Final Report Roadway Pavement Grinding Noise Study

I-215 Salt Lake City

Prepared for

Utah Department of Transportation

Prepared by

Parsons Brinckerhoff Quade & Douglas, Inc.

November 2000

TABLE OF CONTENTS

PAGE

LIST OF TABLES

PAGE

LIST OF FIGURES

PAGE

1.0 INTRODUCTION

Texturing of roadway pavement surfaces is necessary to provide adequate resistance to skidding, and to allow water to escape from under tires to minimize hydroplaning. This texturing, however, has been shown to contribute to tire noise on rigid pavements. Large aggregate mixes have also been shown to increase tire noise. Studies have been conducted by other agencies to evaluate which textures provide the needed safety attributes, while reducing the noise levels or the pure tone frequencies or "whine" that are annoying to the public. Other pavement deficiencies have been shown to contribute to tire noise as well. Joint faulting and other pavement roughness can create increases in pavement noise due to tire slap.

The purpose of this experimental project is to grind a new texture into a 300 foot section of roadway on I-215 and monitor it's performance over a two to three year period. This report presents the results of the noise levels that were conducted before and after the resurfacing was conducted. The results of similar studies performed in other states and in Europe are also provided for comparative purposes.

2.0 PAVEMENT TEST SECTION

The 300 foot test section was located on the east leg of I-215 at approximately 5000 South (M.P. 4.6) on both the northbound and southbound lanes. The surface texturing was performed by diamond grinding the plane-jointed concrete pavement built in 1990. The general condition of the pavement is considered to be good with respect to ride quality, with IRI values in inches per mile of 100 northbound lane (NBL) and 93 southbound lane (SBL). The faulting of the joints is considered to be minor, with more than 90% of the faults less than 0.1 inch in depth.

The original tining placed during construction was raked into the plastic concrete in the transverse direction. The tining was 1/8 inch wide, 1/16 inch deep, and spaced 1/2 inch apart. After 10 years of traffic the tining has been worn down to some degree. Enough of the tining still exists in the wheel-paths to contribute to tire whine.

The diamond grinding gave the surface a longitudinal oriented texture that was about 1/16 inch in depth at the time of construction.

3.0 NOISE MEASUREMENTS

The pre-grinding measurements were conducted on May 9, 2000 at six locations along the northbound lanes of I-215 in Salt Lake City (Figure 1). All measurements were taken during free flow traffic after the AM peak hour. Noise data was recorded for 15-minutes periods at each measurement site and digitally stored on a Larson Davison 2900 two-channel real time sound analyzer.

<u>Sites A</u> - At the edge of shoulder of the northbound lanes (25 feet from the traveled way), 150 feet from the start of the 300-foot grind area.

<u>Site B</u> - At the edge of shoulder of the northbound lanes (25 feet from the traveled way), 200 feet south of channel one, about 50 feet before the grind area. Noise levels at Sites A and B was recorded simultaneously.

<u>Site C</u> – Relocated the microphone from Site A to 25 feet back from edge of shoulder of the northbound lanes (50 feet from the traveled way), 150 feet from the start of the 300-foot grind area.

<u>Site D</u> - Relocated the microphone from Site B to 25 feet back for edge of shoulder of the northbound lanes (50 feet from the traveled way), 200 feet south of channel one, about 50 feet before the grind area. Noise levels at Sites C and D were recorded simultaneously.

<u>Site E</u> –150 feet from the start of the grind area and 75 feet behind Site C, 125 feet form the edge of shoulder of the northbound lanes (150 feet from the traveled way). Noise levels at Sites C and E were recorded simultaneously.

The post grinding noise measurements were conducted on May 31, 2000 at the same locations with the exception of the following additional measurement site that was included at the request of UDOT to measure traffic noise levels from the southbound lanes of I-215.

<u>Site F</u> – At the edge of shoulder of the southbound lanes, 150 feet from the start of the grind area.

<u>Site G</u> – 25 feet from the edge of shoulder of the southbound lanes, 150 feet from the start of the grind area. Noise levels at Sites F and G were recorded simultaneously.

3.1 Results of Measured Noise Data

The measured noise levels were analyzed in 1/3 octave sound pressure levels and are presented in Figures 2 through 6 for the following conditions:

<u>Figure 2:</u> The sound pressure level data at Site A, the edge of shoulder of the northbound lanes, represents the closest microphone location to the traffic. This data compares the measurements made on different days during the same time period before and after grinding at the same measurement location.

<u>Figure 3:</u> The sound pressure level data at Site B, 25 feet from the edge of shoulder of the northbound lanes, compares the measurements made on different days during the same time period before and after grinding at the same measurement location.

<u>Figure 4:</u> The sound pressure level data at Site E, 125 feet from the edge of shoulder of the northbound lanes, compares the measurements made on different days

during the same time period before and after grinding at the same measurement location.

Figure 5: The sound pressure level data presented represents simultaneous noise measurements taken of the same northbound traffic at Site A, edge of shoulder, next to the pavement area that was ground and Site B, next to the original pavement surface that is directly south of the ground pavement.

Figure 6: The sound pressure level data presented represents simultaneous noise measurements taken of the same northbound traffic at Site C, 25 feet from edge of shoulder, next to the pavement area that was ground and Site D, next to the original pavement surface that is directly south of the ground pavement.

Figure 7: The sound pressure level data presented represents simultaneous after grinding noise measurements taken of the same southbound traffic at Site F, edge of shoulder and Site G, 25 feet from edge of shoulder.

The A-scale (dBA) measured noise levels are summarized in Table 1. Data for Sites F and G, requested by UDOT during the post grinding measurements, do not represent the change in traffic noise levels due to the grinding.

3.2 Data Analysis

The noise reduction from the pavement grinding is highest, 5.0 dBA at Site A, where the microphone location was closest to the traveled lanes. As the measurement location is moved further from the travel lanes the reduction is less, 2.6 dBA at Site C and 0.2 dBA at Site E. The measured data indicates that the noise contribution from the tire pavement interaction is more predominate at closer distances to the traffic. This effect is lessened at larger distances where the contribution of truck exhaust stack noise is more prevalent. The other variable in these measured data is the traffic volumes, speed and vehicle mix. The traffic counts on northbound I-215 made during the noise measurements are presented in Table 2.

The comparison of the simultaneous measurements at Sites A and C and Sites B and D indicate lower noise reductions than the data taken at these same sites during different days.

Table 1
Summary of Noise Measurements

Measurement Sites	Microphone Location	Pre-Grinding Noise Levels (dBA)	Post Grinding Noise Levels (dBA)	Noise Reduction due to Pavement Grinding
Site A	Edge of Shoulder - Northbound Lanes	84.2	79.2	5.0
Site C	25 feet from Edge of Shoulder - Northbound Lanes	81.2	78.6	2.6
Site E	125 feet from Edge of Shoulder - Northbound Lanes	76.4	76.2	0.2
Sites A & B	Edge of Shoulder - Northbound Lanes	81.5	79.2	2.3
Sites C & D	25 feet from Edge of Shoulder - Northbound Lanes	79.6	78.6	1.0
Site F	Edge of Shoulder - Southbound Lanes	----	79.0	N/A
Site G	25 feet from Edge of Shoulder - Southbound Lanes	----	77.9	N/A

Table 2
Traffic Counts – Northbound I-215

		15 Minute Count				1 Hour Volume				Vehicle Percent		
		Total	Cars	MT	HT	Total	Cars	MT	HT	Cars	MT	HT
Site A	Pre-Grinding	662	628	19	15	2648	2512	76	60	95%	3%	2%
Site A	Post	664	607	33	24	2656	2428	132	96	91%	5%	4%
Site C	Pre-Grinding	614	571	26	17	2456	2284	104	68	93%	4%	3%
Site C	Post	591	538	27	26	2364	2152	108	104	91%	5%	4%
Site E	Pre-Grinding	562	524	24	14	2248	2096	96	56	93%	4%	2%
Site E	Post	540	488	19	33	2160	1952	76	132	90%	4%	6%

3.3 Summary and Conclusions

Since traffic noise consists of pavement/tire noise and vehicle engine exhaust noise, the benefits of the pavement grinding is reduced by the noise contribution from heavy truck engine stack noise. At speeds of approximately 60 mph or less, the engine stack noise of a heavy truck is higher than the tire noise. At lower speeds, the gap in this relationship widens, where the engine stack exhaust noise is the predominate source of truck noise. The maximum noise reduction of the pavement grinding was measured at the edge of shoulder and decreased as the distance from the traffic increased. At the near field to the tire/pavement noise, the lower frequency truck engine stack exhaust noise, which is at a source height in the range of 8 to 12 feet above the pavement surface, will diffract over the 5-foot high microphone location. As the distance between the microphone and the traffic increases the truck engine stack noise becomes more significant.

The potential traffic noise reduction of the pavement grinding to the communities along I-215 would be in the range of 1 dBA to 2 dBA depending on the percentage of heavy trucks and their speed. The higher the percentage of cars and medium trucks (vehicles without a vertical engine exhaust stack) the better the noise reduction.

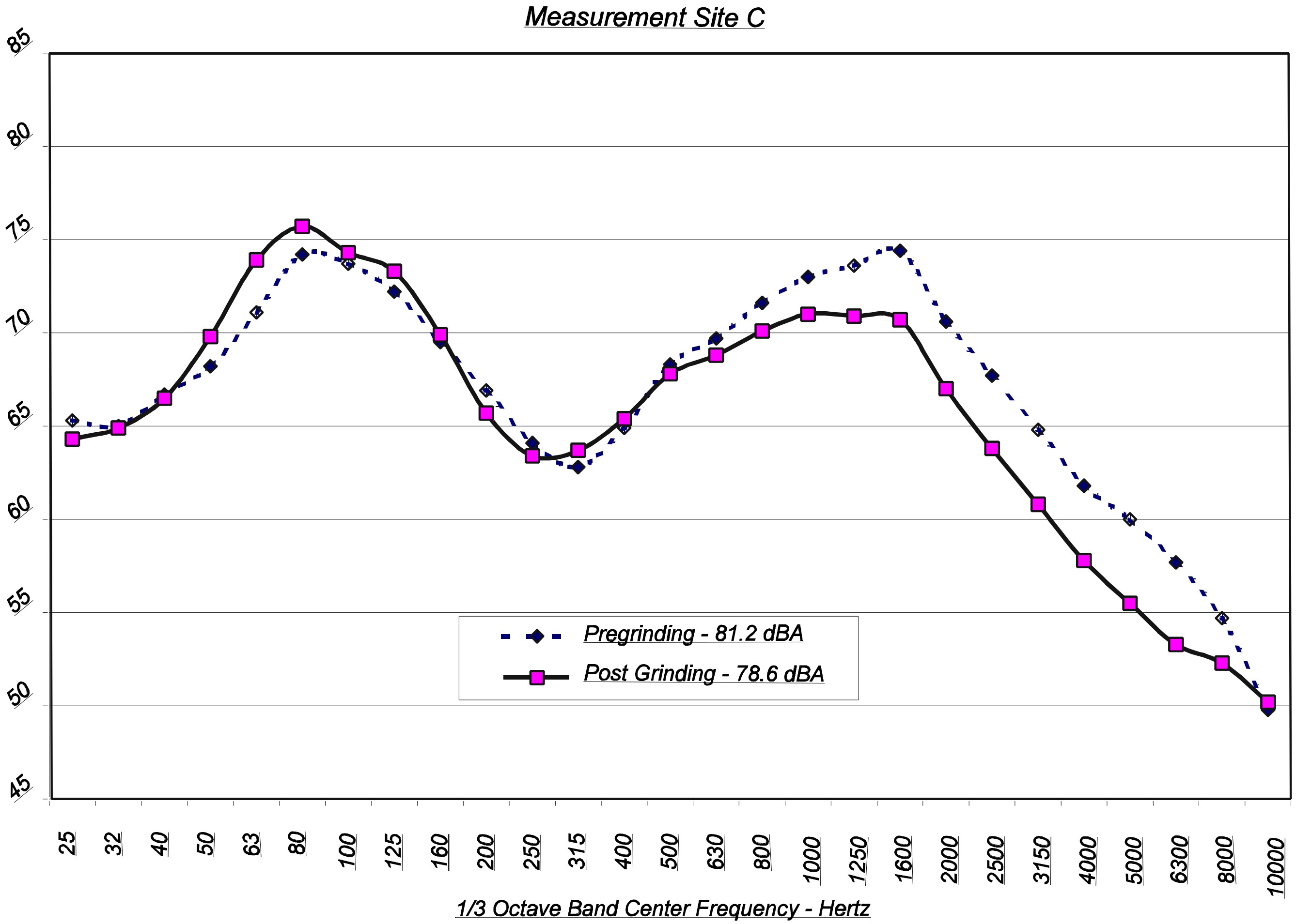
The basic shape of the frequency spectrum before and after the grinding is similar with the exception that at or about the 1600 Hz 1/3 octave band there is more pronounced reduction in sound pressure level. At measurement Site A (Figures 2 and 5), and Site C (Figure 3) there is measured difference in the range of 3 dB to 7 dB at this frequency. The pure tone characteristics of the tire noise have been reduced by the pavement grinding. Subjectively, this would contribute to the perception that the post-ground tire noise is lower in noise level than the A-scale difference of 1 to 2 dBA would indicate.

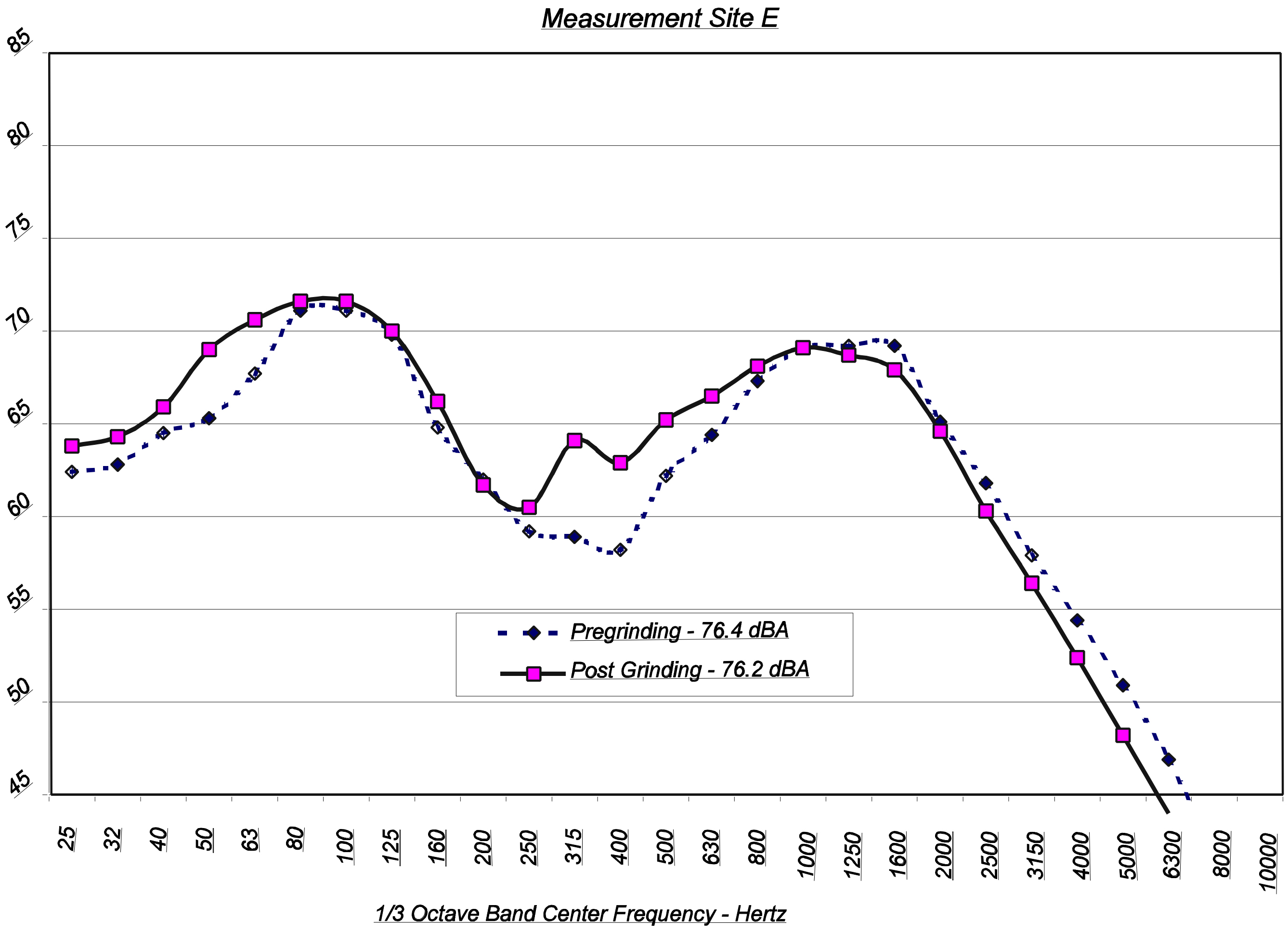
Since the pavement grinding did remove the uniformly spaced transverse tines from the concrete pavement, the high frequency pure tone noise, commonly known as tire whine, has been significantly reduced. Studies conducted in Minnesota, North Dakota and Wisconsin have found that uniformly spaced transverse tined concrete pavement results in the most irritating tire/pavement noise when compared to other transverse or longitudinal tine concrete pavement textures.

The expected reduction of removing the uniformly spaced transverse tined pavement texture would be approximately 3 dB to 5 dB at the pure tone frequencies that generate the tire whine noise. At closer distances to the travel lanes reductions in these same frequencies may be as much as 7 dB.

The use of pavement grinding as a traffic noise abatement measure for I-215 could be beneficial for both reducing tire pavement noise levels and muting the tire whine pure tone sound of the older concrete pavement transverse tining texture.

Figure 1
Noise Measurement Locations


Measurement Site C
85
80
75
70
65
60
55
50
45
Pregrinding - 81.2 dBA
Post Grinding - 78.6 dBA
25 32 40 50 63 80 100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000 10000
1/3 Octave Band Center Frequency - Hertz


Measurement Site E
85
80
75
70
65
60
55
50
45
Pregrinding - 76.4 dBA
Post Grinding - 76.2 dBA
25
32
40
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
10000
1/3 Octave Band Center Frequency - Hertz

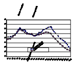
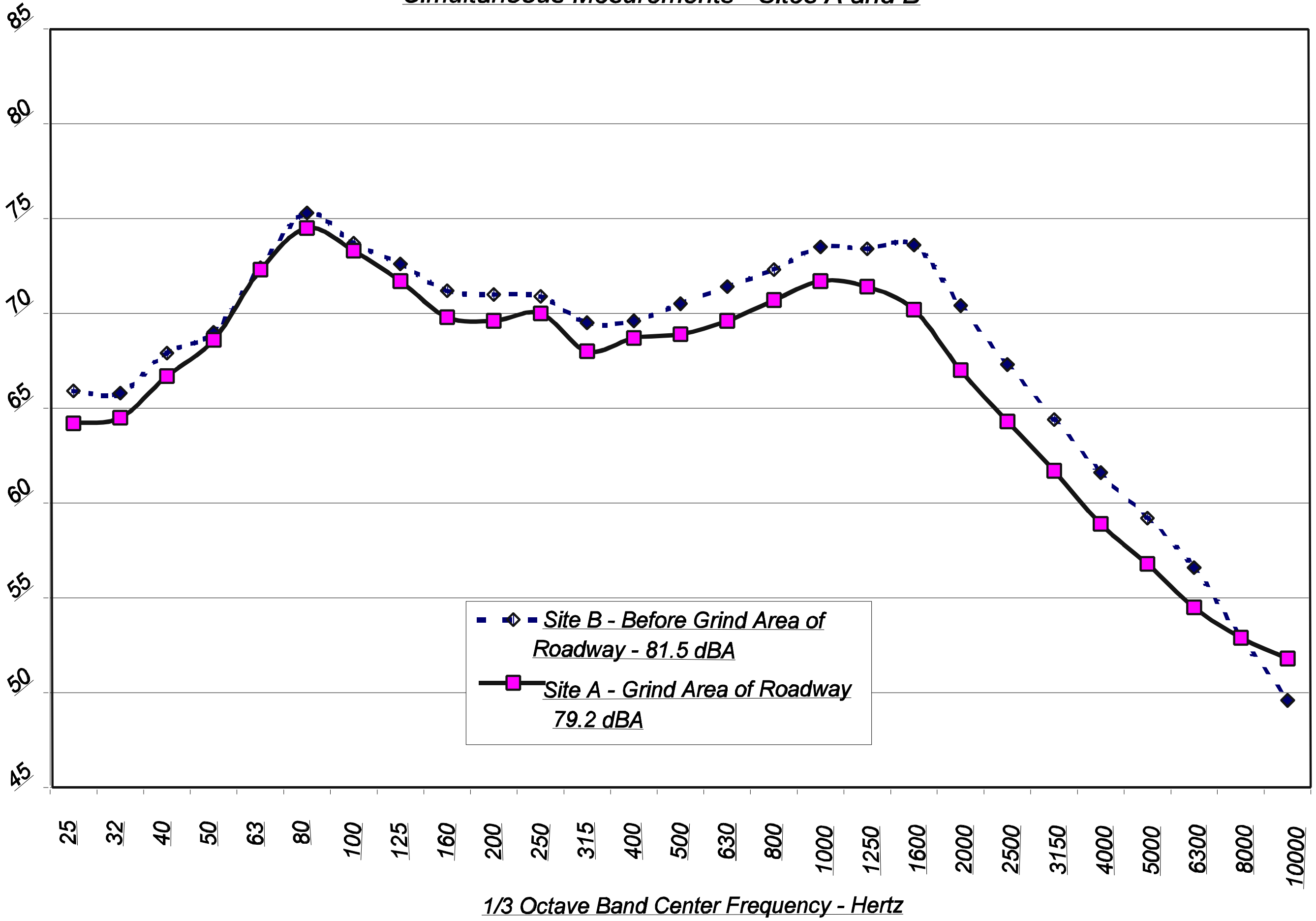
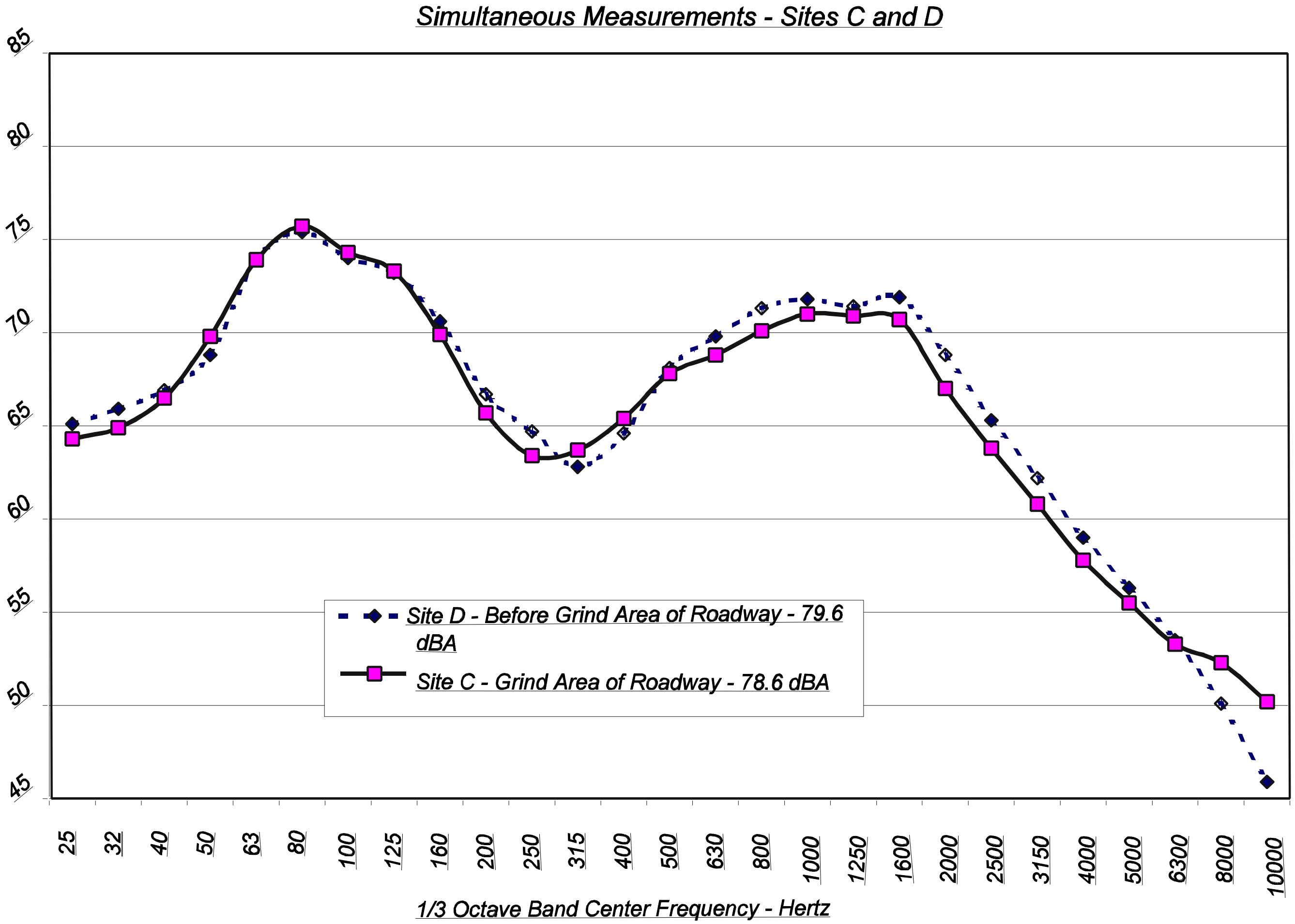
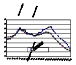


Figure 5 - Comparison of Roadway Grinding at Edge of Shoulder

Simultaneous Mesurements - Sites A and B




Simultaneous Measurements - Sites C and D
85
80
75
70
65
60
55
50
45
Site D - Before Grind Area of Roadway - 79.6 dBA
Site C - Grind Area of Roadway - 78.6 dBA
25
32
40
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
10000
1/3 Octave Band Center Frequency - Hertz



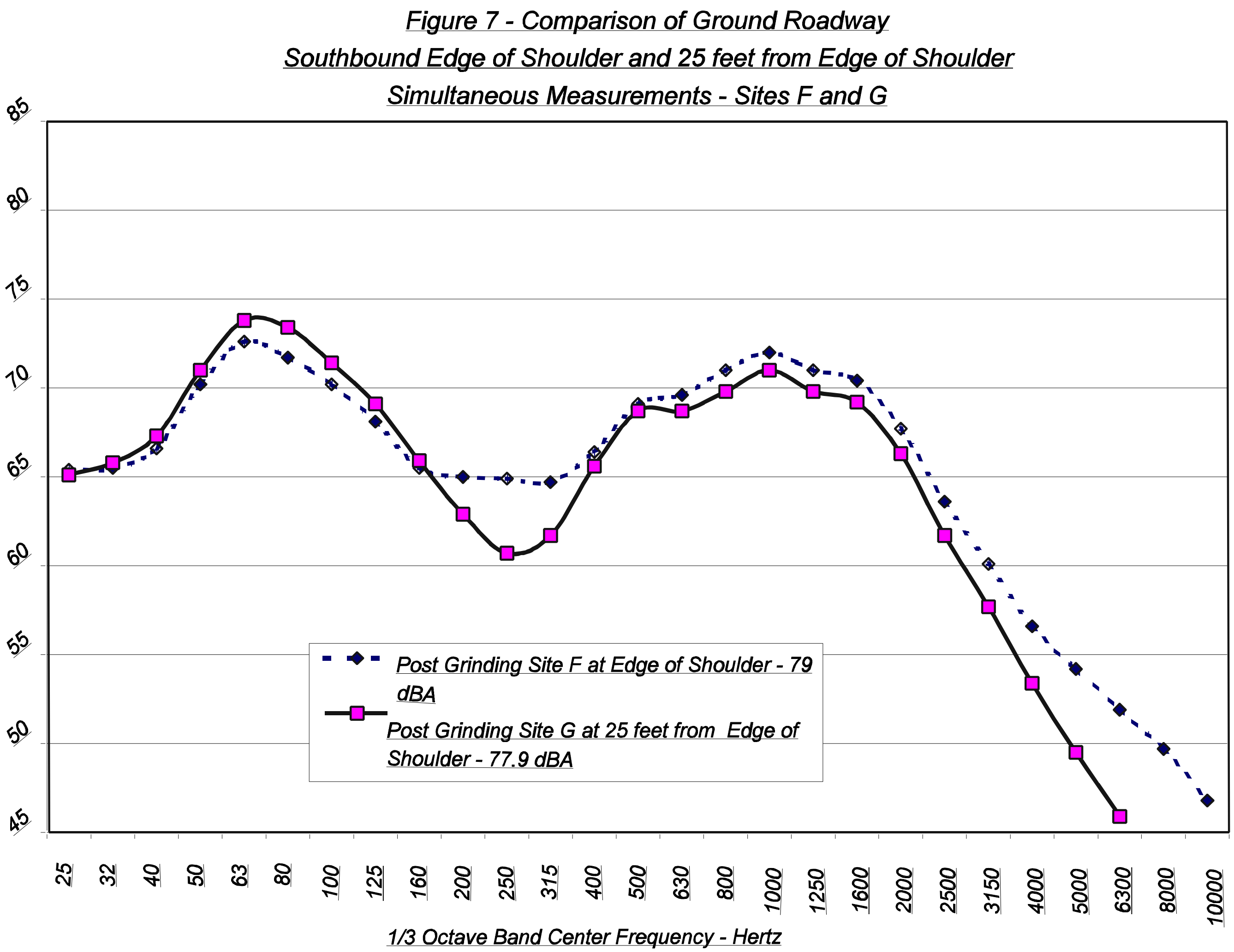
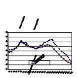


Figure 7 - Comparison of Ground Roadway
Southbound Edge of Shoulder and 25 feet from Edge of Shoulder
Simultaneous Measurements - Sites F and G
85
80
75
70
65
60
55
50
45
Post Grinding Site F at Edge of Shoulder - 79 dBA
Post Grinding Site G at 25 feet from Edge of Shoulder - 77.9 dBA
25
32
40
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
10000
1/3 Octave Band Center Frequency - Hertz



4.0 PAST STUDIES ON PCC PAVEMENTS

Since the 1970s, Portland Concrete Cement (PCC) pavement surfaces in the United States have predominantly been textured by transverse tining. Longitudinal tining has only been used consistently in one state—California—and in one country—Spain—and frequently in southeastern Virginia.

Many highway experts and environmentalists consider longitudinal tining one of the best noise reducing surfaces. Available research studies have been used to identify the strengths and weaknesses of these two texturing methods.

Longitudinal tining preceded by longitudinal burlap drag or broom: The California standard is 19 mm (3/4 in) spacing between the tines: 2.4 to 3.2 mm (3/32 to 1/8 in) wide and 4.8 mm (3/16 in + or - 1/8 in) deep with a minimum required coefficient of friction of 0.30 as measured by the State standard test procedure. The fine aggregate is required to have minimum siliceous sand content of 30 percent.

A longitudinal texture has also been constructed in Spain that is reported to be satisfactory. A plastic brush and a texture depth between 0.7 and 1.0 mm are considered the best compromise between tire / pavement noise and skid resistance.

Advantages:

1. There is a noise reduction when the tire / pavement interaction is isolated.
2. Vehicles on horizontal curves will have greater force acting to prevent them from skidding off the curve.
3. There are no reports by the occupants in a vehicle of irritating noises or tire whining.
4. Where high-quality surface mixes containing a minimum of 25 percent siliceous sand are used, friction numbers may be satisfactory even when using blank tires at speeds of 96 km/h, based on California retest data on one of its experimental sections. Friction numbers were above 40.
5. Friction tests with an ASTM skid trailer on two sinusoidal longitudinally tined sections in Spain had 90+ km/h smooth tire friction numbers of .273 to .307 (4 tests-average sand patch texture depth of 1.1 mm) on one project and .201 to .239 (4 tests-average sand patch texture depth of 0.8 mm) on the other project. These numbers are much lower (but still considered adequate) than those reported by California, although Spain's use of this technique was patterned after California's experience due to similar climatic conditions.

It should also be noted that Germany continues to use only longitudinal burlap texturing on its high-quality concrete surfaces even though the speed is not limited on much of the Autobahn system. However, Germany's accident rate is about twice that of the U.S., and no comparison of available friction test data currently available has yet been made by U.S. researchers. Germany does have a uniform cross slope of 2.5 percent to improve surface drainage.

Disadvantages:

1. Skid resistance is reported to be reduced compared to that of transverse tining because the macrotexture does not provide equivalent friction at higher speeds in wet weather for both stopping distance and rotational stability. Great Britain uses a 130 km/h design speed and will not allow this type of texturing. It also is one of the few countries with published friction standards.
2. Time for surface drainage to take place can exceed other PCC pavement surface types (transverse tining or exposed aggregate), especially on flat grades and sag vertical curve sections. Splash and spray are also increased compared to transverse tining. The inability to remove water becomes a bigger problem in areas of high freezing activity or frequent heavy rainstorms. Increasing the cross slope to 2 to 2.5 percent would alleviate some of the drainage problem.
3. The surface can be disconcerting drivers of vehicles with smaller tires because of the feeling that steering control has been taken by the pavement. It is important that tine width is kept narrow and the 19 to 20 mm tine spacing are used to reduce this concern. The recommended grooving pattern in the *1976 AASHTO Guide for Skid Resistant Design* was coordinated with tire manufacturers to minimize this concern.
4. Even with high-quality surface mixes, this texture has been worn off within 4 years in areas in Austria with high studded tire usage. This effect does not only apply to longitudinal textures, but most other PCC or AC surface textures as well.

4.1 Pavement Noise Characteristics

There have been many different roadway paving studies designed to measure the noise characteristics of different types of paving materials, designs and finishing techniques. A summary of some of these studies is discussed below for Portland Concrete Cement (PCC).

The general conclusions of the PCC pavement studies are:

PCC pavements generally create more noise than other roadway surfaces.

PCC pavements have the advantage of durability and superior surface friction when compared to dense-graded asphalt pavements.

Transverse tining is generally noisier than longitudinal tining. However, longitudinal tining has reduced surface friction, which decreases over time faster than transverse tining.

Uniform transverse tining usually results in a “pure tone” noise that is readily noticeable and more annoying than the other sources of traffic noise.

Where transverse tining is required, randomization of the tining is the measure used to avoid a pure tone noise. Random spacing of the grooves should be by a factor of 3 or more between the minimum and maximum spacing. An example would be a variable spacing of 15 mm, 30 mm and 58 mm.

The tined grooves should be narrow and deep.

Most of the studies that have been conducted on Portland Cement Concrete (PCC) pavements emphasize that the primary purpose of the roadway pavement surface texture is to help reduce the number and severity of wet weather accidents. Well designed and constructed PCC pavement has been shown to provide safe, durable surfaces with low-noise characteristics.

The pavement surface on high-speed (80 km/h or greater) facilities must have sufficient microtexture (usually provided by siliceous sand) and macrotexture (provided by transverse preceded by a longitudinal artificial carpet or burlap drag) to provide good friction characteristics during wet weather conditions. Current research and past experience have shown that longitudinal texturing with only an artificial carpet or burlap drag will generally not provide a safe, durable surface on high-speed facilities. They will usually provide adequate friction on roadways with speeds less than 80 km/h. Both FHWA guidelines and the AASHTO Guide on the Evaluation and Abatement of Traffic Noise recommend that the designer should never jeopardize safety to obtain noise reduction.

4.2 General Pavement Design Considerations

Surface Texture **-** Transverse tining, preceded by a longitudinal artificial carpet or burlap drag, remains the most desirable PCC surface texture method for many high-speed (80 km/h or greater) locations. With quality design and construction, it has been shown that pavements with excellent friction characteristics and low-noise levels can consistently be provided with low-noise characteristics and minimal splash and spray can be constructed.

When used, random transverse tine spacing (minimum spacing of 10 mm and a maximum spacing of 40 mm with no more than 50 percent of the spaces exceeding 25 mm) should be specified pending the results of further research. The actual tine width should be 3 mm (+/- 0.5 mm), and the tined depth should be a minimum of 3 mm and a maximum of 6 mm (provided minimum dislodging of the aggregate particle results). Narrow (less than 4 mm width), deep grooves are considered better than wider, shallow grooves for minimizing noise. The average texture depth as measured by the sand patch test (ASTM E 965) should be 0.8 mm with a minimum of 0.5 mm for individual tests. Measurements of random spacings at two locations in Wisconsin that generate low-noise levels and no tire / pavement whine are as follows:

32/19/22/25/35/22/22/22/22/25/35/13/38 mm
16/25/22/16/32/19/25/25/25/25/19/22/25/22/10/25/25/25/32/38/22/25/22/25 mm

Wisconsin researchers have now developed a noise measuring system in a vehicle and an analysis method that will identify pavement textures that generate objectionable tonal qualities. The revised noise evaluation procedure was developed when previous research reports and the current study revealed that the subjective noise ratings given by persons in test vehicles on transversely tined and certain other types of textured pavements did not correspond with the objective total noise measurements taken 7.5 m from the pavement edge. Noise measurements were taken inside of vehicles with instruments using a Fast Fourier Transform (FFT) analysis mode to observe narrow band frequencies. It was discovered that there are peak sound pressure levels up to 10 dBA around 1,000 Hertz that cause a pure tone that is irritating to the human ear (either a higher frequency tire / pavement whine or, in fewer cases, a lower pitched rumble). The third octave band analysis was not detecting these frequency peaks because averaging of the total sound masked them. The tones were discovered on most uniformly spaced transverse tining. This is a major discovery because surface textures creating these tonal characteristics can be identified so that they can be avoided on future projects.

Jointed Concrete Design - The use of expansion joints between concrete slabs create vibrations and noise when they are traversed by vehicles, particularly heavier vehicles. The use of expansion joints should be avoided. Current pavement design practices no longer require expansion joints. However, where expansion joints are unavoidable the size of the gap should be minimized.

4.3 U.S. Research Studies

A Technical Working Group (TWG) representing State Highway Agencies, industry, academia, and the Federal Highway Administration (FHWA) has been meeting to update guidance on methods to obtain high pavement surface friction values while minimizing tire / pavement noise. The need for this guidance was based on a number of complaints about tire / pavement noise (high-pitched whine and/or low-pitched rumble) from occupants of adjacent residences and from motorists driving over transverse tined pavements. Also, some State legislatures are mandating corrective actions for sections of roadway deemed to have objectionable noise levels. These complaints have raised concerns about the adequacy of existing guidance to assure adequate friction characteristics while minimizing tire / pavement noise.

The TWG initially met on September 27, 1993, to develop a work plan and a field test plan. Preliminary plans for this effort were presented at a special session at the Transportation Research Board meeting in January 1994. The work plan called for review of current guidance on surface texture as it relates to safety (friction and vehicle control); noise (inside and outside of the vehicle); drainage (cross slope, effect of longitudinal, and transverse tining); durability; ride (profile); texture quality; and economy of construction.

The following preliminary conclusions about tire/pavement noise are made from the noise study results in Colorado, Michigan, Minnesota, North Dakota, and Wisconsin. A more detailed discussion of these studies is presented in Appendix A.

Uniformly spaced transverse tines, particularly those spaced over 26 mm, produce the most irritating tire / pavement noise. This is shown in the results from Minnesota (loudest 65 mm and 78 mm spacing), North Dakota (52 mm, 78 mm, and 104 mm spacing), and Wisconsin (39 mm spacing).

The Michigan project has, thus far, not shown a significant total noise or frequency distribution difference between the Michigan standard 26 mm uniformly spaced transversely tined texture and the European exposed aggregate texture. While acceptable, the exposed aggregate surface texture friction numbers are about 10 numbers lower than the standard Michigan transversely tined texture.

The Minnesota study found dense-graded bituminous pavement to be quieter than PCC pavement (more than 3 dBA) based on total noise. However, it should be noted that the average asphalt concrete (AC) texture depth was significantly less than most of the PCC textures, which is the major reason for this difference. Also, a study of the noise frequency spectrum indicated that total noise is not a true indicator of whether the noise is considered objectionable or not.

The interior vehicle noise studies do not show a large range in the total noise levels from the different textures. It is the narrow band frequency distribution (pure tones) that is most significant in determining whether a particular texture results in objectionable tire / pavement noise.

Using transverse and longitudinal tining together (cross hatching) produces consistently higher total noise based on Wisconsin's results.

The noise output from the tire/pavement interaction on PCC pavement changes as speed changes. The transverse plastic broom finish was the quietest in Wisconsin's test section at a passby speed of 96 km/h, but the transversely tined (13 mm spacing) and Skidabrader textures were quietest at 112 km/h passby speed for car and truck test vehicles, respectively.

Colorado's variable transversely tined texture was the loudest but also had the greatest average texture depth. However, Wisconsin found a transversely tined section outside of its test area whose tines had greater randomized spacing (repeated each rake pass) that reduced objectionable noise output significantly when compared to the State standard transverse tined texture. The specified randomness of the spacing and the construction quality are initial factors in determining the generated noise characteristics and, ultimately, the resulting level of annoyance to the human ear.

Colorado's transversely and longitudinally grooved sections (hardened concrete) are quieter than the tined sections (plastic concrete). The difference could be due to construction practice.

REFERENCES

Federal Highway Administration (FHWA); *Highway Construction Noise: Measurement, Prediction, and Mitigation*, 1976

Federal Highway Administration (FHWA); *Procedures for Abatement of Highway Traffic and Construction Noise*, Code of Federal Regulations 23CFR 772, April 1994.

Federal Highway Administration (FHWA); Memorandum: *Highway Traffic Noise Analysis and Abatement - Policy and Guidance*, June 1995.

R. E. Franklin, D. G. Harland, and M. Nelson, *Road Surfaces and Traffic Noise*, TRRL Report 896, Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1979, 33 pp.

P. M. Nelson, G. J. Harris, and B. J. Robinson, *An Examination of the Relationship Between Tire Noise and Safety Performance*, Project Report PR/ENV/047/93, Transport Research Laboratory Unpublished Report, Crowthorne, Berkshire, England, 1993.

Highway Traffic Noise Guidance and Policies and Written Noise Policies, Tony Kane's June 12, 1995, memorandum to FHWA Regional Administrators, 86 pp.

J. D. Chalupnik and D. S. Anderson, *The Effect of Roadway Wear on Tire Noise*, Washington State Transportation Center (TRAC), University of Washington, Seattle, Washington, August 1992, 33 pp.

Guidelines for Skid Resistant Pavement Design, American Association of State Highway and Transportation Officials, AASHTO, 1976, 20 pp.

Guide on Evaluation and Abatement of Traffic Noise, American Association of State Highway and Transportation Officials, AASHTO, 1993, 40 pp.

Neal, B. F., et al., *Surface Textures for PCC Pavements, Report No. FHWA-CA-TL-78-14*, California Department of Transportation, Sacramento, CA, 1978, 63 pp.

Report of the 1992 U.S. Tour of European Concrete Highways, FHWA-SA-93-012, FHWA, December 1992, pp. 113-116.

Jofre, C., *Spanish Practice and Experience with Concrete Pavements*, Paper presented to the U.S. TECH Study Tour, June 1992.

R. I. Aberola, J. Quereda, J. M. Lozano, and A. Medrano, *Modern Construction of Concrete Pavements for Expressways in Concrete Roads*, Madrid, Spain (CEMBUREAU-Brussels), October 1990, pp. 29-39.

Guidelines for Skid Resistant Pavement Design, American Association of State Highway and Transportation Officials, AASHTO, 1976, 20 pp.

P. G. Dierstein, *A Study of PCC Pavement Texturing Characteristics in Illinois*, Final Report, FHWA/IL/PR-095, Illinois Department of Transportation, Springfield, IL, 1982, 54 pp.

R. A. Scarr, Transverse Texturing With Metal Tines, *Highway Focus*, April 1976, Volume 8, No. 2, FHWA, pp. 9-17.

E. E. Rugenstein, Summary and Evaluation of Concrete Pavement Texturing Practices, *Proceedings, International Conference on Concrete Pavement Design*, Purdue University, U.S., 1977, pp. 557-563.

D. A. Kuemmel, J. J. Jaeckel, A. Satanovsky, S. F. Shober, and M. Dobersek, *Noise Characteristics of Pavement Surface Texture in Wisconsin*, Draft TRB Paper, March 1996, 37 pp.

PCCP Texturing Methods, Technical Report, Ahmad Ardani, Colorado DOT, February 1995.

Guide on Evaluation and Abatement of Traffic Noise, AASHTO, 1993, 40 pp.

S. H. Dahir and J. J. Henry, *Alternatives for the Optimization of Aggregate and Pavement Properties Related to Friction and Wear Resistance*, FHWA-RD-78-209, Final Report, FHWA, April 1978, 295 pp.

Fifth International Conference on Concrete Pavement Design and Rehabilitation, Volumes I and II, Purdue University, April 1993, 700 pp.

NCHRP Synthesis 268, Relationship Between Pavement Surface Texture and Highway Traffic Noise, TRB, 1998.

APPENDIX A

RESULTS AND STATUS OF STATE STUDIES ON PAVEMENT NOISE STUDIES

A summary of the experimental studies relevant to the different types of PCC pavement surfaces underway or recently completed in the various States is presented in this section.

Colorado

Scope: Texture, friction, profile, and noise tests were performed on nine test textures before traffic was released on the reconstructed pavement in the fall of 1994. Tests were repeated in July 1995. The test textures are longitudinal and transverse tining, longitudinal and transverse astroturf drag, and transverse saw cut grooving (see description below).

Findings: The variable transverse tining had the highest friction numbers, while the longitudinal astroturf drag and longitudinally tined sections had the lowest noise generation. The transverse and longitudinal burlap dragged sections resulted in very low friction numbers (smooth tire: 15 and 11; ribbed tire: 40 and 32, respectively) at 96 km/h even with 80 to 90 percent silica sand and do not provide adequate macrotexture for good surface drainage. Also, the friction numbers decreased significantly in the first year of traffic. The friction number on the longitudinally tined section was above 36 when tested with a smooth tire at 96 km/h, which is very good. No direct comparison of the splash and spray between the longitudinally and transversely tined or grooved sections was made. A comparison of variable transversely tined (plastic concrete) and variable transversely grooved (diamond sawed into the hardened concrete) sections indicated that tined sections performed slightly better in providing friction and the saw grooved sections were slightly quieter (up to 4 dBA).

Test Results: The following are noise, and texture results for 1994 and 1995:

SECTION	DESCRIPTION
1	Transverse tining, uniform 26 mm spacing (State standard)
2	Transverse astroturf drag
3	Transverse random tining (16 mm - 22 mm - 19 mm)*
4	Transverse tining, uniform 13 mm spacing*
5	Transverse random sawing (16 mm - 22 mm - 19 mm)*
6	Transverse tining, uniform 26 mm spacing*
7	Longitudinal sawing, 19 mm spacing*
8	Longitudinal astroturf drag
9	Longitudinal tining, 19 mm spacing*

*Preceded by longitudinal astroturf drag.
All sections first received a longitudinal burlap drag. Sections were planned to be 3 mm deep and 3 mm wide (as constructed measurements were not recorded).

Colorado Test Section: I-70 at Deertrail

Test Results: Noise [dBA] at 105 km/hr

Pvt. Section	**Inside Vehicle**		**7.5 m from Road**		**Wheel Well**	
	1994	1995	1994	1995	1994	1995
1	68	67	89	87	104	107
2	67	66	87	83	102	104
3	68	68	90	88	103	106
4	68	68	87	86	102	105
5	66	67	88	86	103	106
6	67	67	87	86	102	105
7	66	66	85	82	99	103
8	66	65	84	82	99	101
9	68	67	88	84	101	104

Test vehicle was a 1994 Oldsmobile Cutlass station wagon.

Test Results: Friction (ASTM Method E 274)

Pvt. Section	**64 km/h**		**80 km/h**		**96 km/h**	
	1994	1995	1994	1995	1994	1995
1	*56/54	56/43	58/48	50/41	52/45	46/35
2	68/48	52/22	68/40	45/18	52/35	40/14
3	69/67	59/52	68/58	52/50	58/52	51/45
4	68/62	59/55	68/58	56/55	58/55	57/49
5	60/59	52/50	60/52	50/45	49/45	46/41
6	60/55	56/42	59/49	50/39	51/43	49/35
7	54/55	50/48	52/49	48/46	44/41	39/32
8	52/30	49/20	48/21	39/16	39/19	33/11
9	65/57	55/50	61/52	52/49	51/44	42/36

*Ribbed tire/Smooth tire

Michigan

<u>Scope:</u> The Detroit, Michigan, I-75 European Demonstration Project compares the exposed aggregate surface treatment and high-quality two-layer concrete mix design to Michigan's standard concrete mix design (including higher quality aggregates not normally used) with a standard transversely tined texture. This section has a very high volume of heavy trucks (5,000 per day) and tire / pavement noise does not dominate.

<u>Findings:</u> Friction tests on the sections before they were opened to traffic in 1993 and tests performed in 1994 showed friction increased during this period but that the exposed aggregate surface is about 10 numbers lower than Michigan's standard tined surface (from an average of 37.6 to 42.1 for the exposed aggregate surface and from 46.0 to 53.2 on the Michigan transversely tined section). Reports from Austria have also shown lower friction results initially until the contractors become more experienced with the exposed aggregate surface treatment. A review of the Michigan test sections in May 1994 revealed that many

of the 4 to 8 mm particles were oriented with a flat side rather than with an edge pointed up, perhaps because of overfinishing the surface. Also, the sand used was 0 to 4 mm, not 0 to 1 mm as recommended, and some of these larger smooth sand particles were on the surface also. Both these factors would contribute to lower initial skid resistance. With more experience, these deficiencies can be corrected. However, noise values for the two sections, both inside and outside the vehicle using third octave band analysis procedures, were virtually identical.

Results: Michigan Standard (25 mm Transversely Tined) Texture vs. European Exposed Aggregate Section: I-75 in Detroit, Noise and Friction.

Measurements taken 17 m from the Michigan and European Sections using a sound level meter (1.5 m high) and a Nagra tape recorder:

European	75.9 dBA,	76.7 dBA,	76.0 dBA
Michigan	75.7 dBA,	76.1 dBA,	76.4 dBA

Measurements inside a Dodge Dynasty traveling at 80 km/h taken with the windows open and closed, using the sound level meter and the Nagra tape recorder:

	Windows Closed	**Windows Open**
European	64.5 dBA - meter 66.3 dBA – tape	66.8 dBA - meter 66.7 dBA – tape
Michigan	65.2 dBA - meter 65.9 dBA - tape	67.4 dBA - meter 67.4 dBA - tape

Minnesota

Scope: Texture test sections originally constructed in 1987 on TH 12 near Willmar and I-90 near Albert Lea. The Willmar section was retested for noise production in 1994. The texture sections consisted of transverse tines uniformly spaced from 26 to 78 mm; a variable spaced transversely tined section, an astroturf drag (control) section, and a bituminous section.

Findings: The quietest section was the asphalt concrete, followed by the longitudinal astroturf drag control section, followed by the 26 mm transversely tined section. Measurements inside and outside the vehicle were consistent in their outcome. Minnesota concluded that the tire / pavement noise does not begin to dominate until the vehicle reaches 80 km/h, and the noise spectra middle frequency range (third octave band analysis) can differ greatly from one texture to the next without a significant change in the total overall noise. Recent observations by others during a rain indicated that the transversely tined sections had less splash and spray than the dense-graded asphalt section.

Results: Noise results are from the 1987 test at Willmar and the 1995 test. The Sand Patch

Test (ASTM E 965) took texture tests.

Pavement Section	Texture Depth (mm)
Transverse Variable (26, 39, 52, 65 mm)	0.41
Transverse (78 mm space)	0.61
Transverse (65 mm space)	0.61
Transverse (52 mm space)	0.68
Transverse (45 mm space)	0.57
Transverse (26 mm space)	0.75
Asphalt Concrete	0.28
Astroturf Drag (Long.)	0.26

Minnesota Test Section: STA 12 at Willmar

Pavement Section	Ext. Avg. Car @ 88 km/h		Ext. Control Car @ 88 km/h		Int. Control Car
	1987	**1995**	**1987**	**1995**	**1987**
26, 39, 52, 65 mm repeated	78.5*	78.7	79.5	78.2	71.4
Astroturf	74.0	75.0	73.5	74.5	67.8
26 mm	76.0	76.5	75.5	76.1?	68.1
45 mm	80.5	82.0	80.5	81.1	71.1
52 mm	80.0	80.6	81.0	79.9	71.9
65 mm	80.5	81.6	82.0	81.9	72.0
78 mm	77.5	79.1	78.5	79.1	72.1
Bituminous	70.2**	72.5	68.8**	72.4	65.1

*All noise measurements in dBA.
**Average of three bituminous pavements
All PCC sections transversely tined. The astroturf section is the control section.

North Dakota

<u>Scope:</u> Reports analyzing the 1993 and 1994 testing in North Dakota are now available. Nine test textures composed of transverse tines uniformly spaced from 13 to 104 mm, transverse variable spaced tining, and a longitudinally tined section are being monitored.

<u>Findings:</u> Noise measurements for the nine textured sections were taken 10.7 and 45.7 m from the travel lane and inside four test vehicles. The skewed tining and the variable spaced tining had the lowest noise production outside the vehicle. Noise inside the vehicles was very close in range, with no one section having a great advantage or disadvantage.

<u>Results:</u> The texture information was determined in 1995 by ASTM E 965. Noise data presented here was obtained in 1994. The 1995 noise data is currently being analyzed.

Pavement Section	Texture Depth (mm)—ASTM E 965
Transverse (26 mm skew)	0.60
Transverse (19 mm spacing)	0.82
Transverse (52 mm spacing)	0.69
Transverse (78 mm spacing)	0.49
Transverse (104 mm spacing)	0.53
Transverse (Variable) (26, 52, 78, and 104 mm)	0.43
Transverse (13 mm spacing)	1.17
Longitudinal (19 mm spacing)	0.37
Transverse (control-26 mm spacing)	0.76

North Dakota Test Section: I-94 at Eagles Nest

Pavement Section	Exterior (105 km/h)		Interior			
	10.7 m	45.7 m	Ford Tempo	Dodge Shadow	Suburban	Dodge Van
26 mm skew	70*	65	73	74.3	71.3	75.0
19 mm	71	69	74.3	74.9	71.6	75.2
52 mm	69	66	73.9	74.2	72.3	73.9
78 mm	69	68	73.7	73.7	72.2	73.6
104 mm	70	67	72.8	75.1	71.8	74.3
Var. **	67	65	73.1	74.2	71.4	74.4
13 mm	70	69	73.9	74.5	72.7	73.9
19 mm Long.	69	69	74.7	74.5	72.1	74.7
26 mm control	69	68	75.1	75.8	72.1	76.7

*All noise measurements in dBA.
**Variably spaced at 26, 52, 78, and 104 mm.

Exterior noise for the 26 mm skew and variable tine spacing are questionable because they are located near an overhead structure. All sections are transversely textured unless otherwise stated.

Wisconsin

Scope: Wisconsin DOT is conducting a major research study to quantify the impacts of the pavement surface texture on noise, safety, and winter maintenance. The concrete texture test sections, consisting of longitudinally tined, transversely tined, skewed tined, and Skidabrader (shotblasted) surfaces, are located on STH 29 near Eau Claire. The bituminous sections, consisting of standard dense-graded, stone matrix, and SHRP mix design asphalt surfaces are located on I-43 near Milwaukee. A literature search of U.S. and European studies was conducted before the test phase. An addendum to the research project measured interior narrow band noise frequencies on nine of the PCCP transverse tined sections, three of the ACP sections, and one of the continuously ground sections. The additional work was performed in cooperation with the Minnesota DOT, and its purpose is to measure the irritating whine that is not detected by total noise measurements.

Findings: The passby method was initially used to measure noise with a test car and flatbed truck and was later supplemented by interior vehicle noise measurements. Friction tests were performed with a ribbed and smooth tire at 65 and 80 km/h. Preliminary results showed that the transversely tined sections have the best friction, but also have dominant frequencies in the noise spectra (peak pure tone pressure levels up to 10 dBA around 1,000 Hz). The asphalt pavements and longitudinally tined sections do not have dominant noise frequencies. The Skidabrader results indicate this equipment might also provide an acceptable exposed aggregate surface if the top layer has a high-quality concrete mixture.

Section	Description (as planned*) and Texture
1	Longitudinal turf drag, 0.22 mm**
2	Transverse tining, 26 mm spacing, 3 mm deep
3	Transverse tining, 39 mm spacing, 3 mm deep, 0.22 mm**
4	Long., 26 mm spaced/Trans., 156 mm spacing, 0.36 mm**
5	Long. tining, 26 mm spacing, 1.5 mm deep, 0.40 mm**
6	Longitudinal tining, 26 mm spacing, 3 mm deep, 0.45 mm**
7	Transverse tining, 26 mm spacing, 3 mm deep
8	Skewed (1:6), 26 mm spacing, 3 mm deep, 0.46 mm**
9	Transverse tining, 13 mm spacing, 3 mm deep, 0.46 mm**
10	Transverse tining, 19 mm spacing, 3 mm deep, 0.47 mm**
11	Transverse tining, random spacing, 3 mm deep, 0.55 mm**
12	Transverse plastic broom, 1.5 mm deep, 0.59 mm**
13	Transverse tining, 26 mm spacing, 3 mm deep
14	Transverse tining, 26 mm spacing, 1.5 mm deep, 0.60 mm**
15	Transverse tining, 26 mm spacing, 3 mm deep, 0.60 mm**
16	Longitudinal turf drag and Skidabrader, 0.65 mm**

*Actual spacing, width, and depth were not measured. It is recommended that measurements be taken at 30 locations to verify the texture that was actually constructed. The FHWA texture beam measurements taken in 1995 can be used to obtain this data where tests were taken.
** Sand patch texture depth (ASTM E 965)

Wisconsin Test Section: STH 29 Clark County

Pavement Section	FN 40R **	Texture mm ASTM E 965	Exterior Noise Car			Exterior Noise Truck		
			96 km/h	105 km/h	112 km/h	96 km/h	105 km/h	112 km/h
1	41	0.22	79.4*	80.0	81.6	90.9	93.2	-
2	-	-	-	-	-	-	-	-
3	51	0.22	83.8	84.8	88.7	92.7	93.9	-
4	49	0.36	85.3	87.2	88.8	93.2	95.0	95.6
5	40	0.40	80.1	81.0	83.0	92.3	92.6	94.5
6	45	0.45	80.1	84.8	82.6	91.1	93.0	94.5
7	-	-	-	-	-	-	-	-
8	41	0.46	80.4	82.9	83.3	92.1	91.7	-
9	47	0.46	78.0	79.3	79.5	90.8	92.0	92.3
10	46	0.47	79.2	80.2	81.5	90.2	91.0	92.8
11	43	0.55	80.8	81.7	83.9	91.6	93.5	93.3
12	42	0.59	77.2	78.8	80.0	91.5	93.1	93.9
13	-	-	-	-	-	-	-	-
14	41	0.60	80.2	81.3	82.5	91.5	92.5	93.0
15	46	0.60	81.9	82.7	84.2	92.5	94.0	93.7
16	52	0.65	81.1	82.1	83.1	90.5	91.6	92.4

*All noise measurements in dBA.
**Friction tests performed in early 1995 (ASTM Method E 274 Skid Trailer with ribbed tire-E 501).