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NOISE AND TEXTURE ON PCC PAVEMENTS
RESULTS OF A MULTI-STATE STUDY

FINAL REPORT

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16. Abstract

This report represents the second phase of a project sponsored by the Wisconsin DOT and the FHWA researching the texture and noise characteristics of Portland cement concrete (PCC) pavements. The team of Marquette University and the HNTB Corporation measured noise, texture and friction of 57 test sites in Colorado, Iowa, Michigan, Minnesota, North Dakota and Wisconsin. During 1997, new test sections were constructed in Wisconsin, including random transverse, skewed and longitudinally tined PCC pavements. Interior and exterior noise was measured on all 57 sites using the Fast Fourier Transform method with a Larson-Davis two channel real time acoustical analyzer. Subjective testing of interior noise was measured on 21 selected sections with 24 subjects with good hearing in a closed acoustical environment. Texture on all test sites was measured with the Road Surface Analyzer (ROSAN). Sand patch tests, a measure of surface texture, were also performed on most of the 22 test sections in Wisconsin. Highway noise cannot be characterized by one single type of noise measurement. For this reason, conclusions were drawn using the data acquired from all of the different measurements. These include: exterior, interior, subjective, and prominent frequency noise analysis as well as texture characteristics. Some pavement textures exhibit a definite distinctive noise that is often described as "a whine", and is exhibited as a prominent tone or discrete frequency also described as a "spike". Generally, the longitudinal tined PCC and the Asphaltic concrete (AC) pavements exhibited the lowest exterior noise levels. The AC pavements and the longitudinally tined and random skewed PCC pavements and the European texture exhibit the lowest interior noise levels. ROSAN texture measurements were relied upon and proved invaluable in analyzing the reason why different textures exhibited different noise characteristics. The ROSAN mean profile depth (MPD) and estimated texture depth (ETD) correlated very closely with sand patch. There was good correlation between tining depth and width, using the ROSAN data, and some of the loudest transverse tined pavements had both greater depth and widths, but it could not be determined which was responsible for the greater noise. Spectral analysis of the ROSAN outputs was utilized to recommend the proper random pattern for transverse tining. The patterns were tested in 1999 and both subjective and objective analyses confirmed the lack of discrete frequencies.

Conclusions include that tining depths vary tremendously among the pavements constructed, even within a single test section, uniform tined pavements exhibit a discrete frequency or whine and should be avoided, transverse tined pavements with the deepest and widest textures were often the noisiest, longitudinal and random skewed tining (1:6 skew) can be easily built, eliminate discrete frequencies while substantially reducing noise levels, and random transverse tining must be carefully designed to eliminate discrete frequencies, but may not substantially reduce overall noise levels. When comparing different pavement textures with the same mean texture depth (approximately 0.7 mm) to that of uniform 25 mm, transverse tined PCC pavements, a well randomized transverse will result in a 1 to 3 dBA exterior noise reduction, a random skew 4 dBA, a longitudinal tined 4 to 7 dBA and an opened textured AC pavement 5 dBA, based on this study. Interior noise reduction were approximately half of the exterior reductions. Recommendations include improving the quality control over tine spacing depth and width, future research on wet pavement accidents and longitudinal tining and the relative affects of tining depth and width on tire pavement noise, and specific recommendation on when to use longitudinal, random skewed and random transverse tining. Long term monitoring of noise differences of these 57 test sections is recommended in order to determine if surface texture differences can be reflected in FHWA noise models.

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NOISE AND TESTURE ON PCC PAVEMENTS -
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WisDOT Highway Research Study # 93-05
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EXECUTIVE SUMMARY

This report represents the second phase of a project researching the texture and noise characteristics of Portland cement concrete (PCC) pavements. A few asphaltic concrete pavements (AC) were also included in the study to provide comparative measures of the noise characteristics of this pavement type. The project was sponsored by the Wisconsin Department of Transportation (WisDOT) and the Federal Highway Administration (FHWA). Ten new PCC pavement test sites were built on Wisconsin State Highway 29 between Owen and Abbotsford in Clark County. These sites are located approximately 15 miles east of the 1994 Phase I test sites. The team of Marquette University and the HNTB Corporation were hired to measure the noise and texture of 57 test sites in Colorado, Iowa, Michigan, Minnesota, North Dakota and Wisconsin.

An updated literature search summarizes substantial interest and effort underway in many states to find the correct tining pattern for PCC pavements. Both the American Association of State Highway Transportation Officials (AASHTO) and FHWA have cautioned against compromising safety for slight reductions in noise levels. Based on Wisconsin's Phase I work, an interim guideline for random transverse tining was issued by FHWA and was followed by Wisconsin starting with 1996 construction.

During 1997, test sections with randomly spaced tines placed transversely, skewed and longitudinally were constructed on Highway 29 west of Abbottsford, Wisconsin. All patterns were successfully constructed, although consistency of tining depth was a problem. The random 1:4 skewed pattern was more difficult to build than the 1:6 skewed.

Interior and exterior noise was measured with a Larson-Davis two channel real time acoustical analyzer, using the Fast Fourier Transform analysis. In addition to the interior measurements, simultaneous audio recordings of interior noise were also made with a portable digital recorder. These recordings were later transferred to a compact disc for the subjective testing. Twenty-four people with good hearing were used to subjectively rate the interior noise levels of 21 selected test sections from recordings made with a digital recorder.

Texture on all test sites was measured with the Road Surface Analyzer (ROSAN) provided by the FHWA Turner Fairbanks Research Center.. The ROSAN is a van equipped with precision instruments designed to record and analyze road surface texture at highway speeds. FHWA personnel trained and supported the research team in the data gathering and analysis process. Sand patch tests, a measure of surface texture, were also performed on most test sections in Wisconsin.

Highway noise cannot be characterized by one single type of noise measurement. For this reason, conclusions were drawn using the data acquired from all of the different measurements. These include: exterior, interior, subjective, and prominent frequency noise analysis as well as texture characteristics. Some pavement textures exhibit a definite distinctive noise that is often described as "a whine", and is exhibited as a prominent tone or discrete frequency also described as a "spike".

Generally, the longitudinal tined PCC and the Asphaltic concrete (AC) pavements exhibited the lowest exterior noise levels. No significant advantage was found regarding exterior noise levels for special textures such as the European or Skidabrader. Diamond grinding of recently constructed, transverse tined PCC pavements was found to reduce exterior noise levels 2 to 3 dB (L_{10}). The diamond ground PCC pavement in this study did not have any discrete frequencies (spikes) exhibited in the interior or exterior noise spectrum. Another study recently completed in Wisconsin showed a 3 dBA reduction in exterior noise after diamond grinding transverse tined PCC pavement.

The AC pavements and the longitudinally tined and random skewed PCC pavements and the European texture exhibit the lowest interior noise levels. Tone corrected perceived noise level (PNLT) was applied to quantify the phenomena of predominant frequencies but was not successful in identifying the relative magnitude among test sections.

Twenty-one of the 57 pavements were ranked subjectively for recorded interior noise. The best PCC textures were identified (in order) as the random skewed, the longitudinally tined, and the European texture. The AC pavement was also subjectively ranked as one of the best pavements.

ROSAN texture measurements were relied upon and proved invaluable in analyzing the reason why different textures exhibited different noise characteristics. The ROSAN mean profile depth (MPD) and estimated texture depth (ETD) correlated very closely with sand patch. The correlation was not as good with friction measurements. There was good correlation between tining depth and width, using the ROSAN data, and some of the loudest pavements had both greater depth and widths, but it could not be determined which was responsible for the greater noise.

Each state's pavements are analyzed and summarized in the report. Spectral analysis of the ROSAN outputs was utilized to recommend the proper random pattern for transverse tining. The patterns were tested in 1999 and both subjective and objective analyses confirmed the lack of discrete frequencies.

Conclusions, based on analysis of all noise, texture and friction data, are summarized as follows:

- Tining depths vary tremendously among the pavements constructed, even within a single test section. This was found to be the case throughout the states analyzed. In many cases, depths specified by the highway agencies were not achieved.

- Uniform tined pavements exhibit discrete frequencies (a whine) and should be avoided.

- For all transverse tined pavements, those with the widest and deepest textures were often among the noisiest.

- Longitudinal tined PCC pavements and an AC pavement exhibited the lowest exterior noise while still providing adequate texture. The performance of longitudinal tining in wet weather has not been documented in any recent accident study.

- One AC pavement, and the longitudinally tined and random skew tined (1:6 skewed) PCC pavements exhibit the lowest interior noise while providing adequate texture. The random skewed can be easily built and eliminates discrete frequencies.

- Random transverse tining can significantly reduce discrete frequencies, but may still exhibit some discrete frequencies unless carefully designed and constructed, and will not substantially reduce overall noise;

- When comparing different pavement textures with Mean Texture Depths (MTD) approximately equal (and in the vicinity of an MTD of 0.7) the following noise reductions were observed in this study, when compared to a uniform, transversely tined, PCC pavement

PAVEMENT TEXTURE	**NOISE REDUCTIONS**	
	Exterior (L_{max})	**Interior** (L_{eq})
a) random transverse with no whine:	1 to 3 dBA	< 1 dBA
b) random skewed, 1:6	4 dBA	1.5 to 2 dBA
c) longitudinal	4 to7 dBA	2 dBA
d) opened textured AC	5 dBA	2 - 3 dBA

- Spectral analysis was used to design a random spaced rake. Two test sections were built using the rake and subjective and objective noise testing confirmed no discrete frequencies were present.

- Diamond ground PCC pavements exhibited no discrete frequencies and lower exterior noise levels (compared to random transverse) approximately 3 dB.

- FHWA noise models do not recognize the noise differences due to pavement surface texture because of lack of information over a long term and lack of state specifications guaranteeing noise performance of pavements.

Recommendations are summarized as follows:

- Quality control of macrotexture needs to be improved so that a specified texture can be built to the depth required for safety. Curing and tining operations must be separate and continuous so each can be applied at the appropriate time by separate operators.

- Research to document the amount of texture required for satisfactory wet weather accident performance of all pavements should be a high priority. Likewise, future research needs to address the relative effects of tining depth and width on tire/pavement noise characteristics, to determine which is most influential.

- If overall noise considerations are paramount, longitudinal tining that provides satisfactory friction may be considered. A spacing of 19 mm uniform tining will provide adequate friction. It should follow AASHTO and FHWA guidelines, and according to other studies, it will minimize any affects on small tired vehicles. The safety aspects of longitudinal tining have not as yet been documented and caution is urged so that safety is not compromised.

- If subjective perceptions and texture considerations are paramount, a random skewed 1:6 textured pavement, offset the opposite of any skewed for the sawed joints, may be used to achieve the texture and friction of a transverse tined pavement and most of the noise benefits of the longitudinally tined pavement, with no discrete tones;

- If texture considerations are paramount, and a skewed pattern is impractical, random-transverse tined pavements may be utilized. They should be carefully designed and built using a highly variable spacing. A 10 foot long rake with spaces between10 mm and 76 mm, designed using spectral analysis, is recommended, and has been successfully tested by three states. It is possible that a rake meeting these criteria may still result in pavements with higher overall noise levels than those with random skewed or longitudinal tining.

- Diamond grinding, if sufficiently deep to remove most of the uniform transverse texture, can be considered a treatment for PCC pavements with excessive whine.

- Research to monitor relative texture and noise on a number of these 57 test sections over a substantial time period is recommended to provide what if any noise reductions are long term and can be reflected in FHWA noise models.

INTRODUCTION

Background

As traffic volume and speed increased on the nation's highway system, Wisconsin and other states began experiencing noise problems on Portland cement concrete (PCC) pavements. It was recognized that the transverse tining on PCC pavements plays a critical role in highway noise.

In the early 1990's exterior and interior noise - generally referred to as a whine or singing noise - began to create extra expense and changes in pavement finishing practices, especially in Urban areas in Wisconsin. The DOT established a committee to resolve this problem in the early 90's. As a result of the committee work, a Research Problem Statement to study the issue was prepared by the Pavement section of the bureau of Highway Construction. In 1994, Wisconsin built 16 experimental textures on PCC pavements with the cooperation of the Wisconsin Concrete Pavement Association. Marquette University was hired to analyze noise (both interior and exterior), texture and friction characteristics of these 16 test pavements. The Center for Highway and Traffic Engineering at Marquette University teamed with the HNTB Corporation (HNTB) to measure and document the source of the noticeable high pitch whine associated with uniformly spaced, transverse tining. Traditional sound measuring techniques did not correlate with subjective ratings of sound. With the cooperation of the Minnesota DOT, who joined the project in process, a new application of the Fast Fourier Transform (FFT) method was used in measurement and analysis of interior noise, that resolved the lack of agreement with subjective ratings. The findings confirmed subjective perceptions and led to an interim FHWA guideline (1) for randomly spaced, transversely tined PCC Pavements.

During this time, a number of other states, including Colorado, Iowa, Michigan, Minnesota and North Dakota, began building experimental pavements as well. In 1997, the FHWA launched its High Performance Rigid Pavement initiative and agreed to fund construction of more experimental textures in Wisconsin. Subsequently, Marquette University and HNTB were hired again to document noise, texture and friction characteristics of over 50 different textures in the six states and present the results at a national open house and workshop.

Phase II, Impacts of Surface Texture in Wisconsin

The goals of the second project were to build on the success of Phase I and explore the issues of texture and noise in greater depth than possible in Phase I. Other states had been studying and reporting on noise and texture issues, sometimes with conflicting results. FHWA wanted a single research team to measure noise characteristics and evaluate a uniform texture measuring procedure as well. The objective of the study was to develop national guidelines for texturing PCC pavements based on national experience. These would combine the quietest possible PCC pavement texturing with superior friction and low noise characteristics. This was to be accomplished by:

- construction of 10 added test sites in Wisconsin;

- measurement of noise (interior and exterior), friction and texture of test sites in Wisconsin, Colorado, Iowa, Michigan, Minnesota, and North Dakota;

- use of the FFT method for both interior and exterior noise measurements;

- assessment of the public perception through the use of standard audiology testing by a panel of non-highway agency raters;

- selection of the best pavement textures and demonstration at an open house and workshop conducted near the new Wisconsin test sections.

A secondary objective was to perform similar measurements at 14 previously constructed test sites in Wisconsin. These include three sections built under the interim FHWA and Wisconsin guidelines for random transverse tining (a truly random pattern varying from 10 to 40 mm with at least half the spacing less than 25 mm).

The benefits anticipated are:

1) development of a new national guideline for PCC pavement texturing,

2) exploration of innovative texturing concepts,

3) reduced public complaints,

4) for no increase in cost an agency can provide acoustical relief without sacrificing friction or safety characteristics, and

5) the possibility of a national tining guideline that results in an improved tire tread design.

LITERATURE SEARCH

Noise

Since 1995, when the Phase I Literature Review was written, several related articles and reports were published in the field of tire/pavement noise generation and reduction. The following review summarizes the latest developments in the field.

A comprehensive technical report published by FHWA in 1996 (1), covered the areas of tire pavement noise and safety performance. The report presents information on the pavement research status in California, Colorado, Iowa, Michigan, Minnesota, North Dakota, Virginia, and Wisconsin, as well as in foreign countries.

In Colorado, an experimental project on I-70 east of Denver consisted of nine different texture sections. Friction, noise, texture, and profile tests were taken in 1994 before the pavement was open to traffic, and again in 1995. The study found that the longitudinal astro-turf dragged section had the lowest noise and the lowest friction number. The longitudinally tined section also produced a low noise level. The variable transverse tining sections had the highest friction values, but they were also the noisiest sections.

In Michigan, a 2 km section of pavement with an exposed aggregate surface treatment (constructed according to the German/Austrian design guidelines) was built in 1993 adjacent to a 2 km section of pavement with Michigan's standard concrete mix design with its standard transversely-tined (25 mm spacing) texture. As it was mentioned in the FHWA report (1), the noise measurements taken in 1993-1994 showed very little difference in overall exterior noise level, as well as in 1/3 octave band frequencies between the two sections. The exposed aggregate pavement is included in this study and referred to as European texture.

A significant finding was reported in the Minnesota study where the test sections consisted of various transversely tined pavements. Based on the noise results, it was concluded that noise frequency could differ greatly from one texture to the next without a change in the overall noise levels. This finding highlights the inadequacy of the highway noise measurements and analysis procedures previously used for detecting annoying tonal characteristics.

Nine test sections were constructed in 1993 on I-94 at Eagles Nest in North Dakota. The textures were tested for exterior and interior noise. Results indicated that the skewed tining and variable spaced tining produced the lowest exterior noise levels. This study also concluded that there are no significant differences between the transversely tined, longitudinally tined, or skewed-tined textures in terms of interior noise levels. Several of these test sections are included in this study.

The referenced report (1) also presented several conclusions from the foreign research projects.

A German study, for example, indicated that the exterior noise levels measured on the longitudinally tined and exposed aggregate surfaces were within 1 dBA of each other, while the transversely tined sections were about 3 dBA higher as measured with the pass-by method.

There was no correlation found between the friction and acoustic properties. Australian researchers concluded that the quietest surface texture produced to date (light burlap drag with light transverse tine depth and a randomized, average 13-mm spacing) had acceptable skid resistance.

Several other important issues were discussed in recently published articles on tire/pavement noise. Japanese researchers, for example, who investigated the relationship between road texture and tire/pavement noise, found that the noise increases with the increase of texture depths for almost all tires (2). Australian authors reported a trend in gradation of individual vehicle noise levels with different road surfaces (3). They concluded that up to 3.5 dBA-higher noise level can be expected on tined concrete surfaces for an individual car pass-by as compared to asphaltic concretes.

In March of 1998, A National Cooperative Highway Research Program Synthesis, Relationship Between Pavement Surface Texture and Highway Traffic Noise, was prepared by Roger Wayson (4). This report summarized the latest developments in the field and covers the majority of past and continuing research in the USA and foreign countries. The report also presents a summary of noise and pavement measuring techniques utilized throughout the world to study tire/pavement noise. The major conclusions of the report pertaining to noise and texture on PCC pavements are:

- Transverse tining causes the greatest roadside noise levels and may lead to irritating pure tone noise.

- Randomized spacing reduces the tonality of the tire/pavement noise and reduces overall noise levels.

- Texture depth of transverse tining also seems important to roadside noise levels from PCC pavements. "Australian test results showed that an increased depth led to a slight noise benefit (reduction), while trends for U.S. data showed even more benefit from increased depth." (This conflicts with the authors reverse comment within the Synthesis on page 39, which states: "Texture depth of the tining would also seem to play an important role. In some U.S. cases, the greatest noise was generated with the greatest average texture depth." The latter is supported by case examples within the Synthesis.)

- Construction quality is an important consideration in the final overall noise generation no matter which pavement type/texture is selected.

- Pass-by and interior noise levels do not seem to correlate.

The report also presented results of the several major studies on new concrete pavements to warrant further examination. Exposed aggregate PCC surfaces, for example, provide better acoustical qualities while maintaining good frictional characteristics and durability. Porous PCC pavements would also seem to offer an alternative in the future to reduce sideline noise levels.

However, new problems with appropriate maintenance and cleaning must be solved for all porous pavement types.

In regard to asphalt pavements, both a dense graded asphalt and, especially open graded asphalt, generally showed the greatest potential for noise reduction. This noise reduction seem to decline with surface age. As with porous concrete, a porous asphalt suffers from such problems as plugging and deterioration due to freeze/thaw cycles. Stone mastic and rubberized asphalt do not appear to give the noise reduction of open graded asphalt but were equal or better than dense graded asphalt (4).

Analyzing the widespread use of PCC pavements in the U.S., Swedish researchers (5) pointed out that some of the reported problems could be mitigated based on previous experience in dealing with excessive noise on PCC pavements. The author pointed out that in the early versions of the US traffic noise prediction method, there was a penalty of 5 to 10 dBA for grooved concrete surfacing to compensate for the objectionable pure tones. The problem of tonal noise was thoroughly studied in Europe in the late 1970’s. As a result of these activities, the use of grooved or tined concrete pavements in Europe was essentially abandoned in the 80’s. Non-randomized grooving, in particular, is very rarely used in residential areas. The authors suggested the use of random-spaced transverse-tined or longitudinal-tined textures. In the case of randomized tining, the noise levels will not be necessarily less, but it will spread acoustical energy over the range of frequencies, thereby reducing the annoyance of tire/pavement noise.

In 1998, the same authors (Swedish researchers) published a comprehensive review on texturing of PCC pavements to reduce traffic noise emissions (6). The authors reported good results for the longitudinal grinding of both new and used pavements, as well as the exposed aggregate technique that has been employed in order to reduce noise emission. Grinding of old PCC pavements eliminated the noise “penalty” (approximately 3 dBA) of the cement concrete in relation to an “ordinary” asphalt concrete.

On the issue of a subjective response to the traffic noise, it was noted that the noise having pronounced tonal characteristics was more objectionable than the noise without tonal character. Some authorities prescribed a penalty of around 5 dBA when assessing environmental impact of noise containing clear tones. Since PCC pavements textured with periodic tining cause tonal noise (often characterized as “whine”), traffic noise on these pavements will be more objectionable than on other pavements even if the A-weighted levels would be similar.

Some interesting information on the same subject was found in the above referenced report (1). According to the Rubber Manufacturers Association (RMA), “due to the manner in which the human ear evaluates the sound quality, it is not possible to measure or predict a level correlating to subjective judgement, unless it is to determine a relative ranking between sounds which are identical or similar except for the noise level.” Numerous psycho-acoustic techniques, such as perceived loudness, roughness, sharpness, harmony, etc., can be used to improve the correlation between objective measurements and subjective analysis performed by the human ear. RMA concluded that these techniques still cannot replace subjective noise evaluations.

At the same time, without objective measures, it would be very difficult and cumbersome to assess sound quality or write specifications that are based on subjective tests. All objective measures of sound quality are an attempt to generate physically measurable quantities that correlate with perceived sound quality (7). While there are a number of objective tools that can be used to provide objective measures of sound quality, the exact analysis will generally be different for each different product.

Signals with discrete components, like a typical spectrum of tire/pavement noise generated on transversely-tined textures with uniform spacing, can be characterized by "tonality" that causes poor sound quality. Such "tonality" can be determined by examining the critical band spectrum for peaks.

As it was mentioned above, when discrete tone appears in an otherwise broadband noise spectra, that noise sounds more annoying than the broadband signal itself without the tone. The amount of such annoyance seems to correlate with the amount by which the tone "sticks out" above the noise. This phenomenon is called "prominence". A literature search was performed in the attempt to quantify these prominent frequencies generated on transversely-tined pavements. A significant amount of information exists on the subject of prominent discrete tones exhibited by the stationary machines and equipment, but little information was found related to the tire/pavement noise.

Several researchers proposed procedures that would apply correction factors to the measured data to account for the increased annoyance of the tonal components. Examples include Federal Aviation Regulation (FAR) Part 36, the Federal Aviation Administration (FAA) Noise Standard, Society of Automotive Engineers (SAE) ARP 1071, the SAE Recommended Practice, and others.

For example, various scales for evaluation of annoyance for single aircraft events are used to evaluate and compare the annoyance of aircraft noise. These scales attempt to account for observer reaction to aircraft noise and to correlate observer annoyance with community annoyance. The noise scales in most common use for specifying single-event aircraft noise include the A-weighted sound level and effective perceived noise level (PNL). The latter scale is used by the FAA in the noise certification of new aircraft. The PNL scale includes the effects of the sound pressure level, frequency spectra (including presence of pure tones), duration, etc.

Tone corrected perceived noise level (PNLT) is PNL with the addition of a tone correction factor. This tone correction factor is intended to account for the added annoyance due to spectrum irregularity or discrete frequency components, such as tones. PNLT was developed for use by the FAA, specifically for evaluation of noise generated by aircraft, to improve the noisiness assessment for those sounds with prominent discrete frequencies. Like PNL, it is used in assessing subjective response to single event aircraft flyovers, which commonly contain pure tones (8).

The calculation of the PNLT is associated with relatively wide (1/3-octave) bandwidths-based tone corrections specified for this method. This would require a conversion of narrow-band measurement data (when they are available) to the one-third octave spectra before applying the procedure. At the same time, the calculation of the PNL takes into account an observer's response to the disturbing effect of pure tones such as whines and screeches.

Another possible scale to evaluate sounds with high frequency components is the D-weighting characteristic. D-weighted sound level was developed as a simple approximation of perceived noise level. Because the calculation procedure for PNL is fairly complicated, it was thought that a similar more direct measure that would allow an immediate estimate of the effect of aircraft flyover should be developed. Further, it was intended to be a more precise measure than A-weighted sound level to approximate the relative noisiness or annoyance of many commonly occurring sounds (8).

The D-weighted sound level is sound pressure level modified to de-emphasize the low frequency and emphasize the high frequency portion of sounds. The D-scale response is enhanced in the frequency range from 1250 to 10000 Hz, with the highest adjustments of up to 11 dB at 3000-4000 Hz frequencies. Similar to other measurement networks, these weighting adjustments are relative to the sound level meter response at 1000 Hz. Unlike A, B, and C-networks, the D-scale is not widely used in the industry.

The measurement standards that contain procedures for identifying discrete tones include ANSI S1.13-1976, Appendix A, and ANSI S12.10-1985, Appendix B. Identification procedure of prominent discrete tones, per ANSI S12.10-1985, is the following: “ The sound pressure level , in dB, of the discrete tone, Lt, and the sound pressure level, in dB, of the masking tone, Ln, exclusive of the tone, contained within the critical band centered at the frequency of the tone, shall be determined”. These standards uses wider Zwicker critical bands instead of narrower Fletcher critical bands utilized in ANSI S1.13-1976. A discrete tone is identified as prominent if (Lt-Ln)>= 6.0 dB. Presumably, a prominent tone might require the addition of a tone “penalty” to a measured sound pressure level.

Critical band is the largest frequency bandwidth of flat (constant spectrum level) random noise that has the same loudness as a pure tone of the same sound pressure level at a frequency equal to the geometric mean frequency of the critical band. If the band width is less than the a critical band, the loudness of the band of noise and the pure tone will be the same if they have the same sound pressure level. If the bandwidth is greater, the loudness of the band will be greater than that of the pure tone of the same sound pressure level. There is a substantial disagreement as to the relative width of critical bands.

Several authors (9)(10) criticized the ANSI 12.10-1985 procedure, called “tone-to-noise ratio” method, for notable limitations. When the method is applied to certain noise spectra (particularly spectra containing multiple tones located close together in frequency and spectra that are very irregular in amplitude) it may rate them as “not prominent”. The “prominence ratio” method was suggested to overcome these difficulties (11). Instead of using the ratio of tone power to noise power of the critical band, the prominence ratio method uses the ratio of total power of the critical (“middle”) band containing the tone to the average power in the immediately adjacent critical bands called “lower” and “upper” bands. The discrete tone is classified as prominent if the prominence ratio of the tone under investigation is equal to or greater than 7 dB. The authors of this new procedure state that their results are consistent with the subjective impression (this method will be tested in this study).

Significant differences in the perception of tire/pavement noise from the objective and subjective points of view necessitate a careful consideration of many individual (suitable) objective noise metrics. In addition, linear/nonlinear regression analysis models consisting of several objective noise metrics that most highly correlate to the subjective response should be investigated.

Friction, Texture and Ride

Texture terminology

An international standard for terminology in road surface texture has been set by the Technical Committee on Surface Characteristics of the World Road Association's Permanent International Association of Road Congresses (PIARC), as follows (12):

microtexture < 0.5 mm (0.02 in)

macrotexture 0.5 mm to 50 mm (0.02 to 2.0 in)

megatexture 50 mm to 500 mm (2.0 to 20.0 in)

In texturing of PCC pavements, microtexture and macrotexture are important for wet weather friction (1). While macrotexture has an important effect on noise and friction, highway engineers have looked to macrotexture's effect on the drainage capacity of a surface under tire pressure to reduce wet weather accidents (13). Attention to drainage capacity also reduces splash and spray, another cause of wet weather accidents.

Tire-Pavement Friction

Road surface friction is measured to determine pavement skid resistance. Skid resistance is defined in ASME Standard E 867 as the retarding force generated by the interaction between a pavement and a tire under locked, non rotating wheel condition (14). To ensure measurements made at various places and times can be compared, a standardized tire and a specific amount of water is applied to dry pavement ahead of the tire. Details are described in ASTM Standard E 274. Results are reported as the friction number (FN) - formerly referred to as skid numbers. Friction number is computed ass 100 times the force required to slide the locked test tire (at a stated speed, usually 64 km/h or 40 mph) divided by the effective wheel load.

ASTM E 274 recommends a ribbed tire (ASTM Standard E 501) for the tire. Requirements for a smooth (blank) tire are specified in ASTM E 524. Normally, five tests are made within each pavement section at intervals not greater than 0.8 km. The method in E 274 is recommended in all states (14).

Other devices are used to measure friction, but in the US, only the ASTM E 274 with either ribbed or blank tire is used. In England, a Sideways-Force Routine Investigation Machine (SCRIM) has been developed, with side friction reported as Mu number (MuN). This method is described in ASTM Standard E 670. The SCRIM measuring device uses a two wheel trailer, wheels fixed at tow-out angle of 7.5 degrees, and yields an average of two wheels, only one of which is in the wheel path (14).

It is desirable to have knowledge of pavement friction throughout a range of speeds. This may be derived by measuring friction at one or more higher speeds (higher than 64 km/h) or can be derived from texture evaluation. as well. Speed gradient is the difference in FN divided by the difference in speeds at which the friction is measured. Studies have shown that the greater the texture, the less the gradient or deterioration of friction with speed. Textures developed by steel tines were superior in friction, and maintained better friction at higher speeds because of flatter gradients. The FHWA report included testing of the friction predictive ability of texture measurements and recognized the variables in friction testing (15).

The Long-Term Pavement Performance (LTTP) division of FHWA is currently conducting a friction study and at the time of this literature search (1999) the analysis was still underway and further data acquisition remains. The goal of the study is to assess the quality of friction data that was collected, and determine whether friction testing is worthwhile. The status report on this study (16) states that friction data is significantly affected by day to day and seasonal variations. A preliminary data quality check was performed on those sections that had repeated data. According to the ASTM E 274, the recommended acceptable standard deviation used to identify problematic data is 2 SN units. Possible causes for this bad variable data could be (16):

1. Period between last equipment calibration and friction test
2. Air temperature at time of testing
3. Type of equipment used

In addition to this study, the FHWA has also set up friction test centers around the U.S. It has found that "different skid trailers (as per ASTM E 274) can be expected to measure similar values when tests are performed by well-trained technicians and if equipment is calibrated regularly (16)."

The minimum needs for friction levels are based on a variety of conditions including roadway geometry, climate and economics. As a result, FHWA has resisted specifying a minimum friction level. It is felt that each state is best qualified to determine the necessary level of friction in each given situation (17).

The United Kingdom reported efforts to at least establish guidelines for testing and setting acceptable levels. Levels are recommended but adoption is reported to be difficult because of liability concerns. Recommended levels of friction are reported for side friction and vary from 0.30 to 0.75 (18) depending on the importance of the road geometry and possibility of accidents. Generally, in the U.S. a friction number of 40 with a ribbed tire ($FN_{40}R$ at 64 km/h or 40 mph) is considered minimum for new PCC pavements.

There are many methods that can and are being used to measure friction. An experiment was conducted to develop a reference to which results from all the different methods could be related. This reference is known as the International Friction Index (IFI). One of the parameters of the IFI is the speed constant, S_p. It was found that most macrotexture measures were good predictors of S_p, but Mean Profile Depth (MPD) measured with a laser-based high speed texture meter turned out to be the best (19).

In a presentation at PIARC in 1995, Sandburg (20) recommended a laser texture measuring device to be used for measuring macro texture. This would compliment the use of an International Friction Index (IFI) and correlates highly with the speed component of the IFI.

Wet Pavement Safety

According to reports of the National Transportation Safety Board and FHWA, approximately 13.5 percent of fatal accidents and as many as 25 percent of all accidents occur when pavements are wet (21, 22).

The importance of transverse tining compared to longitudinal tining and its impact on safety were recognized as early as 1973. In a paper presented by Weaver (23) at the Symposium of the Cement and Concrete Association in England The paper references PIARC's Technical Committee on Slipperiness at the XIV Congress in 1971. Weaver concluded that "continuous channels parallel to the direction of the cross fall (cross-slope) facilitate drainage," while "continuous channels normal to the cross fall will also hold water on the pavement, requiring drainage to occur above the running surface." This led to the interest in transverse tining in the US since the mid 1970s.

Conclusions (by Weaver) of the second European symposium on concrete roads (24):

1) A machine has been developed to apply a transverse grooved texture to concrete pavements at the time of construction of the pavement.

2) The resistances to skidding of deeply brushed and grooved textures show similar initial performances; the deep grooved texture is expected to maintain the high level of resistance to skidding, particularly at high-speed, for a very long time.

3) Grooved textures can often be applied using the vibrating grooving head when the concrete cannot be textured by brushing, as a result of weather conditions or delays, saving the contractor the considerable cost of remedial texturing.

4) The machine does not require specially designed concrete mixes or construction details; concretes with maximum size of aggregate of 38 mm have been textured satisfactorily.

5) The riding quality of brush and grooved surfaces showed no significant difference; brushing

appeared to give slightly better performance but, with greater operational experience of the grooving machine, a marked improvement of riding quality was produced.

6) Randomization of the spacing of grooves in the pavement surface prevents the generation of a ‘pure tone’ or whistle which has been the cause of criticism.

7) A comprehensive machine for grooving hardened concrete pavement, as a method of retexturing, is being developed.

During field testing of various surfaces by FHWA in 1987 (25), a blank tire produced the lowest friction results on all surfaces of PCC and AC pavements and is considered a good indicator of wet pavement safety. Conclusions resulting from the study were as follows:

- Pavement texture is the dominant factor in determining wet pavement friction. Both good micro- and macrotexture characteristics are essential for good tire-pavement friction. The water present at the tire-pavement interface is expelled through the channels in the pavement macrotexture. The rough peaks of the surface microtexture penetrate the remaining thin water film and regain direct contact with the vehicle tire. On pavements with poor macrotexture, the thin water film inhibits tire pavement contact.

- Tire tread, like pavement macrotexture, provides the channels for water expulsion during wet tire-pavement friction. The reduction of tire-pavement friction due to wetness is much greater for worn tires than for new tires.

- A very small amount of water can significantly reduce tire-pavement friction. In some tests, a 0.02 mm (0.001") water film reduced friction 75 percent of the difference between the dry and wet value. This level of wetness is likely to be exceeded during any hour in which at least 0.25 mm (0.01") of rain falls.

Expulsion of water from the tire tread during braking not only requires adequate channels in pavement macrotexture and tire tread, but also sufficient time for water to flow through those channels. This time depends on vehicle speed. The higher the speed, the less the time. This time became critical in the FHWA tests (25) when speed was increased to 64 km/h (40 mph).

Skid resistance requirements are summed in the FHWA Manual (14) as follows:

- Skid resistance is generally available at adequate levels on most dry pavement surfaces. Providing adequate skid resistance is difficult when the pavement surface becomes lubricated, usually with rain water.

- Skid resistance is primarily a function of the availability of surface macrotexture to assist in draining water from the pavement-tire interface and the availability of microtexture to provide friction between the tire and the pavement surface (through adhesion).

These two conditions are required to maintain long-lasting skid resistance on pavement surfaces under varying environmental and traffic conditions. However, several factors must be taken into consideration. The most significant of these are:

- Skid resistant materials used in constructing the surface, primarily the aggregate (course for AC pavements and fine for PCC pavements).

- Pavement surface design and construction techniques that optimize surface texture (mix design for AC pavements and surface finish for PCC pavements).

- Pavement surface maintenance procedures required to prolong or restore skid resistance to properly designed and constructed pavement surfaces.

In safety analysis of driving on wet roads, it is difficult to determine how much friction is reduced because of a water film covering the road and how much wetness substantially reduces tire-pavement friction. The magnitude of this friction can be reduced by water film thickness, pavement texture, vehicle speed and tire tread. When friction falls below 75 percent of the friction difference between dry surface value and thick (>0.38 mm or 0.015") wet surface value, it is deemed critical. This critical water film thickness can vary from 0.025 to 0.23 mm (0.001 to 0.009") (14).

A U.S. study between 1970 and 1972 compared wet pavement accidents and friction on 1240 km (770 miles) of Kentucky freeways and parkways. Various measures of skid resistance were analyzed. Wet weather accident rates in terms of accidents per million vehicle miles of travel were found to increase for 112 km/h (70 mph) highways when $FN_{40}R$ decreased below 27 (26).

A study in Great Britain was summarized in 1973. It analyzed how surface characteristics of concrete roads affect wet weather accidents on these roads. An assessment was done that compared wet and dry weather on roads with similar traffic and other conditions. The assessment showed a 50 percent increase in accidents on the wet roads as opposed to the dry roads. It was also shown that the effect of wetness is greater in darkness than in light. Accidents on wet roads in darkness were 20 percent in excess of what would be expected under other conditions of light and wetness (27).

A measure of the increase in accidents involving skidding due to road wetness can be obtained by comparing dry and wet road skidding accident rates. In 1971, the difference between wet road skidding rates (27.8%) over the dry road rate (11.8%) represented an increase of 13,000 injury accidents. Factors other than skidding that contribute to wet weather accidents include impaired visibility due to spray and streaky reflections and glare at night (27).

Sabey (27) concluded that tire tread cannot make up for lack of texture. Experience of reductions in wet road accidents resulting from changes in surface texture to improve skidding resistance suggests that a level between 60 and 80% reduction in these accidents should be within reach.

An informal survey and analysis on the effect of transverse PCC tining was conducted by a Minnesota District traffic engineer and reported in 1996 in the WisDOT Phase I report (28). It showed that there was a reduction of about 8 percent in the wet/total accident rates on transverse tined concrete pavements compared to other more worn pavement surfaces. A reduction in splash and spray during wet pavement conditions was also noticed on the tined surfaces. This was another contributing factor to the lower wet/total accident rate (1).

When performing wet pavement accident studies, the proportion of annual hours during which the pavement is wet varies with geographic variations within a state and with variations of climate from year to year. This makes wet pavement accident studies very difficult and time consuming if exposure time to wet pavements is recognized. A procedure for estimating wet pavement exposure was developed in the 1987 study by FHWA (25), using the WETTIME model and is summarized in the Skid Resistance Manual. Pages showing curves developed for each state for three years during the 1980's are included in an Appendix A, Reference (14).

The FHWA Skid Resistance Manual (14) discusses what friction safety margin is necessary on a highway. It points out the difficulty, due to the large number of variables. Since this demand for friction is very difficult to measure, highway engineers typically look for relatively high wet pavement accident rates to determine if demand for friction exceeds available friction. Curves showing variation in typical accident rates with variation in friction number are shown in the Skid Resistance Manual.

Similar findings resulted from a study performed on the Edens Expressway reconstruction project in Illinois and are reported in 1988 (29). Transverse texture was provided by tines spaced not less than ½ inches and not more than 1 inch. Random spacing was encouraged to reduce noise that develops from uniform spacing. The total accidents, four years before the construction compared to four years after the construction, were reduced by 22.9 percent. Wet, snow/ice accidents reduced by 40.8 percent. Additional benefits observed on pavements with deeper textures included reduction in water spray due to improved surface drainage and reduction in headlight glare due to rougher pavement surfaces (29).

A French study (30) of accident rates on AC road surfaces was conducted in 1996. Its results showed that for 90 percent confidence interval using Poisson’s distribution, the accident rate when wet increased by at least 50 percent when moving from a section with a Sideway Force Coefficient (SFC) > 0.60 to a section with an SFC < 0.50. This change in SFC results in a <u>fivefold</u> increase in wet weather accidents. (Note: SFC values are similar to U.S. standard friction values. The threshold value for SFC for which its wet weather accident rate increased significantly was a SFC of 0.50. The study’s conclusion resulted in establishing a minimum threshold value for friction of SFC = 0.50 and a minimum value for macrotexture of ETD = 0.40 mm (30).

Texture Measurement Methods

Methods for measuring texture include the sand patch, grease patch, silicone-putty, stereo-photographic analysis, profile tracing, water outflow method, and more recently, pulsed laser light. The sand patch test is described in ASTM E 965, and consists of spreading a specific volume of fine glass beads of uniform gradation to a single layer thickness with a hockey puck and measuring the resultant diameter. A formula is given to convert to mean texture depth (MTD). A minimum MTD value for sand patch of 0.8 mm with a minimum of 0.5 mm for any individual test is recommended as a guide by the FHWA TWG (31).

The sand patch (or volumetric patch method) is deemed crude, depends on the operator, and can only be used on portions of the pavement closed to traffic (27). Great variability of results often occurs (but this can also be due to variability of texture as well) (32).

This has given rise to the use of non-contact surface profiling techniques that can be used to measure the mean texture depths of the pavement. The results of these techniques generally correlate well with texture depths measured with the volumetric patch method. Standards and definitions have been developed to improve such correlation and provide uniform world wide compatibility of measurements.

Before the advent of the laser-based, high speed texture meter (HSTM) it was impossible to successfully determine the relationship between texture depth and accident rates. This was due to the fact that texture depth could not be measured on a large scale on in-service roads. Roe, Webster and West (33) conducted a test in Great Britain using the HSTM to calculate the average texture depth for 10-meter lengths of road throughout a few networks of roadways. This measurement is known as the sensor-measured texture depth (SMTD). When comparing these values against the accident rates, it was shown that "the accidents occur on the lower textures at a greater frequency than would be expected on the basis of the existence of such textures on the road". The approach that they used to estimate adequate texture levels was to "determine the texture level at which the proportion of accidents exceeds the proportion of textures on the network". The range of texture levels fell between 0.6 and 0.8 mm. This translates to a high risk of accidents on roads with an average SMTD below 0.7 mm. In general, it was shown that a higher road friction coefficient will result in a lower accident rate (33).

The original and primary goal of the Road Surface Analyzer ($ROSAN_{v)}$ project at FHWA's Turner-Fairbanks Highway Research Center, Pavement Surface Analysis lab was the development of a portable and automated system for the measurement of pavement texture at highway speeds along a linear path as a replacement of the manual Volumetric Patch Method as outlined by ASTM-E965 and ISO 10844. Volumetric Patch Method procedures are valid for concrete or asphalt paving whose surface has not been treated or designed for improved drainage (such as grooving, tining, or open-graded porous asphalt) or milled or to remove rutting. Prior to completion of the $ROSAN_v$ research work, ASTM Committee E-17 approved in November of 1996, ASTM Standard E1845, "Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth" from a profile of pavement macrotexture.

An automated measurement system such as $ROSAN_v$ provides a larger quantity of valuable and less expensive texture data while greatly reducing the safety and traffic control problems inherent to the manually performed Volumetric Patch Method. The "v" in $ROSAN_v$ stands for "vehicle-mounted" in that $ROSAN_v$ can be mounted on any vehicle using a temporary bumper hitch (34) .

ASTM Standard E1845 computes a Mean Profile Depth (MPD) based on a computational procedure and uses a linear transform for Estimated Texture Depth (ETD) which is equivalent to the mean texture depth (MTD) of the sand patch test. The $ROSAN_v$ system relies upon an algorithm that mimics the rubber pad (puck) movement across the pavement surface as used in the Volumetric Patch Method. This may be more desirable for measuring MPD as it would be the Volumetric Patch Method measurements to which the system would be calibrated. The MPD computed using the ROSAN algorithm is denoted as RMPD. The research team was very pleased with the correlation found between the Volumetric Patch Methods and the Mean Profile Depths (MPD) computed using the ROSAN MPD algorithm (34).

The measurement process and the reliability of the Mean Profile Depth (MPD) and Estimated Texture Depth (ETD) results were discussed in a paper presented by Sandburg at the PIARC World Congress in 1995 (20). The advantages of this method over the sand patch are covered. A close correlation of MPD/ETD with field tests on 42 sites was found, as well as a close comparison of friction gradient (speed component) and MPD.

Construction Problems with Texturing

In an interim report of the FHWA TWG (31), the importance of the AASHTO Guidelines for concrete mix design was summarized. The report recommended 25 percent siliceous sand and recommended following the PCA and ACI mix design procedures covering water cement ratio, air content, cement factor and non-polishing aggregate.

Prior researchers have reported problems with the texturing procedure for PCC pavements. Due to the weather variations and configuration of the paving train, the tining of PCC pavements is quite variable. Often the concrete has begun to set prior to the tining operation (23, 28, 31). Quality of curing of PCC pavements and bridge decking is considered a problem in the U.S.

Requirements for Surface Textures in Concrete

Studies of the performance of textures in concrete surfaces indicated that where particles of aggregate were contained in the surface they were more durable than those composed only of laitance. Also, the experience of many pavement engineers has shown that under certain weather conditions, or as the result of plant breakdowns and delays, the concrete used in road construction stiffened too quickly to allow the specified texture depth to be achieved using a wire brush. Therefore, the following fundamental requirements were indicated (35):

1. The required surface profile should be molded in homogeneous concrete, thereby ensuring that the texture does not comprise weak mortar and disturbed particles;
2. Variations in the stiffness of the concrete in the pavement surface - due to weather conditions, delays or water content - must be overcome to produce the required texture.

Plastic Concrete Grooved Surfaces

Transverse grooves cut into the surface of hardened concrete have been shown to restore high levels of resistance to skidding; the inadequacy of longitudinal grooving for this purpose has been clearly demonstrated (35).

Texturing trials using patterned rollers and tined rakes were tried with limited success in very workable concrete, but in dense well-compacted concrete particularly in warm weather, satisfactory penetration could not be achieved at all. Frequently, torn or disrupted surfaces with poor riding quality resulted. These methods were therefore rejected (35).

A profiled steel float with ribs mounted on its surface proved successful even in warm weather (and even after delays) if the concrete at the surface could be remobilized by a vibrator mounted on the float. The machine spans the pavement and is controlled by a single operator standing at the control console. The grooving head is towed across the pavement surface from a carriage. A rotary vibrator is mounted on the grooving head. The operator and his controls travel across the machine with the grooving head. This gives him a close view of the head at all times and permits grooving in both directions across the pavement (35).

Longitudinally Tined and Diamond Ground PCC Pavements

The 1996 FHWA report (1) summarized the safety performance of longitudinally tined pavements and stated that they provide good initial friction, but long term studies indicate they can lose their desirable friction properties. This is related to the quality of aggregate used as well. Both spacing and width are important to avoid motorcyclist's complaints. Drainage problems can occur in sag vertical curves, super-elevation transitions and on flat longitudinal grades where rainfall is heavy and/or where pavements are subject to frequent freezing conditions. The FHWA report indicates regular use of longitudinal tined pavement in California, but notes that the United Kingdom had prohibited longitudinal tining because it will not meet their published friction standards.

The FHWA report (1) also stated that a longitudinally tined texture spaced at 20 mm, 3 mm wide and an average depth of 5 mm (3 - 6 mm range) provides a quiet ride. Recent friction tests in Virginia and California show satisfactory values of friction after 20 years of interstate traffic. The principal advantage is noise reduction, and the principle disadvantage is a lower FN, due to slower surface drainage and greater splash and spray compared to transverse tining. Increasing pavement cross slope to 2.5 percent was suggested to alleviate some of this problem.

No definitive, wet-pavement accident studies have been conducted comparing longitudinal and transverse tined PCC pavements. This need is often stated but remains to be addressed.

AASHTO has recommended that longitudinal grooving of PCC pavements should be 2.4 mm wide, spaced at 19 mm and at a depth of 3.2 - 4.8 mm. Closer spacing and shallower depth result in less durability, while wider spacing added significantly to noise and loss of directional control in light weight cars and motorcycles (14). Longitudinal grooving (diamond grinding) reduces wet weather accidents (compared to the "before grooving" condition), although the FN_{40} does not increase significantly. Vehicles track in the grooves and the grooves provide for escape of water, reducing hydroplaning.

A recent before and after noise study on the effects of diamond grinding of PCC pavements was reported by Marquette University and HNTB in November, 1998 (36). The locations are on northbound and southbound I-94 in St. Paul, Minnesota, including the adjacent bridge deck over the Mississippi River. Part of the pavement and bridge deck was transversely tined with a 38 mm random pattern (1995) and part transversely tined with a 19 mm random pattern (different construction stages). Because of objections to the noise from adjacent residents, the pavements and bridge deck were diamond ground in 1998, with before and after noise measurements taken in June and September, respectively. The conclusion of the study is that diamond grinding of tined PCC pavement reduces the L_{10} (sound pressure level exceeded 10 percent of the time) traffic noise by 2-3 dB (36). In a 1999 WisDOT study, diamond grinding of older uniform transverse tined PCC pavement resulted in an exterior noise reduction of 3 dBA (37).

The New Jersey DOT (NJDOT) conducted an extensive noise evaluation study along I-287 in New Jersey. This study was in response to reports of high noise levels along I-287 between the city of Montville and the New York State border. The main objective of this study was to determine whether eligible receptors were subject to traffic noise levels that warrant abatement consideration. The source of the high noise levels along this road is the transverse tining provided for friction (38).

It has been observed that this transverse-tined surface generates high levels of "narrow-band" noise which can be described as a whine. To document the noise contribution of the transverse-tined concrete, an extensive technical analysis was conducted. The purpose of this analysis was to develop an input factor that could be incorporated into the noise model (STAMINA) in order that the model would be able to address noise levels form varying roadway surface conditions. In order to obtain conclusive data regarding the transverse-tined concrete noise contribution, a 1500-ft section of I-287 was diamond-ground to remove the transverse tining and impart a longitudinal tining (sic) pattern, and the section was then included in the noise study. As there is a safety compromise reportedly associated with longitudinal tining a safety comparison test was conducted between the transverse and longitudinal patterns. An older section on I-78 with transverse tining was also selected to be included in the noise study to determine the effect of wear on noise contribution. Measurements were taken along asphalt sections of I-287 as well (38). Analysis indicated that the transverse-tined concrete roadway surface contributes an additional approximate 4 dB to the traffic noise level along I-287 as compared to asphalt and longitudinal tined concrete (38).

As mentioned, though, longitudinal tining does have safety compromises. Longitudinal tining poses potential water runoff problems as the longitudinal tines retain water as opposed to the transverse tines which are designed to promote surface drainage. Inadequate surface drainage can cause hazards including roadway spray and ice formation in cold weather. Water retention that causes ice formation would require the use of additional deicing chemicals to eliminate slippery surface conditions. Excessive deicing chemicals can affect the wear of the pavement, pollutant loading in receiving water bodies of the vicinity, and add to winter maintenance costs. Additionally, water retention on the roadway surface may cause premature pavement deterioration and cracking thereby requiring more frequent maintenance and life-cycle costs (38).

Skid tests were performed to compare the wet weather skid resistance of the transverse-tined surface with the longitudinal-tined section. The test consisted of a skid test trailer towed along the roadway at 60 mph while spraying water on the surface just ahead of the test wheel and then locking the test wheel. The test tire was a smooth, blank tire. The results indicated a 16 percent reduction in the wet weather skid resistance of the longitudinal tining when compared with the transverse tining (38).

In conclusion, roadway surface alteration to longitudinal tining for noise abatement has been determined to be unacceptable and not recommended for implementation prior to this study (38).

In a study conducted by Marquette University in cooperation with WisDOT, crash rates were compared between 290 km of continuously ground and 115 km of transversely tined concrete pavements in Wisconsin. All 11,219 reported crashes at the study sites during the 6-year period 1988 through 1993 were analyzed. The study found that longitudinally ground PCC pavements had lower overall crash rates than transversely tined PCC pavements (39).

Ride

The international roughness index (IRI) was established following international efforts to develop a uniform method of measuring road roughness. Work supported by the World Bank established an experiment to develop standardization, and by the 1990's, the US had moved to adopt same. But inconsistencies exist not only between agencies using different devices, but even within the same agency on the same section (40). No prior work was found comparing the impact of IRI on road noise.

Noise vs. Safety Issue

Issues surrounding the trade-off between noise and safety have begun to arise. An FHWA Technical Work Group (TWG) met between 1993 and 1996 to “update guidance on methods to obtain high pavement surface friction values while minimizing tire/pavement noise.” The impetus to that effort was a number of complaints of residents and motorists driving over transversely tined pavements, as well as several legislative mandates calling for corrective action on roadway sections deemed to have objectionable noise. A report was issued (1) summarizing ongoing research in eight states. The noise portion has been summarized earlier in this report. The report concluded that a pavement “material type selection should not be based solely on noise considerations from the tire/pavement interaction.” Both FHWA and AASHTO currently recommend that safety should not be compromised to obtain a slight, usually short term, initial reduction in noise levels. This corresponds with written memorandums of FHWA on highway noise. The work of this TWG led to an interim guideline on randomization of transverse tining, primarily based on work of the WisDOT (28).

METHODOLOGY

Construction

Test sections were designed to afford a complete range of texture possibilities, based on the best results from Phase I in Wisconsin, without adding substantial cost to construction. European technology (layered construction with exposed aggregate) was not considered because of limited results in Michigan and the added costs. A complete range of random transverse, random skewed and longitudinal sections were built, with little added cost, in the westbound direction of a ten mile section of Wisconsin Highway 29, west of Abbotsford, just east of the test sections built in 1994.

Construction was completed in July, 1997, but noise and texture measurements were delayed until the full divided highway was opened in Fall, 1997. Texture measurements were completed in early 1998.

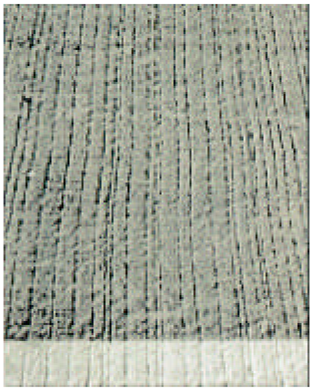
Because of the warm spring and early summer weather, depth of tining was an issue. The problem occurred on hot and windy days when the tining machine had to fall back and apply curing compound to the pavement. By the time it caught up with the paving train, the pavement had begun to set. The placement of a research assistant on site during all construction was necessary to continually monitor and report problems.

The textures constructed were as follows:

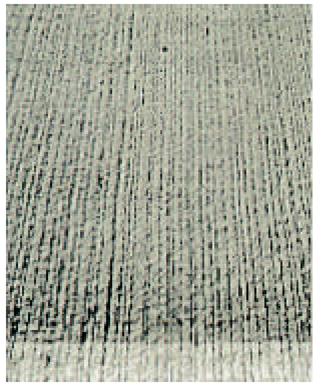
1. Random 1 Transverse, 25 mm (1") average spacing (with 50% under 25 mm)
2. Random 2 Transverse, 19 mm (3/4") average spacing (with 50% under 25 mm)
3. 25 mm (1") uniform transverse (former state standard, for comparative purposes)
4. Random 1 skewed, 1:6 Left Hand Forward (LHF)
5. Random 2 skewed, 1:6 LHF
6. Random 1 skewed, 1:4 LHF
7. Random 2 skewed, 1:4 LHF
8. Random 1 Longitudinal
9. Random 2 Longitudinal
10. 25 mm (1") uniform Longitudinal

All texturing was preceded by longitudinal turf drag and all depths were specified to be 3 mm deep. Photos of each texture taken at the time of noise or texture measurements are shown in Figures 1a and 1b. Captions beneath show ROSAN ETD (ETD), mean tine depth (d) and width (w), all in mm.

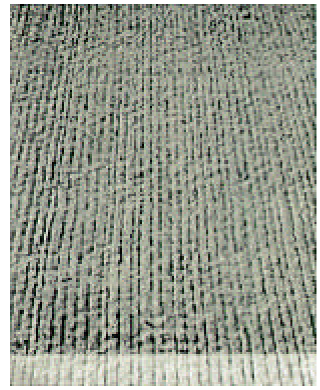
The contractor had no problems constructing the 1:6 skew, or the longitudinal tining pattern. He did report that the 1:4 skew pattern was more challenging, though. The advance notification of the skewed patterns allowed the contractor to experiment with skewing the tining machine by advancing one side (left hand forward) to accomplish the tining. The normal tining rake width of 3 meters (10 feet) had to be reduced to 2.4 m (8 feet) to accomplish the skew.



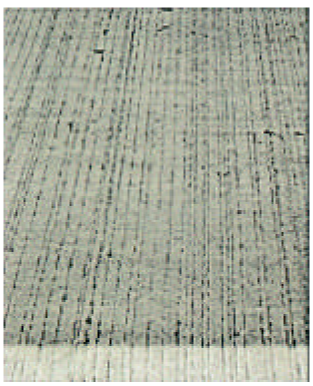
25 mm Random 1 Transverse
ETD = 0.656, d = 2, w = 5.7



19 mm Random 2 Transverse
ETD = 0.766, d = 2.2, w = 6.1

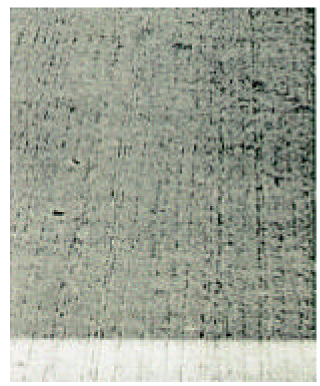


25 mm Uniform Transverse
ETD = 0.659, d = 1.9, w = 5.3



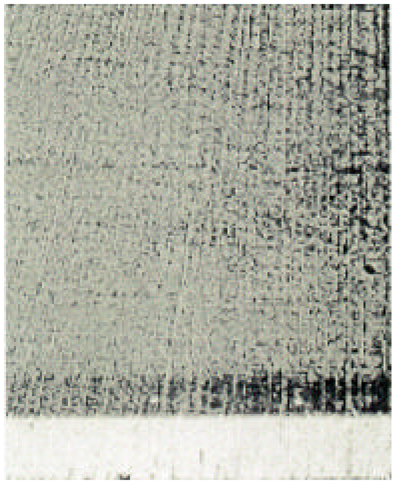
Random 1 Skewed, 1: 6 LHF
ETD = 0.955, d = 2.3, w = 5.5

Random 2 Skewed, 1: 6 LHF
ETD = 0.708, d = 1.6, w = 4.8



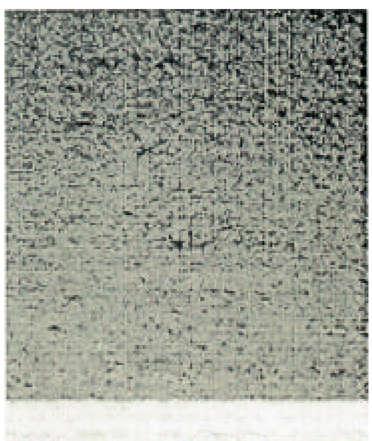
Random 1 skewed, 1: 4 LHF
ETD = 0.834, d = 2.6, w = 5.7

Figure 1a: New Wisconsin



Random 2 Skewed, 1:4 LHF
ETD = 0.718, d = 1.5, w = 4.9

Random 1 Longitudinal
ETD = 0.712, d = NA, w = NA



Random 2 Longitudinal
ETD = 0.794, d = NA, w = NA

25mm Uniform Longitudinal
ETD = 1.249, d = NA, w = NA

Figure 1b: New Wisconsin

Prior Wisconsin Test Pavements

Eight of the 16 PCC pavement test sections built in 1994 Wisconsin as part of the Phase I project were included in this project. They are located on Wisconsin State Trunk Highway (STH) 29, from Stanley to Owen, and are as follows with their original numbers (all preceded by a longitudinal turf drag and all at 3 mm depth, except where noted):

- 6. 25 mm (1") uniform longitudinal
- 8. 25 mm (1") uniform skewed, 1:6 LHF, 1.5 mm (1/16") depth
- 9a. 13 mm (½") uniform transverse,
- 9. 13 mm (½") uniform transverse, 1.5 mm (1/16")
- 10. 19 mm (3/4") uniform transverse,
- 11. Manufactured random
- 15. 25 mm (1") uniform transverse (former WisDOT standard)
- 16. Skidabrader (a blasted, set, but uncured PCC pavement with LTD only prior to treatment)

The following test sections are located on I-43 southwest of Milwaukee:

- I-43 # 1. Waukesha County SHRP Asphaltic Concrete Pavement (ACP), 1992
- I-43 # 2. Waukesha County Standard ACP, dense graded, 1992
- I-43 # 3. Walworth County Standard ACP, dense graded, 1993
- I-43 # 4. Walworth County Stone Matrix Asphalt (SMA), 16 mm (5/8") max. aggregate, 1993
- I-43 # 5. Walworth County Ground PCC pavement (constructed in 1978, diamond ground in 1993)
- I-43 # 6. Waukesha County SMA, 9 mm (3/8") max. aggregate, 1992.

Photos of each texture at the time of noise or texture measurements are shown in Figures 2 and 3.

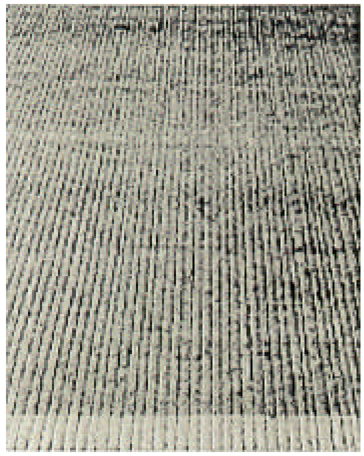
Other Random Transversely Tined Pavements in Wisconsin

Since new guidelines on tining had been adopted by WisDOT, several random transversely tined pavements have been constructed. Four different pavements were included to see the impact of the variable spaced tining in practice. The four, with this project's test numbers are:

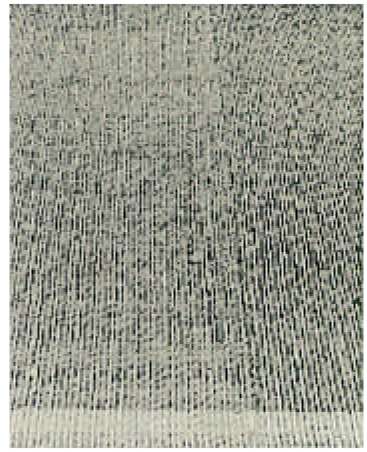
- R0. Wis. Hwy. 29 eastbound, opposite the westbound test sites and part of Phase I interior noise testing, built by Streu Construction (1994) and measured in Phase I; 21 mm avg.
- R1. US 51, N. of Merrill, built by Vinton Construction (1996); with 25 mm avg.
- R2. US 151, near Beaver Dam, built by Zignego Construction (1996) with 25 mm avg.
- R3. Wis. 26, near Jefferson, built by Trierweiller Construction (1996) with 25 mm avg.

Photos of each texture taken at the time of noise or texture measurements are shown in Figure 4.

25 mm Uniform Longitudinal
ETD = 0.7, d = NA, w = NA

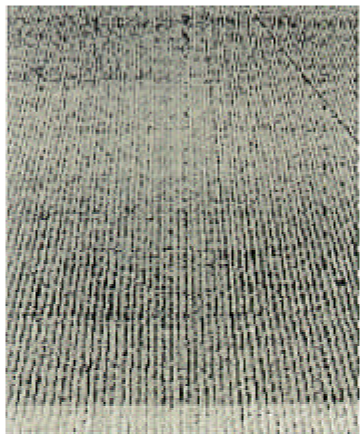


25 mm Skewed 1:6 LHF
ETD = 0.7, d = 1.3, w = 4.6

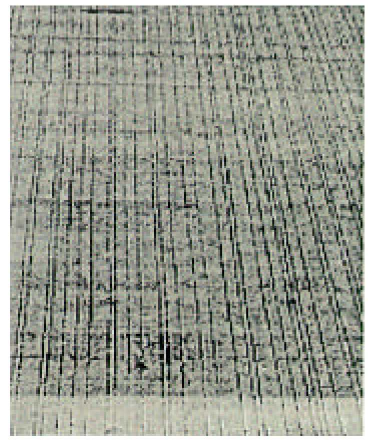


13 mm Uniform Transverse
ETD = 0.417, d = 1, w = 3.4

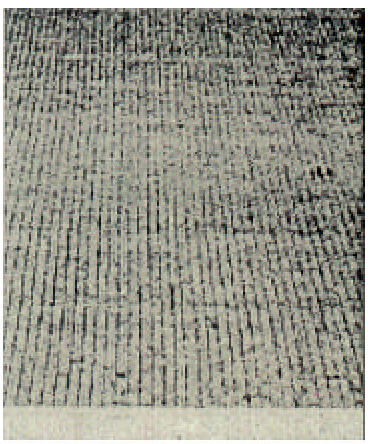
13 mm Uniform Transverse
ETD = 0.399, d = 1, w = 3.5



19 mm Uniform Transverse
ETD = 0.283, d = 1.1, w = 4



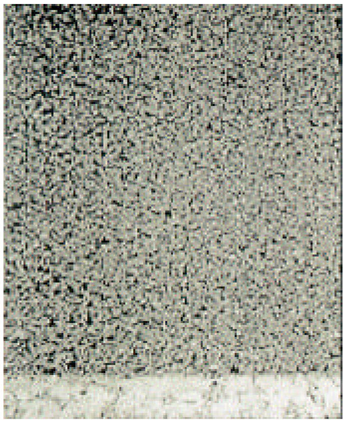
Manufactured Random Trans.
ETD = 0.274, d = 1.2, w = 4.1



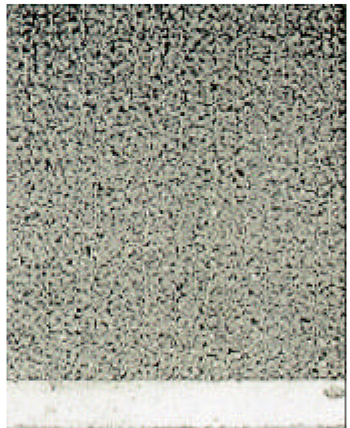
25 mm Uniform Transverse
ETD = 0.27, d = 1, w = 4.1

Skidabrader
ETD = 0.83, d = NA, w = NA

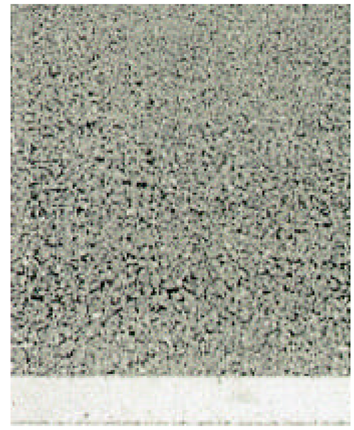
Figure 2: Prior Wisconsin



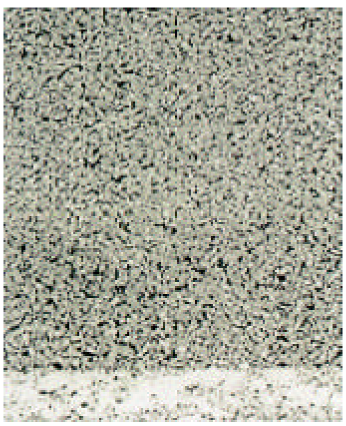
I-43 #1, Waukesha Cty. SHRP ACP
ETD = 0.248



I-43 #2 Waukesha Cty. Std. ACP
ETD = 0.174

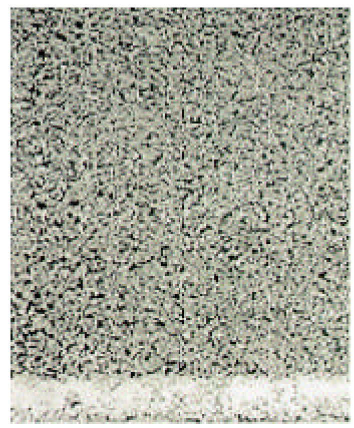


I-43 #3Walworth Cty. Std. ACP
ETD = 0.097



I-43 Walworth 16 mm SMA
ETD = 0.748

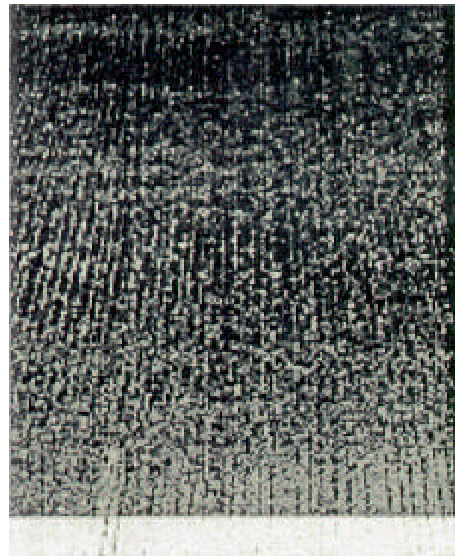
I-43 #5 Diamond Ground PCCP
ETD = 0.918



I-43 Waukesha 9 mm SMA
ETD = 0.616

Figure 3: Prior Wisconsin

RO Hw. 29 EB 21 mm Random Transverse ETD = 1.138, d = 2.4, w = 6.7



R1 US 51, 25 mm Random Transverse ETD = 0.869, d = 2.2, w = 5.2

R2 US 151, 25 mm Random Transverse ETD = 0.713, d = 1.9, w = 5.2

R3 Hw. 26, 25 mm Random Transverse ETD = 0.952, d = 2.6, w = 6.5

Figure 4: Other Wis. Random

Other States Test Pavements

Colorado

In 1994, the Colorado DOT constructed nine test sections on I-70 near Deertrail. Five of those test sections were selected for this study. All sections were preceded by LTD, and planned to be 3 mm deep and 3 mm wide. They are as follows:

1. 25 mm (1") uniform transverse tining, (Colorado's standard at the time)
3. 19 mm (3/4") average random transverse tining (16, 22 and 19 mm)
4. 13 mm (½") uniform transverse tining
5. 19 mm (3/4") average random transverse saw cut (16, 22 and 19 mm)
7. 19 mm uniform longitudinal saw cut
9. 19 mm uniform longitudinal tining

Photos of each texture taken at the time of noise or texture measurements are shown in Figure 5.

Iowa

Iowa constructed nine test sections in 1993, and seven were chosen for inclusion in this study. They are located on Iowa Highway 163 in Polk County northeast of Des Moines, all with initial LTD, as follows:

1. 13 mm (½") uniform transverse, 3-5 mm deep
2A. 19 mm (3/4") uniform transverse, 3 mm deep
3. 19 mm (3/4") uniform longitudinal, 1.5 mm deep
4. 19 mm (3/4") uniform longitudinal, 3-5 mm deep
5. 19 mm (3/4") variable transverse, 3-5 mm deep
8. Milled PCC pavement (carbide ground)
9. 13 mm (½") uniform transverse, sawed

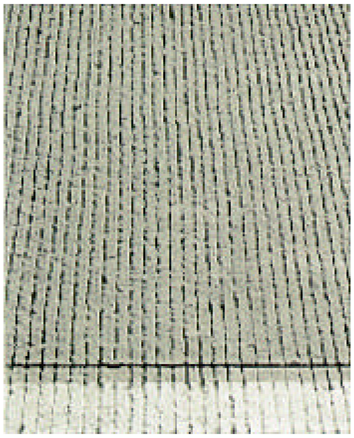
Photos of each texture taken at the time of noise or texture measurements are shown in Figure 6.

Michigan

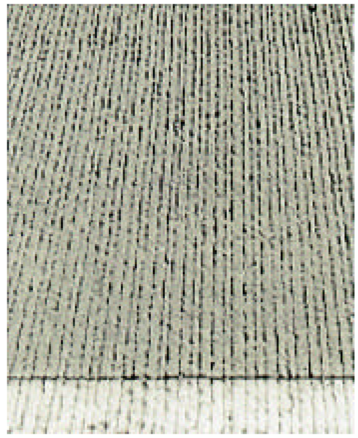
Michigan constructed a two layer European exposed aggregate pavement on I-75 in downtown Detroit in 1993. Two test sections were selected for this study, as follows:

1. European Exposed Aggregate surface
2. 25 mm (1") uniform transverse (Michigan standard)

Photos of each texture taken at the time of noise or texture measurements are shown in Figure 6.

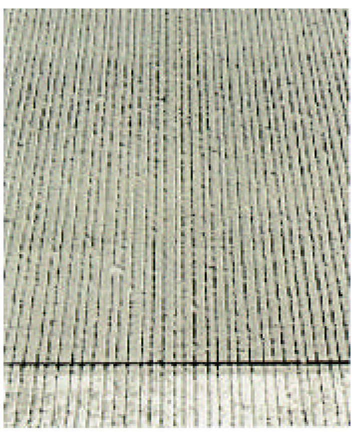


25 mm Uniform Transverse
ETD = 1.247, d = 3.4, w = 7.4

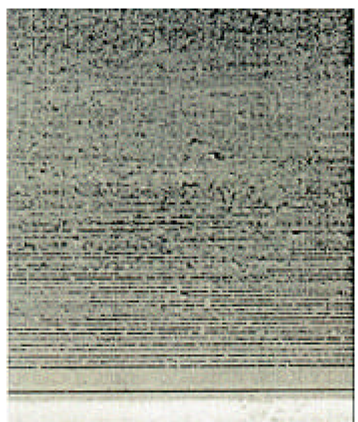


19 mm Random Transverse
ETD = 1.834, d = 3.5, w = 7.2

13 mm Uniform Transverse
ETD = 1.793, d = 2.2, w = 6.2



19 mm Random Transverse saw cut
ETD = 1.738, d = 4, w = 7

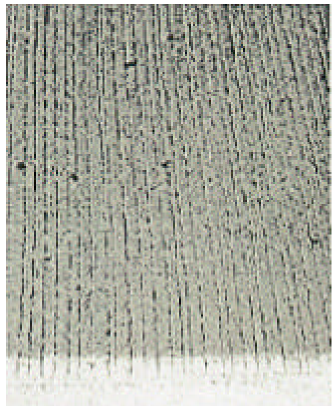


19 mm Uniform Longitudinal saw cut
ETD = 3.22, d = NA, w = NA

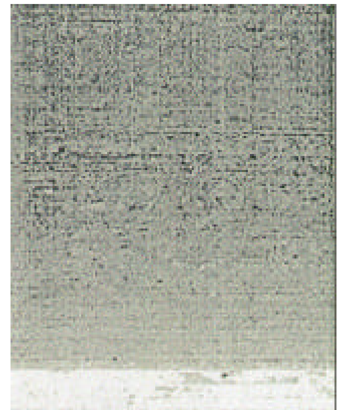
19 mm Uniform Longitudinal
ETD = 1.736, d = NA, w = NA

Figure 5: Colorado

13 mm Unif. Trans. IA
ETD = 0.701, d = 1.3, w = 5.1



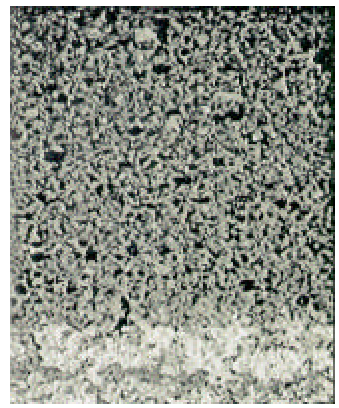
19 mm Unif. Trans. IA
ETD = 0.726, d = 1.7, w = 5.4



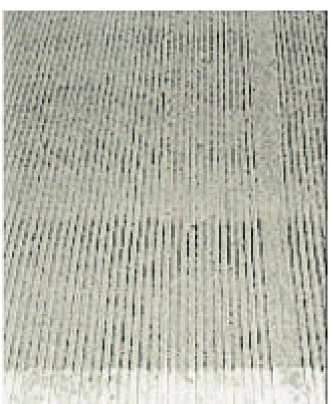
19 mm Unif. Long., IA
ETD = 0.838, d = NA, w = NA

19 mm Uniform Longitudinal, IA
ETD = 1.253, d = NA, w = NA

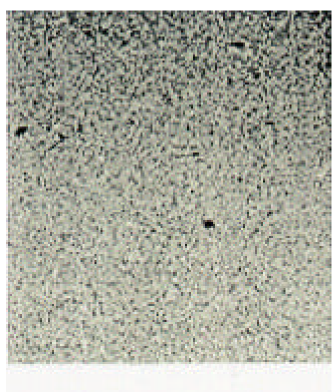
19 mm Random Trans., IA
ETD = 0.85, d = 1.5, w = 5.6



Milled Surface PCCP, IA
ETD = 0.835, d = NA, w = NA



13 mm Unif. Trans. Saw Cut, IA
ETD = 1.046, d = 2.2, w = 5.9



European Texture, MI
ETD = 0.414, d = NA, w = NA

25 mm Uniform Trans., MI
ETD = 0.523, d = 1.2, w = 4.2

Figure 6: Iowa and Michigan

Minnesota

Minnesota selected three sections of pavements constructed in the past for this study. Because they wished to have more test sections, they separately contracted with Marquette University to have five more included. They are reported on in this report for comparative purposes. The eight sections (all with LTD) are as follows:

1. 19 mm (3/4") uniform longitudinal tining (built in 1996 on US 169);
2. 19 mm (3/4") random transverse (built in 1996 on US 169);
3. 19 mm (3/4") random transverse (built in 1996 on US 12);
4. 38 mm (1 ½") random transverse (built in 1994 on Minn Hw. 55);
5. LTD only (built in 1990 on I-494);
6. 38 mm (1 ½") random transverse (built in 1994 on US 169)
7. LTD only (built in 1996 on US 169)
8. 19 mm uniform longitudinal tining (built in 1996 on US 169)

Photos of each texture taken at the time of noise or texture measurements are shown in Figure 7.

North Dakota

North Dakota built nine test sections on I-94 near Eagle's Nest in 1994. Six were selected for inclusion in this study. They include initial LTD textures and are as follows:

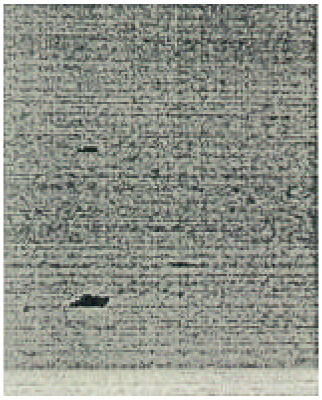
1. 25 mm (1") uniform skew, 1:6 RHF
2. 19 mm (3/4") uniform transverse
6. Variable (26, 51, 76 and 102 mm, or 1",2", 3" and 4") random transverse
7. 13 mm (½") uniform transverse
8. 19 mm (3/4") uniform longitudinal
1. 25 mm (1") uniform transverse (for control)

Photos of each texture taken at the time of noise or texture measurements are shown in Figure 8.

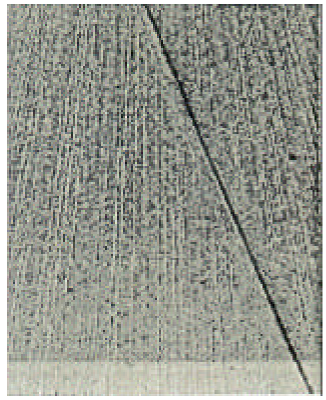
Exterior Noise Measurements

Test Vehicles

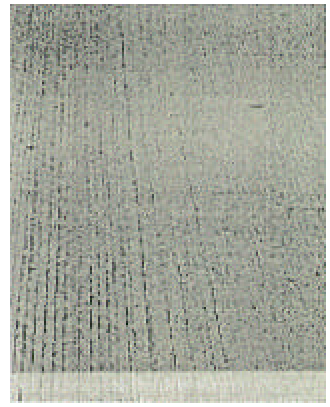
A 1996 Ford Taurus was used for all exterior and interior noise measurements. Tire air pressure was monitored throughout all measurements and kept at manufacturer's specification. The vehicle and close up photo of the tire are shown in Figure 9.



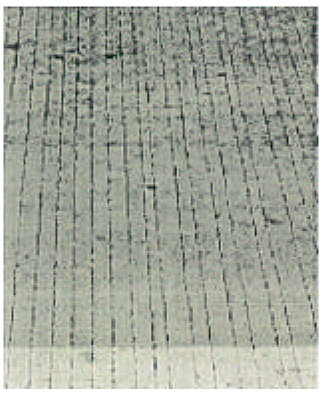
19 mm Uniform Longitudinal
ETD = 0.928, d = NA, w = NA



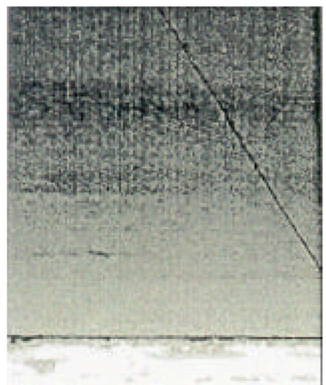
19 mm Random Trans.
ETD = 0.556, d = 1.5, w = 4.7



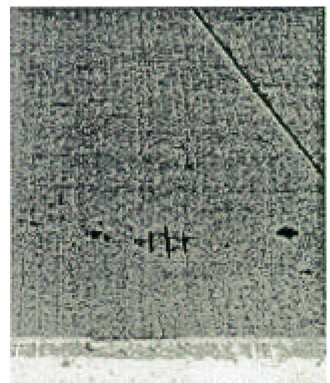
19 mm Random Trans.
ETD = 0.573, d = 1.6, w = 4.9



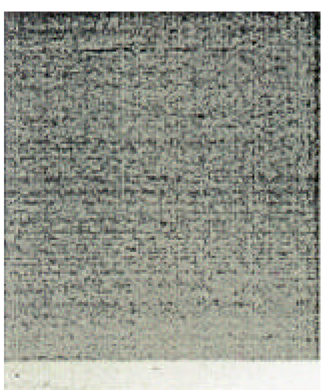
38 mm Random Trans.
ETD = 0.338, d = 1.8, w = 4.9



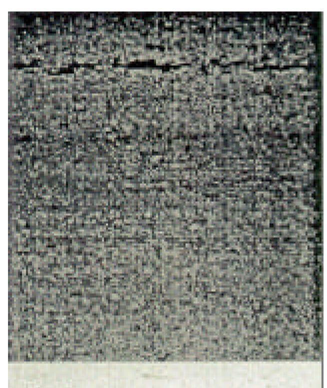
Longitudinal Turf Drag (LTD)
ETD = 0.219, d = NA, w = NA



38 mm Random Trans.
ETD = 0.568, d = 1.9, w = 6.1



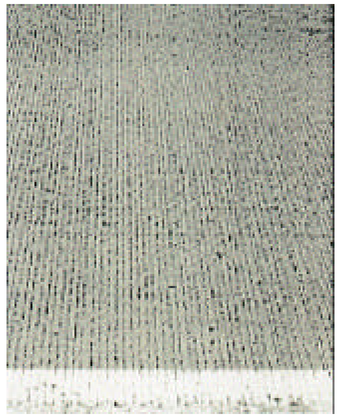
Longitudinal Turf Drag (LTD)
ETD = 0.281, d = NA, w = NA



19 mm Random Longitudinal
ETD = 0.768, d = NA, w = NA

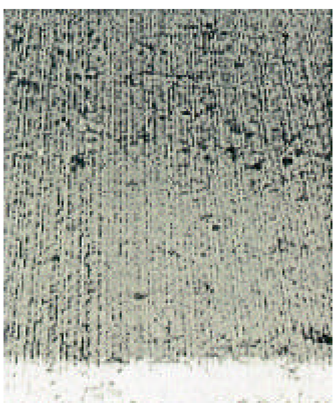
Figure 7: Minnesota

25 mm Uniform Skew 1:6 RHF
ETD = 0.334, d = 1.2, w = 4.1

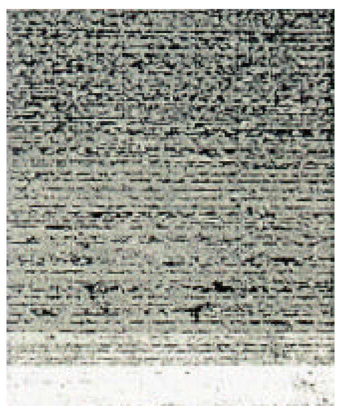


19 mm Uniform Trans.
ETD = 0.77, d = 1.8, w = 5.3

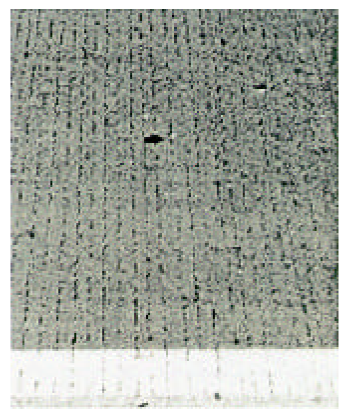
26.51.76.102 mm Random Trans.
ETD = 0.378, d = 1.3, w = 4.4



13 mm Uniform Trans.
ETD = 0.767, d = 1.4, w = 4.4



19 mm Uniform Longitudinal
ETD = 1.263, d = NA, w = NA



25 mm Uniform Trans.
ETD = 0.541, d = 1.8, w = 5.1

Figure 8: North Dakota

Figure 9: Ford Taurus Test Vehicle with Tire Close-up

Noise Measurement Procedures

Similar to the Phase I study, the exterior noise measurement procedure was based on the French-German controlled pass-by method where the noise from a single car is measured with the engine running. Such measurements were performed with a test vehicle under real traffic conditions. The advantages of this method for the comparison of various road surfaces are described in the Phase I Report (34).

Exterior noise levels were recorded with two microphones mounted 1.5 m (5') above the pavement and positioned 7.6 m (25 ft) from the centerline of the nearest traffic lane, 61 m (200 ft) apart from each other. A two-microphone setup was utilized to monitor potentially significant differences between the. microphones due to possible changes in vehicle speed and/or driving behavior, road and terrain conditions, uncontrolled measurement errors, etc. Selection of measurement sites was based on the FHWA's procedures for measuring highway noise, except for the measurement distance of 7.6 m (25 ft). This distance was selected to significantly reduce site variability due to ground cover sound absorption and wind effect reportedly associated with longer, 15.2 m (50 ft) distances. The shorter distance would also require much less minimal separation distance between the test car and preceding or following car to ensure the quality of the noise event data collected. In addition, the 7.6 m (25 ft) measurements versus 15.2 m (50 ft) measurements would improve signal to noise ratio by 5 dBA, reducing the interference caused when a car traveling in the opposite direction coincides with the test car pass-by.

A Type 2900 Larson-Davis two-channel real-time acoustical analyzer was used for the noise measurements. To achieve a higher frequency resolution, the analyzer's Fast Fourier Transform (FFT) analysis option was used to better examine the frequency spectra associated with the pavements.

The analyzer first was set to analyze noise spectra from 0 Hz to 10 kHz, providing a maximum frequency resolution of 25 Hz for the two-channel configuration. Such analyses were carried out for all the pavements to determine any particular pavement which would exhibit a prominent discrete tone. Thus, 400-line FFT sound pressure levels were recorded for each vehicle pass-by for 10 seconds in 0.1-second intervals. This duration was based on the time necessary for the vehicle to pass both microphones.

All noise measurements were performed with the same car, at operating speeds of 96, 104, and 112 km/h (60, 65, and 70 mph) in the right lane. A minimum of three valid runs was needed to collect enough data for each speed. To prevent contamination of data, only runs with no or insignificant opposite traffic were considered valid for car pass-bys. All measurements were performed on dry pavements, with wind velocity less than 24 km/h (15 mph).

Field measurement quality control practices consisted of:

1. the visual observation of surrounding traffic during pass-bys to ensure a necessary separation between the same class of vehicles (e.g. 45.8 m or 150 ft for cars),

2. driver's observations of their actual speed achieved and maintained,

3. direct comparisons between noise data from similar tests performed, and

4. elimination of events recorded with significant noise interference (airplanes, etc.).

Quality control of the measured data included review of the field notes and validation that the "pass-by peaks" exceeded the background noise levels by at least 10 dBA.

Data Summary and Processing

The noise field data were transformed into a spreadsheet format for each of the test runs to identify the noise spectrum associated with the maximum noise levels during vehicle pass-bys. This procedure, performed separately for each analyzer's channel, consisted of identifying the maximum overall sound pressure level (A-weighted), and the values immediately preceding and following the maximum. These three values along with associated (three) sets of 400-line FFT frequency spectra were logarithmically averaged to obtain a representative pass-by spectrum for each channel. Finally, all of the test runs' data, both the A-weighted and frequency spectrum values, were averaged. The resulting data sets were considered representative of the particular pavement, at a certain vehicle speed. Individual noise levels for each vehicle speed and test section were graphed to allow comparisons. An example of a single set of exterior noise graphs one test section is shown in Appendix A.

Interior Noise Measurements

The measurement procedure was designed to collect interior noise data for different pavements during continuous (uninterrupted) driving with the same test car (the 1996 Ford Taurus) which was used for the exterior measurements. For a 5-second duration, the instrument would collect a pre-programmed set of noise data and store them in memory with a specific file name. The duration of tests was based on the time it took for the vehicle to pass through a specific length of the section being tested for both the speeds, and, to ensure enough time for the instrument to save a newly collected data file and reset itself for the next measurement. The measurement procedure was based in part on the SAE J1477 Recommended Practice for Measurement of Interior Sound Levels of Light Vehicles.

A Type 2900 Larson-Davis two-channel real-time acoustical analyzer was used for the interior noise measurements. The analyzer's Fast Fourier Transform (FFT) analysis was used to determine the narrow band frequency spectra associated with the pavements.

To collect a full frequency range data, the analyzer first was set to analyze from 20 Hz to 10 kHz, providing a frequency resolution of 12.5 Hz. Such analyses were carried out for all the pavements to determine a narrower frequency range in which any particular pavement would exhibit a prominent discrete tone. These measurements were taken for two speeds only: 96 and 112 km/h (60 and 70 mph). Three runs per speed were utilized. Then, to achieve higher frequency resolution of approximately 3 Hz, the narrower range of 250 to 2750 Hz was utilized.

Such measurements were taken at the same three speeds (three runs per speed) as for exterior measurements. An example of one test section's data is shown in Appendix B.

The 800-line FFT sound pressure levels were recorded for 5 seconds for each vehicle pass-by in 1-second intervals. Along with the 5 linear spectra thus recorded for each pavement, the equivalent 5-second sound pressure level for each individual frequency was calculated for the entire 5-second period. The equivalent continuous sound level is the level of steady sound, which, in a stated time period (5 seconds in this case), has the same sound energy as the time varying sound. An example is also shown in Appendix B. Quality control in the field consisted of visual observations of the measurement conditions outside the vehicle, driver's observations of actual vehicle speed, direct comparisons between noise data from similar tests performed, and elimination of the events recorded with significant noise interference.

In addition to the sound pressure measurements, simultaneous audio recordings were taken inside the car. A SONY Type 932 digital data recorder and a microphone were used.

Texture Measurement

ROSAN Measurements

The FHWA has developed the Road Surface Analyzer (ROSAN). The Turner-Fairbanks Highway Research Center made the equipment available for this project. Two different measuring techniques are included. The $ROSAN_v$ incorporates a laser sensor mounted on a vehicle's front bumper and can be operated at speeds of up to 112 km/h (70 mph), eliminating the need for costly traffic control to make measurements of texture using the ASTM E 965 or Sandpatch method. The laser sensor was set to collect data at 1 mm intervals for approximately 122 meters (400' or the distance from 100 feet before the first microphone to 100 feet beyond the second microphone). Data acquisition and storage is accomplished using an onboard computer. The IBM laptop used was connected to a voltage inverter located in the back of the vehicle. The vehicle is shown in Figure 10.

Prior to beginning the measurement on transversely tined or skewed sections, the measuring crew places two rubber tube markers, one 30 meters (100') in advance of the first microphone and one 30 m (100') following the second microphone. These leave prominent markers on the profile recorded on the computer and are later visible on the screen as the beginning and end of the calculation section. The $ROSAN_v$ software, developed by the Turner Fairbanks Research staff, calculates the mean profile depth (MPD) every meter and an average for the entire 122 meters. The estimated texture depth (ETD), a value comparable to the sand patch texture value, is calculated from the MPD by an equation developed specifically for ROSAN. The software also gives an ASTM MPD and ETD as well. Three runs were made in each wheel path. Sample outputs for a single run are shown in Appendix C.

ROSAN v

ROSAN b

Figure 10: Road Surface Analyzer (ROSAN)

A program was created to utilize the ROSAN data and calculate the depth, width and spacing of each tine of a given section and give average values for each characteristic. Using the depths of tine that were calculated, a plot of all the tines in a given section could be printed. An example of a 1.2 m long plot is shown in Appendix D.

The $ROSAN_b$ developed for longitudinally tined pavements has the laser mounted on a metal frame. The frame is positioned transversely across most of the lane being analyzed (lane closure is obviously required). A computer controlled trolley carries the laser across the stationary frame. The readings that are taken are stored in the same IBM laptop computer as for the $ROSAN_v$. Readings were taken three times on each side of the microphone locations, and averaged for the value of ETD. The ETD is then converted to MPD to compare with other MPDs on transverse sections. The $ROSAN_b$ data as representative of the actual ETD as the $ROSAN_b$ as the $ROSAN_v$ because fewer measurements were included in the survey. $ROSAN_b$ requires a lane closure much like the sand patch. The $ROSAN_b$ is shown in Figure 10.

Because of the cost and time that would have been consumed with sand patch testing and because it was believed that the $ROSAN_v$ would give much more accurate results for texture than minimal sand patch testing, only $ROSAN_v$ or $ROSAN_b$ was used in other states.

Sand Patch Testing

Sand patch testing was limited to four lane highways with Wisconsin test sites where lane closures were close together and economical, and were performed in accordance with ASTM E 965. Four tests, each with four measurements, were taken in the right wheel path at each microphone, to compare with the ETD output of the $ROSAN_v$ software. The test consists of spreading a given volume of glass beads of uniform size with a hockey puck and measuring the resulting diameter. Correlation between ROSAN outputs and sand patch was also conducted.

Friction Data Collection

Friction data was collected by the individual states at a time in close proximity with the texture and noise measurements. Measurements followed ASTM 274-77 and were taken with a KJ Law friction tester. The device is a trailer that has a locked wheel with a bald tire and a constant load. It is dragged over a wetted pavement at a constant speed to determine steady state friction force. All states were requested to obtain friction numbers at 64 km/h (40 mph) and at one other speed in order to obtain a speed gradient. A bald tire was used because it was believed that this gives a more realistic idea of the wet pavement accident potential. Correlation analysis between ROSAN outputs, friction, and friction gradient was also conducted.

Subjective Testing of Relative Interior Noise

Twenty test sites were selected across the ranking of interior noise, with 10 above the median and 10 below the median interior noise level. The recorded sounds were transferred to a CD in order to allow randomization of the noise recordings. The comparator was selected as Wisconsin's interim random transverse tining standard, with an interior noise about half way between the loudest and quietest pavements. The pavements selected and the comparator, with corresponding L_{eq} noise levels, are shown in Table 1.

Twenty four (24) persons were used to rate the "noisiness" of twenty (20) road surfaces. Subjects ranged in age from 20 to 39 years old (mean = 24.5). All subjects had normal hearing defined as hearing thresholds less than or equal to 15 dBHL at the audiometric frequencies of 500, 1000, 2000, 3000 and 4000 Hz.

Sound level measurements and audio recording of the interior noise level present while driving over different road surfaces in the Ford Taurus at 96 km/hr (60 mph) were collected (see Table 1). Five-second samples of the digital audio recordings were then transferred to a compact disc. Each five second sample was preceded by a five second sample of road surface #21 (the comparator).

Play back of the audio recordings was accomplished using a compact disc player (SONY CDP-291) and were transduced to the subjects through speakers having a flat frequency response. The presentation level (in dB) was controlled using a clinical audiometer (GSI 16) and adjusted to reflect the measured interior noise level in dBA using a sound level meter (Quest 155).

The relative "noisiness" of the road surfaces was determined using direct magnitude estimation. With this method, which theoretically results in a ratio scale, each of a set of stimuli is compared to a point on an internally generated scale, or continuum, for the attribute being rated - in this case noisiness.

Using direct magnitude estimation, subjects rated the "noisiness" of each road surface by comparing it to the "noisiness" of road surface #21 (standard/comparator). The noisiness of the standard/comparator was given an assigned value of 100 points. If, for example, a subject judged the noisiness of a road surface to be twice as noisy as the standard, then the subject would assign it 200 points. If, on the other hand, the subject judged the noisiness of a road surface to be half as loud as the standard, then the subject would assign it 50 points. Subjects could use any point assignment they wanted and did not have to limit themselves to fractions or multiples of the 100 points assigned to the noisiness of the standard. They could use any assignment they chose if it represented their judgement of the relative noisiness of the road surface to the noisiness of the standard.

All subjects were given a training session to familiarize them in using direct magnitude estimation to make relative judgements. Each subject listened to the twenty road surfaces twice. Presentation of the road surfaces was randomized within and among the subjects. The data obtained during the second listening trial was averaged across subjects and used to rank the "noisiness" of the road surfaces using the resulting ratio scale. Subject instructions were as follows:

> *"I am going to have you listen to audio recordings of road surface noise. Each audio recording will be preceded by an audio recording of road surface noise that we will use as a comparator. For each road surface, I want you to compare the noisiness of that road*

surface to the noisiness of the comparator road surface. The noisiness of the comparator is given an assigned value of 100 points. If, for example, you judge the noisiness of a road surface to be twice as noisy as the comparator, then you would assign it 200 points. If on the other hand, you judge the noisiness of a road surface to be half as noisy as the standard, then you would assign it 50 points. You can use any point assignment you want and need not limit yourself to fractions or multiples of the 100 points assigned to the noisiness of the standard. You can use any assignment you choose if it represents your judgement of the relative noisiness of that road surface compared to the noisiness of the comparator."

Table 1 Samples: Interior Noise - Taurus @ 96 km/hr (60 mph)

Number	State	Road	Sec.	Texture	L_{eq}
1	Iowa	I-163	8	Milled PCCP	72.0
2	Iowa	I-163	5	19mm random trans. (3-5mm d)	70.0
3	Colorado	I-70	1	25mm uniform trans. (CO. Std.)	69.7
4	Minnesota	US 169	6	38mm random trans.	69.4
5	Wisconsin	STH 29	15	25mm uniform trans.	69.5
6	Wisconsin	I-43	5	Ground PCCP	69.2
7	Iowa	I-163	9	13mm uniform trans., saw cut	69.2
8	New Wisconsin	STH 29	1	25mm random trans.	68.9
9	Wisconsin	STH 29	9a	13mm uniform trans.	69.3
10	Wisconsin	STH 29	10	19mm uniform trans.	69.1
11	Colorado	I-70	5	Random trans. saw cut (16,22,19 mm)	68.6
12	Wisconsin	US 151	R2	25mm random trans. (Zignego)	68.6
13	Iowa	I-163	1	13mm uniform trans., (3-5mm d)	68.2
14	New Wisconsin	STH 29	10	25mm uniform long.	68.0
15	North Dakota	I-94	F	Random trans., var., 26,51,76,102mm	67.7
16	Michigan	I-75	1	European Texture	67.5
17	Minnesota	MN 55	4	38mm Random Trans.	66.9
18	New Wisconsin	STH 29	7	19mm Random Skew 1:4	67.2
19	New Wisconsin	STH 29	5	19mm Random Skew 1:6	67.6
20	Wisconsin	I-43	1	SHRP ACP	65.9
21©	New Wisconsin	STH 29	2	19mm Random Trans.	68.7

All tined PCC surfaces are 3 mm deep unless otherwise specified.

ANALYSIS

Exterior Noise

The noise data were analyzed separately for each of the pavement parameters. In this report, only the data corresponding to 96 km/h (60 mph), except where noted, are presented for conciseness. Pavements are ranked by exterior noise (L_{max}) and are shown in Table 2.

Transverse PCC Pavement (Texture Group "T") Texturing

Figures 11 and 12 compare FFT frequency spectra measured for the transverse-tined concrete pavements with different spacings and tine depths. These spectra exhibit similar shape to the 1/3 octave band spectra collected during the Phase I study for similar pavements. At the same time, these FFT spectra provide much better frequency resolution in regard to identification of frequencies characteristic of the transverse-tined pavements. These characteristic frequencies depend on the tine spacing and the vehicle speed. When the spacing increases, these frequencies decrease (shift left) for the surfaces with uniform spacing, as shown in Figure 12.

For example, the calculated characteristic frequencies (speed in mm/sec divided by spacing in mm) at 96 km/h (60 mph) should be as follows: for 38 mm (1-1/2") spacing - 704 Hz, for 25 mm (1") spacing - 1056 Hz, for 18 mm (3/4") spacing -1408 Hz, and for 13 mm (½") spacing - 2112 Hz. As it can be seen from Figures 11 and 12, the field measurement results generally follow this trend. Minnesota #6, 38 mm, (considered random, but ROSAN texture plots indicate a high degree of uniformity) exhibits first and second harmonics at 700 and 1400 Hz frequencies. The 25 mm pavements, Wisconsin #15 and Colorado Standard, exhibit similar 1000 Hz characteristic frequency. Wisconsin #10, 19 mm, exhibits peaks at approximately 1400 Hz, while Wisconsin #9A, 13 mm, is characterized by the frequency of 2100 Hz. Second harmonics for both the 25 mm pavements can also be seen at this frequency (2100 Hz) but of much smaller amplitude than the first ones.

The transversely tined pavement with 13 mm (½") spacing exhibits the smoothest noise spectrum. This pavement is almost 5 dBA quieter than the 38 mm (1-1/2") pavement. An analysis of the effect of the tining depth for two of the 13 mm sections (Iowa #1 and Wisconsin #9), showed that the texture with the specified 3-5 mm tining depth (in Iowa) exhibited 1 dBA higher overall noise levels than the 1.5 mm-deep Wisconsin section, for all of the three car speeds tested. The Iowa #1 section also had a wider tine width than Wisconsin #9 (5.1 mm vs. 3.5 mm). The tining depth for Iowa #1 is based on specified depths, but the ROSAN ETD for Iowa # 1 is 0.701 and Wisconsin #9 is 0.399.

The transverse pavements with saw cuts, both with regular (Iowa, #9) and random (Colorado, #5) cuts, did not demonstrate good acoustical qualities. Both the pavements exhibited characteristic frequencies, which were detected within "unexpected" frequency ranges. These frequencies were apparently a function of the saw cut's configuration and/or geometry. Both had deep textures with wide tine widths (ROSAN ETD > 1.0). The bridge deck groover had 3 randomized spacings with an overall width of 0.8m (29") which acted like uniform tine spacings.

Table 2 Ranking of all Test Sections by Exterior Noise (L_{MAX}), Car at 96 km/h (60 mph)

State	Road	Section	Texture	Lmax
Wisconsin	I-43	3	Std. ACP	78.9
Iowa	I-163	3	19mm uniform long. (1.5 mm d)	79.0
Colorado	I-70	7	19mm uniform long. saw cut	79.6
Iowa	I-163	4	19mm uniform long. (1.5 mm d)	79.9
Wisconsin	I-43	2	Std. ACP	79.9
Wisconsin	I-43	6	SMA, 9mm stone	80.5
Colorado	I-70	9	19mm uniform long.	80.9
North Dakota	I-94	F	Trans., var., 26,51,76,102mm	81.0
Wisconsin	I-43	1	SHRP ACP	81.1
Wisconsin	I-43	5	Ground PCCP	81.2
North Dakota	I-94	H	19mm uniform long.	81.5
Wisconsin	STH 29	6	25mm uniform long.	81.5
Wisconsin	I-43	4	SMA, 16mm stone	81.6
Minnesota	US 169	1	19mm uniform long.	81.7
Wisconsin	STH 29	9	13mm uniform trans., (1.5mm d)	81.9
Wisconsin	STH 29	9a	13mm uniform trans.	82.1
North Dakota	I-94	G	13mm uniform trans.	82.2
New Wisconsin	STH 29	5	19mm random skew 1:6, LHF	82.4
Minnesota	US 55	4	38mm random trans.	82.6
New Wisconsin	STH 29	8	25mm random long.	82.7
North Dakota	I-94	A	25mm uniform skewed 1:6, RHF	82.7
Iowa	I-163	1	13mm uniform trans. (3-5mm d)	82.8
Colorado	I-70	4	13mm uniform trans.	83.0
North Dakota	I-94	B	19mm uniform trans.	83.0
New Wisconsin	STH 29	7	19mm random skew 1:4, LHF	83.1
Iowa	I-163	2A	19mm uniform trans., (IA. Std.)	83.3
Wisconsin	US 151	R2	25mm random trans. (Zignego)	83.4
New Wisconsin	STH 29	6	25mm random skew 1:4, LHF	83.5
Minnesota	US 169	7	LTD only	83.7
North Dakota	I-94	I	25mm uniform trans.	83.7
Iowa	I-163	8	Milled PCCP	83.8
New Wisconsin	STH 29	4	25mm random skew 1:6, LHF	83.8
Wisconsin	STH 26	R3	25mm random trans. (Trierweiller)	83.8
Minnesota	US 12	3	19mm random trans.	83.9
New Wisconsin	STH 29	10	25mm uniform long.	83.9
Wisconsin	STH 29	11	Manuf. random trans.	83.9
Wisconsin	STH 29	8	25mm uniform skewed 1:6, LHF (1.5mm d)	83.9
Wisconsin	STH 29	10	19mm uniform trans.	84.0
Colorado	I-70	5	Random trans. saw cuts (16,22,19 mm)	84.1
Minnesota	US 169	8	19mm Unif. Long.	84.3
Colorado	I-70	3	Random trans. (16,22,19 mm)	84.4
Iowa	I-163	9	13mm uniform trans., sawcut	84.6
Wisconsin	STH 29	16	Skidabrader, PCCP	84.6
Wisconsin	US 51	R1	25mm random trans. (Vinton)	84.8
Minnesota	US 169	2	19mm random trans.	84.9
New Wisconsin	STH 29	9	19mm random long.	85.3
Wisconsin	STH 29	R0	21mm truly random trans.	85.4
Iowa	I-163	5	19mm random trans. (3-5 mm d)	85.5
New Wisconsin	STH 29	2	19mm random trans.	86.3
Wisconsin	STH 29	15	25mm uniform trans.	86.3
Colorado	I-70	1	25mm uniform trans. (CO. Std.)	86.4
New Wisconsin	STH 29	1	25mm random trans.	86.6
New Wisconsin	STH 29	3	25mm uniform trans.	86.6
Minnesota	US 169	6	38mm random trans.	87.3

All tined PCC surfaces are 3 mm deep unless otherwise specified

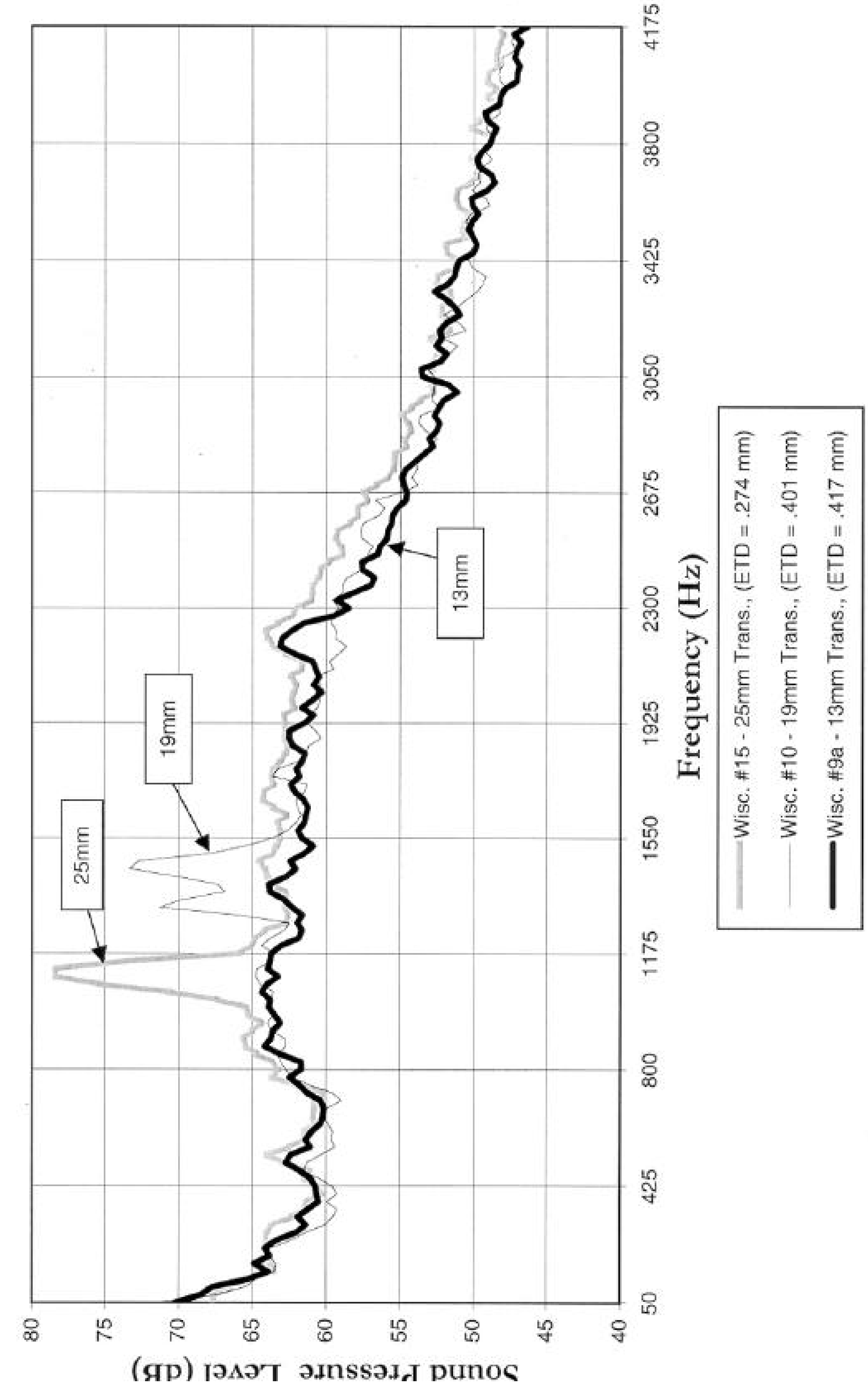


Figure 11: Comparison Exterior Noise of Uniform Transversely Tined PCC Pavements

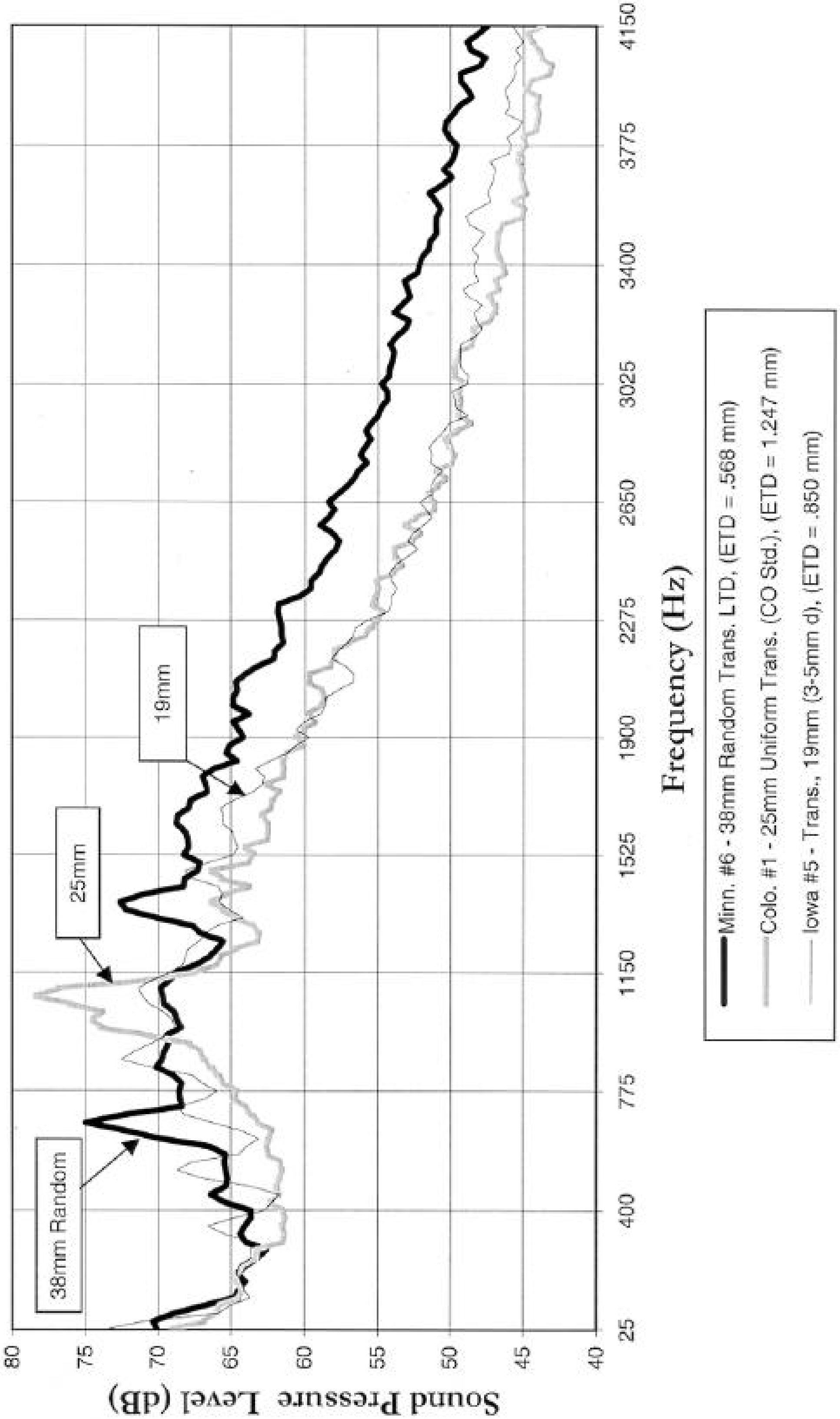


Figure 12: Comparison of Exterior Noise, Uniform, Transversely Tined PCC Pavements

Transverse PCC Texturing with Random Tining (Texture Group "TR")

Figure 13 compares four different PCC pavements with random transverse tining. Minnesota #4, 38 mm, and Wisconsin R2 (25 mm "truly random") are characterized by significantly better acoustical qualities than New Wisconsin #1 and #2, 19 and 25 mm, respectively . However, Minnesota #4 has a ROSAN ETD of 0.388 but the Wisconsin R2 has an ETD of 0.713. Wisconsin R2 also has a wider mean tine width (based on the ROSAN algorithm). New Wisconsin #1 has a ROSAN ETD of 0.456 and #2 has an ETD of 1.284 and a wider mean tine width. The Minnesota surface still has a characteristic peak of 7-8 dB at approximately 700 Hz that does not significantly affect the A-weighted level. The characteristic frequency of 1000 Hz for Wisconsin R2 is also noticeable while the overall acoustical performance for the remainder of the frequency spectrum is satisfactory. Both "better" pavements are significantly less noisy throughout the entire measurement spectrum.

Random Skew Tining (Texture Group "SK")

Figure 14 shows New Wisconsin #5 and #7, with the 19 mm skewed random tining. Both pavements demonstrate good acoustical qualities for the random textures, without any significant characteristic peaks in their noise spectra. It is interesting to note that in the frequency range of 800 to 1500 Hz, the 1:6 skewed pavement is characterized by lower SPLs than the 1:4 texture. (See discussion of skewed pavements later.) Both have ROSAN ETD slightly over 0.700.

Longitudinal (Texture Group "L") and Special (Texture Group "S") PCC Pavements

Longitudinal and special PCC pavement noise characteristics are shown in Figure 15. Similar to the Phase I study, no characteristic frequencies were found for these textures. Many of the longitudinal tined pavements had low exterior noise levels.

The Skidabrader pavement (Wisconsin #16) has an acceptable acoustical performance at lower and higher frequencies. However, at frequencies between 400 and 1000 Hz, this texture loses its advantage. The milled pavement (Iowa #8) has a very similar acoustical spectrum, while the ground pavement (Wisconsin, I-43 #5) is characterized by a better performance in the same frequency range. The ground pavement was approximately 3 dBA quieter in overall SPL as compared to the other special PCC.

Asphalt Pavements (Texture Group "A")

Figure 16 illustrates the acoustical performance of the asphalt pavements constructed in 1992 and 1993 and measured in 1997. The SMA pavement provides the best acoustical qualities at frequencies higher than 2000 Hz, while the standard asphalt is better for the 500 to 2000 Hz range. The SHRP pavement did not show any advantages over standard dense pavements. When comparing SMA with 9 mm (3/8") and 16 mm (5/8") stones (Figure 16), the pavement with smaller aggregate (less texture) shows better acoustical qualities for all three speeds tested.

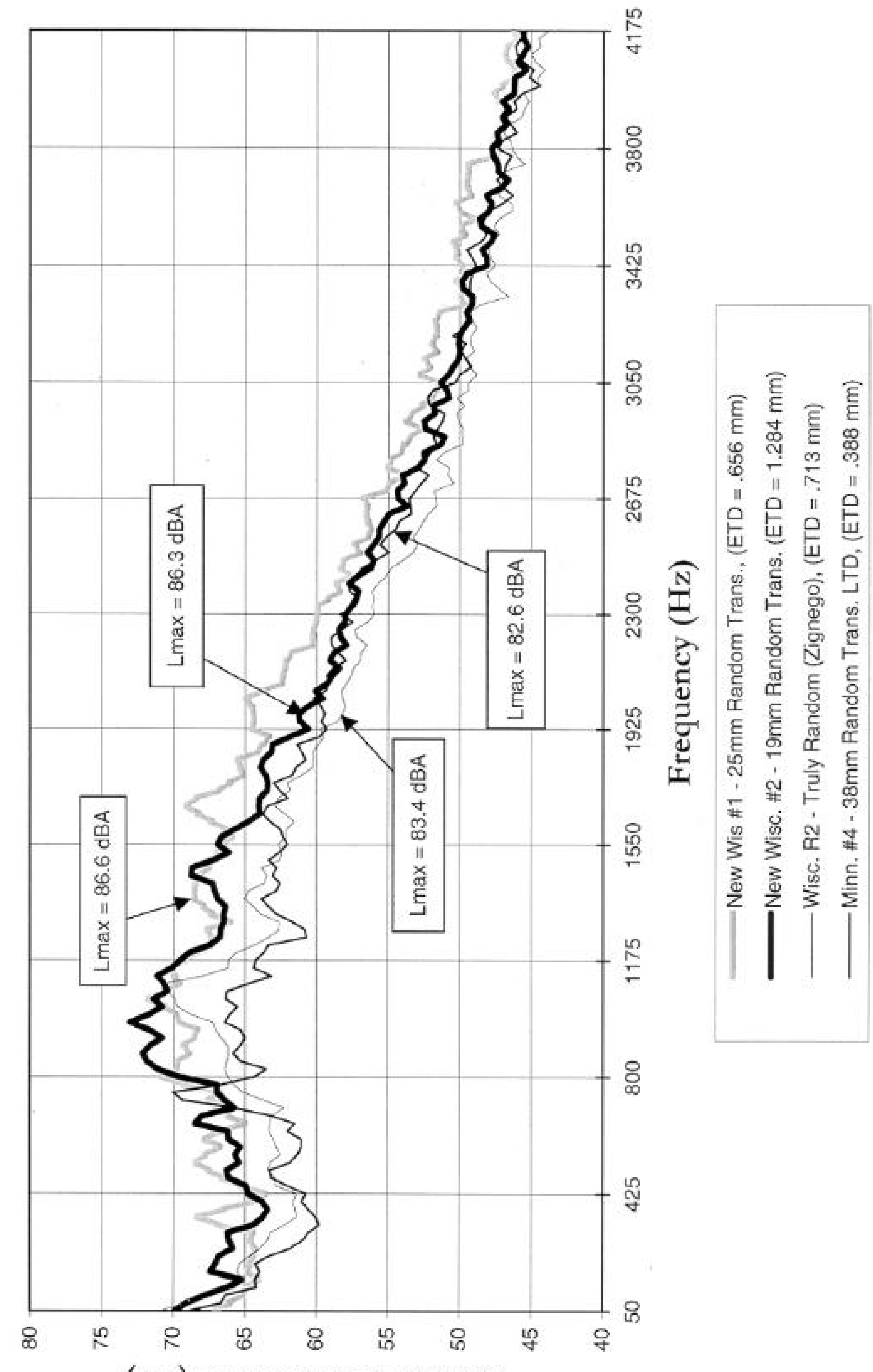


Figure 13: Comparison of Exterior Noise of Random Tined PCC Pavements

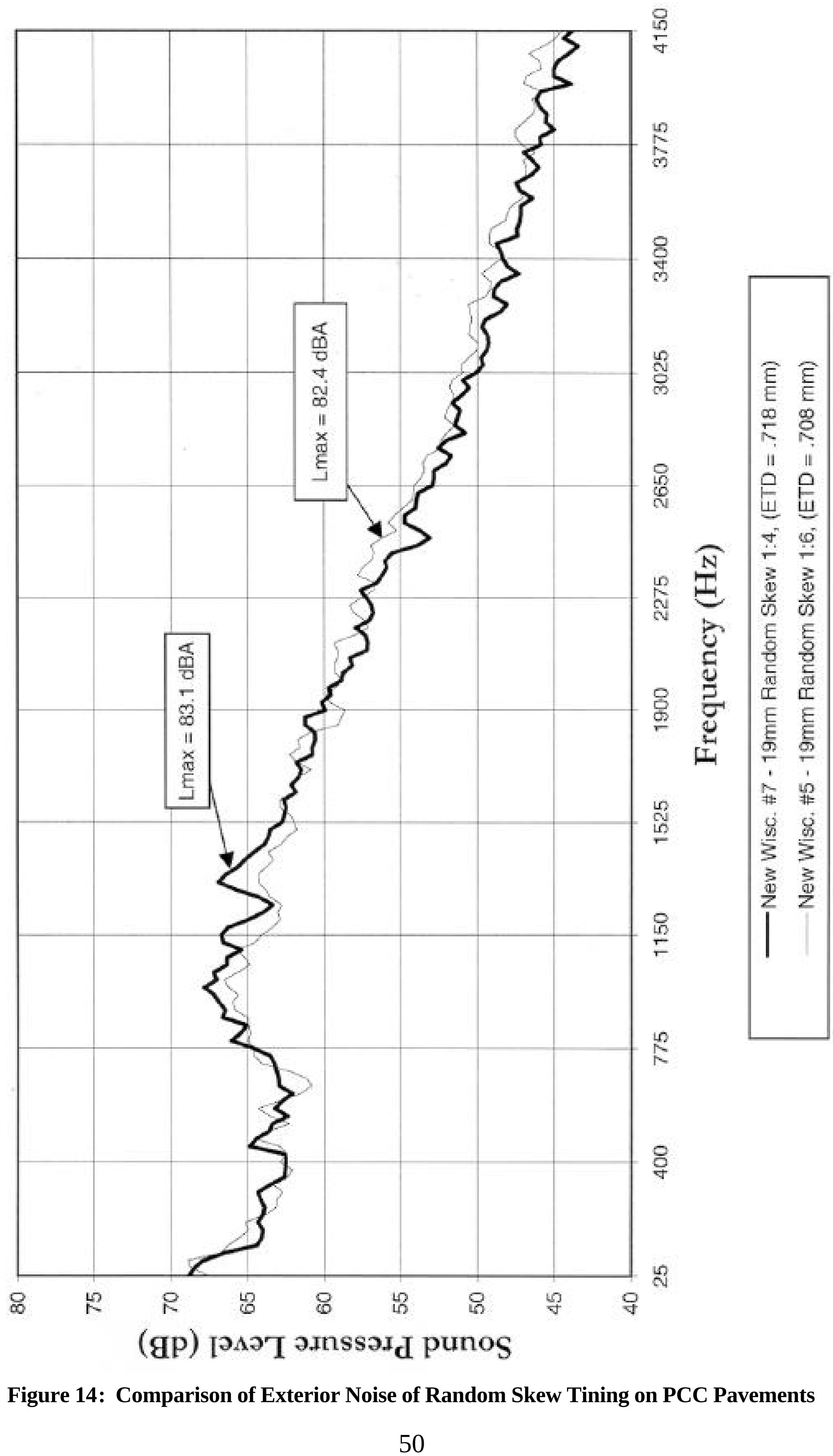


Figure 14: Comparison of Exterior Noise of Random Skew Tining on PCC Pavements

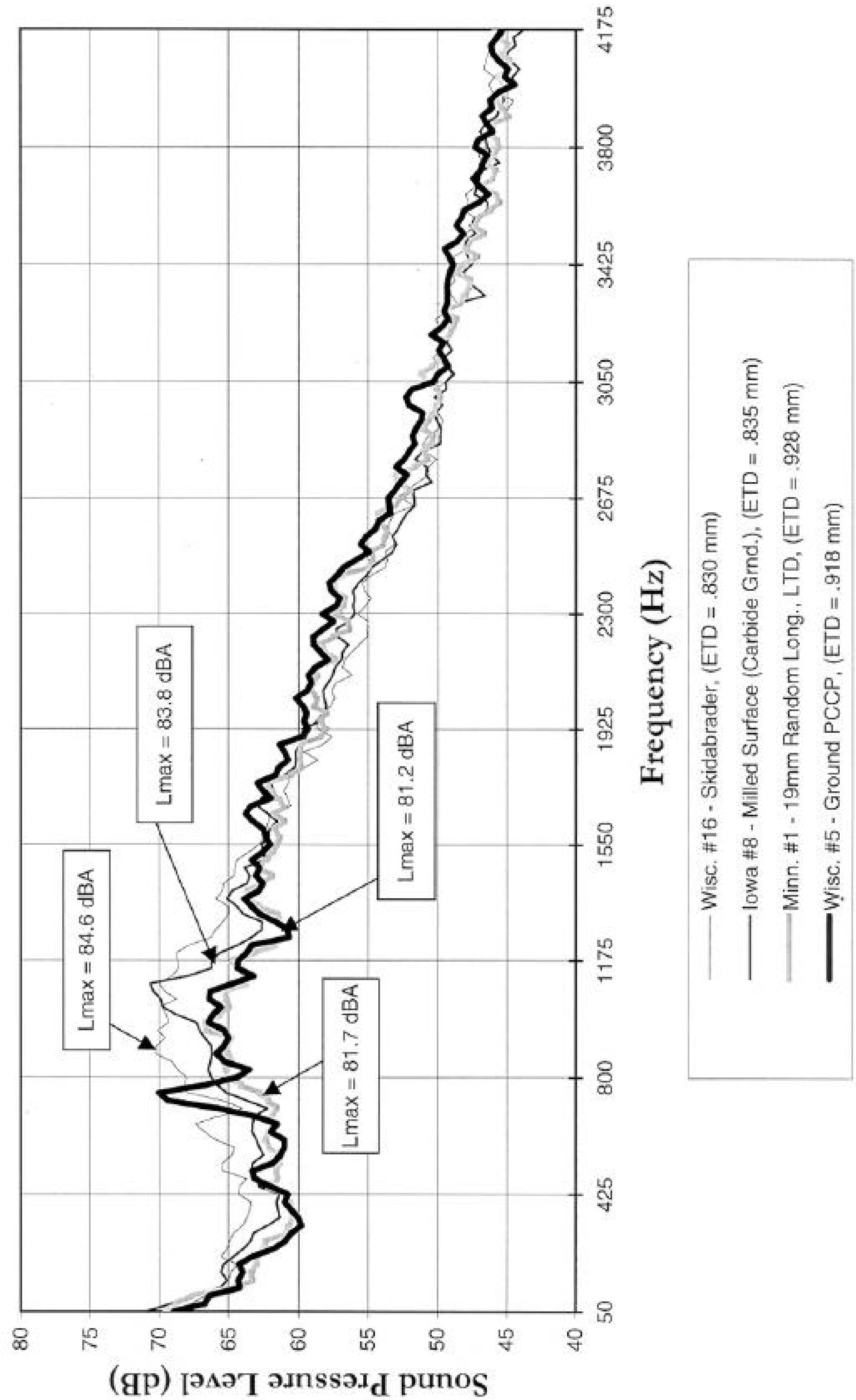


Figure 15: Comparison of Exterior Noise of Longitudinally Tined and Special PCC Pavements

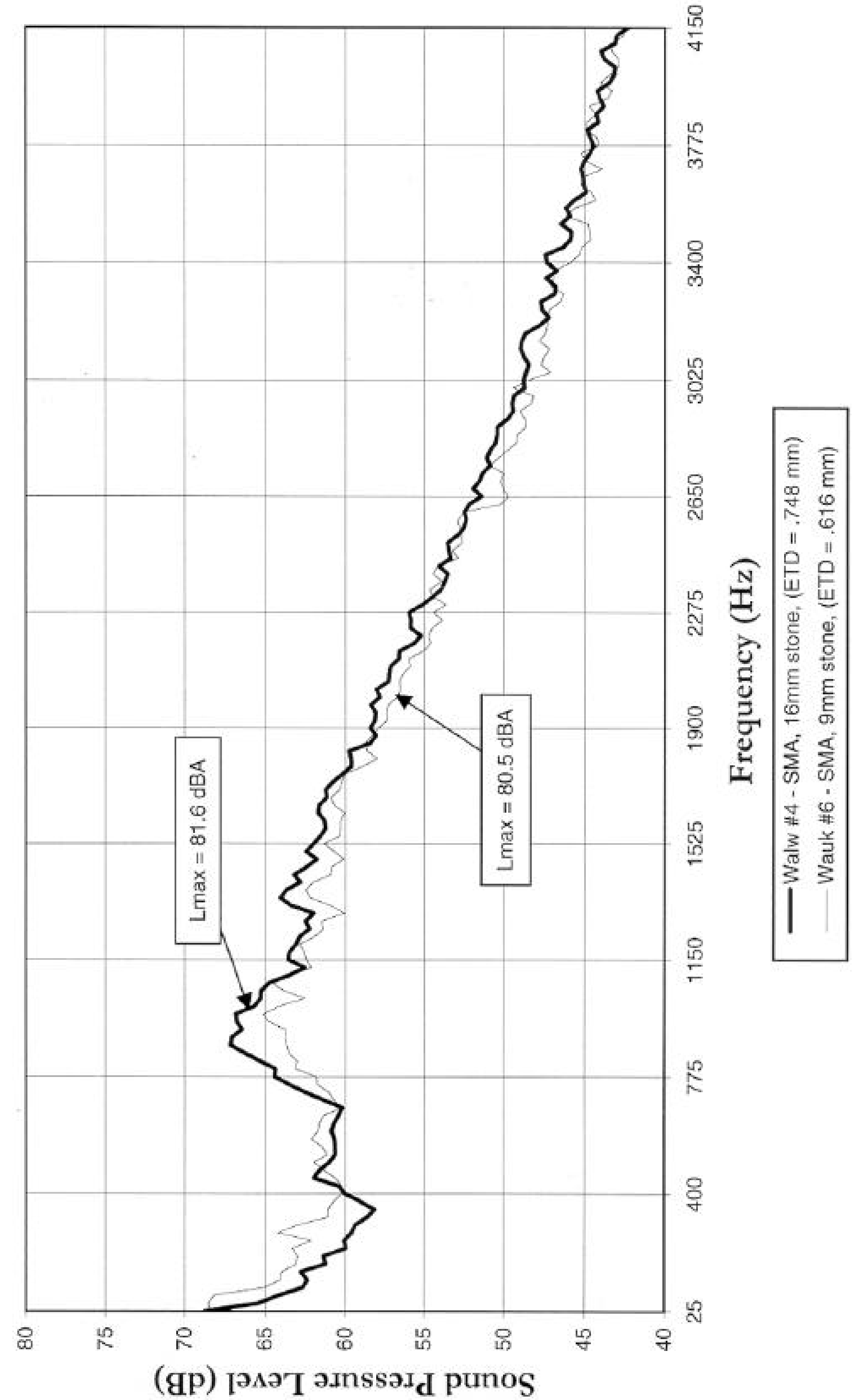


Figure 16: Comparison of Exterior Noise on SMA Pavements

Comparison of Pavement Friction, Texture Depth, Tining Width and Exterior Noise

Simple linear regression analyses were performed comparing $FN_{40}B$, tine depth and tine width data (as independent variables) to exterior noise (L_{max}) as the dependent variable. When all the friction data were utilized, practically no correlation was found (resultant R^2 = 0.1). When $FN_{40}B/L_{max}$ correlation analyses were performed separately for each state's section, only Wisconsin's data showed some correlation of (L_{max}) with $FN_{40}B$ (R^2 = 0.43) . When correlated by texture and pavement types, only a few correlated (highest R2 = 0.55) with either ETD or $FN_{40}B$, but these had few pavements included.

Additional regression analysis was also performed on L_{max} and texture depth represented by both ROSAN ETD and texture mean depth from the ROSAN algorithm. Only the AC and special textured PCC pavements showed some correlation between L_{max} and ROSAN ETD (R^2 of approximately 0.7 maximum), but there were very few pavement sections involved. There was low correlation between all pavement textures and exterior noise (R^2 = 0.12).

Correlation analysis between exterior noise (L_{max}) and tine width, (based on widths from the algorithm prepared from ROSAN data, where tine width is available), shows some positive correlation (the greater the tine width, the greater L_{max}) for all data (R^2 = 0.24). Data within the individual states (except Wisconsin) shows greater correlation (R^2 from 0.33 to 0.80) but the other states had fewer test sections. There is some correlation, but it is insufficient for firm conclusions.

There was also some correlation between ROSAN ETD and MPD with $FN_{40}B$ (friction as dependent variable), when looked at within pavement texture type, but again, the low number of samples is inadequate for conclusive results.

Since prior research (28) had shown noise to increase with tine depth, correlation analysis between tine depth and tine width was performed using the ROSAN data as the independent variable. The ROSAN data plots showed the tined grooves to be essentially “V” shaped, with the deeper the tine groove, the wider the width of tine groove measured at the top. It showed that tine width is dependent on tine depth, with a positive correlation and an R^2 of 0.83 including the saw cut pavements. This may have been partly due to the tearing away of the surface layer of the concrete at the time of construction (or sawing). It may also have been partly due to the angle of the laser beam on the bumper of the $ROSAN_{v.}$

Interior Noise

Ranking of All Test Sections and Noise Comparisons

All test sections were ranked based on interior noise (L_{eq}) with the car at 96 km/h (60 mph) and are shown in Table 3.

As can be seen from Figure 17, the uniform transversely tined concrete pavements generated discrete frequencies inversely proportional to the tine spacing. For example, the 25 mm (1") texture, Colorado #1, exhibited a discrete frequency approximately 1.5 times greater than the first harmonic of the 38 mm (1.5") texture's discrete frequency (Minnesota #6). In addition, a proportional increase in discrete frequency was observed when the car speed increased from 96 to 112 km/h (60 to 70 mph).

Table 3 Ranking of All Test Sections by Interior Noise (L_{eq}), Car at 96 km/h (60 mph)

State	Road	Section	Texture	Leq
Wisconsin	I-43 (WALW.)	3	Std. ACP	65.0
Wisconsin	I-43 (WAUK.)	1	SHRP ACP	65.9
Wisconsin	I-43 (WAUK.)	2	Std. ACP	66.0
Wisconsin	I-43 (WALW.)	4	SMA, 16mm stone	66.7
Minnesota	I-494	5	LTD only	66.8
Minnesota	MN 55	4	38mm random trans.	66.9
Iowa	I-163	3	19mm uniform long. (1.5 mm d)	67.2
Minnesota	US 169	1	19mm uniform long.	67.2
New Wisconsin	STH 29	7	19mm random skew 1:4, LHF	67.2
Michigan	I-75	1	European texture	67.5
Iowa	I-163	4	19mm uniform long. (3-5 mm d)	67.6
New Wisconsin	STH 29	5	19mm random skew 1:6, LHF	67.6
North Dakota	I-94	A	25mm uniform skewed 1:6, RHF	67.6
Wisconsin	I-43 (WAUK.)	6	SMA, 9mm stone	67.6
New Wisconsin	STH 29	4	25mm random skew 1:6	67.7
North Dakota	I-94	F	Random trans., var., 26,51,76,102mm	67.7
New Wisconsin	STH 29	8	25mm random long.	67.8
New Wisconsin	STH 29	10	25mm uniform long.	68.0
Colorado	I-70	7	19mm uniform long. saw cut	68.1
Iowa	I-163	1	13mm uniform trans. (3-5mm d)	68.2
Iowa	I-163	2A	19mm uniform trans. (IA. Std.)	68.2
Minnesota	US 169	7	LTD only	68.3
Colorado	I-70	9	19mm uniform long.	68.4
Minnesota	US 12	3	19mm random trans.	68.4
Michigan	I-75	2	25mm uniform trans. (MI. Std.)	68.5
New Wisconsin	STH 29	6	25mm random skew 1:4, LHF	68.5
North Dakota	I-94	B	19mm uniform trans.	68.5
North Dakota	I-94	G	13mm uniform trans.	68.5
North Dakota	I-94	I	25mm uniform trans.	68.5
Colorado	I-70	5	Random trans. saw cuts (16,22,19 mm)	68.6
Wisconsin	US 151	R2	25mm random trans. (Zignego)	68.6
New Wisconsin	STH 29	2	19mm random trans.	68.7
North Dakota	I-94	H	19mm uniform long.	68.7
New Wisconsin	STH 29	3	25mm uniform trans.	68.8
Wisconsin	STH 29 (EB)	R0	21mm truly random trans.	68.8
Minnesota	US 169	2	19mm random trans.	68.9
New Wisconsin	STH 29	1	25mm random trans.	68.9
Wisconsin	STH 26	R3	25mm random trans. (Trierweiller)	68.9
Wisconsin	STH 29	9	13mm uniform trans., (1.5mm d)	69.0
Wisconsin	STH 29	10	19mm uniform trans.	69.1
Iowa	I-163	9	13mm uniform trans., saw cut	69.2
Wisconsin	I-43 (WALW.)	5	Ground PCCP	69.2
Wisconsin	STH 29	6	25mm uniform long.	69.2
Wisconsin	STH 29	9a	13mm uniform trans.	69.3
Colorado	I-70	4	13mm uniform trans.	69.4
Minnesota	US 169	6	38mm random trans.	69.4
Minnesota	US 169	8	19mm uniform long.	69.4
Wisconsin	STH 29	8	25mm uniform skewed 1:6 LHF (1.5mm d)	69.4
Wisconsin	US 51	R1	25mm random trans. (Vinton)	69.4
New Wisconsin	STH 29	9	19mm random long.	69.5
Wisconsin	STH 29	15	25mm uniform trans.	69.5
Colorado	I-70	1	25mm uniform trans. (CO. Std.)	69.7
Colorado	I-70	3	Random trans. (16,22,19 mm)	69.9
Iowa	I-163	5	19mm random trans. (3-5 mm d)	70.0
Wisconsin	STH 29	11	Manuf. random trans.	70.2
Wisconsin	STH 29	16	Skidabrader, PCCP	70.6
Iowa	I-163	8	Milled PCCP	72.0

All tined PCC surfaces are 3 mm deep unless otherwise specified.

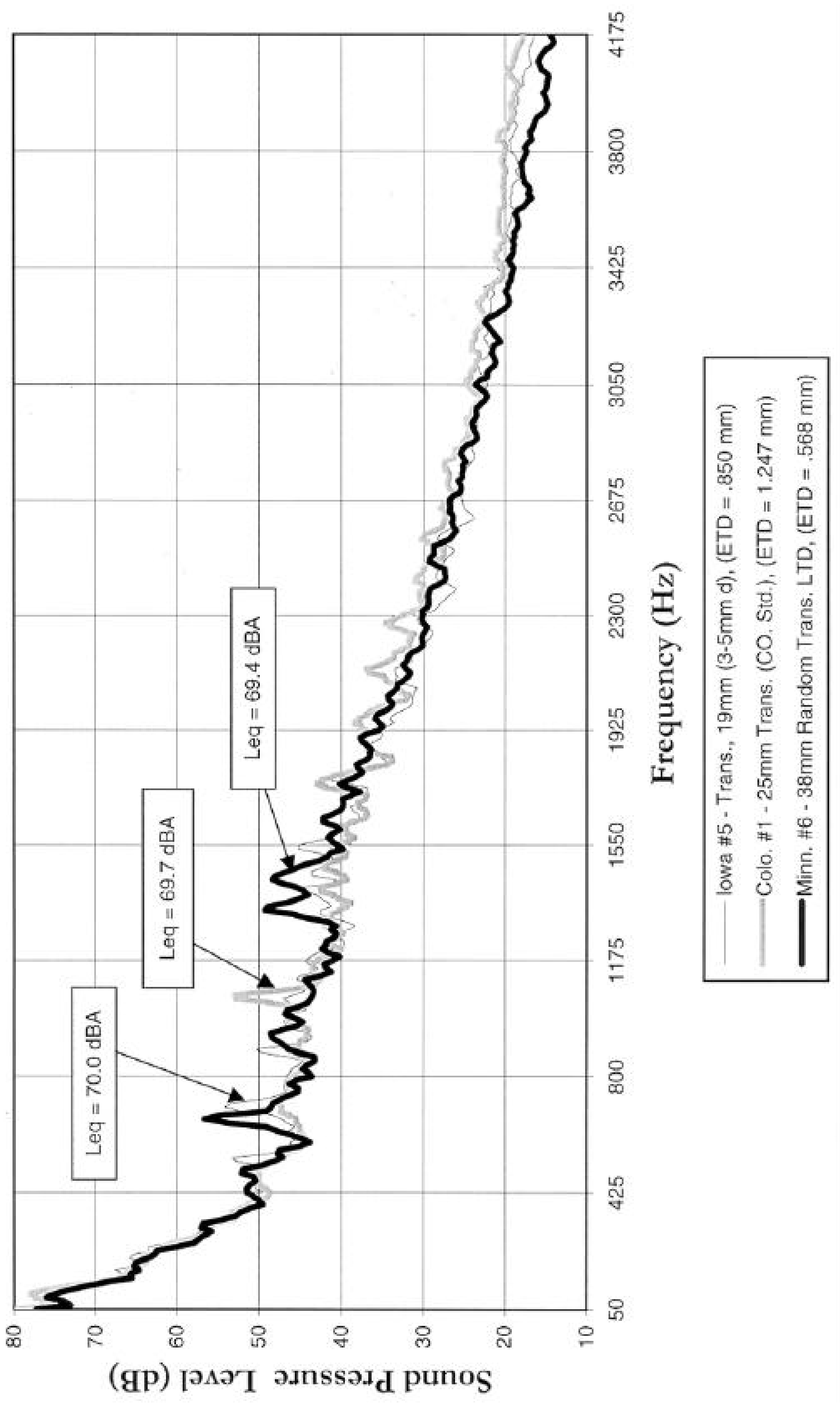


Figure 17: Comparison of Interior Noise on Uniform Transverse Tining of PCC Pavements

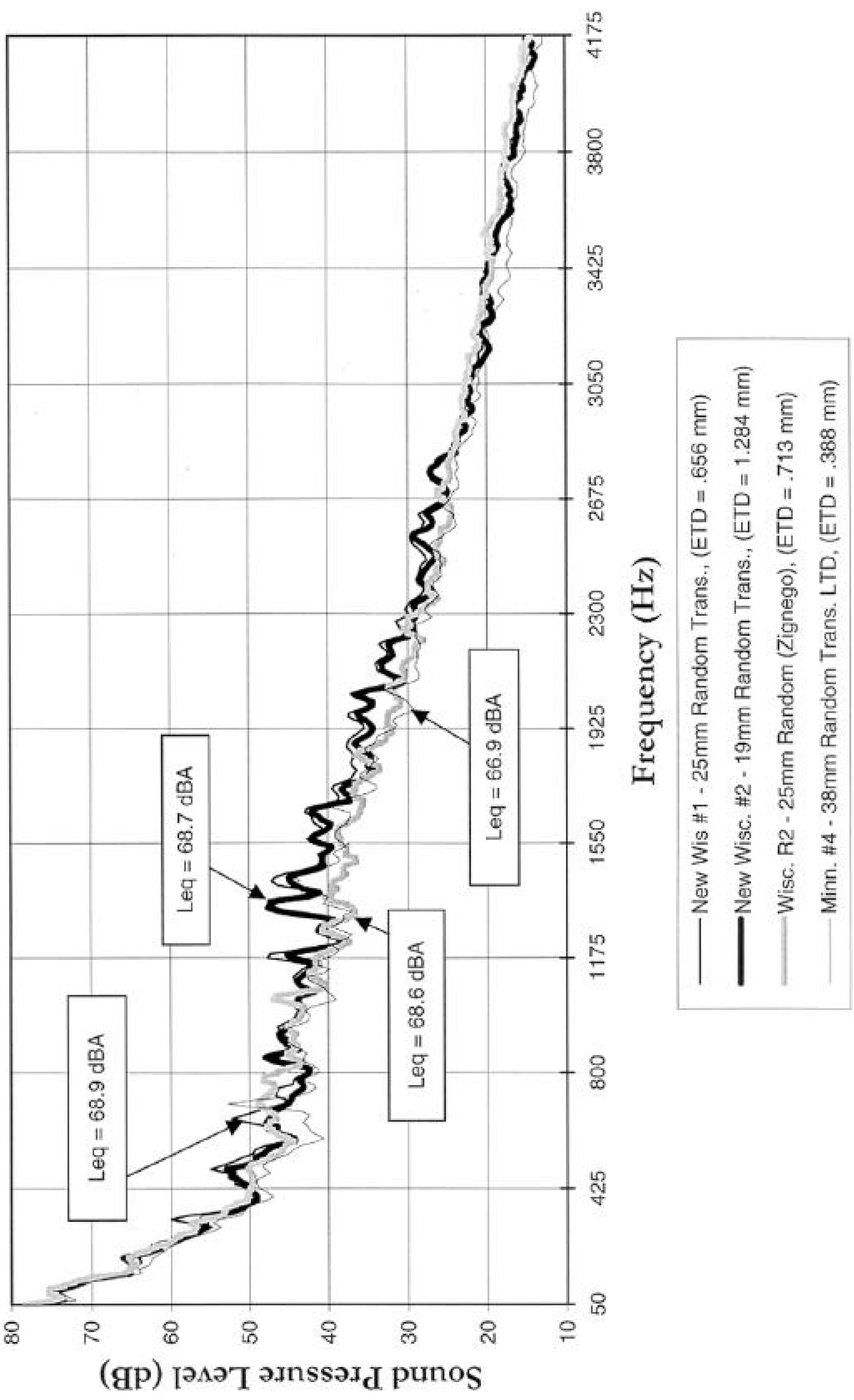


Figure 18: Comparison of Interior Noise on Random Tined PCC Pavements

The frequency spectra of the transverse random textures were clearly dependent on a randomization pattern. The 38-mm Minnesota pavement, #4, shown in Figure 18, contained characteristic first and the second harmonic peaks at approximately 700 and 1400 Hz, which was not observed for the Wisconsin R2 truly random pavement. The examination of the ROSAN texture plots indicate the 38 mm random of Minnesota #4 is close to uniform and the ROSAN mean spacing is 31.5 mm.

Comparison of Pavement Friction, Texture Depth, Tining Width and Interior Noise

Separate linear regression analyses were performed between interior noise (as the dependent variable) and $FN_{40}B$, ROSAN ETD, tine depth and width (from the ROSAN algorithm). The correlation results were with similar to the results of the regression analysis of the texture measurements with exterior noise but exhibited even lower R values. The correlation between $FN_{40}B$ and interior noise was the same as with exterior noise ($R^2 = 0.1$). Correlation between $FN_{40}B$ and interior noise in Wisconsin showed an R^2 of 0.16.

Correlation between ROSAN ETD and interior noise showed low correlation for all pavements but showed an R^2 of 0.66 for special pavements and 0.70 for AC pavements. Correlation between ROSAN mean depth and interior noise was non existent. This was true even within texture types.

Similar analysis between interior noise (L_{eq}) and tine width shows fair positive correlation ($R^2 = 0.45$) if the Wisconsin data is removed, since L_{eq} for Wisconsin was negatively correlated with tine width. Again, this is insufficient for firm conclusions.

Subjective Noise

The results of the subjective rating of the “noisiness” of the selected road surfaces using direct magnitude estimation can be found in Table 4. In order to determine the reliability of the data, a split-half method was used. The subjects were divided into two groups, each consisting of twelve subjects. Scale values (ratings) were computed from the estimates for each group. A correlation between the two sets of scales exceeded 0.9 which suggests that the scale values are highly reliable. It should be pointed out that the three newly constructed Wisconsin pavements were in the top six subjectively ranked pavements. These were the 19 mm random skew with both 1:6 and 1:4 skews (ranked 1 and 2 respectively) and the 25 mm uniform longitudinal (ranked 5th). The fourth ranked pavement is a North Dakota random transverse and the sixth ranked is Michigan’s European Texture (both with ROSAN ETD below 0.6). Other textures ranking in the top 10 included three of Iowa’s (they are described under that State’s sections). Unfortunately, the number of sounds (and hence pavements) that a person could listen to at one sitting is limited, so only 20 pavements could be compared.

Comparison of subjective results with D-weighted and PNLT levels

The AC and PCC pavements were ranked according to the results of the subjective evaluations. Table 5 contains calculated interior and exterior A-weighted SPL and PNLT values. An attempt was made to compare (correlate) these values with the results of the subjective evaluation. Little

Table 4 Subjective Rating of Interior Noise L_{eq} Listed in Order From Least Noisy to Noisiest

Test No.	State	Road	Sec.	Texture	Rating
19	New Wisconsin	STH 29	5	19mm Random Skew 1:6, LHF	82.5
18	New Wisconsin	STH 29	7	19mm Random Skew 1:4, LHF	88.9
20	Wisconsin	I-43	1	SHRP ACP	93.4
15	North Dakota	I-94	F	Random trans., Var., 26,51,76,102mm	93.8
14	New Wisconsin	STH 29	10	25mm uniform long.	96.8
16	Michigan	I-75	1	European texture	97.3
17	Minnesota	MN 55	4	38mm random trans.	98.0
7	Iowa	I-163	9	13mm uniform trans., saw cut	99.4
21©	**New Wisconsin**	**STH 29**	**2**	19mm random trans.	**100.0**
2	Iowa	I-163	5	19mm random trans., (3-5mm d)	102.0
1	Iowa	I-163	8	Milled PCCP	104.6
13	Iowa	I-163	1	13mm uniform trans., (3-5mm d)	107.6
6	Wisconsin	I-43	5	Ground PCCP	108.0
8	New Wisconsin	STH 29	1	25mm random trans.	109.8
3	Colorado	I-70	1	25mm uniform trans. (CO. Std.)	110.3
12	Wisconsin	US 151	R2	25mm random trans. (Zignego)	113.5
9	Wisconsin	STH 29	9a	13mm uniform trans.	124.2
4	Minnesota	US 169	6	38mm random trans.	127.7
10	Wisconsin	STH 29	10	19mm uniform trans.	140.8
11	Colorado	I-70	5	Random trans. saw cut (16,22,19 mm)	144.5
5	Wisconsin	STH 29	15	25mm uniform trans.	150.4

Results of the subjective rating of the "noisiness" of the road surfaces are listed in order from least noisy to noisiest.

Table 5 Comparison of Subjective and Objective Evaluations of Interior Noise Levels

State	Road	Section	Texture	Subjec	Interior	PNLT	Exterior
NW	STH 29	5	19mm Random Skew 1:6, LHF	1	67.6	82.9	82.4
NW	STH 29	7	19mm Random Skew 1:4, LHF	2	67.2	82.4	83.1
WI	I-43	1	SHRP ACP	3	65.9	81.8	81.1
ND	I-94	F	Random trans. var., 26,51,76,102mm	4	67.7	83.2	81.0
NW	STH 29	10	25mm uniform long.	5	68	82.6	83.9
MI	I-75	1	European texture	6	67.4	82.6	NA
MN	US 55	4	38mm random trans.	7	66.9	81.7	82.6
IA	I-163	9	13mm uniform trans., saw cut	8	69.2	85.2	83.3
IA	I-163	5	19mm random trans, (3-5mm d)	9	70	85.4	83.8
IA	I-163	8	Milled PCCP	10	72.1	88.4	84.6
IA	I-163	1	13 mm uniform trans. (3-5 mm d)	11	68.2	84.6	82.8
WI	I-43	5	Ground PCCP	12	69.3	85.9	81.2
NW	STH 29	1	25mm random trans.	13	68.8	83.1	86.6
CO	I-70	1	25mm uniform trans. (CO Std.)	14	69.7	86	86.4
WI	US 151	R2	25mm random trans. (Zignego)	15	68.6	84	83.4
WI	STH 29	9a	13mm uniform trans.	16	69.3	84.7	82.1
MN	US 169	6	38mm random trans.	17	69.4	84.3	87.3
WI	STH 29	10	19mm uniform trans.	18	69.1	84.7	84.0
CO	I-70	5	Random trans. saw cut (16,22,19mm)	19	68.6	84.7	84.1
WI	STH 29	15	25mm uniform trans.	20	69.6	85.3	86.3

correlation was found between A-weighted and subjective rankings when all the pavements were utilized. Similarly, PNLT values did not correlate with the subjective rankings. This is probably because the measure was developed for jet aircraft noise.

A better correlation was achieved when only the PNLTs of pavements with tonal components were compared with subjective rankings. At the same time, PNLT levels are not suitable metrics for the evaluation of pavements with tonal characteristics. There are significant spectral differences between tire/pavement noise, where the majority of the annoying frequency components lies within 700-2000 Hz, and the aircraft fly-over noise, for which this metric was developed.

Evaluation of tonal components

Based on the literature search, an attempt was made to quantify the prominence of the tones generated by different transverse-tined pavements. Both the exterior and interior narrow-band spectra were evaluated for three different transverse textures: 13 mm (½"), 18 mm (3/4"), and 38 mm (1 ½"), for 112 km/h (70 mph) car speed (Figures 11 and 19). The higher speeds were used for this purpose because they exhibited larger discrete frequencies. Based on the Fletcher's concept that a masking noise is mainly a result of the noise energy within a certain frequency band, the prominence ratio method was slightly modified. To calculate the prominence ratio, noise energy (total mean-square sound pressure ratios) was compared for the middle, lower, and upper bands.

The above method yielded ratios of 5 to 7 dB when the wider, Zwicker's, critical bands were utilized. With the ratios of 3 to 6 dB, objectionable discrete tones generated on 25 mm and 38 mm spaced transverse-tined textures (Figures 5, 6, and 10) were not rated as prominent. Then the same procedure was applied with narrower, Fletcher's, critical bands. The calculated ratios, Table 6, seemed to be much more reflective in terms of the expected annoyance.

Comparison of Interior, Exterior, and Subjective Rankings

A bar chart showing relative ranks of the 21 test sections included in the subjective testing is shown in Figure 20.

Noise and IRI Correlation

IRI (for those test sections for which it was available in all states) as the independent variable was compared to exterior noise (L_{ax}) and showed very low correlation of 0.00. This is not surprising in light of the literature search showing existing variation in use of IRI among states, except as noted in Colorado. When IRI was compared for test sections within individual states, better correlation was found in Wisconsin (R^2 of 0.25) and Colorado (R^2 of 0.77). Colorado had a more uniform texturing on its six test sections than that of the 28 sections in Wisconsin. However, the correlation was positive in Wisconsin (the greater IRI the greater the noise) whereas it was negative in Colorado (the greater the IRI the lower the noise). IRI in all states as a whole, excluding Colorado was correlated positively but with a low R^2 of 0.06. The IRI may therefore be a factor in noise, and

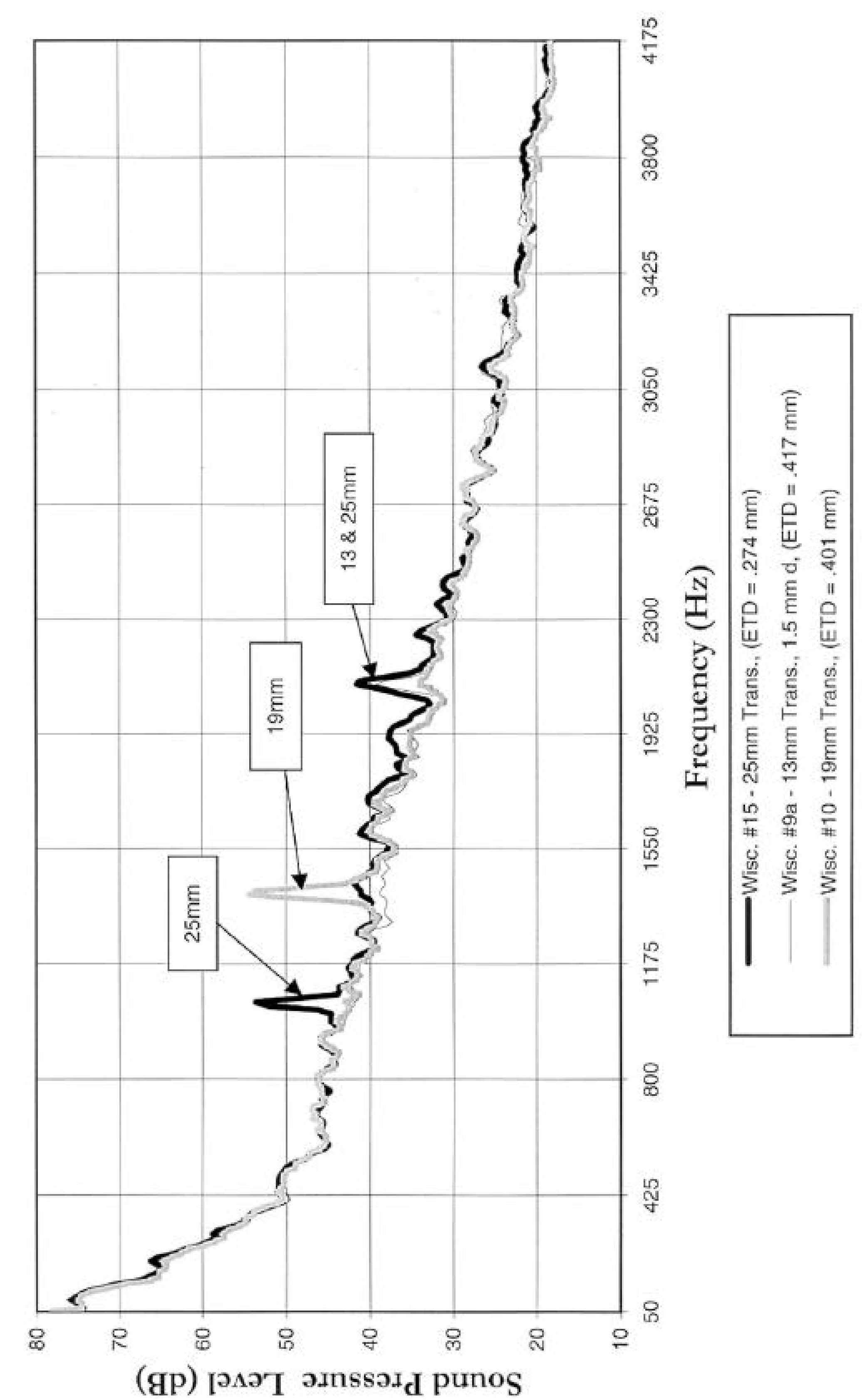


Figure 19: Comparison of Interior Noise for Uniform Transverse Tined PCC Pavements

Table 6 Prominence Ratios of Selected Transversely-tined Concrete Pavements

Pavement	Type of Measurements	Tone Frequency, Hz	Fletcher Critical Bandwidth, Hz	Zwicker Critical Bandwidth, Hz	Prominence Ratio based on Fletcher Bandwidth,dB	Prominence Ratio based on Zwicker Bandwidth,dB
Minnesota, 38 mm	Interior, 3Hz Resolution	745	54	136.5	7.5	5.3
Minnesota, 38 mm	Interior, 12.5Hz Resolution	763	54	138.1	8.8	5.6
Minnesota, 38 mm	Exterior,25Hz Resolution	800	58	141.6	6.4	5.7
Wisconsin, 25 mm	Interior,3Hz Resolution	1153	65	179.9	8	3
Wisconsin, 19 mm	Interior,3Hz Resolution	1549	82	232.1	8.9	6.7
Wisconsin, 13 mm	Interior,3Hz Resolution	2438	122	374.8	2.3	-0.1

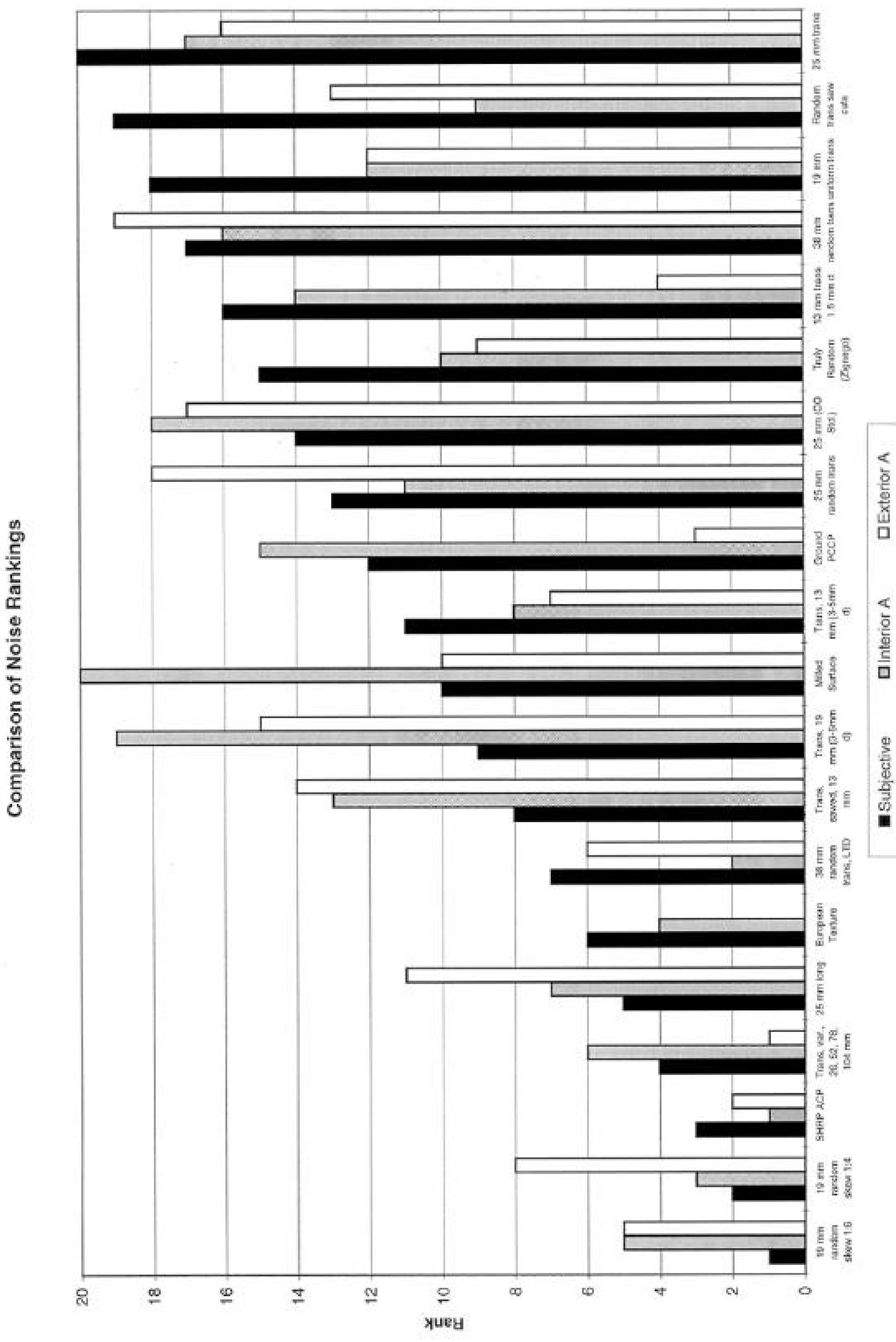


Figure 20: Sections Included in Subjective Tests

intuitively makes sense, but this study is inconclusive because of low correlation with exterior noise.

Correlation analysis between IRI and interior noise (L_{eq}) was also performed. Again there was low correlation when data from all states was used (R^2 of 0.09). The R^2 improved to 0.12 when Colorado data was excluded, since Colorado was negatively correlated. Correlation of IRI with L_{eq} for Wisconsin was the highest of the states (R^2 of 0.19).

Texture and Friction Correlation

Correlation between ROSAN ETD (independent variable) and sand patch for all pavements is very good ($R^2 = 0.73$) considering the limitations of the sand patch method. It rises to an R^2 greater than 0.90 for all but the transverse random tining, and these have an R^2 of 0.59.

Correlation between ROSAN ETD and friction is very low when all pavements were considered together ($R^2 = 0.13$). When individual pavement types are analyzed, correlation between ROSAN
ETD and the transverse and skewed are high ($R^2 = 0.50$ and 0.95 respectively).

Correlation analysis between ROSAN ETD (again as the independent variable) and speed gradient of friction is low or non-existent but negatively correlated (the greater the ROSAN ETD the lower the speed gradient) with an R^2 of 0.04. Correlation within pavement texturing types is also low, except for skewed texturing (negatively correlated R^2 of 0.80). Since friction measurements are less accurate because of the methodology (infrequent spot measurements for friction and different state's measurements, vs. 12000 measurements for ROSAN ETD by a single value), this is not surprising, considering the variation of texture within each test section. Although intuitively the greater the texture the lower the friction gradient, this study methodology used for friction can not support that conclusion.

RESULTS

Comparison of Interior, Exterior and Subjective Criteria for "Desirable Test Sections"

A spread sheet showing all data is shown in Appendix E. In reviewing the noise and textures of all 57 pavements, the research team used judgement to select desirable textures for further analysis and possible recommendations, based on all noise and texture characteristics of each of the test sections. To be "desirable" a pavement had to exhibit the following criteria:

- a maximum exterior noise level (L_{max}) of approximately 83.0 dBA (among the best 25 ranked sections);
- a maximum interior noise level (L_{eq}) of approximately 68.0 dBA (among the best 18 ranked sections);
- a subjective noise rating of 100 or less (the best 9, plus the comparator of 100);
- no predominant spikes or discrete frequencies (all longitudinal, special and skewed pavements, and four random transverse tined); and
- a ROSAN ETD of 0.7 mm or above (based on references 30, 31, 33); all but minimally tined PCC and dense graded AC pavements fell above this level, as shown in Appendix E.

Friction was measured by the states, rather than by the research team. Like texture, friction has great variability during measurements, according to knowledgeable state research engineers. An $FN_{40}R$ of 40 measured with a ribbed tire is considered minimum for a new or relatively new PCC pavement (according to Wisconsin DOT). Speed gradient is more indicative of the adequacy of texture to provide for safety concerns on wet pavements. Due to the fact that friction's measurements were made with a bald tire for this study and were outside of the research's control and with no US standard set, this study makes no recommendation on minimum friction, but reports $FN_{40}R$ measured with a bald tire where it is deemed important.

Summary of Each States Rankings

Colorado

All of Colorado's test sections have substantial texture depth and width and are among those with the largest ROSAN ETD. The lowest ETD is above 1.2 while most are above 1.7. Hence, only two (#7 and #9) are near the established cut-offs of 68.0 dBA for interior noise. However, these two sections, 7 and 9, are among the best (ranked third and seventh respectively) for exterior noise. Both are longitudinal, one tined (#9) and one saw cut (#7). Three of Colorado's sections, all transverse tined, are in the worst nine for interior noise is one among the worst four for exterior noise. Only two (#1 and #5) are included in the subjective testing and they are among the loudest, with ratings of 110 and 144 respectively, placing them among the worst seven. All sections were among those with deepest tining. The transverse tined sections were among those with the greatest width.

Iowa

Two of Iowa's pavements (# 3 and 4) are among those with an acceptable level described previously for interior and exterior noise. Both are longitudinal, falling very close in rank with longitudinally tined pavements in other states. Both had substantial ROSAN ETD (> 0.8). Iowa #3 had the second best exterior noise ranking of all pavements and acceptable interior noise and ROSAN ETD, even though specified 1.5 mm deep. Four of Iowa sections (#9, 5, 8 and 1) were included in the subjective study and they were all quite close to the comparator (99, 102, 105, and 108 respectively). Iowa #9 is the 13 mm uniform sawed transverse tined PCC pavement but has some prominent discrete tones.

Michigan

Two sections were included in Michigan, in order to include the only section constructed with European two layer construction, and the Michigan standard adjacent to it. Because of the presence of retaining walls, only interior noise could be measured. The European texture ranks 10th best in interior noise but has a relatively low ROSAN ETD of 0.414. The Michigan standard (1" uniform transverse) has a higher noise level. The European texture ranks sixth on the subjective noise rankings with a 97.3, close to the comparator. The ROSAN ETD of 0.414 and $FN_{40}B$ of 26 are below the thresholds set for PCC pavements.

Minnesota

Three of the recently constructed (1996) PCC pavements were included with the national study. In addition, the Minnesota DOT (MinnDOT) separately contracted with Marquette University to complete the noise and ROSAN ETD on five added sections constructed earlier between 1990 and 1996. All are summarized in this report.

In exterior noise, the longitudinally tined pavement (#1, built in 1996) is at 81.7 dBA, with a satisfactory ROSAN ETD of 0.928. The 38 mm random transverse (#4, 1996) is also below the 83.0 dBA criteria (82.7) but has a low ROSAN ETD (0.388).

In interior noise, the LTD-only texture (#5, built in 1990) was the quietest PCC pavement (ranked fifth overall) but had a ROSAN MPD below 0.3. This is less than any other PCC pavement and below the threshold. The 38 mm random transverse PCC pavement (#4, built in 1994) is the sixth quietest for interior noise, but as mentioned, has a low ROSAN ETD and has prominent discrete frequencies and is discussed later. The longitudinal tined pavement (#1) also ranks among the quietest (7th) for interior noise, and has a good ROSAN ETD of 0.928. The LTD-only pavement constructed in 1996 (# 7) was just above the cutoff (68.3 dBA) but has a low ROSAN ETD. This is closely followed by the 19 mm random transverse (#3, at 68.4 dBA) constructed in 1996 and has an adequate ROSAN ETD.

Only two pavements (#4 and # 6) were selected for subjective testing, both with 38 mm random transverse tining (1994 construction). Only # 4 had a satisfactory score of 98 but also had the low ROSAN MPD. The other section (#6) also has a low texture (ROSAN ETD of 0.568) but it ranked 17th with a score of 128 in subjective testing. Minnesota #6 has a very prominent discrete frequency. Both are shown in Figure 21. All eight pavements have an FN_{40} B above 40.

North Dakota

Five sections (built in 1994) were included in the study for North Dakota. For interior noise, sections A and F were ranked satisfactorily, the 26 mm skewed ranked 11th and the random transverse 26, 52, 78 and 104 mm (or 1, 2, 3 and 4" respectively) ranked 15th. Both had low ROSAN ETD (below 0.4). Sections F and H were ranked 8th and 11th in exterior noise (F is the random transverse described previously). Section H is tined longitudinally with a 19 mm spacing and has a high ROSAN ETD of 1.26. Only section F was included in the subjective and ranked 4th with a 94 rating. No friction data measured with a bald tire was available in North Dakota.

Prior Wisconsin Test Sections

PCC Pavements - Not every prior section was included in this report, only those of interest for future study. Nine of the 16 were included and they were listed previously. Generally the transverse textured PCC pavements included in the study ranked poorly in interior, exterior and subjective testing. The random transverse sections (RO through R3 and Wisconsin #11) are above 68.0 dBA (interior) and on the noisy end of the exterior ranking. The 25 mm (1") transverse was near the worst in subjective rankings in the prior study. Three 1994 PCC pavements were included in the subjective testing (15, 9A and 10) and they ranked among the worst (#16, 18 and 20 respectively).

Asphalt Pavements - The asphalt pavements tested that were constructed in prior years rank near the best in all cases but the Waukesha County SMA (I43#6). This one ranks 11th from the best in interior noise but 6th in exterior noise. Generally, they are quieter, but except for both SMA pavements, had substantially lower ROSAN ETD (below 0.25 mm). The SHRP ACP, the only AC pavement included in subjective testing ranked third best, but had a low ROSAN ETD (0.248). All AC pavements had an FN_{40}B below 34.

Special Pavements - The ground PCC pavement (I-43 Sect. 5) was poor in interior noise, but satisfactory (below 82.0 dBA) in exterior noise. It ranks 13th out of 21 in subjective noise, and has no predominant spikes. The higher level may be the result of it being an older pavement (built in 1976, ground in 1993). The Skidabrader ranked near the loudest in both interior and exterior noise. It was not included in the subjective testing. It exhibited higher noise levels across the frequency spectrum.

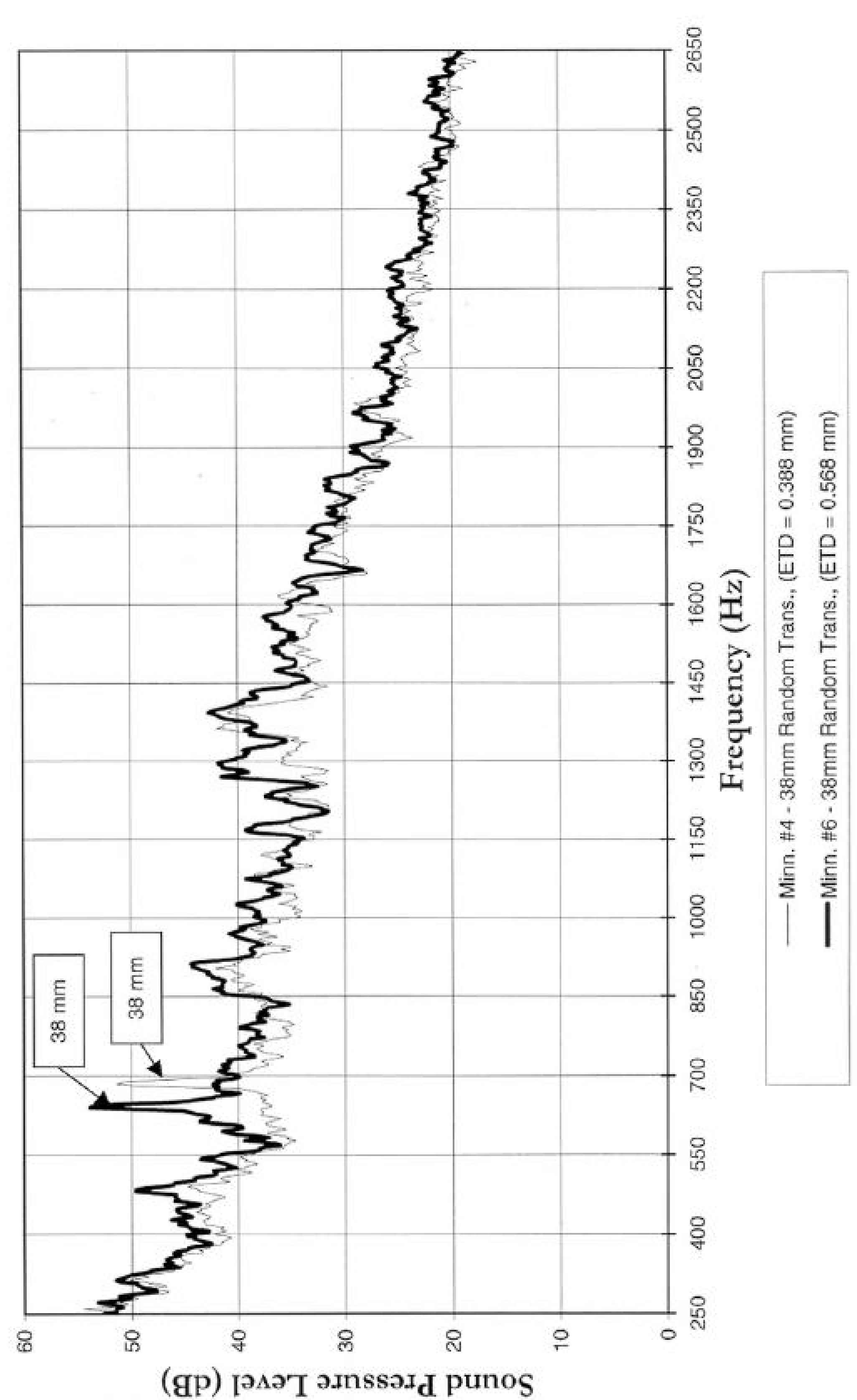


Figure 21: Comparison of 38 mm Random Transverse Pavements

New Wisconsin PCC Pavement Test Sections

Five of the ten newly constructed test sections fell at or below the level of 68.0 set as a criterion for interior noise. All had ROSAN ETD of above 0.70. In terms of interior noise, three were random skew and two were longitudinal. Another random skew was close enough (68.5) to also be considered. The best was New Wisconsin (NW) 7 (19 mm random skew 1:4) at 67.2, comparable to one of the SMA pavements and better than all the new and prior random transverse tined PCC pavements.

On the basis of exterior noise, only three sections (#5, 8 and 7) were at or close to the 83.0 dBA criteria. These also had a ROSAN ETD of approximately 0.7 or above. The 19 mm random 1:4 skew (#7) at 83.1 dBA was also the best for interior noise among new Wisconsin sections. The 25 mm random longitudinal had an FN_{40} B of 36.6.

Subjective rankings for the best interior and exterior included three of the new Wisconsin sections in the top five. They are both 19 mm random skews (#5 and #7) and the 25 mm longitudinal (#10), with subjective scores of 83, 89 and 97, respectively. The 19 mm average random transverse tined pavement (which was the comparator) is 9th with its assigned 100 points.

Random Transverse Tining

In the previous study, random transverse tining was found to eliminate the obnoxious, high pitched whine caused by uniformly spaced transverse tining on PCC pavements. Since then, a number of states have built test sections. Fifteen different sections in four states were included in this project. A special analysis of Wisconsin's sections was also to be included in the study.

Colorado had two sections included in the study with random tining. Section 5 was a random transverse saw cut, 19 mm average spacing, with very deep grooves. It had moderate interior and exterior noise (68.6 and 84.1 dBA), it was near the worst (20 out of 21) in subjective rankings, and had a 15 dB spike in interior noise frequency. Because of the saw cut, it's tining depth and width are quite large (ROSAN ETD of 1.738). Colorado's other random (# 3) was moderate in interior and loud in exterior noise (69.9 and 84.4 dBA), and was not ranked subjectively. It had a very deep ROSAN ETD of 1.834. It is interesting to note that this random was a 16, 22, 19 mm random, and because it used only those three spacings, also exhibited a discrete frequency or whine since it was close to uniform (19 mm average).

Iowa #5 has an 8 dB spike at approximately 700 Hz (96 km/h) and is among the loudest in both interior and exterior noise rankings. Its ROSAN depth, width, and ETD are not large.

North Dakota section F was constructed with a wide range of random spacing (26,51,76, and 102 mm) and had no discrete frequency exhibited until 112 km/hr (70 mph), with a slight 5 dB spike. It exhibited low noise characteristics, had very low ROSAN ETD (0.378), but had moderate depth and width of tinings.

Wisconsin had seven random transverse tined sections included. Five prior sections (Wis. 11 and R0, R1, R2 and R3) were included to see how five different contractor's randomly tined pavements would compare. Wis. 11 (built with the 1994 test sections) was the loudest ranked randomly tined section. This was explained in the prior report (28), and led to the current interim guideline to have a more closely spaced random pattern. Even though the texture was minimal (ROSAN ETD of 0.283) it had high interior and exterior noise, was not ranked subjectively, and had a spike of 10 dB.

R0 was constructed in 1994 on eastbound Hw. 29 across from the westbound test sections in Phase I of the project with a specified 22 mm avg. random pattern, and had a ROSAN ETD of 1.138. It has a computer calculated mean tine spacing of 21.1 mm and median spacing of 21 mm, has no predominant frequency or spike and was not rated subjectively.

Three other sections were constructed by different contractors in 1996 (R1, R2 and R3 according to interim guidelines of WisDOT, 10 to 40 mm with 50 percent under 25 mm). All had moderately deep textures (ROSAN ETD over 0.7), and had a noise level over 68.0 and 83.0 for interior and exterior noise, respectively. Section R1 (US 51) has a mean tine spacing of 17.6 mm, a median of 17.5 mm and a predominant frequency of approximately 5 to 7 dB. Section R2 (US 151) has a mean tine spacing of 21.3 mm, a median spacing of 21.5 mm and a predominant frequency magnitude of approximately 5 dB. Section R3 has a mean tine spacing of 22.9 mm, a median spacing of 24 mm and a predominant frequency magnitude of 8 dB. It was thought that those with spacing over and under a certain width exhibit some predominant frequencies (spikes), so all random transverse were studied.

Two new random transverse tined sections were constructed for this project in Wisconsin. New Wisconsin #1 has a 25 mm average random spacing and has a spike or approximately 5 dB. It ranks among the loudest in exterior noise (86.6 dBA) and in the middle for interior noise (68.9). Its ROSAN ETD was 0.656. New Wisconsin #2 has a 19 mm average random tining and has several spikes at 104 km/h (65 mph), the largest of 8 dB at 900 Hz. It also ranks near the loudest in exterior noise (86.3 dBA) and is in the middle of the interior noise rankings (68.7 dBA). It was chosen as the comparator for subjective noise testing and hence was assigned a score of 100, ranking it ninth out of 21 sections. The ROSAN ETD was 1.284.

A review of Colorado section 3 shows the same. It has larger spikes because of the greater mean tining depth and width and a mean spacing of 18.3 mm (median of 17.5 mm). Likewise, Colorado 5 saw cut shows a mean and a median depth of 4 mm and even larger spikes because of the greater depth and widths. Minnesota 2 with a 18.6 mm computer generated mean spacing and 17.5 mm median spacing has a slight spike of 5 dB. It was among the louder pavements, yet had inadequate ROSAN ETD. Minnesota 3 with a 22.7 mm mean spacing and a 20.5 mm median spacing has a slight spike (5 dB), yet it also did not meet any criteria for noise or texture. Minnesota 4 and 6 with mean and median spacings over 29 mm have large predominant spikes. Except for the Colorado saw cut, the spacing seems to make some difference. Neither depth nor width correlate well with noise in this texture group, probably because of the varying levels of discrete frequencies. Since data on the length of the tining rake is unavailable in other states, this factor could not be analyzed. Another tool was necessary leading to the selection of spectral analysis to explain a measure of randomness.

In Wisconsin, friction was not measured on R0 and the remaining sections had an $FN_{40}B$ above 40 except R3 at 38.1. In Colorado and Minnesota, the random tined sections all had satisfactory $FN_{40}B$ above 40.

Spectral Analysis of Randomization of Tining Patterns

Spectral analysis, a method for quantifying repetitive or periodic phenomena in a time series or sequence of numbers, may be applied to the ROSAN data to determine the presence and source of discrete frequencies or tones in random transverse road sections. All 15 random transverse road sections, including the saw cut test sections, were examined. Dr. Kristina Ropella and Mr. Ziad Saad of Marquette University's Biomedical Engineering Department have considerable expertise in power spectrum analysis of biomedical data such as electrocardiograms and brain mapping imaging time series. With the assistance of the two researchers, power spectrum analysis was implemented in the analysis of periodicity in the ROSAN data. The digital series representing the sequential location of groove patterns on the pavement, has characteristics similar to a number of biomedical time series. Thus, the ROSAN data may be analyzed with the same spectral and statistical tools used on biomedical signals. To date, software has been developed to not only examine the power spectrum characteristics of the ROSAN data, but also to simulate the "sound" heard by a passenger driving a car over the random transverse road sections represented by the ROSAN data. In addition, software has been written to allow the user to create and test different random groove patterns, rake lengths and car speeds in order to simulate "sounds" produced by an automobile driving over the proposed random transverse section. While the audio simulation does not account for the sound filtering effects of the car and other noise sources such as those generated by the engine and the wind, the sound simulation allows relative comparison of noise quality produced by various rake patterns. The simulation allows one to "hear" discrete tones mixed with noise, and the power spectrum analysis shows the presence or absence of significant peaks of power that give rise to the discrete tones. In general, the more "flat" the power spectrum over a band of frequencies, the more random or "white" the noise produced by the random transverse section. White noise has no distinct tones that stand out to the observer. In contrast, significant "peaks" in the power spectrum produce sound with one or more discrete tones that stand out to the observer.

To date, the power spectrum analysis of the ROSAN data indicates significant peaks of power (relative to the average noise levels between 0 and 4000 Hz) in those random transverse sections that are reported to produce sounds with discrete tones. In addition, these peaks of power correlate with the peak frequencies in the interior sound spectrums that are recorded simultaneously with the ROSAN data. Simulations demonstrate that the location of power spectrum peaks are altered by the mean inter-groove width, and the spread (bandwidth) of the power spectrum is a function of the variance or the inter-groove width and the spatial sequence of the randomized grooves. The sounds generated by driving over the random transverse pattern is a function of the randomness of the groove patterns, the rake length and the car speed.

All 15 random transverse sections were analyzed using this spectral analysis technique.

Although a full discussion was prepared for another report to TRB, the brief conclusions are reported here. Of the 15 sections, four had none or only slight observable discrete frequency in interior or exterior noise. They are Minnesota # 2 and # 3, North Dakota F and Prior Wisconsin R0.

The four above pavements have little or no discrete frequencies because their ROSAN power spectrum is well spread out (like the noise spectrum), and if peaks occur, they are either outside of the peaks in the noise spectrum or have little or no harmonics shown. The four have arelatively low ratio of ROSAN maximum spacing to minimum tine spacing (hereafter referred to as ROSAN max/min), which helps explain the spread in spacing.

Other random transverse textures, for example, Iowa # 5 and Prior Wisconsin # 11 are well spread out, but have numerous harmonics (repetitive doubling of a frequency) and hence have a spike in the noise spectrum. The Wisconsin R1, R2 and R3, all built under the same specification, have peaks in their ROSAN Spectrum at or near the peaks in the noise spectrum, and are not well spread compared to other random transverse without spikes in the noise spectrum (ROSAN max/min from 4.0 to 7.65). New Wisconsin #1 and #2 are very well spread, but have harmonics present in the ROSAN spectrum and slight spikes in the noise spectrum. Both are quite loud however.

Minnesota # 2 and #3, both 19 mm random transverse, have only slight spikes in the noise spectrum, and their ROSAN spectrum is well spread, without harmonics, and among the lower spectra in ROSAN max/min (1.99 and 3.4 respectively). North Dakota F (26, 51, 76, 102 mm) is unique, exhibits a broad ROSAN spectrum (max/min of 2.04), has harmonics in the ROSAN spacing, has a peak that coincides with the noise spectrum, yet has a spike at only showing at 112 km/hr (70 mph). It is among the very shallowest texturing however, because of the large spacing (up to 102 mm or 4") and relatively low mean tining depth and width. Wisconsin R0 remains an anomaly, with a well spread ROSAN spectrum, a single peak that coincides with the noise spectrum peak near 1000 Hz, and a modest ROSAN max/min of 3.95. This section has almost no spikes and no detectable whine.

Brief conclusions from this first spectral analysis suggest that if a tining rake can be built longer (the longer the better), a more random pattern can be built to theoretically eliminate the whine. Three rake patterns were generated for 3 m (10') rakes which are optimized to produce minimal whine or discrete frequency in the noise spectrum (3 m rakes exceed the wheel-base of most passenger cars, vans and sport utility vehicles currently on the road). The three patterns are from 10 to 51 mm, 10 to 76 mm and 10 to 102 mm, all with good randomization, and all tested by all spectral analysis techniques used in this project. The largest spread (10 to 102 mm) resulted in the least ratio of ROSAN max/min (1.34), but has the lowest total theoretical texture depth (theoretically comparable to ROSAN ETD). The shortest (10 to 51 mm, with a max/min ratio of 1.58) would be closest to the current guideline in Wisconsin (10 to 40 mm with 50 percent < 25 mm). Since 38 mm uniform texture has been used for years in some states (Minnesota and Nevada), the medium spread pattern, from 10 to 76 mm was also generated for comparison, and the ROSAN max/min (1.41) is very close to the larger random (10 to 102 mm with ROSAN max/min of 1.34). The power spectrum analysis of its ROSAN spacing and the rake tine pattern for this medium spread rake, 3m (10') in length, is shown in Appendix F.

The theoretical rake pattern was tested in Wisconsin in 1999, and Iowa and Michigan each built sections as well using different tine spacing with rakes designed by spectral analysis. A random transverse section and a random skew section were constructed on STH 29 in Marathon County, Wisconsin just east of Abbotsford late in Summer, 1999. The rake with tine spacing ranging from 11 to 74 mm was built very close to that recommended spacing. A list of the actual tine spacing (as built) is included in Appendix G.

Spectral analysis was conducted on as built dimensions of tine spacing, and showed the same broad spread spectrum, with a ratio of max/min tine spacing of 1.48 (just above the theoretical best of 1.41 shown in Appendix F for the theoretical rake). In November of 1999, both interior and exterior noise measurements were gathered on both test sections using the same methodology described in this report and the same passenger car driven at the same speeds. Different tires had been mounted on the car after the major part of the field work for this project was complete (1998) and were in place for this later study.

The team believes the random transverse section in Wisconsin exhibits no discrete frequency or whine due to tire pavement noise, nor does the random skew, 1:6 LHF section. The actual noise spectra shown in Appendix G have a broad peaks of 5 to 7 db that occur at the same frequency of 1100 Hz, for all speeds for interior noise measurements. Similar peaks which do not shift with speed also show on exterior noise spectrums, but are not as easy to see since narrow band analyses was not used.

These assumptions were confirmed by driving of the test sections by both WisDOT engineers and this research team members. Neither the theoretical random or the random skew have noticeable whines. In searching for the cause of the broad peaks, it was realized after the noise measurements that the passenger car had been in an accident in April, 1999, before the 1999 field measurements. Damage to the body as well as wheel bearings and steering was repaired. The noise spectrum is typical of that which would not change do to speed, and hence is attributed to the vehicle.

The random skew tining section built in 1999 exhibited a lower overall exterior noise level of 3 dbA compared to the random transverse, but texture measurements were not made to compare textures, so this is not a validated reduction like those made earlier, since textures could be different..

Observations have not been made by the research team of the sections built following the theoretical rake design in Michigan (0 to 51 mm) and Iowa (0 - 76 mm).

Skewed Tining

Five of the skewed texture sections are close to the criteria for interior and exterior noise established by the team. The loudest is Prior Wisconsin Section 8, with uniform spacing that has a discrete frequency or spike at 1000 Hz of approximately 10 dB. This discrete frequency occurs even with the specified low tining depth of 1.5 mm (and the low ROSAN ETD of 0.376). This confirms that randomized spacing is important even with the skewed tining. The best section for interior noise is New Wisconsin # 5, the 19 mm random skew 1:6 LHF. It has a ROSAN ETD of 0.708 and exhibits substantial variation in texture but no predominant frequencies or spikes. The North Dakota A (25 mm uniform skew, 1:6 RHF) is also satisfactory for both interior and exterior noise, but exhibits a spike of approximately 12 dB near 1000 Hz at 104 km/h (65 mph). New Wisconsin #7, a 19 mm random 1:4 skew LHF, has an exterior noise level of 83.1, close to the criteria of 83.0 and a ROSAN ETD near 0.718, but has no discrete frequency.

All skewed tining sections have satisfactory friction. The New Wisconsin # 5 and 7 ranked best (first and second) with scores of 82 and 89 on the subjective testing (compared to 100 for the New Wisconsin #2 - 19 mm random transverse).

Longitudinal Tining

Eight of the 11 longitudinally tined sections had good exterior noise characteristics, ranging from Iowa's #3 at an L_{max} of 79 dBA to the new Wisconsin # 8 (L_{max} of 82.7 dBA). All had a ROSAN ETD of 0.7 or above, although the old Wisconsin #6 was at the criteria of acceptance for texture. Five of the 11 had acceptable interior noise levels, ranging from a low of 67.2 on Minnesota #1 to Colorado # 7 with 68.1. The latter was the 19 mm saw cut with very deep texture (ROSAN ETD of 3.22). All texture was at or well above the minimum criteria. The only longitudinally tined section included in subjective rankings was new Wisconsin #10 and it was acceptable, with a ranking of 96.8. All longitudinal tined sections except the new Wisconsin #8 had acceptable friction.

One phenomena noticed about ROSAN ETD on longitudinally tined PCC pavements is that textures substantially deeper than the minimum threshold (0.7 mm) did not necessarily increase the exterior or interior noise levels. For example, the saw cut pavement in Colorado 7 (ETD 3.22 mm) was double that of Colorado 9 (ETD 1.74mm) and four times the minimum threshold, yet exterior and interior noise levels only increased less than 1dBA. Comparing Iowa 3 (deliberately specified at only 1.5 mm depth instead of the standard 3 – 5 mm depth) and Iowa 4 (ROSAN ETD of 0.84 and 1.25 respectively), exterior and interior noise changed by less than 1 dBA. Comparing New Wisconsin 8 and 9, section 9 has an ETD 2.5 times that of section 8 (1.71 ETD to 0.7 ETD respectively), but noise levels increased on section 9 approximately 3 dBA so the phenomena was not universal. However, the tining on the longitudinal sections in Colorado and Iowa was specified as 19 mm uniform and that on the two Wisconsin sections were both specified with different random spacing.

Asphalt

All AC pavements in Wisconsin met the criteria for interior and exterior noise. The only AC (SHRP) pavement included in the subjective ranking is third with a score of 93.4. The ROSAN ETD however was inadequate for both the standard dense graded AC pavements and the SHRP AC pavement. The ROSAN ETD was adequate for 16 mm max aggregate SMA pavement but inadequate for the SMA with smaller aggregate. Friction was at or below an $FN_{40}B$ of 34 for all AC pavements. These pavements were constructed in 1992 and 1993.

Summary

The texture types that could be classified as the best of their kind (close to or meeting the criteria) for exterior noise are compared in Figure 22 (at 96 km/h). This includes Iowa #3 longitudinal, Wisconsin I-43 #4 (SMA with largest aggregate), the new Wisconsin # 5 random skew, and the best random transverse (Wisconsin R2) that came closest to the thresholds established for analysis of satisfactory pavements. What is striking is the closeness of the only AC pavement with texture comparable to PCC pavements (Wisconsin I-43 #4) to that of the longitudinally and skewed tined PCC pavements. All have ROSAN ETDs above 0.7, with the Iowa #4 longitudinal having the deepest texture (ROSAN ETD of 1.253) and the lowest exterior noise of the four. This could mean depth is not a factor in noise characteristics of longitudinally tined pavement. This width could not be measured on longitudinally tined pavements with $ROSAN_b$, since this application had not yet been developed by the Turner Fairbanks Research Center at the time of the measurements.

The same four are very close to or the best texture of their kind (close to or meeting the criteria) for interior noise, and they are compared in Figure 23 (at 96 km/h). Again, the closeness of the longitudinally and skewed-tined PCC with the AC pavement for interior noise is striking. The slight spiking of the R2 Wisconsin random transverse also shows in Figure 23 at a frequency of approximately 1000 Hz.

Currently, FHWA noise models do not recognize pavement surface type differences. This is partly due to the fact that there are no noise thresholds in surface texture performance specifications that can guarantee noise changes over time. Until more research on these noise and texture changes over time occurs, such changes are unlikely. Therefore, if the benefits of this research are to be realized and reflected in FHWA noise models, noise and texture studies such as this one need to be repeated after a sufficient time. to show the initial benefits of texture selection remain. This, coupled with establishment of a minimum initial and maintained texture for wet pavement safety, are both necessary if any change in recognition of surface texture in FHWA noise models is to be considered.

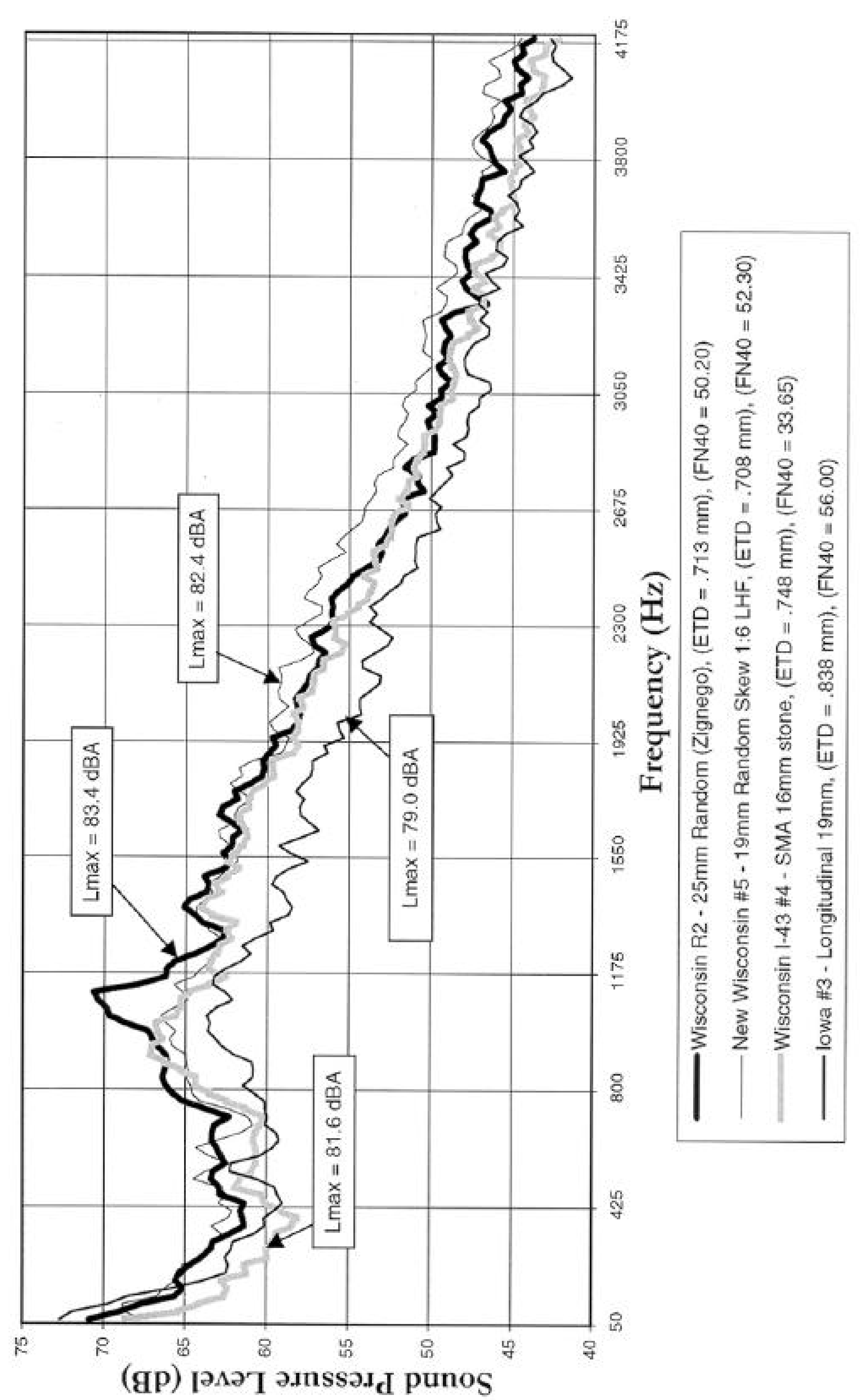


Figure 22: Comparison of Exterior Noise for the "Best" of the Different Pavement Texture Types

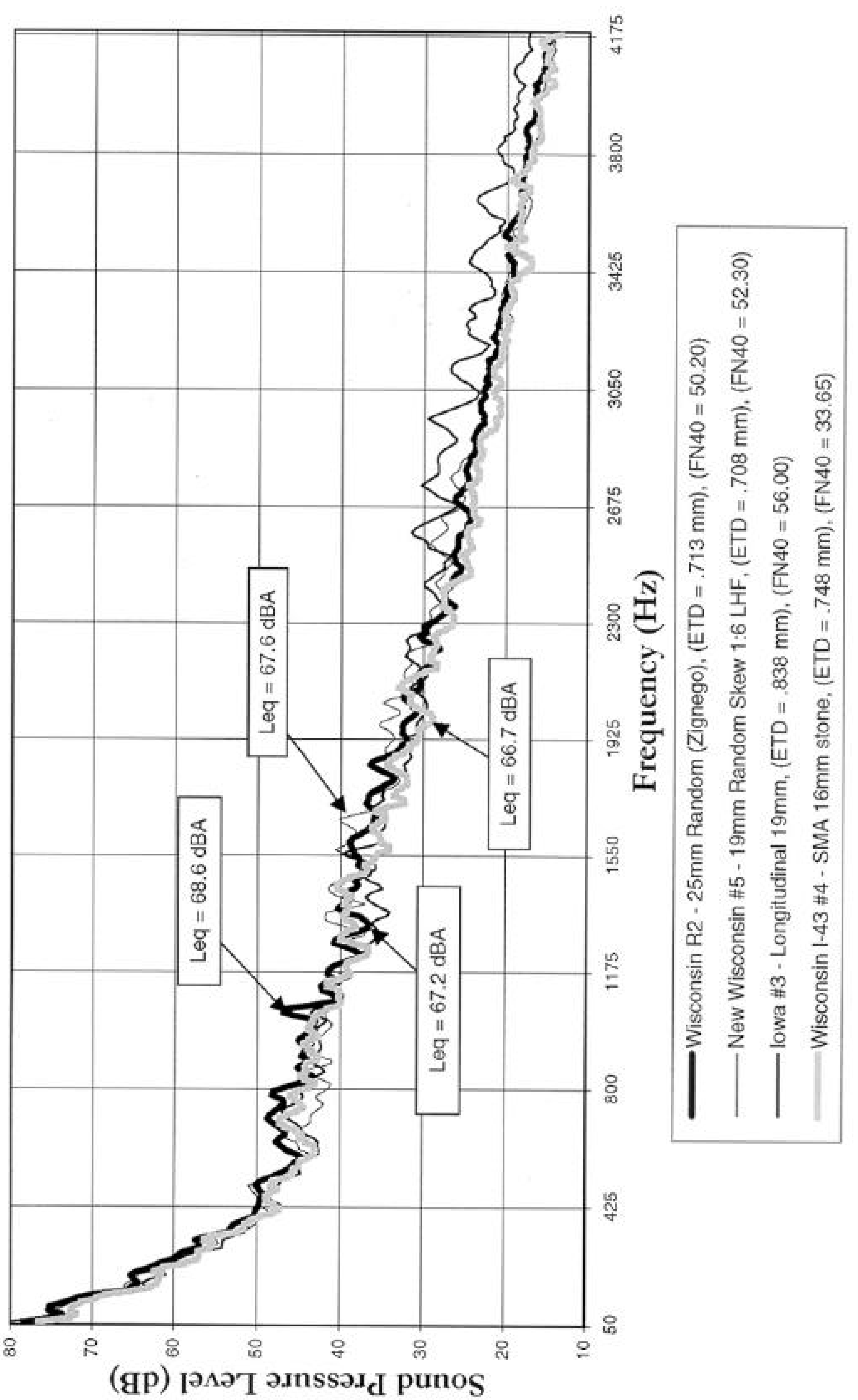


Figure 23: Comparison of Interior Noise for the "Best" of the Different Pavement Texture Types

CONCLUSIONS

Interior and exterior noise and relative pavement texture was successfully measured at 57 test sites in six states, using the same procedures, test vehicle and measurement equipment. The Fast Fourier Transform (FFT) function narrow band analysis was used to analyze both exterior pass-by noise measurements and interior noise measurements. The exterior noise measurements exhibited discrete frequencies similar to those found during the interior noise measurements both using the FFT method.

The ROSAN texture van provided valuable information about texture depth and spacing in both transverse and longitudinal tined PCC pavements. It proved to be a reliable resource to explain texture variations, which impact noise characteristics.

Subjective testing with recorded interior noise was rendered credible and is an important criterion to assess pavement textures included in relative noise comparisons.

The following are significant conclusions:

1. Uniform transverse tining exhibits discrete frequencies that coincide with calculated locations on the sound spectrum based on tine spacing and vehicle speeds. This causes the whine found annoying to most drivers.

2. Relatively low correlation was found between either exterior or interior noise with texture depth (ROSAN ETD or mean tine depth), texture width or $FN_{40}B$. This is believed to be due to the great variation in texture depth in all states. This is contrary to the conclusions of Phase I of this study. Pavements were all constructed under the same specification for width of tines (3 mm or 1/8”). However, those pavements with the widest and deepest transverse tining (as measured by the ROSAN algorithm) were often among the noisiest. It could be that the ROSAN procedure partially explains the variation in width. Since width of tining correlates well with depth, it is hard to say which contributes to the pavement noise, but apparently both do (since deeper transverse tining was also generally wider).

3. There is little correlation between IRI and noise, and although it may be a factor, this study was inconclusive on the correlation.

4. The PNLT metric is not suitable for the evaluation of the tire/pavement noise with tonal components.

5. AC and longitudinal tined PCC pavements exhibit the lowest exterior noise levels. If longitudinal texture is constructed with a 19 mm uniform spacing, experience from other research indicates it can reduce impact on motorcycles and compact vehicles (however, splash and spray has been noted to be greater on longitudinal compared to transverse textured PCC pavement).

6. The AC pavements, the longitudinal tined, the LTD only, the random skewed PCC pavements, and the European texture exhibit the lowest interior noise levels in that order. However, most of the AC pavements, the LTD only and the European texture did not provide high texture or high friction.

7. Of the 21 pavements tested subjectively, the random skewed PCC pavements, the AC pavement, the random transverse, the longitudinal and the European texture PCC pavements exhibit the lowest subjective interior noise levels in that order. However, the AC pavement, one of the random transverse PCC pavements and the European texture had low texture and all but the random transverse, low friction.

8. The ROSAN texture van verified the great texture variation that existed among all 57 test sections, between different test sections and within any single test section, especially among PCC pavements, where variations of over 100 percent generally exist. Even among AC pavements, variation is as much as 75 percent between the deepest and shallowest depths existing within several meters of pavement. Measurement of texture with a device like ROSAN is essential for noise comparisons to explain noise characteristics for any tire/pavement noise field evaluation.

9. ROSAN ETD correlated poorly with friction when all pavements were analyzed together, but correlate highly for both transverse and skewed tining on PCC pavements. ROSAN ETD correlates well with sand patch for all pavements and is highly correlated when compared within similar pavement types.

10. Colorado's test sections have the greatest ROSAN mean tining width (even though constructed with the 3 mm specified width) and also had the greatest ROSAN mean texture depth, and were among the noisiest. The ETD ranged from 1.2 to 3.2 mm compared to the FHWA guideline of 0.8 mm minimum average sand patch. This reinforces the hypothesis that as ROSAN mean texture depth and width increase, so do both interior and exterior noise. Yet correlation between noise and texture depth is low as well as between noise and texture width. Texture depth and width are not the only factors to consider in tire pavement noise generation, however. It is undetermined which is the cause of increased noise, tine depth or tine width, although greater tine depth caused greater tine width in most cases with transverse or skewed tining.

11. Longitudinally and random skewed tined PCC pavements are among the quietest pavements for both interior and exterior noise. They can be constructed easily, have good subjective ratings, have no prominent discrete frequencies and can provide good friction and texture. The 25mm random longitudinal (New Wisconsin #8) has low friction (Fn40 bald of 36.6) yet satisfactory texture (ETD of .71 but a low sand patch of 0.5). This can not be explained except that the 19 mm spacing has more grooves for water film to escape. The 19 mm spacing is the current FHWA and AASHTO guideline that should be followed for construction. In four states with longitudinal pavements, increases in texture depth of

between 50 and 250 percent occurred between test sections, yet only modest or no increase in exterior noise occurred (for example, for Colorado 7 and 9).

12. Random skewed (1:6) textured pavements can be constructed relatively easily, exhibit low interior noise and no discrete frequencies, and have the best subjective ranking. They have higher levels of exterior noise than longitudinal tined PCC and AC pavements, but lower than random transverse PCC pavements. They have good friction and texture.

13. Random transverse textured pavements are very sensitive to spacing patterns. They can be satisfactory but when spacing tends to be more uniform, discrete frequencies may develop. This can cause objectionable whine. This was the case in 11 of 15 random transverse tined sections in five states. The majority followed the FHWA random spaced guidelines for tining (developed by WisDOT).

15. When comparing different pavement textures with similar MTDs (in the vicinity of 0.7 mm) the following noise reductions resulted in this study, when compared to a 25 mm uniform, transversely tined, PCC pavement (W15 and NW3, see Appendix E):

PAVEMENT TEXTURE	**NOISE REDUCTIONS**	
	Exterior (L_{max})	**Interior** (L_{eq})
a) random transverse with no whine: (based on WI R2, R3 & IA 5, all which have slight frequency spikes)	1 to 3 dBA	< 1 dBA
b) random skew, 1:6 (based on NW5)	4 dBA	1.5 to 2 dBA
c) longitudinal (based on IA3, IA4, NW8)	4 to7 dBA	2 dBA
d) opened textured AC (based on WI I43-4, SMA)	5 dBA	2 - 3 dBA

16. Spectral analysis can be a useful tool in further research of acoustical qualities of pavements before their construction. The tool was used to design a rake tine spacing and this rake was used to tine two additional test sections in Wisconsin. No discrete frequency due to tire/pavement noise was discovered in objective noise measurements, and no whine was detected by subjective observations of pavement engineers and the researchers. Objective noise levels were lower than similarly textured test sections built in Wisconsin in 1997, but no texture measurements were taken, so the comparison is not valid. As-built measurements of the tine spacing were used to analyze the power spectrum. It showed a

low max./min. ratio of 1.48, close to the theoretical best rake. Similar rake spacing was used in the construction of pavements in Iowa and Michigan, but the research team did not observe these at the time of this report.

17. The ground PCC pavement, although not as quiet as other PCC pavements, exhibited no predominant frequency or spike (the pavement was built over 20 years ago, but ground in 1993).

18. A 1998 project comparing before and after (B/A) noise measurements on recently constructed, random transverse tined pavement and a bridge deck in St. Paul, Minnesota showed a noise reduction of 2 to 3 dB (L_{10}) after diamond grinding. Another B/A project in Wisconsin (2000) showed a 3 dBA reduction in exterior noise (L_{max}) after grinding transverse tined PCC pavement. Both eliminated the whine associated with the tining.

19. This study added substantial and significant data on noise and texture characteristics of PCC pavements. There is no recognition of noise differences due to surface texture in FHWA noise models at the present time. This is because there is no extensive long term evidence of changes in noise and texture over time, nor do states specifications guarantee texture or noise thresholds over time. Therefore, benefits to states who select a texture based on lower initial noise (yet adequate friction and texture depth) can not have this reflected when it comes to using the FHWA noise models to determine the need for noise barriers on urban freeways. One of the goals of this research is to lead to national guidelines for texture, yet if no benefit accrues in urban areas as it affects noise barriers, there is no incentive to states to standardize, and hence, no incentive to tire manufacturers to standardize tread design.

RECOMMENDATIONS

Textures now being built across the country have substantial variation from what is specified. Since pavements which are noisier within a given texture group also often have deeper and wider tining, if a shallower and hence narrower texture width could be built uniformly, significant improvement would result in overall noise (for example Iowa #3). No target exists for minimum bald tire friction levels or minimum ROSAN ETD or sand patch that would relate to wet weather accident levels, in order to set a minimum $FN_{40}B$, or a minimum texture depth or width. This makes framing recommendations that are absolute and clear very difficult.

1. Quality control of tine spacing, depth and width needs to be improved to achieve any tining recommendations included in a national guideline for tining PCC pavements. Curing and tining operations must be separate and continuous so each can be applied at the appropriate time by separate operators.

2. A study of wet pavement accidents should be conducted using current accident data and comparing longitudinal and transverse tined pavements to determine what texture and friction values will provide the necessary safety as well as minimize noise. AC pavements should also be included in the study. The current guidelines for tining depth are not being achieved uniformly in any state studied. What impact this has on safety is unknown.

3. Future research needs to address the relative effects of tining depth and width on tire/pavement noise characteristics, to determine which is most influential.

4. If overall noise considerations are paramount, longitudinal tining that provides satisfactory friction may be considered. A spacing of 19 mm uniform tining will provide adequate friction. It should also comply with current AASHTO and FHWA guidelines and, according to other studies, it will minimize any effects on small-tired vehicles. However, splash and spray on longitudinal textures has been reported to be greater than on transverse tined PCC pavements. The safety aspects of longitudinal tining have not as yet been documented and caution is urged so that safety is not compromised.

5. If subjective perceptions and texture considerations are paramount a random skew 1:6 textured pavement, offset the opposite of the skew for the sawed joints, may be used to achieve the friction of a transverse pavement and most of the noise benefits of the longitudinal pavement, with no discrete tones.

6. If texture considerations are paramount, and a skewed pattern is impractical, randomly tined pavements may be utilized. They should be carefully designed and built, using a highly variable spacing. A tining rake at least 3 m (10') long should be utilized. Theoretically, a rake with random spacing between 10 and 76 mm, with tine spacing as shown in Appendix F, will eliminate significant discrete frequencies. A rake meeting these criteria has been manufactured and field tested by three states. It is possible that a rake meeting these criteria may still result in textures which have higher overall noise levels than those of random

skewed or longitudinally tined PCC pavements. Further information on theoretical rake patterns is in Appendix F and may be obtained from Marquette University.

7. Diamond grinding, if sufficiently deep to remove most of the transverse texture, can be considered a treatment for PCC pavements with excessive whine. Based on current research, safety is not compromised and no discrete frequencies have been measured or heard.

8. If the benefits of this research are to be fully realized, FHWA should initiate research to monitor relative noise and texture levels on a number of these 57 test sections over a substantial time period to determine the long term affects of pavement texture types on noise levels. This research, in conjunction with wet pavement safety impacts, would give states guidance for specifying minimum noise and texture levels, and address the question of recognizing what if any noise reductions are long term and hence can be reflected in the FHWA noise models.

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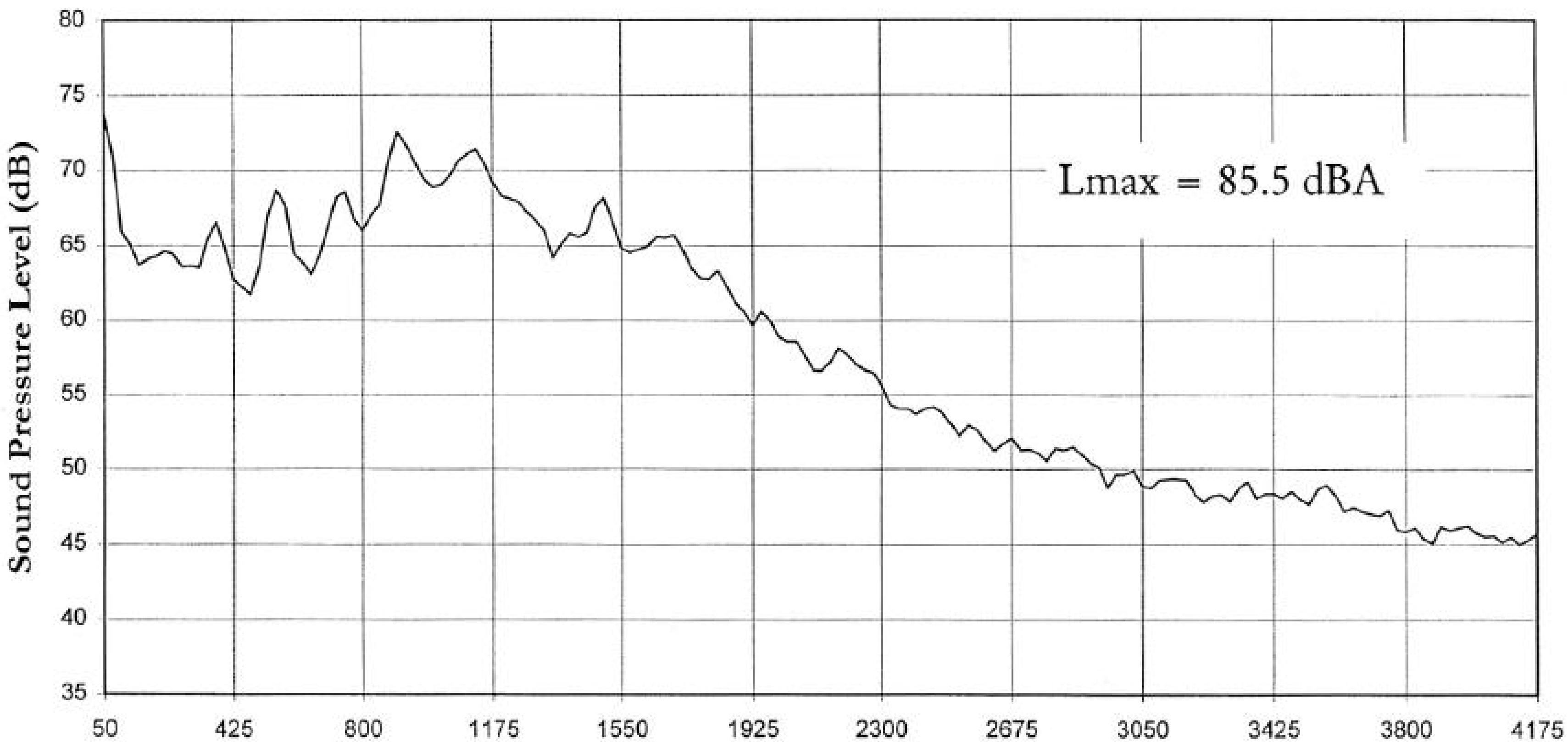
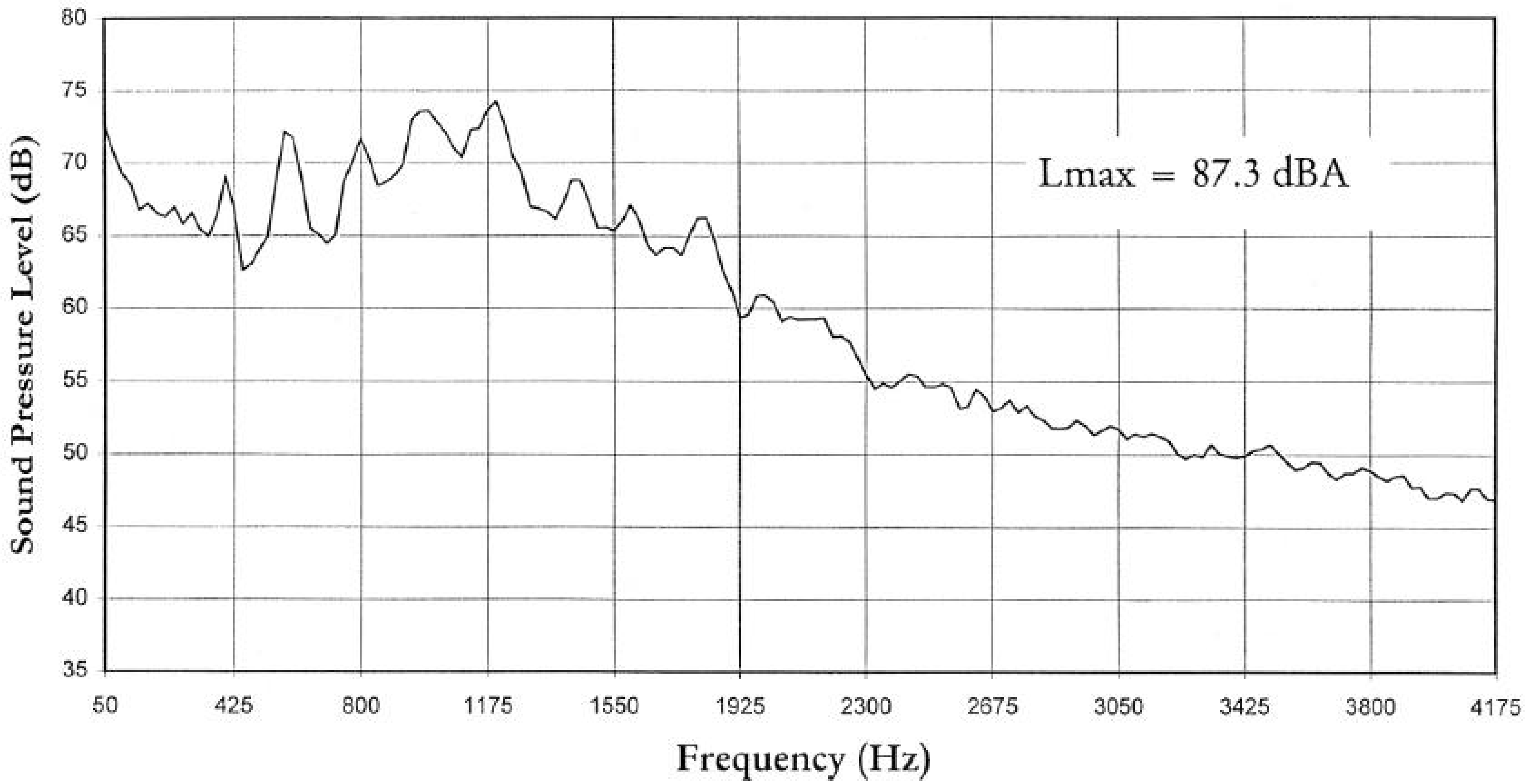
APPENDIX A - EXTERIOR NOISE GRAPHS

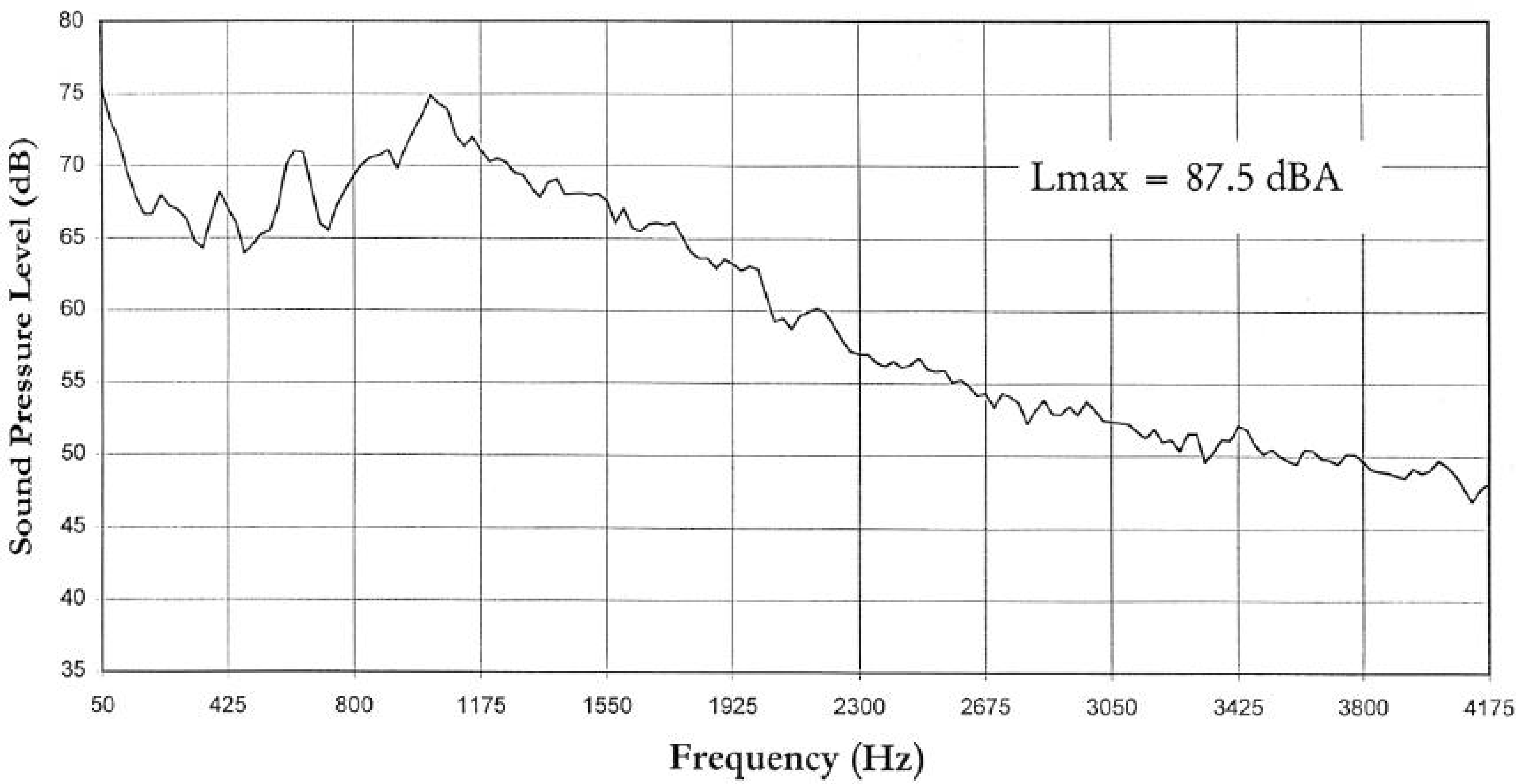
Exterior Noise - Iowa I163
Section 5 - Transverse, 19mm, var., 3-5mm d
Taurus @ 60 mph
7/16/97



Exterior Noise - Iowa I163
Section 5 - Transverse, 19mm, var., 3-5mm d
Taurus @ 65 mph
7/16/97

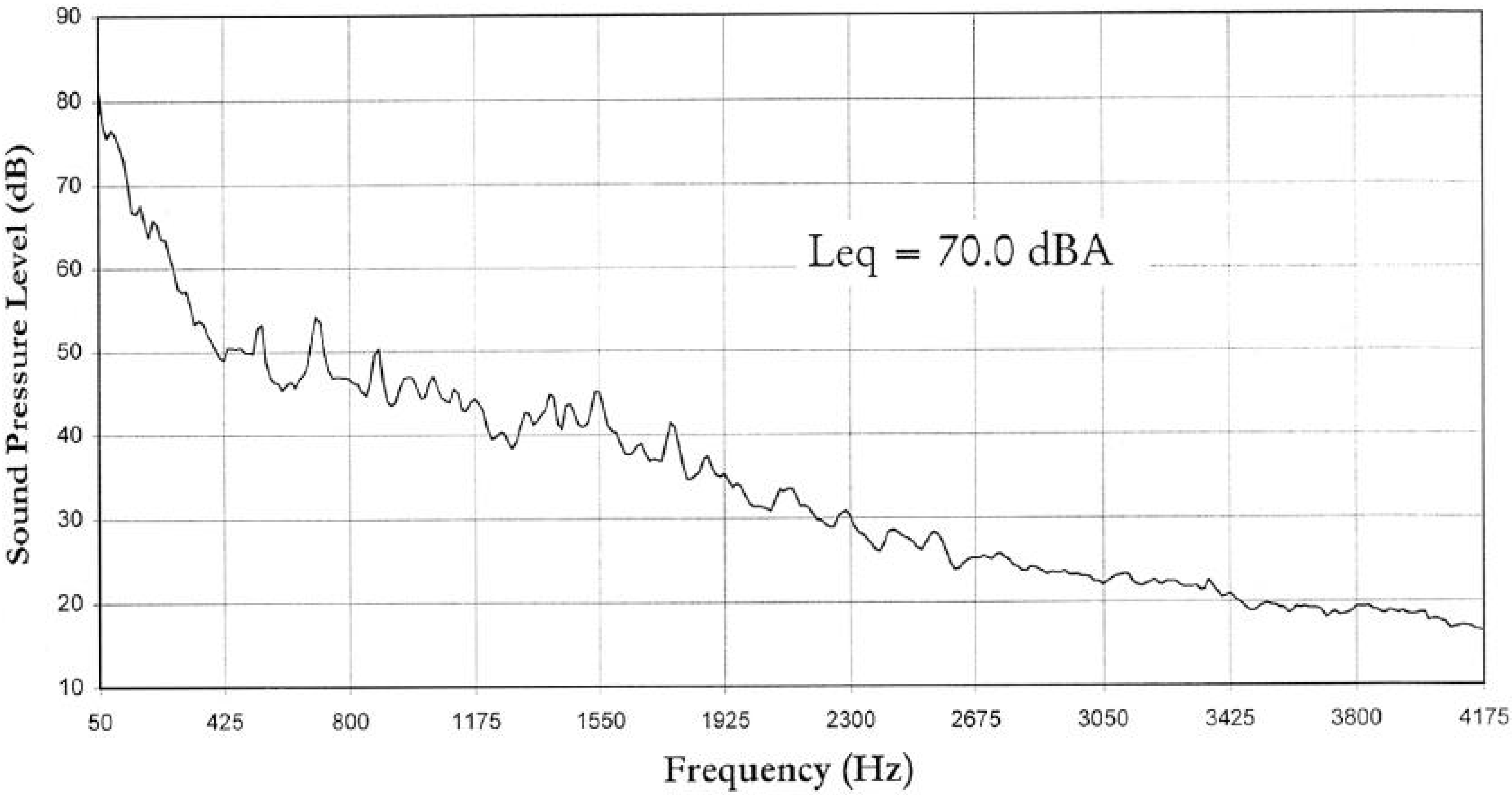


Exterior Noise - Iowa I163
Section 5 - Transverse, 19mm, var., 3-5mm d
Taurus @ 70 mph
7/16/97

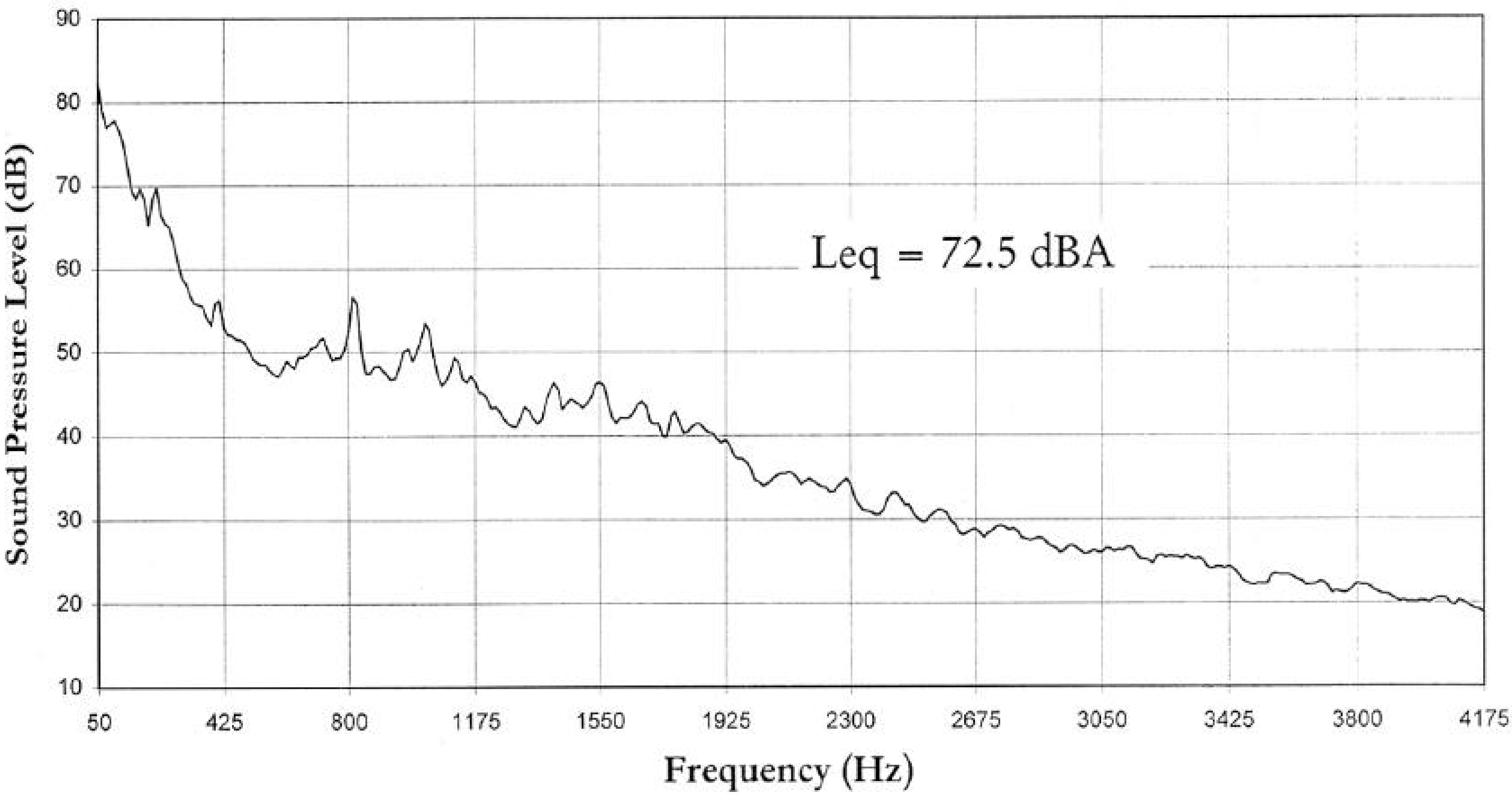


APPENDIX B - INTERIOR NOISE GRAPHS

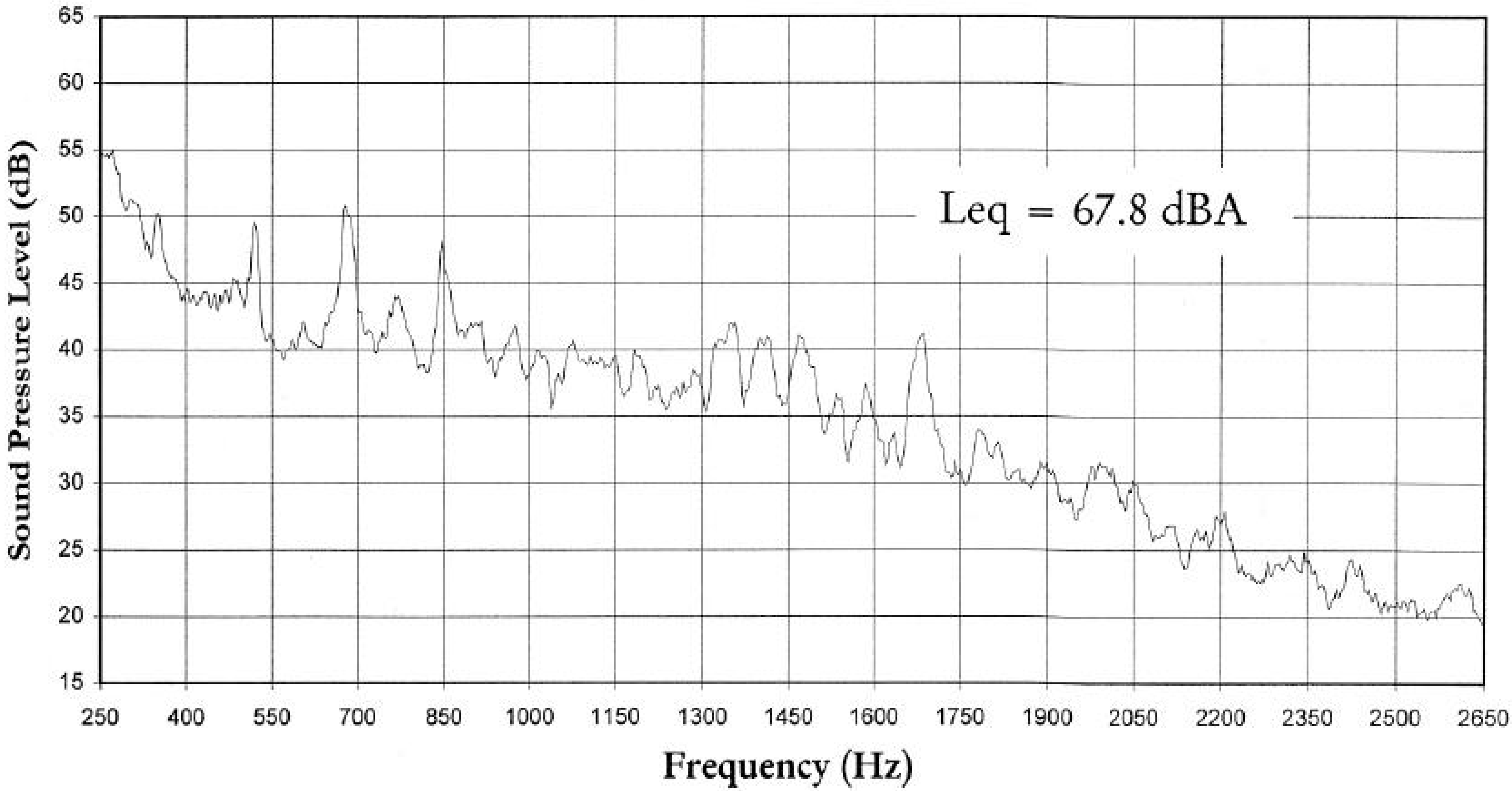
Interior Noise - Iowa I163
Section 5 - Transverse, 19mm, var., 3-5mm d
Taurus @ 60 mph
7/17/97



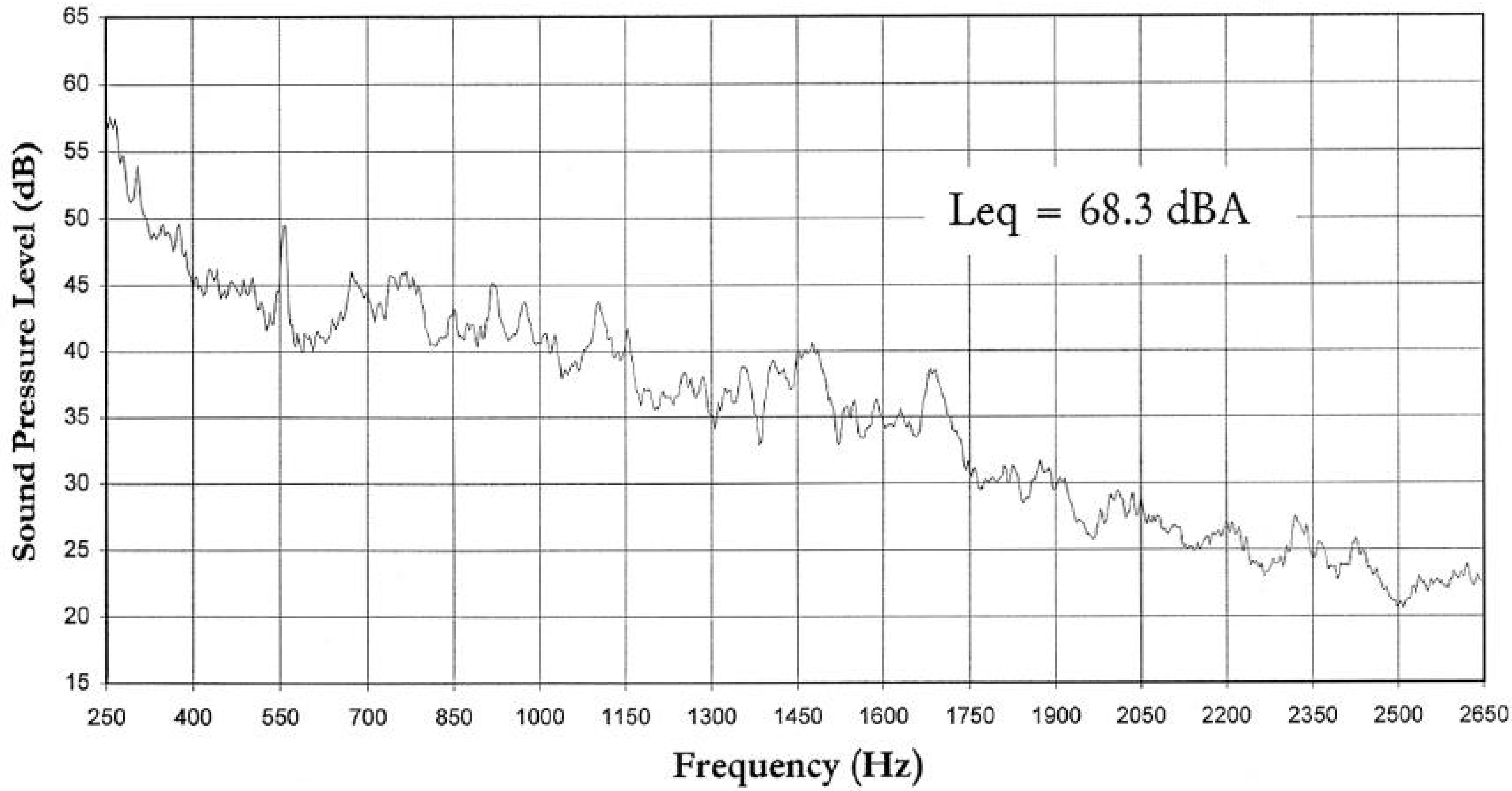
Interior Noise - Iowa I163
Section 5 - Transverse, 19mm, var., 3-5mm d
Taurus @ 70 mph
7/17/97



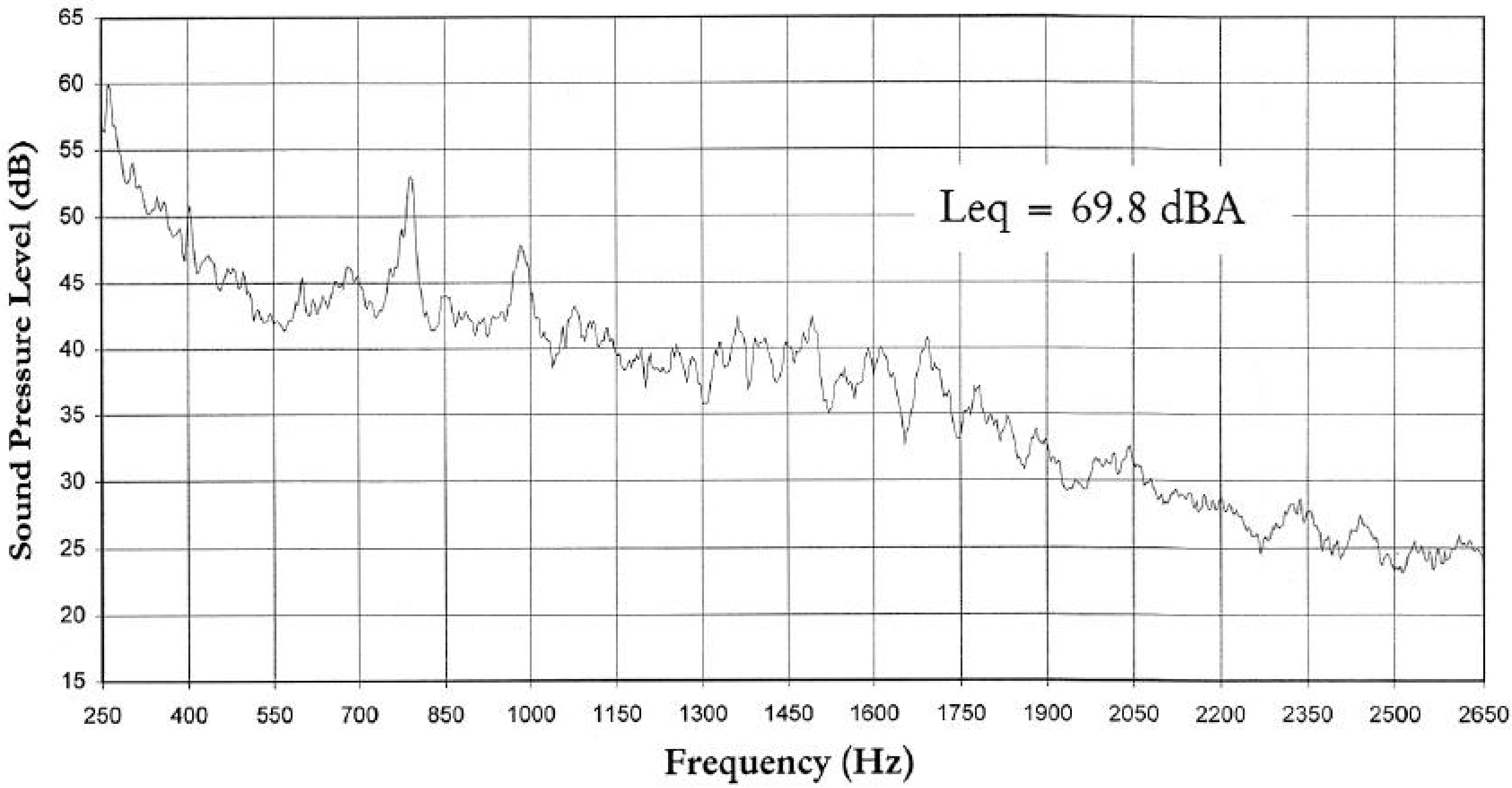
Interior Noise - Iowa I163
Section 5 - Transverse, 19mm, var., 3-5mm d
Taurus @ 60 mph
7/18/97



Interior Noise - Iowa I163
Section 5 - Transverse, 19mm, var., 3-5mm d
Taurus @ 65 mph
7/18/97



Interior Noise - Iowa I163
Section 5 - Transverse, 19mm, var., 3-5mm d
Taurus @ 70 mph
7/18/97



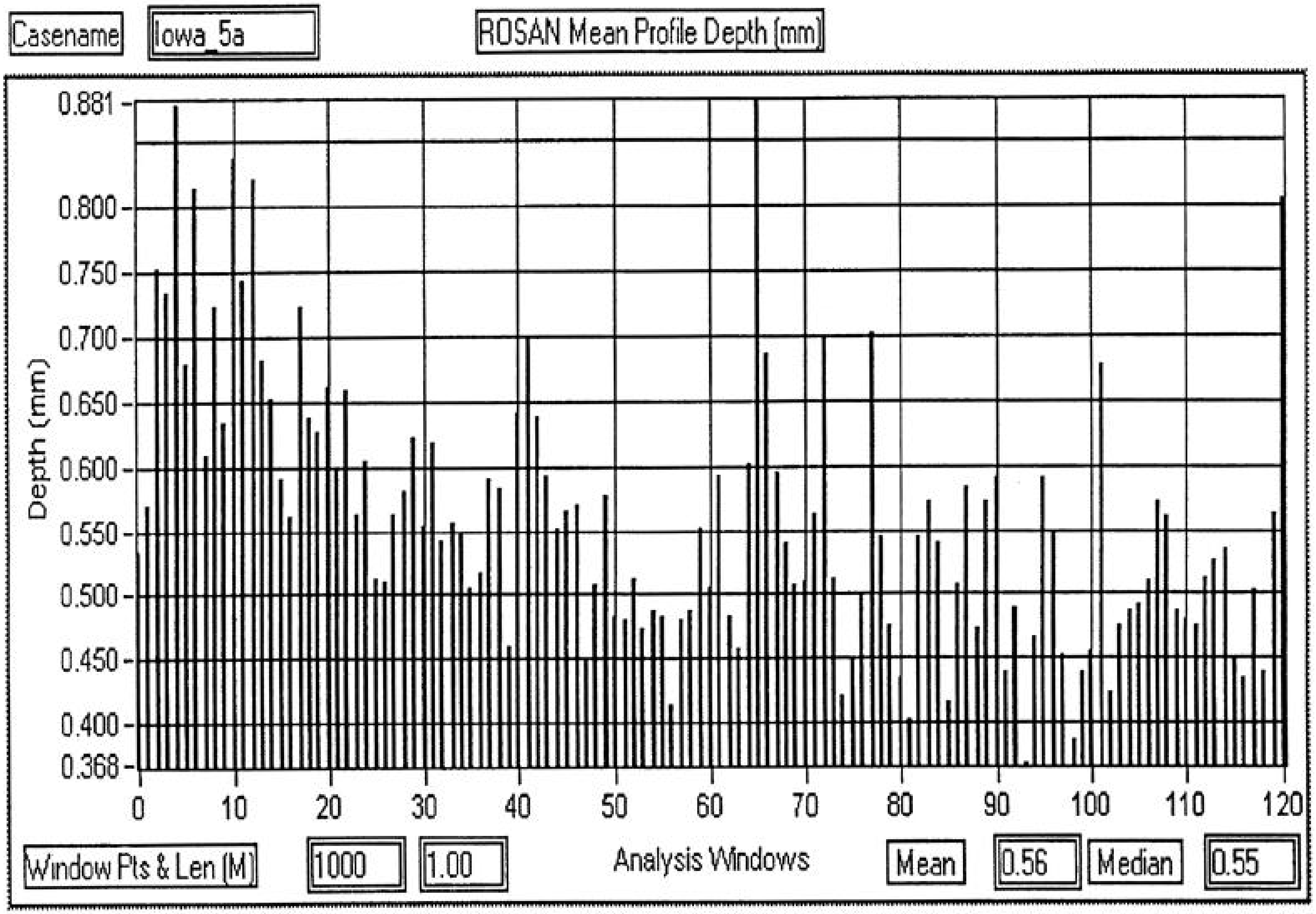
APPENDIX C - SAMPLE ROSAN OUTPUTS

CASENAME	Iowa_5a
USERNAME	THURSDAY
DATE	07-17-1997
TIME	18:40:19
LOCATION	IOWA SITE 5. OWP RUN 1
INTERVAL(mm)	1.00
SPEED(kph)	76
PULSER DATA(ON=1)	1

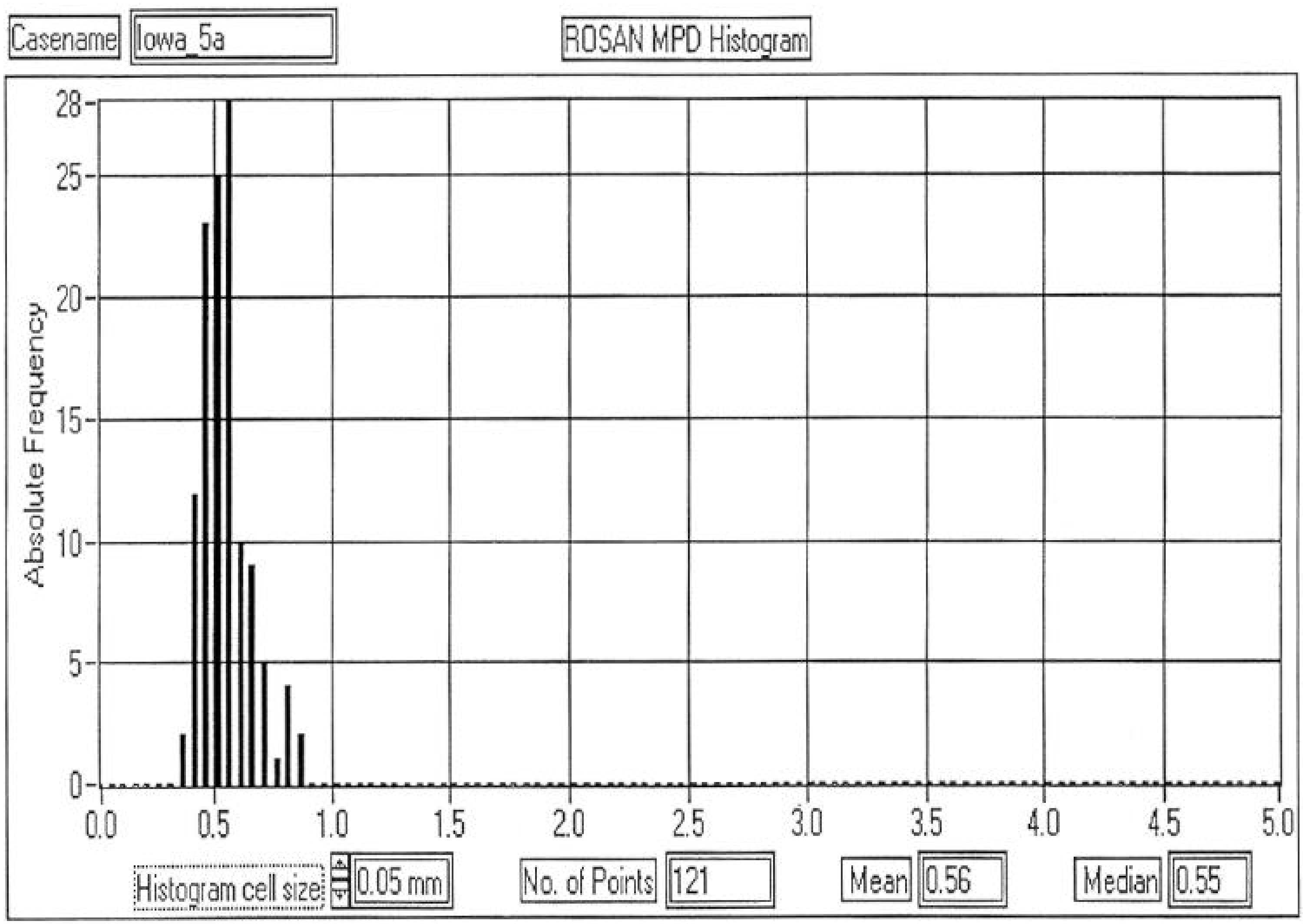
Window (size)	=	1000
ASTM Seg/Window	=	10
Window Length (M)	=	1.000
Drop Lead Points	=	22207
Beginning Window	=	0
Ending Window	=	120
No. of Windows	=	121
Total Length (M)	=	121.000000
Pulser (1=Y,0=N)	=	1

NOTE: ETD(G) is estimated texture depth for Grooved pavement.

Window Statistic		ASTM MPD	ASTM ETD	ROSAN MPD	ROSAN ETD	ROSAN ETD(G)	ASTM Segment MPD
mean	=	1.108	1.086	0.559	0.850	0.703	1.108
median	=	1.073	1.058	0.546	0.821	0.686	1.055
minimum	=	0.793	0.834	0.368	0.447	0.469	0.537
maximum	=	1.630	1.504	0.881	1.526	1.097	3.988
StdDev	=	0.179	0.143	0.104	0.219	0.128	0.316

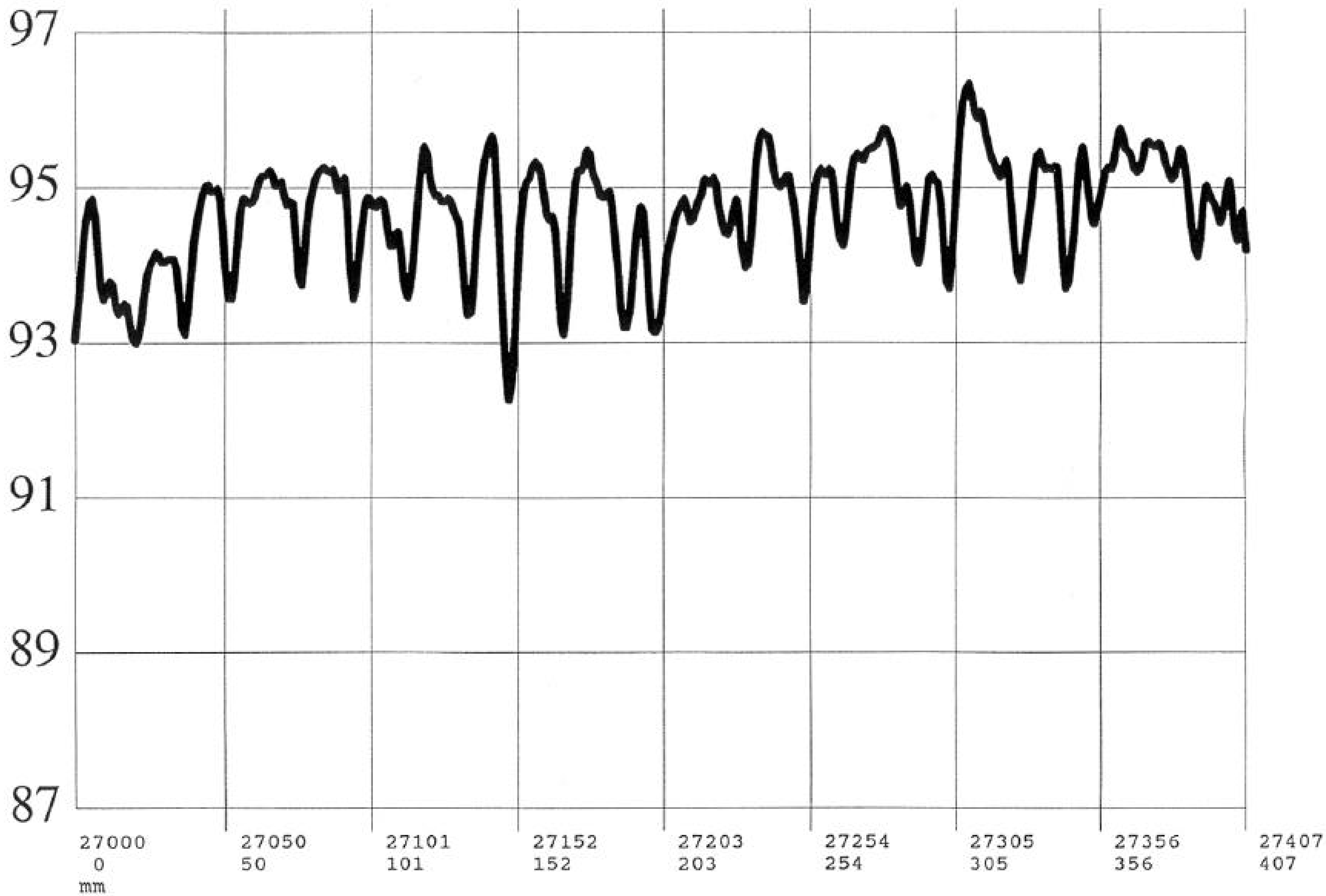


Casename
Iowa_5a
ROSAN Mean Profile Depth (mm)
Depth (mm)
0.881
0.800
0.750
0.700
0.650
0.600
0.550
0.500
0.450
0.400
0.368
0
10
20
30
40
50
60
70
80
90
100
110
120
Window Pts & Len (M)
1000
1.00
Analysis Windows
Mean
0.56
Median
0.55

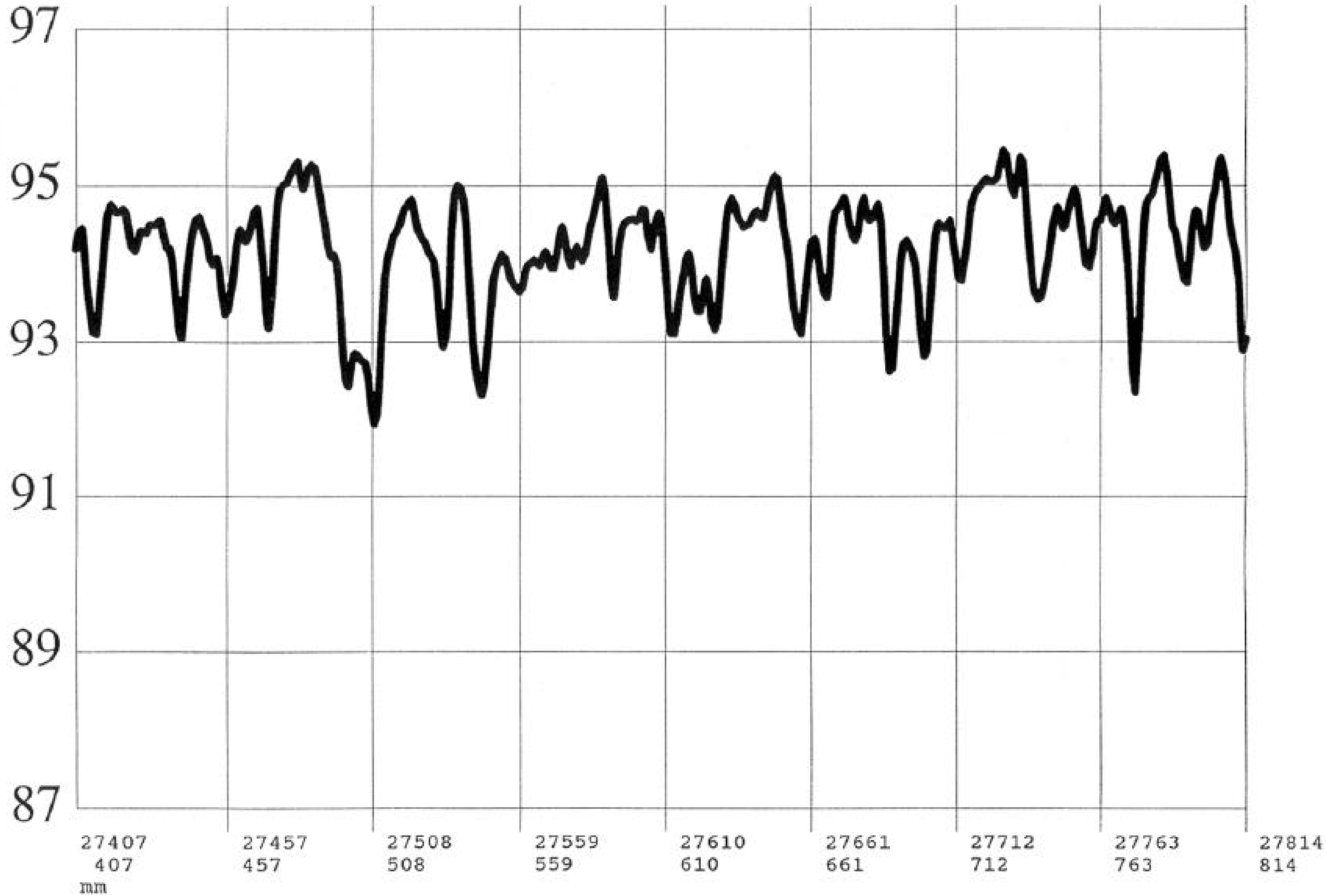

Casename
Iowa_5a
ROSAN MPD Histogram
Absolute Frequency
28
25
20
15
10
5
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Histogram cell size
0.05 mm
No. of Points
121
Mean
0.56
Median
0.55

APPENDIX D - SAMPLE ROSAN PROFILE PLOTS

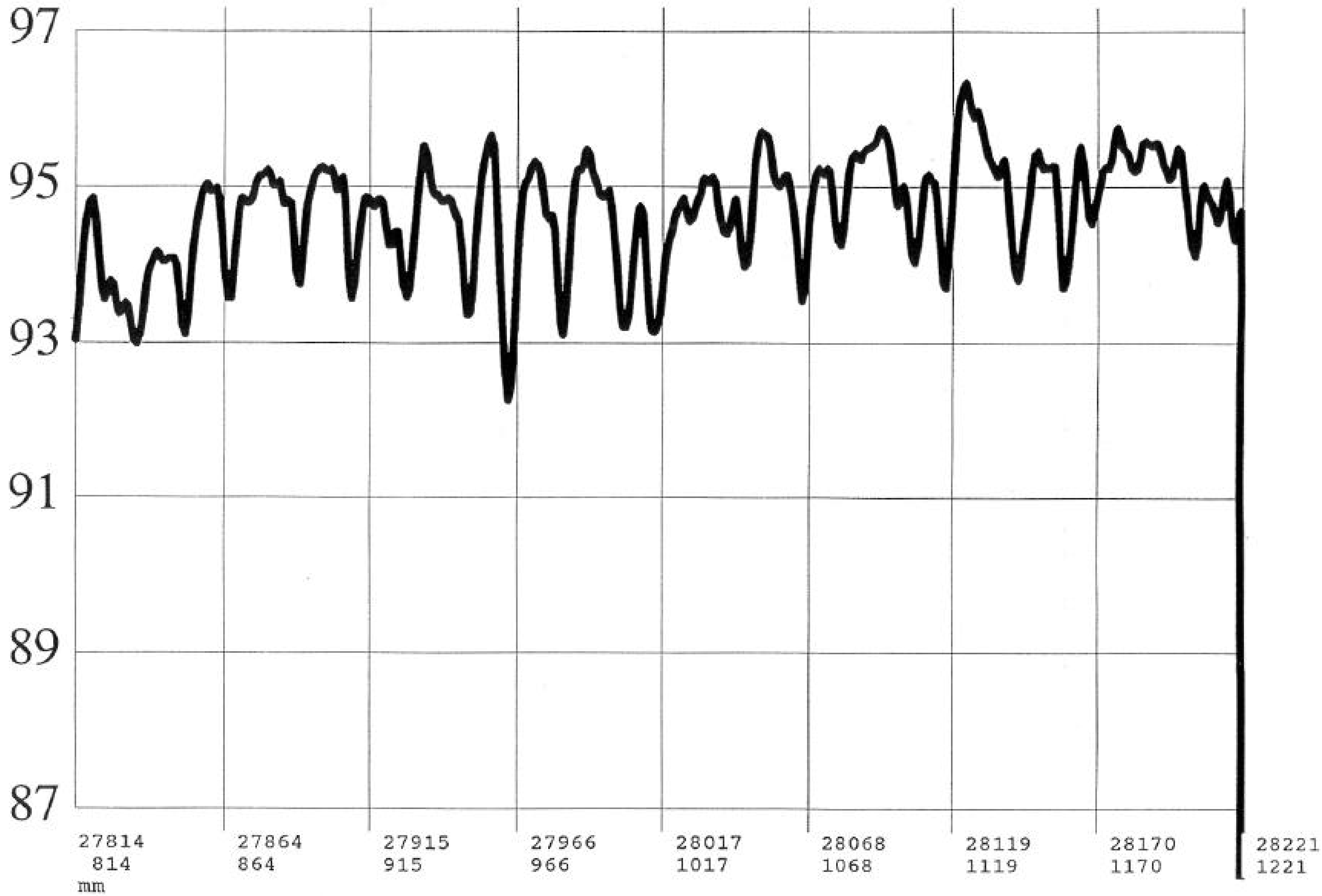
Iwoa I-163
Section 5
Trans., 19mm (3-5 mm d)
\\Civilmodel5\c\rsnv95\vfp\Iowa_5a.VFP
Graph 1 of 3



Iwoa I-163
Section 5
Trans., 19mm (3-5 mm d)
\\Civilmodel5\c\rsnv95\vfp\Iowa_5a.VFP
Graph 2 of 3



Iwoa I-163
Section 5
Trans., 19mm (3-5 mm d)
\\Civilmodel5\c\rsnv95\vfp\Iowa_5a.VFP
Graph 3 of 3



APPENDIX E - SPREAD SHEET, DATA COLLECTION BY TEST SECTION

LEGEND:

T = Transverse Uniform

TR = Transverse Random

SK = Skewed

L = Longitudinal

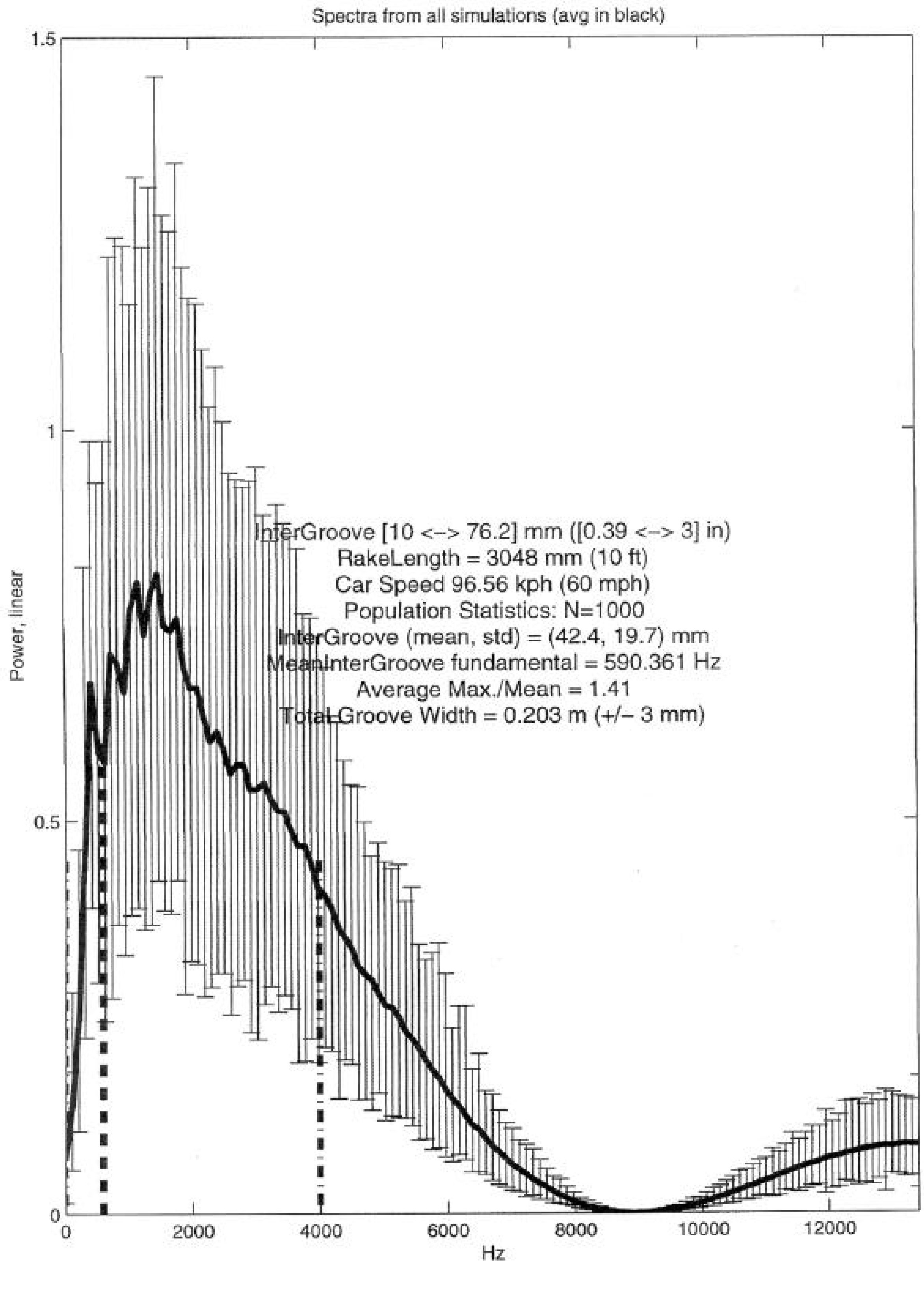
S = Special

A = AC Pavements

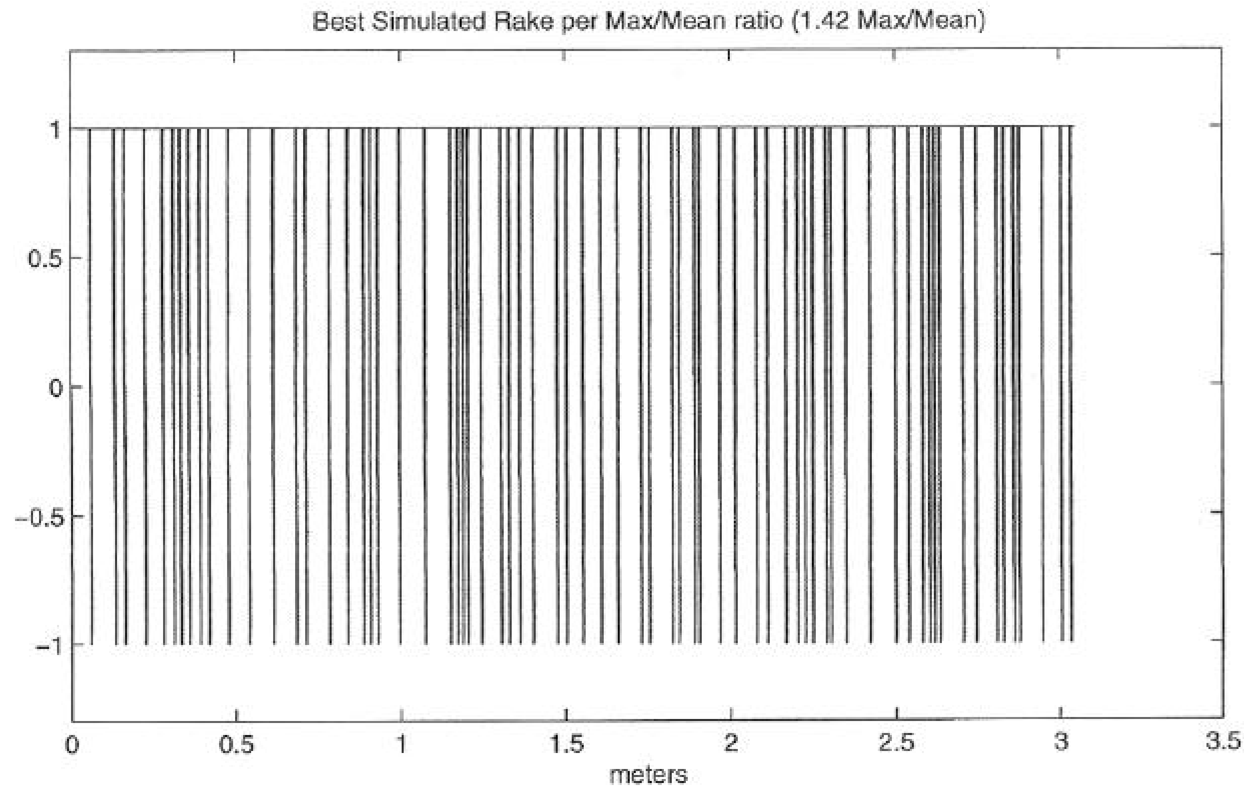
Group	Texture	Section	Subj Rank	Lmax	Leq	Descrete Freq	ROSAN Outer Wheel Path			ROSAN Inner Wheel Path		
							MPD	ETD	Sdev	MPD	ETD	Sdev
CO	T	1	14	86.4	69.7	Y	0.748	1.247	0.189	0.75	1.25	0.184
CO	TR	3		84.4	69.9	Y	1.027	1.834	0.307	0.861	1.484	0.239
CO	T	4		83	69.4	Y	1.008	1.793	0.305	0.956	1.685	0.233
CO	TR	5	19	84.1	68.6	Y	0.981	1.738	0.128	0.898	1.562	0.085
CO	L	7		79.6	68.1	N	1.686	3.221	NA	1.686	3.221	NA
CO	L	9		80.9	68.4	N	0.98	1.736	NA	0.98	1.736	NA
IA	T	1	11	82.8	68.2	Y	0.489	0.701	0.093	0.555	0.839	0.096
IA	L	3		79	67.2	N	0.554	0.838	NA	0.554	0.838	NA
IA	L	4		79.9	67.6	N	0.751	1.253	NA	0.751	1.253	NA
IA	TR	5	9	85.5	70	Y	0.559	0.85	0.104	0.552	0.833	0.087
IA	S	8	10	83.8	72	N	0.552	0.835	0.18	0.525	0.777	0.115
IA	T	9	8	84.6	69.2	Y	0.653	1.046	0.17	0.652	1.044	0.113
IA	T	2a		83.3	68.2	Y	0.501	0.726	0.071	0.546	0.822	0.069
MI	S	1	6	NA	67.5	N	0.353	0.414	0.096	NA	NA	NA
MI	T	2		NA	68.5	Y	0.404	0.523	0.068	NA	NA	NA
MN	L	1		81.7	67.2	N	0.597	0.928	NA	0.597	0.928	NA
MN	TR	2		84.9	68.9	N	0.42	0.556	0.059	0.454	0.628	0.056
MN	TR	3		83.9	68.4	N	0.428	0.573	0.081	NA	NA	NA
MN	TR	4	7	82.6	66.9	Y	0.34	0.388	0.051	0.316	0.338	0.048
MN	S	5		NA	66.8	N	0.26	0.219	NA	0.26	0.219	NA
MN	TR	6	17	87.3	69.4	Y	0.426	0.568	0.054	0.429	0.575	0.054
MN	S	7		83.7	68.3	N	0.289	0.281	NA	0.289	0.281	NA
MN	L	8		84.3	69.4	N	0.521	0.768	NA	0.521	0.768	NA
ND	SK	A		82.7	67.6	Y	0.314	0.334	0.045	0.348	0.405	0.051
ND	T	B		83	68.5	Y	0.522	0.77	0.08	0.525	0.778	0.08
ND	TR	F	4	81	67.7	N	0.335	0.378	0.036	0.303	0.309	0.034
ND	T	G		82.2	68.5	N	0.52	0.767	0.12	0.827	1.412	0.279
ND	L	H		81.5	68.7	N	0.755	1.262	NA	0.755	1.262	NA
ND	T	I		83.7	68.5	Y	0.413	0.541	0.055	0.411	0.538	0.051
NW	TR	1	13	86.6	68.9	Y	0.468	0.656	0.109	NA	NA	NA
NW	TR	2	comp.	86.3	68.7	Y	0.766	1.284	0.2	0.841	1.442	0.23
NW	T	3		86.6	68.8	Y	0.469	0.659	0.105	0.423	0.563	0.07
NW	SK	4		83.8	67.7	N	0.609	0.955	0.108	0.698	1.141	0.114
NW	SK	5	1	82.4	67.6	N	0.492	0.708	0.116	0.612	0.96	0.126
NW	SK	6		83.5	68.5	N	0.552	0.834	0.081	0.664	1.07	0.116
NW	SK	7	2	83.1	67.2	N	0.497	0.718	0.145	0.585	0.904	0.147
NW	L	8		82.7	67.8	N	0.494	0.712	NA	0.494	0.712	NA
NW	L	9		85.3	69.5	N	1.008	1.794	NA	1.008	1.794	NA
NW	L	10	5	83.9	68	N	0.749	1.249	NA	0.749	1.249	NA
WI	L	6		81.5	69.2	N	0.489	0.7	NA	0.489	0.7	NA
WI	SK	8		83.9	69.4	Y	0.335	0.376	0.061	0.303	0.31	0.06
WI	T	9		81.9	69	Y	0.345	0.399	0.09	0.379	0.47	0.092
WI	T	10	18	84	69.1	Y	0.346	0.401	0.065	0.367	0.444	0.06
WI	TR	11		83.9	70.2	Y	0.29	0.283	0.051	0.303	0.31	0.083
WI	T	15	20	86.3	69.5	Y	0.286	0.274	0.064	0.367	0.446	0.119
WI	S	16		84.6	70.6	N	0.55	0.83	0.089	0.39	0.494	0.071
WI	T	9A	16	82.1	69.3	Y	0.354	0.417	0.076	0.436	0.589	0.143
WI	TR	R0		85.4	68.8	N	0.696	1.138	0.179	0.847	1.455	0.184
WI	TR	R1		84.8	69.4	Y	0.569	0.869	0.098	0.53	0.788	0.11
WI	TR	R2	15	83.4	68.6	Y	0.495	0.713	0.141	0.515	0.757	0.133
WI	TR	R3		83.8	68.9	Y	0.608	0.952	0.152	NA	NA	NA
WI43	A-SHRP	1	3	81.1	65.9	N	0.274	0.248	0.038	0.341	0.391	0.034
WI43	A	2		79.9	66	N	0.238	0.174	0.049	0.251	0.201	0.031
WI43	A	3		78.9	65	N	0.202	0.097	0.024	0.242	0.181	0.022
WI43	A-SMA	4		81.6	66.7	N	0.511	0.748	0.057	0.602	0.939	0.076
WI43	S	5	12	81.2	69.2	N	0.592	0.918	NA	0.592	0.918	NA
WI43	A-SMA	6		80.5	67.6	N	0.448	0.616	0.049	0.584	0.901	0.067

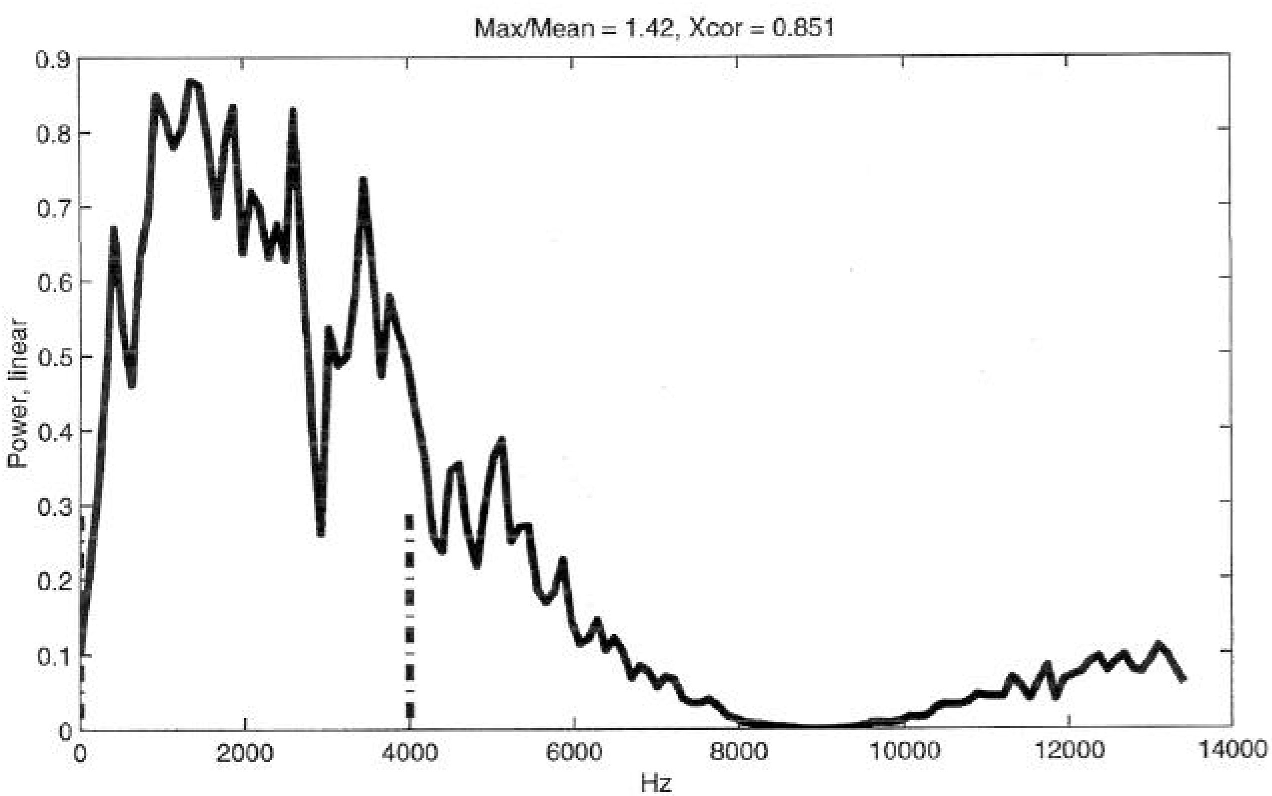
Group	Texture Code	Section No.	Mean Tine Depth	Median Tine Depth	Mean Tine Width	Mean Tine Spacing	Mean Sand Patch	Fn 40 bald	Fn 50 bald	Friction gradient	IRI
CO	T	1	3.4	3.3	7.4	23.8	NA	46.7	38.8	0.79	1.78
CO	TR	3	3.5	3.3	7.2	18.3	NA	51.2	45.1	0.61	1.73
CO	T	4	2.2	2	6.2	12.8	NA	52.7	46.9	0.58	1.84
CO	TR	5	4	4	7	18.8	NA	48.6	46.2	0.24	1.70
CO	L	7	NA	NA	NA	NA	NA	50.9	44.3	0.66	2.96
CO	L	9	NA	NA	NA	NA	NA	49.1	42.6	0.65	2.31
IA	T	1	1.3	1.2	5.1	16.8	NA	54.0	51.0	0.30	1.53
IA	L	3	NA	NA	NA	NA	NA	56.0	51.0	0.50	1.60
IA	L	4	NA	NA	NA	NA	NA	53.0	48.0	0.50	1.99
IA	TR	5	1.5	1.3	5.6	16.5	NA	50.0	47.0	0.30	1.50
IA	S	8	NA	NA	NA	NA	NA	NA	NA	NA	2.02
IA	T	9	2.2	2.1	5.9	17.3	NA	NA	NA	NA	1.53
IA	T	2a	1.7	1.6	5.4	18.1	NA	46.0	NA	NA	1.43
MI	S	1	NA	NA	NA	NA	NA	26.0	NA	NA	1.71
MI	T	2	1.2	1.1	4.2	15.6	NA	39.0	NA	NA	1.22
MN	L	1	NA	NA	NA	NA	NA	74.8	63.0	1.18	0.92
MN	TR	2	1.5	1.5	4.7	18.6	NA	67.9	62.9	0.50	0.68
MN	TR	3	1.6	1.4	4.9	22.7	NA	69.5	65.2	0.43	1.20
MN	TR	4	1.8	1.7	4.9	31.5	NA	73.7	60.6	1.31	0.74
MN	S	5	NA	NA	NA	NA	NA	40.4	21.0	1.94	1.33
MN	TR	6	1.9	1.8	6.1	29.2	NA	55.8	44.6	1.12	1.22
MN	S	7	NA	NA	NA	NA	NA	48.8	41.3	0.75	1.01
MN	L	8	NA	NA	NA	NA	NA	76.6	63.5	1.31	1.06
ND	SK	A	1.2	1	4.1	26.2	NA	NA	NA	NA	0.99
ND	T	B	1.8	1.6	5.3	17.3	NA	NA	NA	NA	0.90
ND	TR	F	1.3	0.9	4.4	31.7	NA	NA	NA	NA	0.88
ND	T	G	1.4	1.2	4.4	12.6	NA	NA	NA	NA	0.85
ND	L	H	NA	NA	NA	NA	NA	NA	NA	NA	1.01
ND	T	I	1.8	1.6	5.1	23.8	NA	NA	NA	NA	0.99
NW	TR	1	2	1.9	5.7	25.2	0.66	NA	NA	NA	1.90
NW	TR	2	2.2	2.1	6.1	16.4	1.06	58.8	54.7	0.41	1.79
NW	T	3	1.9	1.8	5.3	22.9	0.84	46.3	48.8	-0.25	1.32
NW	SK	4	2.3	2.3	5.5	19.2	0.97	59.3	54.8	0.45	1.82
NW	SK	5	1.6	1.5	4.8	16.5	0.66	52.3	45.9	0.64	1.90
NW	SK	6	2	2	5.7	20.7	0.91	58.1	55.8	0.23	1.79
NW	SK	7	1.5	1.4	4.9	17.4	0.81	52.5	45.6	0.69	1.81
NW	L	8	NA	NA	NA	NA	0.5	36.6	28.5	0.81	1.67
NW	L	9	NA	NA	NA	NA	1.42	53.2	50.3	0.29	1.71
NW	L	10	NA	NA	NA	NA	0.94	47.5	46.0	0.15	2.06
WI	L	6	NA	NA	NA	NA	0.38	45.8	38.4	0.74	1.26
WI	SK	8	1.3	1.2	4.6	24.3	0.5	46.2	35.2	1.10	1.41
WI	T	9	1	0.9	3.5	17.7	0.5	41.7	NA	NA	1.30
WI	T	10	1.2	1.1	4.2	19.1	0.54	39.6	36.9	0.27	1.78
WI	TR	11	1.1	1	4	26.5	0.44	30.5	26.3	0.43	1.23
WI	T	15	1	0.9	4.1	30.5	0.44	NA	NA	NA	1.94
WI	S	16	NA	NA	NA	NA	0.92	45.9	38.8	0.71	1.69
WI	T	9A	1	0.9	3.4	15	0.57	37.6	NA	NA	1.41
WI	TR	R0	2.4	2.2	6.7	21.1	1	NA	NA	NA	1.47
WI	TR	R1	2.2	2.1	5.2	17.6	NA	45.9	36.1	0.98	1.63
WI	TR	R2	1.9	1.7	5.2	21.3	1.14	50.2	43.4	0.68	1.37
WI	TR	R3	2.6	2.4	6.5	22.9	NA	38.1	37.2	0.09	1.02
WI43	A-SHRP	1	NA	NA	NA	NA	0.48	20.5	14.9	0.56	1.13
WI43	A	2	NA	NA	NA	NA	0.44	20.0	19.9	0.01	0.99
WI43	A	3	NA	NA	NA	NA	0.42	31.3	21.7	0.96	0.69
WI43	A-SMA	4	NA	NA	NA	NA	1.12	33.7	30.3	0.34	1.02
WI43	S	5	NA	NA	NA	NA	0.85	37.0	26.1	1.09	2.20
WI43	A-SMA	6	NA	NA	NA	NA	0.97	30.6	27.1	0.35	1.34

APPENDIX F - THEORETICAL RANDOM TRANSVERSE TINING RAKE



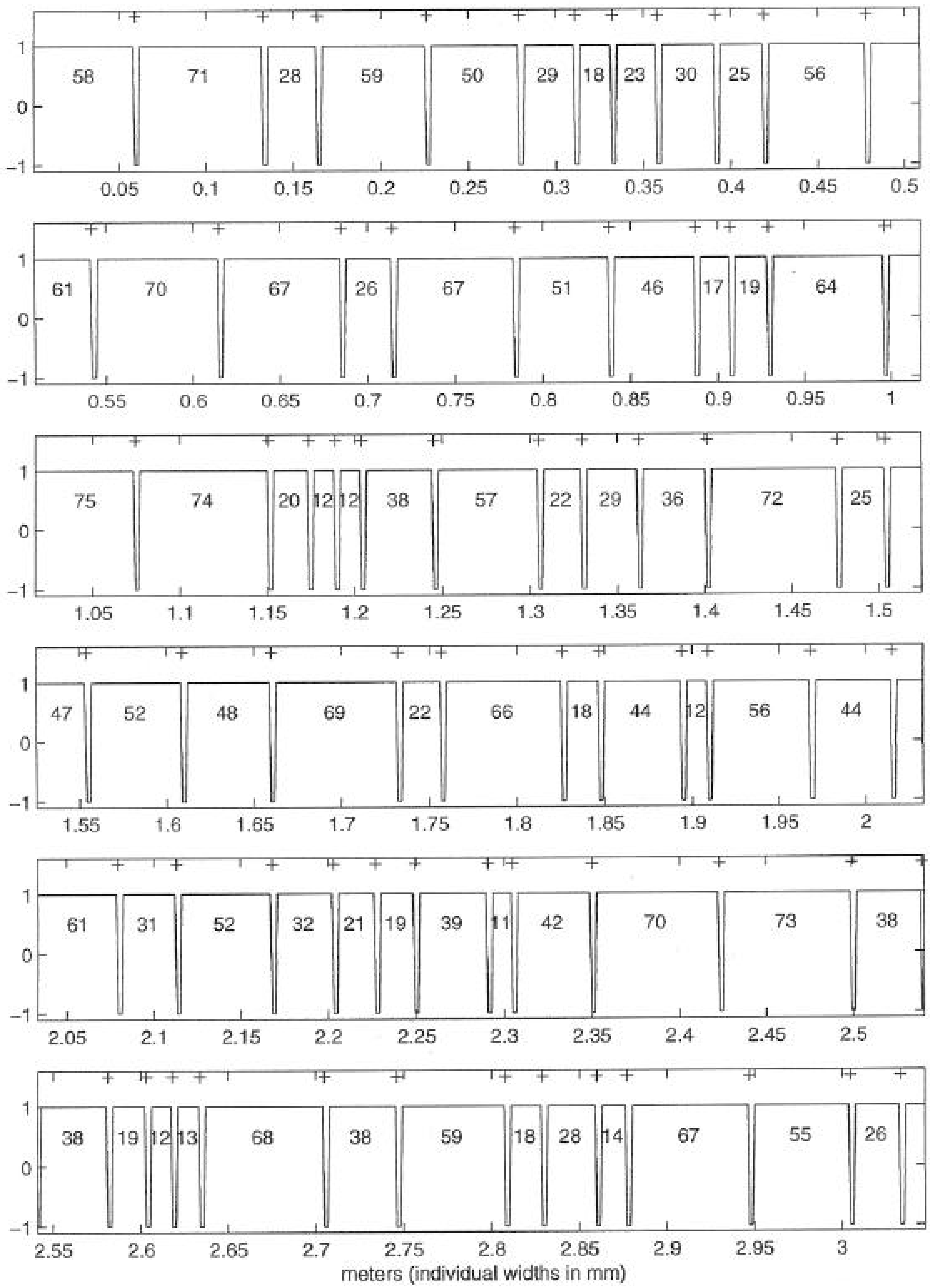
K.M.Ropella PhD, Z.S.Saad PhD candidate 20-Aug-1999
image:/usr5/people/ziad/Work/road/RoadTripSim_Optimize





K.M.Ropella PhD, Z.S.Saad PhD candidate 20–Aug–1999

Best Simulated Rake per Max/Mean ratio (1.42 Max/Mean)



K.M.Ropella PhD, Z.S.Saad PhD candidate 20-Aug-1999
image:/usr5/people/ziad/Work/road/RoadTripSim_Optimize_ShowRake

APPENDIX G - TESTING OF EXPERIMENTAL TINING RAKE IN WISCONSIN

Two test sections were built by Strueh Construction on the eastbound roadway of STH 29 approximately 7 km (5 mi.) east of Abbotsford. The theoretical random transverse test section begins approximately 500 m east of CTH F in Marathon County and extends east for 300 meters. The contractor continued using that rake across the intersection of CTH F until reaching the second section, approximately 700 m east of the centerline of CTH F. The theoretical random rake was used to tine a skewed pattern (skewed 1:6 LHF) for the next 300 m east.

No unusual patterns were observed for the exterior noise measurements. The exterior noise measurements for the random transverse are shown in Figure G-1 and for the random skewed are shown in Figure G-2, both at 96 km/h (60 mph). The narrow band interior measurements are shown superimposed for all three speeds in Figures G - 3 for the random transverse, and in Figure G - 4 for the random skew 1:6 pattern. Note that there is a 3 dBA difference between the random transverse and the random skew, and only small differences between the two patterns in interior noise. Although this patterns the findings from the major part of this study, the texture was not measured, so this comparison is not as important as those where texture measurements could also be compared.

Table G-1 shows the table of actual spacing built by Strueh Construction, (Two Rivers, WI) for use on the 1999 project. Figure G-5 shows the power spectrum of the as-built rake used on these sections. It has a max/min ratio of 1.48, very close to the theoretical best rake with a ratio of 1.41. Table G-2 shows the recommended spacing with center to center dimensions recommended for a 3 m (10') long rake. The pattern ranges from 13 mm (½ inch) to 79 mm (3 1/8) inches center to center of tines, and agrees with the sketch at the end of Appendix F.

Figure G-1 Exterior Noise Random Transverse

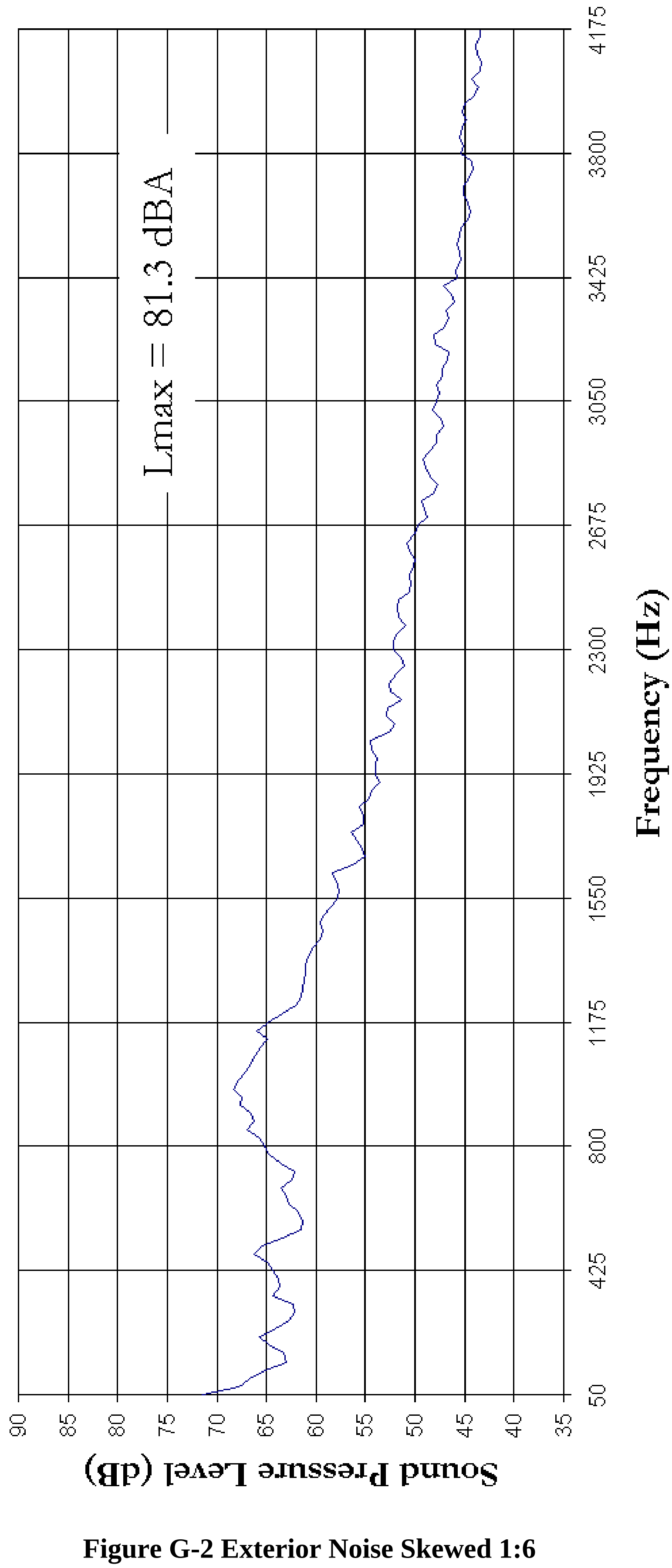


Figure G-2 Exterior Noise Skewed 1:6

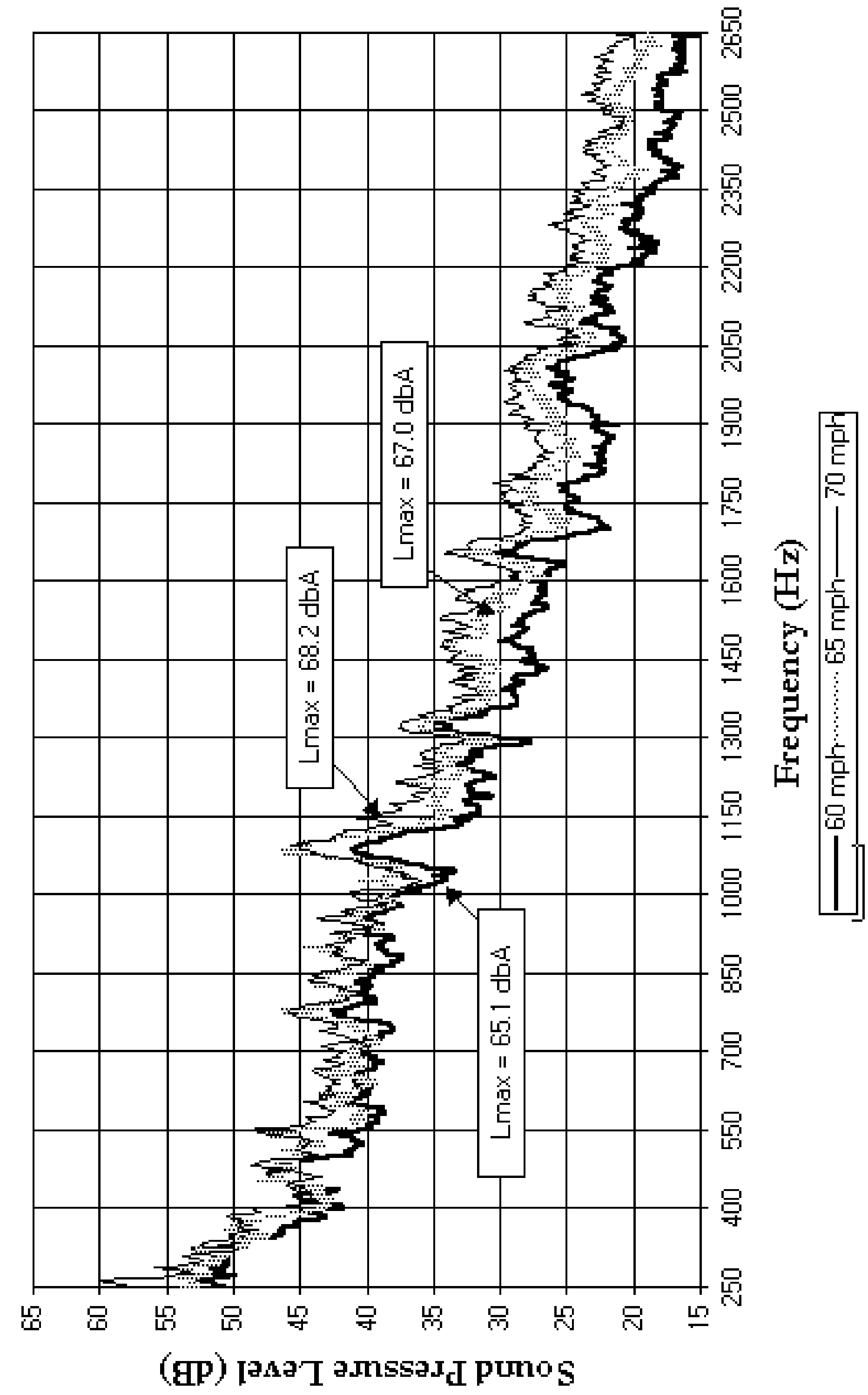


Figure G-3 Interior Noise, Random Transverse

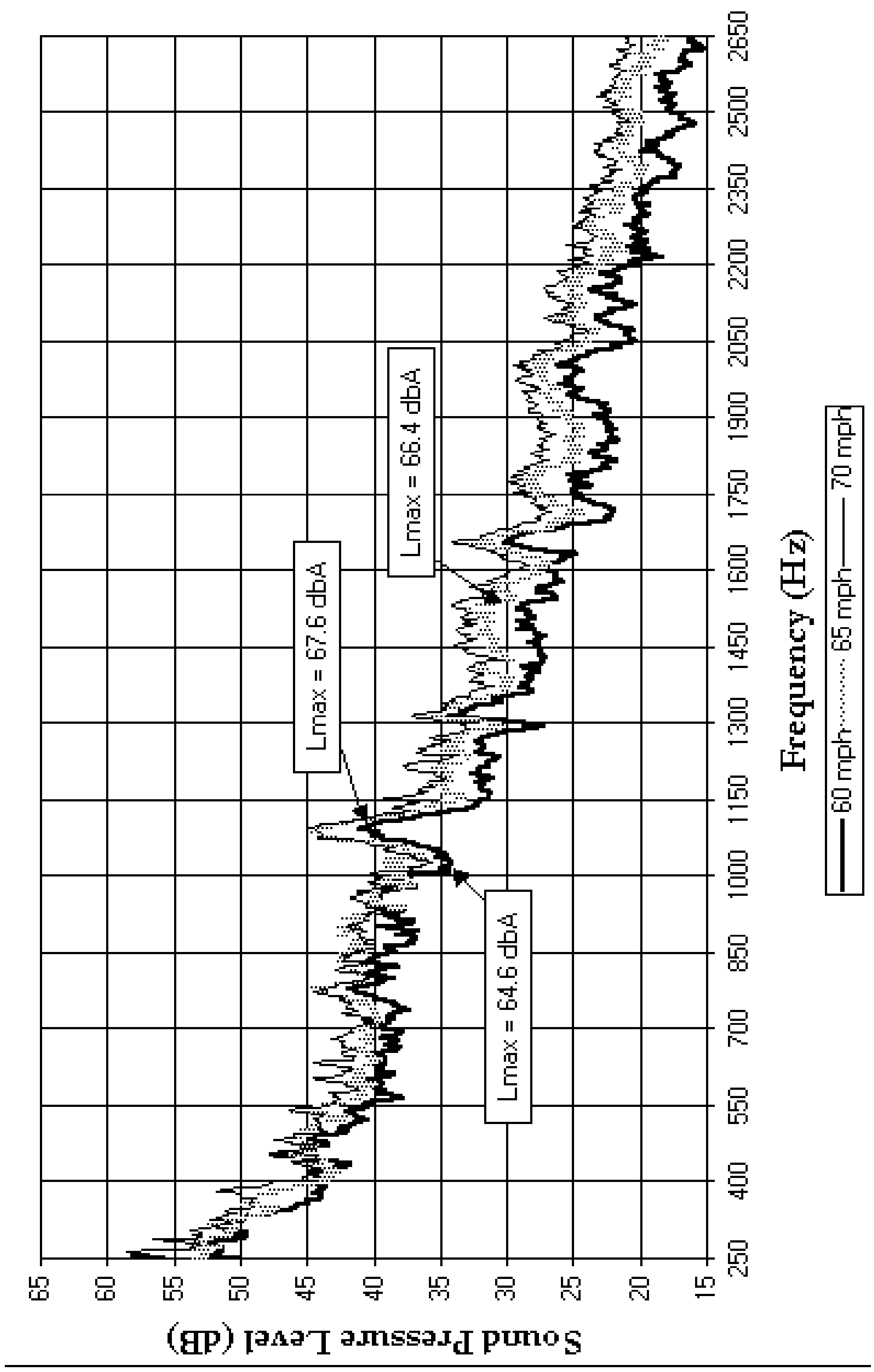


Figure G-4 interior Noise, Skewed 1:6

Table G-1, New Test Sections on Hwy. 29 Using Theoretical Rake Pattern

Rake Length: 9.4 ft

		Beg.	End
Test Section 1	Transverse	22 + 900	23 +200
Test Section 2	Skewed 6:1 RHF	24 +100	24 + 400

Tine Width: 3 mm

Tine Spacing (Center to Center of Tines, mm):

51	58.5	47.25	27.75	40	52	54.5	77.5	29.5	53.5	58.5
17	52	39	27.5	14.5	63	36.5	70.5	55.5	46	33
34.5	22	63.5	49	76.5	21	26	33	49	44	73.5
36.75	71	46	26.5	17	43	38	64	19	56.5	65.5
37.5	59	21	46	68.25	30	58.25	15	52.75	41	32
29.5	56.5	72.5	23	57.5	70.5	68	50.5			

Total Length: 2868.5 mm

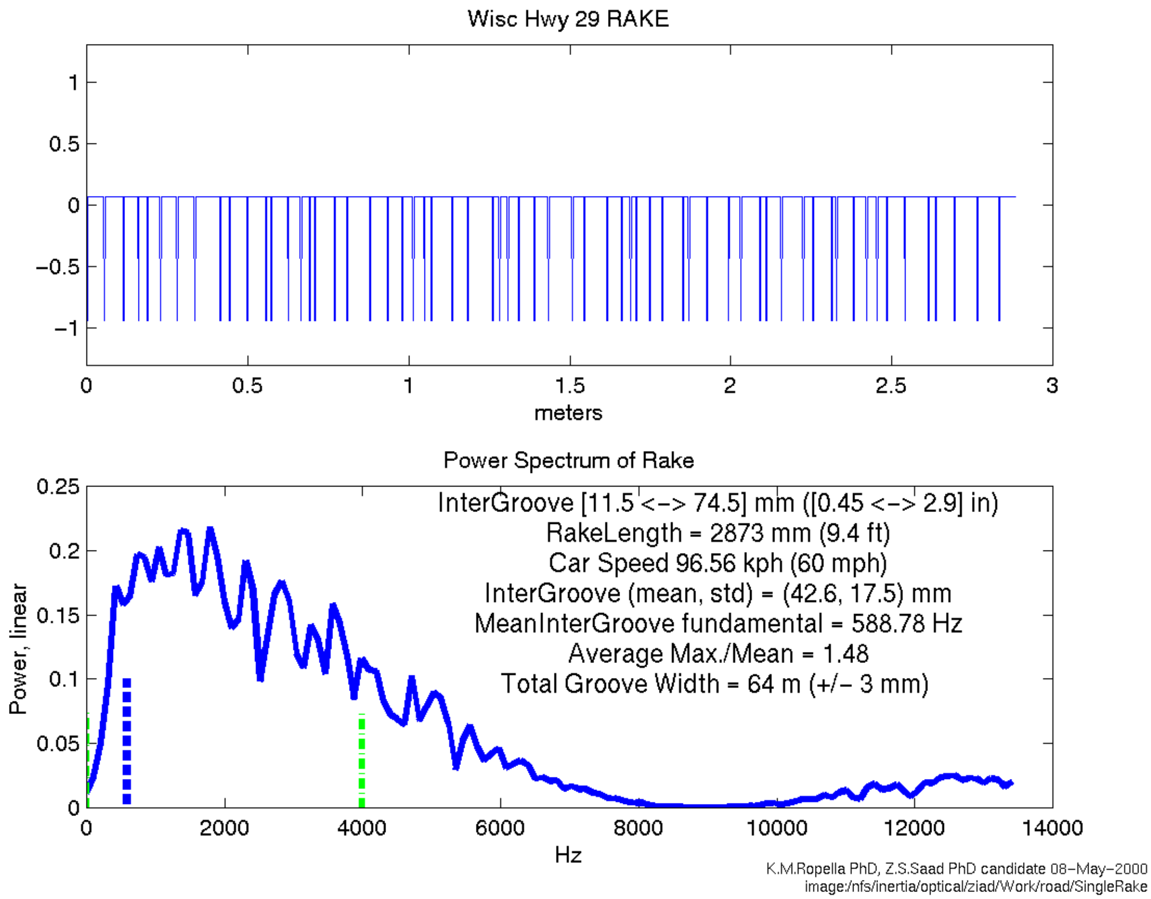


Figure G-5,Power Spectrum, As-built 10' Rake, Used on Hw. 29, 1999, Wisconsin

Table G-2,Recommended Tine Spacing, Theoretical Rake Pattern

Rake Length: 3m (**10 ft**)

Tine Width: 3mm

Tine Spacing (**Center to Center of Tines, mm**):

58	74	31	62	53	32	21	26	33	28	59
64	73	70	29	70	54	49	20	22	67	78
77	23	15	15	41	60	25	32	39	75	28
50	55	51	72	25	69	21	47	15	59	47
64	34	55	35	24	22	42	14	45	73	76
41	41	22	15	16	71	41	62	21	31	17
70	58	29								

Total Length: 3000 mm