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Use of High Friction Surface for Highway Noise Reduction

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Research of several standardized methods of testing led to the selection of Statistical Pass-By Method (SPB) as the best method of measuring highway noise levels. While SPB calls for testing of a specific amount of random car pass-bys in order to draw a sound level conclusion, the team utilized a modified SPB testing method using one specific car for all test passes, creating a more controlled testing environment due to the wide variety of vehicle types traveling on the highways.

The Kansas State Senior Design Team decided upon a test strip of 300 ft in order to accurately evaluate the HFS. The Kansas Department of Transportation (KDOT) in Wamego, KS, placed an HFS test strip of 300 ft on US Highway 24. The Kansas State Senior Design Team purchased the resin for the test strip from Transpo Industries, and Flint Rock donated the aggregate. KDOT and Performance Contracting Inc. (PCI) completed the test strip on June 22, 2016.

To perform simple and accurate testing, the Senior Design Team created a detailed testing setup and procedure for the testing. Using the testing procedure and a SoundTrack LxT, the team performed four different tests (three modified SPB and a final normal SPB test). The data collected from these tests resulted in an average sound change less than the 5-dB amount considered noticeable to the human ear. As a result, this report concludes that HFS is not an effective stand-alone alternative to sound barrier walls but could be used in conjunction with other actions to reach an acceptable level of noise reduction in urban areas.

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Abstract

With noise issues arising frequently in urban areas due to heavy traffic, it might be possible to use High Friction Surfaces (HFS) to reduce the sound to an acceptable level without a barrier wall or in conjunction with one. This research project determines the influence of HFS on traffic noise levels. The purpose of this project is to extend on previous research by including more evaluation on HFS Polymer Overlays.

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Acknowledgements

Special thanks are extended to Kansas Department of Transportation (KDOT) personnel Dave Meggers and Joan Myer for their guidance and support during the course of the project. Thanks are also extended to the KDOT personnel in Wamego for helping place the High Friction Surface (HFS) test strip and Tom Donnelly from Transpo Industries for providing the epoxy and assisting in placing the test strip.

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Chapter 1: Introduction

1.1 Overview

With noise issues arising frequently in urban areas due to heavy traffic, it might be possible to use High Friction Surface (HFS) to reduce the sound to an acceptable level without a barrier wall or in conjunction with one. This research project measures the influence of HFS and Multi-Layer Polymer Overlay material on traffic noise levels. The purpose of this project is to extend on previous research by including more evaluation on HFS. This will be done by testing sound levels of the surfaces of two adjacent roadway sections in hopes of finding a significant difference between the two.

1.2 Background Information

The Kansas Department of Transportation (KDOT) began using multi-layer polymer for bridge decks in 1999. The original purpose of this material was to prevent the intrusion of water and chlorides through existing cracks in the concrete and prevent corrosion. After several years, remarks were made about how quiet the bridge decks were compared to adjacent pavements. A short study conducted in 2008 evaluated the reduction of tire noise due to the multi-layer polymer overlays, shown in Figure 1.1. This study produced promising results of possible noise reduction but due to the cost of the materials, there was little movement to pursue using it for other applications.

Figure 1.1: Multi-Layer Polymer

1.3 Problem Statement

In 2009, the Kansas Department of Transportation began looking into High Friction Surfaces (HFS) for enhanced skid resistance in certain areas. The HFS uses the same material as the multi-layer polymer but only one coat is used in HFS, thus making it less costly for use in possible noise reduction situations.

1.4 Objectives

The Kansas State Senior Design Team worked with Dave Meggers and Joan Meyer from KDOT to evaluate the noise reduction potential of the HFS.

The following tasks were completed by the Kansas State Senior Design Team:

- Evaluated appropriate audio equipment to perform the evaluation of HFS.
- Determined what equipment KDOT should use for future testing.
- Developed an audio system to perform the research.
- Included a drive-by sensing unit for the testing processes.
- Included a mobile sensing system for the testing processes.
- Evaluated the HFS test strip.
- Produced a final KDOT report of the research performed.

The purpose of the project is to see if HFS can be used in some cases to reduce road noise to an acceptable level without the use of a barrier wall or to be used in conjunction with a barrier wall.

Chapter 2: Project Planning

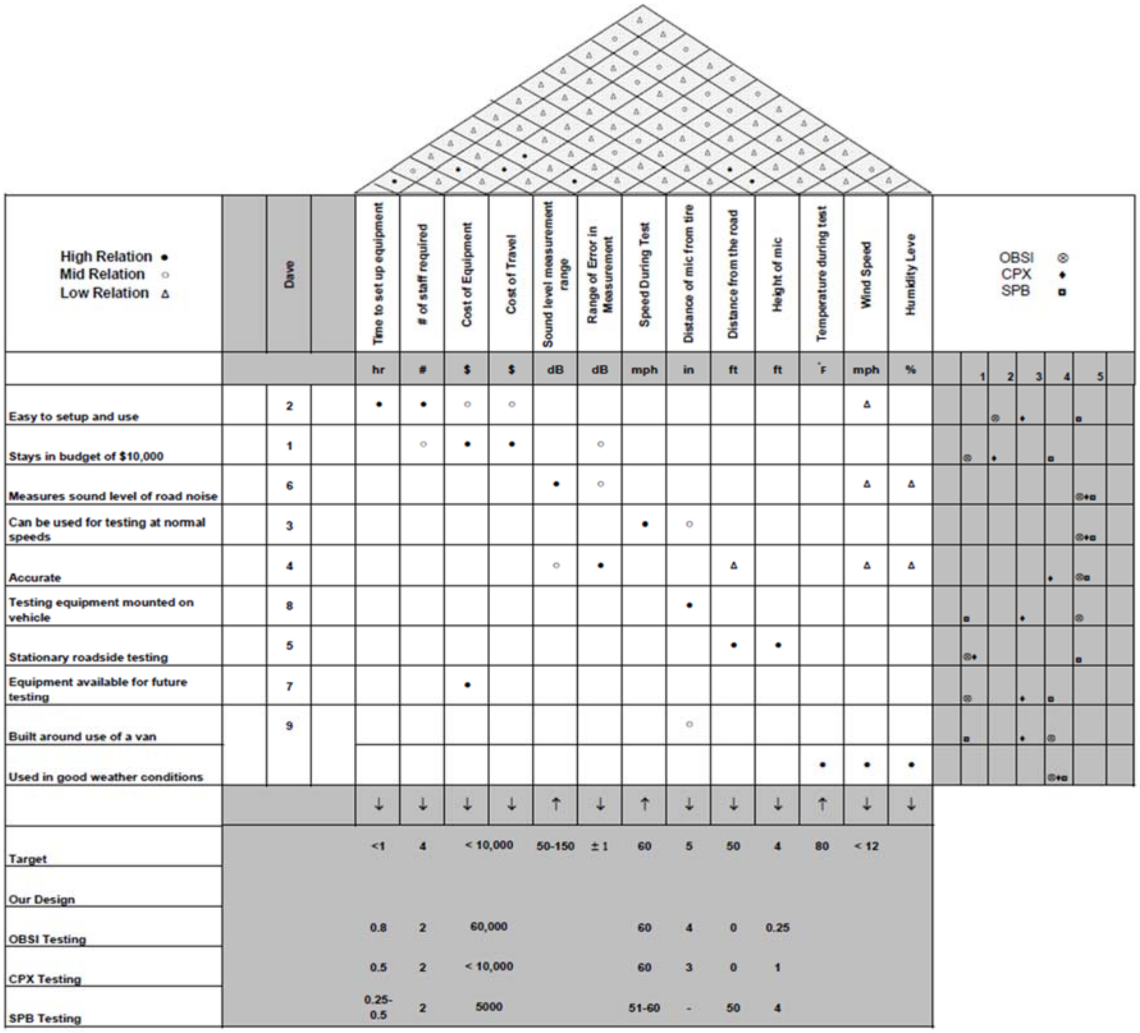
The planning process is the foundation of any project, which provides an outline and schedule for the duration of the project. Two commonly used methods during the planning process are Gantt charts and Quality Function Deployment (QFD).

2.1 Gantt Chart

A Gantt chart is a tool that visually displays the project schedule from beginning to end. There are five main columns in the Gantt chart along with a timeline. The first column lists out the tasks to be completed. This list orders the tasks in chronological order, along with grouping sections and subsections. The next column states the amount of time each task is required to take. This column is linked to the start and finish columns located to the right of it. The start and finish columns list the actual calendar dates in which each task is to begin or end. The last column in the Gantt chart describes any tasks that are predecessors to others. The last part of the Gantt chart is the timeline to the right of the columns. Here bars represent the duration for each task along with arrows connecting them in order. The complete Gantt chart for this project is located in Appendix B.

2.2 Quality Function Deployment (QFD)

QFD is a method that translates the consumer's voice into design parameters. One commonly used tool in the QFD method is the House of Quality. The House of Quality is a diagram, whose structure resembles a house, which accomplishes the translation of the consumer's voice using several matrices. These matrices match consumer demands with technical requirements and show how each requirement interacts with other requirements. It usually compares how multiple competitors or producers of a product meet the given requirements, but since this project does not really have competitors, each matrix instead shows how different methods of sound measurement meet the requirements.



High Relation ●
Mid Relation ○
Low Relation Δ

OBSI ⊗
CPX ♦
SPB ▣

	Dave	Time to set up equipment	# of staff required	Cost of Equipment	Cost of Travel	Sound level measurement range	Range of Error in Measurement	Speed During Test	Distance of mic from tire	Distance from the road	Height of mic	Temperature during test	Wind Speed	Humidity Leve	1	2	3	4	5
		hr	#	$	$	dB	dB	mph	in	ft	ft	°F	mph	%					
Easy to setup and use	2	●	●	○	○								Δ			⊗	♦		▣
Stays in budget of $10,000	1		○	●	●		○								⊗	♦		▣	
Measures sound level of road noise	6					●	○						Δ	Δ					⊗♦▣
Can be used for testing at normal speeds	3							●	○										⊗♦▣
Accurate	4					○	●			Δ			Δ	Δ				♦	⊗▣
Testing equipment mounted on vehicle	8								●						▣		♦		⊗
Stationary roadside testing	5									●	●				⊗♦				▣
Equipment available for future testing	7			●											⊗		♦	▣	
Built around use of a van	9								○						▣		♦	⊗	
Used in good weather conditions												●	●	●				⊗♦▣	
		↓	↓	↓	↓	↑	↓	↑	↓	↓	↓	↑	↓	↓					
Target		<1	4	< 10,000		50-150	± 1	60	5	50	4	80	< 12						
Our Design																			
OBSI Testing		0.8	2	60,000				60	4	0	0.25								
CPX Testing		0.5	2	< 10,000				60	3	0	1								
SPB Testing		0.25- 0.5	2	5000				51-60	-	50	4								

Figure 2.1: Sample of QFD

Figure 2.1 shows the House of Quality used for this project. The far-left vertical matrix contains the consumer demands, with the vertical matrix directly to the right of it numerically stating the order of importance from 1 to 9. The top horizontal matrix lists the technical requirements, which are physically measurable entities that correlate with the consumer demands. The middle matrix, which is also the largest matrix, compares each consumer demand with each technical requirement, assigning the comparison a rating of high, mid, low, or no relation. This ensures that each consumer demand has adequate representation from the technical requirements, especially the demands with greater importance. The far-right matrix compares how well each method meets the consumer demands. This is done by giving each method a value from 1 to 5, with 5 being the greatest, on how well it accomplishes the demand. The bottom matrix essentially does the same thing, except for the technical requirements. Instead of comparing each method on a scale, actual values for each method show how they would meet the technical requirements. Arrows directly above this matrix indicate whether the ideal design would have a low or high value for each requirement. The triangular matrix, or roof of the house, compares how the technical requirements relate to each other.

The House of Quality not only assisted in choosing a method of sound measurement, but it also assisted in creating a testing checklist, which is described later in this report. The testing checklist contains many of the technical requirements from the House of Quality. This ensures that the testing process meets the consumer demands.

Chapter 3: Background on Sound

3.1 Decibels and Pascals

Decibel (dB) is the scale of loudness of sounds and used to measure sound level. It is a logarithmic way of describing a ratio. Sound pressure is measured in Pascals (Pa) or microPascals (μPa) and is the amplitude of sound. When using dB to give the sound level for a single sound rather than a ratio, a reference level is required. For sound pressure, the reference level for air is usually chosen as 20 microPascals. Table 3.1 shows sound pressure converted to sound pressure level with examples.

Table 3.1: Sound Pressure and Level with Examples

Sound Pressure (microPascals)	Sound Level (dB)	Example
200,000,000	140	Threshold of pain
	130	Riveting on steel plate
20,000,000	120	Pneumatic drill
	110	Loud car horn at 1 m
2,000,000	100	Alarm clock at 1 m
	90	Inside underground train
200,000	80	Inside bus
	70	Street-corner traffic
20,000	60	Conversational speech
	50	Business office
2000	40	Living room
	30	Bedroom at night
200	20	Broadcasting studio
	10	Normal breathing
20	0	Threshold of hearing (at 1 kHz)

The relationship between sound pressure and sound pressure level is:

$$Sound\ Pressure\ Level\ (dB) = 10\ log\left(\frac{p^2}{{p_{reference}}^2}\right) = 20\ log\left(\frac{p}{p_{reference}}\right)$$

Equation 3.1

Where:

p is sound pressure, and

$p_{reference}$ is the sound pressure of the reference level.

When there is the combination of two or more sound pressure levels at the same location, it is called decibel addition. For example, if the noise from one bus resulted in a sound pressure level of 70 dB, the noise from two buses would be 73 dB. Example is shown in Equation 3.2.

$$10\log_{10}(2p^2/p_{ref}^2) = 10\log_{10}(p^2/p_{ref}^2) + 10\log_{10}(2) = 10\log_{10}(p^2/p_{ref}^2) + 3$$

Equation 3.2

3.2 Frequency

The frequency of a sound is the number of oscillations of a sound wave in 1 second. The unit of measurement is hertz (Hz) and the dimensions are per time (t^{-1}). The frequency of a sound increases as the number of oscillations per second increase. The frequency is 1 Hz when one oscillation occurs in 1 second. When 1,000 oscillations occur in 1 second, the frequency is 1,000 Hz, or 1 kHz. Sound frequency (f) in hertz is related to wavelength (λ) in ft and sound velocity (c) in ft per second, and the equation is:

$$f = \frac{c}{\lambda}$$

Equation 3.3

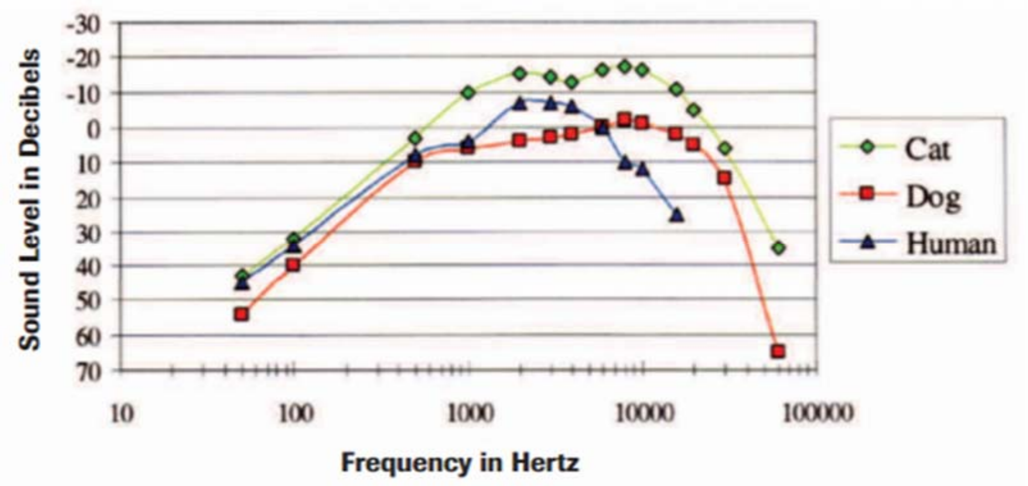


Figure 3.1: Hearing Sensitivity
Source: Bacou-Dalloz Hearing Safety Group (2005)

Figure 3.1 shows the measured hearing sensitivity for a cat and dog compared with a human. Humans have hearing that is most sensitive for soft tones in the mid to high frequencies of the chart, but less sensitive in the low frequencies. At very loud tones, the sensitivity of the human ear has difficulty distinguishing differences in loudness between a low frequency 80 Hz tone and a high-frequency 4,000 Hz tone. To the human ear, they sound equally loud. Thus, in high noise levels, the loudness sensitivity of the ear is quite flat (Joutsenvirta, 2009). Sound frequency between 20 and 20,000 Hz are interpreted as sound by a normal healthy person. Humans can hear best from 1,000 to 5,000 Hz.

3.3 Weighting Scales

There are A-, B-, and C-weighting scales used in noise measurement. A-weighting is the most commonly used weighting scale in transit noise measurement. Because the A-weighting curve in Figure 3.2 is very similar to the human hearing sensitivity curve in Figure 3.1, A-weighted sound level is considered best to represent the human response. A-weighted sound levels are measured in dBA and the letter “A” indicates that the sound has been filtered to reduce the strength of very low and very high frequency sounds. Without setting on A-weighting, a sound level meter will respond to the sound that people cannot hear such as high- and low-frequency sound. B-weighting is the frequency sensitivity of the human ear at moderate levels and used in the past for predicting performance of loudspeakers and stereos. C-weighting is the frequency sensitivity of the human ear at very high noise levels.

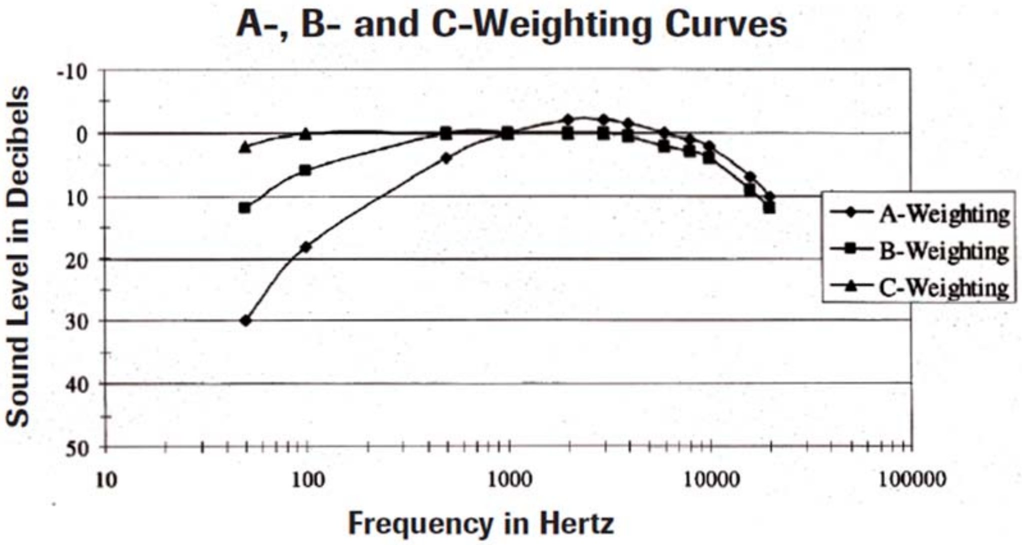


Figure 3.2: Frequency Weighting Curves
Source: Bacou-Dalloz Hearing Safety Group (2005)

According to Hanson, Towers, and Meister (2006), A-weighting scale will be used for this measurement testing because:

1. It can be easily measured.
2. It approximates human ear’s sensitivity to sounds of different frequencies.
3. It matches attitudinal-survey tests of annoyance better than do other weighting scales.
4. It has been in use since the early 1930s.
5. It is endorsed as the proper basic scale for environmental noise by nearly every agency concerned with community noise throughout the world.

3.4 Maximum, Minimum, Equivalent, and Peak Sound Level

The letter "L" indicates Sound Level. L_{max} is the highest root mean square (RMS) sound pressure level within the measuring period. L_{min} is the lowest RMS sound pressure level within the measuring period. L_{eq} is equivalent RMS sound pressure level measured over a period of time. Peak level is the crest of the sound pressure within the measuring period and it is not RMS value. The reason for using RMS values is it provides a clearer understanding of a noise level which makes calculations and measurements easier for a noise source waveform, which is constantly changing in its magnitude (Castle Group, n.d.). Figure 3.3 shows L_{peak} is the crest of the sound pressure and is not RMS value.

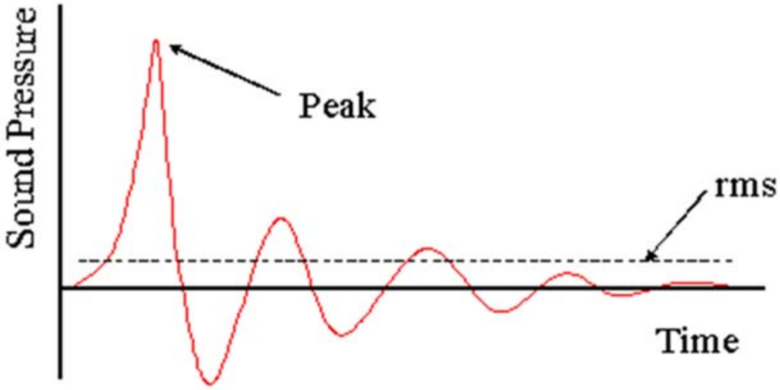


Figure 3.3: Sound Pressure vs. Time
Source: Castle Group (n.d.)

Figure 3.4 is a sound level versus time graph example. It was measured by the Canadian Transportation Agency. It shows L_{max} and L_{eq} values in the graph that their sound level meter measured. Not shown on the graph is L_{min}, but it is the lowest point and can be estimated at about 43 dBA at 60 seconds.

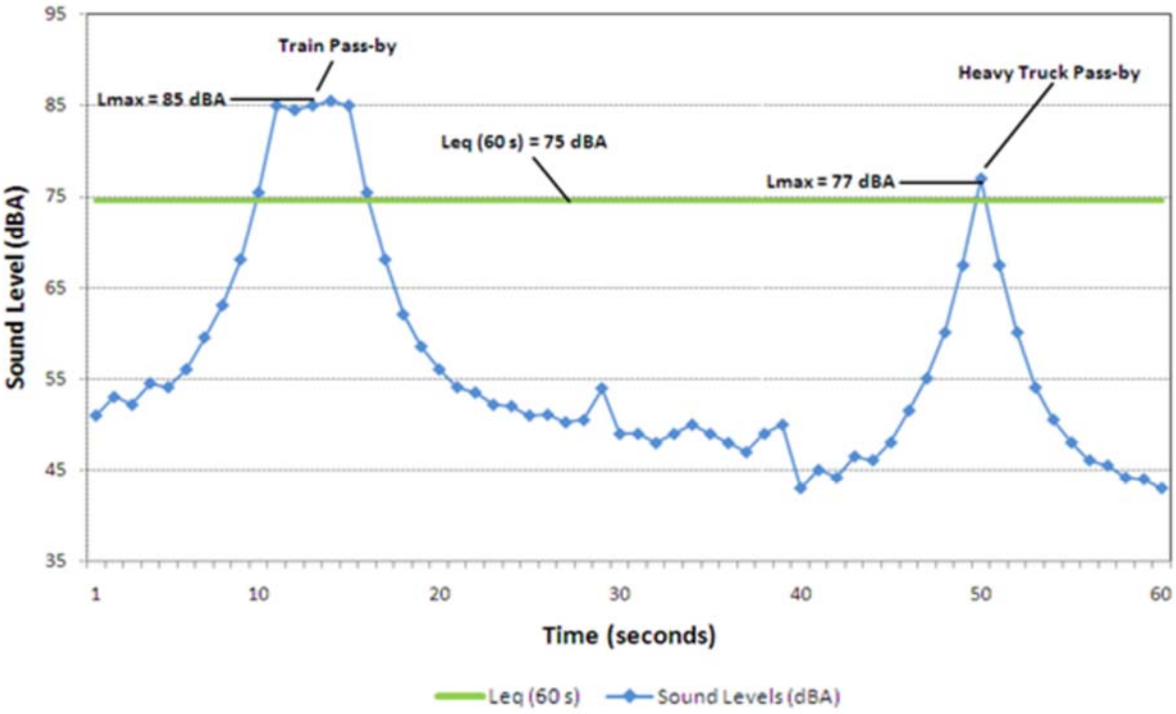


Figure 3.4: Sound Level vs. Time
Source: Canadian Transportation Agency (2011)

In transit noise measurement testing, as a vehicle approaches and passes by, the A-weighted sound level rises, reaches a maximum, and then fades into the background noise. When the A-weighted sound level reaches a maximum during the passby, it is called the maximum A-weighted sound level (LAF_{max}).

Chapter 4: Methods for Measuring Road Noise

4.1 On-Board Sound Intensity Method (OBSI)

The On-Board Sound Intensity (OBSI) method measures tire-pavement noise using microphones. A sound intensity probe configuration is mounted to the outside of a vehicle, near the tire-pavement interface. The OBSI measurement hardware consists of a probe held next to the tire-pavement contact surface by a fixture attached to the wheel studs of the test tire. The microphone is cabled to the interior of the vehicle where the signals are simultaneously captured on a recorder and processed by a real time-analyzer.

General Motors developed the OBSI method for tire sound research in the 1980s. In recent years, standardization efforts were initiated and the acronym OBSI was adopted. The OBSI method, first standardized by the American Association of State Highway and Transportation Officials (AASHTO) in 2008, has undergone annual updates as provisional standard TP 76. Early versions of the test procedure used a fixture that positioned only a single sound intensity probe. Most OBSI systems in use today employ a dual-probe; one positioned at the leading edge and a second positioned at the trailing edge of the tire.

Figure 4.1: OBSI Configuration with a Dual Probe (left) and Single Probe (right)
Source: Lodico (2010)

During OBSI testing, the location of sound intensity probes is important. Tire-pavement noise can be well described by measuring at two principal locations near the tire-pavement interface. The leading and trailing edge of the contact surface define these locations. The OBSI test procedure specifies that the probes be located close to these locations: more specifically, 4 inches horizontal from the tire sidewall, 3 inches vertical above the pavement, and 4.125 inches in front and behind the axle centerline. A special fixture mounts the probes at the specified locations. Figure 4.2 shows dual sound intensity probe position from the side view and the top view.

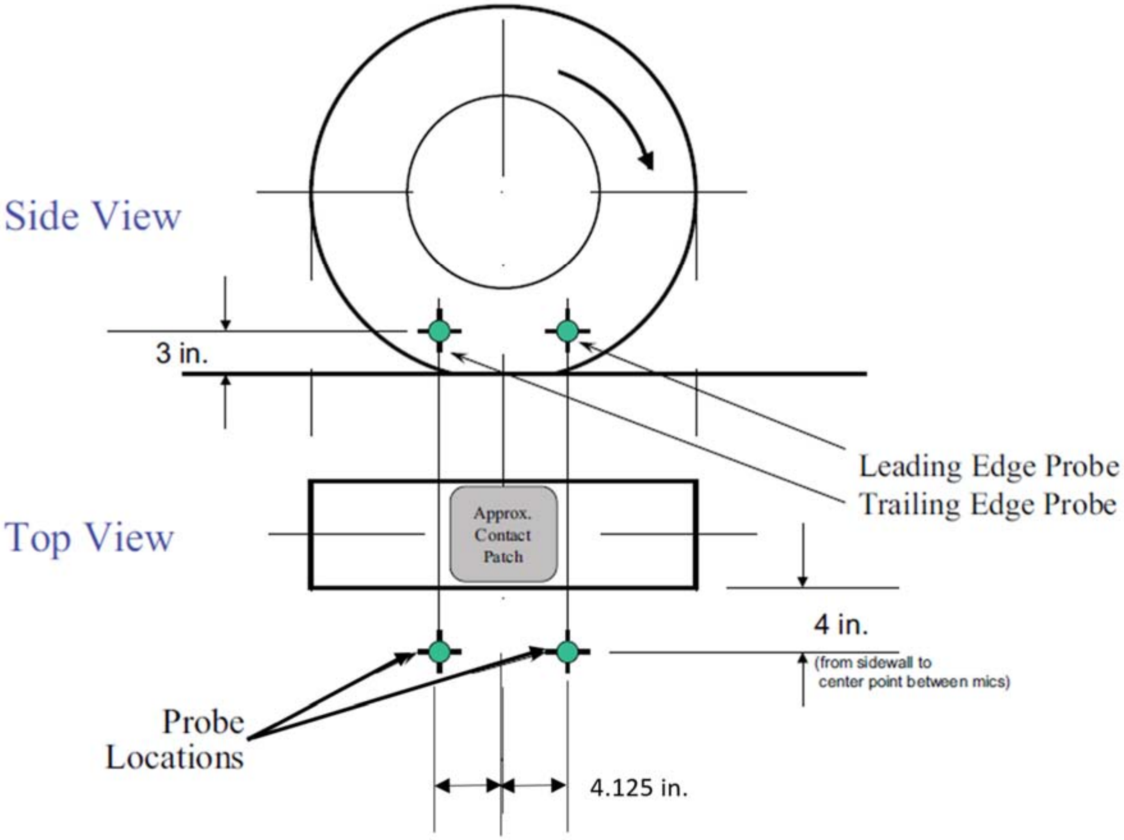


Figure 4.2: Dual Sound Intensity Probe Position
Source: Rasmussen, Sohaney, and Wiegand (2011)

During testing, test tire, vehicle speed, and vehicle noise must be controlled (Rasmussen, Sohaney, & Wiegand, 2011). For the test tire, the current OBSI standard specifies use of an ASTM F2493 Standard Reference Test Tire (SRTT; P225/60R16). For vehicle speed, the OBSI standard specifies a vehicle speed of 60 mph. In situations where safety does not permit this speed, the variance must be clearly noted. For small variations in speed, a correction factor can be applied during post processing. For larger variations, error can be introduced if a single correction is applied. The relationship between speed and sound level varies significantly depending on the specific combination of tire and pavement surface. For vehicle noise, the test vehicle must not make any abnormal noise that could contaminate the tire-pavement noise measurement. Examples include noise caused by foreign matter on the tire tread, suspension/shock squeak, wheel bearing squeal, and brake noises. The AASHTO TP 76 OBSI standard requires test sections that are 440 ft long. At 60 mph, it takes the test vehicle 5 seconds to traverse a test section, and the results are an average over this 5-second interval.

OBSI equipment has great durability. From the research data, it had only one incident in over 70 tests over 3.5 years (Sexton, 2010). In addition, it eliminates effects of traffic, wind, and ambient sources. OBSI software is not difficult to use for non-experts, but it costs $35,000 for initial equipment and $6,000 for installation and alignment of the hardware.

4.2 Close Proximity Measurement (CPX)

Close Proximity (CPX) is a standardized (ISO 11819-2) method of measuring tire-pavement noise. In the late 1990s, a towed trailer setup for measuring tire-pavement noise was developed in Europe (Wang, Shores, Botts, & Hibbett, 2011). The traditional CPX test utilizes a test tire mounted inside a small trailer; often the trailer is enclosed to provide a windscreen (Figure 4.3). CPX allows for dynamic road noise testing and is not impacted by other traffic as much as pass-by noise measurement. CPX has been used in the United States, Korea, South America, Canada, and European countries.

Figure 4.3: Enclosed CPX Trailer
Source: Trevino and Dossey (2009)

With CPX, one or more microphones are placed close to the test tire to measure noise level (Figure 4.4); the noise signal picked up by the microphones is sent to a laptop inside the vehicle and can be processed in real time. This system has been proven to provide accurate and repeatable measurements (Trevino & Dossey, 2009).

Figure 4.4: CPX Microphone Placement and Trailer Interior
Source: Trevino and Dossey (2009)

Trailer CPX noise, measured primarily from a single tire, can serve only as a relative representation of overall traffic noise. The trailer does not give an accurate representation of the weight a vehicle places on the tire. It is also unclear how much the trailer enclosure traps sound waves and affects the measurement. Still, CPX is a proven tool for estimating noise levels between different types of pavement. Open CPX trailers have also been used for data collection (Figure 4.5).

Figure 4.5: Example of Open-Air CPX Trailer
Source: Trevino and Dossey (2009)

A 2012 study created a new method of measurement called "tube CPX" (Slama, 2012). This method requires fabricating a fiberglass horn (Figure 4.6) to place in the wheel well of a vehicle; this horn attaches to a tube that contains the microphone isolated from vibrations. This method significantly lowered material costs versus trailer CPX and has shown results consistent with both pass-by and trailer CPX, but it is not as easy to transfer among different vehicles and would require design tests to determine the best horn shape and microphone location.

Figure 4.6: Clockwise from top-left: CPX Tube Mounted on Vehicle; Close-Up of CPX Tube; Test Vehicle; Second Angle of Mounted CPX Tube
Source: Slama (2012)

4.3 Statistical Pass-By Method (SPB)

The statistical pass-by method consists of placing microphones at a defined distance from the vehicle path at the side of the roadway (Figure 4.7). In Europe, the ISO Standard 11819-1 calls for placing microphones 25 feet from the center of the vehicle lane at a height of 5 feet above the pavement. It also requires obtaining the noise characteristics and speed of 180 vehicles (100 automobiles and 80 dual-axle and multi-axle trucks).

The use of ISO 1680:2013 as a noise test code ensures the reproducibility of the determination of the noise emission characteristics within specified limits determined by the grade of accuracy of the basic noise measurement method used. Noise measurement methods allowed by ISO 1680:2013 are precision methods (Grade 1), engineering methods (Grade 2), and survey methods (Grade 3). Grade 1 is the most accurate and reliable.

The Federal Highway Administration procedure developed by the Volpe Transportation Systems Center calls for the placement of a microphone or microphones 50 feet (instead of 25 feet) from the center of the travel lane. The ground surface within the measurement area must be representative of acoustically soft terrain; the site must be located away from known noise surfaces and is to exhibit constant-speed roadway traffic operating under cruise conditions. The testing conditions required to conduct these measurements are very restrictive. The roadway must be essentially straight and level, there is a limit on the background noise, no acoustically reflective surfaces can be within 30 feet of the microphone position, and the traffic must be moving at a relatively uniform speed. The result of these restrictions is that a limited number of pavement surfaces can be tested economically.

The cost can vary depending on the style of recording equipment. The noise monitoring systems come in three different setups: permanent installations, semi-permanent and portable, or hand-held and attended. Each setup will require a different amount of time and effort to set up, the permanent and semi-permanent options being slightly more elaborate than the hand-held. The systems are all similar with a user-friendly platform for measuring noise levels. The handheld as well as the semi portable systems both come in Grade 1 which meets ISO regulations, but will not be as detailed or sophisticated as the permanent systems.

Figure 4.7: SPB Roadside Setup
Source: Sandberg (2014)

Some of the advantages of using the SPB method are the ability to measure the complete noise output of road vehicles, test realistic listening situations, and collect data from all vehicles instead of just one; it also provides a large statistical sample, is accurate, and in a form that allows future studies to be repeated with ease.

Some of the disadvantages that come along with using the SPB method are the fact that it is a spot method which requires large, straight, level segments of road to test (~100 meters). Conditions from the surface to the surroundings must be acoustically controlled with no obstacles in the way, as traffic density and variation of speeds from vehicles can lead to be time consuming.

Despite some drawbacks, the SPB method is currently the most established and widely used method for classification. If test sites can be constructed or found that meet all the necessary requirements, it appears to be the method of choice. The SPB method is especially suitable for general classification purposes and whenever the complete road traffic noise emission, including engine noise and tire/road noise from heavy vehicles, is important.

The Minnesota Department of Transportation (MDOT) conducted a study similar to this project where they used the SPB method and gathered the following, "The SPB measurements showed that a so-called innovative grind pavement surface was quieter than the other measured pavement surfaces. This difference was clear for four wheeled passenger vehicles. It was also shown to be quieter for dual-axle and multi-axle heavy vehicles, but some specific comparisons are not conclusive due to a small sample size, particularly for dual-axle heavy vehicles" (Hanson & Waller, 2005).

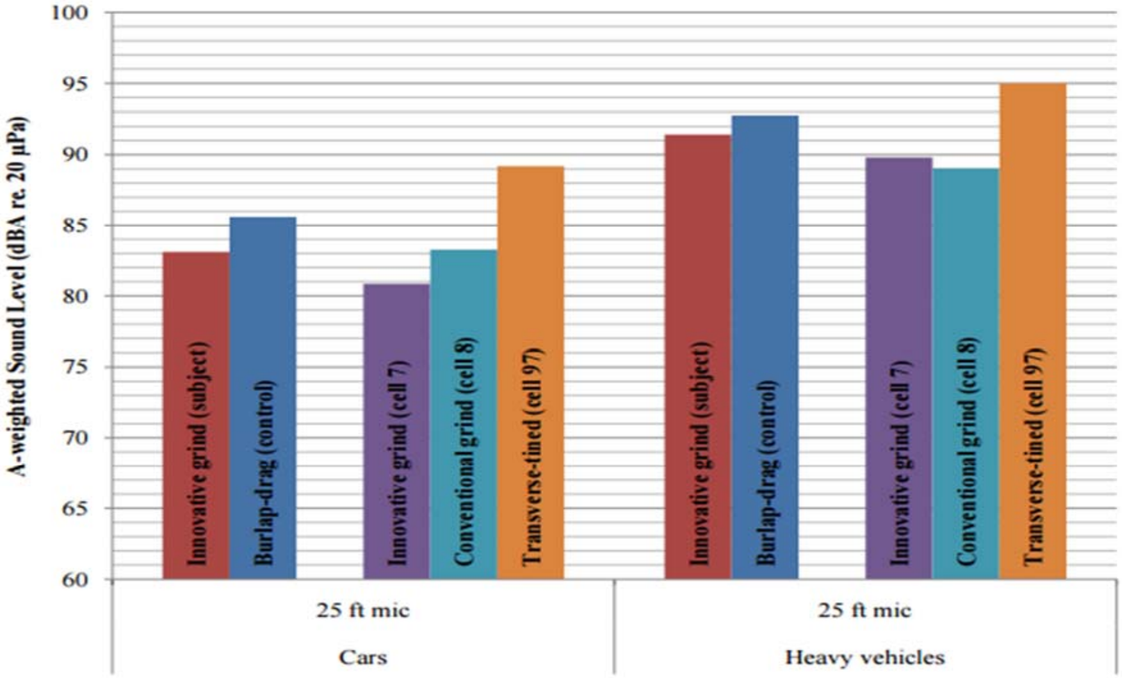


Figure 4.8: SPB Overall Measurements from MDOT
Source: Dick, Izevbekhai, and Casey (2010)

Figure 4.8 is a comparison of the measurements gathered in Minnesota. The measurements were based off an innovative grind pavement, a test pavement, and a regular strip of highway. The graph shows that the innovative grind pavement is quieter than the other pavement specimens.

The significance of the Minnesota Department of Transportation report is that they utilized the SPB method to prove that different pavements can result in quieter road noise.

Chapter 5: Equipment

5.1 Larson Davis SoundTrack LxT

Figures 5.1, 5.2, and 5.3 show the Larson Davis SoundTrack LxT purchased by the Senior Design Team to allow the team ready access, at their schedule, to the proper equipment. Initial testing was performed with a Larson Davis 720 Sound Level Meter. An accessory kit came with it that includes a calibrator, windscreen, USB cables, calibration certificates, manual CD, and G4 software CD. The order verification and packing list are in Appendix B.

Figure 5.1: SoundTrack LxT and Accessory Kit

Figure 5.2: SoundTrack LxT SLM

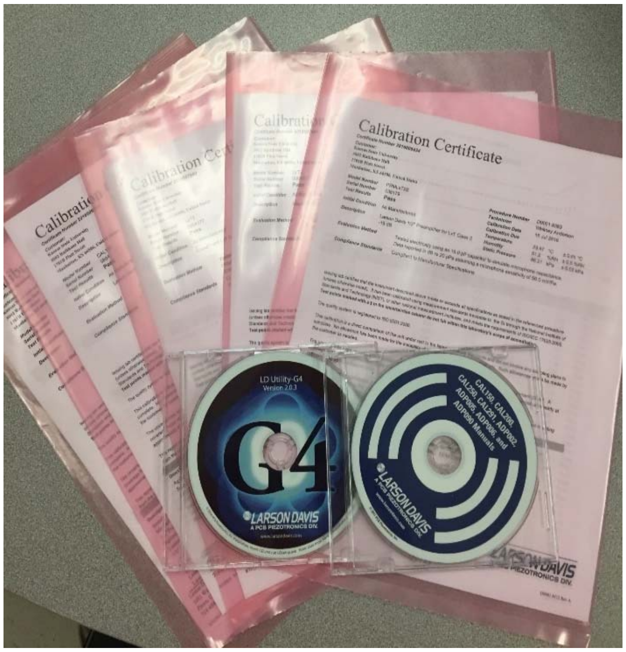
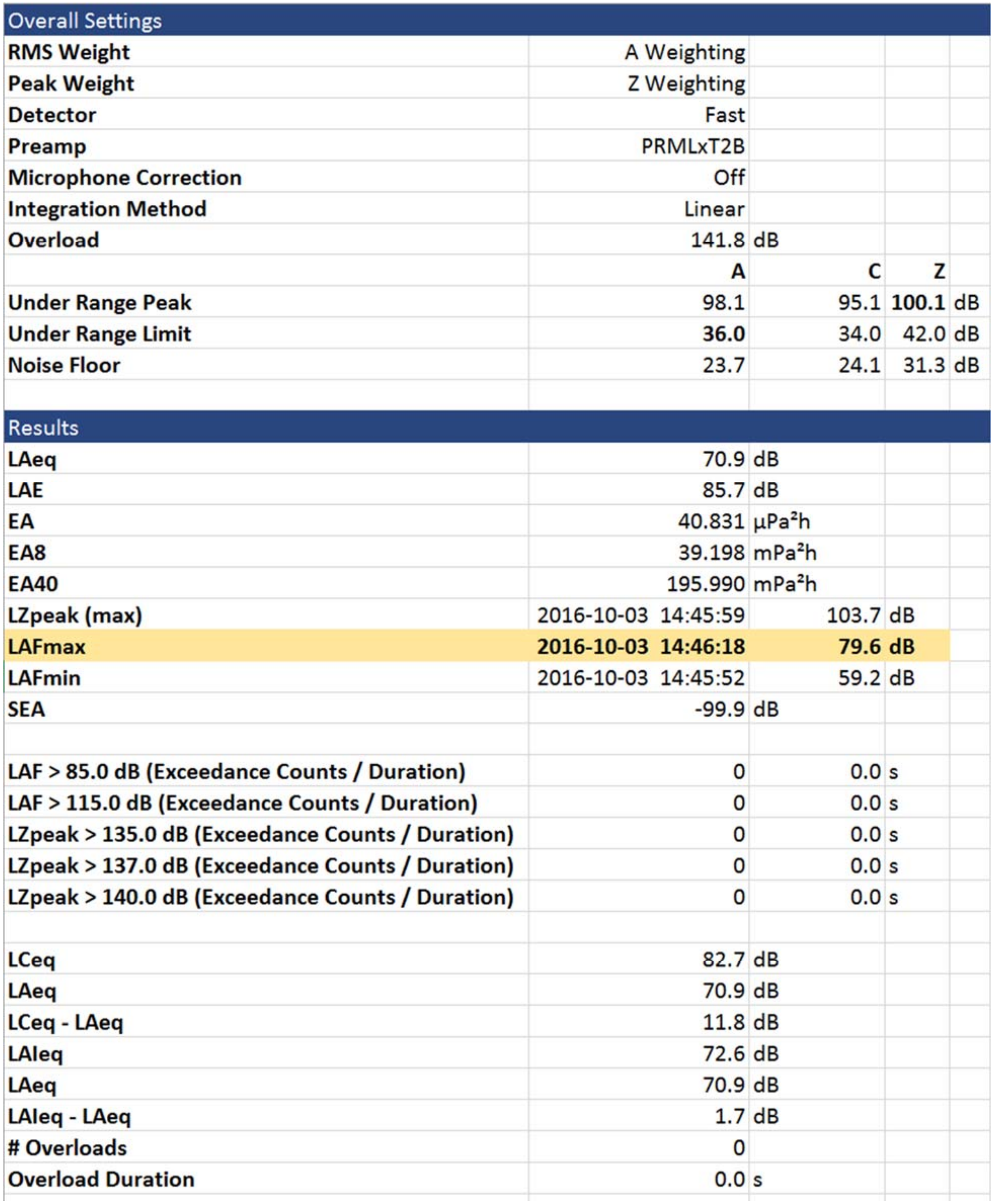


Figure 5.3: Calibration Certificate

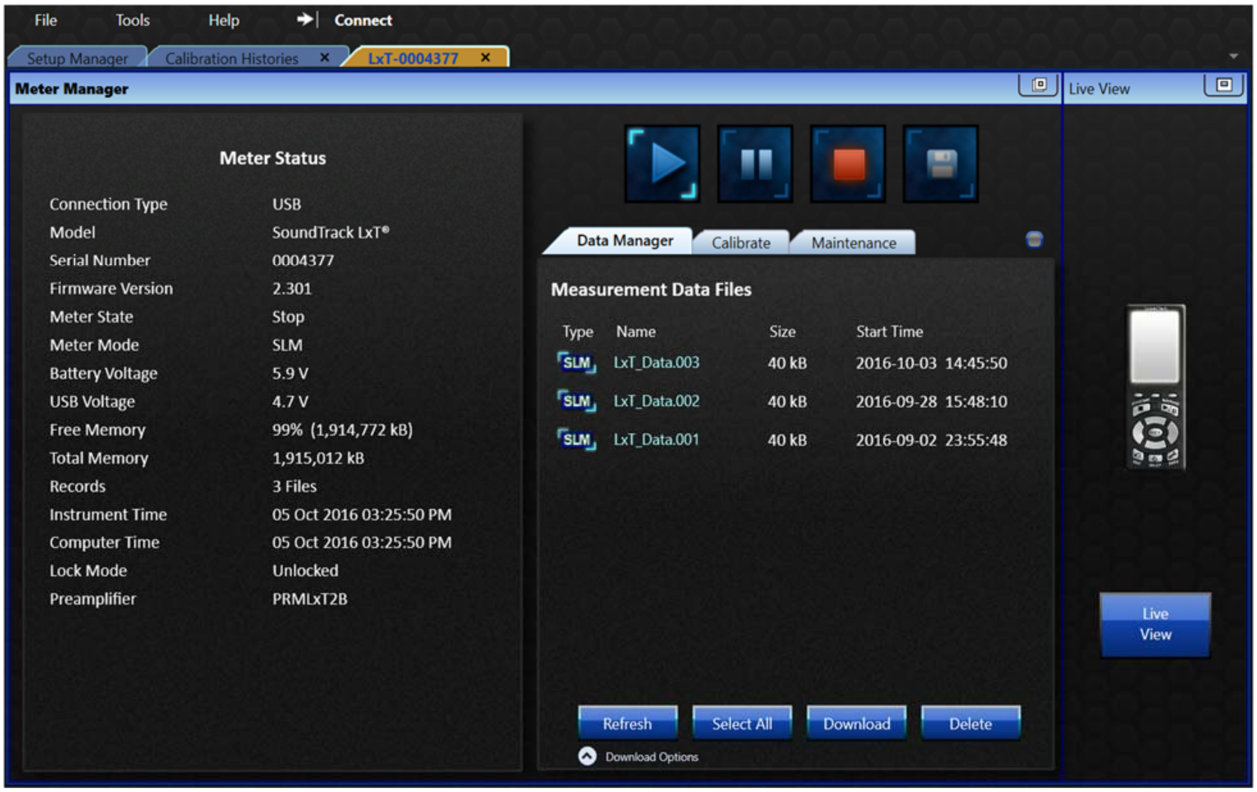
5.2 SLM Utility-G4 Software

SLM Utility-G4 software is used for managing SoundTrack LxT setups and data files. This software can import sound data files and translate them for viewing and manipulation in spreadsheets and graphs. The spreadsheet example is in Figure 5.4. For SPB measurement testing, LAF_{max} (Sound Level, A-weighted, Fast, Maximum) will be recorded as data. The reason is that for noise compliance tests of transient sources, such as moving transit vehicles under controlled conditions with smooth wheel and rail conditions, L_{max} is typically measured with the sound level meter's switch set on "fast." Figure 5.5 shows the user interface.



Overall Settings				
RMS Weight	A Weighting			
Peak Weight	Z Weighting			
Detector	Fast			
Preamp	PRMLxT2B			
Microphone Correction	Off			
Integration Method	Linear			
Overload	141.8	dB		
	A	**C**	**Z**	
Under Range Peak	98.1	95.1	**100.1**	dB
Under Range Limit	**36.0**	34.0	42.0	dB
Noise Floor	23.7	24.1	31.3	dB
Results				
LAeq	70.9	dB		
LAE	85.7	dB		
EA	40.831	µPa^{2}h		
EA8	39.198	mPa^{2}h		
EA40	195.990	mPa^{2}h		
LZpeak (max)	2016-10-03 14:45:59	103.7	dB	
LAFmax	**2016-10-03 14:46:18**	**79.6**	**dB**	
LAFmin	2016-10-03 14:45:52	59.2	dB	
SEA	-99.9	dB		
LAF > 85.0 dB (Exceedance Counts / Duration)	0	0.0	s	
LAF > 115.0 dB (Exceedance Counts / Duration)	0	0.0	s	
LZpeak > 135.0 dB (Exceedance Counts / Duration)	0	0.0	s	
LZpeak > 137.0 dB (Exceedance Counts / Duration)	0	0.0	s	
LZpeak > 140.0 dB (Exceedance Counts / Duration)	0	0.0	s	
LCeq	82.7	dB		
LAeq	70.9	dB		
LCeq - LAeq	11.8	dB		
LAIeq	72.6	dB		
LAeq	70.9	dB		
LAIeq - LAeq	1.7	dB		
# Overloads	0			
Overload Duration	0.0	s		

Figure 5.4: Data Spreadsheet Example



Meter Status

Connection Type	USB
Model	SoundTrack LxT®
Serial Number	0004377
Firmware Version	2.301
Meter State	Stop
Meter Mode	SLM
Battery Voltage	5.9 V
USB Voltage	4.7 V
Free Memory	99% (1,914,772 kB)
Total Memory	1,915,012 kB
Records	3 Files
Instrument Time	05 Oct 2016 03:25:50 PM
Computer Time	05 Oct 2016 03:25:50 PM
Lock Mode	Unlocked
Preamplifier	PRMLxT2B

Measurement Data Files

Type	Name	Size	Start Time
SLM	LxT_Data.003	40 kB	2016-10-03 14:45:50
SLM	LxT_Data.002	40 kB	2016-09-28 15:48:10
SLM	LxT_Data.001	40 kB	2016-09-02 23:55:48

Figure 5.5: Software User Interface

5.3 Tripod and LxT Assembly

In order to elevate and stabilize the LxT, the team utilized an existing camera tripod. In order to add additional height and mount the LxT, the team fabricated an extension that attached to existing hardware on the tripod. Figure 5.6 shows the final tripod and LxT assembly.

Figure 5.6: Final Tripod and LxT Assembly

Chapter 6: Testing

6.1 Method of Choice

After carefully evaluating the three different methods researched to evaluate HFS, the group concluded that the Statistical Pass-By Method was the best choice for this project. This method is the most cost-efficient since you only have to acquire a sound level meter, which then can be used anytime at any location in the future. Another advantage is that it is simple to use. This will lead to an additional savings in the future by not having to hire specialized technicians or have engineers on standby to run new tests. One more reason why this method trumps the others is the fact that the SPB is known as the ISO 11819-1 Traffic Noise Measurement Method, which is an international standard overseen by a worldwide federation. This decision was made by comparing the research the Senior Design Team had gathered to the list of priorities created by the KDOT representatives.

6.2 Preliminary Testing

Prior to the group being able to use the Larson Davis 720 Sound Level Meter, it was necessary to get the supplied software working. This task was a lot more daunting than it sounds, because the 720 is an obsolete unit. The software provided needed a computer that was running the 32-bit version of Windows 7. None of the computers available at Kansas State University had proper software installed. The Senior Design Team worked with engineering tech support to help us understand how to get the software to work. The first task was to source a computer that had a serial port so the 720 SLM could be plugged in. Then the team downloaded VirtualBox allowing us to open a second operating system within a computer running Windows 7 (32-bit). From there, the team was able to open the software and communicate with the device.

On April 14th, 2016, the team went out and tested a street in Manhattan, Kansas, as practice. The street chosen to test was Juliette Street (Figure 6.1) due to the unique road surface. Being a brick street, the road is notably louder to travel on than normal concrete. The team tested this street in two locations. The first location was the brick portion and the second was concrete pavement. Both tests were performed at the same speed. The team used a 2016 Toyota Corolla as the test vehicle. The test vehicle passed by the testing set up three times at each location at

30 mph. The testers, positioned 25 feet away from the centerline of the passing vehicle, had the Larson Davis 720 Sound Probe positioned 4 feet above ground level. From the measurements recorded, the brick resulted in an average of 70 dB while the concrete paved road averaged 62 dB. So according to the decibel logarithmic scale, the brick portion was almost twice as loud when compared to the normal concrete portion of the street.

Figure 6.1: Juliette Pavement Surface

Figure 6.2: Larson Davis 720

6.3 Test Surface

To perform the experimental sound measurement, a test location was created on US Highway 24 between Manhattan and Wamego. A 300-ft section of the High Friction Surface (HFS) constructed on an adjacent section of the highway was identified as the control. Materials were supplied by Transpo Industries and Flint Rock, Inc., and construction services were provided by PCI. and KDOT. Appendix A provides a listing of material needed.

Figure 6.3: Test Strip Location
Source: Google Maps (2016)

The HFS is comprised of an aggregate (flint rock) and an epoxy polymer, E-Bond 526s, Thixotropic Epoxy for High Friction Surfacing and Polymer Overlay, from Transpo Industries. E-Bond 526s is a single layer 100% solids single lift high friction/anti-skid epoxy system for asphalt, concrete, and other surfaces. Its normal application is enhancing the high-friction/anti-skid properties of the driving surface, reducing accidents and fatalities by improving braking distances. It also helps to reduce skidding and hydroplaning and improves driver awareness (Transpo Industries, Inc., 2018). HFS is recommended for horizontal curves and ramps, intersections/intersection approaches, steep grades, roundabouts, and other areas where improved safety is desired. See Appendix A for the physical properties of the epoxy.

The application of the HFS began with shot blasting of the road surface by PCI. Following the preparation of the roadway, the KDOT workers applied the epoxy. The epoxy was first mixed in 30-gallon containers and then placed on the road at a minimum application rate of 0.33 gal/yd^2 by using squeegees for even application. Following the spreading of the epoxy, the KDOT workers broadcast the flint rock by hand in an even manner to excess (Figure 6.4).

Figure 6.4: Application of HFS

6.4 Testing Setup

Figure 6.5 illustrates where the SoundTrack LxT was placed in relation to the testing surface. To minimize wind noise and adjacent traffic noise, the tests were performed in the early morning hours. The test vehicle traveled at 60 mph across a 300-ft × 11-ft test strip. A test speed of 60 mph was chosen as it best replicates the typical speed of cars on a highway (which is where this surface would be used if found to be effective in reducing traffic noise). The sound probe is specified to be placed a distance of 25 ft from the centerline of the test strip. This was based on previous tests that have been done by other researchers. In some cases, it will be important to also test distances greater than 25 ft from the centerline of the road in order to test the sound levels where housing areas would be located. The sound probe was positioned 150 ft from the end of the test strip, or approximately the center, as shown in Figure 6.5. This allowed for good reading of the sound of the test car as it approached and moved away from the sound probe. Figure 6.5 is the plan view of the testing layout.

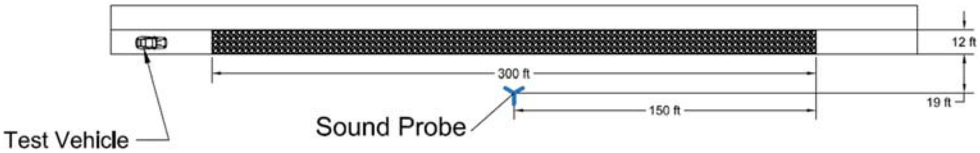


Figure 6.5: Testing Diagram Top View

Prior to performing preliminary tests, the team needed to survey the site in order to determine proper microphone stand height. To properly survey the site, the team needed to measure the distance from the center of the lane that the microphone will be placed and then utilize a level and leveling rod (pictured in Figure 6.6) to accurately measure and record the elevation height change from the center of the lane to the microphone stand position. The team acquired surveying equipment from the Kansas State Civil Engineering Department. In the surveying test, the team measured an elevation of 4.23 ft above the center of the lane to be level with 5.12 ft above the microphone location. These numbers indicate that when performing the test, the microphone must be elevated 5.89 ft above the ground in order to get the desired 5 ft above the centerline of the roadway. Figures 6.7 and 6.8 show the test site.

Figure 6.6: Survey Equipment

Figure 6.7: Test Strip and Northern Ditch

Figure 6.8: Test Strip and Shoulder

The sound probe is placed 5 ft above the centerline of the test lane surface. This decision was based off KDOT's previous testing setup and the ISO standard. The sound probe is mounted to a tripod at the desired 5 ft height above the pavement. In addition to the sound testing equipment, testers needed a tripod for mounting the LxT for the testing as well as a laptop to view real-time data. While testing, the team was wearing high visibility vests to increase their visibility to passing traffic. Figure 6.9 is the testing profile view, which illustrates the sound probe placement in regard to the test surface. Depending on the time of day testing was performed, the testers considered other items such as flashlights to illuminate equipment and improve visibility. Two team members were positioned with the equipment to monitor both the LxT and the laptop to start/stop the data at the proper times. Minimizing the members present near the LxT minimized outside noise sources that could affect recorded data.

After measuring the test location, the team conducted a reference test of the adjacent untreated pavement. This was performed to compare the sound levels measured from the test location to a typical pavement. The test for the reference location used the same setup procedure as the HFS test strip.

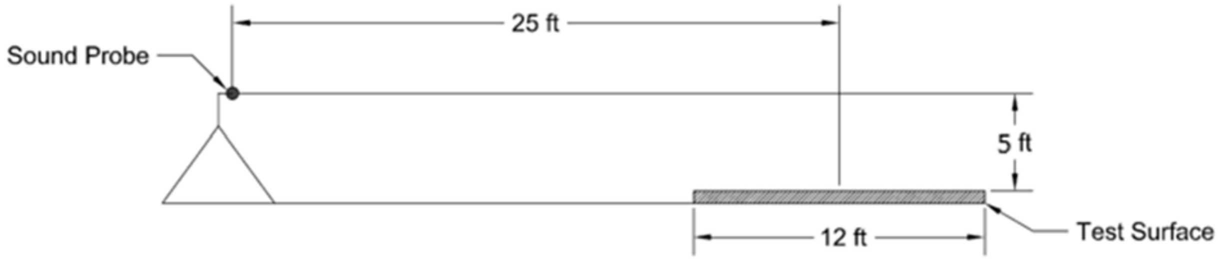


Figure 6.9: Testing Diagram Side View
(Note: Pavement will not be flat as shown; a slight crown is to be expected for water drainage)

6.5 Testing Procedure

To ensure that the testing is consistent, the team created a checklist to record information about each test. This checklist combines the engineering parameters from the QFD along with other important information such as what type of car is used and whether other traffic interferences exist. Figure 6.12 is an example of the checklist, with the full completed testing lists from each test session found in Appendix C.

Wind speed and traffic levels are both important things to consider during noise testing. The team found that evening testing gave the best combination of low wind levels and low traffic levels. If wind is present, the wind noise skews the data, while heavy traffic makes it difficult to record just the test vehicle going past the microphone.

Previous to testing, both the HFS and regular pavement were surveyed in order to get the height of 5 ft for the sound probe above the centerline of the road at 25 ft away from the centerline of the pavement. This is performed with a level. An adjustable tripod was used for the testing to allow for easy adjustment. KDOT was informed when and where testing would occur. Figures 6.10 and 6.11 show the instrumentation set-up.

Equipment used for testing:

- Tripod
- Sound Probe (Windscreen, cables, etc.)
- Microphone
- Tape Measure
- Safety Vests
- Testing Checklists
- Pen
- Test Vehicle
- Laptop (optional)
- Cell Phone or Walkie Talkies for communication
- Hearing Protection

Procedure for conducting test:

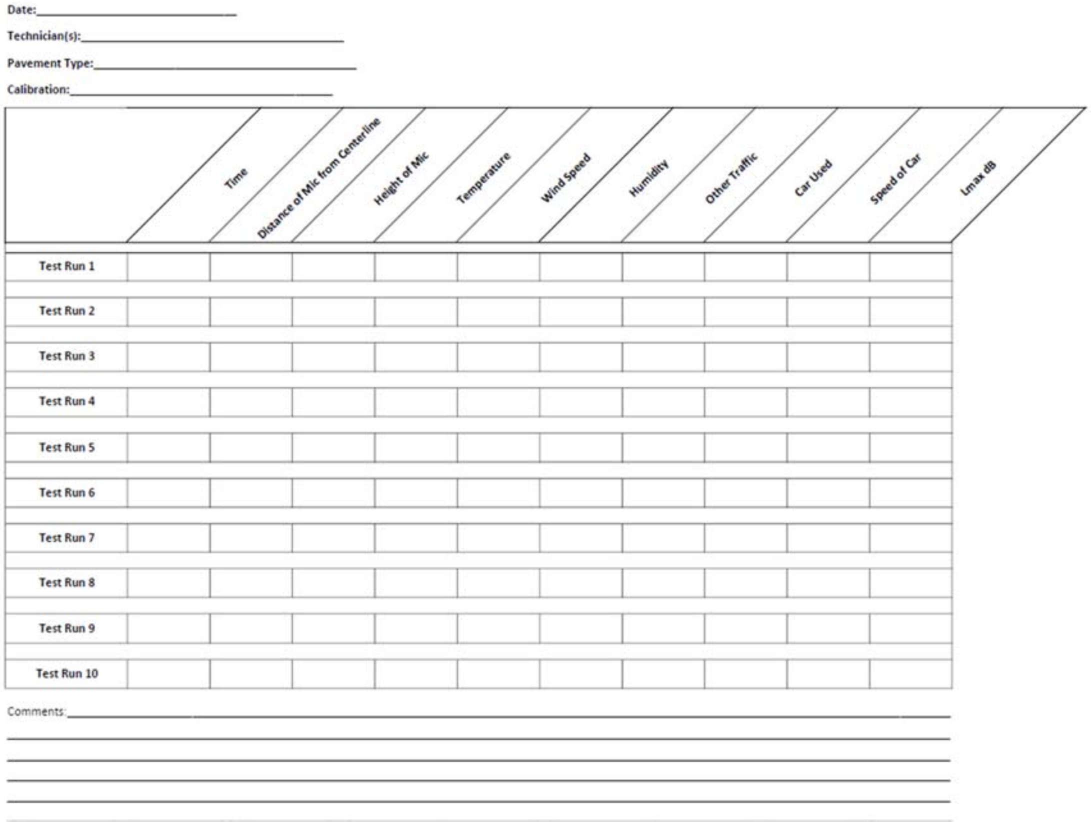
1. Calibrate SoundTrack LxT per instruction manual. (Recommend this be performed daily prior to arriving at test site.)
2. Fill out testing checklist found in Appendix C (Temp, humidity, time, distance from centerline, height of microphone, and wind speed). Recheck temperature, humidity, and wind speed periodically.
3. Set up the testing equipment 25 feet from the center of the test lane and 5 feet above the centerline.
4. Conduct test run to make sure equipment is working properly.
5. Perform 10 tests with the test vehicle:
    a. Wait until no cars are driving on the adjacent lane before performing tests to prevent contamination from the adjacent lane.
    b. Set the cruise control to 60 mph and confirm the speed with the speed sign located on the shoulder.

    c. Wait until the test vehicle has passed a marker located 50 ft before the test strip before taking measurements with the sound probe.
    d. After each test, fill out remaining checklist blanks (Car used, speed of car, other traffic, measured decibel level). Note: recheck temperature and humidity every three tests.

6. Relocate the test equipment to the reference test strip, verifying proper distance and height measurements from center of the test strip.
7. Conduct test run to make sure equipment is working properly.
8. Fill out testing checklist for reference strip test (Temperature, humidity, time, distance from centerline, height of microphone, and wind speed).
9. Repeat Step 5 for reference test strip.
10. Remove all test equipment from the testing site. Mark tripod location for future site testing.
11. Save all raw data for later analysis.

Figure 6.10: Mason Stewart and Ethan Linden Preparing the Tripod for Testing

Figure 6.11: Ethan Linden Preparing to Take Data



Date:________________________

Technician(s):________________________

Pavement Type:________________________

Calibration:________________________

	Time	Distance of Mic from Centerline	Height of Mic	Temperature	Wind Speed	Humidity	Other Traffic	Car Used	Speed of Car	Lmax dB
Test Run 1										
Test Run 2										
Test Run 3										
Test Run 4										
Test Run 5										
Test Run 6										
Test Run 7										
Test Run 8										
Test Run 9										
Test Run 10										

Comments:________________________

Figure 6.12: Testing Checklist

Chapter 7: Results

7.1 HFS vs. Uncoated Pavement

Table 7.1 includes the data collected from the three tests comparing LAF_{max} of both HFS and the normal pavement. The row that is bold and highlighted corresponds to the highest LAF_{max} recorded for both surfaces. Figure 7.1 is a graphical depiction of the data.

7.1.1 Test 1 (10/27/2016)

For the data taken on the October 27, 2016, a sample rate of 500 ms was selected. The LAF_{max} difference between HFS and the normal pavement was 2.6 dBA.

Table 7.1: HFS vs. Normal Pavement (10/27/2016)

Time (s)	HFS Average (dBA)	Normal Average (dBA)	Difference (dBA)
0.5	71.1	71.2	0.1
1.0	71.4	70.2	-1.3
1.5	72.8	72.7	0.0
2.0	75.5	74.4	-1.1
2.5	79.2	78.8	-0.4
3.0	81.5	84.8	3.3
3.5	**82.3**	**84.9**	**2.6**
4.0	79.0	84.2	5.2
4.5	73.5	79.7	6.1
5.0	70.0	75.3	5.3
5.5	70.4	74.0	3.7

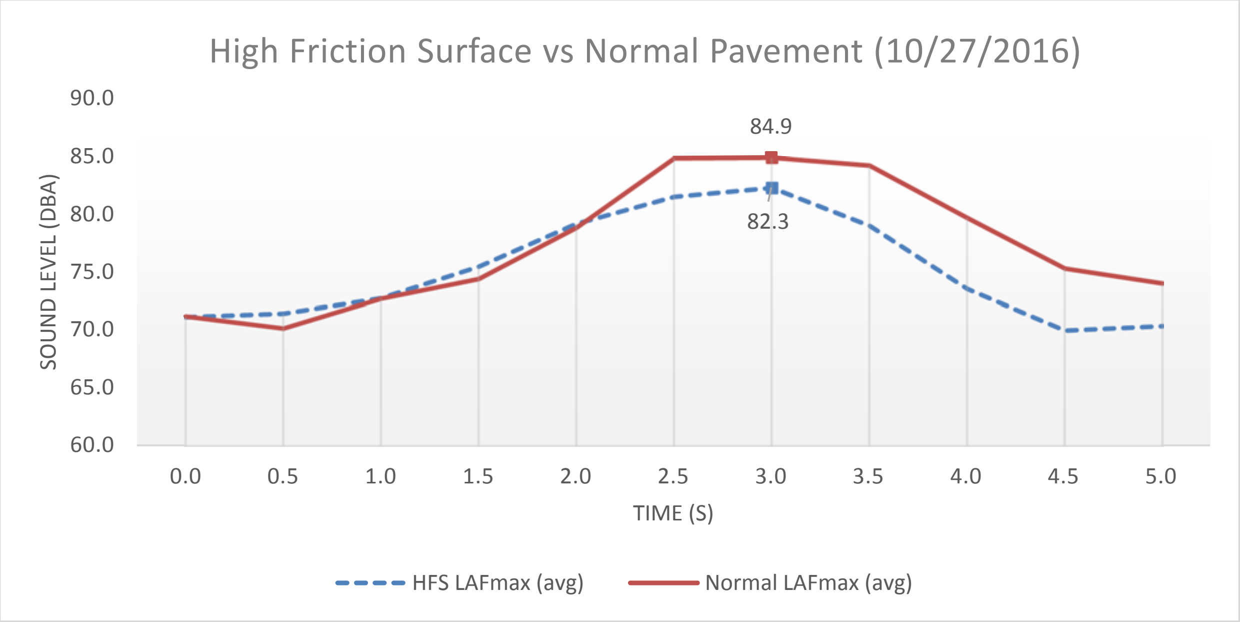


Figure 7.1: Graph of LAF$_{max}$ vs. Time for HFS and Normal Pavement for Test on 10/27/2016

7.1.2 Test 2 (11/03/2016)

For the second test, performed on November 3, 2016, a sample rate of 100 ms was selected to create more data points to better compare the two surfaces. In order to use a sample rate of 100 ms, the Senior Design Team purchased the LxT High-Speed Time History Enhancement. The order verification is located in Appendix B. The LAF$_{max}$ difference between HFS and the normal pavement was 3.1 dBA. Table 7.2 and Figure 7.2 contain the acquired data.

Table 7.2: HFS vs. Normal Pavement (11/03/2016)

Time (s)	HFS LAF_{max} Average (dBA)	Normal LAF_{max} Average (dBA)	Difference (dBA)
0.1	74.0	74.0	0.0
0.2	73.4	74.3	0.9
0.3	73.0	74.4	1.4
0.4	73.1	74.9	1.8
0.5	73.3	75.2	1.9
0.6	74.2	75.9	1.7
0.7	75.1	76.6	1.4
0.8	75.7	77.4	1.7
0.9	76.8	78.1	1.3
1.0	77.9	78.7	0.7
1.1	78.8	79.2	0.4
1.2	79.9	80.1	0.2
1.3	80.4	81.6	1.2
1.4	81.0	83.3	2.2
1.5	81.6	84.2	2.6
1.6	81.7	84.9	3.2
1.7	**82.1**	**85.2**	**3.1**
1.8	81.6	85.0	3.4
1.9	81.2	84.8	3.6
2.0	80.4	84.3	4.0
2.1	79.5	84.0	4.5
2.2	78.8	83.8	5.0
2.3	77.9	83.5	5.7
2.4	76.7	83.0	6.3
2.5	75.6	82.0	6.5
2.6	74.5	81.1	6.6
2.7	73.7	80.1	6.4
2.8	72.9	79.4	6.5
2.9	72.6	78.4	5.8

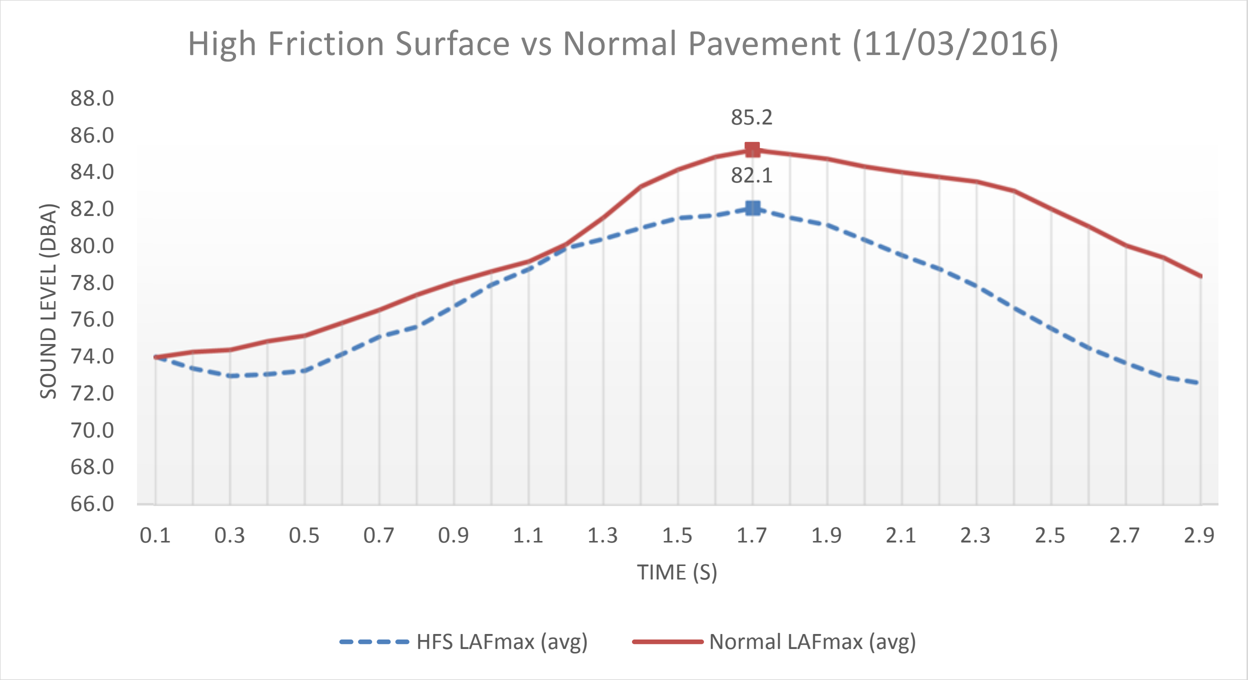


Figure 7.2: Graph of LAF_{max} vs. Time for HFS and Normal Pavement for Test on 11/03/2016

7.1.3 Test 3 (11/14/2016)

For the third test, performed on November 14, 2016, the team used a sample rate of 100 ms. The LAF_{max} difference between HFS and the normal pavement was 2.9 dBA. The test data is contained in Table 7.3 and Figure 7.3.

Table 7.3: HFS vs. Normal Pavement (11/14/2016)

Time (s)	HFS LAF$_{max}$ Average (dBA)	Normal LAF$_{max}$ Average (dBA)	LAF$_{max}$ Difference (dBA)
0.1	74.5	74.1	-0.4
0.2	74.2	74.2	0.0
0.3	74.0	74.6	0.6
0.4	74.0	74.9	0.9
0.5	74.3	76.3	2.0
0.6	74.7	76.6	1.9
0.7	75.7	77.2	1.5
0.8	76.6	77.7	1.1
0.9	77.3	78.2	0.9
1.0	78.4	78.6	0.1
1.1	79.5	79.4	-0.1
1.2	80.1	80.5	0.4
1.3	80.6	82.1	1.5
1.4	81.2	83.0	1.8
1.5	81.5	83.8	2.3
1.6	81.4	84.3	2.9
1.7	**81.9**	**84.8**	**2.9**
1.8	81.7	84.6	3.0
1.9	81.3	84.1	2.8
2.0	80.6	83.8	3.1
2.1	79.8	83.6	3.7
2.2	79.0	83.2	4.2
2.3	78.0	82.9	4.9
2.4	76.9	82.2	5.3
2.5	75.9	81.5	5.6
2.6	75.1	80.7	5.6
2.7	74.4	79.7	5.3
2.8	73.9	78.9	5.0
2.9	73.5	78.1	4.6

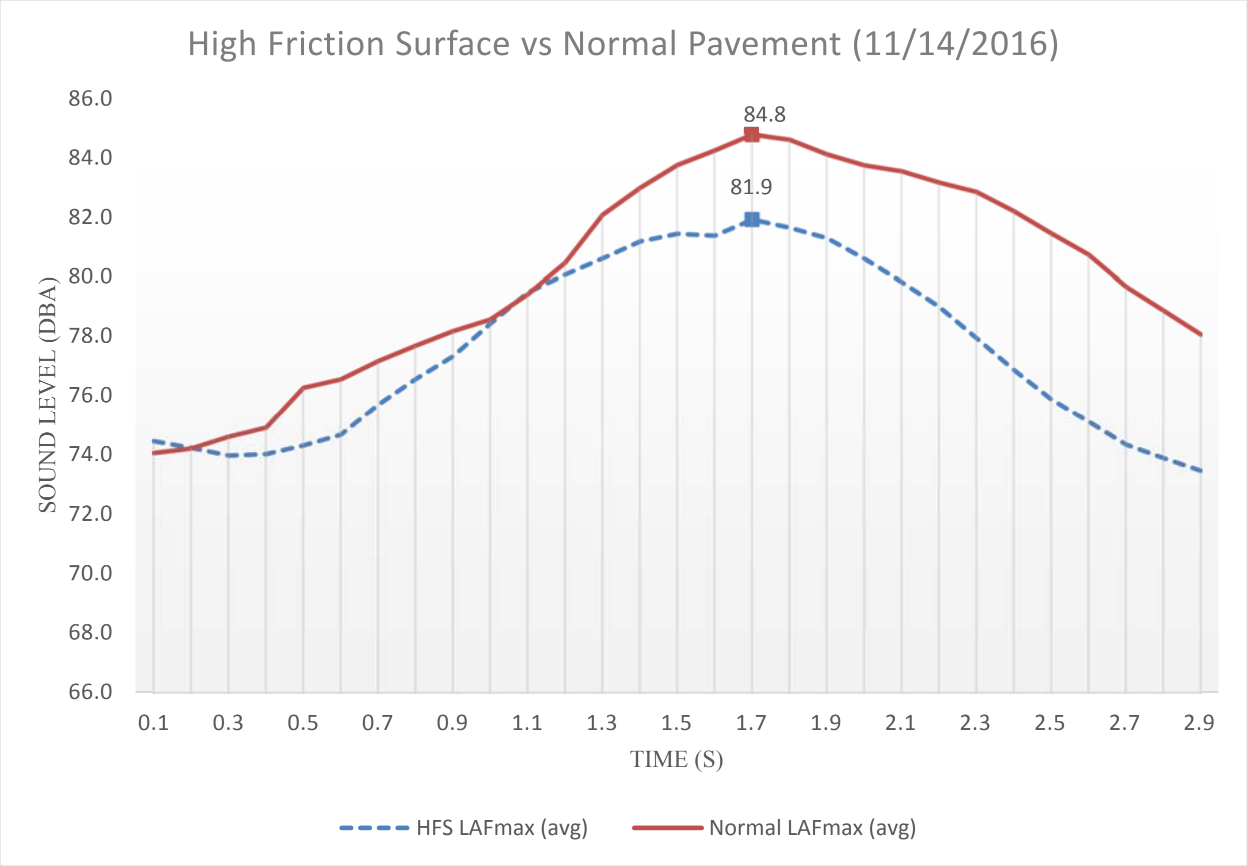


Figure 7.3: Graph of LAF$_{max}$ vs. Time for HFS and Normal Pavement for Data Taken on 11/14/2016

7.2 Testing Inside of the Car

The team theorized that the HFS measurements could be inflated due to the uniformly placed expansion joints in the surface that create an audible noise as a car travels over them. In an effort to isolate the noise level created by the gaps in the HFS surface, the team recorded the sound level from within the moving car using the theory that the HFS would create a constant sound level with uniform spikes representing the expansion joints. Figures 7.4 and 7.5 represent the data recorded from inside the vehicle.

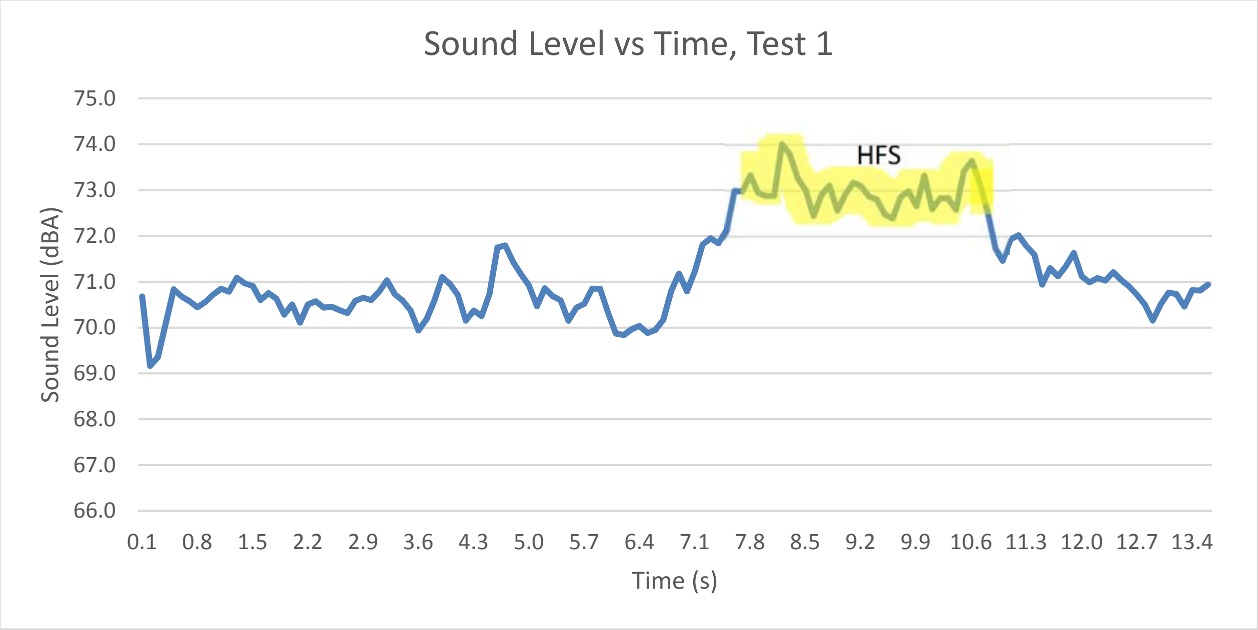


Figure 7.4: Graph of LAF$_{max}$ vs. Time for Data Taken Inside of the Car, 1

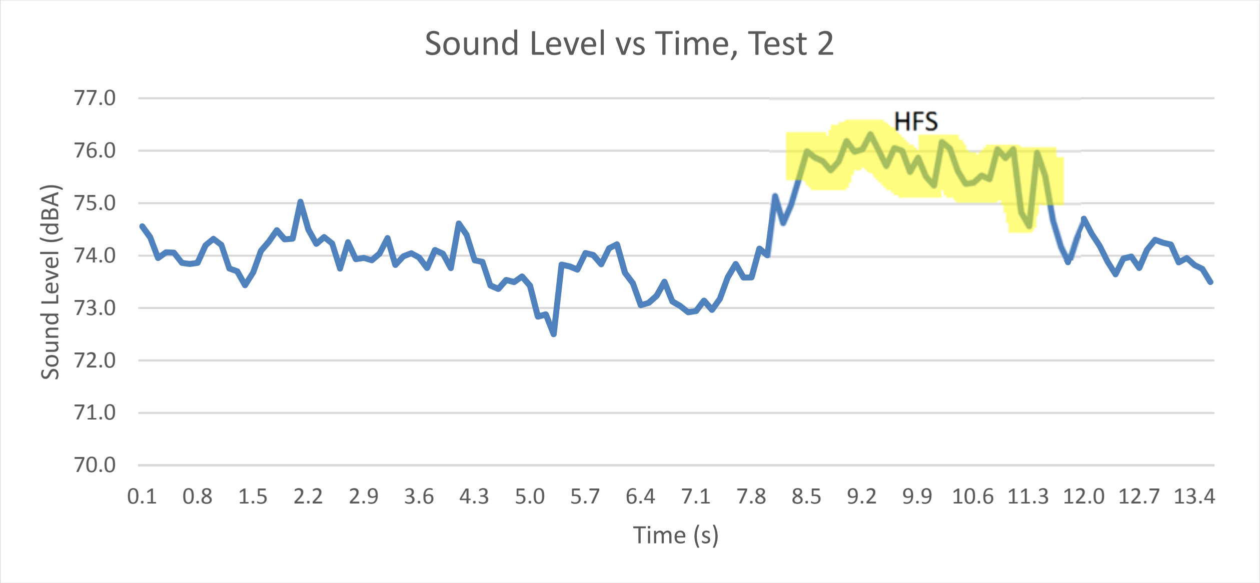


Figure 7.5: Graph of LAF$_{max}$ vs. Time for Data Taken Inside of the Car, 2

With the recorded data, it was not possible to determine a uniform noise level increase created by the expansion joints in the HFS surface. However, from this experiment, the Senior Design Team could conclude that the HFS noise inside of the car was about 2dB louder than normal pavement, which is somewhat surprising considering that people have stated the polymer bridge deck overlays seemed quieter than the adjacent pavement.

Chapter 8: Conclusions and Recommendation

8.1 Conclusion

This project spanned two semesters and many stages leading up to this final report. Beginning February 2016, the team researched various standards of road noise level testing and determined the best option for the project based on cost, ease of use, and accuracy. Following the initial research, the team determined and purchased various necessary equipment and familiarized themselves with the operation of the equipment. To create a controlled testing location within an accessible distance from the K-State campus, KDOT placed a test strip of HFS on US Highway 24 between Wamego and Manhattan, allowing the team to perform sound level testing at their convenience. Utilizing a detailed testing procedure, the team performed four testing sessions at the location in order to collect enough data to accurately draw a conclusion on the impact of HFS on road noise.

After four tests, we have determined that the HFS test strip created a smaller decrease in exterior road noise than the 5 dB that had been the targeted sound level reduction. The team found that it was not possible to measure the sound increase that resulted as a car hit the expansion joints in the HFS surface; we hypothesize that lower sound levels would be measured if these expansion joints where filled in.

8.2 Recommendation

The findings of the team indicated the HFS creates a noticeably different sound, appearing quieter or less offensive to the human ear. This is probably due to a shift in the frequency of the sound to a point that is not as offensive. In conjunction with other noise control techniques, the HFS could be used to shift the frequency on a marginal system or perhaps may be used by itself for noise with lower intensity, thus benefitting or correcting the noise issues.

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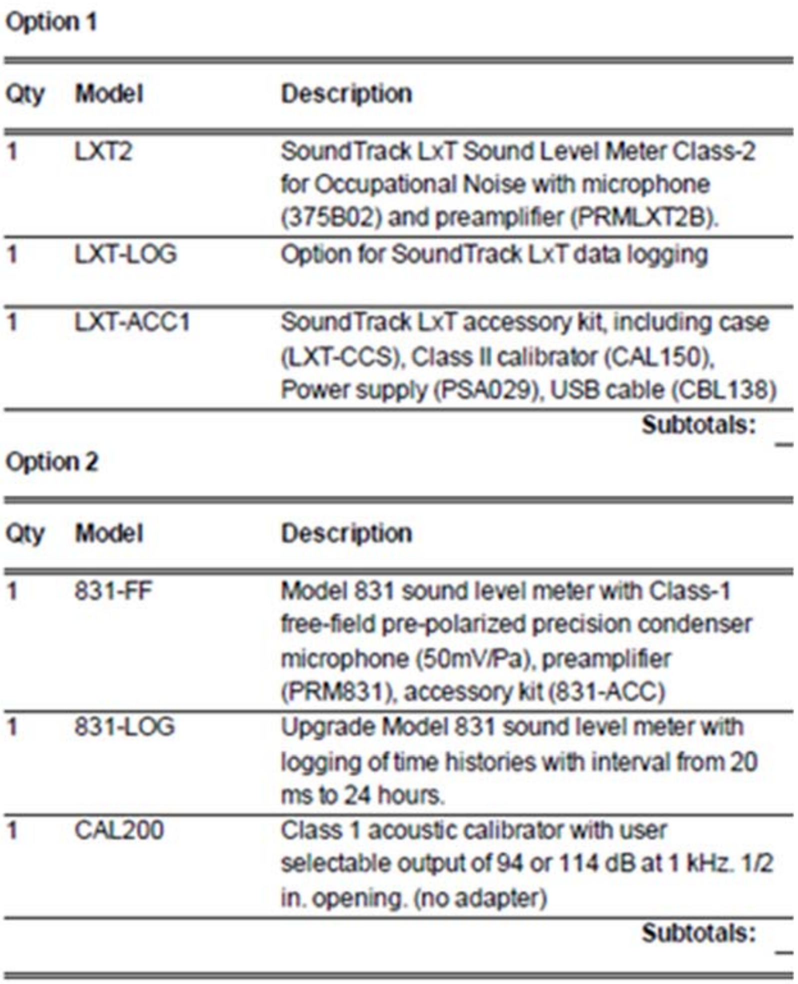
Appendix A: Equipment Lists



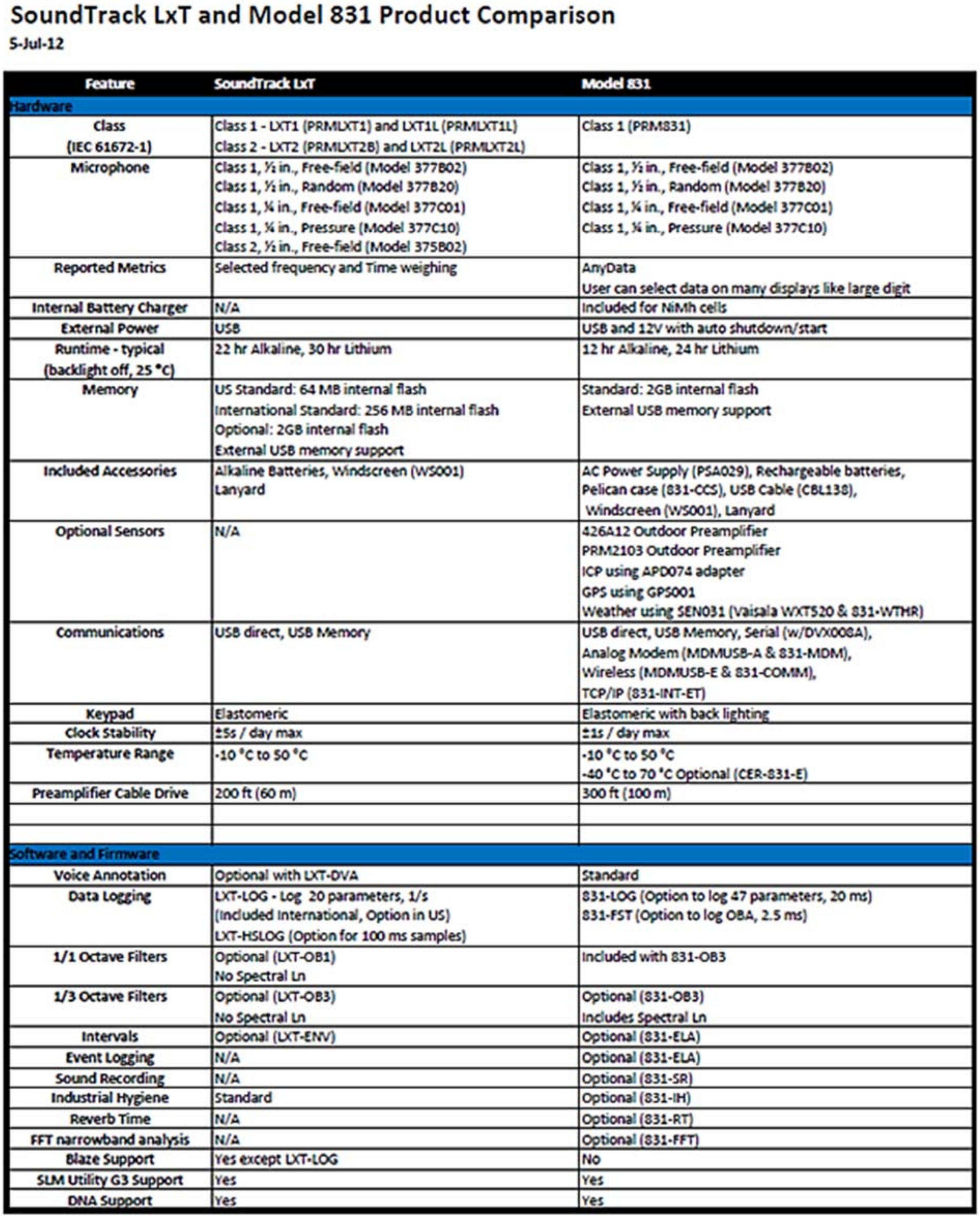
Option 1

Qty	Model	Description
1	LXT2	SoundTrack LxT Sound Level Meter Class-2 for Occupational Noise with microphone (375B02) and preamplifier (PRMLXT2B).
1	LXT-LOG	Option for SoundTrack LxT data logging
1	LXT-ACC1	SoundTrack LxT accessory kit, including case (LXT-CCS), Class II calibrator (CAL150), Power supply (PSA029), USB cable (CBL138)
		Subtotals:

Option 2

Qty	Model	Description
1	831-FF	Model 831 sound level meter with Class-1 free-field pre-polarized precision condenser microphone (50mV/Pa), preamplifier (PRM831), accessory kit (831-ACC)
1	831-LOG	Upgrade Model 831 sound level meter with logging of time histories with interval from 20 ms to 24 hours.
1	CAL200	Class 1 acoustic calibrator with user selectable output of 94 or 114 dB at 1 kHz. 1/2 in. opening. (no adapter)
		Subtotals:

Figure A.1: Equipment List from Larson Davis

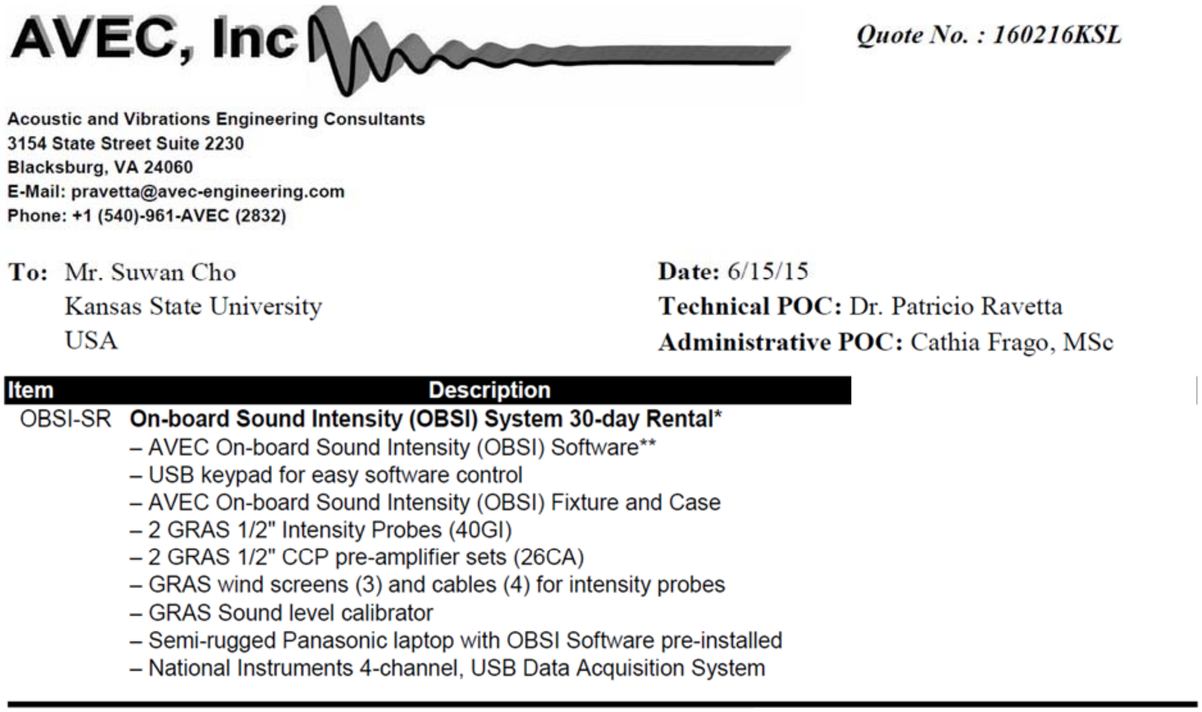


SoundTrack LxT and Model 831 Product Comparison

5-Jul-12

Feature	SoundTrack LxT	Model 831
Hardware		
Class (IEC 61672-1)	Class 1 - LXT1 (PRMLXT1) and LXT1L (PRMLXT1L) Class 2 - LXT2 (PRMLXT2B) and LXT2L (PRMLXT2L)	Class 1 (PRM831)
Microphone	Class 1, ½ in., Free-field (Model 377B02) Class 1, ½ in., Random (Model 377B20) Class 1, ¼ in., Free-field (Model 377C01) Class 1, ¼ in., Pressure (Model 377C10) Class 2, ½ in., Free-field (Model 375B02)	Class 1, ½ in., Free-field (Model 377B02) Class 1, ½ in., Random (Model 377B20) Class 1, ¼ in., Free-field (Model 377C01) Class 1, ¼ in., Pressure (Model 377C10)
Reported Metrics	Selected frequency and Time weighing	AnyData User can select data on many displays like large digit
Internal Battery Charger	N/A	Included for NiMh cells
External Power	USB	USB and 12V with auto shutdown/start
Runtime - typical (backlight off, 25 °C)	22 hr Alkaline, 30 hr Lithium	12 hr Alkaline, 24 hr Lithium
Memory	US Standard: 64 MB internal flash International Standard: 256 MB internal flash Optional: 2GB internal flash External USB memory support	Standard: 2GB internal flash External USB memory support
Included Accessories	Alkaline Batteries, Windscreen (WS001) Lanyard	AC Power Supply (PSA029), Rechargeable batteries, Pelican case (831-CCS), USB Cable (CBL138), Windscreen (WS001), Lanyard
Optional Sensors	N/A	426A12 Outdoor Preamplifier PRM2103 Outdoor Preamplifier ICP using APD074 adapter GPS using GPS001 Weather using SEN031 (Vaisala WXT520 & 831-WTHR)
Communications	USB direct, USB Memory	USB direct, USB Memory, Serial (w/DVX008A), Analog Modem (MDMUSB-A & 831-MDM), Wireless (MDMUSB-E & 831-COMM), TCP/IP (831-INT-ET)
Keypad	Elastomeric	Elastomeric with back lighting
Clock Stability	±5s / day max	±1s / day max
Temperature Range	-10 °C to 50 °C	-10 °C to 50 °C -40 °C to 70 °C Optional (CER-831-E)
Preamplifier Cable Drive	200 ft (60 m)	300 ft (100 m)
Software and Firmware		
Voice Annotation	Optional with LXT-DVA	Standard
Data Logging	LXT-LOG - Log 20 parameters, 1/s (Included International, Option in US) LXT-HSLOG (Option for 100 ms samples)	831-LOG (Option to log 47 parameters, 20 ms) 831-FST (Option to log OBA, 2.5 ms)
1/1 Octave Filters	Optional (LXT-OB1) No Spectral Ln	Included with 831-OB3
1/3 Octave Filters	Optional (LXT-OB3) No Spectral Ln	Optional (831-OB3) Includes Spectral Ln
Intervals	Optional (LXT-ENV)	Optional (831-ELA)
Event Logging	N/A	Optional (831-ELA)
Sound Recording	N/A	Optional (831-SR)
Industrial Hygiene	Standard	Optional (831-IH)
Reverb Time	N/A	Optional (831-RT)
FFT narrowband analysis	N/A	Optional (831-FFT)
Blaze Support	Yes except LXT-LOG	No
SLM Utility G3 Support	Yes	Yes
DNA Support	Yes	Yes

Figure A.2: Product Comparison



AVEC, Inc

Quote No. : 160216KSL

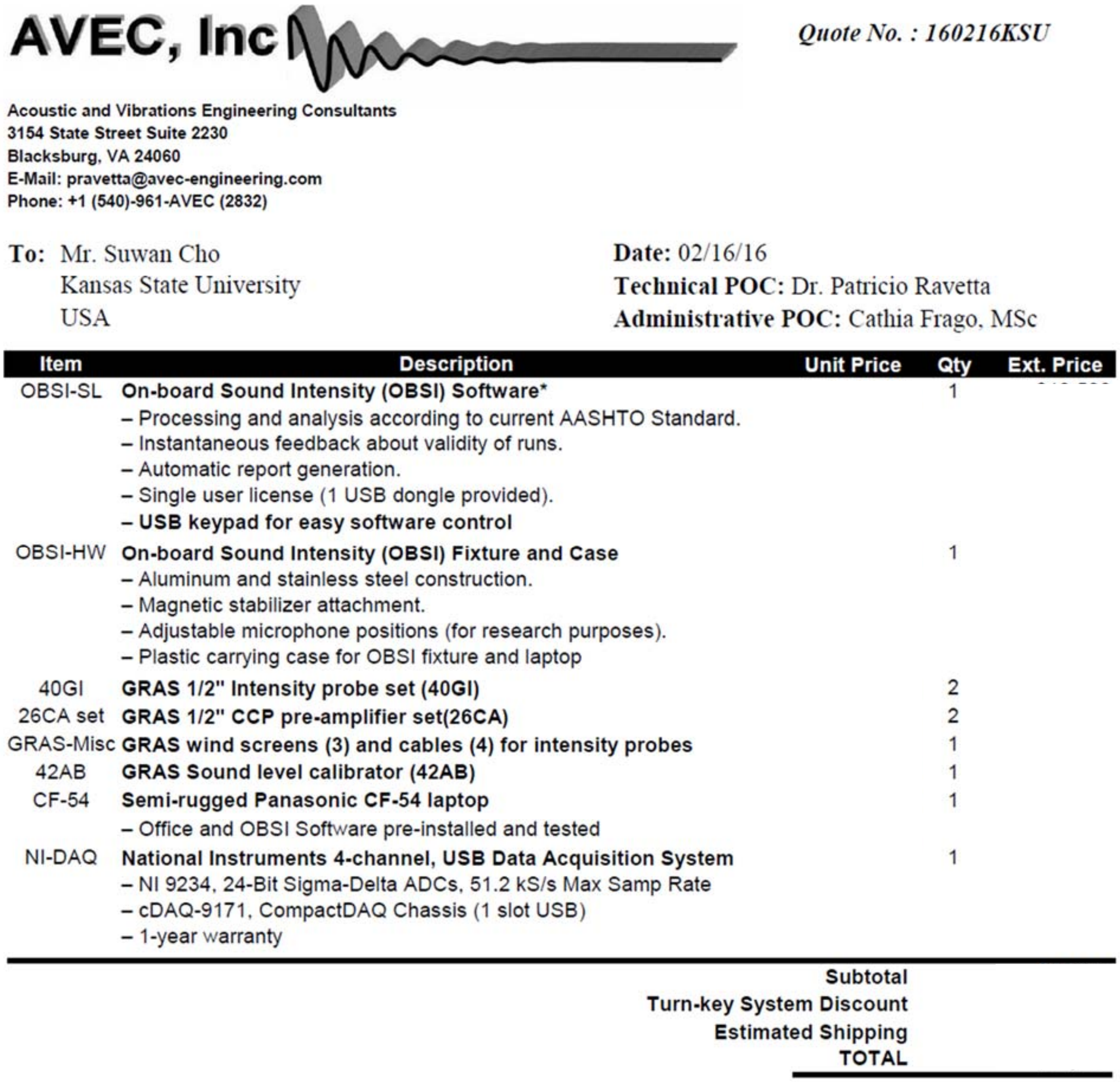
Acoustic and Vibrations Engineering Consultants
3154 State Street Suite 2230
Blacksburg, VA 24060
E-Mail: pravetta@avec-engineering.com
Phone: +1 (540)-961-AVEC (2832)

To: Mr. Suwan Cho
Kansas State University
USA

Date: 6/15/15
Technical POC: Dr. Patricio Ravetta
Administrative POC: Cathia Frago, MSc

Item	Description
OBSI-SR	**On-board Sound Intensity (OBSI) System 30-day Rental*** – AVEC On-board Sound Intensity (OBSI) Software** – USB keypad for easy software control – AVEC On-board Sound Intensity (OBSI) Fixture and Case – 2 GRAS 1/2" Intensity Probes (40GI) – 2 GRAS 1/2" CCP pre-amplifier sets (26CA) – GRAS wind screens (3) and cables (4) for intensity probes – GRAS Sound level calibrator – Semi-rugged Panasonic laptop with OBSI Software pre-installed – National Instruments 4-channel, USB Data Acquisition System

Figure A.3: Equipment List from AVEC, Inc



AVEC, Inc

Quote No. : 160216KSU

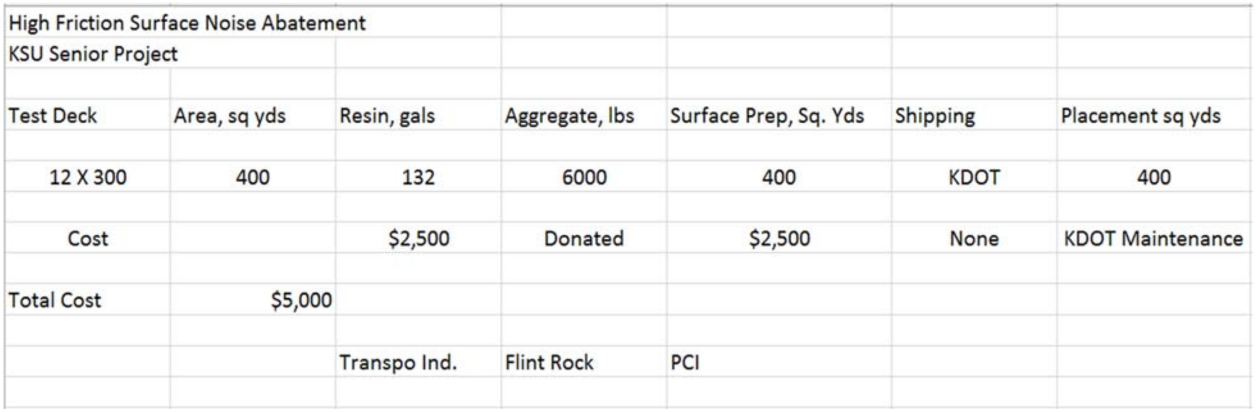
Acoustic and Vibrations Engineering Consultants
3154 State Street Suite 2230
Blacksburg, VA 24060
E-Mail: pravetta@avec-engineering.com
Phone: +1 (540)-961-AVEC (2832)

To: Mr. Suwan Cho
Kansas State University
USA

Date: 02/16/16
Technical POC: Dr. Patricio Ravetta
Administrative POC: Cathia Frago, MSc

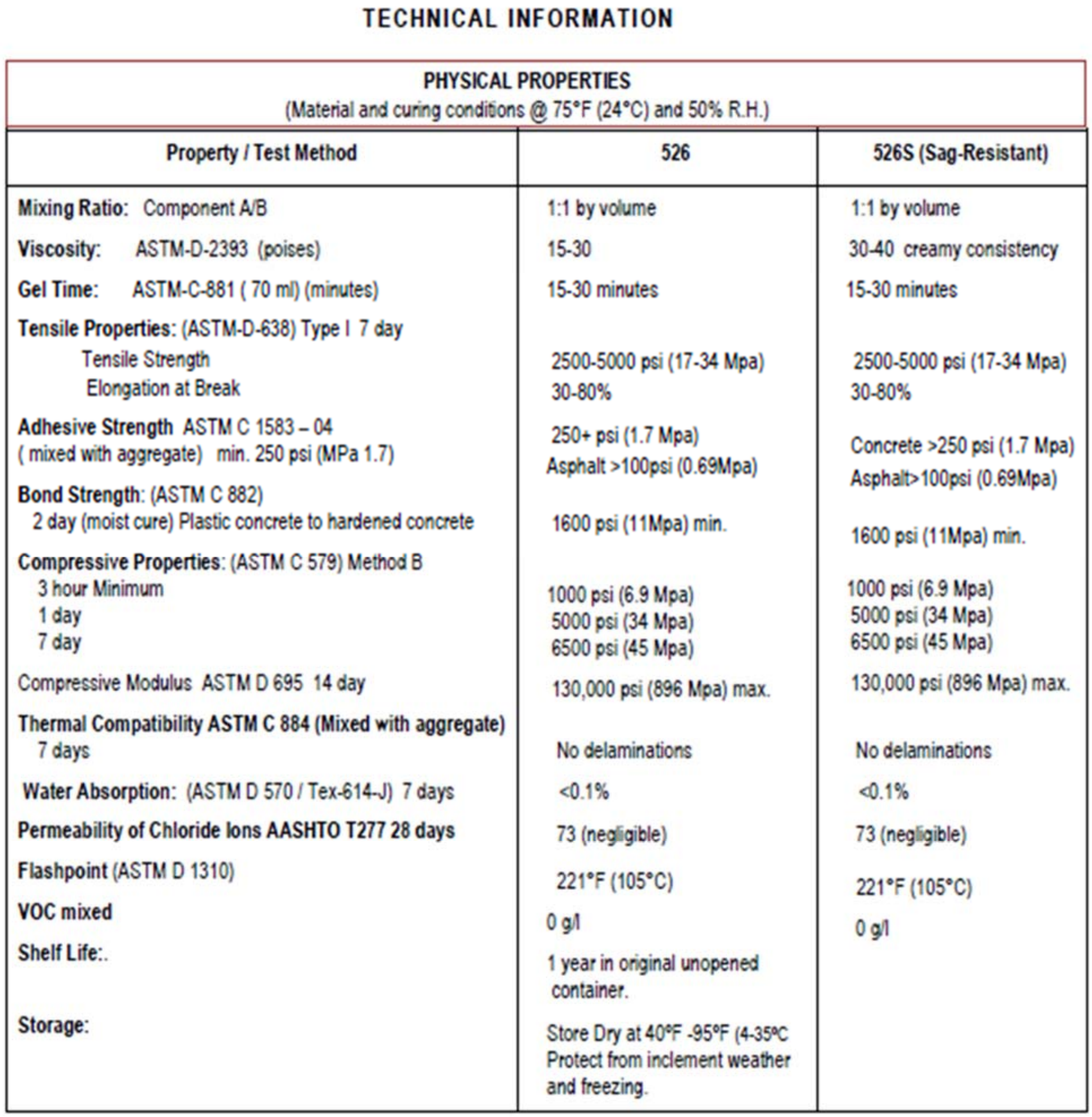
Item	Description	Unit Price	Qty	Ext. Price
OBSI-SL	**On-board Sound Intensity (OBSI) Software*** – Processing and analysis according to current AASHTO Standard. – Instantaneous feedback about validity of runs. – Automatic report generation. – Single user license (1 USB dongle provided). **– USB keypad for easy software control**		1	
OBSI-HW	**On-board Sound Intensity (OBSI) Fixture and Case** – Aluminum and stainless steel construction. – Magnetic stabilizer attachment. – Adjustable microphone positions (for research purposes). – Plastic carrying case for OBSI fixture and laptop		1	
40GI	**GRAS 1/2" Intensity probe set (40GI)**		2	
26CA set	**GRAS 1/2" CCP pre-amplifier set(26CA)**		2	
GRAS-Misc	**GRAS wind screens (3) and cables (4) for intensity probes**		1	
42AB	**GRAS Sound level calibrator (42AB)**		1	
CF-54	**Semi-rugged Panasonic CF-54 laptop** – Office and OBSI Software pre-installed and tested		1	
NI-DAQ	**National Instruments 4-channel, USB Data Acquisition System** – NI 9234, 24-Bit Sigma-Delta ADCs, 51.2 kS/s Max Samp Rate – cDAQ-9171, CompactDAQ Chassis (1 slot USB) – 1-year warranty		1	
		Subtotal		
		Turn-key System Discount		
		Estimated Shipping		
		TOTAL		

Figure A.4: Purchasing Price Quotes from AVEC, Inc



High Friction Surface Noise Abatement						
KSU Senior Project						
Test Deck	Area, sq yds	Resin, gals	Aggregate, lbs	Surface Prep, Sq. Yds	Shipping	Placement sq yds
12 X 300	400	132	6000	400	KDOT	400
Cost		$2,500	Donated	$2,500	None	KDOT Maintenance
Total Cost	$5,000					
		Transpo Ind.	Flint Rock	PCI		

Figure A.5: Excel Sheet of Material and Cost Estimates Provided by Dave Meggers

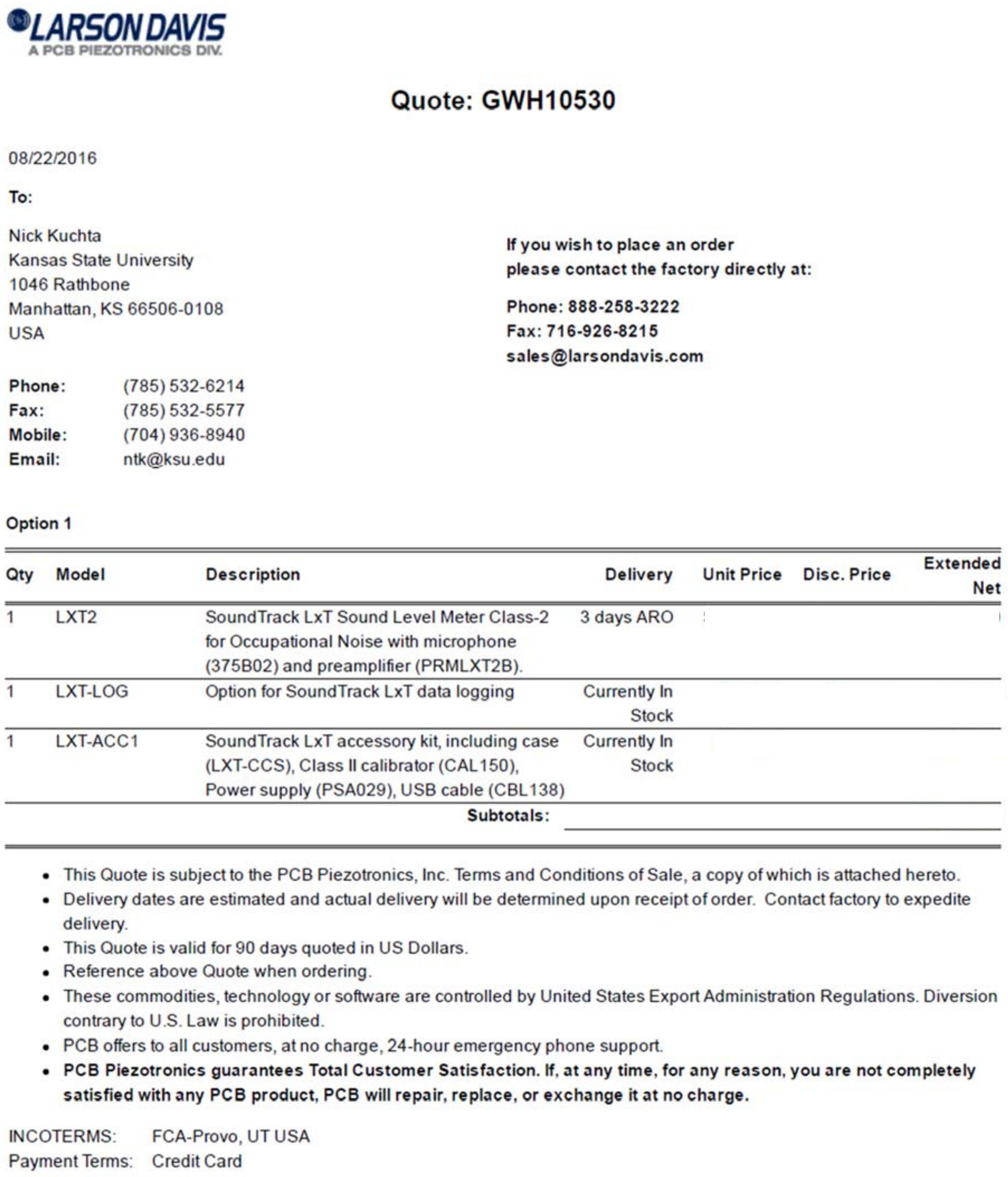


TECHNICAL INFORMATION

PHYSICAL PROPERTIES
(Material and curing conditions @ 75°F (24°C) and 50% R.H.)

Property / Test Method	526	526S (Sag-Resistant)
Mixing Ratio: Component A/B	1:1 by volume	1:1 by volume
Viscosity: ASTM-D-2393 (poises)	15-30	30-40 creamy consistency
Gel Time: ASTM-C-881 (70 ml) (minutes)	15-30 minutes	15-30 minutes
Tensile Properties: (ASTM-D-638) Type I 7 day		
Tensile Strength	2500-5000 psi (17-34 Mpa)	2500-5000 psi (17-34 Mpa)
Elongation at Break	30-80%	30-80%
Adhesive Strength ASTM C 1583 – 04 (mixed with aggregate) min. 250 psi (MPa 1.7)	250+ psi (1.7 Mpa) Asphalt >100psi (0.69Mpa)	Concrete >250 psi (1.7 Mpa) Asphalt>100psi (0.69Mpa)
Bond Strength: (ASTM C 882) 2 day (moist cure) Plastic concrete to hardened concrete	1600 psi (11Mpa) min.	1600 psi (11Mpa) min.
Compressive Properties: (ASTM C 579) Method B		
3 hour Minimum	1000 psi (6.9 Mpa)	1000 psi (6.9 Mpa)
1 day	5000 psi (34 Mpa)	5000 psi (34 Mpa)
7 day	6500 psi (45 Mpa)	6500 psi (45 Mpa)
Compressive Modulus ASTM D 695 14 day	130,000 psi (896 Mpa) max.	130,000 psi (896 Mpa) max.
Thermal Compatibility ASTM C 884 (Mixed with aggregate) 7 days	No delaminations	No delaminations
Water Absorption: (ASTM D 570 / Tex-614-J) 7 days	<0.1%	<0.1%
Permeability of Chloride Ions AASHTO T277 28 days	73 (negligible)	73 (negligible)
Flashpoint (ASTM D 1310)	221°F (105°C)	221°F (105°C)
VOC mixed	0 g/l	0 g/l
Shelf Life:.	1 year in original unopened container.	
Storage:	Store Dry at 40ºF -95ºF (4-35ºC Protect from inclement weather and freezing.	

Figure A.6: Technical Information



LARSON DAVIS
A PCB PIEZOTRONICS DIV.

Quote: GWH10530

08/22/2016

To:

Nick Kuchta
Kansas State University
1046 Rathbone
Manhattan, KS 66506-0108
USA

Phone: (785) 532-6214
Fax: (785) 532-5577
Mobile: (704) 936-8940
Email: ntk@ksu.edu

If you wish to place an order
please contact the factory directly at:

Phone: 888-258-3222
Fax: 716-926-8215
sales@larsondavis.com

Option 1

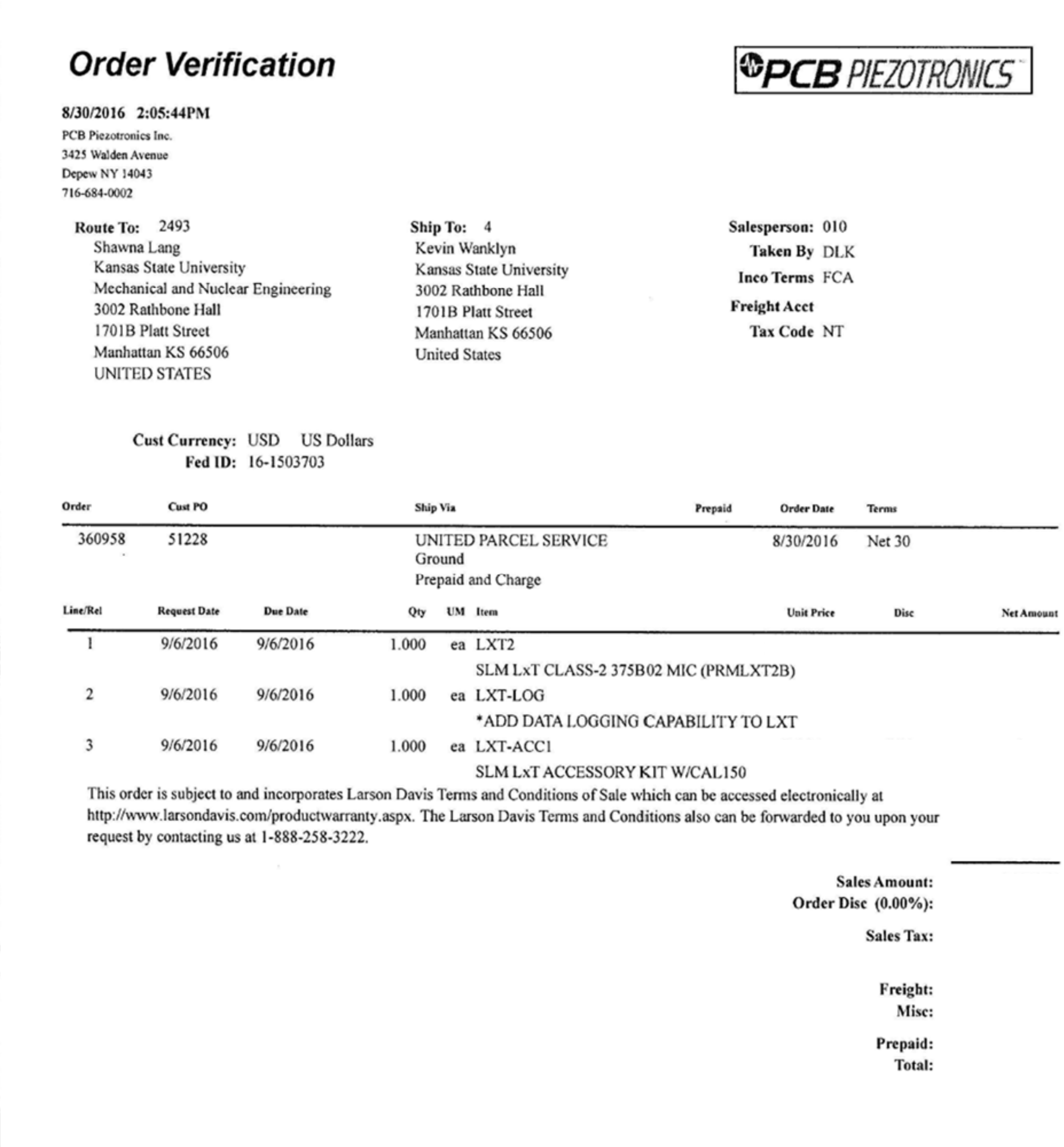
Qty	Model	Description	Delivery	Unit Price	Disc. Price	Extended Net
1	LXT2	SoundTrack LxT Sound Level Meter Class-2 for Occupational Noise with microphone (375B02) and preamplifier (PRMLXT2B).	3 days ARO			
1	LXT-LOG	Option for SoundTrack LxT data logging	Currently In Stock			
1	LXT-ACC1	SoundTrack LxT accessory kit, including case (LXT-CCS), Class II calibrator (CAL150), Power supply (PSA029), USB cable (CBL138)	Currently In Stock			
		Subtotals:				

- This Quote is subject to the PCB Piezotronics, Inc. Terms and Conditions of Sale, a copy of which is attached hereto.
- Delivery dates are estimated and actual delivery will be determined upon receipt of order. Contact factory to expedite delivery.
- This Quote is valid for 90 days quoted in US Dollars.
- Reference above Quote when ordering.
- These commodities, technology or software are controlled by United States Export Administration Regulations. Diversion contrary to U.S. Law is prohibited.
- PCB offers to all customers, at no charge, 24-hour emergency phone support.
- **PCB Piezotronics guarantees Total Customer Satisfaction. If, at any time, for any reason, you are not completely satisfied with any PCB product, PCB will repair, replace, or exchange it at no charge.**

INCOTERMS: FCA-Provo, UT USA
Payment Terms: Credit Card

Figure A.7: Updated List from Larson Davis

Appendix B: Order Verification & Packing List



Order Verification

PCB PIEZOTRONICS

8/30/2016 2:05:44PM
PCB Piezotronics Inc.
3425 Walden Avenue
Depew NY 14043
716-684-0002

Route To: 2493
Shawna Lang
Kansas State University
Mechanical and Nuclear Engineering
3002 Rathbone Hall
1701B Platt Street
Manhattan KS 66506
UNITED STATES

Ship To: 4
Kevin Wanklyn
Kansas State University
3002 Rathbone Hall
1701B Platt Street
Manhattan KS 66506
United States

Salesperson: 010
Taken By DLK
Inco Terms FCA
Freight Acct
Tax Code NT

Cust Currency: USD US Dollars
Fed ID: 16-1503703

Order	Cust PO	Ship Via	Prepaid	Order Date	Terms
360958	51228	UNITED PARCEL SERVICE Ground Prepaid and Charge		8/30/2016	Net 30

Line/Rel	Request Date	Due Date	Qty	UM	Item	Unit Price	Disc	Net Amount
1	9/6/2016	9/6/2016	1.000	ea	LXT2 SLM LxT CLASS-2 375B02 MIC (PRMLXT2B)			
2	9/6/2016	9/6/2016	1.000	ea	LXT-LOG *ADD DATA LOGGING CAPABILITY TO LXT			
3	9/6/2016	9/6/2016	1.000	ea	LXT-ACC1 SLM LxT ACCESSORY KIT W/CAL150			

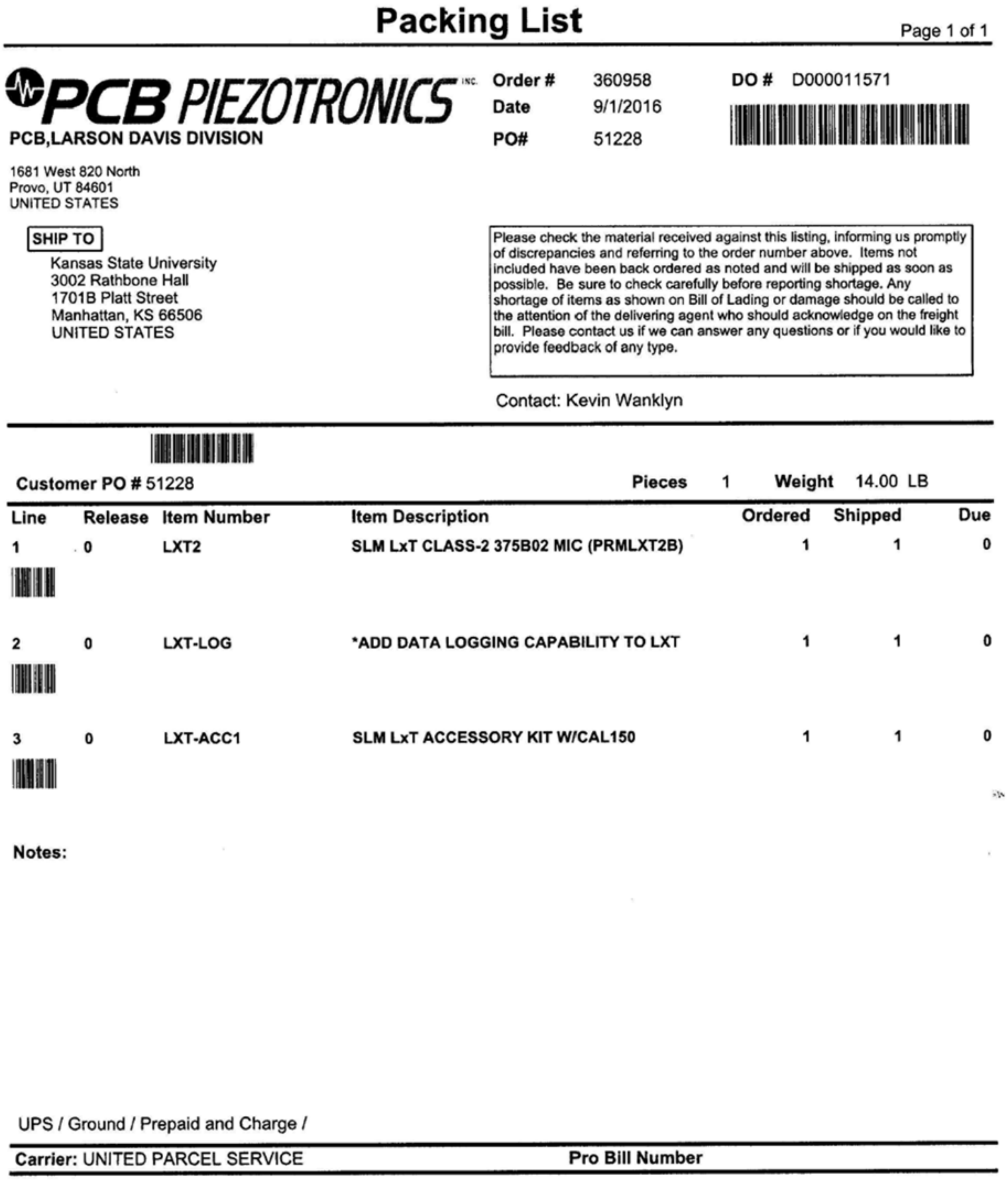
This order is subject to and incorporates Larson Davis Terms and Conditions of Sale which can be accessed electronically at http://www.larsondavis.com/productwarranty.aspx. The Larson Davis Terms and Conditions also can be forwarded to you upon your request by contacting us at 1-888-258-3222.

Sales Amount:
Order Disc (0.00%):
Sales Tax:

Freight:
Misc:

Prepaid:
Total:

Figure B.1: Order Verification of LxT



Packing List

Page 1 of 1

PCB PIEZOTRONICS INC.

PCB,LARSON DAVIS DIVISION

1681 West 820 North
Provo, UT 84601
UNITED STATES

Order # 360958
Date 9/1/2016
PO# 51228

DO # D000011571

SHIP TO

Kansas State University
3002 Rathbone Hall
1701B Platt Street
Manhattan, KS 66506
UNITED STATES

Please check the material received against this listing, informing us promptly of discrepancies and referring to the order number above. Items not included have been back ordered as noted and will be shipped as soon as possible. Be sure to check carefully before reporting shortage. Any shortage of items as shown on Bill of Lading or damage should be called to the attention of the delivering agent who should acknowledge on the freight bill. Please contact us if we can answer any questions or if you would like to provide feedback of any type.

Contact: Kevin Wanklyn

Customer PO # 51228 **Pieces** 1 **Weight** 14.00 LB

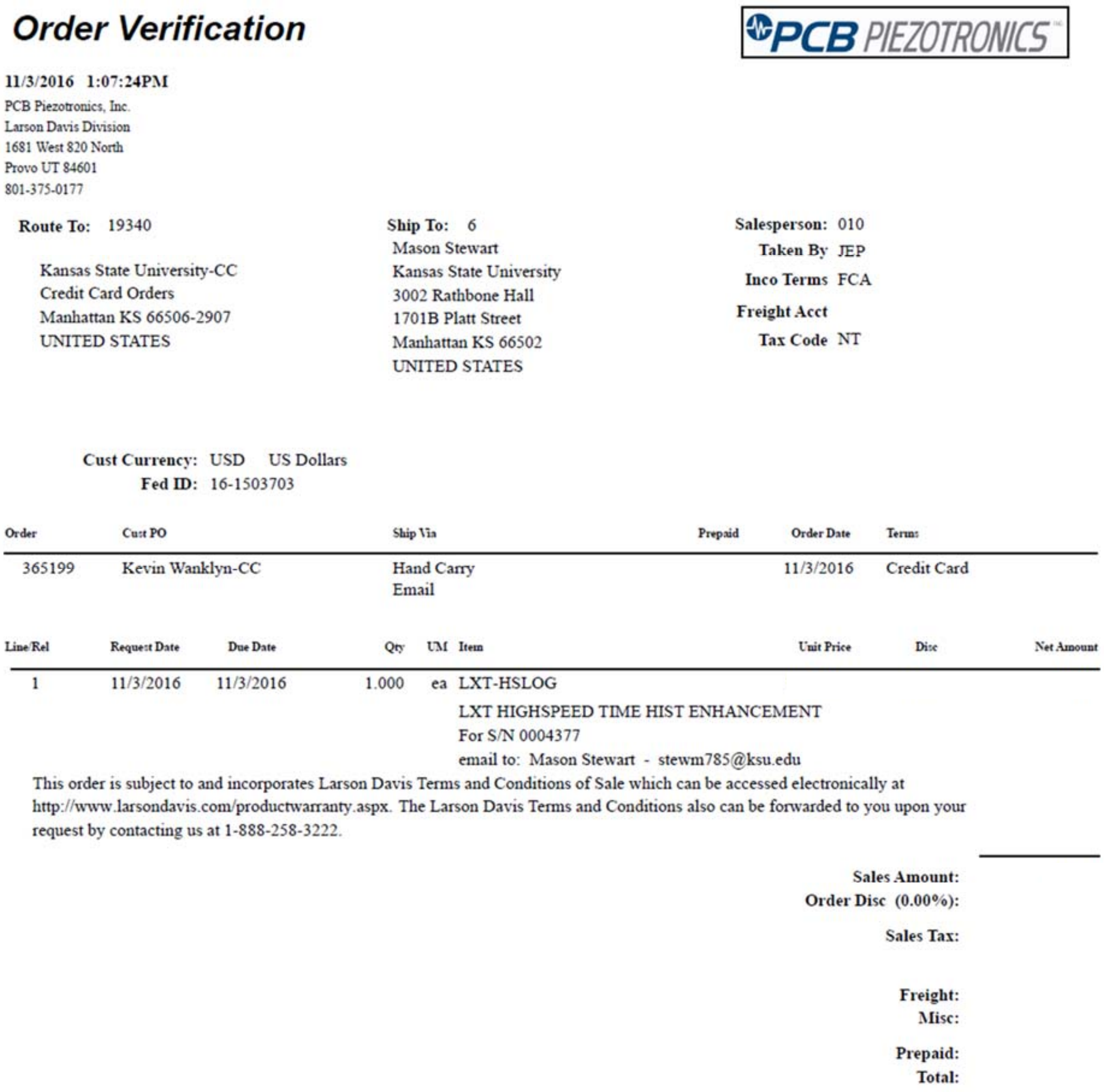
Line	Release	Item Number	Item Description	Ordered	Shipped	Due
1	0	LXT2	SLM LxT CLASS-2 375B02 MIC (PRMLXT2B)	1	1	0
2	0	LXT-LOG	*ADD DATA LOGGING CAPABILITY TO LXT	1	1	0
3	0	LXT-ACC1	SLM LxT ACCESSORY KIT W/CAL150	1	1	0

Notes:

UPS / Ground / Prepaid and Charge /

Carrier: UNITED PARCEL SERVICE **Pro Bill Number**

Figure B.2: Packing List



Order Verification

PCB PIEZOTRONICS

11/3/2016 1:07:24PM

PCB Piezotronics, Inc.
Larson Davis Division
1681 West 820 North
Provo UT 84601
801-375-0177

Route To: 19340

Kansas State University-CC
Credit Card Orders
Manhattan KS 66506-2907
UNITED STATES

Ship To: 6
Mason Stewart
Kansas State University
3002 Rathbone Hall
1701B Platt Street
Manhattan KS 66502
UNITED STATES

Salesperson: 010
Taken By JEP
Inco Terms FCA
Freight Acct
Tax Code NT

Cust Currency: USD US Dollars
Fed ID: 16-1503703

Order	Cust PO	Ship Via	Prepaid	Order Date	Terms
365199	Kevin Wanklyn-CC	Hand Carry Email		11/3/2016	Credit Card

Line/Rel	Request Date	Due Date	Qty	UM	Item	Unit Price	Disc	Net Amount
1	11/3/2016	11/3/2016	1.000	ea	LXT-HSLOG LXT HIGHSPEED TIME HIST ENHANCEMENT For S/N 0004377 email to: Mason Stewart - stewm785@ksu.edu			

This order is subject to and incorporates Larson Davis Terms and Conditions of Sale which can be accessed electronically at http://www.larsondavis.com/productwarranty.aspx. The Larson Davis Terms and Conditions also can be forwarded to you upon your request by contacting us at 1-888-258-3222.

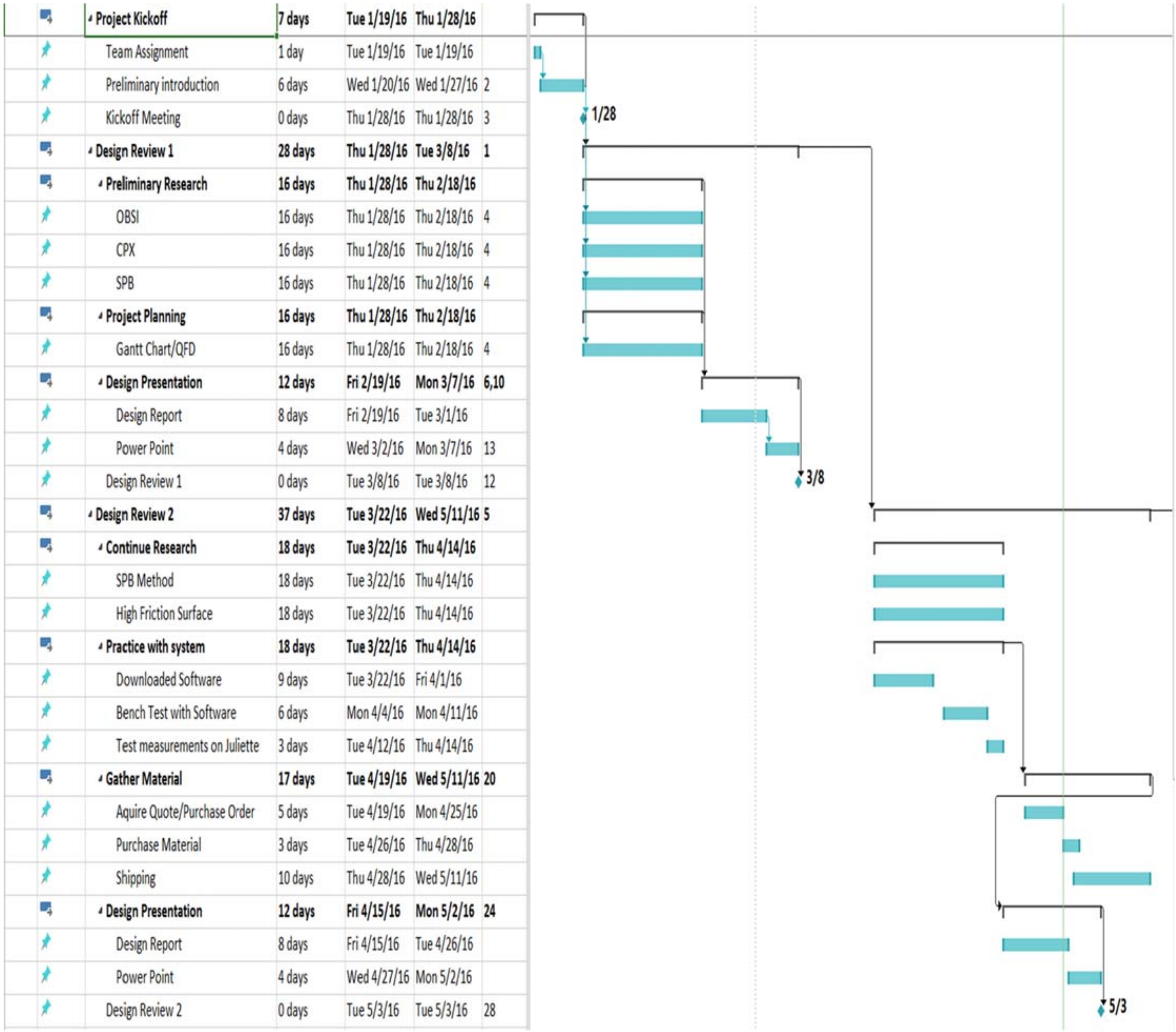
Sales Amount:
Order Disc (0.00%):
Sales Tax:

Freight:
Misc:

Prepaid:
Total:

Figure B.3: Order Verification of LxT High-Speed Log

Appendix C: Charts

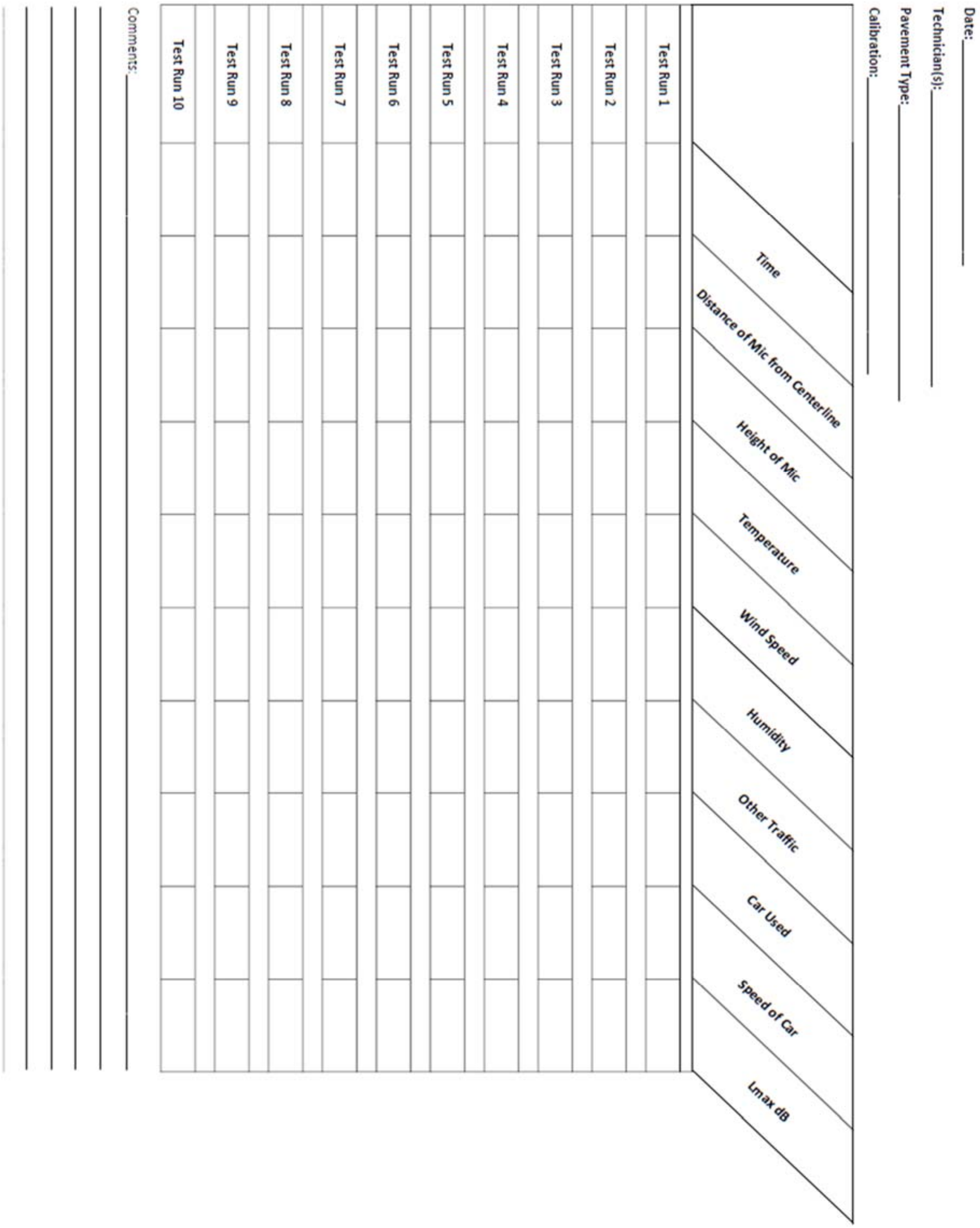


◂ Project Kickoff	**7 days**	**Tue 1/19/16**	**Thu 1/28/16**	
Team Assignment	1 day	Tue 1/19/16	Tue 1/19/16	
Preliminary introduction	6 days	Wed 1/20/16	Wed 1/27/16	2
Kickoff Meeting	0 days	Thu 1/28/16	Thu 1/28/16	3
◂ Design Review 1	**28 days**	**Thu 1/28/16**	**Tue 3/8/16**	**1**
◂ Preliminary Research	**16 days**	**Thu 1/28/16**	**Thu 2/18/16**	
OBSI	16 days	Thu 1/28/16	Thu 2/18/16	4
CPX	16 days	Thu 1/28/16	Thu 2/18/16	4
SPB	16 days	Thu 1/28/16	Thu 2/18/16	4
◂ Project Planning	**16 days**	**Thu 1/28/16**	**Thu 2/18/16**	
Gantt Chart/QFD	16 days	Thu 1/28/16	Thu 2/18/16	4
◂ Design Presentation	**12 days**	**Fri 2/19/16**	**Mon 3/7/16**	**6,10**
Design Report	8 days	Fri 2/19/16	Tue 3/1/16	
Power Point	4 days	Wed 3/2/16	Mon 3/7/16	13
Design Review 1	0 days	Tue 3/8/16	Tue 3/8/16	12
◂ Design Review 2	**37 days**	**Tue 3/22/16**	**Wed 5/11/16**	**5**
◂ Continue Research	**18 days**	**Tue 3/22/16**	**Thu 4/14/16**	
SPB Method	18 days	Tue 3/22/16	Thu 4/14/16	
High Friction Surface	18 days	Tue 3/22/16	Thu 4/14/16	
◂ Practice with system	**18 days**	**Tue 3/22/16**	**Thu 4/14/16**	
Downloaded Software	9 days	Tue 3/22/16	Fri 4/1/16	
Bench Test with Software	6 days	Mon 4/4/16	Mon 4/11/16	
Test measurements on Juliette	3 days	Tue 4/12/16	Thu 4/14/16	
◂ Gather Material	**17 days**	**Tue 4/19/16**	**Wed 5/11/16**	**20**
Aquire Quote/Purchase Order	5 days	Tue 4/19/16	Mon 4/25/16	
Purchase Material	3 days	Tue 4/26/16	Thu 4/28/16	
Shipping	10 days	Thu 4/28/16	Wed 5/11/16	
◂ Design Presentation	**12 days**	**Fri 4/15/16**	**Mon 5/2/16**	**24**
Design Report	8 days	Fri 4/15/16	Tue 4/26/16	
Power Point	4 days	Wed 4/27/16	Mon 5/2/16	
Design Review 2	0 days	Tue 5/3/16	Tue 5/3/16	28

Figure C.1: Gantt Chart (1/28/2016 to 5/3/2016)

Design Review 3	**39 days**	**Mon 8/22/16**	**Thu 10/13/16**	
Develop Testing Procedure	**28 days**	**Mon 8/22/16**	**Wed 9/28/16**	
Visit Test Site/Write Test Procedur	8 days	Mon 8/22/16	Wed 8/31/16	
Obtain Feedback on Procedure	3 days	Thu 9/1/16	Mon 9/5/16	
Update Procedure	18 days	Mon 9/5/16	Wed 9/28/16	
Survey the Test Surface	**3 days**	**Mon 9/19/16**	**Wed 9/21/16**	
Obtain Surveying Equipment	1 day	Mon 9/19/16	Mon 9/19/16	
Survey Test Site	1 day	Wed 9/21/16	Wed 9/21/16	
Preliminary Test	**4 days**	**Fri 9/23/16**	**Wed 9/28/16**	37
Modify Tri-pod/Plan Test Day	2 days	Fri 9/23/16	Mon 9/26/16	
Run Preliminary Test	1 day	Tue 9/27/16	Tue 9/27/16	
Analyze Preliminary Data	1 day	Wed 9/28/16	Wed 9/28/16	
Design Presentation	**12 days**	**Wed 9/28/16**	**Thu 10/13/16**	**40,3**
Design Report	8 days	Thu 9/22/16	Mon 10/3/16	
Power Point	6 days	Wed 10/5/16	Wed 10/12/1	
Design Review 3	0 days	Fri 10/14/16	Fri 10/14/16	44
Design Review 4	**39 days**	**Fri 10/14/16**	**Wed 12/7/16**	**32**
Testing	**30 days**	**Mon 10/17/1**	**Fri 11/25/16**	
Run Tests on HFS	25 days	Mon 10/17/1	Fri 11/18/16	
Analyze HFS Data	20 days	Mon 10/31/1	Fri 11/25/16	
Run Tests on Regular Pavement	25 days	Mon 10/17/1	Fri 11/18/16	
Analyze Regular Pavement Data	20 days	Mon 10/31/1	Fri 11/25/16	
Design Presentation	**9 days**	**Mon 11/28/1**	**Thu 12/8/16**	**49**
Design Report	8 days	Mon 11/28/1	Wed 12/7/16	
Power Point	4 days	Thu 12/8/16	Tue 12/13/16	
Design Review 4	0 days	Wed 12/14/1	Wed 12/14/1	54

Figure C.2: Gantt Chart (8/22/2016 to 12/14/2016)



Date:

Technician(s):

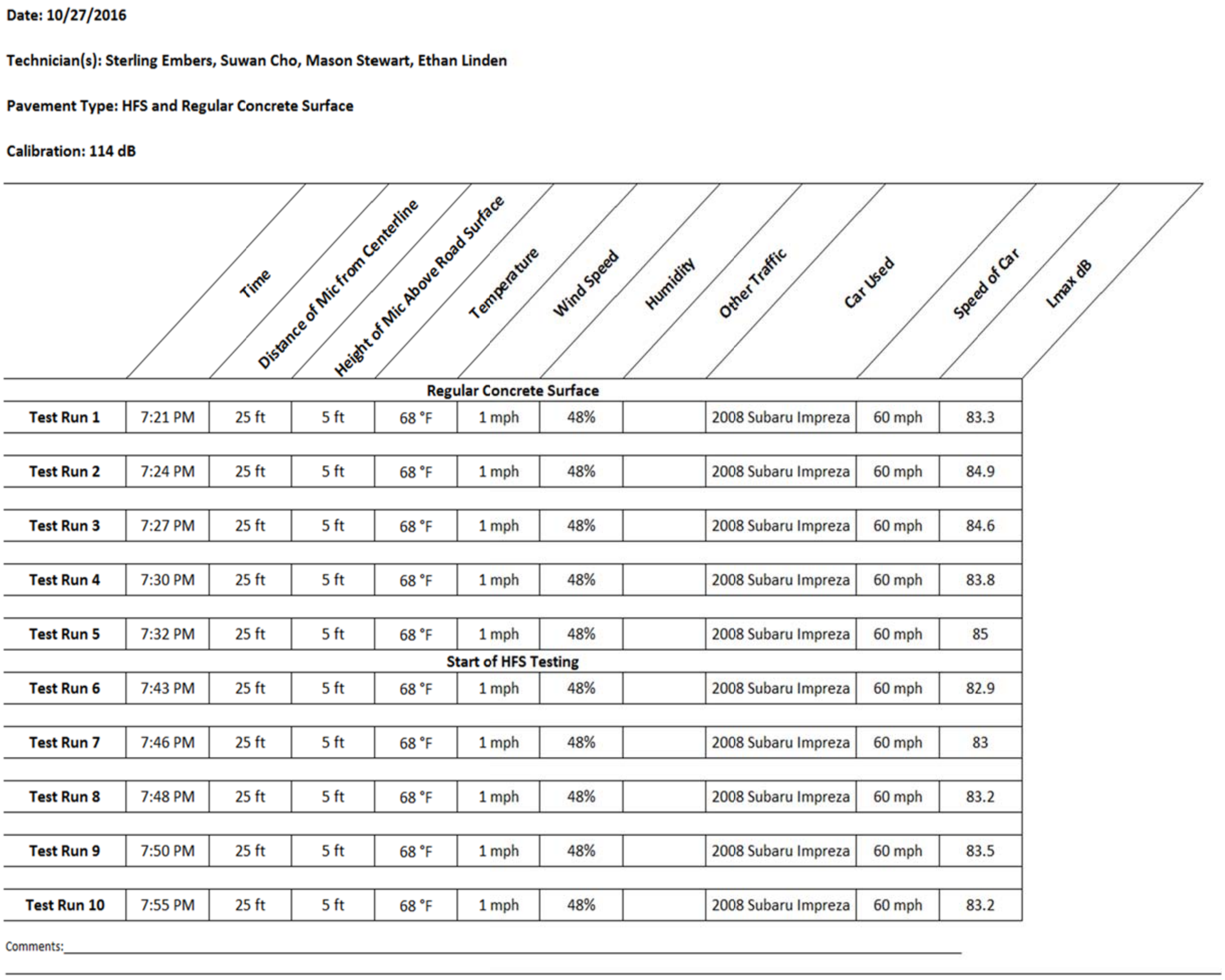
Pavement Type:

Calibration:

	Time	Distance of Mic from Centerline	Height of Mic	Temperature	Wind Speed	Humidity	Other Traffic	Car Used	Speed of Car	Lmax dB
Test Run 1										
Test Run 2										
Test Run 3										
Test Run 4										
Test Run 5										
Test Run 6										
Test Run 7										
Test Run 8										
Test Run 9										
Test Run 10										

Comments:

Figure C.3: Checklist for Testing



Date: 10/27/2016

Technician(s): Sterling Embers, Suwan Cho, Mason Stewart, Ethan Linden

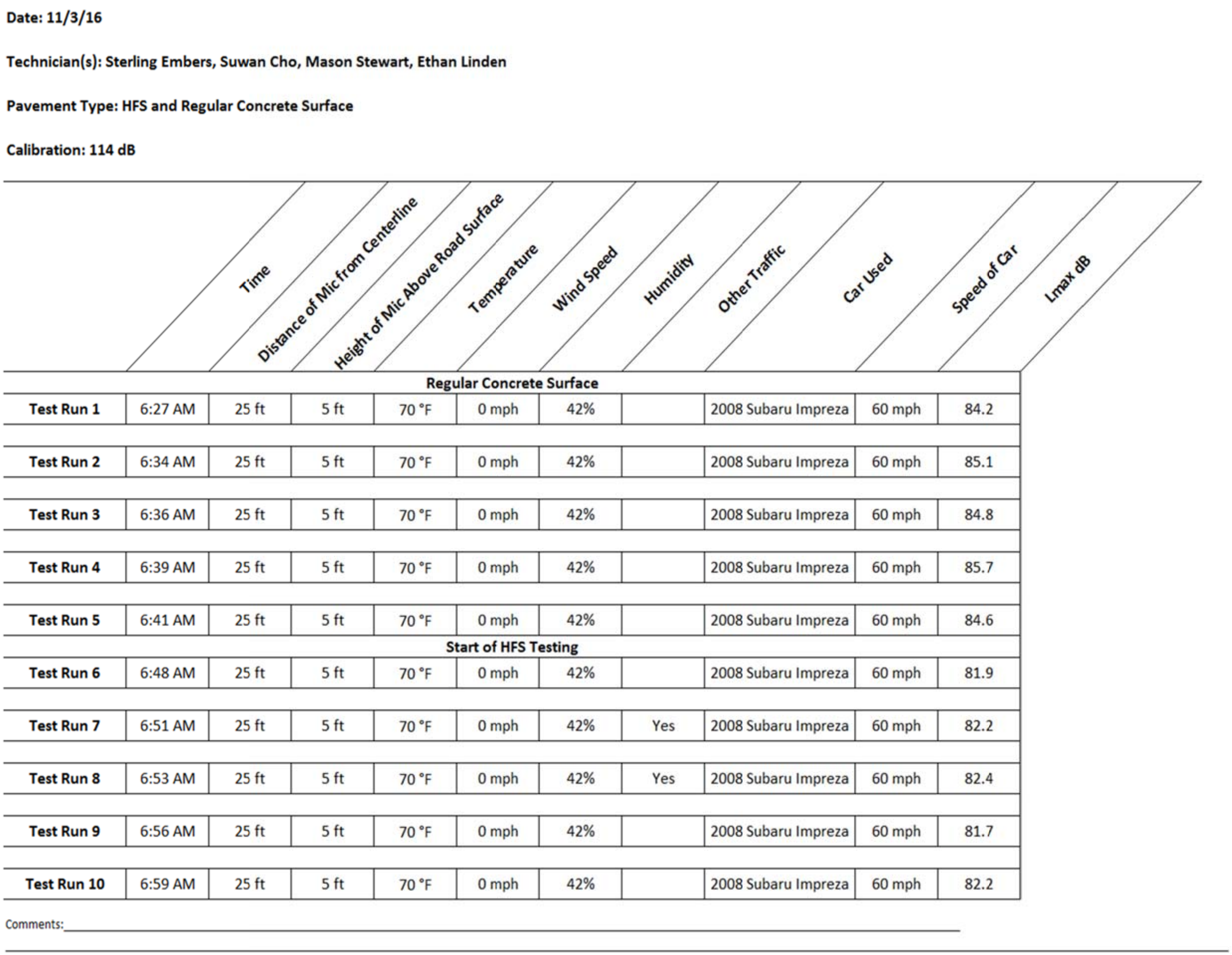
Pavement Type: HFS and Regular Concrete Surface

Calibration: 114 dB

	Time	Distance of Mic from Centerline	Height of Mic Above Road Surface	Temperature	Wind Speed	Humidity	Other Traffic	Car Used	Speed of Car	Lmax dB
					Regular Concrete Surface					
Test Run 1	7:21 PM	25 ft	5 ft	68 °F	1 mph	48%		2008 Subaru Impreza	60 mph	83.3
Test Run 2	7:24 PM	25 ft	5 ft	68 °F	1 mph	48%		2008 Subaru Impreza	60 mph	84.9
Test Run 3	7:27 PM	25 ft	5 ft	68 °F	1 mph	48%		2008 Subaru Impreza	60 mph	84.6
Test Run 4	7:30 PM	25 ft	5 ft	68 °F	1 mph	48%		2008 Subaru Impreza	60 mph	83.8
Test Run 5	7:32 PM	25 ft	5 ft	68 °F	1 mph	48%		2008 Subaru Impreza	60 mph	85
					Start of HFS Testing					
Test Run 6	7:43 PM	25 ft	5 ft	68 °F	1 mph	48%		2008 Subaru Impreza	60 mph	82.9
Test Run 7	7:46 PM	25 ft	5 ft	68 °F	1 mph	48%		2008 Subaru Impreza	60 mph	83
Test Run 8	7:48 PM	25 ft	5 ft	68 °F	1 mph	48%		2008 Subaru Impreza	60 mph	83.2
Test Run 9	7:50 PM	25 ft	5 ft	68 °F	1 mph	48%		2008 Subaru Impreza	60 mph	83.5
Test Run 10	7:55 PM	25 ft	5 ft	68 °F	1 mph	48%		2008 Subaru Impreza	60 mph	83.2

Comments:______________________________

Figure C.4: Checklist for Testing (10/27/2016)



Date: 11/3/16

Technician(s): Sterling Embers, Suwan Cho, Mason Stewart, Ethan Linden

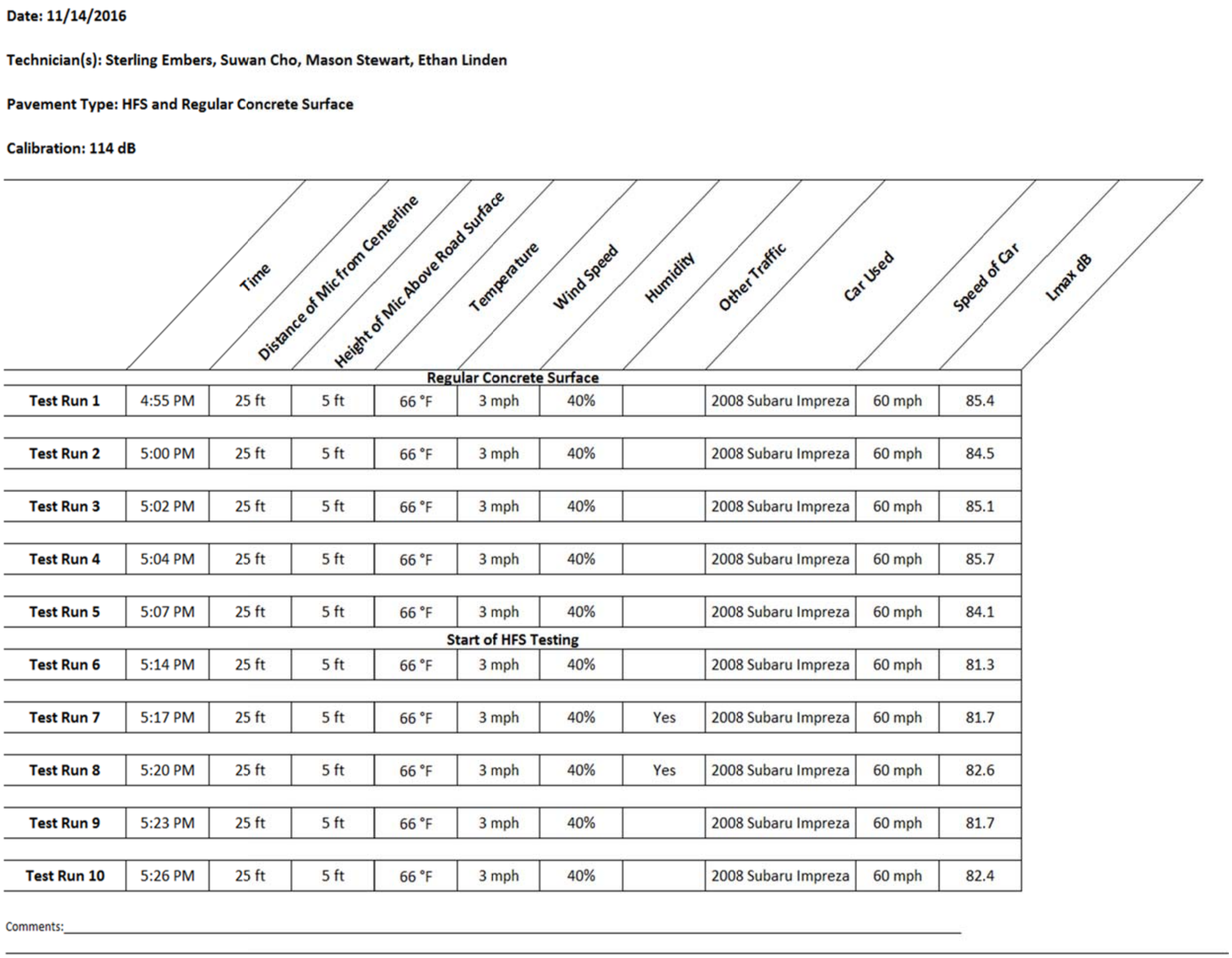
Pavement Type: HFS and Regular Concrete Surface

Calibration: 114 dB

	Time	Distance of Mic from Centerline	Height of Mic Above Road Surface	Temperature	Wind Speed	Humidity	Other Traffic	Car Used	Speed of Car	Lmax dB
Regular Concrete Surface										
Test Run 1	6:27 AM	25 ft	5 ft	70 °F	0 mph	42%		2008 Subaru Impreza	60 mph	84.2
Test Run 2	6:34 AM	25 ft	5 ft	70 °F	0 mph	42%		2008 Subaru Impreza	60 mph	85.1
Test Run 3	6:36 AM	25 ft	5 ft	70 °F	0 mph	42%		2008 Subaru Impreza	60 mph	84.8
Test Run 4	6:39 AM	25 ft	5 ft	70 °F	0 mph	42%		2008 Subaru Impreza	60 mph	85.7
Test Run 5	6:41 AM	25 ft	5 ft	70 °F	0 mph	42%		2008 Subaru Impreza	60 mph	84.6
Start of HFS Testing										
Test Run 6	6:48 AM	25 ft	5 ft	70 °F	0 mph	42%		2008 Subaru Impreza	60 mph	81.9
Test Run 7	6:51 AM	25 ft	5 ft	70 °F	0 mph	42%	Yes	2008 Subaru Impreza	60 mph	82.2
Test Run 8	6:53 AM	25 ft	5 ft	70 °F	0 mph	42%	Yes	2008 Subaru Impreza	60 mph	82.4
Test Run 9	6:56 AM	25 ft	5 ft	70 °F	0 mph	42%		2008 Subaru Impreza	60 mph	81.7
Test Run 10	6:59 AM	25 ft	5 ft	70 °F	0 mph	42%		2008 Subaru Impreza	60 mph	82.2

Comments:____

Figure C.5: Checklist for Testing (11/03/2016)



Date: 11/14/2016

Technician(s): Sterling Embers, Suwan Cho, Mason Stewart, Ethan Linden

Pavement Type: HFS and Regular Concrete Surface

Calibration: 114 dB

	Time	Distance of Mic from Centerline	Height of Mic Above Road Surface	Temperature	Wind Speed	Humidity	Other Traffic	Car Used	Speed of Car	Lmax dB
					Regular Concrete Surface					
Test Run 1	4:55 PM	25 ft	5 ft	66 °F	3 mph	40%		2008 Subaru Impreza	60 mph	85.4
Test Run 2	5:00 PM	25 ft	5 ft	66 °F	3 mph	40%		2008 Subaru Impreza	60 mph	84.5
Test Run 3	5:02 PM	25 ft	5 ft	66 °F	3 mph	40%		2008 Subaru Impreza	60 mph	85.1
Test Run 4	5:04 PM	25 ft	5 ft	66 °F	3 mph	40%		2008 Subaru Impreza	60 mph	85.7
Test Run 5	5:07 PM	25 ft	5 ft	66 °F	3 mph	40%		2008 Subaru Impreza	60 mph	84.1
					Start of HFS Testing					
Test Run 6	5:14 PM	25 ft	5 ft	66 °F	3 mph	40%		2008 Subaru Impreza	60 mph	81.3
Test Run 7	5:17 PM	25 ft	5 ft	66 °F	3 mph	40%	Yes	2008 Subaru Impreza	60 mph	81.7
Test Run 8	5:20 PM	25 ft	5 ft	66 °F	3 mph	40%	Yes	2008 Subaru Impreza	60 mph	82.6
Test Run 9	5:23 PM	25 ft	5 ft	66 °F	3 mph	40%		2008 Subaru Impreza	60 mph	81.7
Test Run 10	5:26 PM	25 ft	5 ft	66 °F	3 mph	40%		2008 Subaru Impreza	60 mph	82.4

Comments:____

Figure C.6: Checklist for Testing (11/14/2016)

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