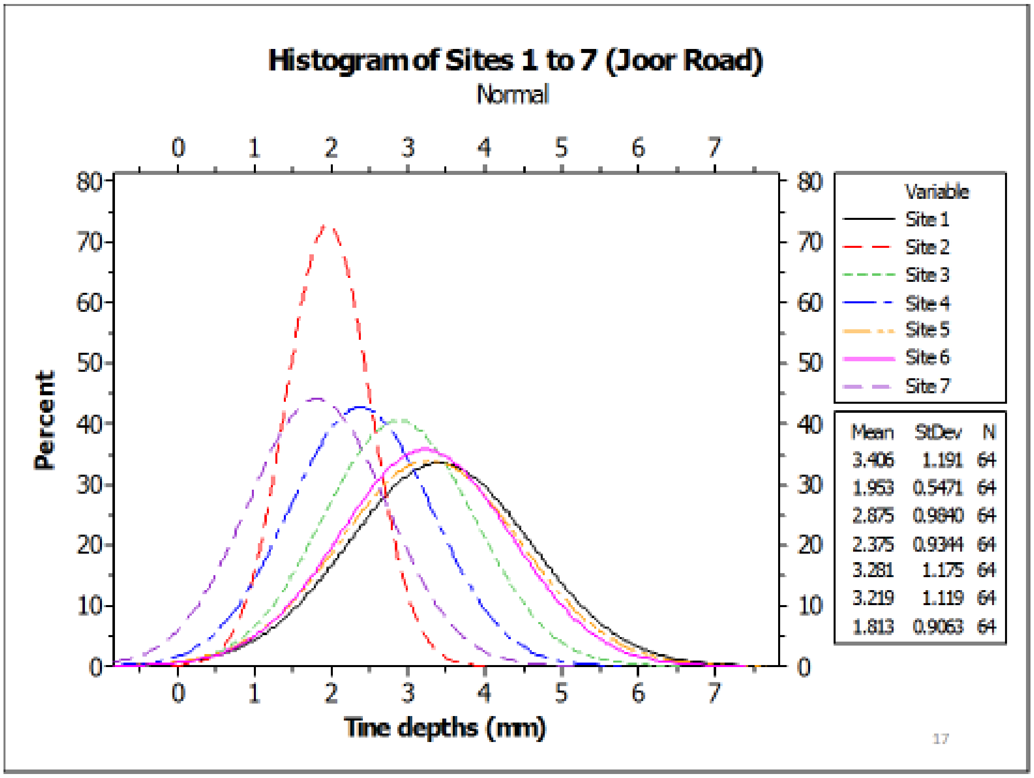


Figure 23
Histograms of tine depths for Joor Road

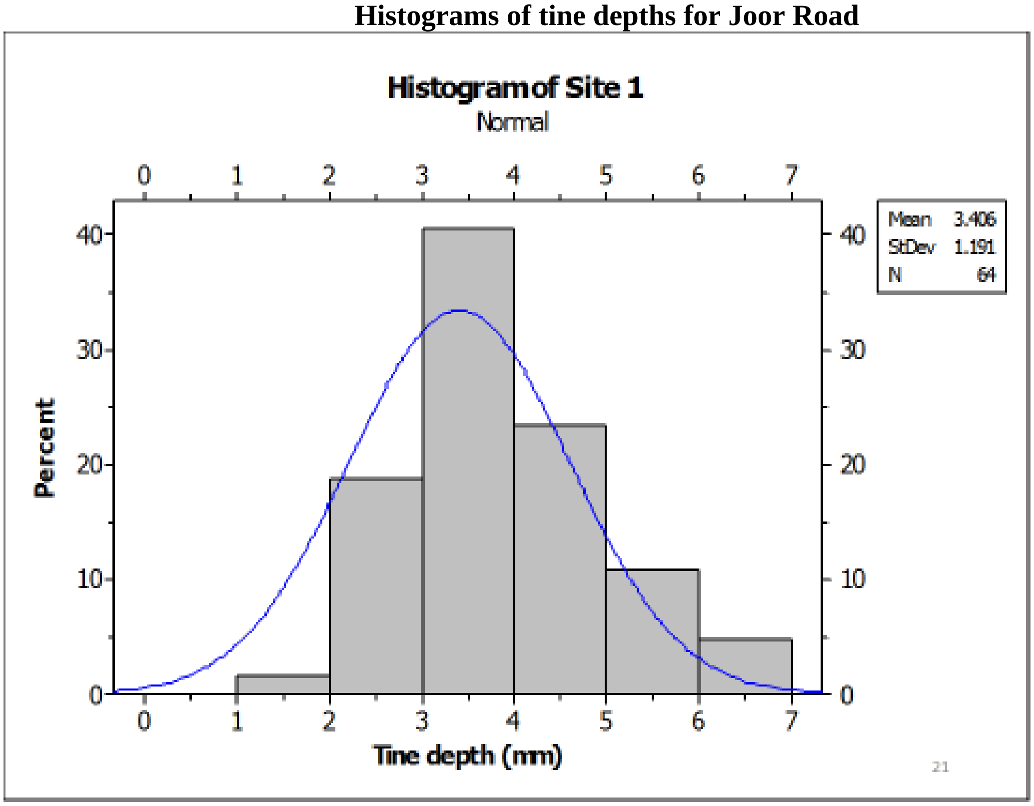


Figure 24
Histogram of tine depths for Site 1

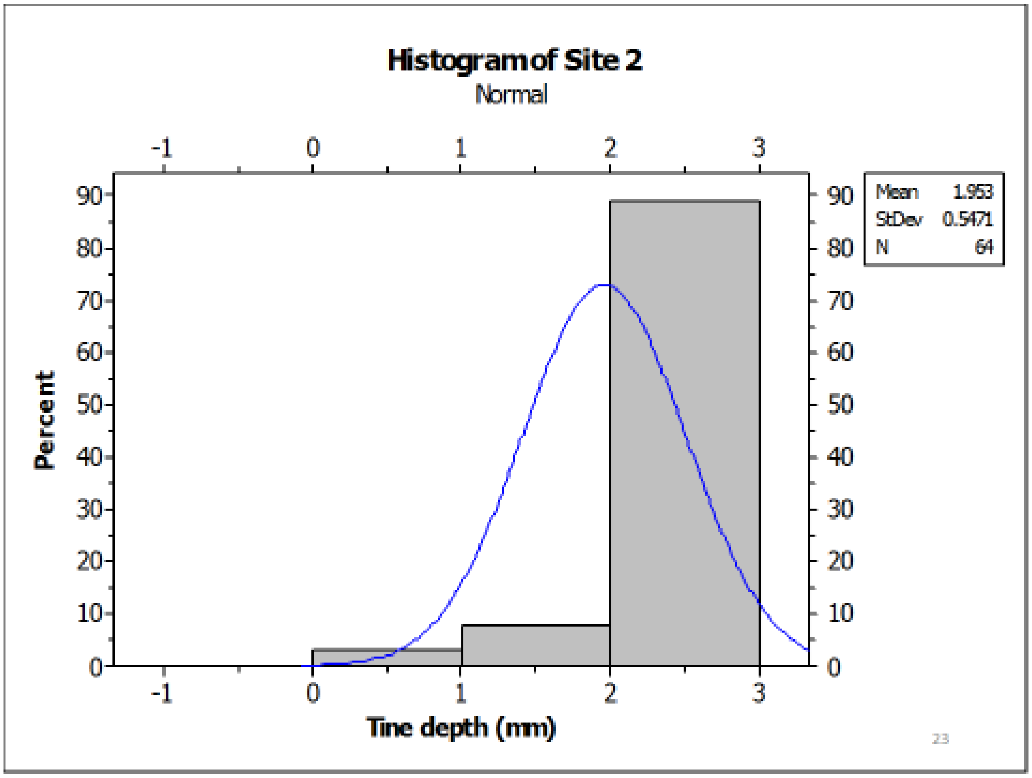


Figure 25
Histogram of tine depth for Site 2

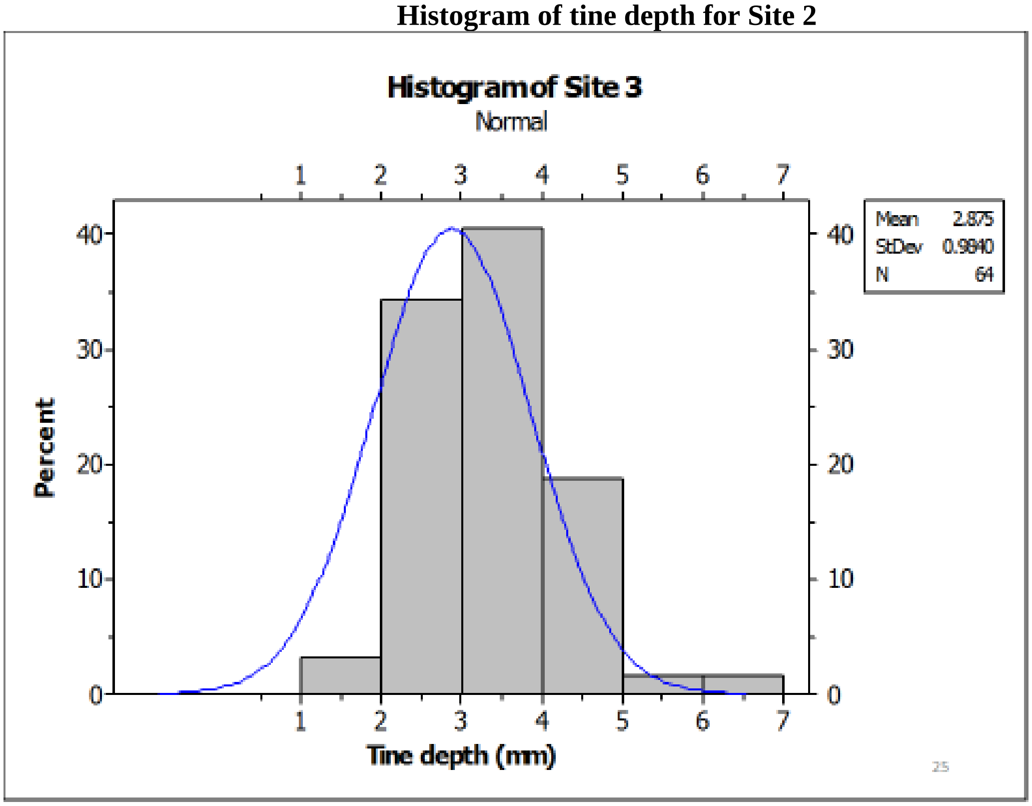


Figure 26
Histogram of tine depth for Site 3

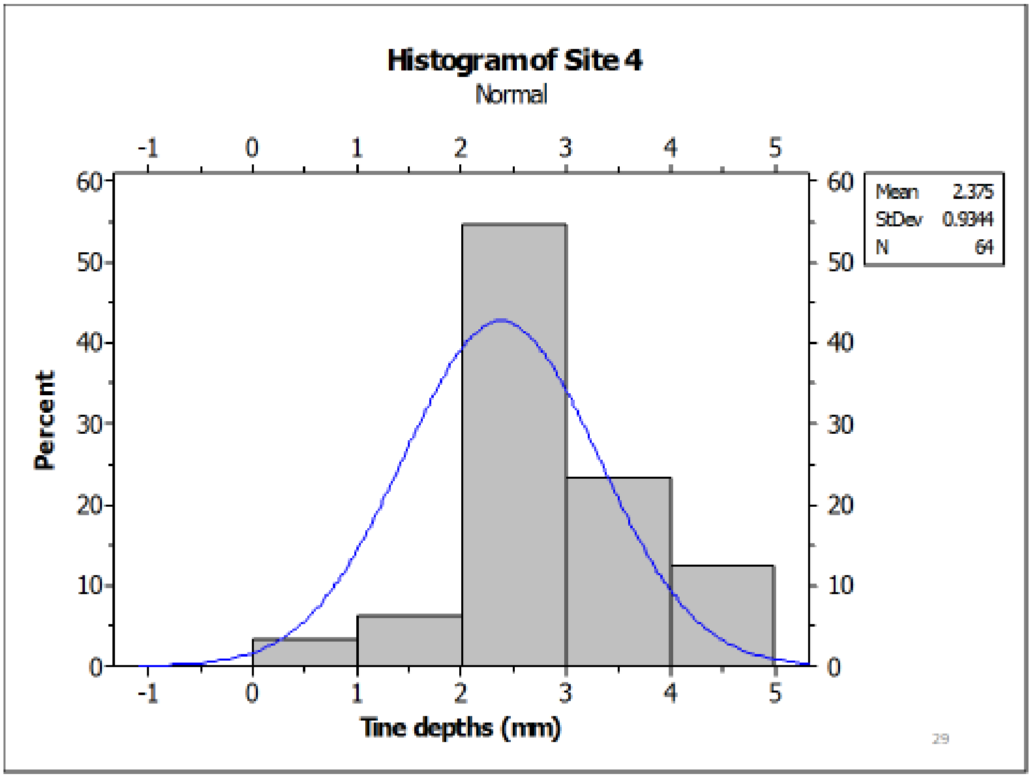


Figure 27
Histogram of tine depth for Site 4

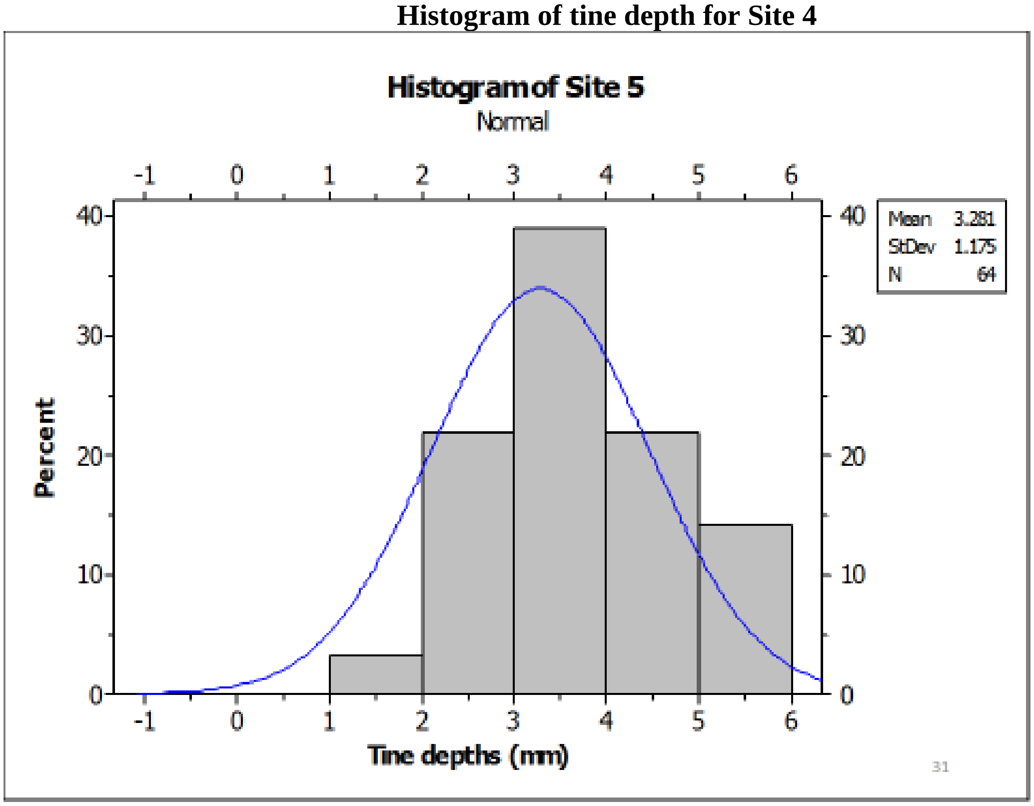


Figure 28
Histogram of tine depth for Site 5

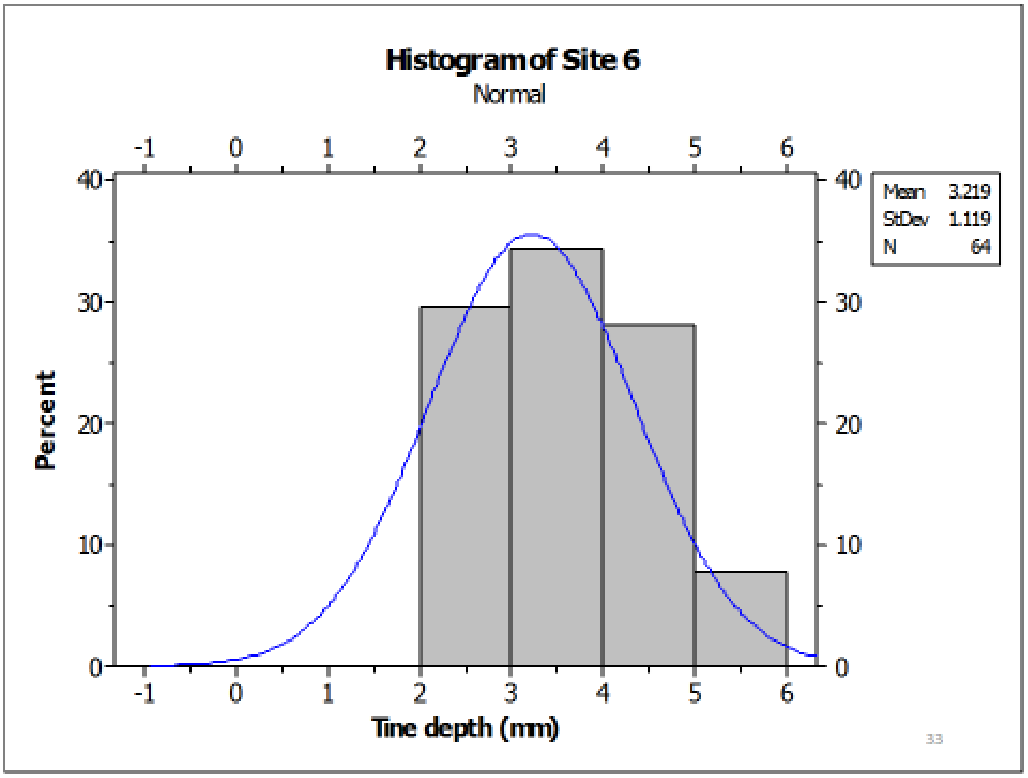


Figure 29
Histogram of tine depth for Site 6

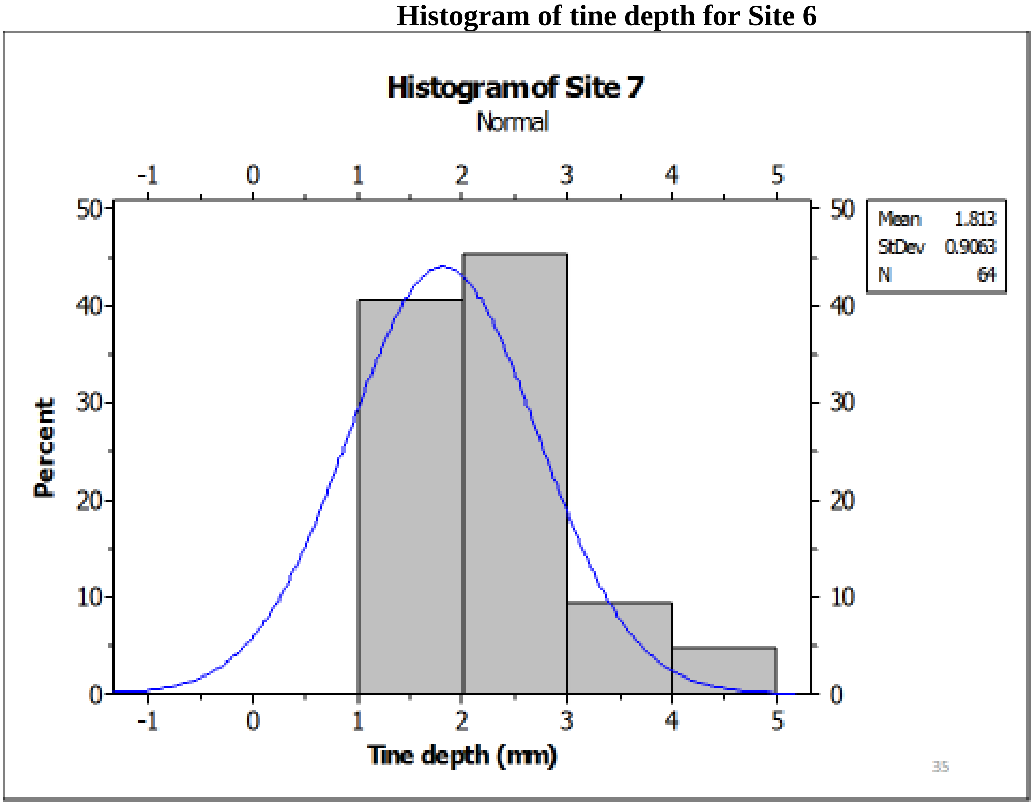


Figure 30
Histogram of tine depth for Site 7

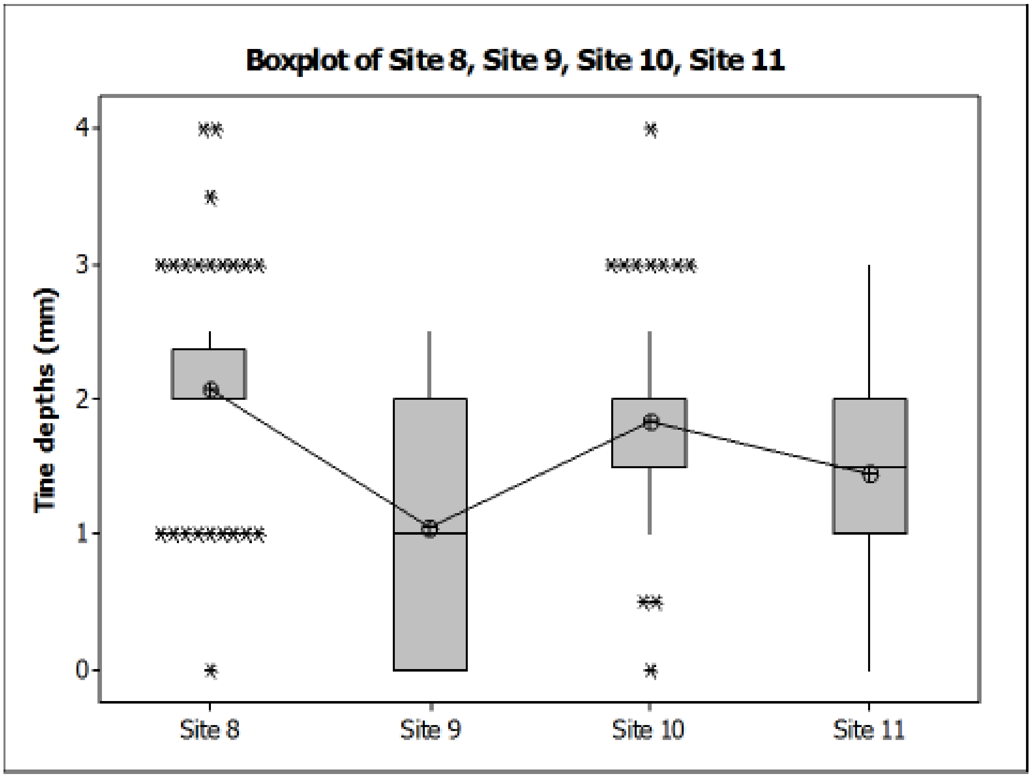


Figure 31
Boxplot of tine depths for O'Neal Lane (Sites 8 to 11)

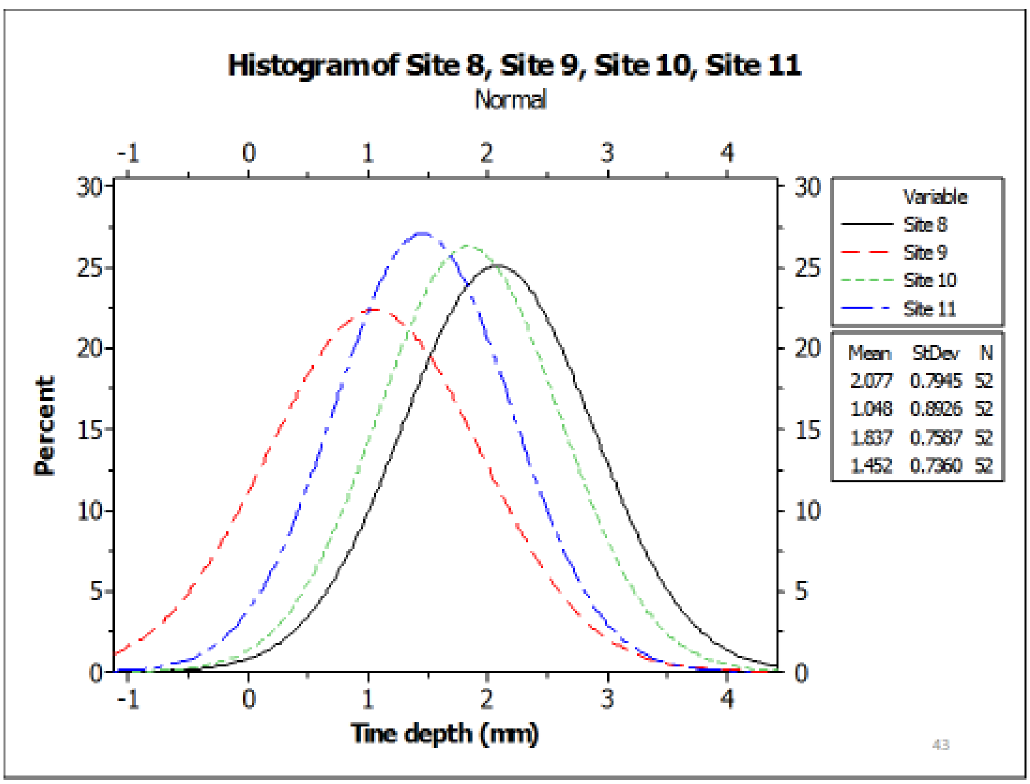


Figure 32
Histograms of tine depths for O'Neal Lane (Sites 8 to 11)

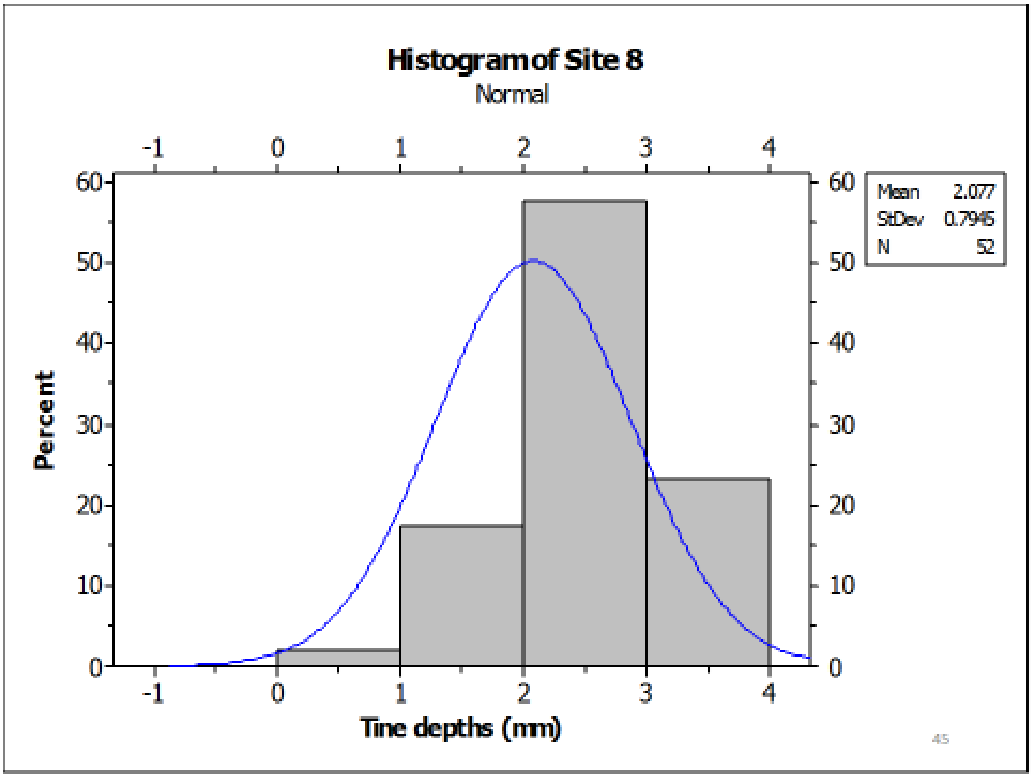


Figure 33
Histogram of tine depths for Site 8

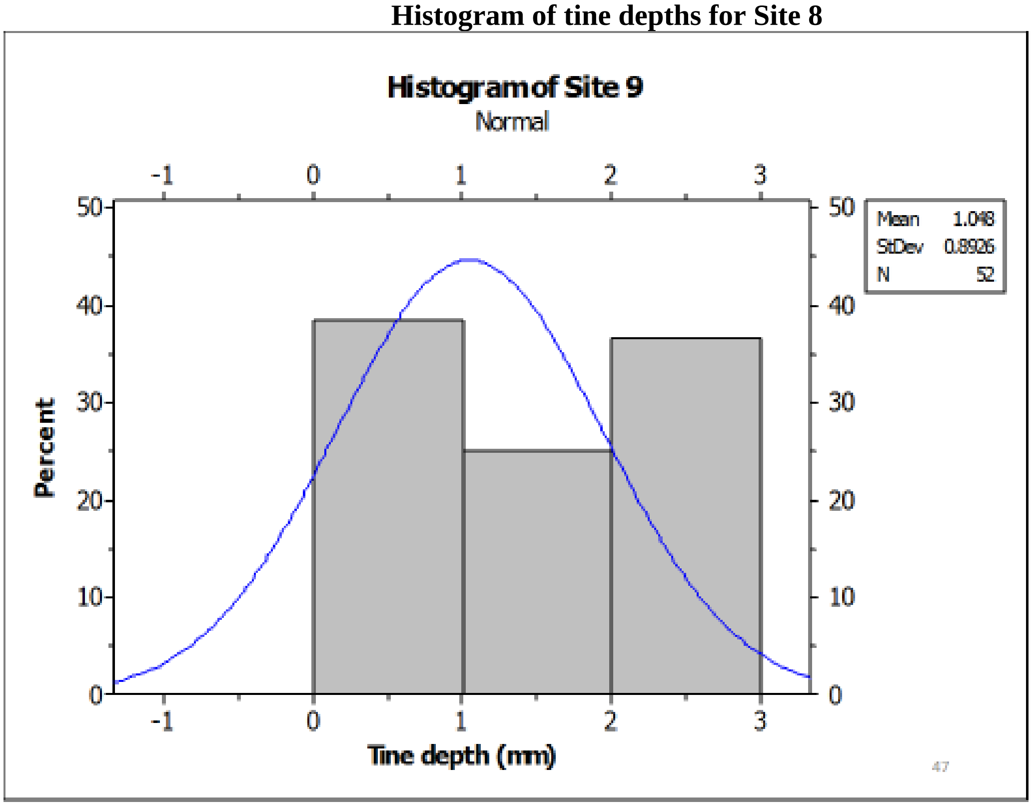


Figure 34
Histogram of tine depths for Site 9

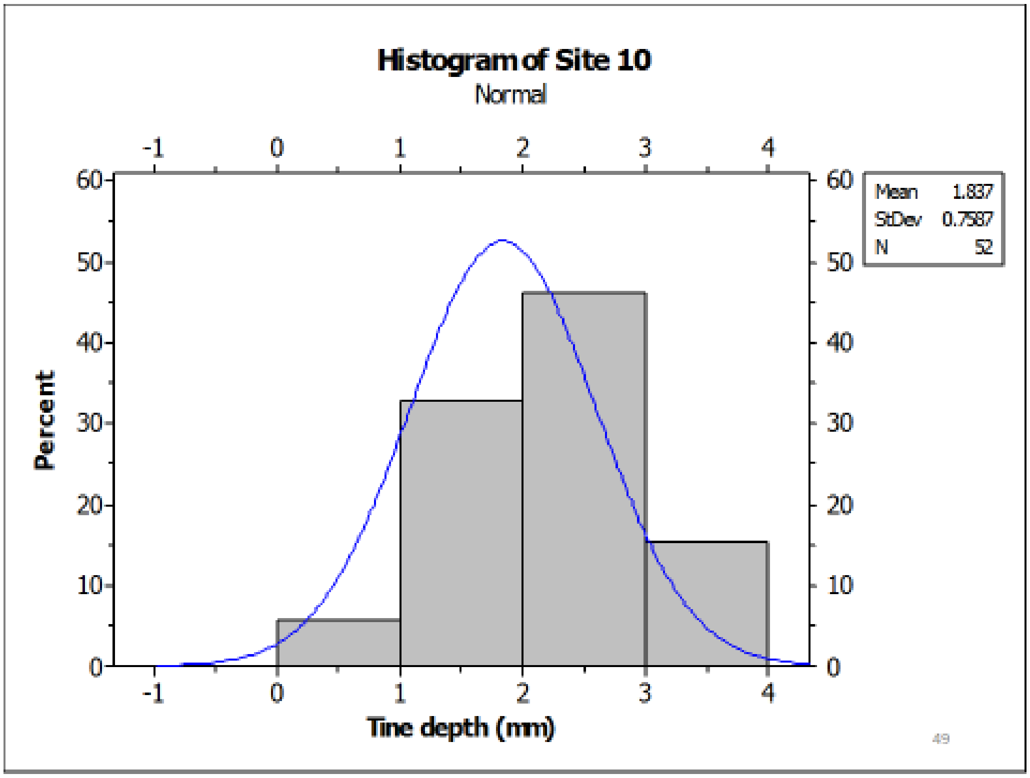


Figure 35
Histogram of tine depths for Site 10

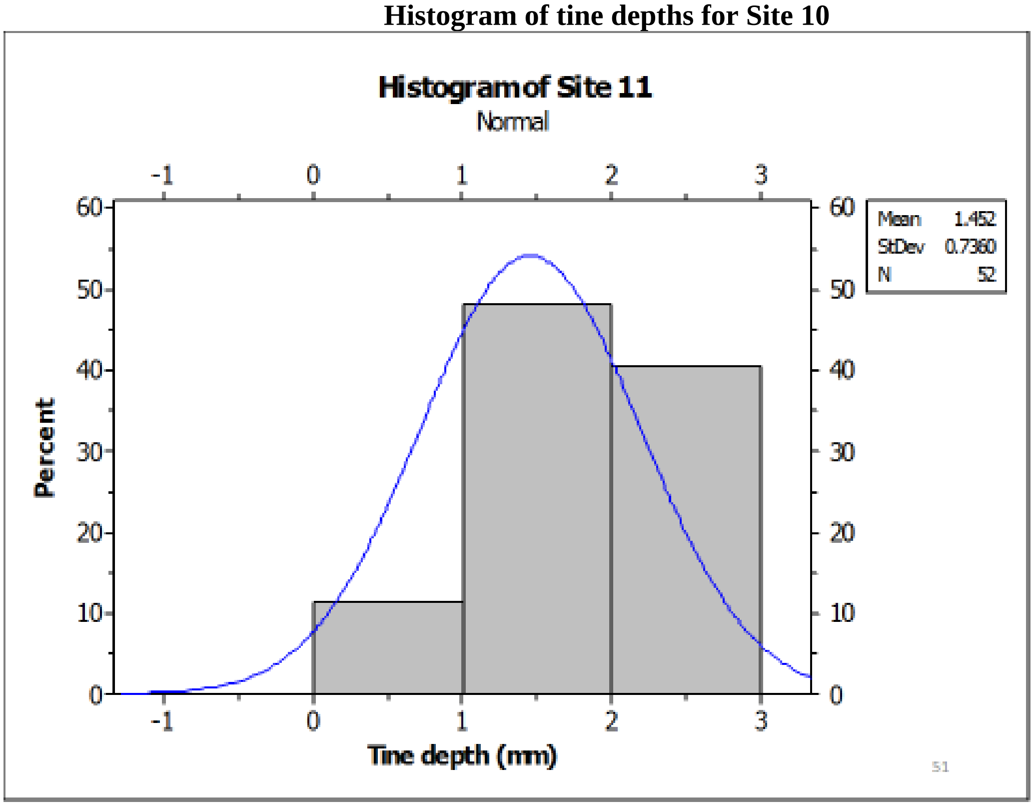


Figure 36
Histogram of tine depths for Site 11

APPENDIX C

Tine Width

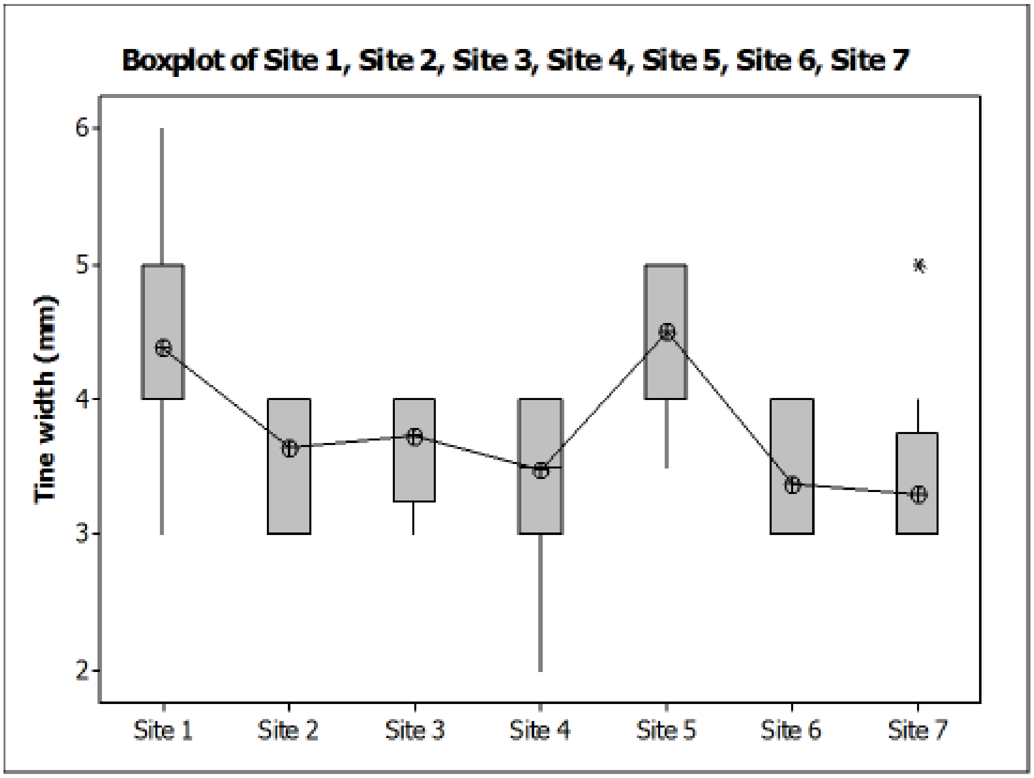


Figure 37
Histogram of boxplots for tine widths

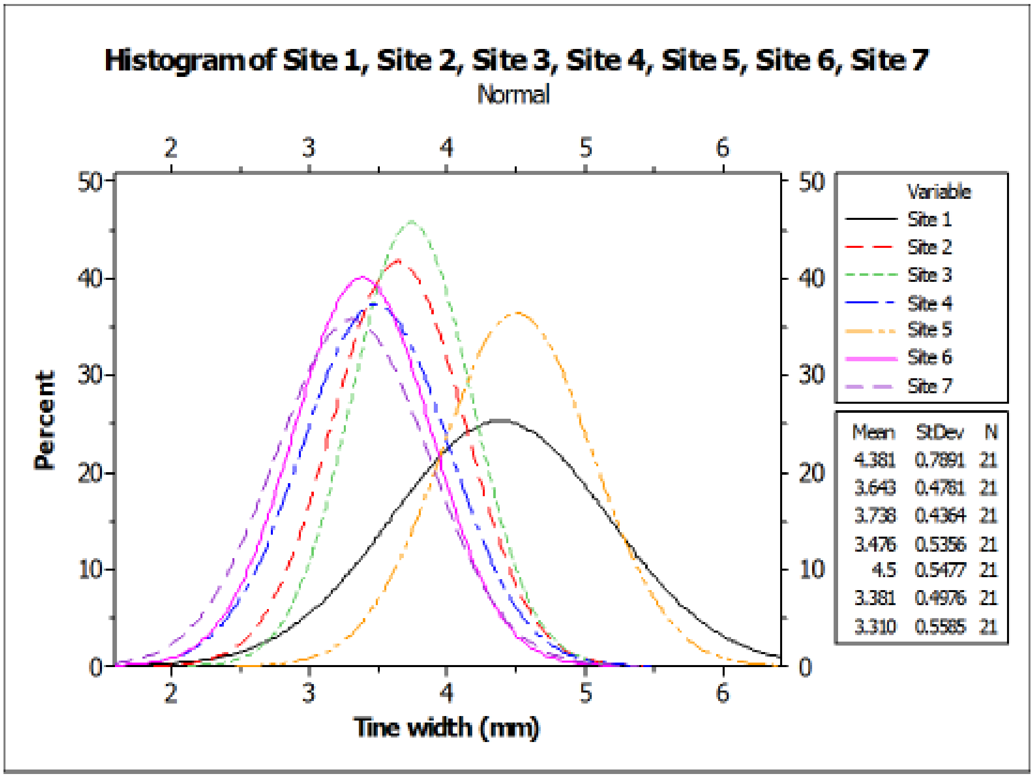


Figure 38
Histogram of tine widths for Sites 1 to 7

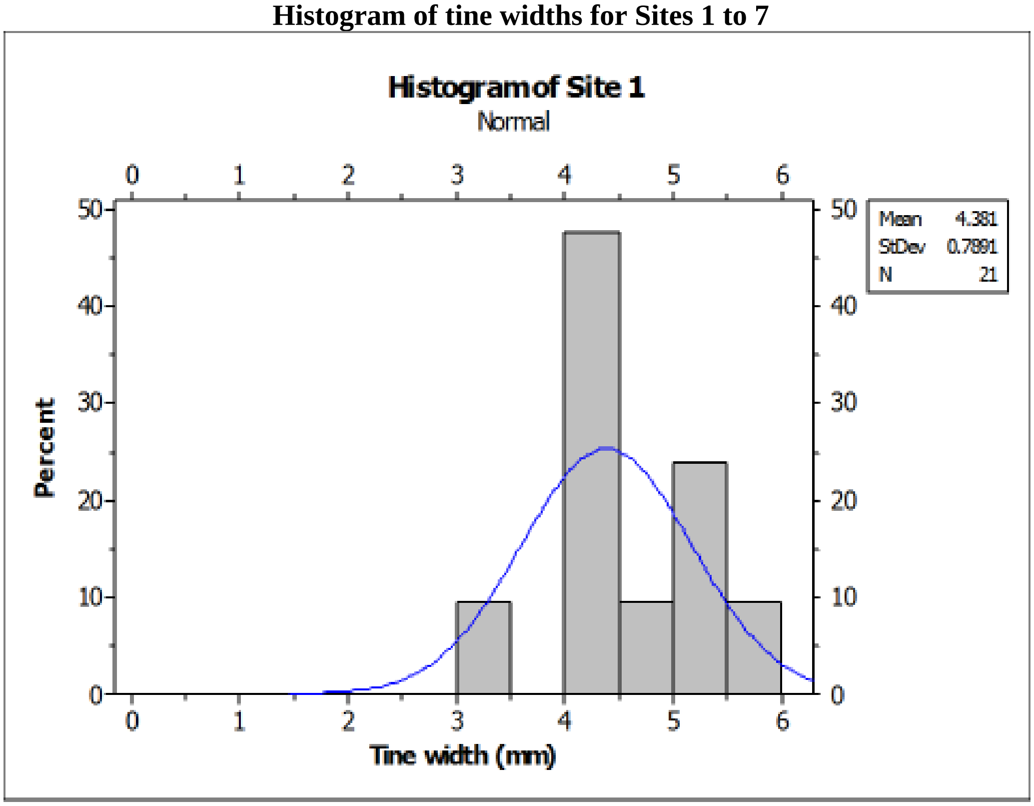


Figure 39
Histogram of tine widths for Site 1

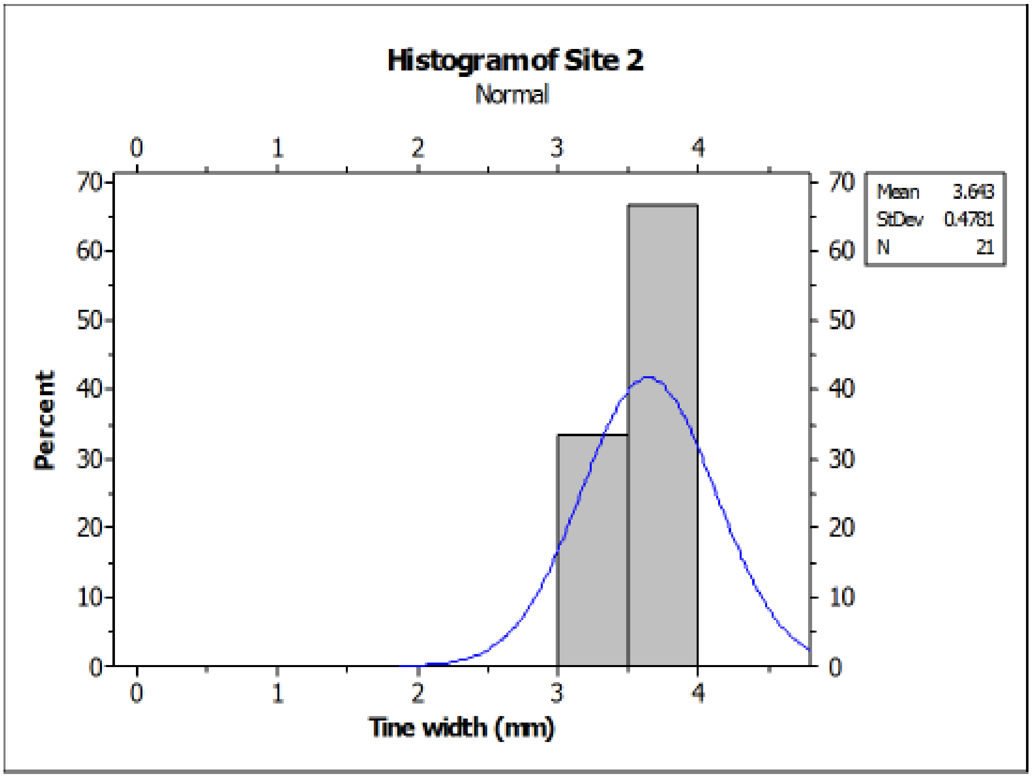


Figure 40
Histogram of tine widths for Site 2

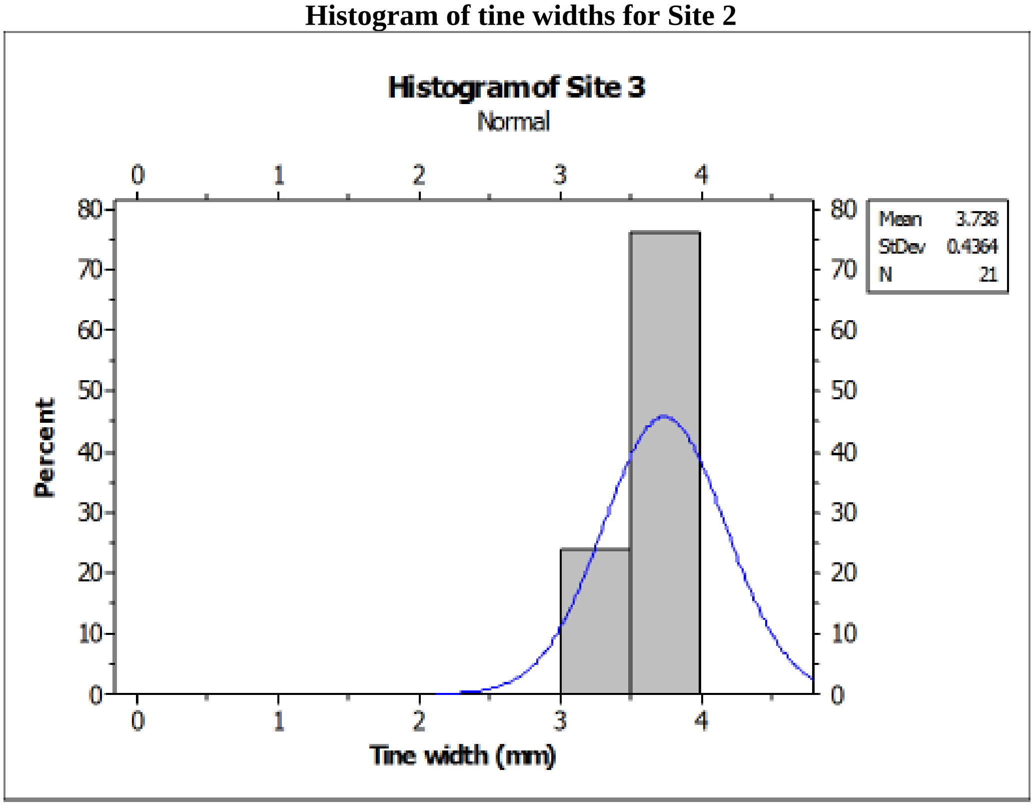


Figure 41
Histogram of tine widths for Site 3

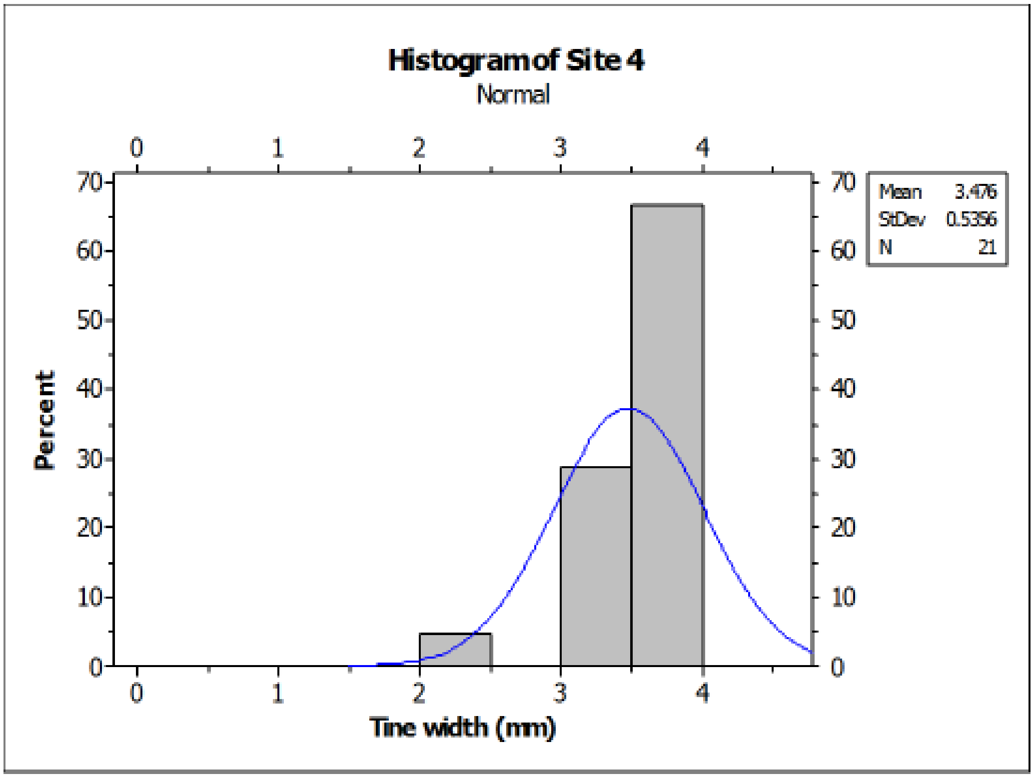


Figure 42
Histogram of tine widths for Site 4

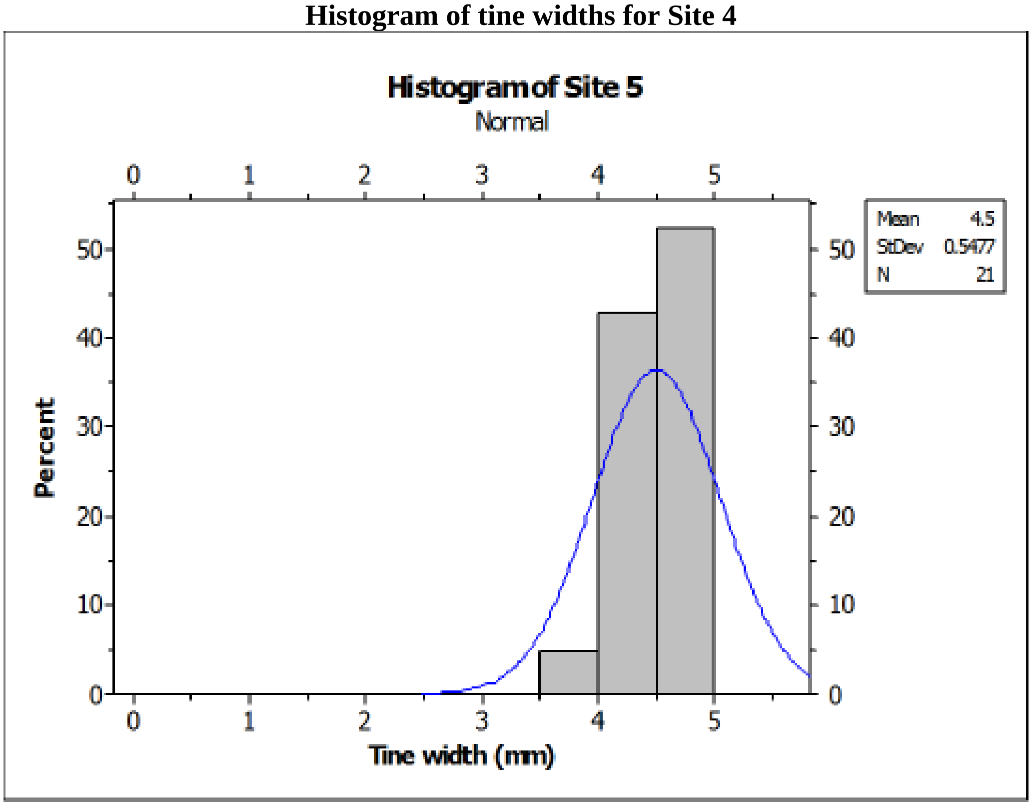


Figure 43
Histogram of tine widths for Site 5

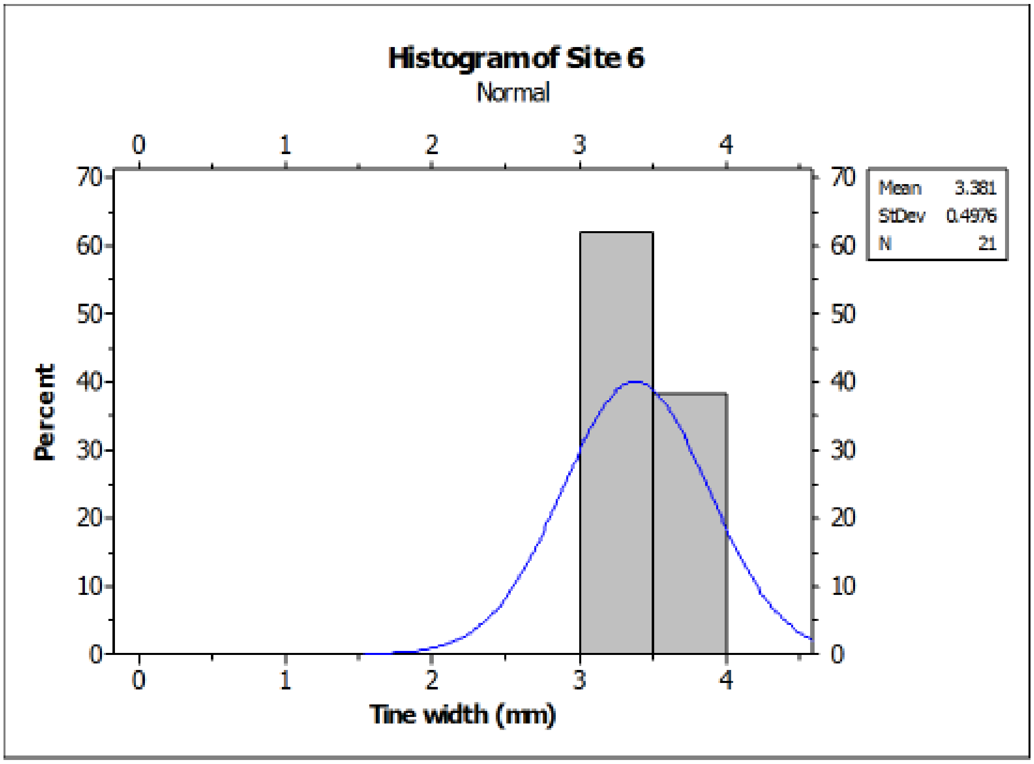


Figure 44
Histogram of tine widths for Site 6

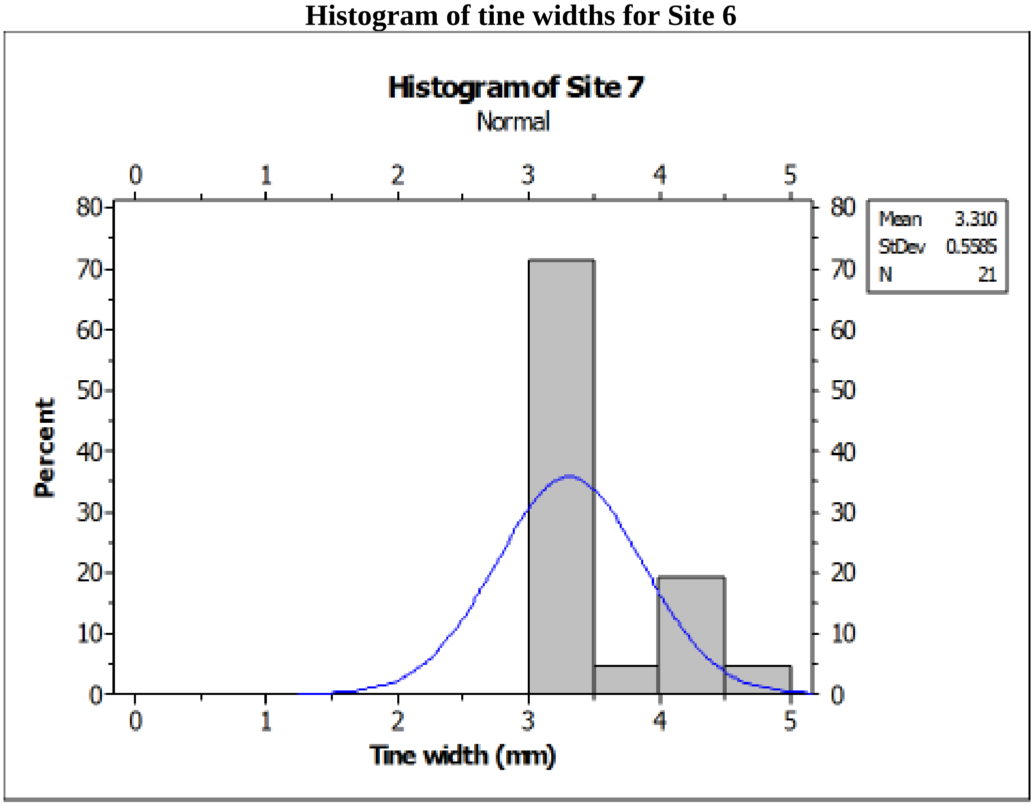


Figure 45
Histogram of tine widths for Site 7

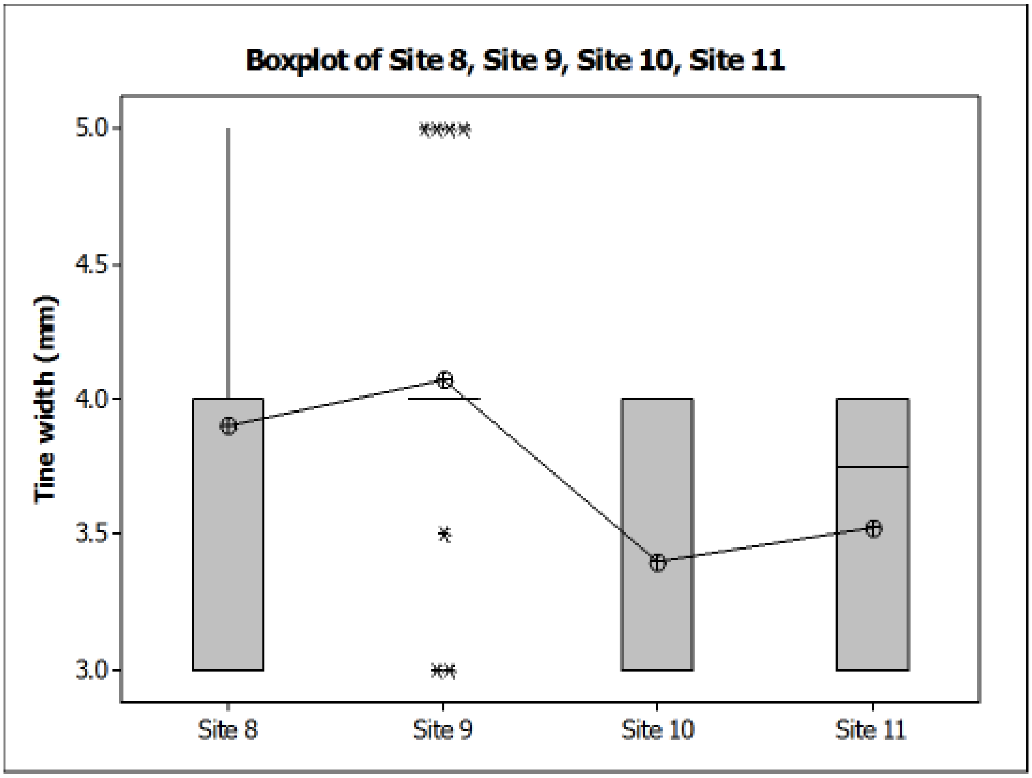


Figure 46
Boxplot of tine widths for Sites 8 to 11 on O'Neal Lane

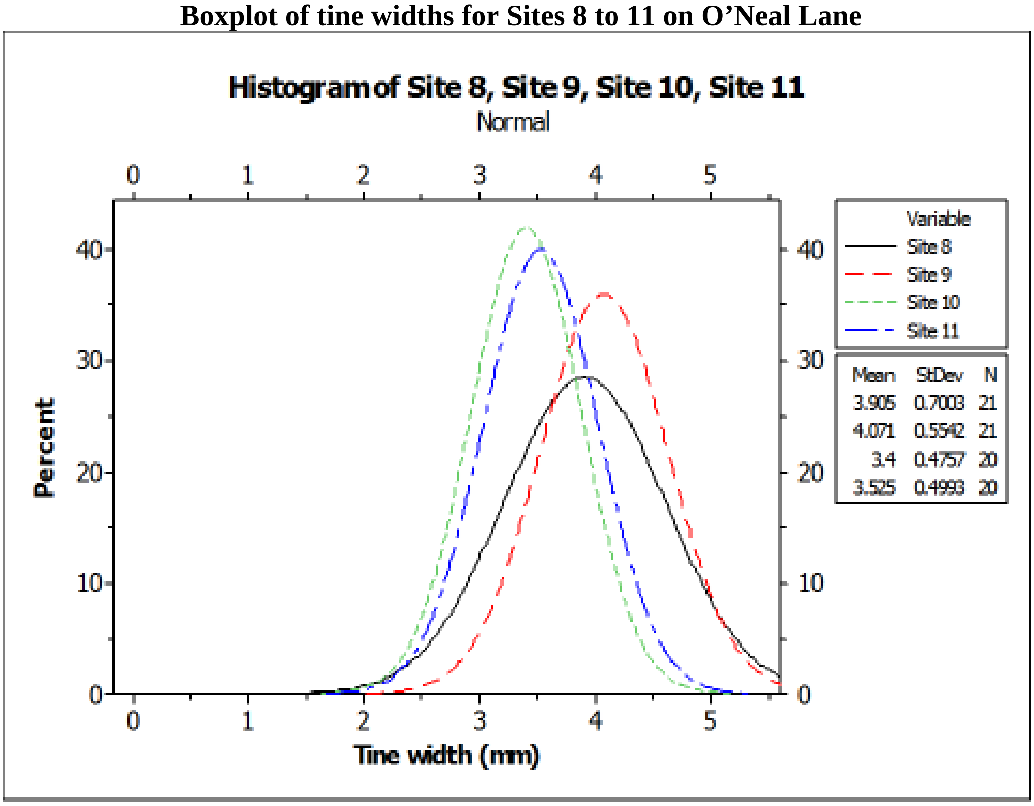


Figure 47
Histogram of tine widths (Sites 8 to 11)

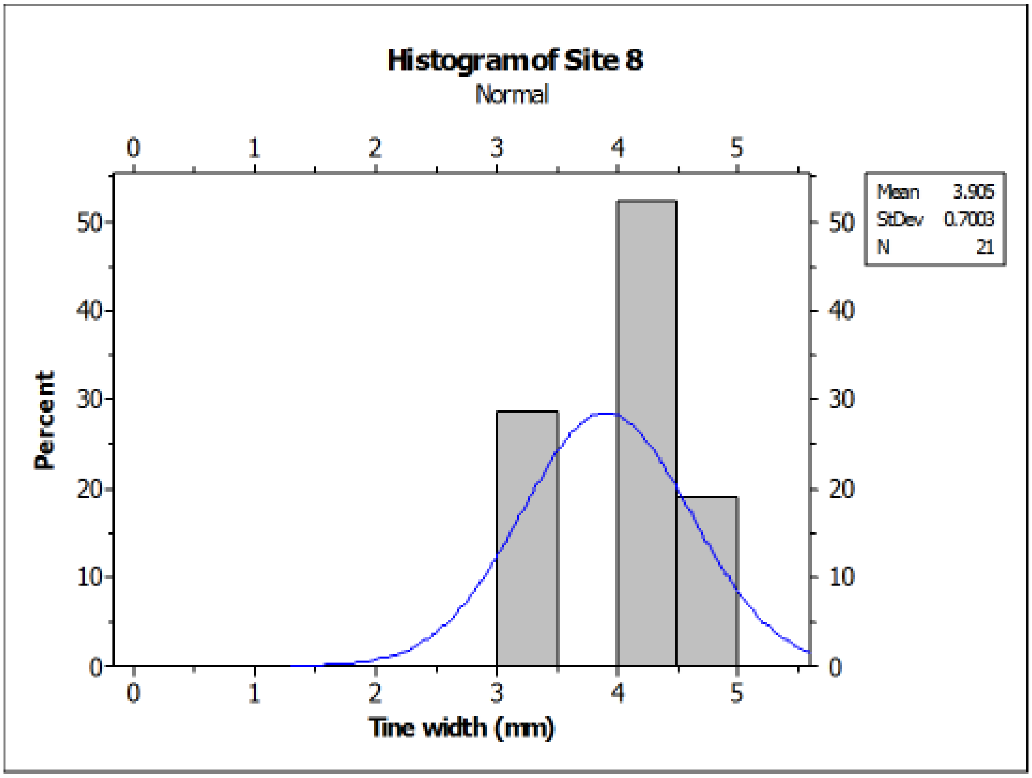


Figure 48
Histogram of tine widths for Site 8

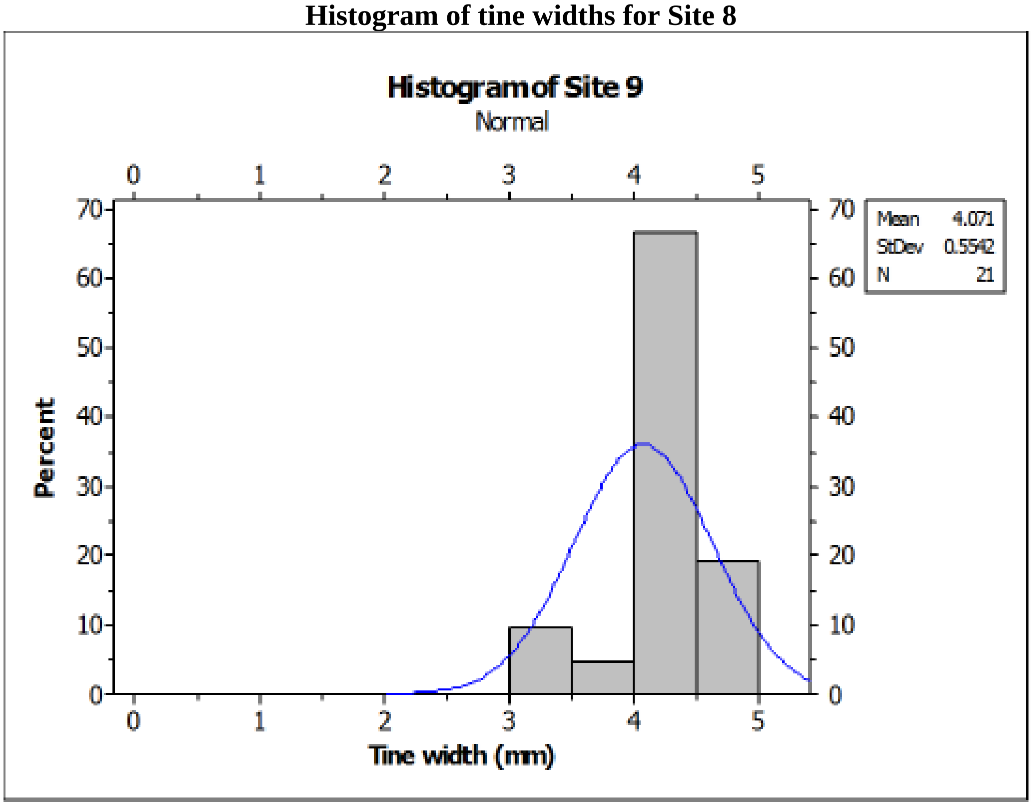


Figure 49
Histograms of tine widths for Site 9

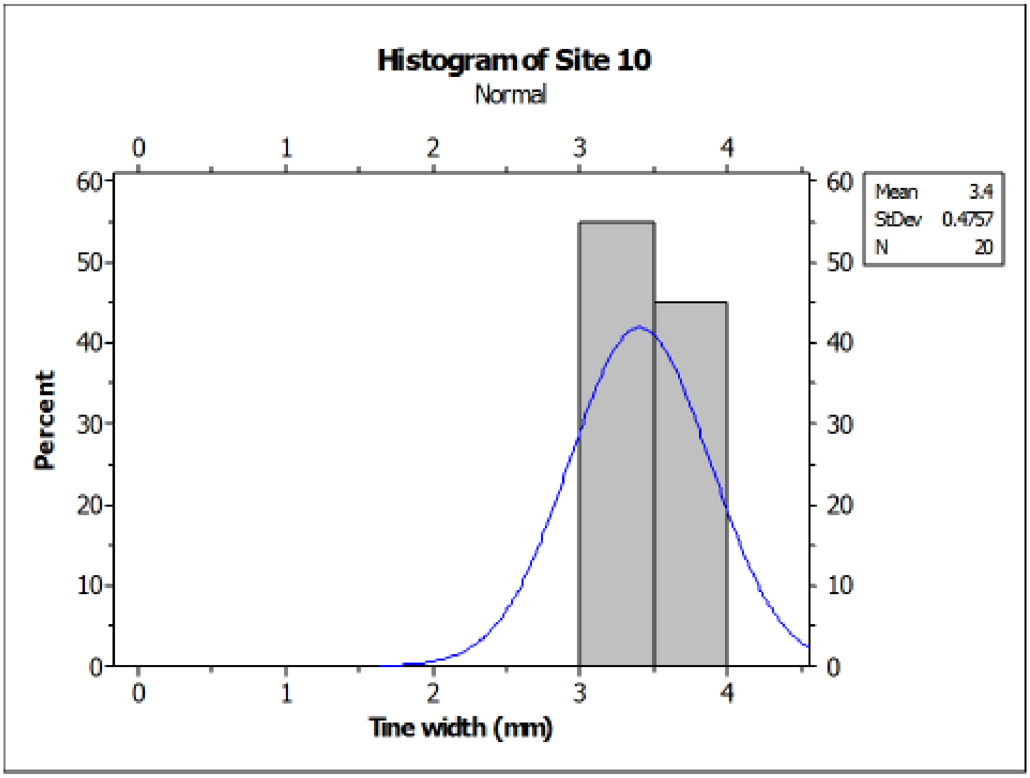


Figure 50
Histograms of tine widths for Site 10

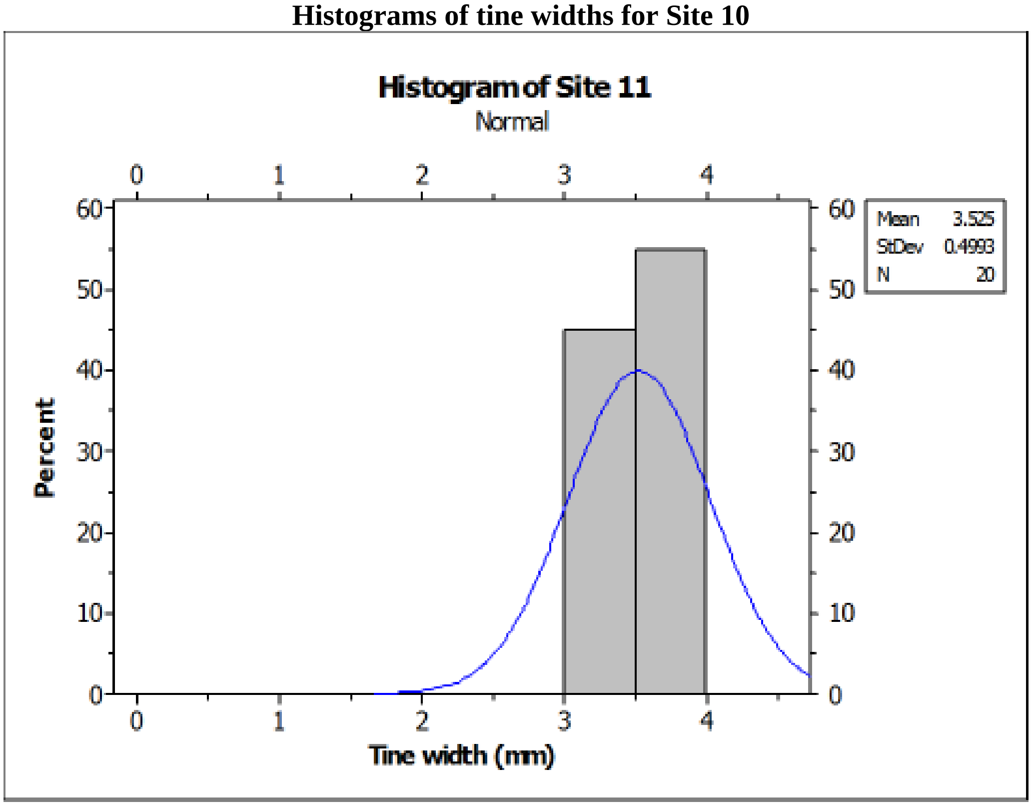


Figure 51
Histogram of tine widths for Site 11

APPENDIX D

Spacing between tines

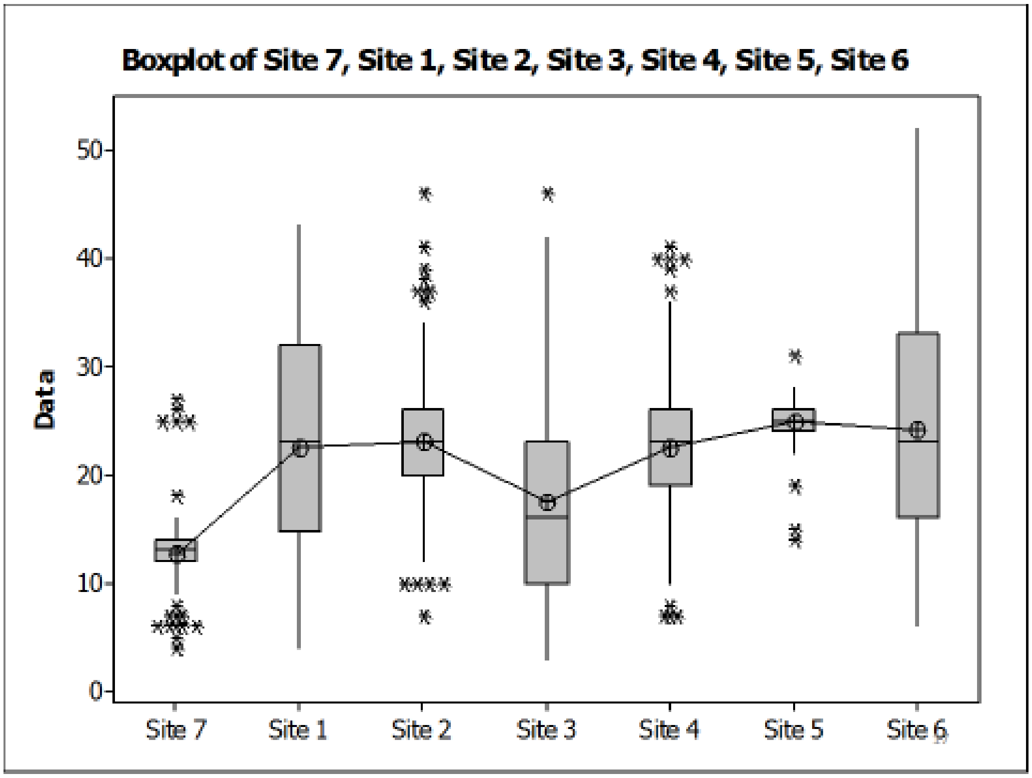


Figure 52
Joor Road boxplots of spacing between tines

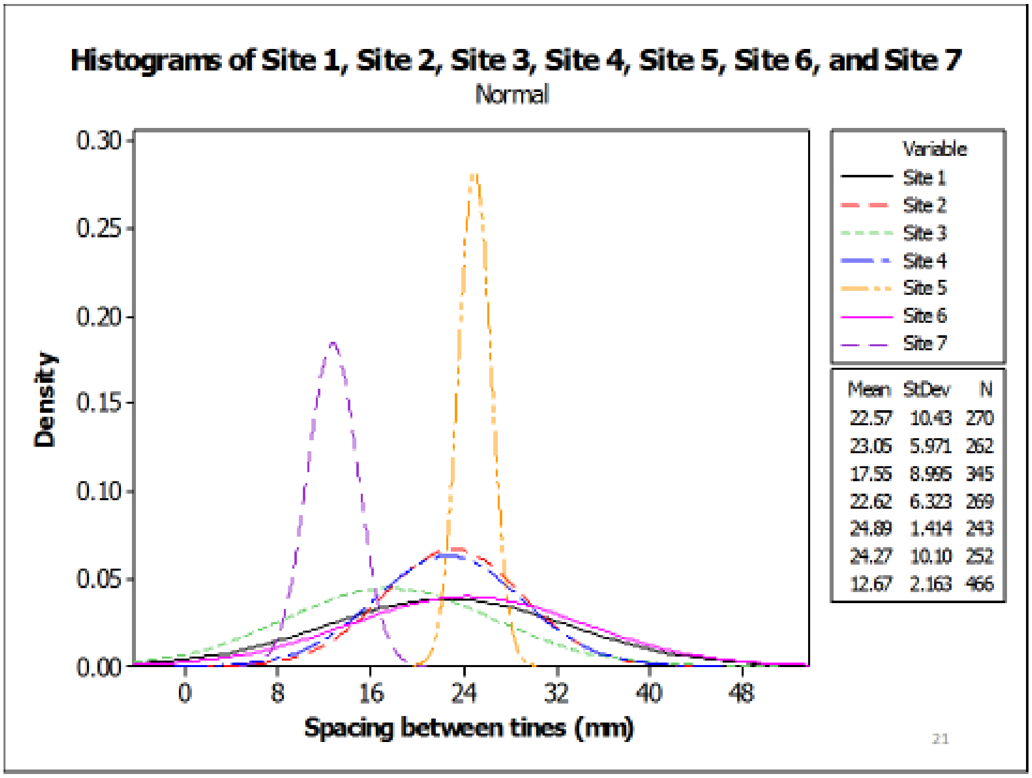


Figure 53
Joor Road histograms of spacing between tines

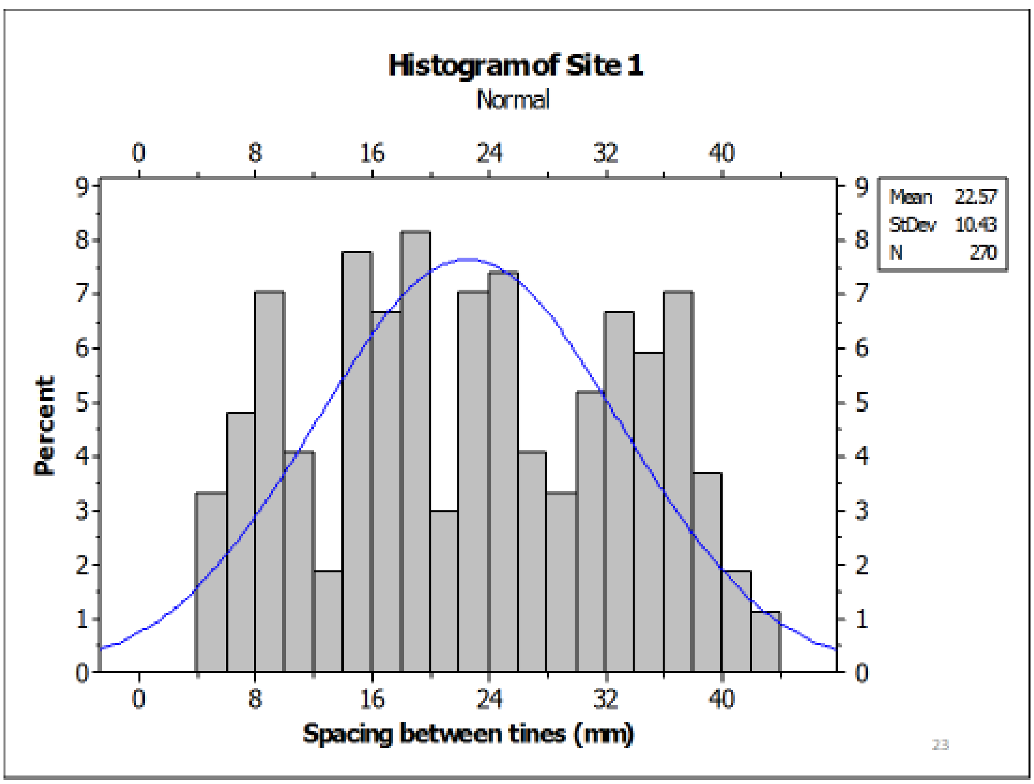


Figure 54
Histograms of spacing between tines for Site 1

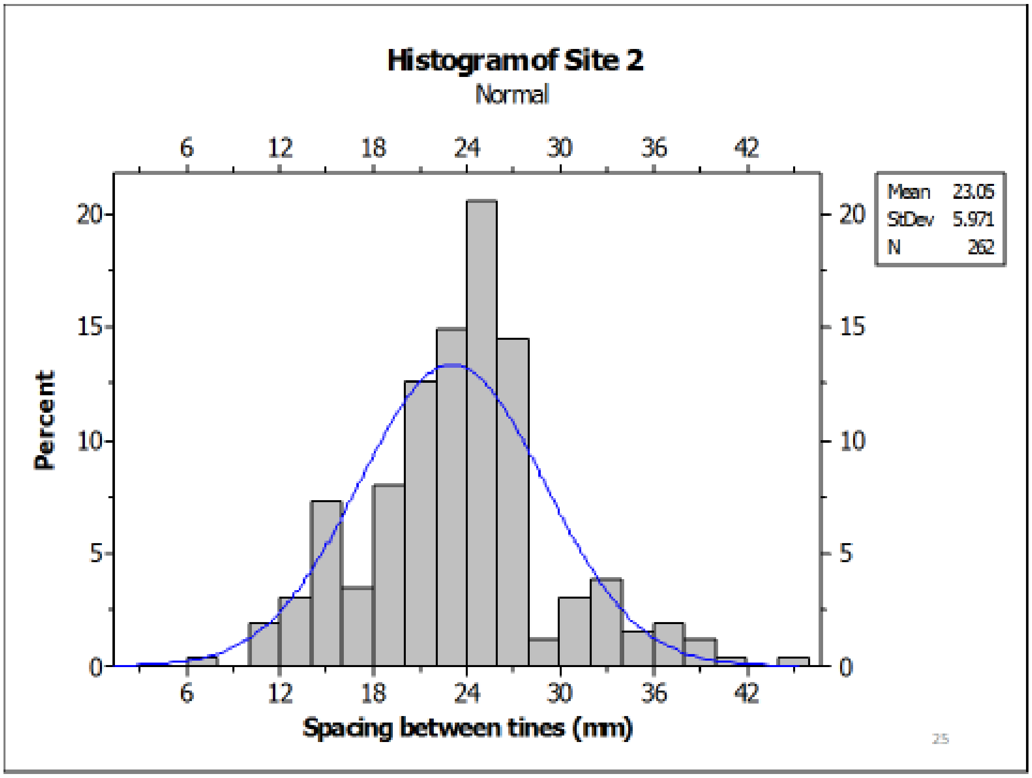


Figure 55
Histogram of spacing between tines for Site 2

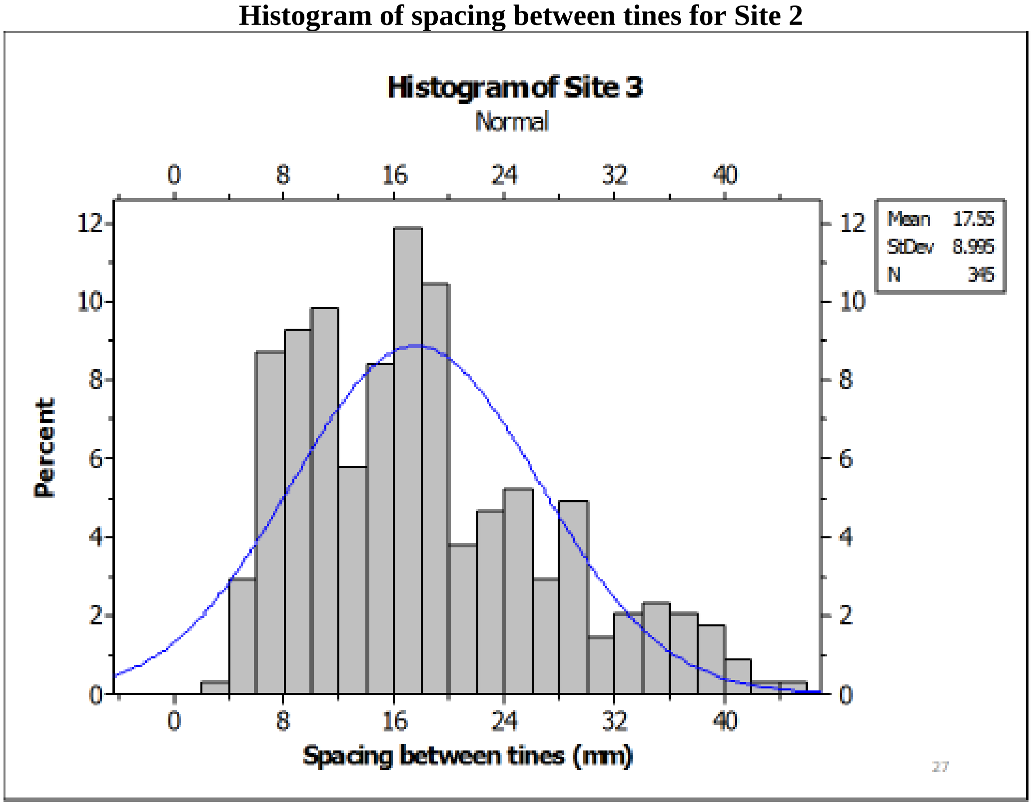


Figure 56
Histograms of spacing between tines for Site 3

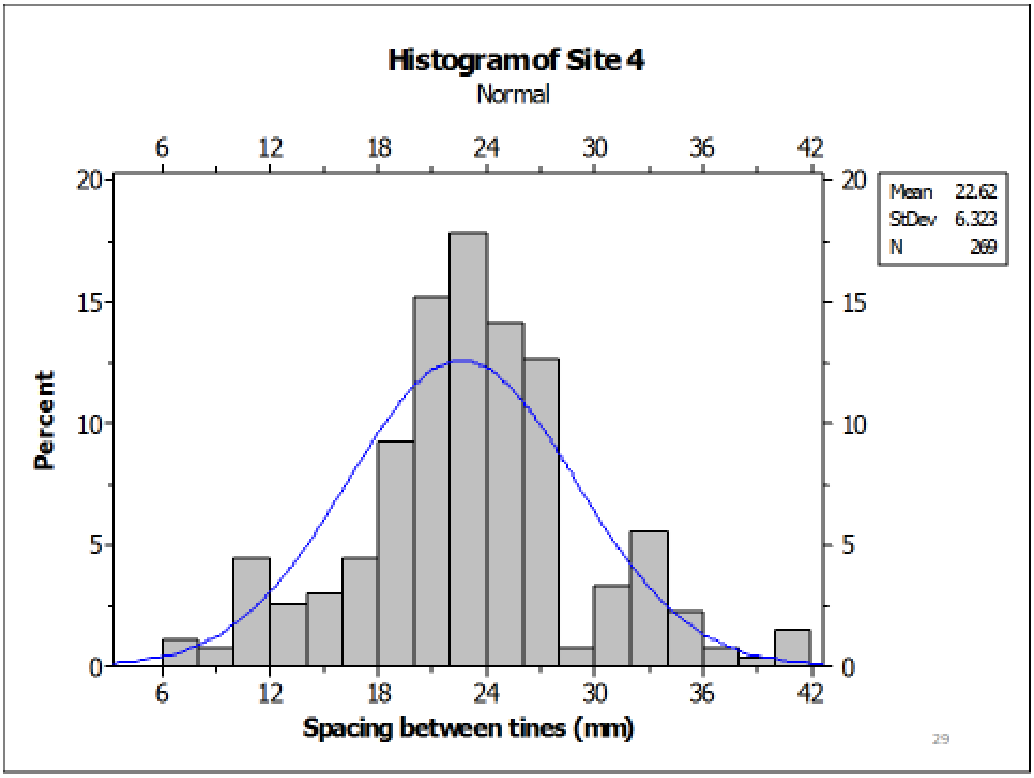


Figure 57
Histograms of spacing between tines for Site 4

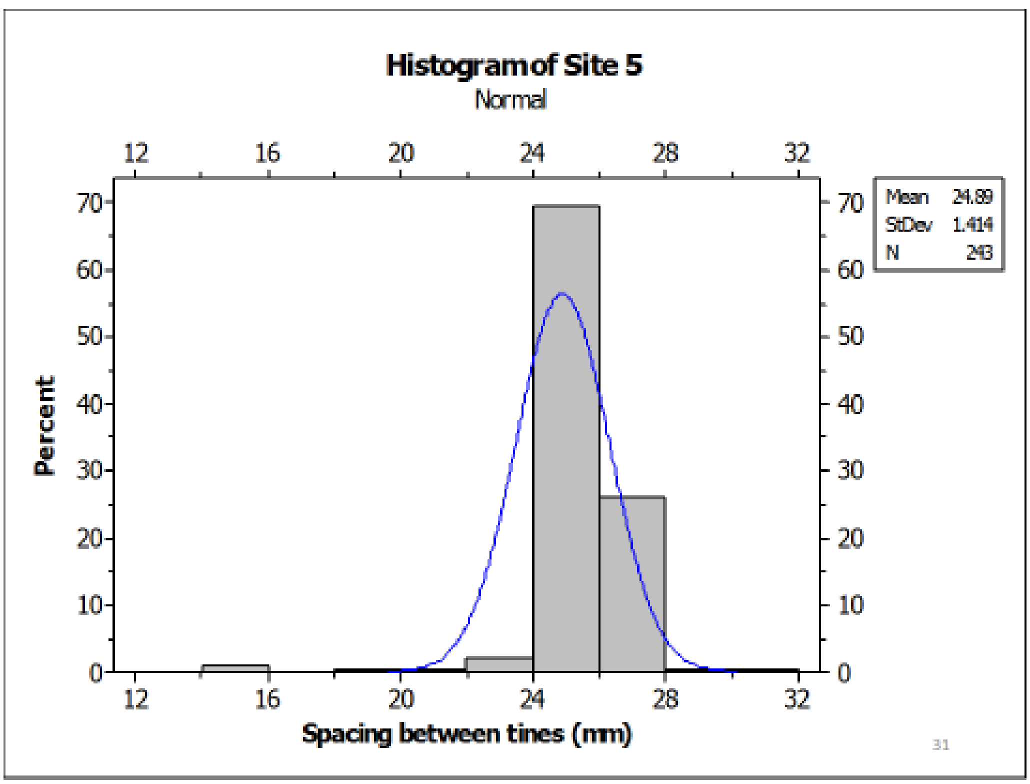


Figure 58
Histogram of spacing between tines for Site 5

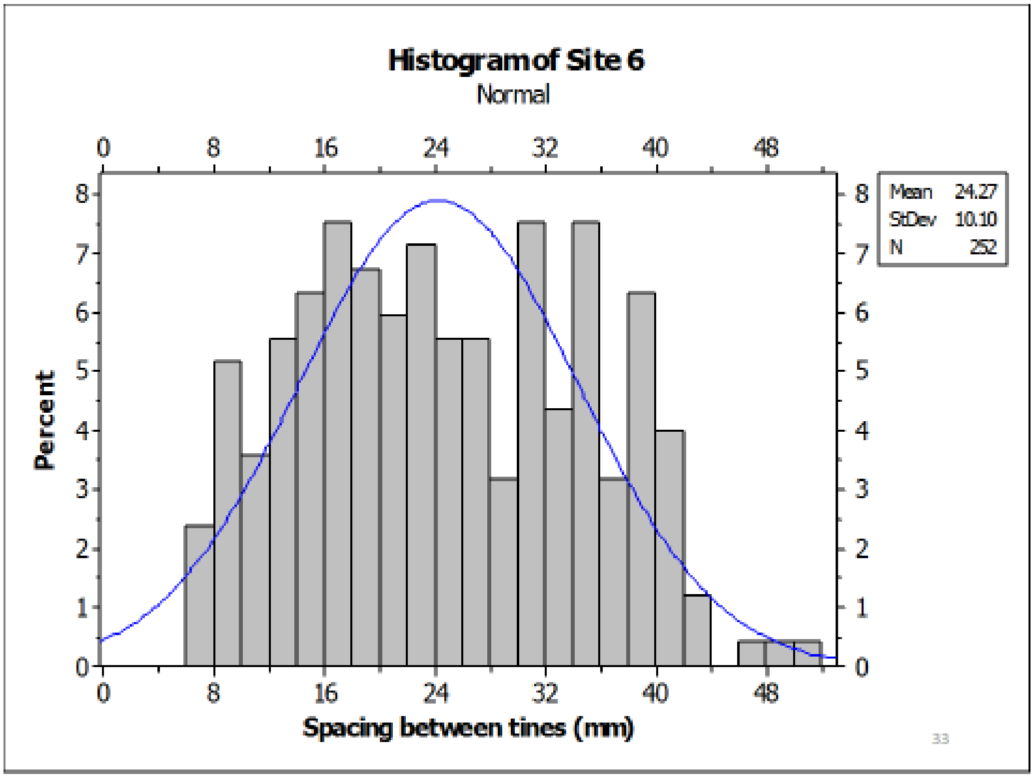


Figure 59
Histograms of spacing between tines for Site 6

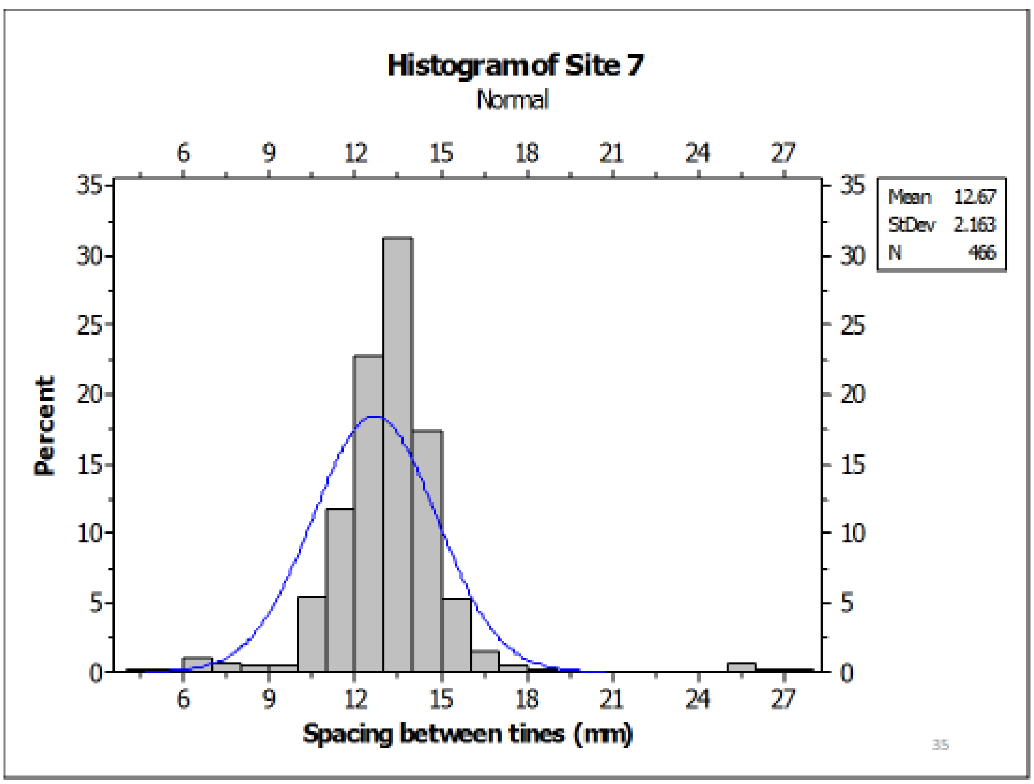


Figure 60
Histograms of spacing between tines for Site 7

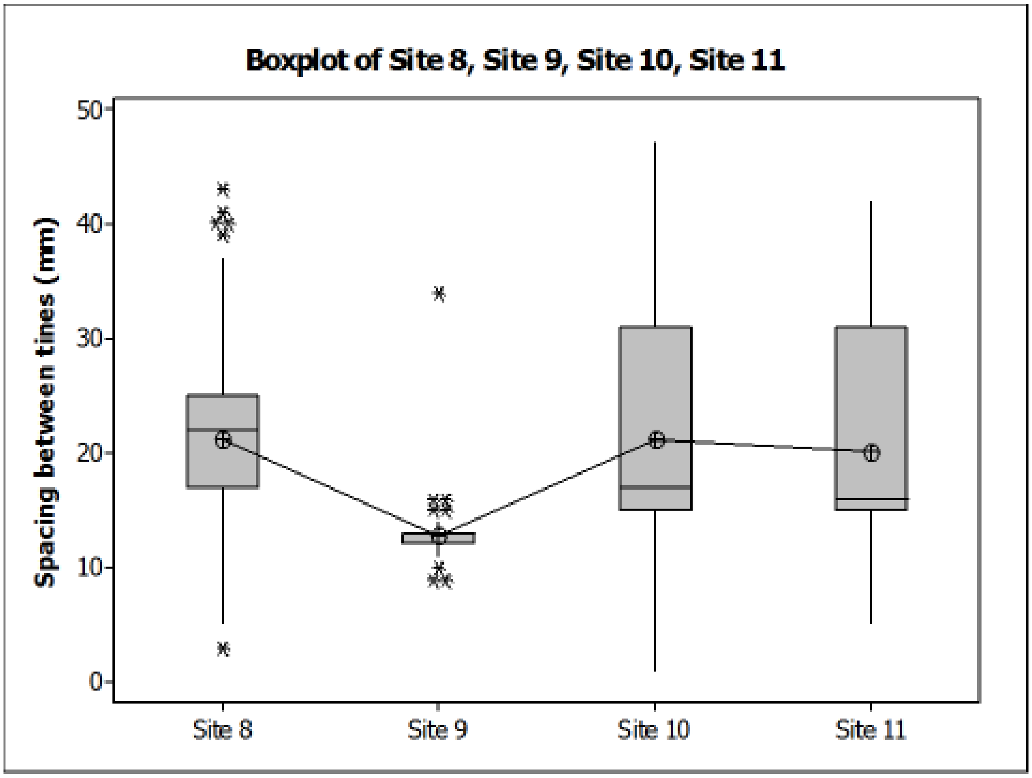


Figure 61
Boxplot of spacing between tines for Sites 8 to 11

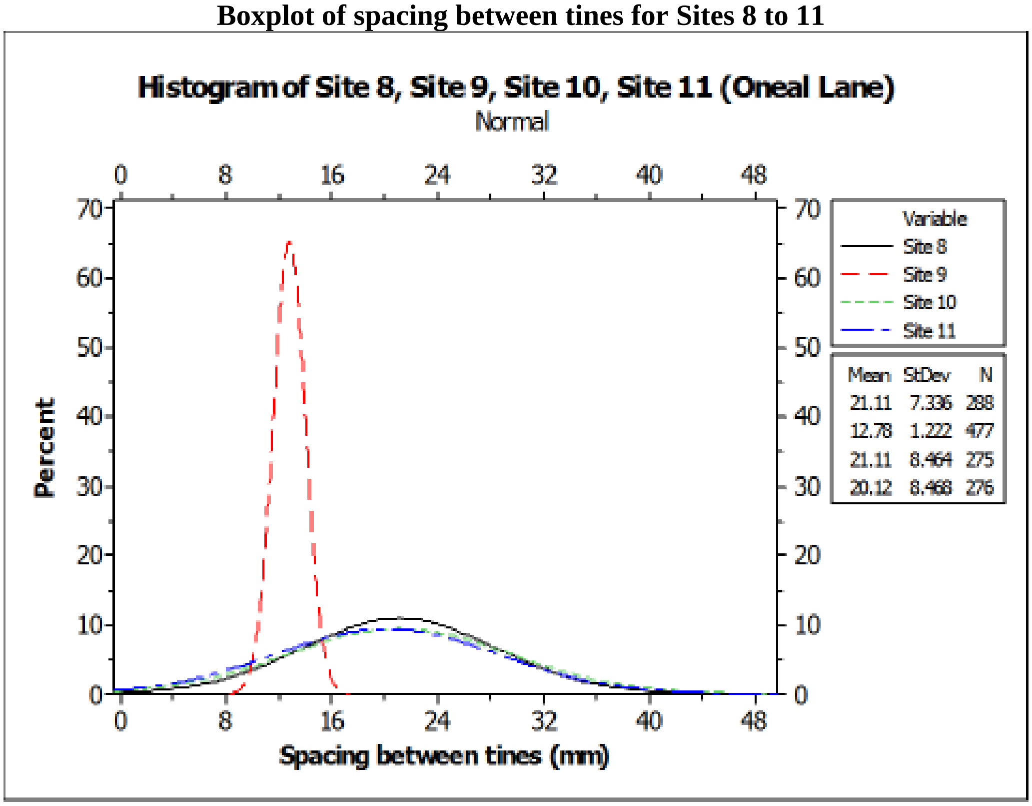


Figure 62
Histograms of spacing between tines for Sites 8 to 11

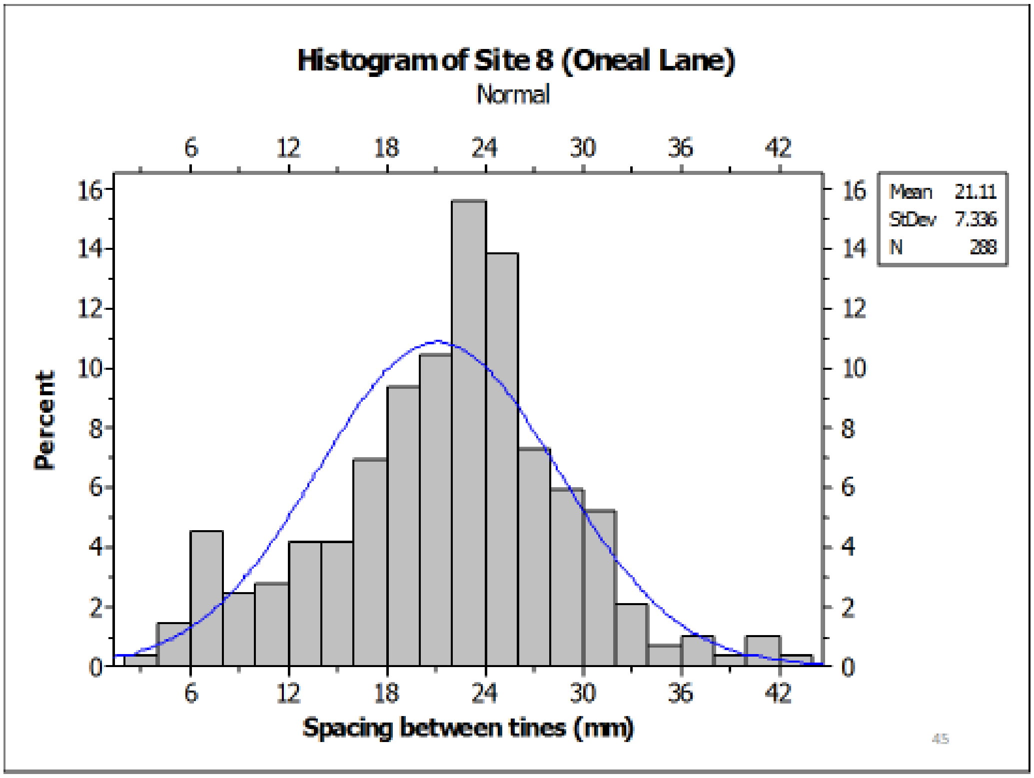


Figure 63
Histogram of spacing between tines for Site 8

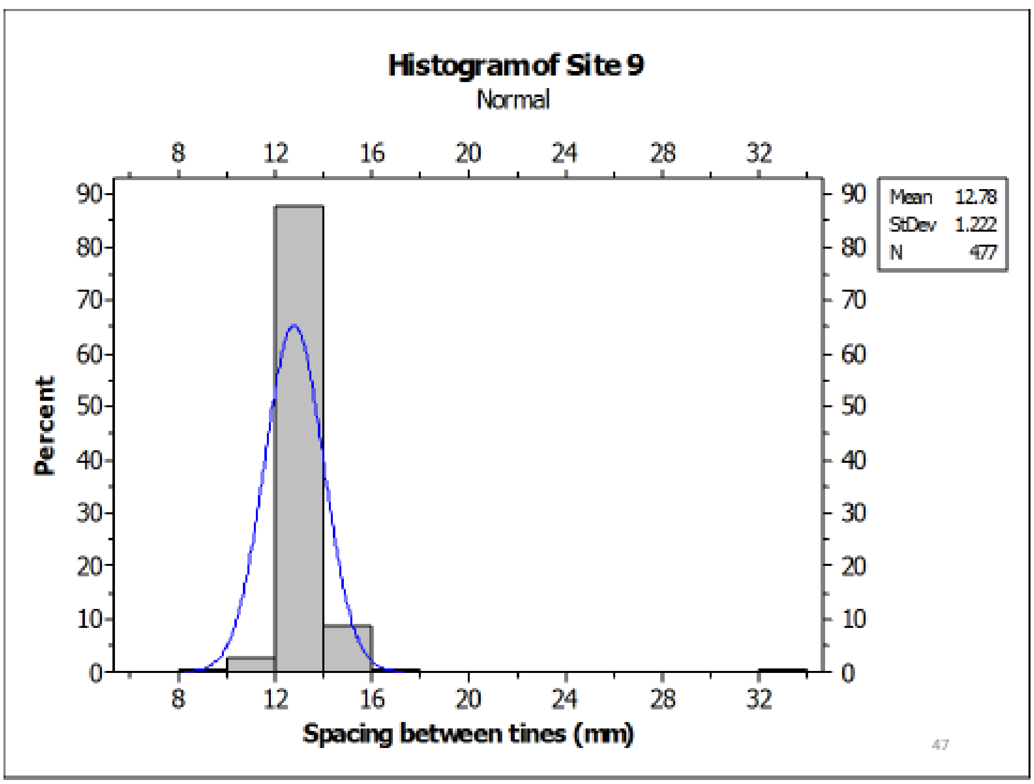


Figure 64
Histogram of spacing between tines for Site 9

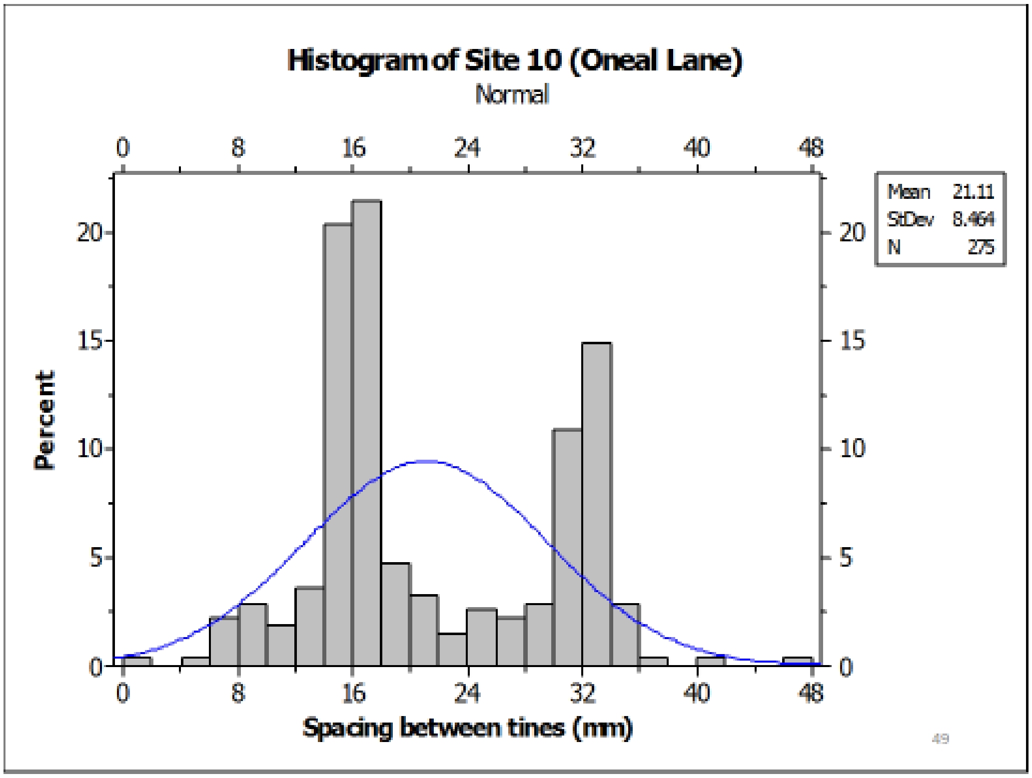


Figure 65
Histograms of spacing between tines for Site 10

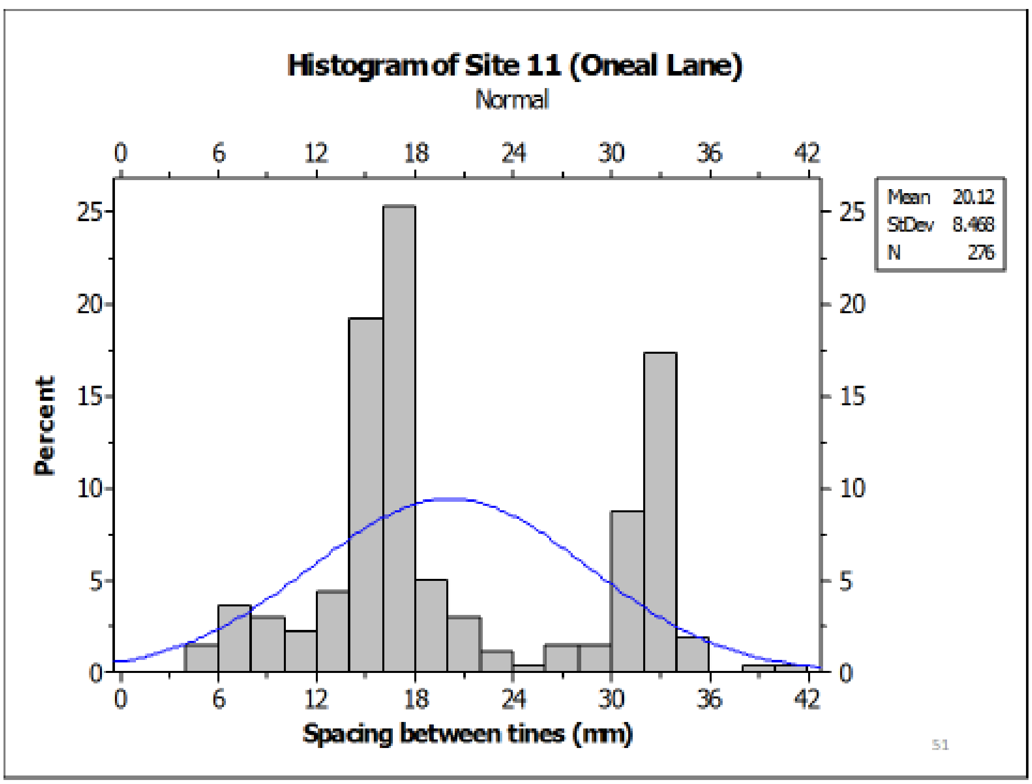


Figure 66
Histogram of spacing between tines for Site 11

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