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PCCP Texturing Methods

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DEPARTMENT OF TRANSPORTATION
RESEARCH

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RESEARCH BRANCH

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16. Abstract

This report presents a 5- year evaluation and construction details of nine test sections with varying textural characteristics. Included in the report is an overview of the methodologies used to texture concrete pavement surfaces and a discussion of frictional attributes of various textures at different speeds and their impact on noise properties. Also included in the report are descriptions of texture-measuring devices and texture-installing equipment, a description of the state-of-the-art equipment used to acquire sound pressure levels, plus a thorough discussion of data acquisition/analysis.

Frictional characteristics of the individual test sections were evaluated using the ASTM E 274 skid testing procedure. Ribbed-tire and smooth-tire friction tests were conducted to acquire skid numbers at three different speeds of 40, 50, and 65 mph. To examine the noise properties of the test sections, noise measurements were acquired to acoustically assess the impact of various surface textures at three different locations:

- Inside the test vehicle
- 25 feet from the center line (3 feet away from the right shoulder)
- Near the right rear tire of the test vehicle, away from the exhaust pipe

Implementation

The results of this study indicated that longitudinal tining, in addition to possessing adequate frictional property, is easier to install and, more importantly, produces a much lower noise level than the traditional CDOT's transverse tining. CDOT has already adopted the longitudinal tining as a preferred method of texturing concrete pavements.

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by

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EXECUTIVE SUMMARY

This report presents the final results of the "PCCP Texturing Methods" research study, documenting the noise properties and the frictional characteristics of various concrete pavement textures. The report describes the testing and construction details of nine test sections with varying textural characteristics. Included in this report is an overview of the methodologies used to texture concrete pavement surface and a discussion of frictional attributes of various surface textures at different speeds and their impact on noise properties. Also included in the report is a description of the state-of-the-art equipment used to acquire sound pressure levels, texture-measuring devices and texture installing equipment, plus a discussion of data acquisition/analysis.

To evaluate the frictional characteristics of individual test sections, skid numbers were acquired according to ASTM E 274 skid testing procedure. Ribbed-tire (ASTM E 501) and smooth-tire (ASTM E 524) friction tests were conducted to obtain skid numbers at 40, 50, and 65 mph for all the test sections. Five skid resistance tests were conducted for each test section, as required by the standard ASTM procedure E 274. The arithmetic averages of the skid resistance tests were then used to indicate the skid number (SN) for individual test sections at a specified speed.

Review of the acquired data revealed a definite relationship between speed, types of surface texture, and the magnitude of skid numbers. As speed increased, the skid numbers declined. This relationship was clearly more pronounced and consistent using the smooth tire. Skid numbers acquired with the smooth tire clearly showed a distinct difference in magnitude for surfaces with macrotexture and microtexture. The difference in skid numbers for microtexture and macrotexture were not as evident or consistent using the ribbed-tire. This phenomenon confirmed the findings of many research papers, revealing the insensitivity of the ribbed-tire towards macrotexture.

Numerous texture-measuring devices provided by FHWA were used to quantitatively measure texture depth. The various methods used to measure the depth of textures included: Texture Van, Texture Beam with an LVDT and a Laser Stylus, Outflow Meter,

Tire Tread Gauge and the standard Sand-Patch Method. Explanations of these innovative techniques are presented in the body of the report.

Noise measurements were acquired as a joint effort between the CDOT's Research Branch and a local noise consultant, David L. Adams Associates, Inc. The primary purpose of the measurements was to acoustically assess the impact of various surface textures installed in the test sections. Sound pressure levels (SPL) were acquired at the following three locations:

- Inside the test vehicle
- 25 feet from the center line (3 feet away from the right shoulder)
- Near the right rear tire of the test vehicle, away from the exhaust pipe

The sound pressure levels generated at the control section were normalized to represent a datum (zero SPL), and were compared with SPL taken from other test sections. Longitudinal macrotexture and microtexture were the most quiet surfaces based on the SPL taken at the shoulder, inside the test vehicle, and at the rear tire. State standard section (combination of uniform 1-inch spacing) exhibited the highest noise level among all the test sections, with the microphone at the rear tire position.

Implementation Statement

The results of this study indicated that longitudinal tining, in addition to possessing adequate frictional properties, provides the following advantages over the traditional CDOT's standard transverse tinning:

- Lower noise level
- Ease of installation
- Lower costs

CDOT has already adopted the longitudinal tining as a preferred method of texturing concrete pavements.

TABLE OF CONTENTS

LIST OF PHOTOGRAPHS

LIST OF FIGURES

1.0 INTRODUCTION

Surface texture in rigid pavements plays an important role in providing safety (providing skid resistant surfaces) for the travelling public. The depth, spacing, and orientation (transverse or longitudinal) of the surface texture can significantly affect the frictional characteristics, noise properties, and quality of ride.

In general, transverse tining has been the only permitted method of texturing used by the Colorado Department of Transportation (CDOT) and the majority of the other transportation agencies. There are a few states that use longitudinal tining or sawing to texture their pavements on a regular basis and are quite satisfied with its performance. Among them is the State of California, which has continued to this date to longitudinally texture concrete pavements.

The frictional characteristics of the concrete pavement surface can be divided into two general groups: microtexture and macrotexture. Microtexture comes primarily from exposing the sand particles in the mortar (1), while macrotexture refers to grooves and channels formed in the plastic and/or in the hardened concrete. Forster (2), in the Transportation Research Record 1215, defines microtexture as those "surface asperities less than 0.5 mm in height and macrotexture as those with surface asperities of greater than 0.5 mm in height".

Macrotexture, with its channels and grooves, provides a drainage system that allows water to escape from under the tire, and consequently plays an important role in reducing the likelihood of hydroplaning. As discussed by the American Concrete Institute Committee (3), the term "hydroplaning" refers to the separation of tire contact from the pavement surface by a layer of water which causes loss of steering and braking control of the vehicle. This phenomenon is complex and is a function of water depth, vehicle speed, tire-inflation pressure, pavement texture and tire-tread depth and design.

The type and quality of fine aggregate used in a concrete mix plays an important role in maintaining adequate skid resistance characteristics. As discussed in the FHWA Technical Advisory T 5050.17 (4), "regardless of the finishing or texturing method used, adequate durable skid resistance characteristics cannot be attained unless the fine aggregate has suitable wear and polish resistance characteristics."

Research by the Portland Cement Association indicates that the siliceous particle content of the fine aggregate should be greater than 25 percent in order to maintain longer lasting skid resistance characteristics. However, it should be noted that the presence of siliceous particles in a concrete mix might pose the possibility of alkali-silica reactions (ASR). Remedial measures should be taken to overcome the ASR reactions.

The most widely used method (indirect method) of acquiring frictional data (skid numbers) in the United States is the ASTM E 274 skid testing procedure with a ribbed tire (ASTM E 501). According to many of the papers reviewed on the subject of the skid testing, the ribbed tire lacks sensitivity to draining capability of pavement macrotexture, while it shows high sensitivity to pavement microtexture.

The primary reason for the ribbed tire's insensitivity to macrotexture is its deep grooves, which provide drainage for water regardless of pavement macrotexture. On the other hand, tests with the smooth tire (ASTM E 524) have produced skid-resistance data which are sensitive to both macrotexture and microtexture (5). Another advantage of using a smooth tire is that the influence of tire wear on the friction data is eliminated (6). Photograph 1 compares the ribbed and the smooth tires.

In general, skid numbers are acquired with a skid trailer by the ASTM method E 274 in the United States. These numbers are used by the states as guidelines for evaluating the frictional characteristics of pavements. However, as discussed in the National Cooperative Highway Research Program (NCHRP) Report Number 104, "no state establishes statutory requirements for

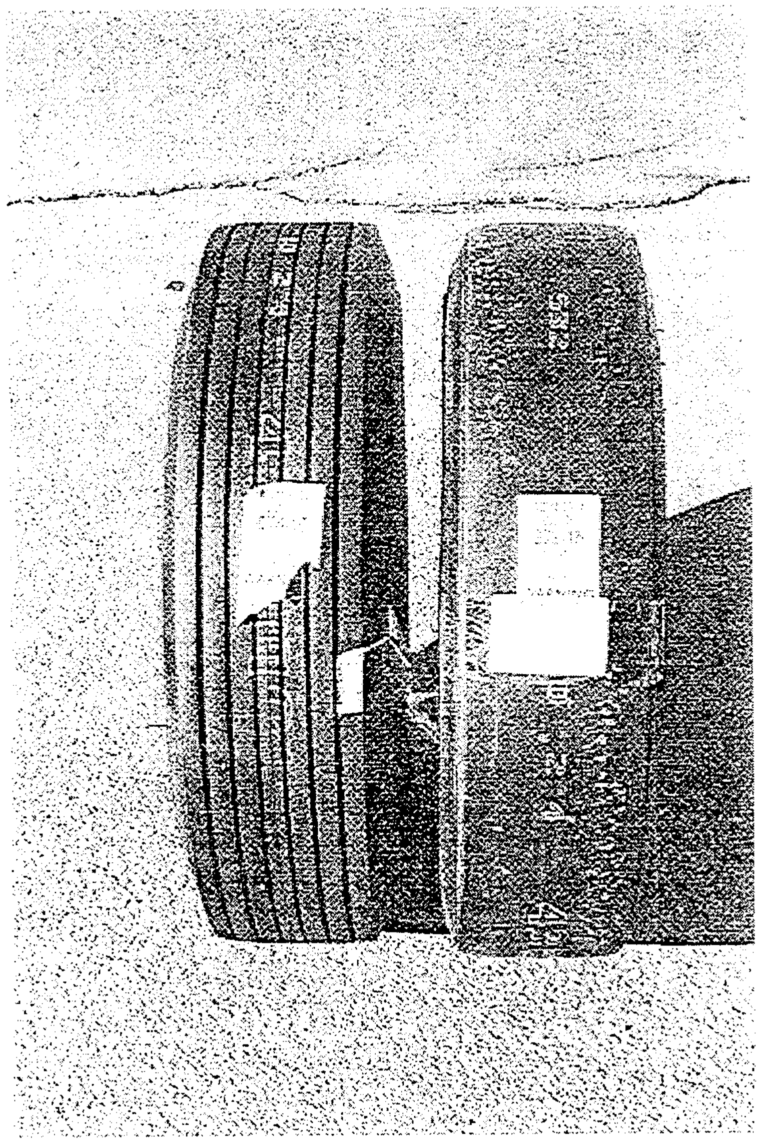


Photo 1: View of the ribbed tire (ASTM E 501 and
The smooth tire (ASTM E524)

minimum skid resistance" (7). Liability implications may be the primary reason for not establishing such statutory requirements for minimum skid resistance.

Reported skid number (SN) guidelines range from 30 to 40 for interstate highways and all highways with legal speeds in excess of 40 mph (65 km/h). Lower skid numbers are generally acceptable for urban areas where speed limits are less than 40 mph and for roads with the average daily traffic (ADT) of less than 3000 vehicles (7).

There are numerous direct methods available to quantitatively measure texture. Among the ones that were used for this study were: the texture van; the texture beam consisting of an LVDT (Linear Voltage Differential Transducer) and a commercial caser stylus; the outflow meter (indirect method); the tire tread depth gauge; and the standard sand patch test. A complete description of all these methods is presented in section 5.2.

The pavement surface texture not only impacts the frictional characteristics, but also plays a major role on the magnitude of the noise generated at the interface of the tire and pavement surface. To examine the noise characteristics of the various surface textures, noise data were acquired at the following three locations:

1. Inside the test vehicle
2. 25 feet from the center line (3 feet away from the right shoulder)
3. Near the right rear tire of the test vehicle away from the exhaust pipe

Noise data acquisition was conducted as a joint effort between the CDOT's Research Branch and a local noise consultant, David L. Adams Associates, INC. The test vehicle used was a 1994 Oldsmobile Cutlass Sierra station wagon provided by CDOT. A thorough analysis of the acquired noise data is presented in Section 5.3.

2.0 BACKGROUND

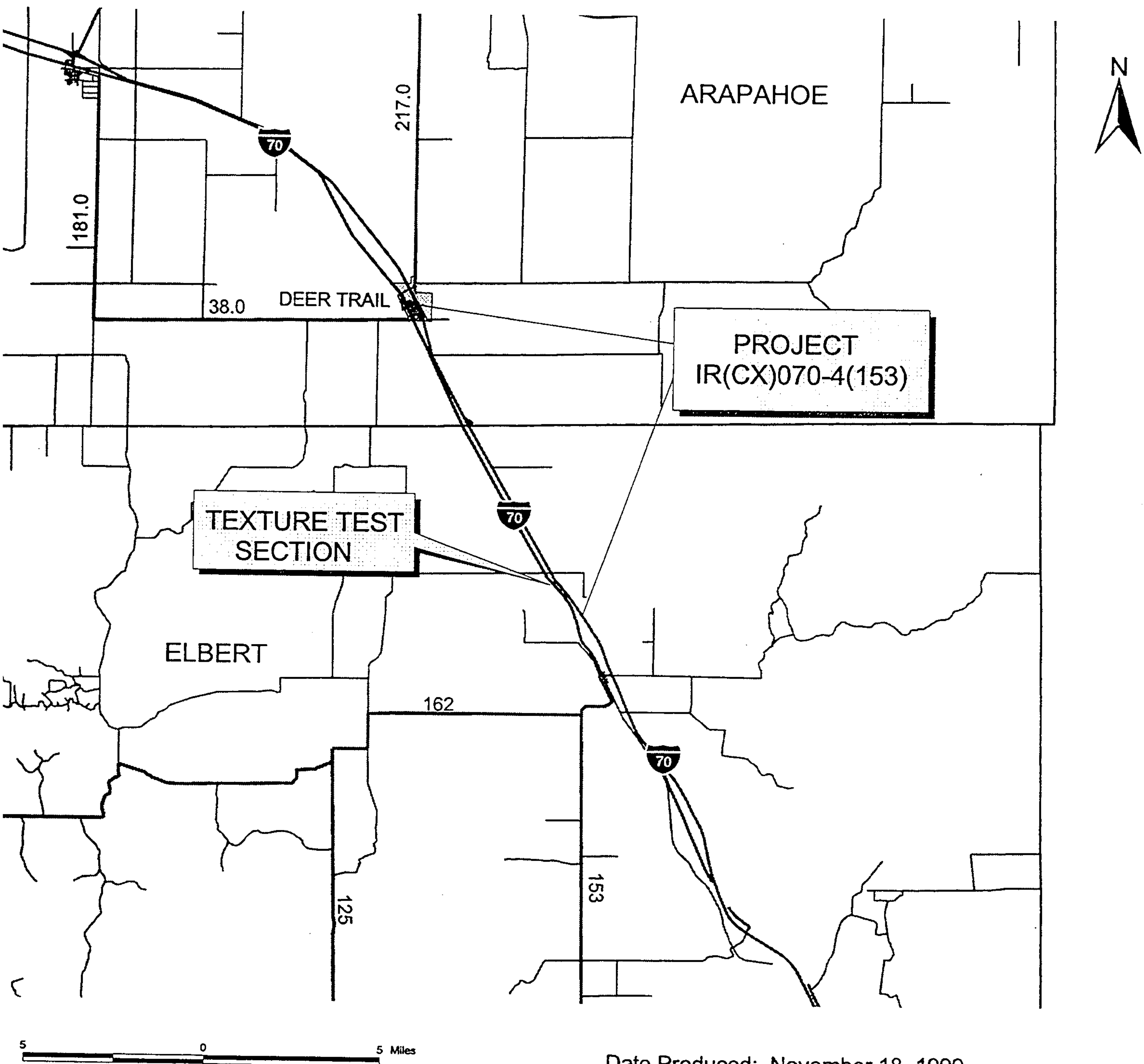
There are a number of methods used to texture the surface of Portland cement concrete pavements. The effects of these texturing methods are not well defined. Some pavement engineers feel that texturing, especially formed when the concrete is in the plastic state, has an adverse effect on the long-term performance of rigid pavements. Some, on the other hand, believe that texturing plays an important role in providing a drainage system for the surface water and creating a skid resistant surface with adequate friction for the travelling public.

There is also the noise issue, both in the urban and rural areas. Some recent research papers have indicated that a change in the surface texture can have a profound effect on the traffic induced noise characteristics. Very little is known about the effectiveness of various texturing methods used by the Colorado Department of Transportation (CDOT) and other transportation agencies.

Questions have been raised regarding constructability, cost, and the performance of various surface textures in rigid pavements. What are the impacts of various texturing methods on the frictional characteristics, noise properties, and on the ride quality of the rigid pavements? Based on the recommendations of the American Concrete Pavement Association (ACPA) and CDOT Oversight Group, and in an attempt to answer some of these questions, the Research Branch of CDOT in cooperation with Region I Materials, initiated a study to examine the pros and cons of various texturing methods.

The ultimate goal of was to develop guidelines and specifications for future construction. To achieve the objectives of this study, nine test sections with various textures were installed on a stretch of Interstate 70, 50 miles east of Denver, Colorado (Figure 1). This final report describes the construction, data collection and data analysis for all the test sections.

Figure 1



Date Produced: November 18, 1999

3.0 OBJECTIVES

The primary objectives of this study were:

1. To document the constructability, costs, and the functional practicability of several PCCP surface textures installed on I-70 for the project IR (CX)70 - 4 (153) in Colorado.

2. To assess the long-term impacts of various surface textures on the frictional characteristics, noise properties, and the ride quality of concrete pavements.

3. To identify the best performing surface texture that is cost-effective, minimizes tire noise and provides adequate frictional characteristics over a long period.

4.0 PCCP TEXTURING METHODS

4.1 Site Description

The subject research site is located on I-70, "Project IR (CX) 070–4," approximately 60 miles east of Denver. It has an average daily traffic (ADT) of 6600 vehicles, with 40 percent of that consisting of heavy vehicles. The construction consisted of paving 10 miles of I-70 from Deer Trail East, beginning at about milepost 328. The 30-year design called for a full depth overlay of concrete Class P with a nominal thickness of 11 inches over the badly deteriorated existing concrete pavement.

The siliceous particle content of the fine aggregate was measured at approximately 96 percent using the ASTM test D 3042. This is well over the limit of 25 percent recommended by the Portland Cement Association, indicating a very polish resistant fine aggregate with very little carbonates. This divided four-lane interstate highway will receive an accumulated 18-K ESAL of 21,300,000 over the next 30 years.

The details of the concrete mix design, including the test results from the siliceous particle content of the fine aggregate, are presented in Appendix C. The following is the description of all the test sections:

Stations	Texturing Method Used	Length in ft.
1) 2715 - 2743	transverse tining 1"/ state standard	2800
2) 2743 - 2768	trans. astro-turf/ no tining	2500
3) 2768 - 2789	long. astro-turf/ trans. tining random	2100
4) 2789 - 2806	long. astro-turf/ trans. tining 1/2"	1700
5) 442 - 452	long. astro-turf/ trans. sawing random	1000
6) 452 - 480	long. astro-turf/ trans. tining 1"	2800
7) 480 - 490	long. astro-turf/ long. sawing 3/4"	1000
8) 490 - 500	long. astro-turf/ no tining	1000
9) 500 - 510	long. astro-turf/ long. tining 3/4"	1000

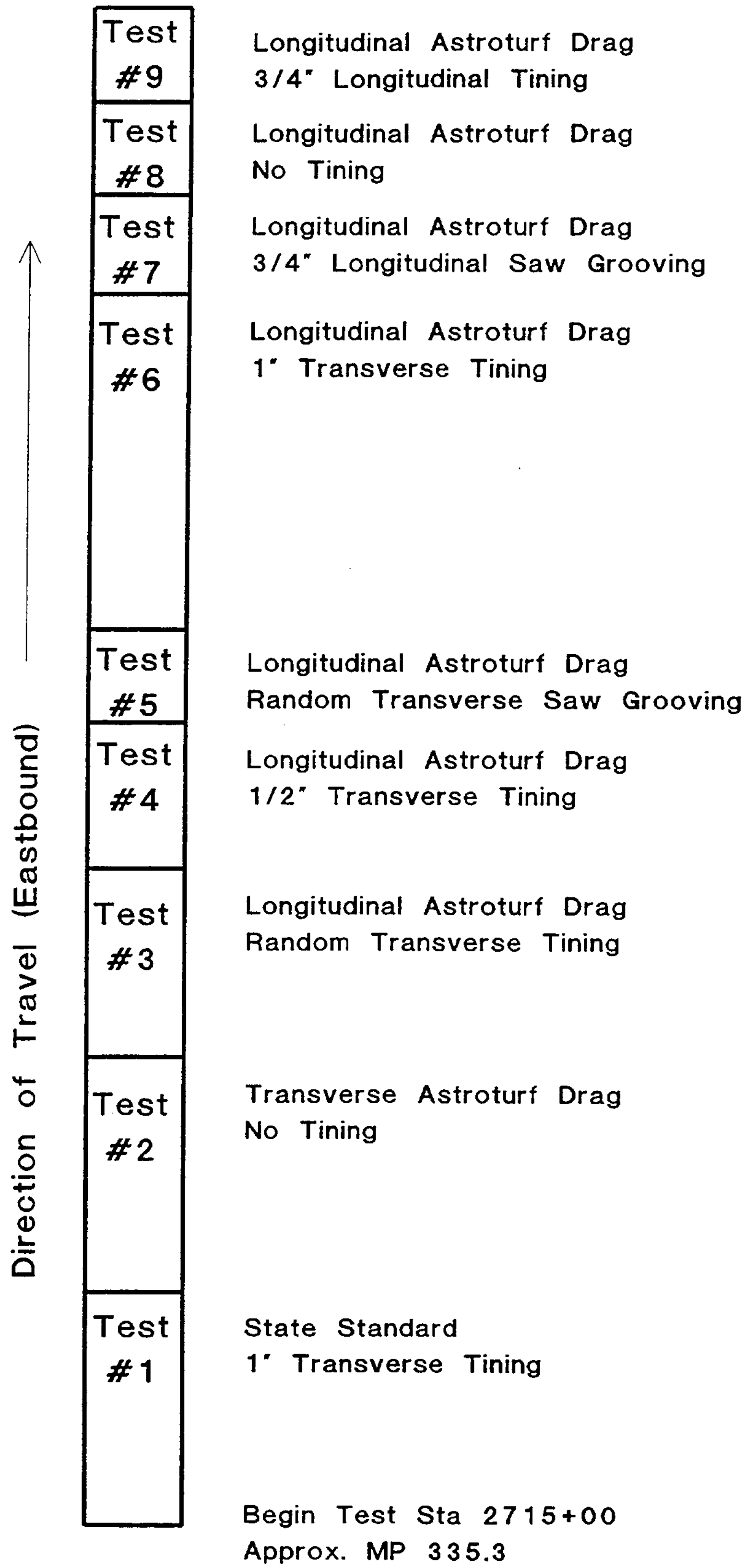


Figure 2
CONCRETE TEXTURING STUDY on I 70 at DEER TRAIL
TEST SECTION LAYOUT
(Length is to scale)

Note: Burlap drag was applied to all test sections immediately behind the paver as shown in Photograph 2. The depth and the width of all the tining and sawing were specified at 1/8" ± 1/16".

Figure 2 shows the sequence of the test sections as constructed.

4.2 Construction of Test Sections

The construction of the test sections began with paving the eastbound lanes from the east end westerly, beginning at station 510. The first test section (section 9) installed was textured with longitudinal astro-turf, followed by longitudinal tining. The tines were uniformly spaced at 3/4-inch intervals. To install longitudinal tining, the tining operator had to modify the tining equipment (bridge). The tining springs were assembled on the bottom of a steel truss, which in turn was secured to the bottom of the tining bridge.

Photograph 3 illustrates the entire tining assembly. Sensors at the four corners of the tining bridge were used to adjust the elevation and to achieve proper compression on the tining springs.

The tining-bridge was also used to drag astro-turf in the front and to apply curing compound from the back. During the installation of the longitudinal tining, the tines rolled the concrete paste (mortar) into popcorn-like balls all over the surface of the pavement (Photograph 4). However, once the concrete cured, these mortar balls were crushed by the traffic at the construction site and then easily removed by brooming.

Every time the tining operation was stopped, the tines formed a transverse indentation across the pavement surface as shown in Photograph 5. For future longitudinal tining, the contractor should be required to make provisions for raising the tines when the tining operation is stopped. This should prevent indentation of the plastic concrete surface.

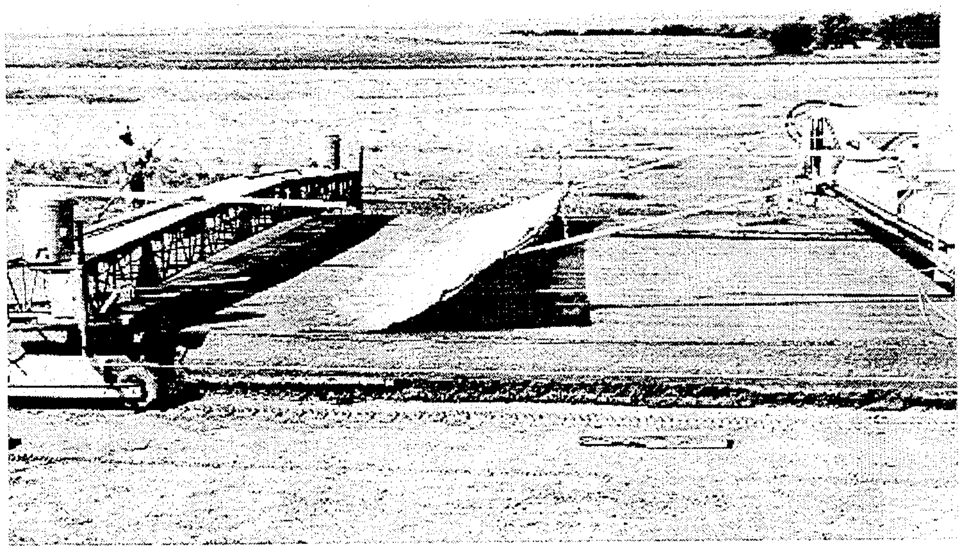


Photo 2: Application of burlap drag to all the test sections

Photo 3: View of the longitudinal timing assembly

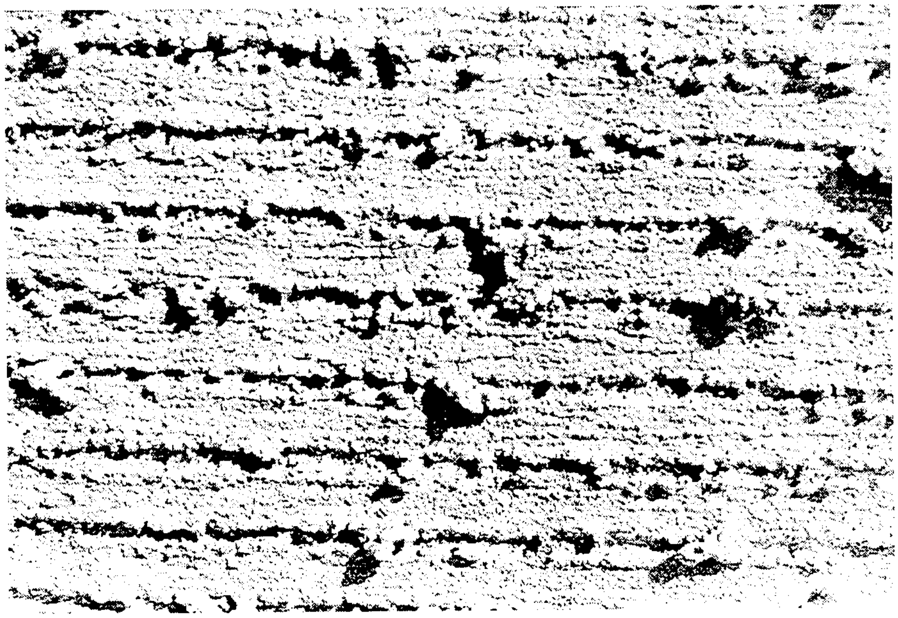


Photo 4: Popcorn-like mortar balls (longitudinal tining)

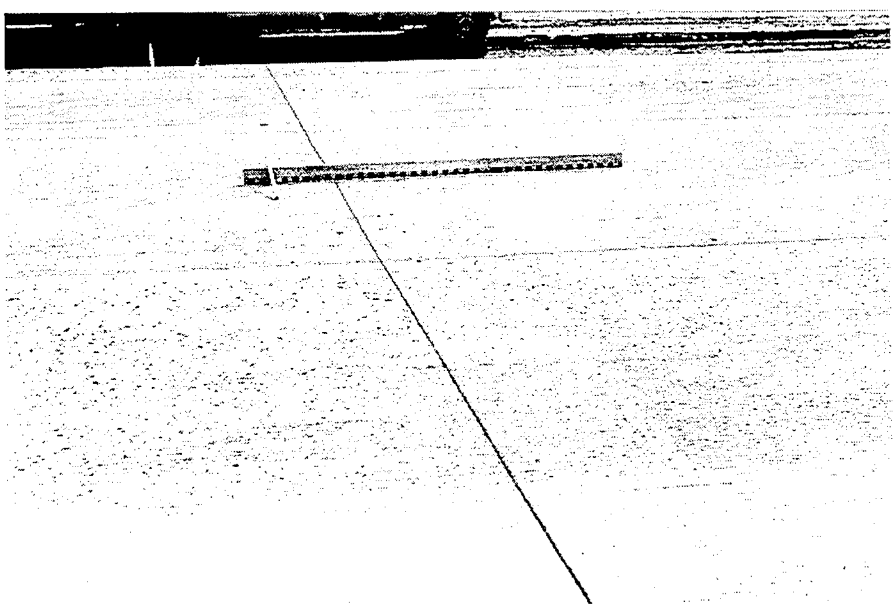


Photo 5: Transverse indentation of plastic concrete

The longitudinal astro-turf drag was applied from the front of the bridge simultaneously with longitudinal tining. The astor-turf used was 38 feet wide, covering the entire width of the pavement surface and 5.8 feet long, of which 4.8 feet contacted the surface. Due to a very stiff mix (slump of less than 1") the astro-turf was not capable of forming deep enough texture. To make the texturing more pronounced, several boards were placed on the astro-turf as shown in Photograph 6. Occasionally, the surface of the contact area became plugged with mortar (Photograph 7) and the tining operator had to raise the astro-turf and shake out the excess grout.

Photograph 8 shows the installation of transverse astro-turf texture. The set-up used was similar to that of transverse tining. A 12 foot wide, 2 foot long piece of astro-turf was folded in half and nailed to a 2" x 2" x 12 foot long piece of wood. The entire unit was then attached to the tining bridge in a manner similar to transverse tines.

Prior to installing transverse astro-turf test section the Principal Investigator (P.I), the Region I Materials Engineer, and the contractor met to discuss the possibility of encountering problems with the transverse texturing operation. It was decided to texture only the first 100 feet of the day's paving with this method to determine its feasibility and its possible continuation for the entire day's paving. If it was determined that transverse astro-turf was not adequately texturing the pavement surface, the contractor could then be directed to convert from transverse astro-turf texturing to longitudinal astro-turf texturing. However, as it can be seen in Photograph 9, the astro-turf adequately textured the pavement surface and as a result, transverse astro-turf texturing was continued for the entire day.

Photograph 10 shows a typical transverse tining operation. The state standard test section (control) which uses a combination of longitudinal burlap drag and 1" uniform transverse tining is shown in Photograph 11. Photograph 12 shows the combination of astro-turf drag with transverse tining of 1/2" uniform spacing. Transverse tining with random spacing of 5/8", 7/8" and 3/4" is shown in Photograph 13.

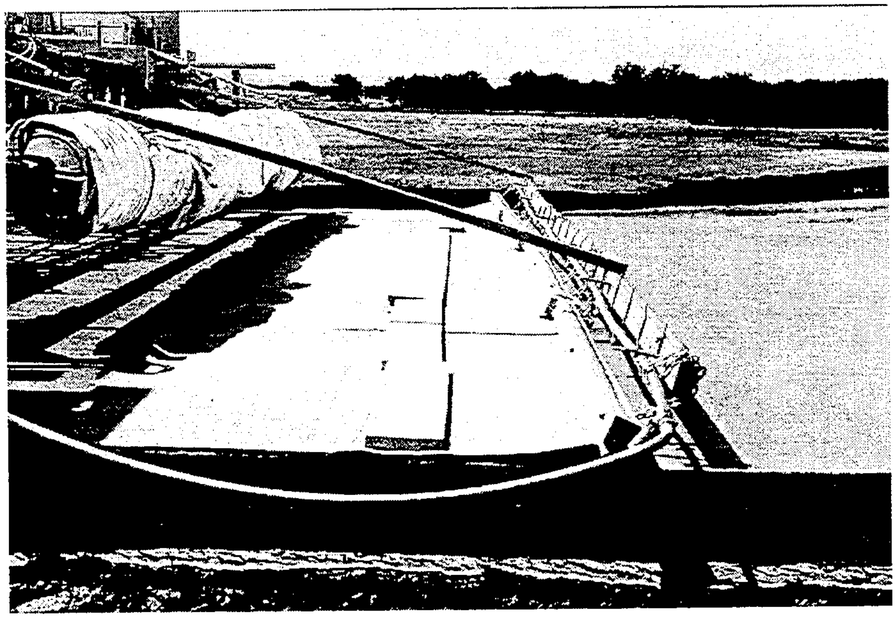


Photo 6: View of the astro-turf drag with planks for added weight

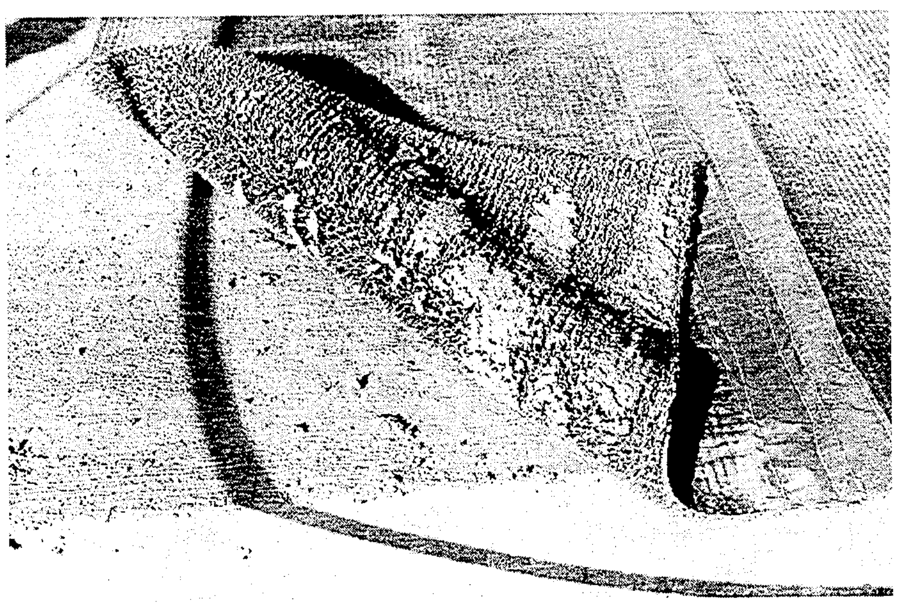


Photo 7: Astro-turf plugged up with grout

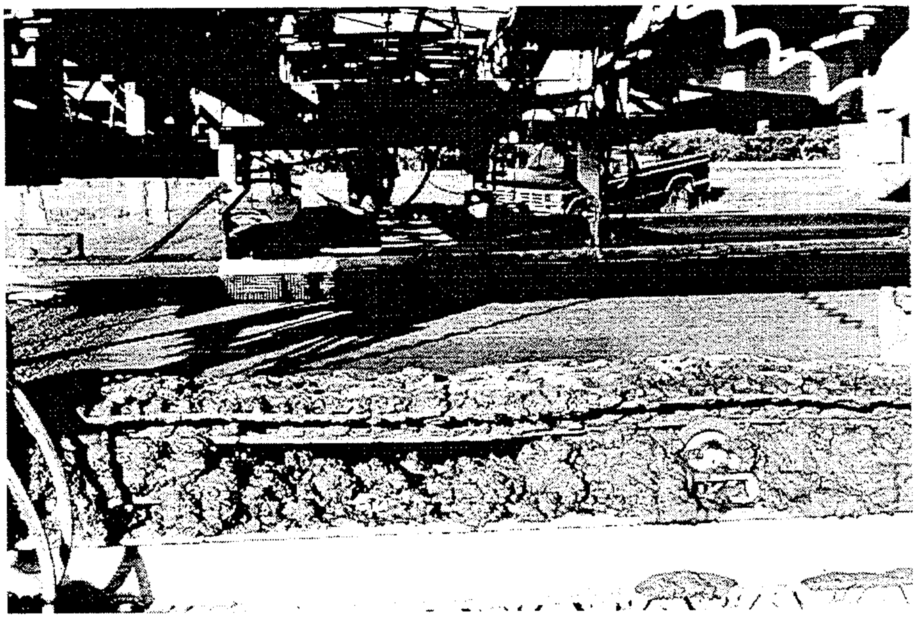


Photo 8: Installation of transverse astro-turf texture

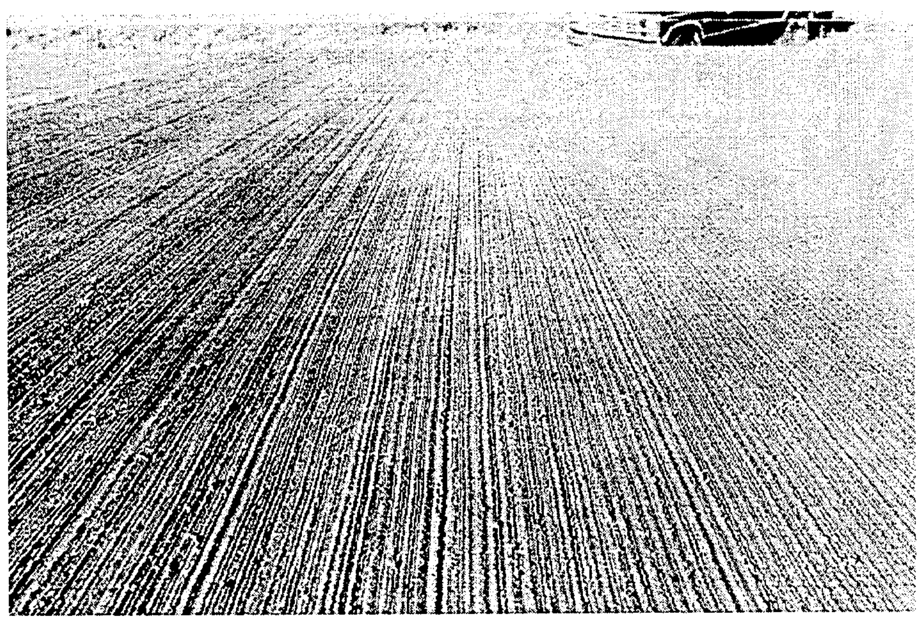


Photo 9: Close-up of transverse astro-turf texture

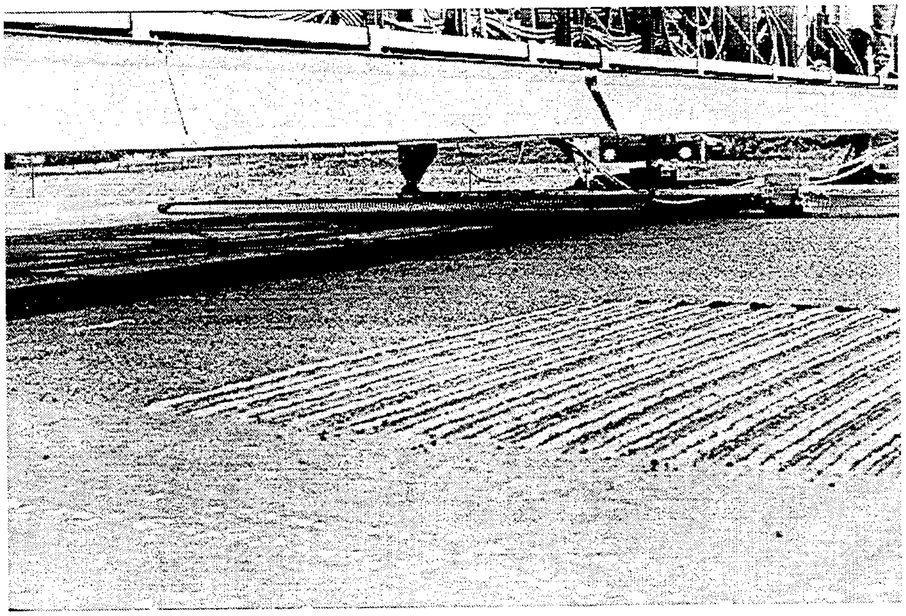


Photo 10: Typical transverse tining operation

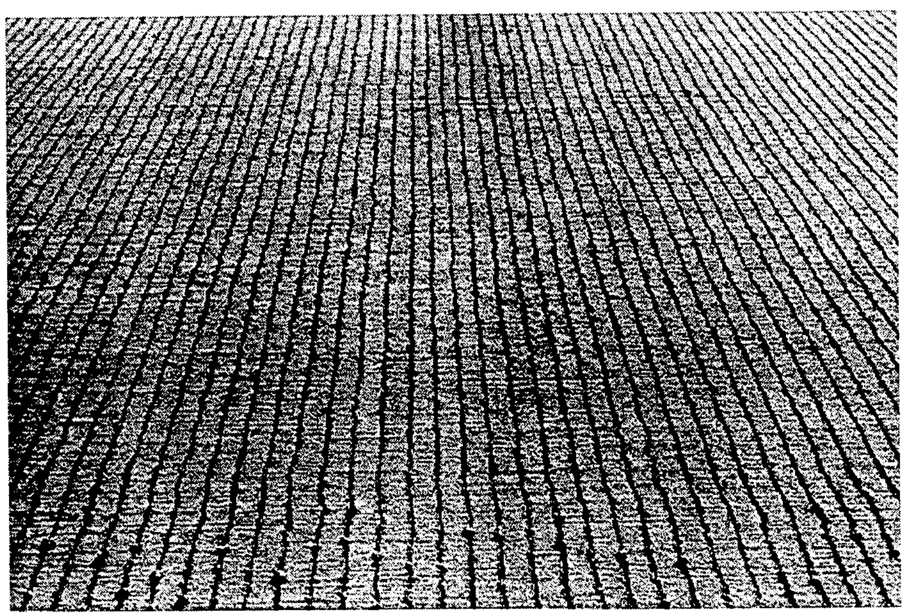


Photo 11: 1-inch uniform spaced transverse tining (state standard)

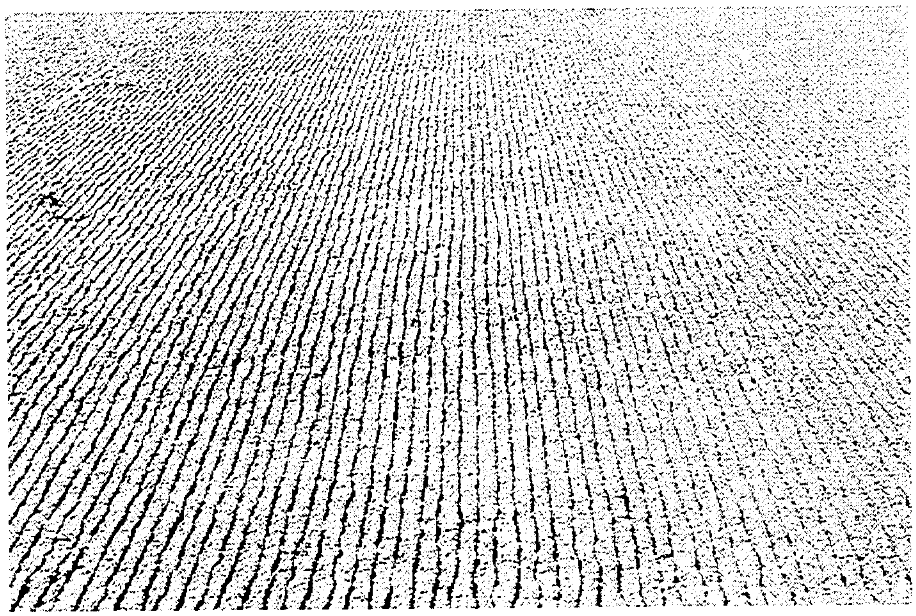


Photo 12: 1/2-inch uniform spaced transverse tining

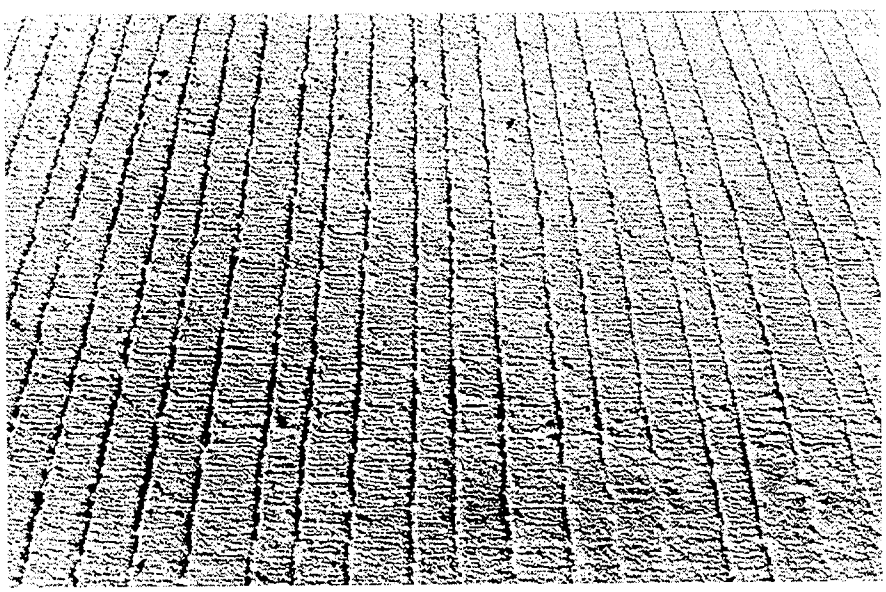


Photo 13: Random transverse tining with 5/8", 7/8", and 3/4" spacing

A self-propelled sawing machine (CUSHIN CUT, HG-130) was used to install the longitudinal grooves with uniform spacing of 3/4 of an inch (Photograph 14). The grooving machine was equipped with 46 blades, 14 inches in diameter each, and had a total effective cutting width of 34-1/2 inches. The machine, which had an approximate cutting rate of 1000 linear feet per hour, required 12 passes to groove the entire test section. Photograph 15 shows a close-up view of the longitudinal grooving. The rumble strips on both the left and the right shoulders were also grooved. Photograph 16 shows a grooved rumble strip on the right shoulder.

A self-propelled Transverse Bridge Deck Groover (TBDG) was used to install the transverse grooves with random spacing of 5/8, 7/8, and 3/4 of an inch, as shown in Photograph 17. The transverse grooving machine was equipped with a moving head, with 38 blades, 14 inches in diameter each, and with a total effective cutting width of 29 inches. A close-up view of the transverse grooving is shown in Photograph 18.

In general, transverse and longitudinal grooving appeared orderly, and aesthetically more pleasing than transverse and longitudinal tining. However, the extra costs associated with these types of texturing may make them economically undesirable. Nevertheless, the longer life that can be achieved with grooved textures may offset their extra initial costs.

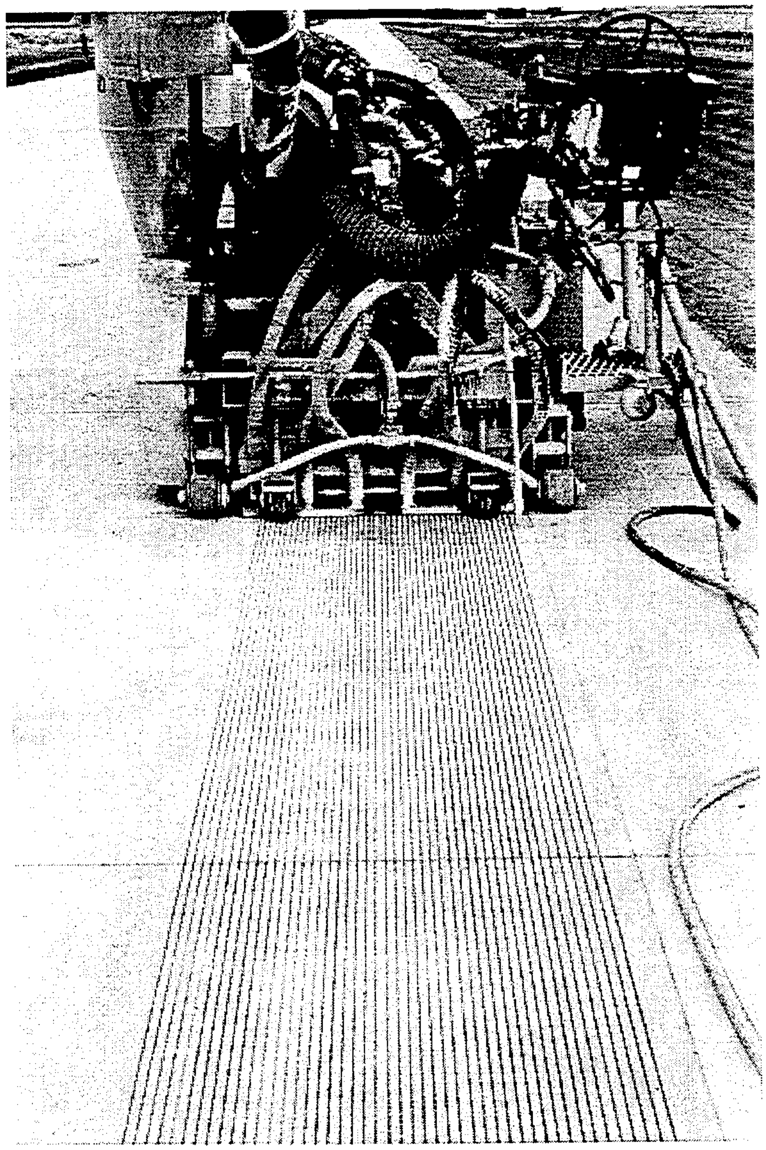


Photo 14: Installation of the longitudinal grooves

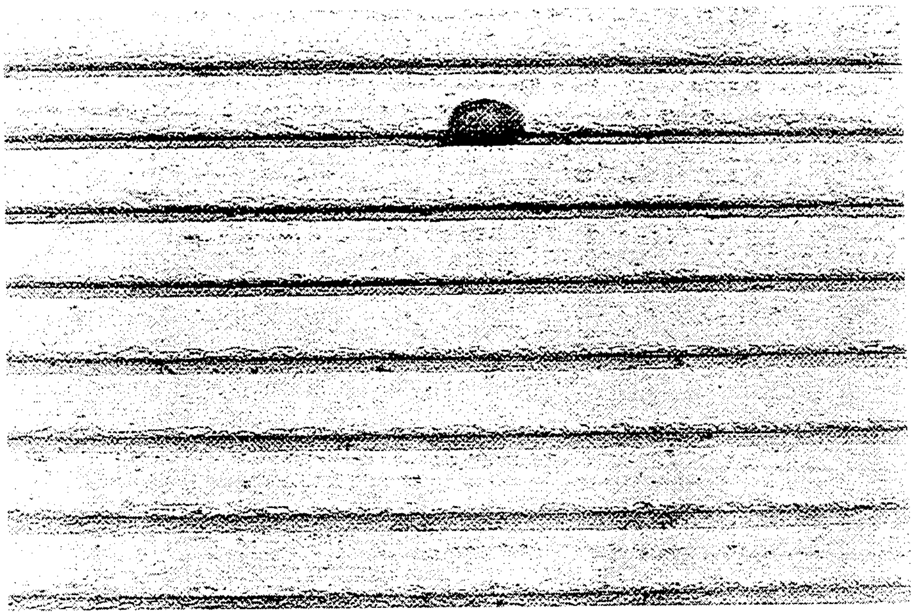


Photo 15: Close up view of longitudinal grooves

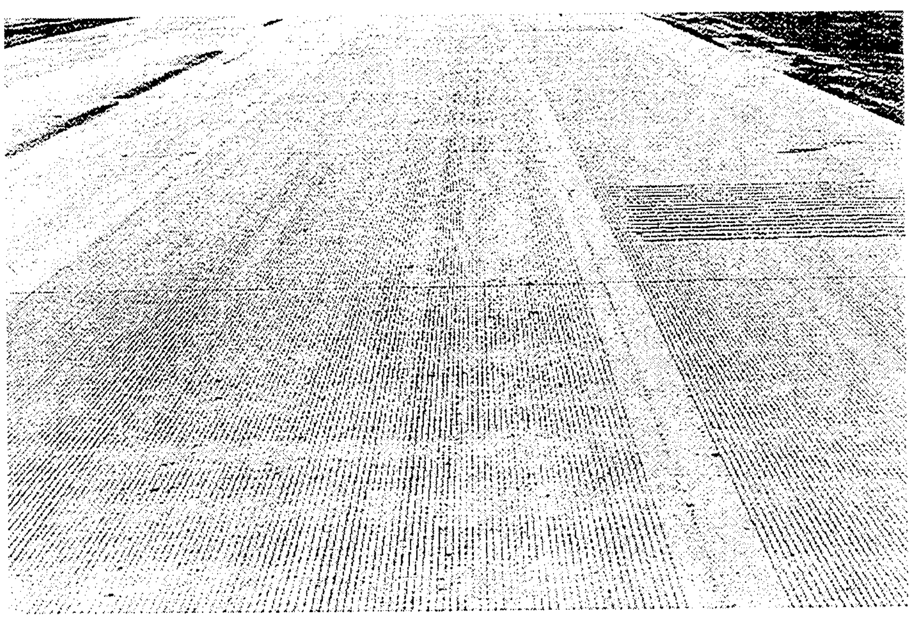


Photo 16: Grooved rumble strip in the right shoulder

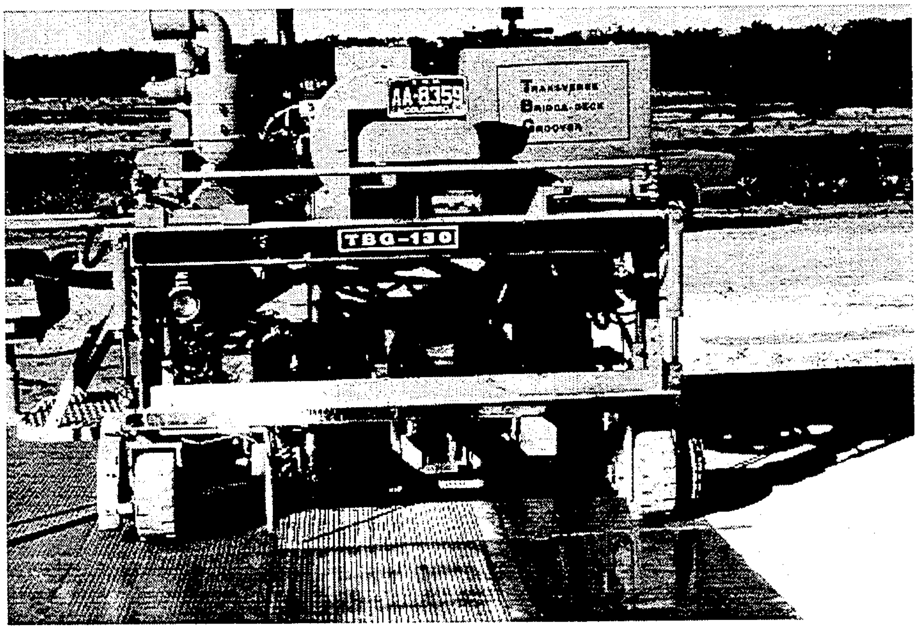


Photo 17: Installation of transverse grooves

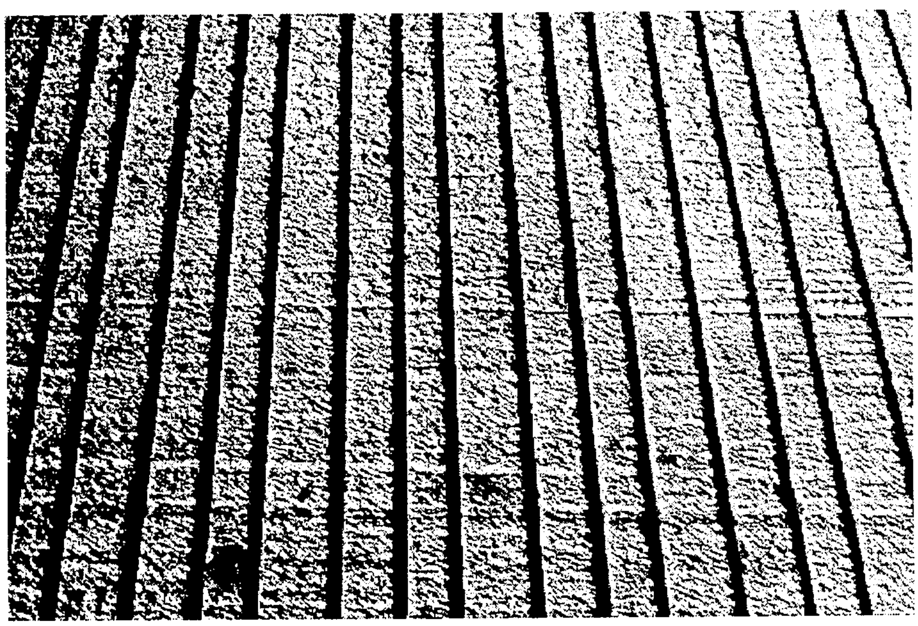


Photo 18: Close-up view of random transverse grooves with 5/8", 7/8", and 3/4" spacing

5.0 DATA ACQUISTION AND ANALYSIS

5.1 Frictional Data

To evaluate the frictional characteristics of individual test sections, skid numbers were acquired according to ASTM skid testing procedure E 274. This procedure measures the locked-wheel frictional forces between a tire of standardized design, size, and inflation pressure, and the wetted road surface at a constant speed of 40 miles per hour (7). Skid number is determined from the force required to slide the locked test tire at a stated speed, divided by the effective wheel load and multiplied by 100 (8).

Ribbed-tire (ASTM E 501) and smooth-tire (ASTM E 524) tests were used to obtain skid numbers at 40, 50, and 65 mph for all the test sections. Five skid resistance tests were conducted for each test section, as required by the standard ASTM procedure E 274. The arithmetic averages of the skid resistance tests were then used to indicate the skid number (SN) for individual test sections at a specified speed. ASTM E 501 and ASTM E 524 skid numbers were acquired at 40, 50, and 65 mph in October of 1994, and the results were plotted in Figure 3 and Figure 4.

A glance at these figures quickly revealed a definite relationship between speed, types of surface texture, and the magnitude of skid numbers. As speed increased, the skid numbers declined. However, this relationship was clearly more pronounced and consistent using the smooth tire. Skid numbers acquired using the smooth tire clearly showed a distinct difference in magnitude for surfaces with macrotexture and microtexture. For example, the smooth tire showed significantly lower skid numbers for test sections 2 and 8, which received only transverse and longitudinal astro-turf (microtexture), and showed higher skid numbers for the rest of the test sections with macrotexture surfaces.

The difference in skid numbers for microtexture and macrotexture were not as evident or consistent using the ribbed tire. This phenomenon confirms the findings of many research papers, revealing the insensitivity of the ribbed-tire towards macrotexture. The primary reason for the

RIBBED-TIRE SKID NUMBERS OCTOBER 1994

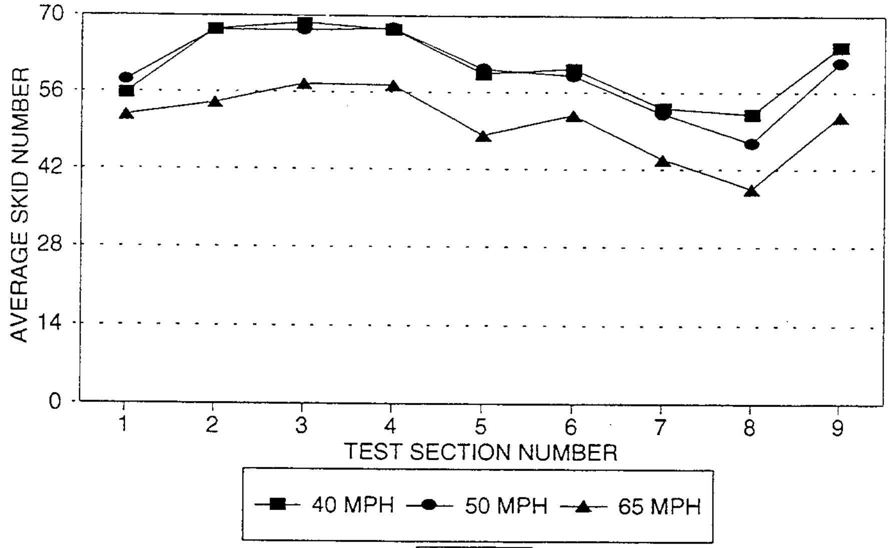


Figure 3

SMOOTH-TIRE SKID NUMBERS OCTOBER 1994

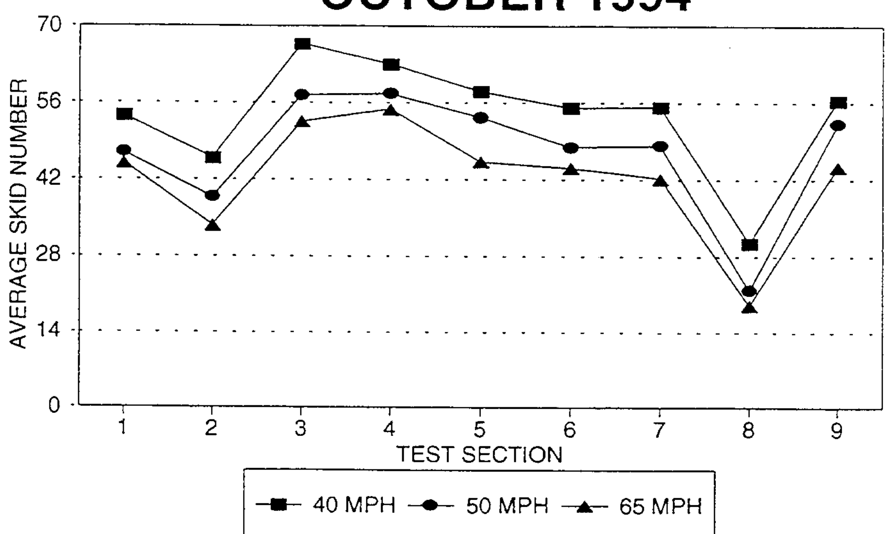


Figure 4

ribbed tire's insensitivity to macrotexture is its deep grooves, which provide drainage for water and somewhat ignore the drainage capability of the sawed or tined surfaces.

Figure 5 through 8 show the ribbed and smooth-tire skid numbers at 40 and 65 mph for years 1994 through 1999. The skid numbers taken in 1995 showed appreciable decline in magnitude in comparison with the skid numbers taken in 1994. For example, skid numbers taken with ribbed tire at 40 mph (SN40R) in 1995 were an average of seven points lower than those taken in 1994. The SN40R for test sections number 2 (textured with astro-turf in the longitudinal direction) showed the highest drop in magnitude, approximately 15 points.

It should be noted however, that even though the 1995 SN40R were much lower than the 1994 SN40R, they were still much higher than the skid number of 35, which is being used by many states as their minimum acceptable limit. The drop in the magnitude of 1995 skid numbers taken with smooth tire at 40 mph (SN40S) was even more pronounced. The 1995 SN40S were an average of 11 points lower than their corresponding 1994 SN40S. As before, test section 2 showed the highest drop, approximately 24 points.

Skid numbers kept declining during 1996; However, the rate of drop in skid numbers magnitude from 1995 to 1996 was significantly lower than the rate of drop in skid numbers from 1994 to 1995. For example, skid numbers taken with ribbed tire at 40 mph were an average of seven points lower than those taken in 1994. The average drop in skid numbers magnitude from 1995 to 1996 measured to be less than 1 point (0.77 to be exact). All the test sections including the microtexture test sections (sections 2 and 8) showed more than adequate skid numbers (SN40R = 49.9).

The rate of reduction in skid numbers for the smooth tire were also minimal. The drop in the skid numbers magnitude from 1995 to 1996 averaged less than 1 point (.80 to be exact), while the rate of drop from 1994 to 1995 averaged 11 points. As before, the two microtexture test sections (test sections 2 and 8) showed very low skid numbers, SN40S = 20.6 and SN40S = 20.4

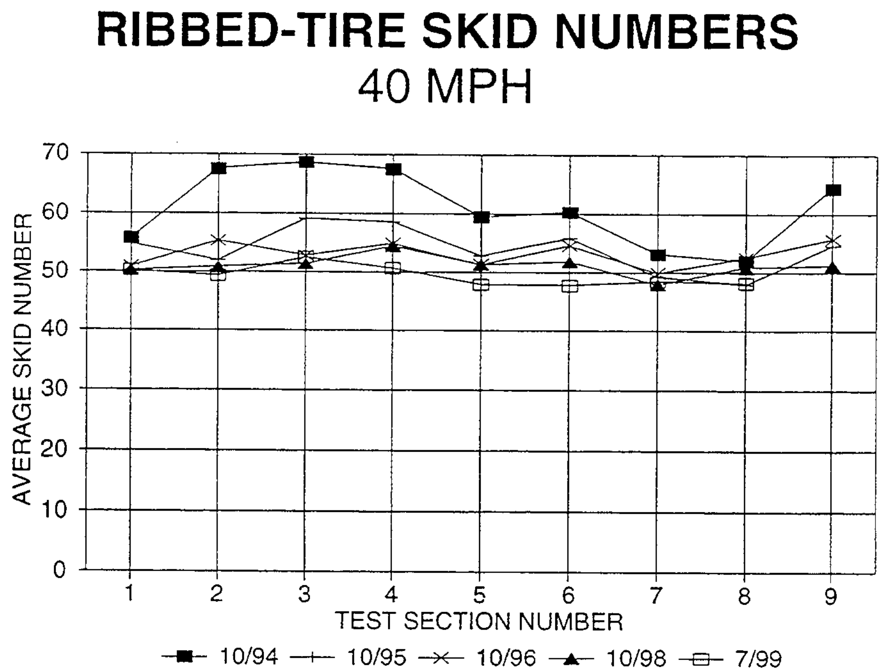


Figure 5

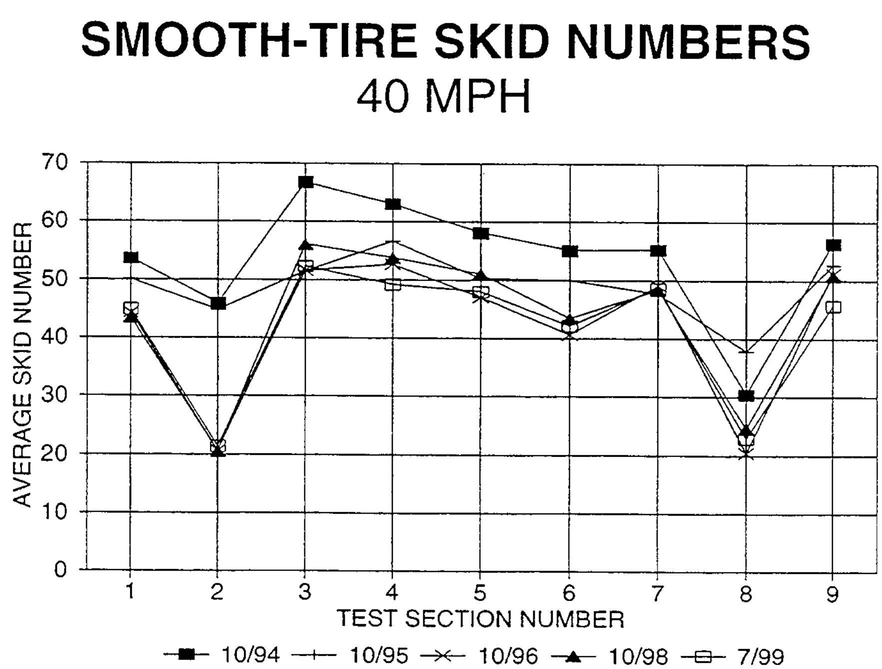


Figure 6

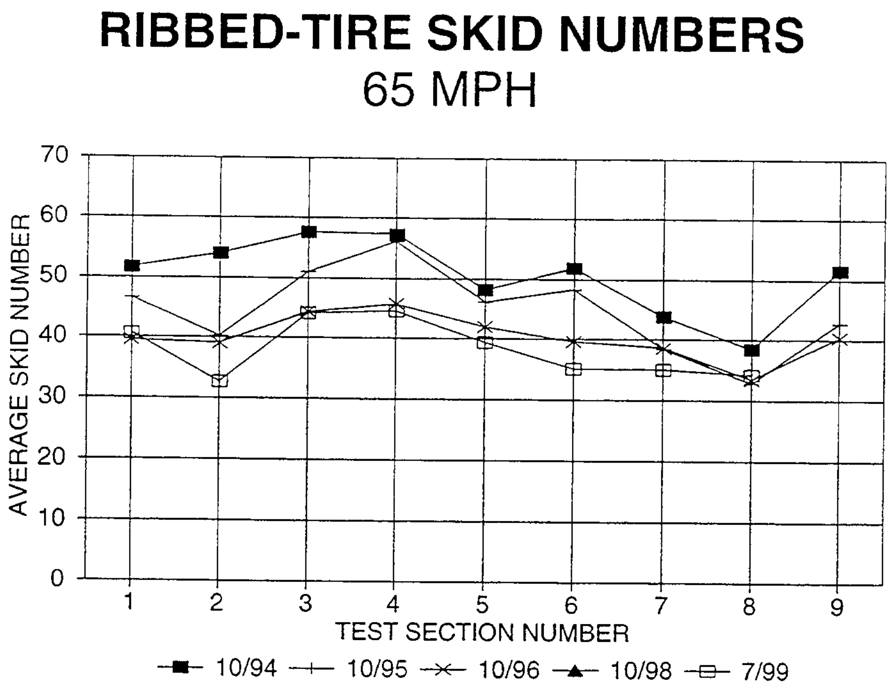


Figure 7

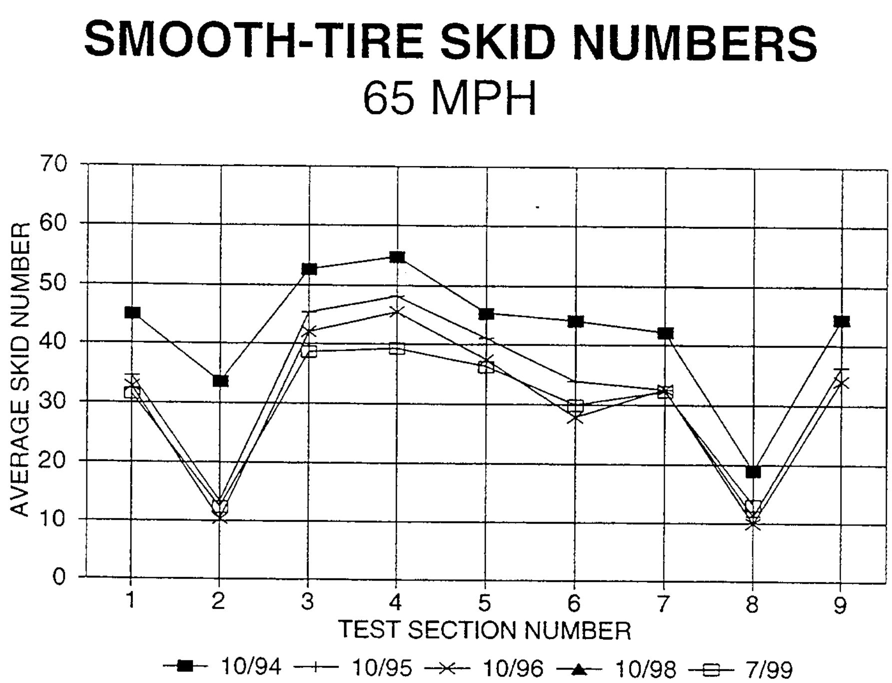


Figure 8

respectively. Overall, the skid numbers showed no appreciable change in magnitude after 1995 through 1999. For complete view of skid numbers at different speeds refer to Appendix A.

The smooth-tire and the ribbed-tire speed gradient for the individual test sections are shown in Figure 9. As shown in Figure 9, the relationship between the skid numbers and the speed appeared to be approximately linear for the smooth tire. However, this relationship was not as linear for most of the test sections using the ribbed tire. The speed gradient variations between 40 and 50 mph were minimal and inconsistent using the ribbed tire. On the other hand, all the test sections tested with the smooth tire showed a consistent drop in gradients as the speed increased.

In general, the smooth-tire gradients were steeper than their corresponding ribbed tire gradients. For more analysis on the relationship between the variables refer to scatter charts in Appendix A.

5.2 Texture Measurement

Several different types of texture measuring devices were utilized to measure the amount of texture in each of the test sections. The following is the summary of the data acquired and the description of the equipment used. Equipment descriptions were provided by the FHWA, Pavement Division (9).

5.2.1 Texture Van (Laser Van)

The texture van equipment (Photograph 19) can measure texture at travel speeds and does not interfere with normal traffic. It uses a television camera to take snapshots of a small pavement section in the wheel track (about 4 inches long). It takes a pre-selected number of exposures spaced about 50 feet apart at 50 miles per hour. To assure image sharpness the exposure time is given by a strobe light, and an infrared sensor assures that the field of view is in focus. A slit mask forms the images over the lens, giving two profile edges at every exposure.

An rms (root mean square) value is computed for each of the two profiles. The final output is an average rms value for the test section. Figure 10 compares the average rms values for the

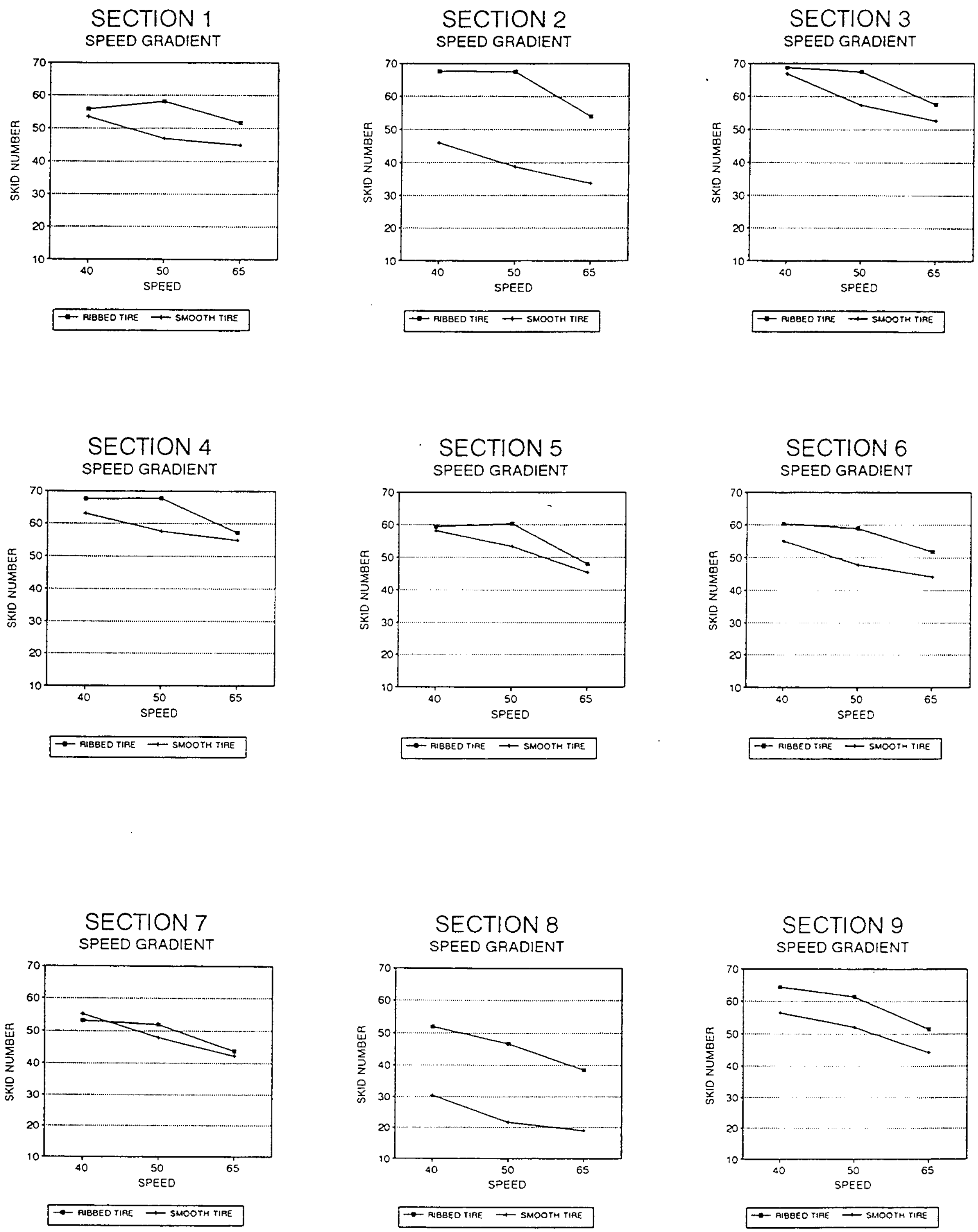

SECTION 1
SPEED GRADIENT
SECTION 2
SPEED GRADIENT
SECTION 3
SPEED GRADIENT
SECTION 4
SPEED GRADIENT
SECTION 5
SPEED GRADIENT
SECTION 6
SPEED GRADIENT
SECTION 7
SPEED GRADIENT
SECTION 8
SPEED GRADIENT
SECTION 9
SPEED GRADIENT
SKID NUMBER
10
20
30
40
50
60
70
SPEED
40
50
65
RIBBED TIRE
SMOOTH TIRE

Figure 9

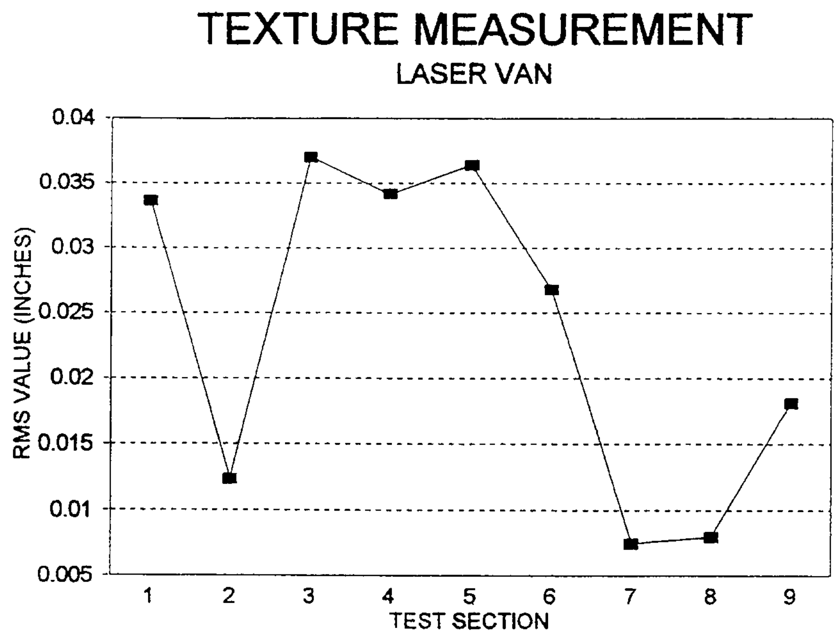


Figure 10

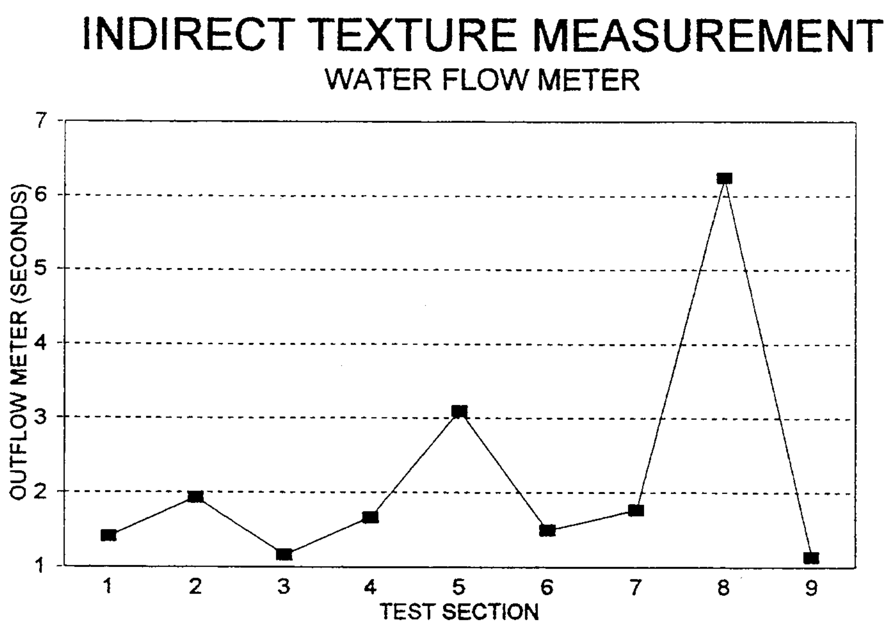


Figure 11

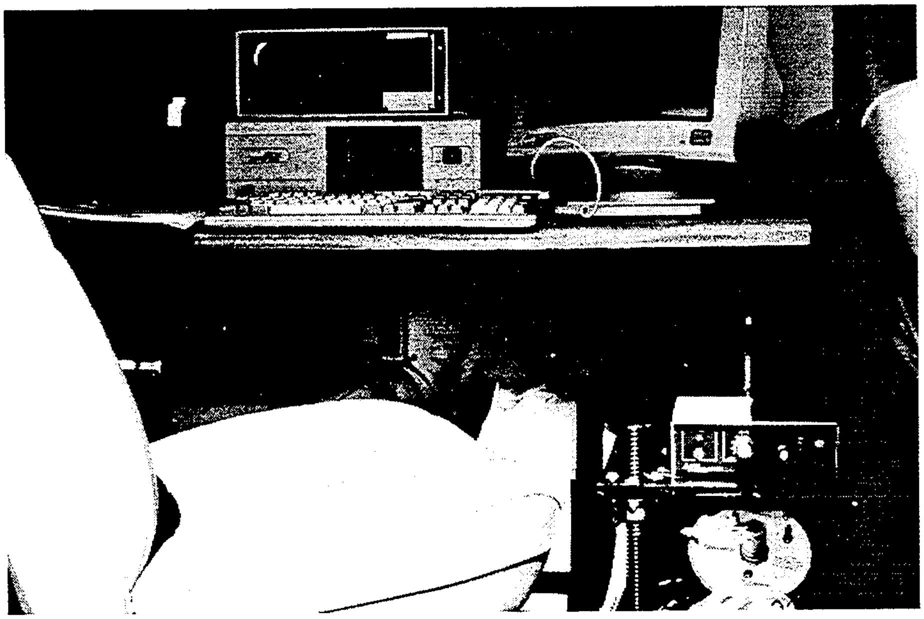


Photo 19: Inside of a texture measuring van

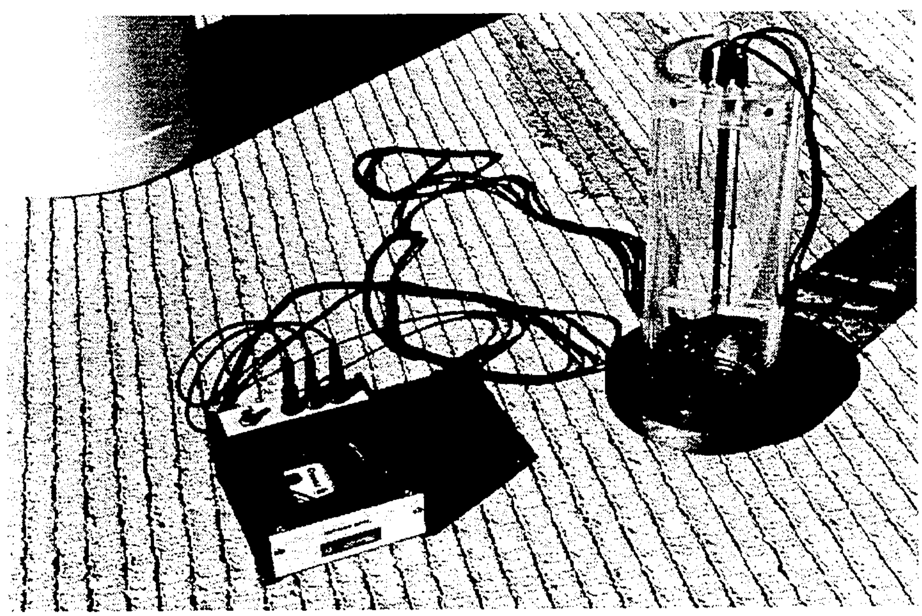


Photo 20: View of an outflow meter

individual test sections. As expected, the texture van showed lower values for sections 2 and 8 with microtexture; however, it also showed low values for longitudinal sawing (test section 7) and for longitudinal tining (test section 9). This may indicate that the laser van is more sensitive to the transverse texture than to the longitudinal texture. It should also be noted that, of the two microtextures (section 2 and 8), section 2 with the transverse orientation showed higher rms values.

5.2.2 Outflow Meter

This is an indirect measure of texture (Photograph 20). A cylinder with rubber seals on its lower end is placed on the surface and loaded by weights to assure good contact. An electric timer is connected to probes inside the cylinder. The cylinder is filled with water. To start the test, the plunger sealing of the outlet is lifted and the water escapes between the rubber seals and the pavement surface. The time for the water to escape is a measure of texture. Deep textured surfaces will allow fast escape of water; i.e. the outflow time for deep textured surfaces is shorter than the outflow time for shallow textured surfaces.

Figure 11 shows the rate of the dissipation of water in seconds for all the test sections. Section 8 with longitudinal astro-turf (microtexture) took the longest to dissipate the water. The fastest draining texture appeared to be test section 9 (longitudinal tining) and test 3 (random transverse tining). In general, the time of water dissipation was less than 2 seconds for most of the test sections.

5.2.3 Texture Beam

The texture beam shown on photograph 21 is capable of tracing texture over a straight line up to two feet long. A motor driven carriage carries two texture sensors. One is a mechanical stylus. The vertical motion is transmitted to an LVDT (Linear Variable Differential Transformer) and the output is recorded via a digitizing board on a computer.

The second sensor is a commercial laser stylus with its power supply and signal processor. The output is treated the same way as the LVDT output. The resulting texture traces can be displayed and processed. An rms value (similar to the texture van) can be computed. The profile can also be processed to display a texture spectrum. Figures 12 and 13 show the average rms values for both the LVDT and the commercial laser stylus. The only questionable rms value detected was for test section 1 (state standard, macrotexture with 1" transverse tining), for which measurements were lower than for the rms values of test section 2 and 8 with microtexture.

5.2.4 Sand patch Method

This method is a volumetric measurement using the ASTM procedure E-965. A given amount of fine sand or glass beads particles (1.5 cubic inches) is poured over a selected spot on the pavement surface. The particles are then spread carefully in a circular pattern until all of them are below the texture peaks. Photograph 22 illustrates texture depth measurement using the sand patch test method. The covered area is estimated by measuring and averaging several diameters. The sand patch texture depth is given by dividing the known volume of glass beads or sand by the estimated area. TD (texture depth) = volume/area.

The results of the sand patch test appeared to be more consistent and realistic than the previously described methods. As shown in figure 14, the two microtexture test sections (test sections 2 and 8) showed lower texture depth than the macrotexture test sections. The average TD for sections 2 and 8 measured to be 0.03 and 0.02 inches respectively, while the average TD of the macrotexture test sections measured from a low of 0.036 inches for section 1 (state standard) to a high of 0.048 inches for section 9 (longitudinal tining).

The sand patch texture depth results correlated favorably with the smooth-tire skid numbers, indicating a linear relationship between the two methods with a correlation factor of r = 0.88. The similarity between the orientation of Figure 4 and Figure 14 further illustrates a good correlation between these two methods.

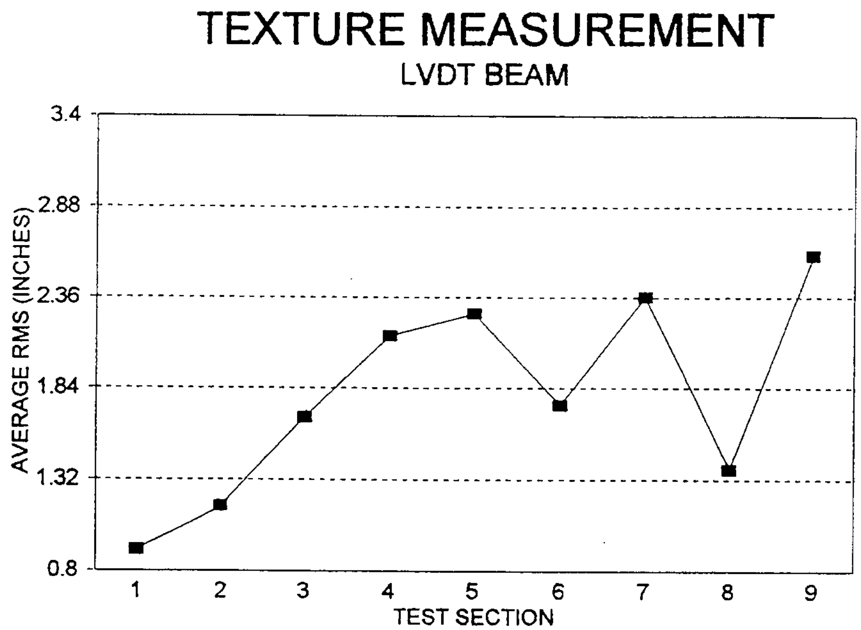


Figure 12

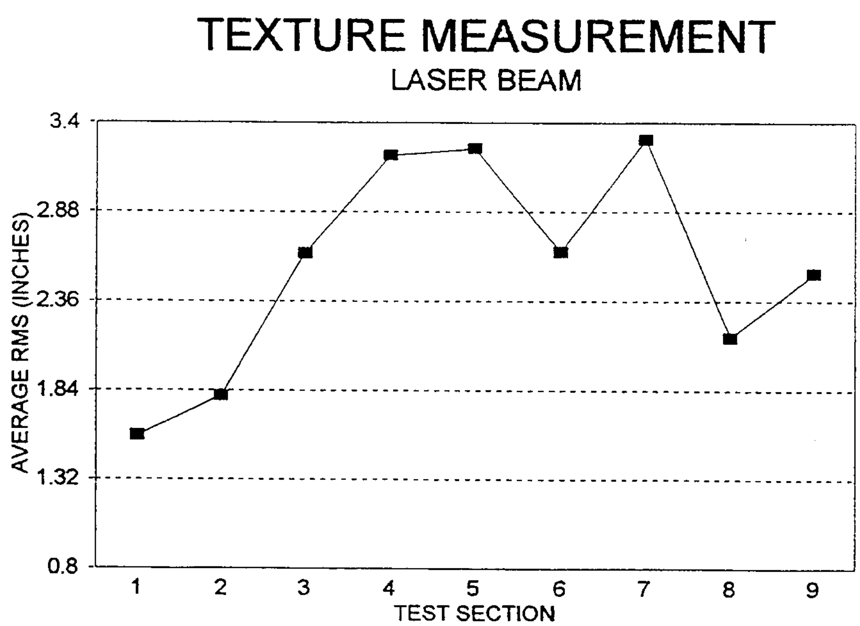


Figure 13

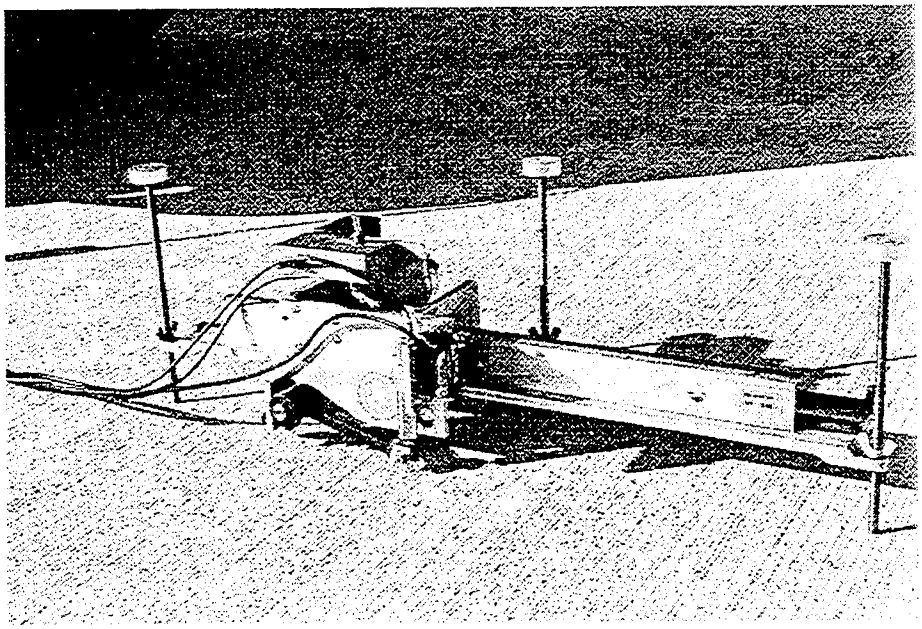


Photo 21: Texture beam, equipped with an LVDT and a laser stylus

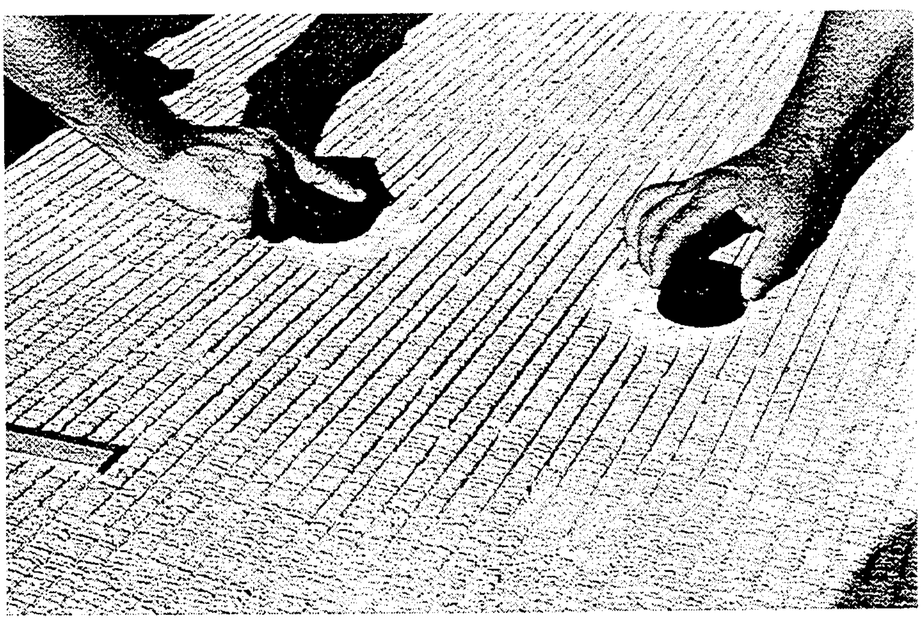


Photo 22: Sand patch test for measuring texture depth

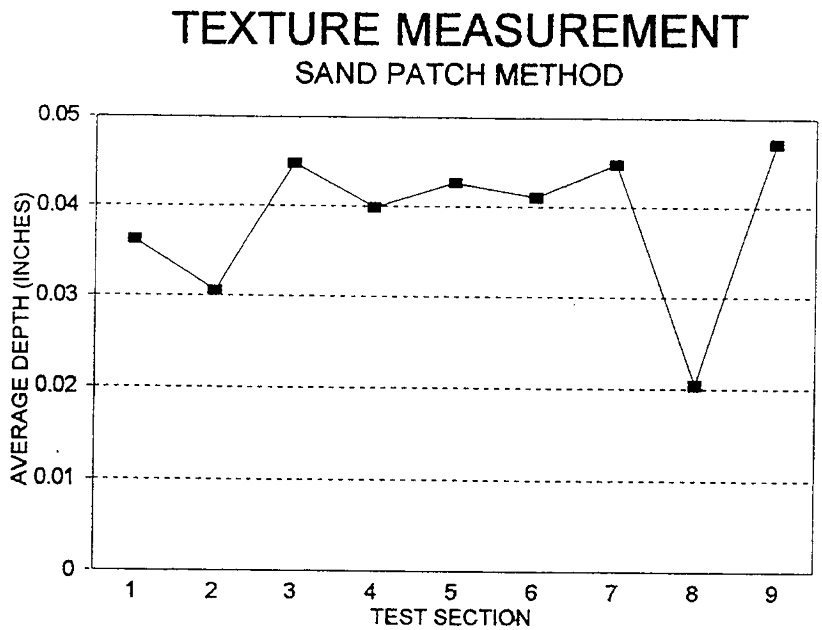


Figure 14

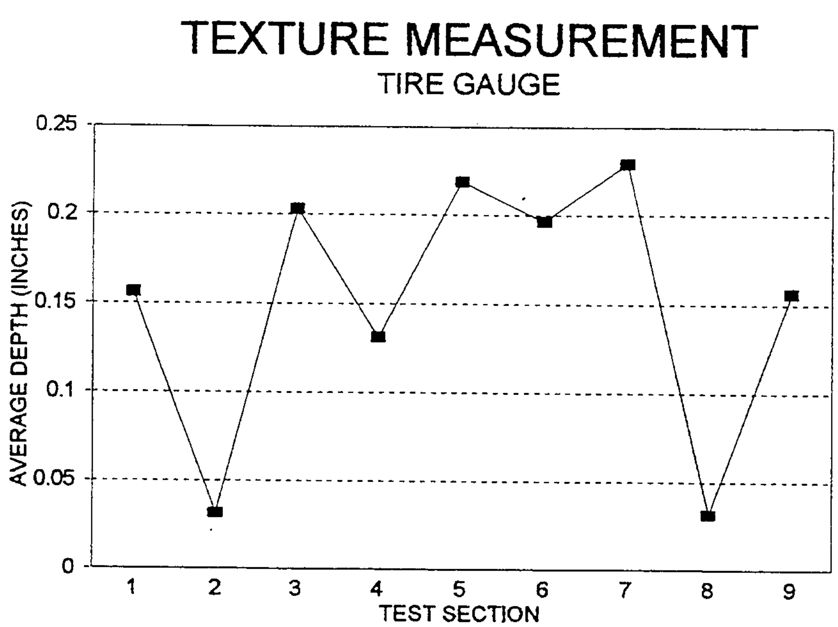


Figure 15

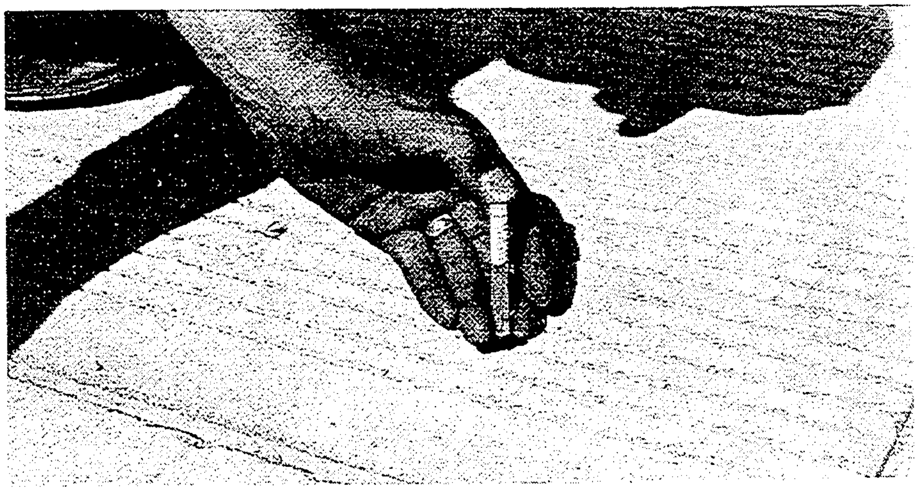


Photo 23: Texture depth measurement using a tire tread depth gauge

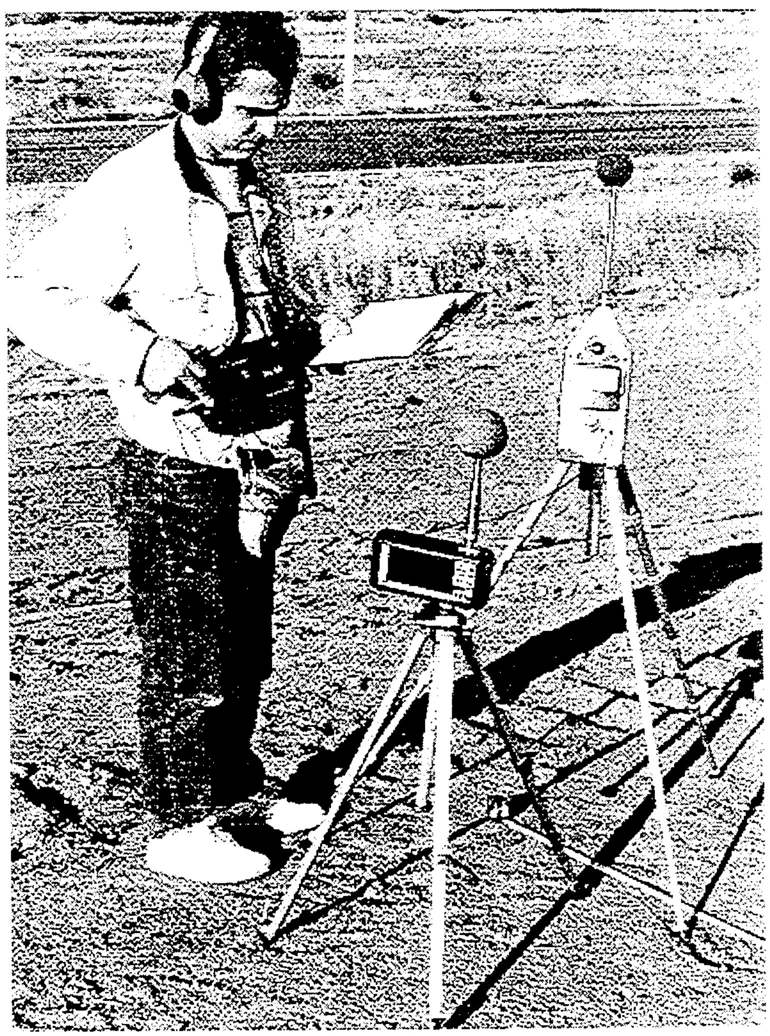


Photo 24: SPL measurement at the roadside

5.2.5 Tire Gauge

A tire tread depth gauge with an accuracy of 1/32 of an inch was also used to measure texture depth (Photograph 23). Five texture depth measurements were taken and averaged at the same spot that the sand patch tests were taken. The results of the tire gauge measurements are shown in Figure 15. These measurements appeared to have a linear relationship with those of the sand patch tests with a correlation factor of $r = 0.89$. For an in-depth look at the test results and the relationships between various variables refer to scatter charts in Appendix A.

5.3 Noise Measurement

Noise measurements were acquired as a joint effort between the CDOT's Research Branch and a local noise consultant, David L. Adams Associates, INC. The primary purpose of the measurements was to acoustically assess the impact of various surface textures installed in the test sections.

The test vehicle used was a 1994 Oldsmobile Cutlass station wagon provided by CDOT. Sound pressure level (SPL) measurements were recorded through a sound level meter to a digital tape recorder. The data extracted from the recordings were A-weighted sound levels, as well as 1/3-octave SPL with frequencies between 100 and 5000 Hz. The description of the equipment used in the assessment was as follows:

Equipment	Manufacturer	Model No.
Impulse Precision Sound Level Meter	Bruel & Kjaer	2209
Strip Chart Recorder Level	Bruel & Kjaer	2306
Digital Audio Recorder	Panasonic	SV-250

Noise data were acquired in the following three conditions:

1. SPL measurements were acquired at 25 feet from the centerline of the test sections. The microphone was placed on a tripod just beyond the shoulder of the road at a height of 4.5

feet (Photograph 24). The Oldsmobile station wagon was traveling in the driving lane at a speed of 65 miles per hour. In an effort to minimize the impact of engine noise, the station wagon coasted out of gear while passing the measurement station.

However, it should be noted that measurements taken with the engine on and with the engine off produced the same SPL, indicating that the tire noise was predominately louder than the engine noise. Figure 16 compares the change in SPL measurements of all the test sections relative to control section (state standard) at the shoulder. The sound generated at the control section was normalized to represent a datum (zero sound level pressure). Except for test section 3 (random transverse tining), all the other test sections showed lower decibels (dB) than the control section. Section 8 showed the lowest sound level pressure (6 dB lower than control).

The following table (reference 10) shows an approximation of human sensitivity to changes in sound level.

Change in Sound Level (dB)	Change in Apparent Loudness
1	Imperceptible
3	Just barely perceptible
6	Clearly noticeable
10	About twice (or half) as loud
20	About 4 times (or one-forth) as loud

2. SPL measurements were acquired inside the test vehicle with the microphone positioned at ear height at the center of the front seat. These SPL measurements, which were taken at the coasting speed of 65 mph, represent the average SPL measurements over individual test sections.

Figure 17 compares the change in SPL measurements of all the test sections relative to the control section (state standard) at the driver's ear height. The sound generated at the control section was normalized to represent a datum (zero sound pressure level). As shown in Figure 13, the SPL measurements for all the test sections showed lower dB or the same dB levels as the control section. However, the lowest SPL measured was only 2 dB lower than the control section.

3. A mounting bracket was constructed and installed to allow SPL measurements to be taken near the right rear tire away from the exhaust pipe (Photograph 25). Figure 18 compares the change in SPL measurements for all the test sections relative to the control section (state standard) at the rear tire. As previously mentioned, the sound generated at the control section was normalized to represent a datum (zero SPL).

All the test sections showed lower sound levels than the control section as shown in Figure 18. Section 7 and 8 showed the lowest dB, 5 1/2 dB lower than the control section. It should be noted that for all the conditions mentioned above, 3 sets of data were acquired and then averaged. Figure 19 compares the A-weighted SPL measurements of all the three conditions. As expected, the SPL measurements taken near the rear tire and inside the test vehicle showed the highest and lowest dB respectively.

The three Figures in Appendix B show the SPL frequency distribution for all the test sections in all three conditions. The data are presented in a 1/3 octave band format. According to Chalupnik and Anderson (11) (12), noise components in the mid to upper frequencies between 1,000 Hz to 4,000 Hz are more annoying than the lower frequencies. These figures show that SPL generated in the control section (near tire and at the roadside) was higher than the other sections at the 1,000 - 1250 frequencies. The lowest SPL generated at the same frequencies was at sections 8 (longitudinal astro-turf, no tining) followed by section 7 (longitudinal sawing).

Figure 20 compares SPL Frequency distribution of a semi-truck with the test vehicle in a 1/3-octave band format (100 – 5000 Hz), as well as A-weighted SPL at the roadside. As can be

SPL AT THE SHOULDER
COMPARED TO STATE STANDARD SECTION

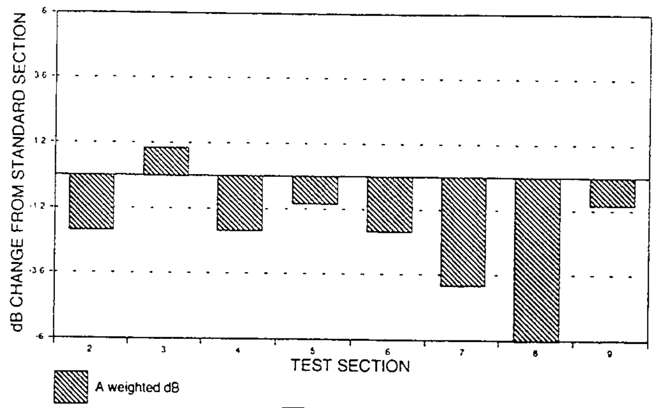


Figure 16

SPL INSIDE TEST VEHICLE
COMPARED TO STATE STANDARD SECTION

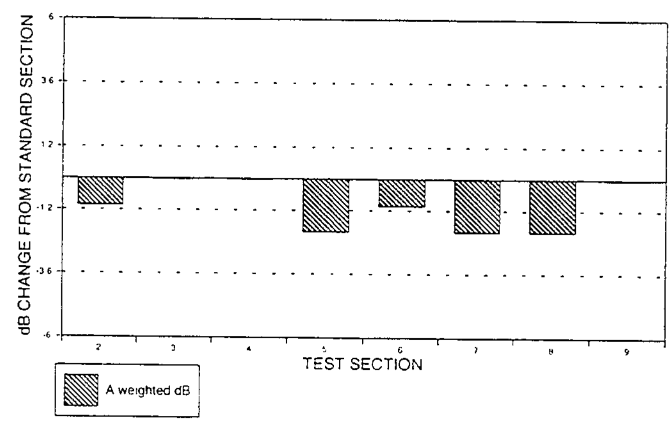


Figure 17

SPL AT REAR TIRE
COMPARED TO STATE STANDARD SECTION

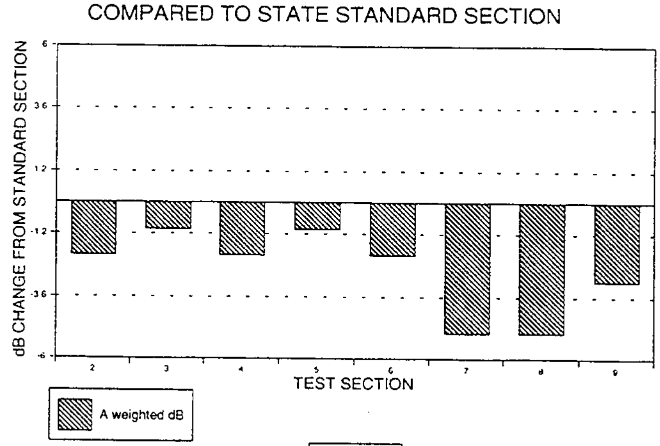


Figure 18

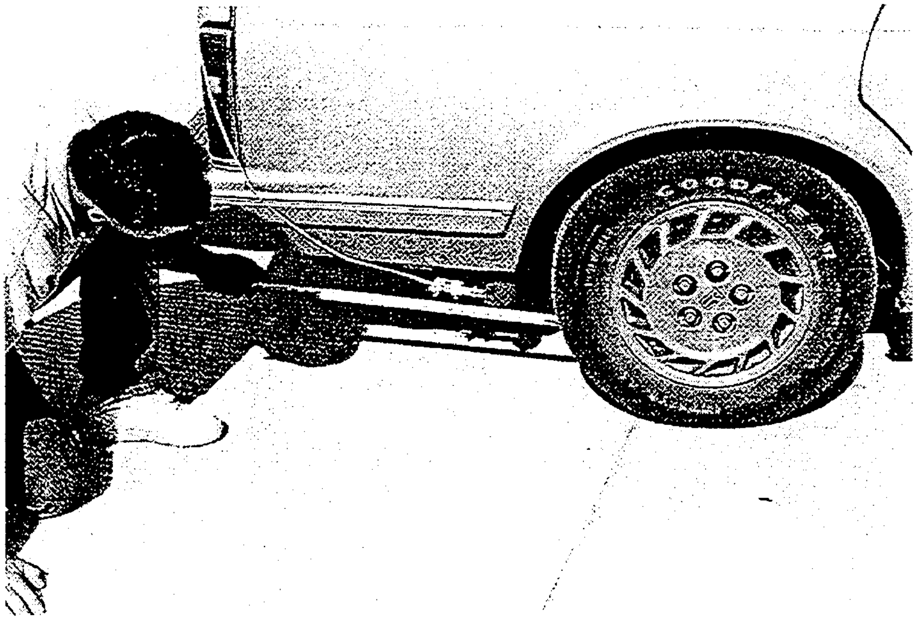


Photo 25: View of the microphone behind the rear tire

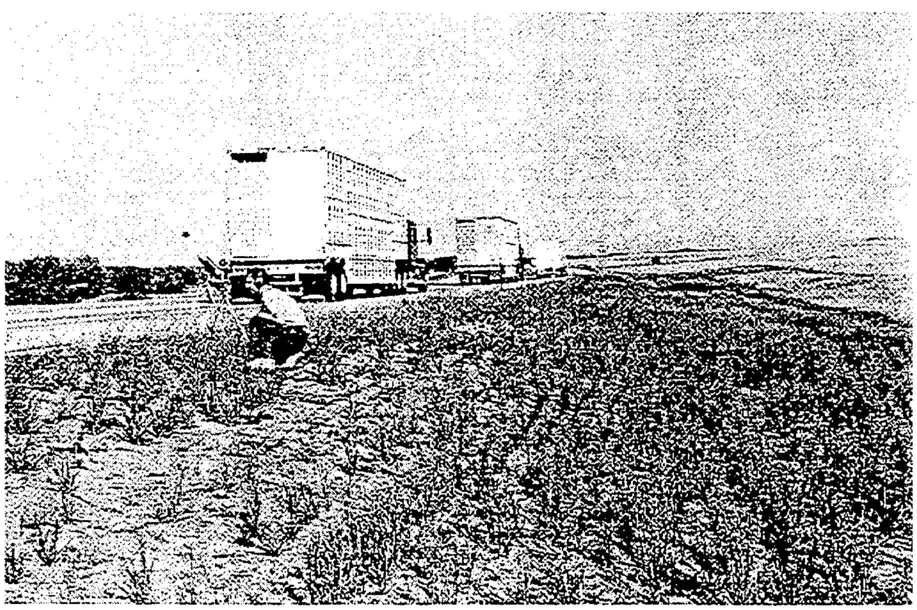


Photo 26: Acquiring truck noise levels at the roadside

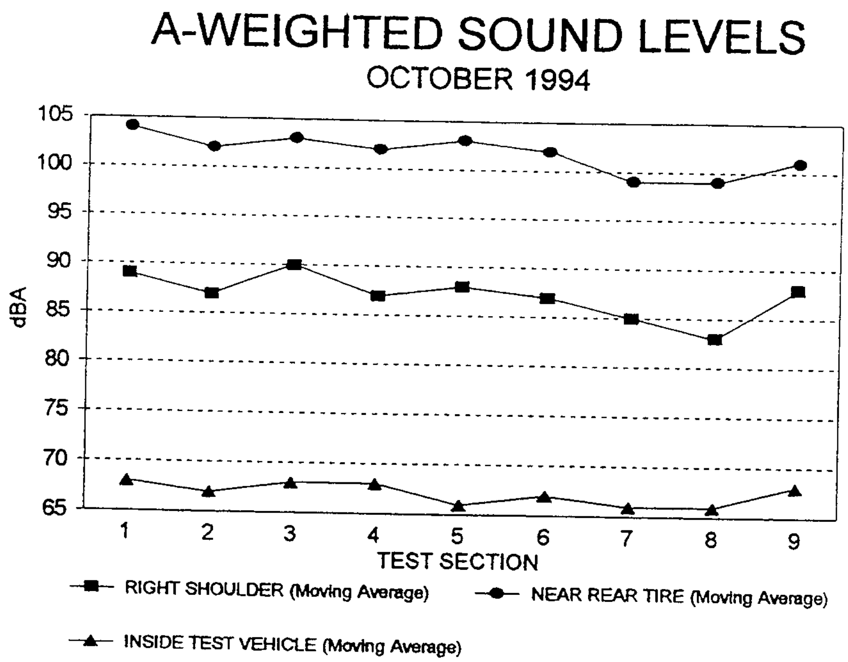


Figure 19

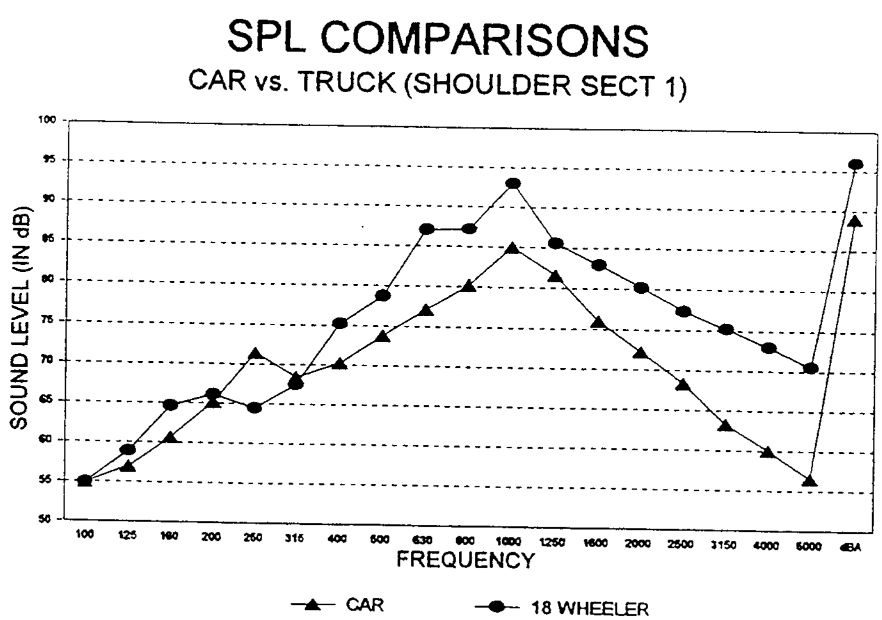


Figure 20

seen in this figure, the SPL for both the truck and the test vehicle peaked at 1000 Hz. However, the figure shows the noise from the truck (Photograph 26) to be at the higher annoyance range (by about 8 dB) than the noise from the test vehicle. The A-weighted dB for the truck was also 7 dB higher than the A- weighted dB of the test vehicle.

5.4 Roughness Data

Figure 21 compares the average right- and left-wheel-path roughness data for all the test sections. Test section 6, which was textured using a combination of longitudinal astro-turf and 1-inch uniform tining, exhibited the highest roughness. It should be noted that dynamic effects that act on suspension systems and generate vibrations inside vehicles are primarily due to megatexture or small-scale roughness (explained below). The influence of surface texture on ride quality, with the exception of noise level, is minimal.

The Technical Committee Report on Surface Characteristics in Belgium (13), defines the various surface irregularities based on their wavelengths as follows:

Wavelength < 0.5 mm	Microtexture
Wavelength 0.5 mm - 50 mm	Macrotexture
Wavelength 50 mm - 500 mm	Megatexture
Wavelength 0.5 m - 50 m	Roughness

Based on the findings of the above mentioned report, it appears that irregularities with wavelengths greater than 50 mm and smaller than 150 mm (megatexture) have the most adverse effects on the quality of ride. Microtexture and macrotexture, with the exception of noise levels, have only beneficial effect (14).

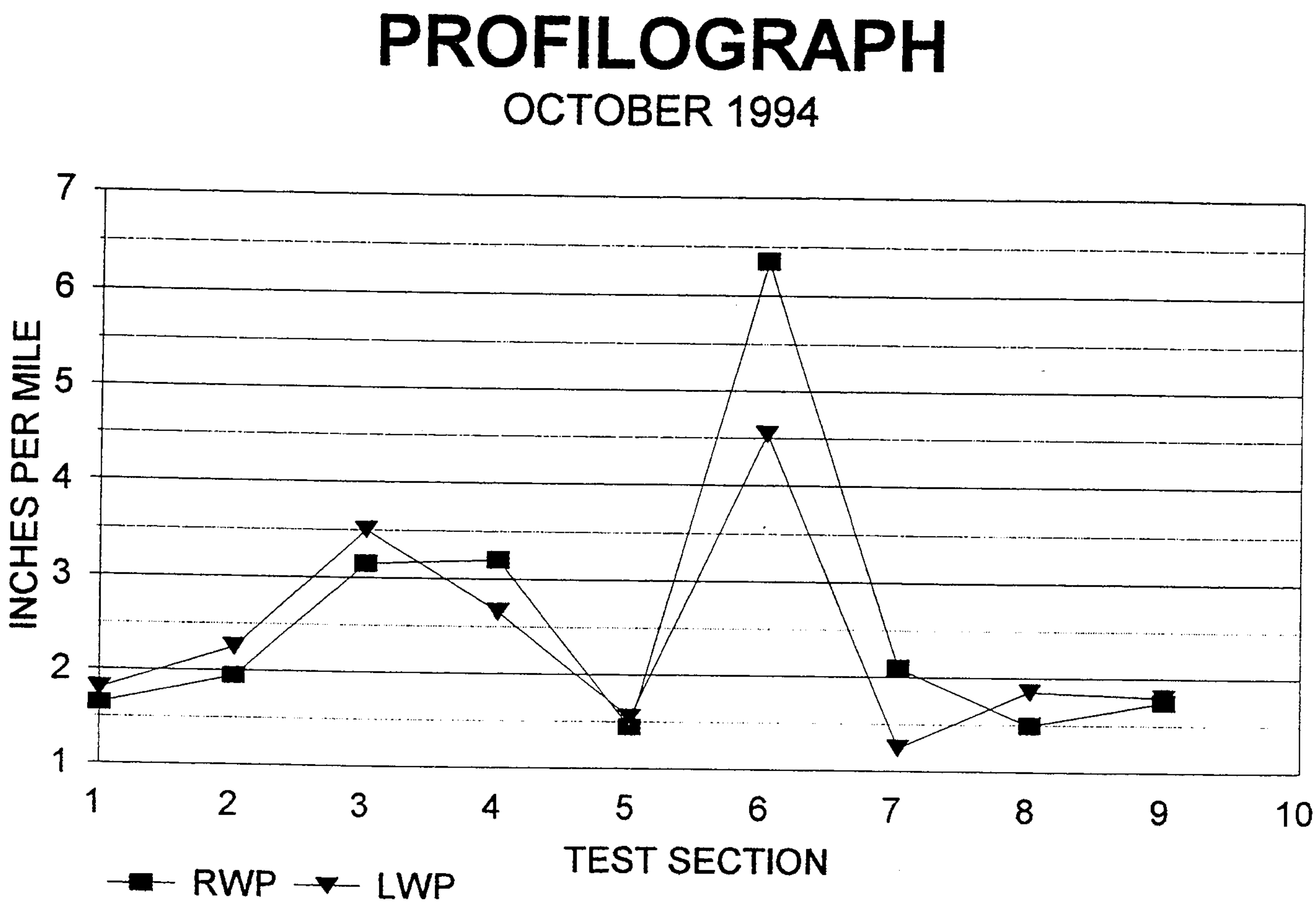

PROFILOGRAPH
OCTOBER 1994
INCHES PER MILE
1
2
3
4
5
6
7
1
2
3
4
5
6
7
8
9
10
TEST SECTION
RWP
LWP

Figure 21

6.0 CONCLUSIONS AND RECOMENDATIONS

The conclusions and recommendations presented here are based on the data that were acquired prior to opening to traffic in 1994 and the subsequent data that were acquired thereafter through 1999. The conclusions are also based in part on a national study called, "Noise and Texture on PCC Pavements." This study was sponsored by FHWA and conducted by Marquette University (15). As part of this national study, Colorado, Iowa, Michigan, Minnesota, North Dakota and Wisconsin provided 57 test sections to study the noise properties and the frictional characteristics of several different PCC textures.

6.1 Conclusions

- The PCC surface texture has a profound effect on the traffic-induced noise characteristics generated at the interface of the tire and the pavement surface. The change in PCC surface texture also has a major effect on the frictional properties.

- Texture depth taken with various texture-measuring devices correlated favorably with the smooth-tire skid numbers taken at 40, 50, and 65 mph, indicating a linear relationship with excellent correlation factors. The results were not as linear with the ribbed-tire skid numbers. For a thorough view of the scatter diagrams (relationship between various variables) refer to Appendix A.

- Section 3 (combination of longitudinal astro-turf and random transverse tining) and section 8 (longitudinal astro-turf) showed the highest and lowest skid numbers respectively, using both the ribbed and the smooth tire.

- The highest drop in skid numbers occurred between the first year and the second year. The change in the magnitude of the skid numbers for both the smooth and the ribbed tire significantly leveled off after the second year.

- The relationship between the skid numbers and the speed appeared to be approximately linear for the smooth tire, and not as linear for the ribbed tire. In general, the smooth-tire speed gradients were steeper than the ribbed-tire speed gradients.

- Longitudinal macrotexture and microtexture were the most quiet surfaces based on the sound pressure levels (SPL) taken at the shoulder, inside the test vehicle, and at the rear tire.

- State standard section (combination of burlap drag and uniform 1" spacing) exhibited the highest noise level among all the test sections with the microphone at the rear tire position.

- SPL taken at the shoulder showed the A-weighted dB of a semi- truck to be approximately 7 dB higher than the A-weighted dB of the test vehicle.

- The influence of surface texture on ride quality is minimal.

6.2 Recommendations

- The use of smooth tire over the ribbed tire as a method of acquiring skid numbers is recommended. The smooth tire (ASTM E 524) showed more sensitivity to both microtexture and macrotexture than the corresponding ribbed tire (ASTM E 521). The primary reason for the ribbed tire's insensitivity to macrotexture is its deep grooves, which provide drainage for water and somewhat ignore the drainage capability of the sawed or tined surfaces.

- Longitudinally tinned PCC Pavements exhibit the lowest noise level and provide adequate friction. Their use is highly recommended.

- The use of the sand patch test method as a texture-depth measuring device is highly recommended. Excellent correlations were achieved using the sand patch test method and smooth-tire skid numbers (Appendix A).

- To ensure proper friction and to minimize noise, quality control for tine spacing and tine depth needs to be improved. Deeper tines generate louder sound levels.

- A research study to document the effects of various surface textures on safety in wet weather conditions is highly recommended.

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12. Chalupnik, James D., Anderson, Donald S., "Roadside Tire Noise," Washington State Department of Transportation, WA-RD 320.1, Final Report, March 1994.
13. PIARC Report of the Technical Committee on Surface Characteristics. Presented at XVIIIth World Road Congress, Brussels, Belgium, 1987.
14. Fuchs, F., "An Overview of European Practice," Belgian Road Research Center.
15. Kuemmel, D., "Noise And Texture on PCC Pavements," Marquette University, 1998.

Appendix A

Texture Measurement Averages						
Site	Laser Van (RMS in.)	Sand Patch (depth in)	Flow Meter (seconds)	Beam Laser (RMS in.)	Beam LVDT (RMS in.)	Tire Gage (in.)
1	0.034	0.036	1.403	1.575	0.919	0.156
2	0.012	0.031	1.923	1.806	1.170	0.031
3	0.037	0.045	1.158	2.639	1.673	0.203
4	0.034	0.040	1.662	3.209	2.139	0.131
5	0.036	0.043	3.093	3.252	2.267	0.219
6	0.027	0.041	1.491	2.648	1.742	0.196
7	0.007	0.045	1.763	3.303	2.360	0.229
8	0.008	0.020	6.247	2.148	1.377	0.031
9	0.018	0.047	1.133	2.519	2.603	0.156

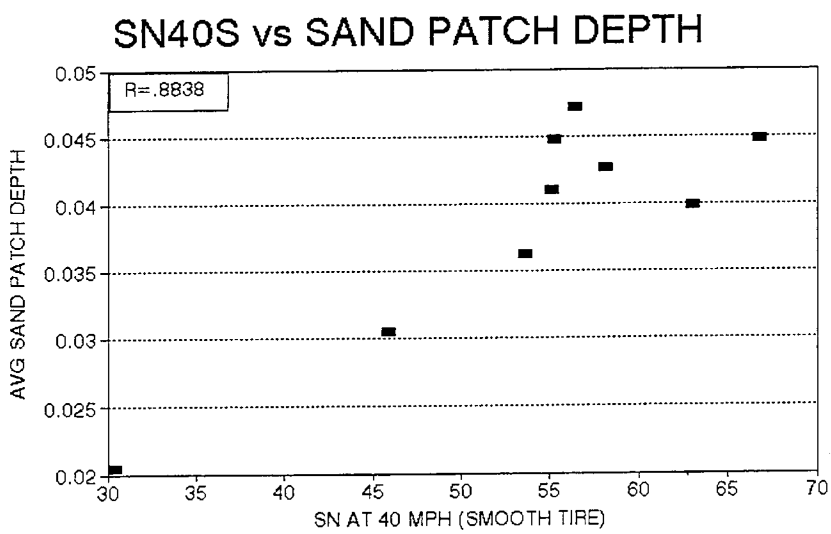
Skid Measurement Averages 1994									
	1	2	3	4	5	6	7	8	9
SN40R	55.8	67.5	68.7	67.5	59.5	60.3	53.1	52	64.4
SN50R	58.1	67.4	67.3	67.7	60.3	59	52	46.7	61.4
SN65R	51.7	54	57.6	57.3	48.1	51.9	43.8	38.4	51.5
SN40S	53.6	45.9	66.8	63	58.1	55.1	55.2	30.4	56.4
SN50S	46.9	38.7	57.4	57.7	53.3	47.9	48.1	21.8	52.1
SN65S	45	33.6	52.6	54.8	45.3	44.1	42.2	19	44.4

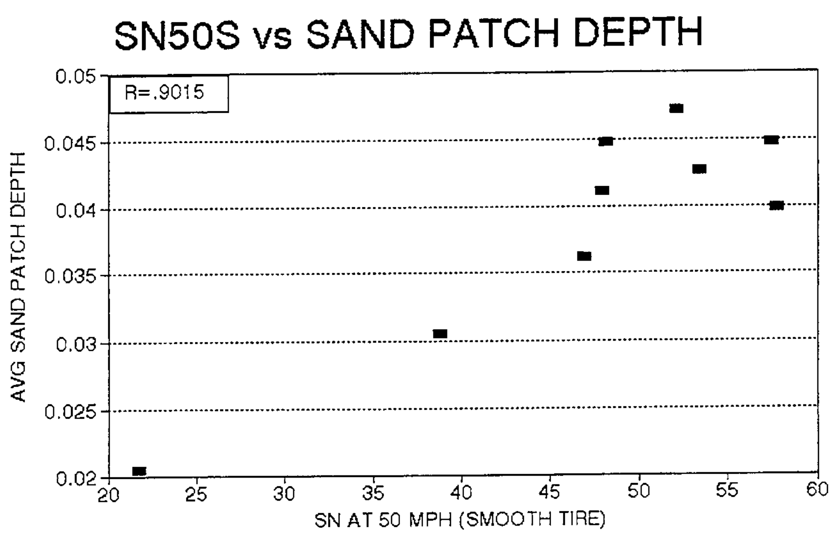
Skid Measurement Averages 1995									
10/95	1	2	3	4	5	6	7	8	9
SN40R	54.7	52	59.1	58.6	52.8	55.9	49.3	47.9	54.6
SN50R	50.1	44.7	51.5	56.7	50.3	49.9	47.7	37.8	52.7
SN65R	46.5	40.2	51	56.1	46.1	48.2	38.4	32.8	42.7
SN40S	42.9	22.1	52.2	56.3	50.7	42.3	47.1	20.6	50.5
SN50S	41.5	17.1	49.7	54.5	45	38.9	45.7	16.3	48.5
SN65S	34.5	13.4	45.3	48.2	41.1	33.9	32.5	11.2	36.3

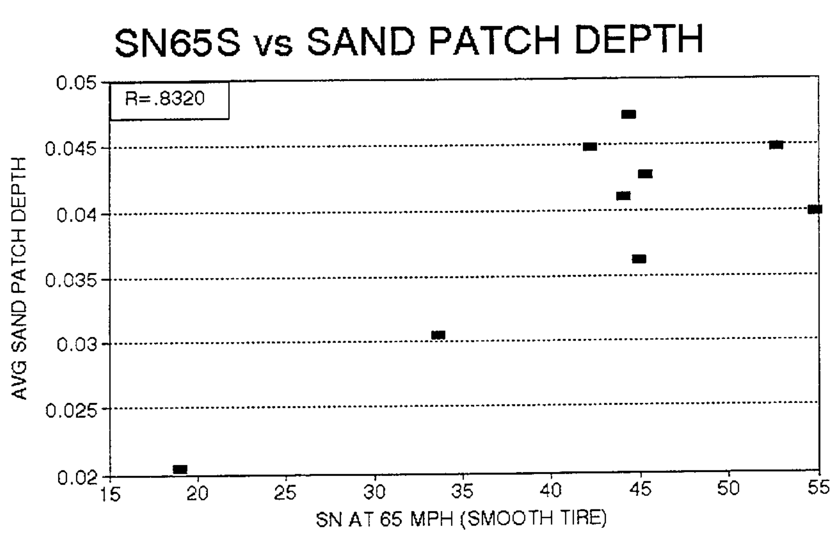
Skid Measurement Averages 1996									
10/96	1	2	3	4	5	6	7	8	9
SN40R	50.9	55.3	52.8	54.9	51.3	54.6	49.9	52.5	55.7
SN50R	45.3	46.4	48.8	49.8	47.1	47.3	47.3	45.6	49
SN65R	39.5	39	44.3	45.7	41.9	39.6	38.6	33.4	40.3
SN40S	44.3	20.6	51.6	52.7	47	40.6	49.1	20.4	51.2
SN50S	38.4	15.2	44.9	47.1	44	35.8	43.3	13.9	43
SN65S	32.8	10.3	42.1	45.5	37.5	27.9	32.6	9.9	34

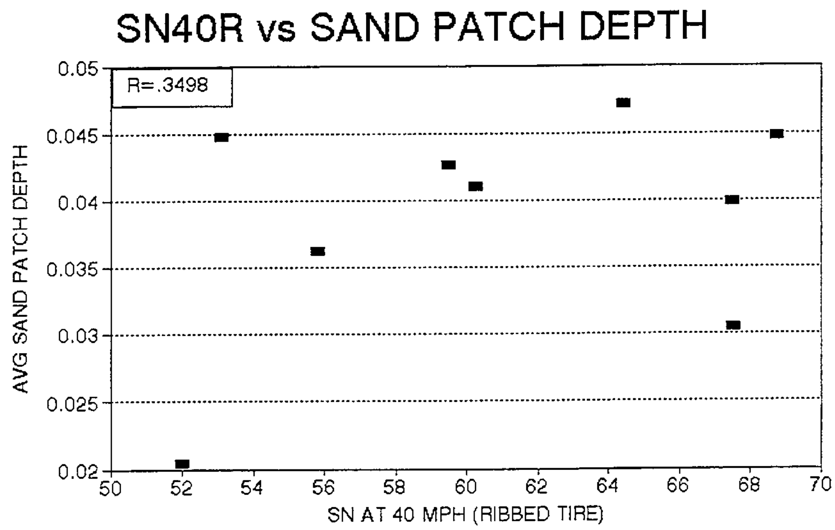
Skid Measurement Averages 1998									
10/98	1	2	3	4	5	6	7	8	9
SN40R	50.3	50.8	51.4	54.5	51.3	51.8	48	50.8	51.2
SN50R									
SN65R									
SN40S	43.4	20.5	56.1	53.8	51	43.4	48.3	24.6	50.8
SN50S									
SN65S									

Skid Measurement Averages 1999									
7/99	1	2	3	4	5	6	7	8	9
SN40R	50.3	49.4	52.5	50.7	47.9	47.8	48.5	48.2	
SN50R									
SN65R	40.6	32.7	44.1	44.5	39.4	35.1	35	34.2	
SN40S	44.9	21.4	52.3	49.2	48	42.2	48.6	22.9	45.7
SN50S									
SN65S	31.5	12.4	38.7	39.3	36.3	29.9	32.2	13.2	

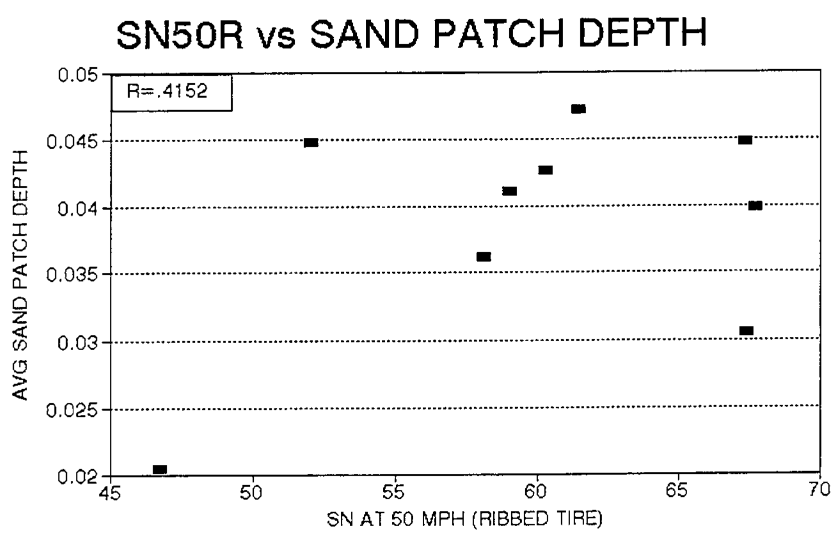

SN40S vs SAND PATCH DEPTH
R=.8838
AVG SAND PATCH DEPTH
0.05
0.045
0.04
0.035
0.03
0.025
0.02
30
35
40
45
50
55
60
65
70
SN AT 40 MPH (SMOOTH TIRE)


SN50S vs SAND PATCH DEPTH
R=.9015
AVG SAND PATCH DEPTH
0.05
0.045
0.04
0.035
0.03
0.025
0.02
20
25
30
35
40
45
50
55
60
SN AT 50 MPH (SMOOTH TIRE)

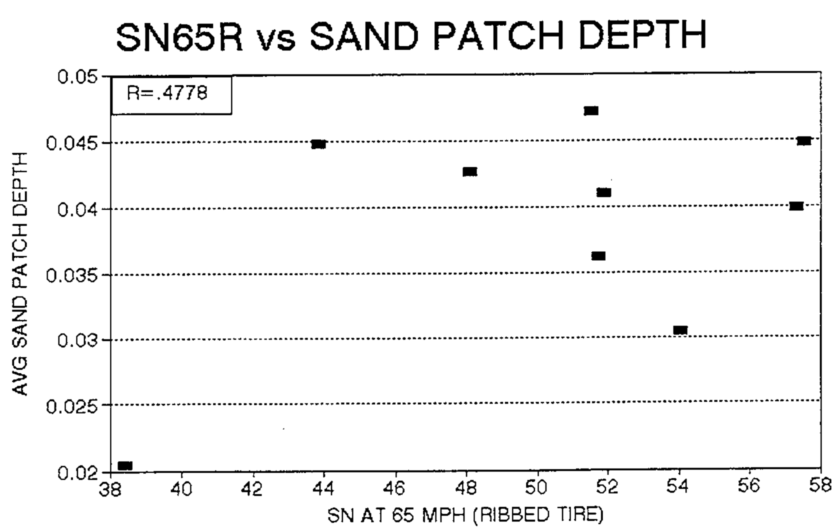

SN65S vs SAND PATCH DEPTH
R=.8320
AVG SAND PATCH DEPTH
0.05
0.045
0.04
0.035
0.03
0.025
0.02
15
20
25
30
35
40
45
50
55
SN AT 65 MPH (SMOOTH TIRE)



SN40R vs SAND PATCH DEPTH
R=.3498
AVG SAND PATCH DEPTH
0.05
0.045
0.04
0.035
0.03
0.025
0.02
50
52
54
56
58
60
62
64
66
68
70
SN AT 40 MPH (RIBBED TIRE)

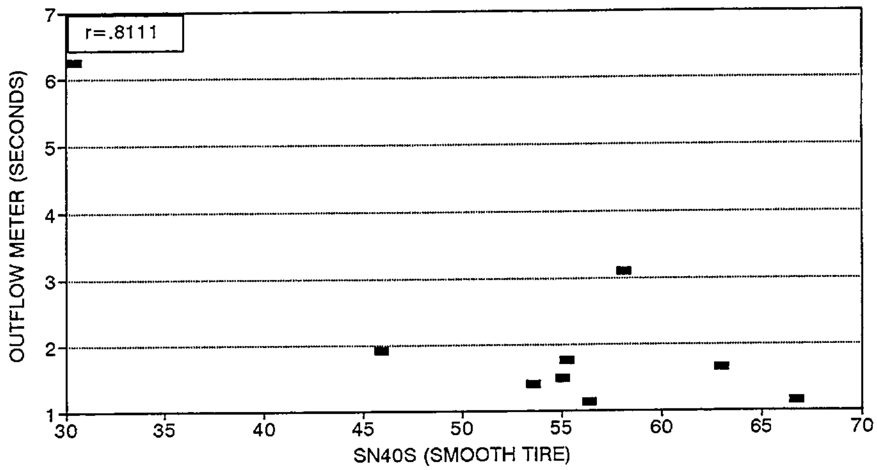


SN50R vs SAND PATCH DEPTH
R=.4152
AVG SAND PATCH DEPTH
0.05
0.045
0.04
0.035
0.03
0.025
0.02
45
50
55
60
65
70
SN AT 50 MPH (RIBBED TIRE)

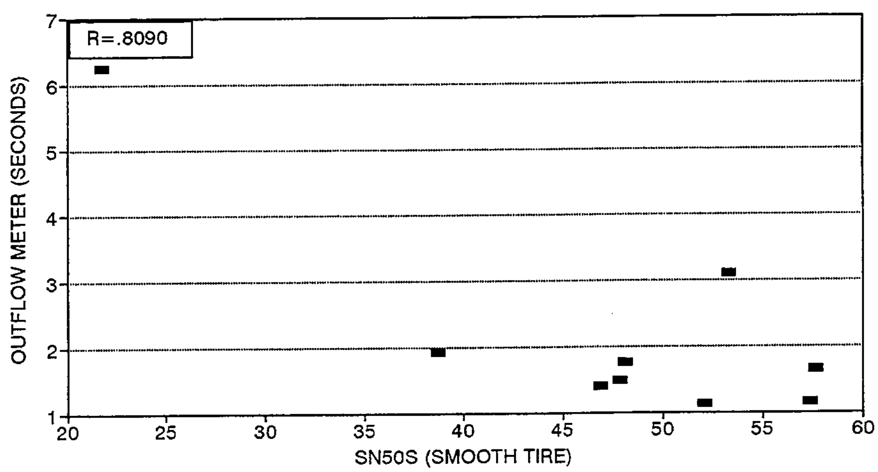


SN65R vs SAND PATCH DEPTH
R=.4778
AVG SAND PATCH DEPTH
0.05
0.045
0.04
0.035
0.03
0.025
0.02
38
40
42
44
46
48
50
52
54
56
58
SN AT 65 MPH (RIBBED TIRE)

SN40S vs. OUTFLOW METER



SN50S vs. OUTFLOW METER



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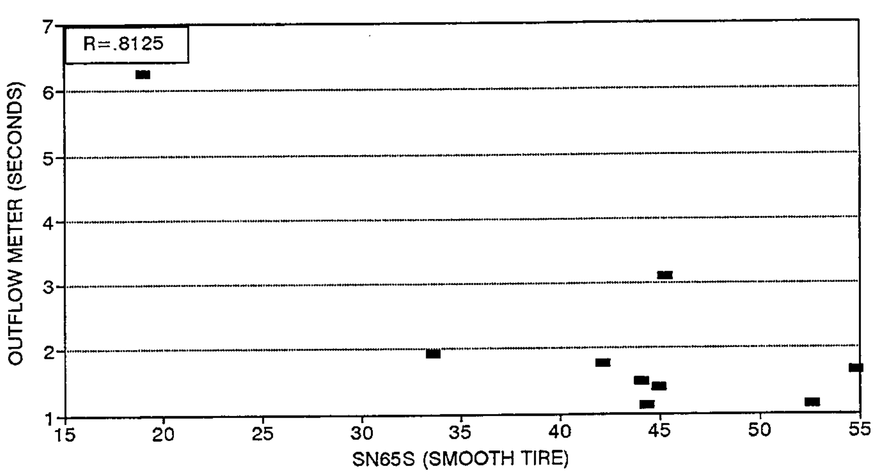
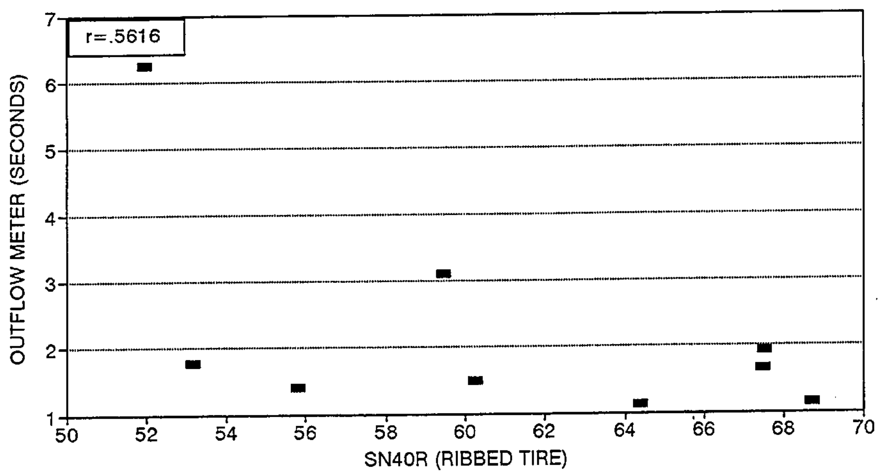
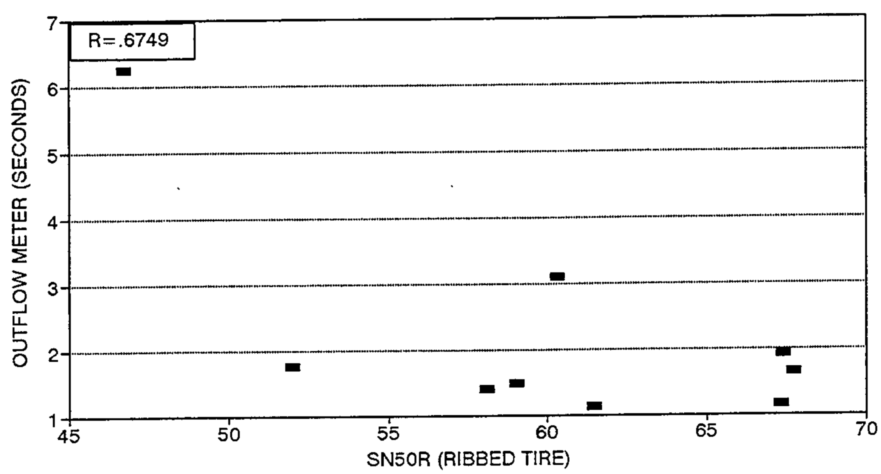


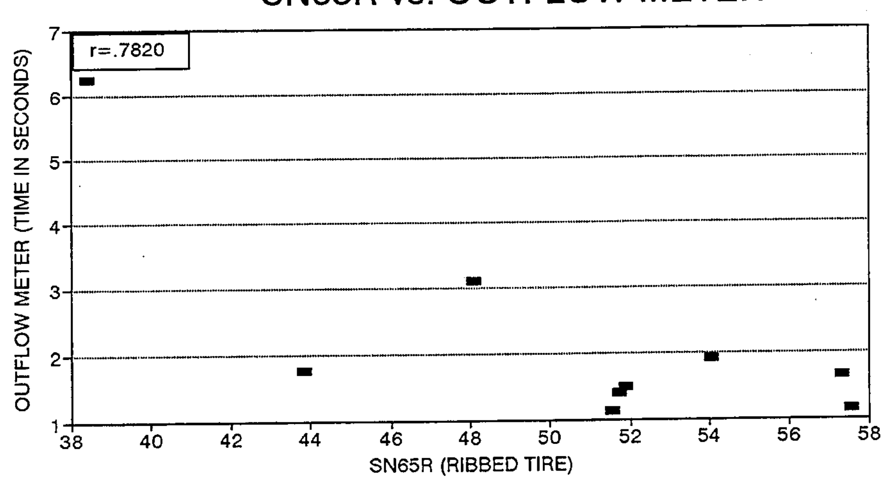
SN40R vs. OUTFLOW METER

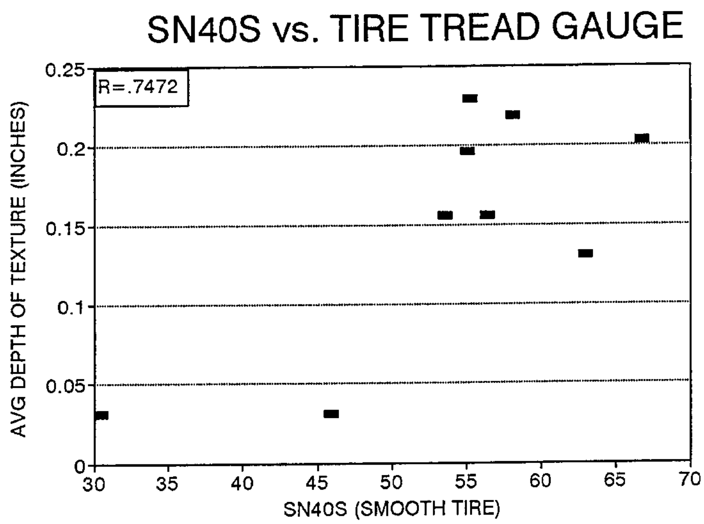


SN50R vs. OUTFLOW METER

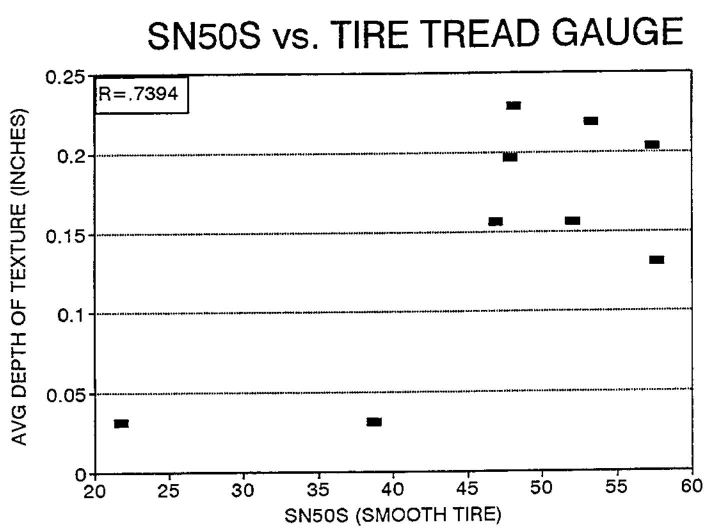


SN65R vs. OUTFLOW METER

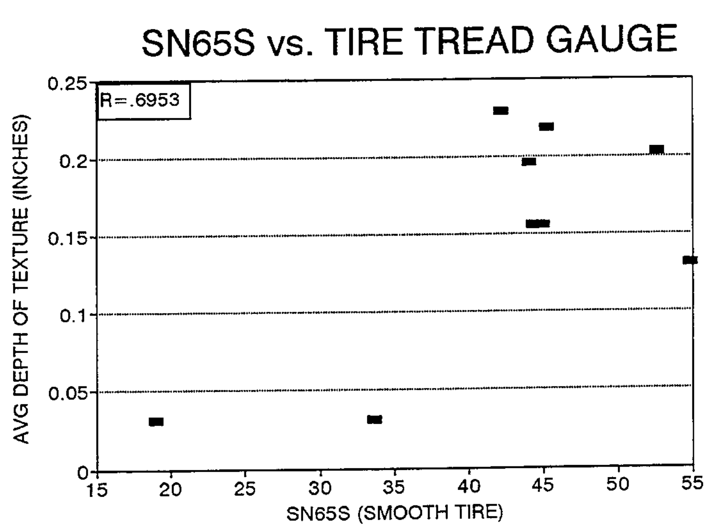




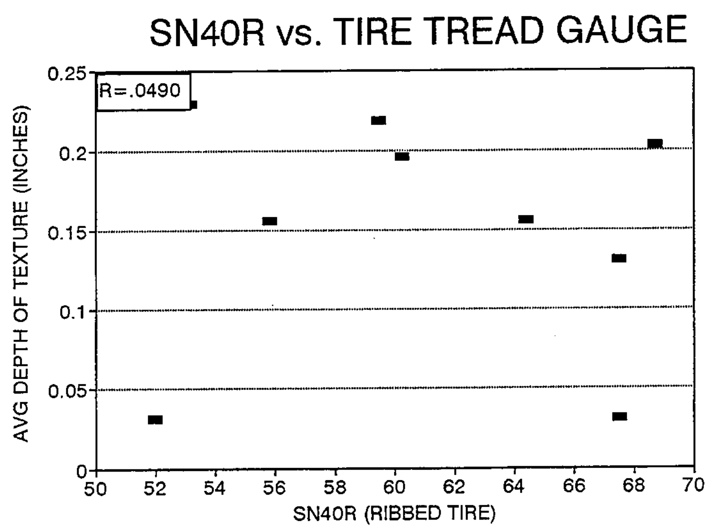
SN40S vs. TIRE TREAD GAUGE
R=.7472
AVG DEPTH OF TEXTURE (INCHES)
0.25
0.2
0.15
0.1
0.05
0
30
35
40
45
50
55
60
65
70
SN40S (SMOOTH TIRE)

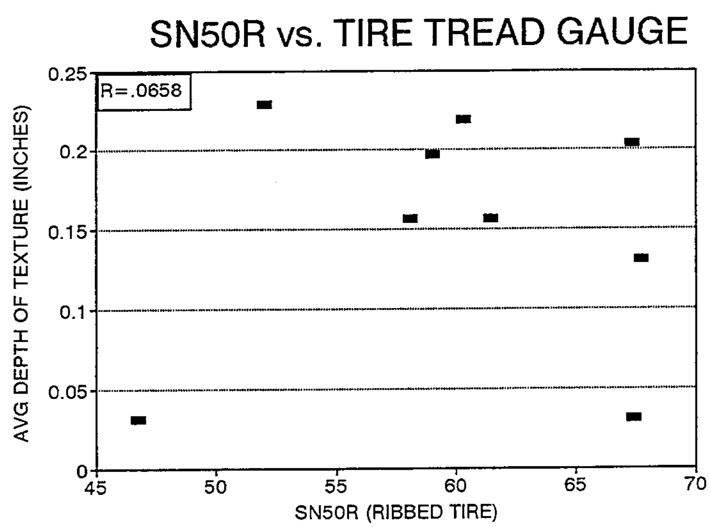


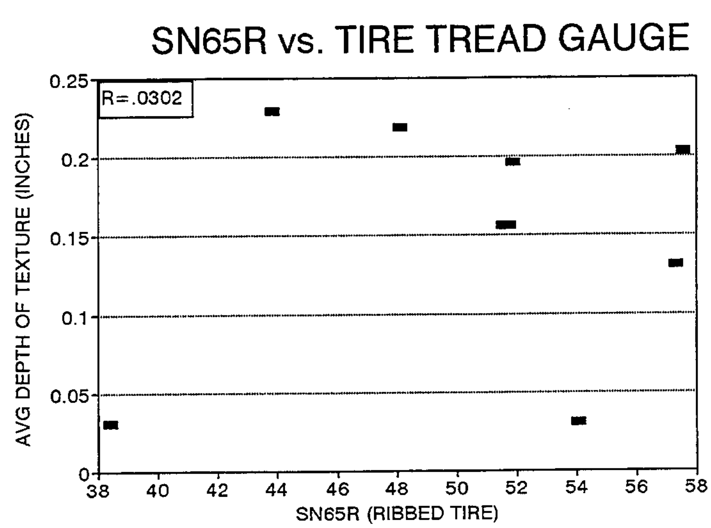
SN50S vs. TIRE TREAD GAUGE
R=.7394
AVG DEPTH OF TEXTURE (INCHES)
0.25
0.2
0.15
0.1
0.05
0
20
25
30
35
40
45
50
55
60
SN50S (SMOOTH TIRE)

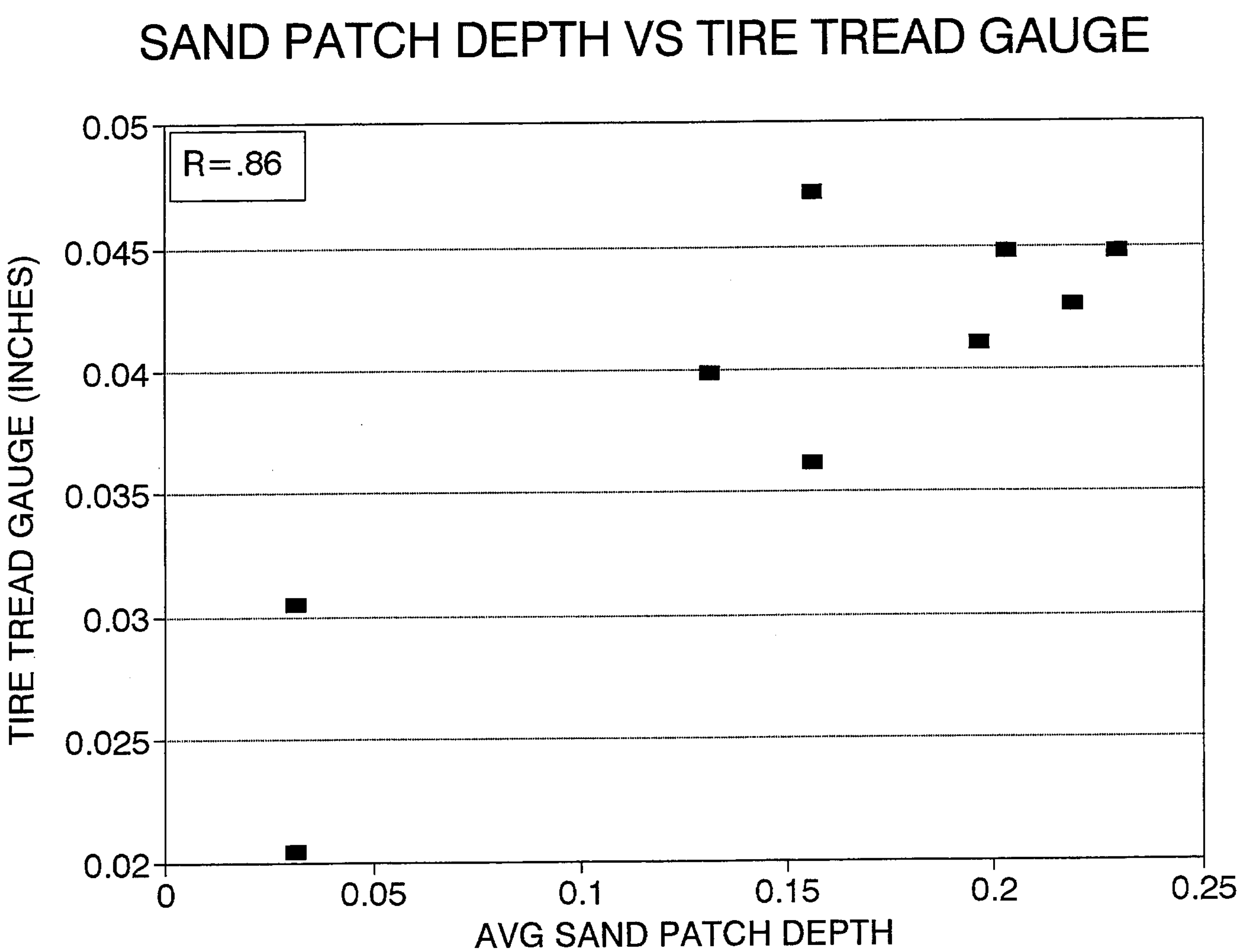


SN65S vs. TIRE TREAD GAUGE
R=.6953
AVG DEPTH OF TEXTURE (INCHES)
0.25
0.2
0.15
0.1
0.05
0
15
20
25
30
35
40
45
50
55
SN65S (SMOOTH TIRE)

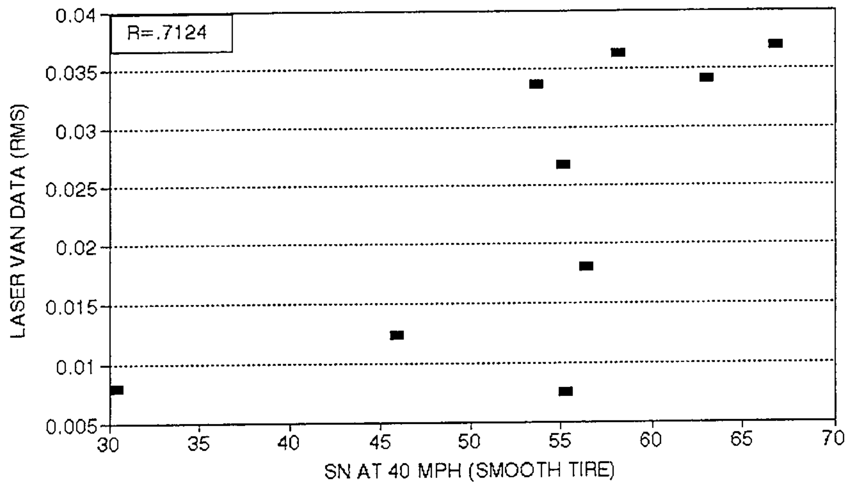

SN40R vs. TIRE TREAD GAUGE
R=.0490
AVG DEPTH OF TEXTURE (INCHES)
0.25
0.2
0.15
0.1
0.05
0
50
52
54
56
58
60
62
64
66
68
70
SN40R (RIBBED TIRE)


SN50R vs. TIRE TREAD GAUGE
R=.0658
AVG DEPTH OF TEXTURE (INCHES)
0.25
0.2
0.15
0.1
0.05
0
45
50
55
60
65
70
SN50R (RIBBED TIRE)

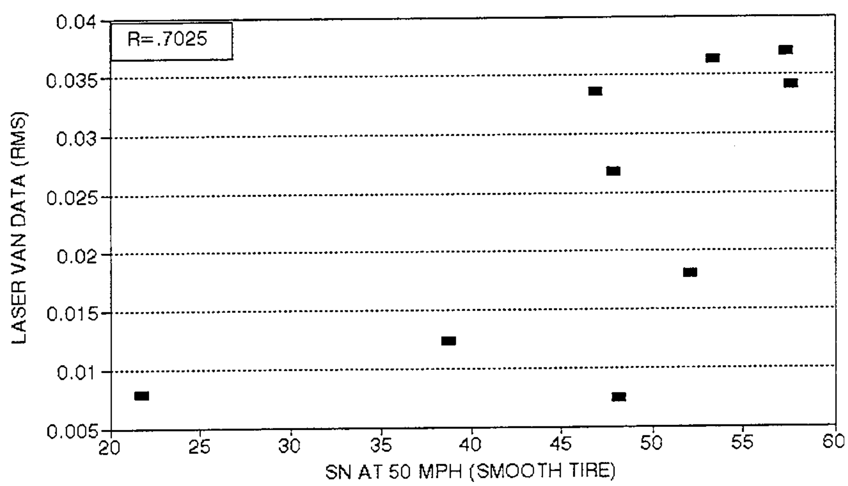

SN65R vs. TIRE TREAD GAUGE
R=.0302
AVG DEPTH OF TEXTURE (INCHES)
0.25
0.2
0.15
0.1
0.05
0
38
40
42
44
46
48
50
52
54
56
58
SN65R (RIBBED TIRE)


SAND PATCH DEPTH VS TIRE TREAD GAUGE
R=.86
TIRE TREAD GAUGE (INCHES)
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0
0.05
0.1
0.15
0.2
0.25
AVG SAND PATCH DEPTH

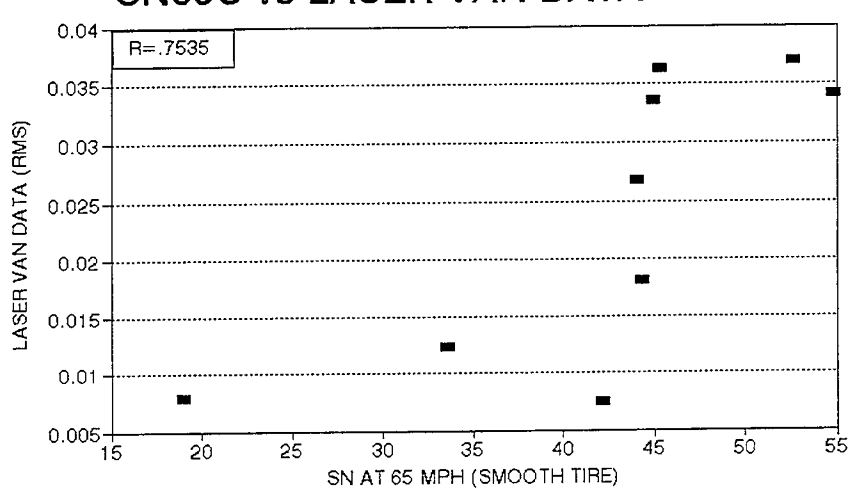
SN40S vs LASER VAN DATA

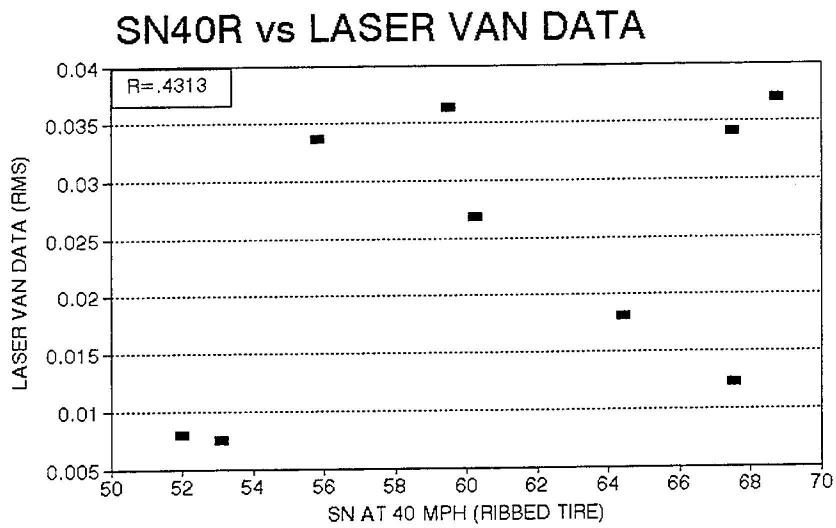


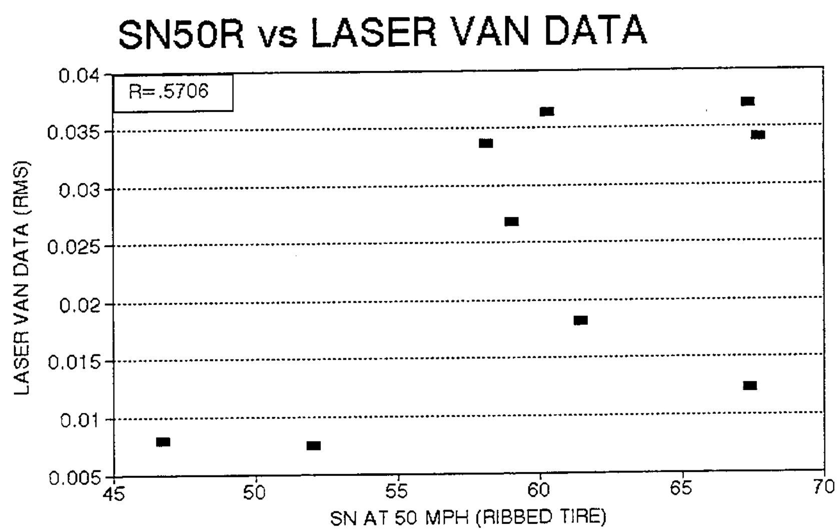
SN50S vs LASER VAN DATA

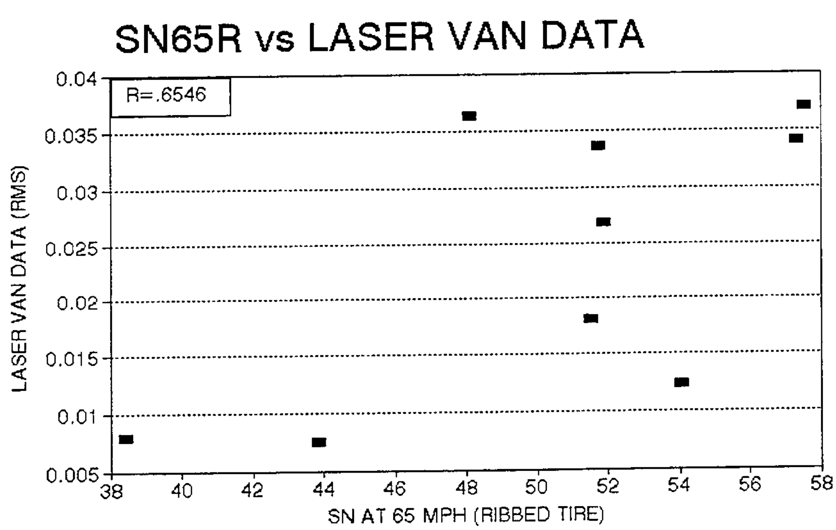


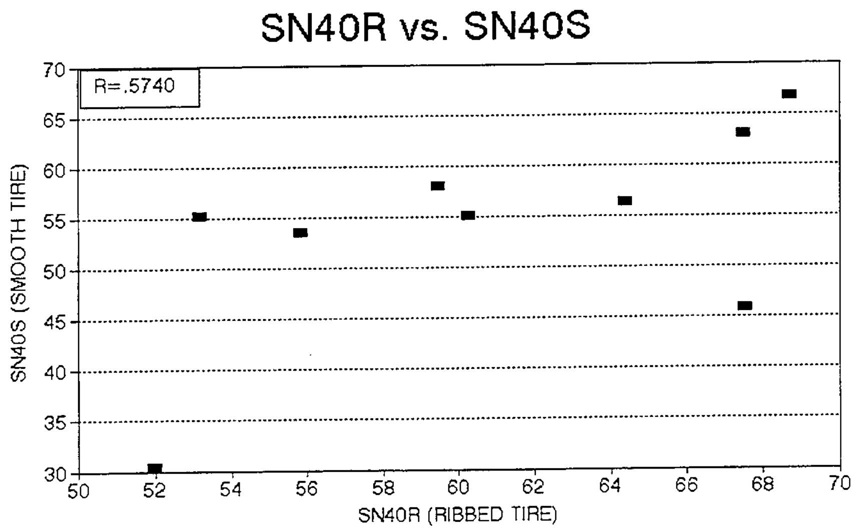
SN65S vs LASER VAN DATA

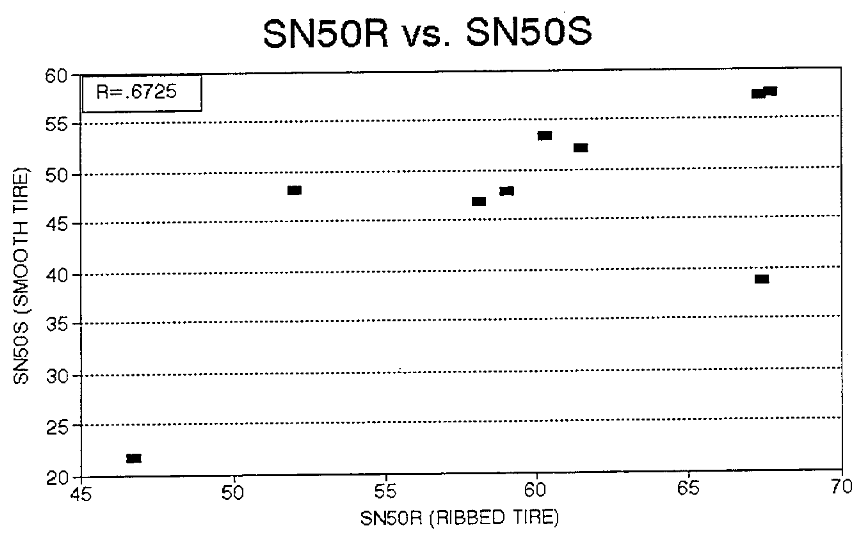


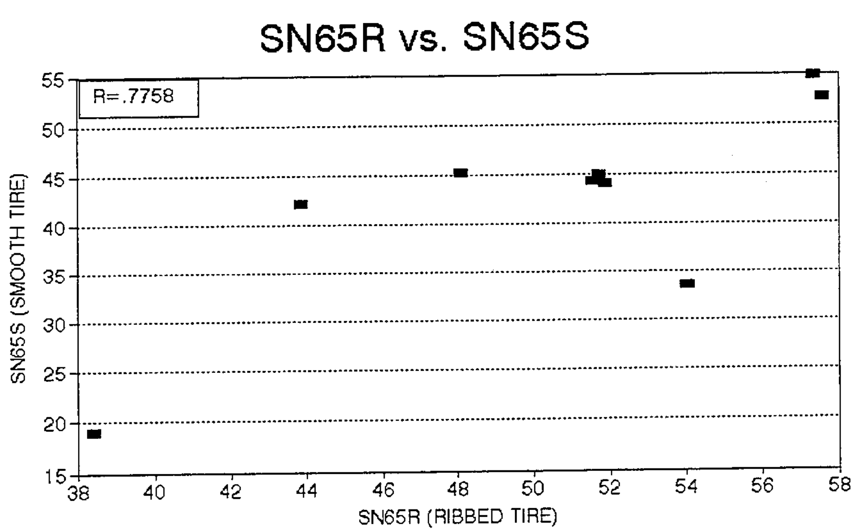

SN40R vs LASER VAN DATA
R=.4313
LASER VAN DATA (RMS)
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
50
52
54
56
58
60
62
64
66
68
70
SN AT 40 MPH (RIBBED TIRE)


SN50R vs LASER VAN DATA
R=.5706
LASER VAN DATA (RMS)
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
45
50
55
60
65
70
SN AT 50 MPH (RIBBED TIRE)

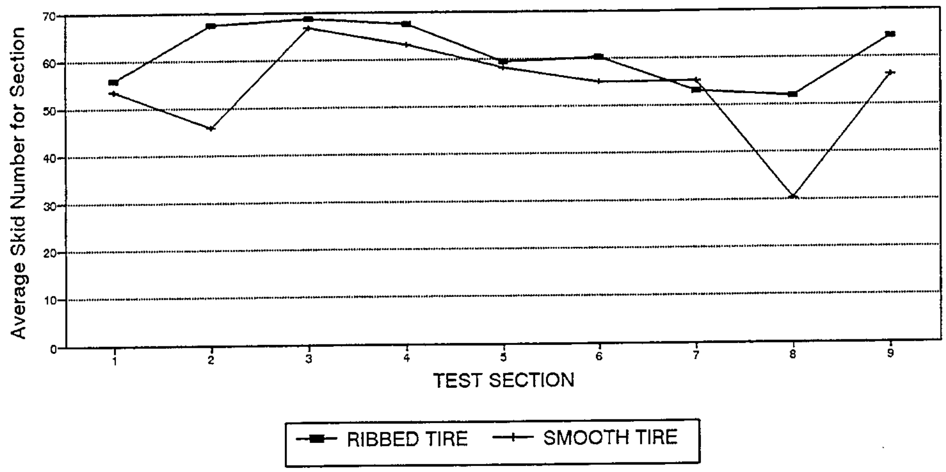

SN65R vs LASER VAN DATA
R=.6546
LASER VAN DATA (RMS)
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
38
40
42
44
46
48
50
52
54
56
58
SN AT 65 MPH (RIBBED TIRE)


SN40R vs. SN40S
R=.5740
SN40S (SMOOTH TIRE)
70
65
60
55
50
45
40
35
30
50
52
54
56
58
60
62
64
66
68
70
SN40R (RIBBED TIRE)

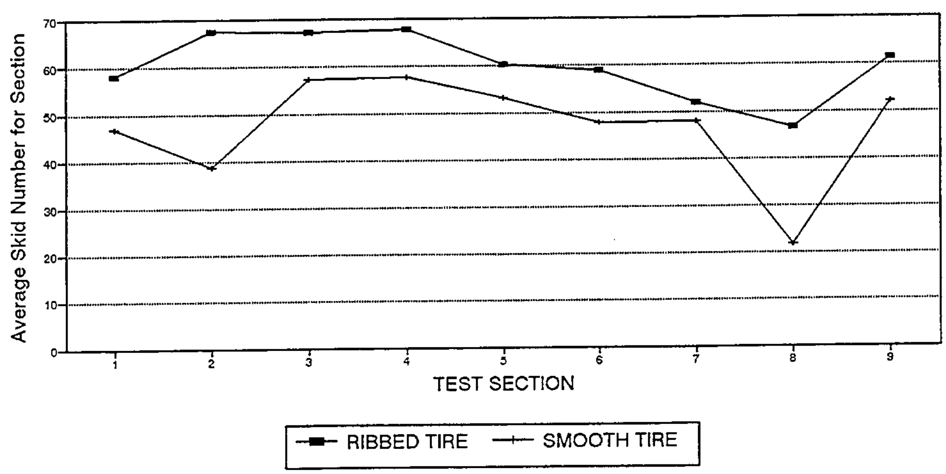

SN50R vs. SN50S
R=.6725
SN50S (SMOOTH TIRE)
60
55
50
45
40
35
30
25
20
45
50
55
60
65
70
SN50R (RIBBED TIRE)


SN65R vs. SN65S
R=.7758
SN65S (SMOOTH TIRE)
55
50
45
40
35
30
25
20
15
38
40
42
44
46
48
50
52
54
56
58
SN65R (RIBBED TIRE)

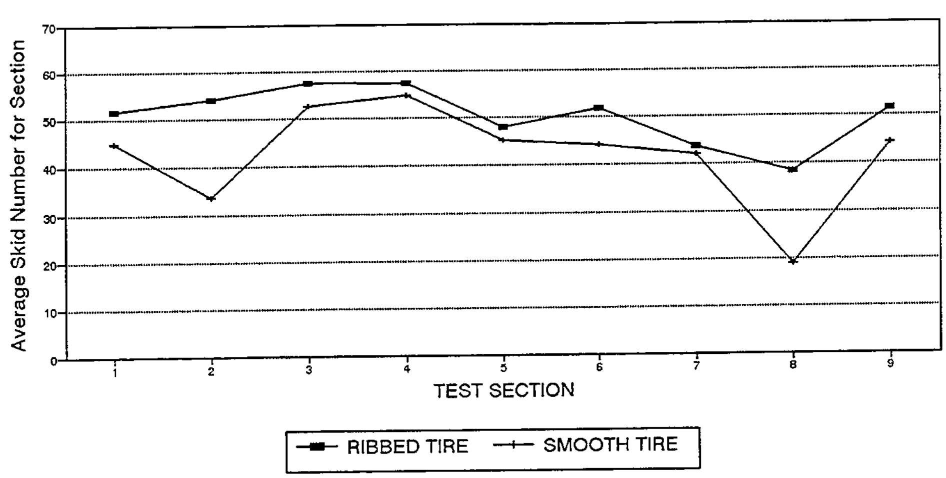
SKID NUMBERS - 40 MPH
SMOOTH vs RIBBED TIRE



SKID NUMBERS - 50 MPH
SMOOTH vs RIBBED TIRE



SKID NUMBERS - 65 MPH
SMOOTH vs RIBBED TIRE

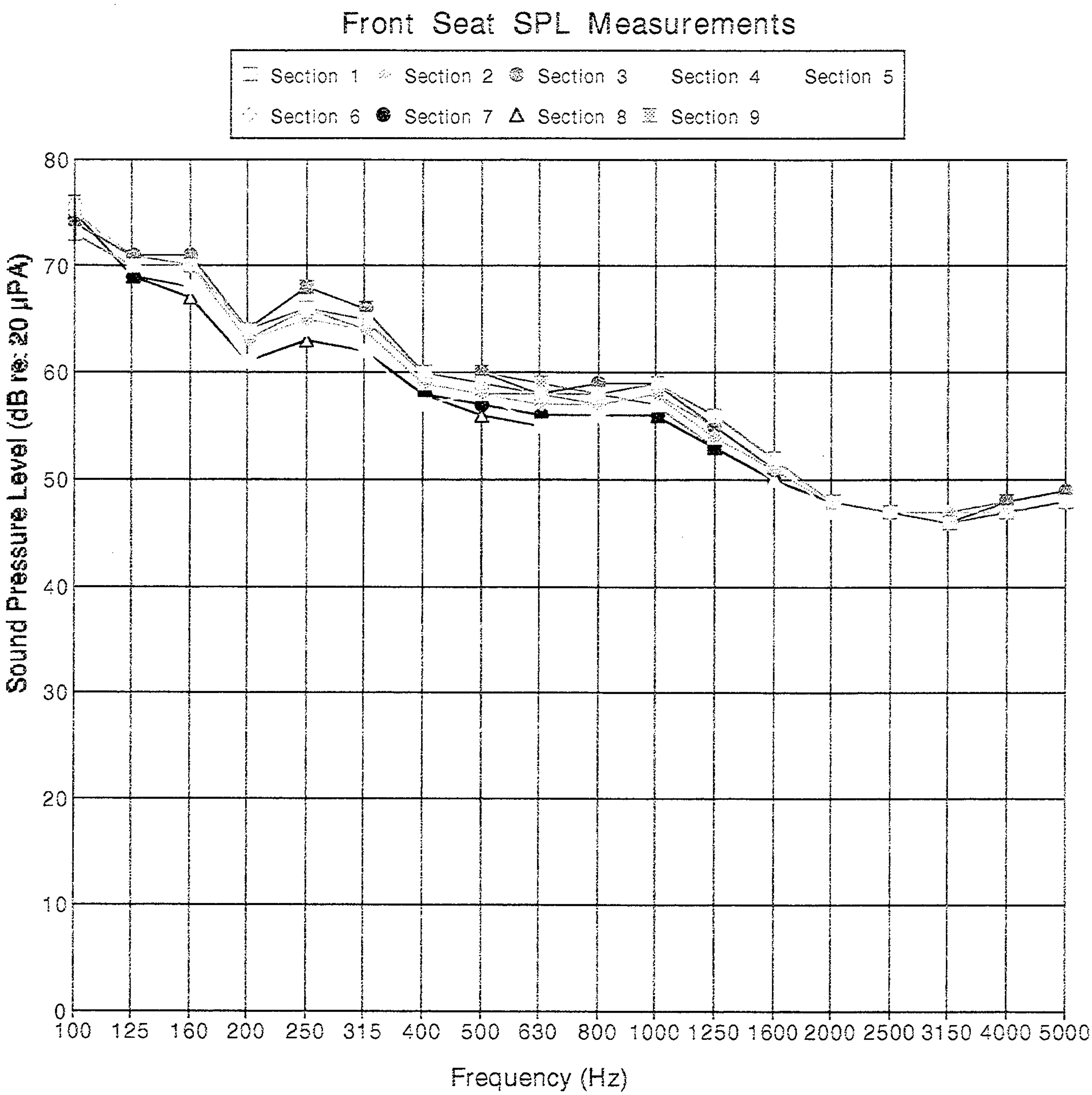


Appendix B

TABLE 1: Sound Measurement Results

Location	1/3 Octave Band SPL (dB) Frequency (Hz.)																	
Roadside	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	dBA
Section 1	74	73	74	76	80	75	75	77	79	81	85	81	75	71	67	62	59	56	**89**
Section 2	75	75	74	75	78	74	75	77	79	81	82	78	75	71	67	62	58	56	**87**
Section 3	74	75	74	76	79	79	79	81	83	83	85	79	74	69	66	61	58	55	**90**
Section 4	75	73	74	74	76	75	76	78	79	81	82	79	73	69	65	60	57	55	**87**
Section 5	76	73	73	75	77	75	74	74	75	80	83	80	80	72	67	62	59	56	**88**
Section 6	75	72	74	75	76	74	74	75	77	81	83	80	74	71	66	61	57	55	**87**
Section 7	72	70	72	71	74	71	72	74	74	79	81	75	72	66	64	59	55	52	**85**
Section 8	71	69	70	72	71	71	69	72	71	74	79	74	72	69	65	60	57	53	**83**
Section 9	73	72	75	74	79	76	76	77	78	83	84	77	71	68	65	60	57	55	**88**
Tire	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	dBA
Section 1	96	93	92	92	90	88	85	88	92	94	98	98	96	90	85	82	78	73	**104**
Section 2	97	93	92	93	90	87	83	88	90	94	95	96	94	89	85	83	78	74	**102**
Section 3	95	92	93	92	91	89	87	94	93	96	98	96	93	88	84	81	77	73	**103**
Section 4	94	91	92	92	90	88	86	91	93	95	97	95	93	87	84	81	77	73	**102**
Section 5	94	90	90	90	87	85	81	87	87	90	95	95	98	88	85	82	77	73	**103**
Section 6	96	93	92	91	89	87	84	88	90	93	97	96	93	88	84	81	77	73	**102**
Section 7	94	91	90	88	86	83	79	84	86	92	94	91	88	85	82	79	75	71	**99**
Section 8	95	90	89	88	86	83	79	83	86	90	92	91	91	87	84	82	77	73	**99**
Section 9	94	91	91	91	90	83	86	91	92	95	96	92	90	86	82	79	75	73	**101**
Front Seat	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	dBA
Section 1	73	70	70	64	66	65	60	59	58	58	59	56	52	48	47	46	47	48	**68**
Section 2	73	70	70	63	65	64	59	58	57	57	58	54	51	48	47	47	47	48	**67**
Section 3	74	71	71	64	68	66	60	60	58	59	59	55	51	48	47	46	48	49	**68**
Section 4	76	70	70	64	67	65	59	59	58	58	58	54	50	47	47	46	48	49	**68**
Section 5	73	70	68	61	64	62	57	58	55	56	57	54	52	47	47	47	47	49	**66**
Section 6	75	71	70	63	66	64	59	58	58	57	58	55	51	48	47	47	48	49	**67**
Section 7	75	69	68	61	64	62	58	57	56	56	56	53	50	47	47	47	48	49	**66**
Section 8	75	69	67	61	63	62	58	56	55	56	56	53	50	48	47	47	48	49	**66**
Section 9	76	70	70	64	68	66	60	60	59	58	57	53	50	48	47	47	48	49	**68**
Typical	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	dBA
Semi- *	74	75	78	77	73	74	80	82	89	88	93	85	82	79	76	74	72	70	**96**

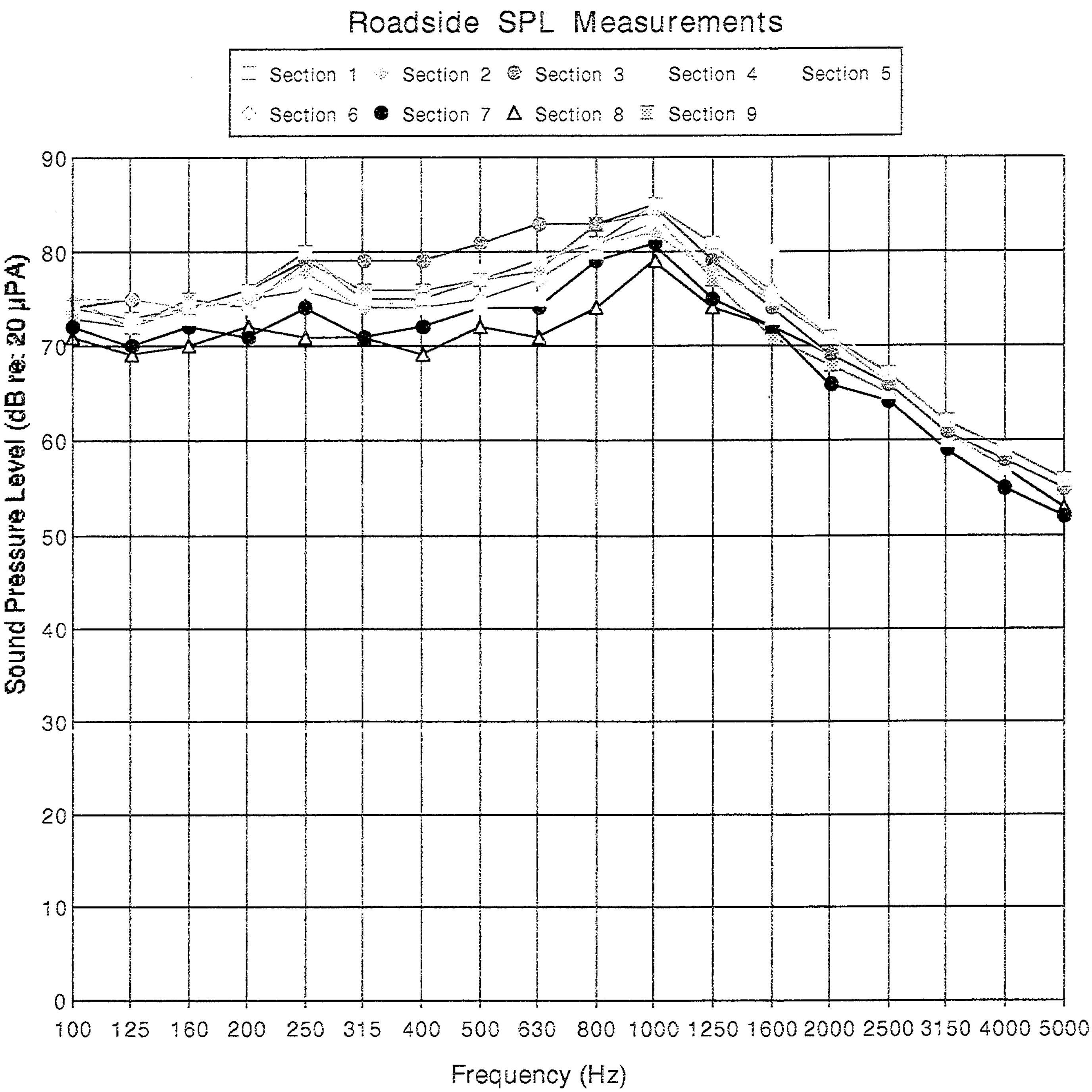
* Sound measurements taken of a typical semitractor-trailer traveling west-bound. Microphone located 25 feet from centerline of the two lanes Truck in nearest lane.



Graph No. 2: 1/3-Octave Band Sound Pressure Level Measurements

Location: Front Seat

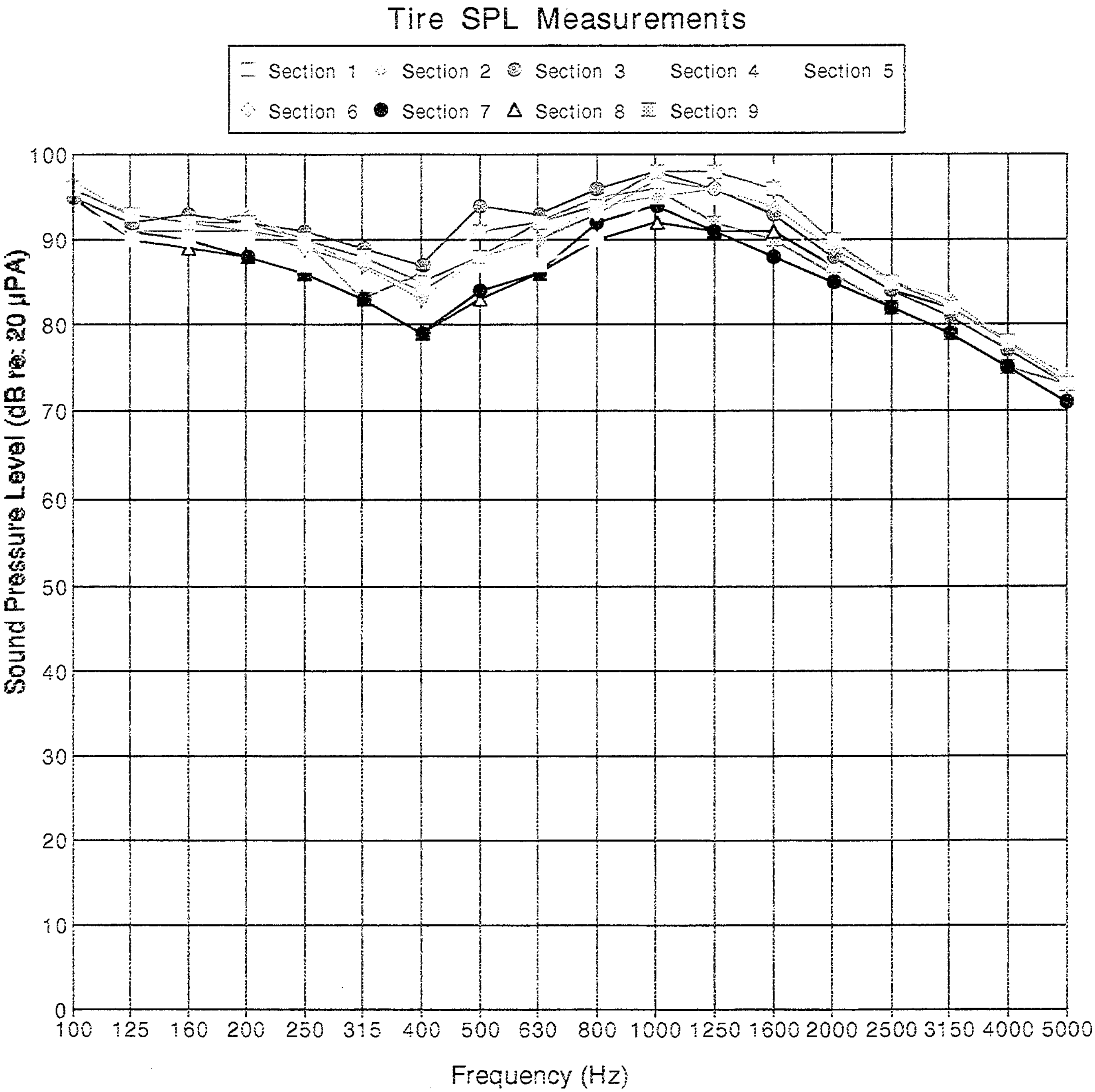
Nov. 9, 1994 CDOT Pavement Noise Measurements DLAA Project No. 5017



Graph No. 1: 1/3-Octave Band Sound Pressure Level Measurements

Location: Roadside

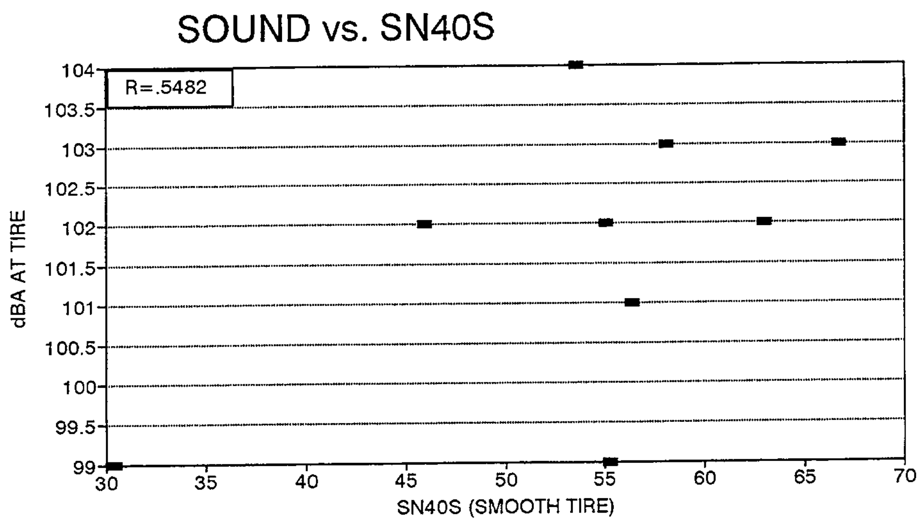
Nov. 9, 1994 CDOT Pavement Noise Measurements DLAA Project No. 5017

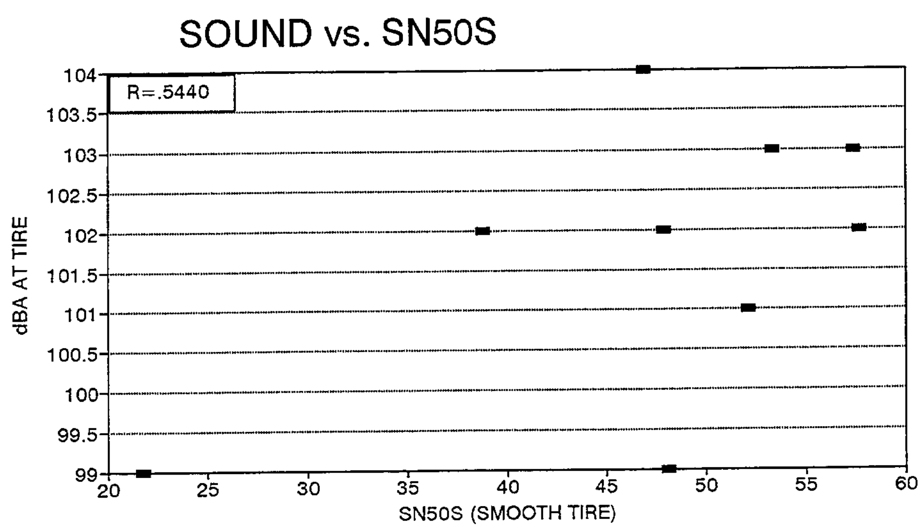


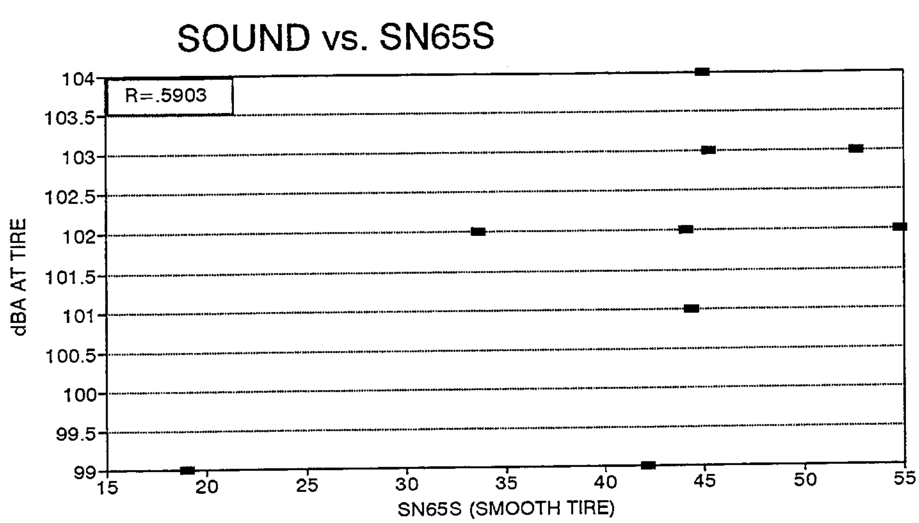
Graph No. 3: 1/3-Octave Band Sound Pressure Level Measurements

Location: Near Tire

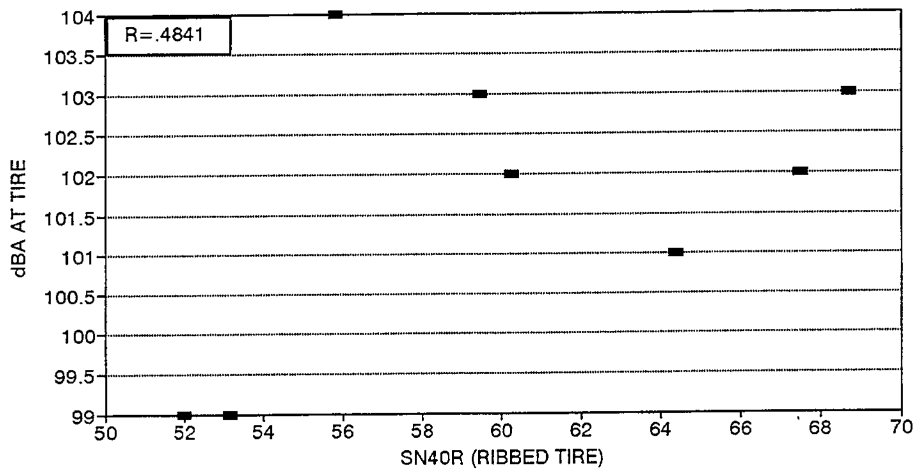
Nov. 9, 1994 CDOT Pavement Noise Measurements DLAA Project No. 5017


SOUND vs. SN40S
R=.5482
dBA AT TIRE
104
103.5
103
102.5
102
101.5
101
100.5
100
99.5
99
30
35
40
45
50
55
60
65
70
SN40S (SMOOTH TIRE)

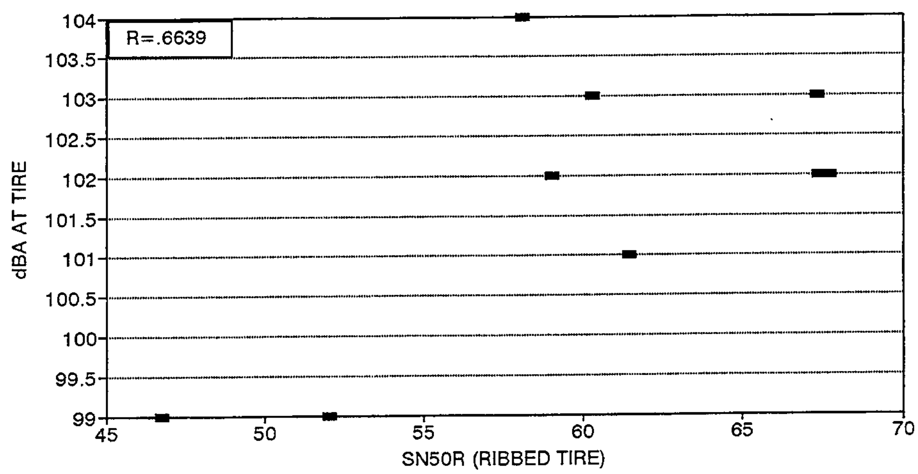

SOUND vs. SN50S
R=.5440
dBA AT TIRE
104
103.5
103
102.5
102
101.5
101
100.5
100
99.5
99
20
25
30
35
40
45
50
55
60
SN50S (SMOOTH TIRE)


SOUND vs. SN65S
R=.5903
dBA AT TIRE
104
103.5
103
102.5
102
101.5
101
100.5
100
99.5
99
15
20
25
30
35
40
45
50
55
SN65S (SMOOTH TIRE)

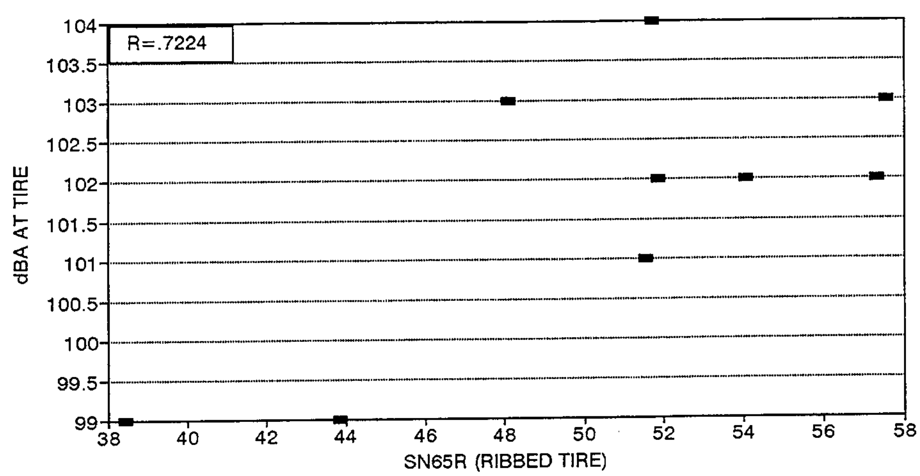
SOUND vs. SN40R



SOUND vs. SN50R



SOUND vs. SN65R



Appendix C

CHEMICAL AND PHYSICAL ANALYSES OF FLY ASH

ICKET NUMBER: 7717-17993 Job Number: 7717 REPORT DATE: 11/22/93

EPORT TO: Pozzolanic International
7525 SE 24th St.
Suite 630
Mercer Island , WA 98040

ANT OF ORIGIN : Jim Bridger
MPLE ID : 18-93
CKETS : T.R. 8420-8557 R.R. 5760-5999
TE SAMPLED : 09/30/93 -
TE RECEIVED : 10/12/93

EMICAL COMPOSITION(%):

			ASTM: C 618-92A SPECIFICATIONS CLASS F	CLASS C
Silicon Dioxide	62.22			
Aluminum Oxide	18.62			
Iron Oxide	4.71			
* * * Total		85.55	70.0 Min	50.0 Min
Sulfur Trioxide		0.25	5.0 Max	5.0 Max
Calcium Oxide		5.73		
Moisture Content		0.05	3.0 Max	3.0 Max
Loss on Ignition		0.25	6.0 Max	6.0 Max

YSICAL TEST RESULTS:

		CLASS F	CLASS C
Fineness			
Retained on #325 sieve, (%)	27.29	34 Max	34 Max
Strength Activity Index			
With Portland Cement (%)			
Ratio to Control @ 7 days	82.1		
Ratio to Control @ 28 days	96.6	75 Min	75 Min
Pozzolanic Activity Index			
With Lime @ 7 days (psi)	1040.0		
Water Requirement, % of Control	99.6	105 Max	105 Max
Soundness			
Autoclave Expansion (%)	-0.016	0.8 Max	0.8 Max
Specific Gravity	2.32		

COMMENTS:

COMMERCIAL TESTING LABORATORIES

by [signature]

Orville R. Werner II, P.E.

COLORADO REGISTERED ORVILLE R. WERNER II 14540 PROFESSIONAL ENGINEER

Ground
Engineering
Consultants, Inc.

March 17, 1994

Subject: Laboratory Test Results, Concrete Mix Designs, DeerTrail Project

Job No. 94-150

Interstate Highway Construction
7135 South Tucson Way
P.O. Box 4356
Englewood, CO 80155
Airport Field Office

Attention: Mr. Cal Thomas

Gentlemen:

We have summarized results of laboratory tests perfomed to date on aggregates delivered to our laboratory for the Deertrail concrete mix designs.

Coarse Aggregate:

Gradation:

Sieve Size or No.	Percent Passing
1-1/2"	100
1"	100
3/4"	81
1/2"	38
3/8"	17
No. 4	1.6
No. 8	1.2

Mositure content of pile (delivered) - 5.0%

Specific Gravity (SSD basis) - 2.630

Absorption - 0.89%

Los Angeles Abrasion - 41.3% loss.

Fine Aggregate:

Gradation:

Sieve Size or No.	Percent Passing
3/8"	100
No. 4	100
No. 8	95
No. 16	78
No. 30	47
No. 50	14
No. 100	3.2
No. 200	1.6

Mositure content of pile (delivered) - 7.0%

Specific Gravity (SSD basis) - 2.608

Absorption - 2.31%

Finess Modulus - 2.63

Sand Equivalent Value - 85

We have also attached mix data for Mix Designs 1, 2 and 3. Compressive and flexural strength test results will be updated as additional values are determined. The tests were completed in accordance with accepted ASTM and AASHTO test procedures. If you have any questions, please do not hesitate to contact our office.

Sincerely,
GROUND ENGINEERING CONSULTANTS, INC.

James B. Kowalsky, P.E.

COLORADO REGISTERED JAMES B. KOWALSKY 27630 PROFESSIONAL ENGINEER

3/17/98

94035

Mix No. 1

BATCH MIXTURE

Item	Description	Weight lbs / Cubic Yard
Cement	Holnam I/II, L.A.	565
Fly Ash	Bridger Pozzolonic, F	113
Coarse Aggregate	Cooley No. 57, Brighton	1586
Fine Aggregate	T&W, Byers	1215
Air Entraining Admixture	Masterbuilders Paveair	10.3 oz
Water	–	287

Physical Properties

Slump	1.5 inches
Air Content	5.9 %
Temperature	62 deg F
Unit Weight	139.9 pcf
Relative Yield	0.9972

Compressive Strength
(psi)

3 days	7 Days	14 Days	28 Days
3220	4810	5840	
3090	5040	6080	

Average Strength (psi): 3155 | 4925 | 5960

Flexural Strength
(psi)

3 days	7 Days	14 Days	28 Days
480	600	675	
520	580	660	

Average Strength (psi): 500 | 590 | 670

HOLNAM INC

Silo Test Certificate
Average of Test Results

18-106-1-B

Consignee: I.H.C
Deer Trail
East I 70

Car or Truck No. ______

Date Shipped ______

Quantity ______

PORTLAND CEMENT — Type I-II LA FEDERAL SPECIFICATION ______

A.S.T.M. DESIGNATION C-150

		Percent
1. Chemical Composition:	Silicon Dioxide (SiO_2)	21.2
	Aluminum Oxide (Al_2O_3)	4.7
	Ferric Oxide (Fe_2O_3)	3.2
	Calcium Oxide (CaO)	64.7
	Magnesium Oxide (MgO)	1.3
	Sulfur Trioxide (SO_3)	2.6
	Loss on Ignition	1.4
	Insoluble Residue	0.2
	Tricalcium Silicate (C_3S)	58
	Dicalcium Silicate (C_2S)	17
	Tricalcium Aluminate (C_3A)	7.0
	Tetracalcium Aluminoferrite (C_4AF)	10
	Alkalies (Na_2O Equivalent)	0.29
2. Specific Surface:	Blaine, Sq. M. PER Kg	400
	Wagner, Sq. M. PER Kg	
3. Soundness:	Autoclave Expansion	0.00 %

4. Time of Setting:

Vicat, Initial Set 1 Hrs. 30 Mins.
Vicat, Final Set 4 Hrs. 05 Mins.

5. Compressive Strength Tests:

1 Day ______ Lbs. per Sq. In.
3 Days 3810 Lbs. per Sq. In.
7 Days 4780 Lbs. per Sq. In.

6. Air Entrainment: % by Volume 5.8

HOLNAM INC is warranted to conform at the time of shipment with the specification designated above. No other warranty is made or to be implied. Having no control over the use of its cements, HOLNAM does not guarantee finished work.

HOLNAM INC

Portland, Colorado Plant

By [signature]
Quality Control Supervisor

.: November 18, 1994

): A.G. Peterson

ROM: Jay Goldbaum

UBJECT: Carbonate sand in PCCP

n order to determine the susceptibility of the sand to polish in project umber IR(CX) 070-4(153), Deertrail - East, ASTM test number D 3042 was erformed. The test uses a hydrochloric acid solution to dissolve the arbonates in a sample.
ccording to some research performed, a higher amount of carbonic materials ound represents a higher possibility of polishing and/or a loss in friction f the pavement surfaces. The maximum amount of carbonates allowed in PCCP is 5 percent.

fter performing ASTM test D 3042 on the sand used in the PCCP at Deertrail, t was found to have 0.42 percent carbonates.

13-Oct-94

IR(CX) 70-4(153)
Deertrail - EAST
Class P Results

Test#	3 Day			7 Day			14 Day			28 Day				28Day			28 DAY		
	Compressive Strength		Average	Compressive Strength		Average	Compressive Strength		Average	Compressive Strength			Average	Tensile Strength		Average	Flexural Strength		Average
EBL																			
61	3030	3040	3035	4660	4630	4645	4980	5230	5105	5510	5570	5240	5440						
62	3860	4020	3940	4340	4560	4450	4750	4730	4740	5490	5860	5480	5610						
63	3310	3350	3330	4320	3970	4145	4120	4610	4365	5430	5280	5330	5347						
64	3310	3370	3340	3760	3990	3875	4070	4510	4290	5250	5150	5030	5143						
65	2960	2850	2905	3680	3550	3615	3980	3930	3955	4800	4680	4490	4657						
66				3590	3570	3580				4680	4830	4440	4650	420	442	431	610	550	580
IAT-66										4660	4270		4465						
67				3750	3660	3705				4670	4620	4612	4634						
68	3410	3350	3380							4820	4720	4900	4813						
69	3310	3210	3260							5220	5050	5530	5267						
70	3500	3570	3535	3520	4340	3930				4880	5110	5210	5067						
71	3410	3330	3370	4200	4290	4245				5390	5010	4800	5067						
IAT-71										5490	5520		5505						
72	3290	3310	3300	4060	4120	4090				5050	5450	5130	5210						
73	2950	2880	2915	3230	3250	3240				4760	4850	4410	4673						
74	2690	2540	2615	3520	3130	3325				4770	4310	4470	4517						
75	3230	3610	3420	4540	4550	4545				6240	6210	5250	5900						
76										5800	6210	5940	5983						
77										4890	5290	4940	5040						
78				3460	3680	3570				4880	5090	4420	4797						
79										5720	5700	5520	5647						
80										5300	5310	5650	5420						
81										5430	5450	5190	5357						
82				4220	4160	4190				5210	5650	5620	5493						
83										5720	5850	5730	5767						
84										4720	5210	5030	4987						
85										4930	4960	4860	4917						
86				4520	4290	4405				5650	5110	5640	5467						
87										5360	5300	5140	5267	354	359	357	605	645	625
IAT-87										5430	5220		5325						
88										5310	5370	5620	5433						
89										5120	4740	4880	4913						
90				4190	4260	4225				5290	5680	5370	5447						
91										5420	5240	5060	5240						
92										4800	4700	4690	4730						
93										5410	5380	5650	5480						
94				4480	4500	4490				5290	5350	5310	5317						
95										5310	5380	5300	5330						
96										4700	4830	5080	4870						
97				3330	3360	3345				4020	4230	4040	4097						
98				4340	3930	4135				5000	4990	4840	4943						
99										4360	4550	4610	4507						
100				3730	3700	3715				4260	4200	4580	4347						
101										4536	4960	4770	4755	440	425	433	615	605	610
102										4400	4270	4250	4307						
103				4200	4340	4270				5160	5230	5110	5167						
104										4140	4540	4690	4457						
105				3340	3700	3520				4340	4220	4340	4300						
106										4570	4590	4200	4453	430	450	440	595	520	558
107										5470	5240	4600	5103						
108										5090	5380	5180	5217						
109				3520	3630	3575				4160	4470	4510	4380						
110										4830	4530	4640	4667						
111				4580	4610	4595				5190	5580	4930	5233						
IAT-111										5750	5800		5775						
112										5580	5530	5390	5500						
113										5390	5040	5070	5167						
114										4890	4880	4640	4803						
115				4490	4530	4510				5720	5640	5440	5600						
116										4690	4460	4540	4563						
117										5420	5360	5670	5483						
118										4740	4420	4610	4590						
119				4480	4530	4505				5200	5170	5270	5213						
120										5220	5350	5040	5203	465	440	453	620	615	618
IAT-120										5260	5230		5245						
121										4790	4660	4700	4717						
122										4350	4390	4300	4347						
123				4590	4620	4605				5170	5540	4990	5233						
124										4440	5440	5200	5027						
125										5160	5040	5370	5190						
126										3850	3940	3910	3900	395	370	383	510	575	543
Average (EB & WB)			3257			4039			4491				4989						613
Std. Dev. (EB & WB)			325.2			520			426				564.1						59.9
Max. Value (EB & WB)			4020			6270			5230				6370						725
Min. Value (EB & WB)			2540			2800			3930				2360						510
Number of tests (EB & WB)			26			70			10				402						24
Average (WB)													4942						
Std. Dev. (WB)													640.6						
Max. Value (WB)													6370						
Min. Value (WB)													2360						
Number of tests (WB)													194						
Average (EB)													5032						
Std. Dev. (EB)													477.7						
Max. Value (EB)													6240						
Min. Value (EB)													3850						

11-Oct-94

IR(CX) 70-4(153)
Deertrail - EAST
Class P Results

Test#	3 Day Compressive Strength	3 Day Average	7 Day Compressive Strength		7 Day Average	14 Day Compressive Strength	14 Day Average	28 Day Compressive Strength			28 Day Average	28Day Tensile Strength		Average	28 DAY Flexural Strength		Average
WBL																	
1			4120	4210	4165			4990	5270	5340	5200						
2			3990	4130	4060			5090	5480	5170	5247						
3			3870	4130	4000			4760	4960	5060	4927						
4								3580	2990	3610	3393						
5			6270	2800	4535			4100	4010	4420	4177						
6			3470	3630	3550			4350	4350		4350						
7			4230	3510	3870			5300	5240		5270						
IAT-7								5300	5240		5270						
8			4000	4250	4125			2520	2360	2560	2480						
9								5220	4860	5260	5113						
10								5480	5240	5600	5440						
10a								5243	5480	5598	5440						
11								5336	5251	4928	5172						
11a								5020	4940	4630	4863						
12								6008	5936	6061	6002						
12a								6010	5940	6060	6003						
13								5100	4870	5210	5060						
14								5640	5530	5440	5537						
15								5780	5830	5110	5573						
16								4830	4720	4600	4717						
17								5140	5180	5250	5190						
18								4890	5270	4940	5033						
19								5060	4780	5080	4973						
20								5230	5510	5010	5250						
21								5240	3320	5370	4643						
22								5900	5950	6370	6073	498	400	449	725	690	708
IAT-22								6250	5830		6040						
23								5170	5110	3890	4723						
24								5170	5330	5250	5250						
25								5320	5370	5330	5340						
26								4930	4700	5020	4883						
27								5060	5620	5380	5353						
28								4680	4660	4410	4583						
29								3800	3960	3660	3807						
30								5630	5620	5970	5740						
IAT-31								4860	5130		4995						
31								5120	5150	5280	5183						
32								5110	5230	5320	5220						
33								5200	5220	5060	5160						
34								5060	5160	5680	5300	497	478	488	715	690	703
35								5010	4760	4290	4687						
36								5220	4740	5210	5057						
37								5250	5230	5080	5187						
38								5100	4990	5380	5157						
39								5110	5340	5080	5177						
IAT-40								4730	4730		4730						
40								4770	4740	4950	4820						
41								5260	5670	5660	5530	460	444	452	680	685	683
42								5480	5190	4850	5173						
43								4730	4740	4970	4813						
44								4890	5020	4740	4883						
45								4230	4170	4200	4200	339	335	337	565	540	553
46								4510	4240	4710	4487						
47								5080	5370	5175	5208						
48								4900	5100	4970	4990						
49								3870	3870	3860	3867						
50								4990	4840		4915						
51								4800	4610	4520	4643						
52								4080	4020	4060	4053	335	340	338	575	560	568
53								5340	4630	5370	5113						
54								5090	4890	5240	5073						
55								4450	4770	4790	4670						
56								4780	4730	4630	4713						
57								5050	5450	5270	5257						
58								3960	3930	4010	3967						
59								5030	5010	4790	4943	439	436	438	650	565	608
60								4170	4000	4310	4160						

CDOT Report Publication List

REPORT PUBLICATION LIST
CDOT RESEARCH

99-1 Colorado Rockfall Simulation Program Update
99-2 Effects of Magnesium Chloride on Asphalt Pavements: Quick Study
99-3 Effects of Geometric Characteristics on Interchanges on Truck Safety
99-4 Initial Curing of Portland Cement Concrete Cylinders
99-5 Evaluation of Design/Build Practices in Colorado
99-6 Improving Colorado Transportation through Investigation and Innovation: Status Report on Research Activities
99-7 Common Performance Measures Practitioner's Guidebook
99-8 Cracking in Bridge Decks: Causes and Mitigation
99-9 Using Ground Tire Rubber in Hot Mix Asphalt Pavement Final Report
99-10 Studies of Environment Effect of Magne

98-1 I-76 Truck Study
98-2 HBP Pilot Void Acceptance Projects in Region 2 in 1997
98-3 1997 Hot Bituminous Pavement QC for Day Pilot Project with Void Acceptance
98-4 Hot Bituminous Pavement QC & QA Project Constructed in 1997 Under QPM2 Specification
98-5 Final Report Evaluation of Iowa Vacuum Tester
98-6 Simulation of 12 High Geosynthetic Reinforced Retaining Walls Under Surcharge Loading by Centrifuge Testing
98-7 Colorado Study on Transfer and Development Length of Pre-stressing Strand in High Performance Concrete Box Girders
98-8 Particulate Matter from Roadways
98-9 Evaluation of Design Build Practice in Colorado - Construction Report
98-10 Whitetopping Thickness Design in Colorado

97-1 Avalanche Forecasting Methods, Highway 550
97-2 Ground Access Assessment of North American Airport Locations
97-3 Special Polymer Modified Asphalt Cement (Final Report)
97-4 Avalanche Detection Using Atmospheric Infrasound
97-5 Keyway Curb (Final Report)
97-6 IAUAC - (Interim Report)
97-7 Evaluation of Design-Build Practice in Colorado (Pre-Construction Report)
97-8 HBP Pilot Void Acceptance Projects Completed in 1993-1996 (Interim Report)
97-9 QC & QA Projects Constructed in 1996 Under QPM2

Specifications (Fifth Annual Report)
97-10 Loading Test of GRS Bridge Pier and Abutment in Denver, CO

97-11 Faulted Pavements at Bridge Abutments

96-1 Long-Term Performance Tests of Soil-Geosynthetic Composites
96-2 Efficiency of Sediment Basins: Analysis of the Sediment Basins Constructed as Part of the Straight Creek Erosion Control Project.
96-3 The Role of Facing Connection Strength in Mechanically Stabilized Backfill Walls
96-4 Revegetation of MSB Slopes
96-5 Roadside Vegetation Management
96-6 Evaluation of Slope Stabilization Methods (US-40 Berthod Pass) (Construction Report)
96-7 SMA (Stone Matrix Asphalt) Colfax Avenue Viaduct
96-8 Determining Asphalt Cement Content Using the NCAT Asphalt Content Oven
96-9 HBP QC & QA Projects Constructed in 1995 Under QPM1 and QPM2 Specifications
96-10 Long-Term Performance of Accelerated Rigid Pavements, Project CXMP 13-006-07
96-11 Determining the Degree of Aggregate Degradation after Using the NCAT Asphalt Content Oven
96-12 Evaluation of Rumble Treatments on Asphalt Shoulders

95-1 SMA (Stone Matrix Asphalt) Flexible Pavement
95-2 PCCP Texturing Methods
95-3 Keyway Curb (Construction Report)
95-4 EPS, Flow Fill and Structure Fill for Bridge Abutment Backfill
95-5 Environmentally Sensitive Sanding and Deicing Practices
95-6 Reference Energy Mean Emission Levels for Noise Prediction in Colorado
95-7 Investigation of the Low Temperature Thermal Cracking in Hot Mix Asphalt
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95-18 Widened Slab Study

94-1 Comparison of the Hamburg Wheel-Tracking Device and the Environmental Conditioning System to Pavements of Known Stripping Performance
1-94 Design and Construction of Simple, Easy, and Low Cost Retaining Walls
94-2 Demonstration of a Volumetric Acceptance Program for Hot Mix Asphalt in Colorado
2-94 The Deep Patch Technique for Landslide Repair
94-3 Comparison of Test Results from Laboratory and Field Compacted Samples
3-94 Independent Facing Panels for Mechanically Stabilized Earth Walls
94-4 Alternative Deicing Chemicals Research
94-5 Large stone Hot Mix Asphalt Pavements
94-6 Implementation of a Fine Aggregate Angularity Test
94-7 Influence of Refining Processes and Crude Oil Sources Used in Colorado on Results from the Hamburg Wheel-Tracking Device
94-8 A Case Study of concrete Deck Behavior in a Four-Span Prestressed Girder Bridge: Correlation of Field Test Numerical Results
94-9 Influence of Compaction Temperature and Anti-Stripping Treatment on the Results from the Hamburg Wheel-Tracking Device
94-10 Denver Metropolitan Area Asphalt Pavement Mix Design Recommendation
94-11 Short-Term Aging of Hot Mix Asphalt
94-12 Dynamic Measurements on Penetrometers for Determination of Foundation Design
94-13 High-Capacity Flexpost Rockfall Fences
94-14 Preliminary Procedure to Predict Bridge Scour in Bedrock