The Effect of Roadway Wear on Tire Noise

WA-RD 276.1

Final Report
August 1992

Washington State Department of Transportation
Washington State Transportation Commission

in cooperation with
U.S. Department of Transportation
Federal Highway Administration

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. WA-RD 276.1	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE THE EFFECT OF ROADWAY WEAR ON TIRE NOISE		5. REPORT DATE August 1992 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) James D. Chalupník and Donald S. Anderson		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Washington State Transportation Center (TRAC) University of Washington, JE-10 The Corbet Building, Suite 204; 4507 University Way N.E. Seattle, Washington 98105		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. GC8719, Task 3
12. SPONSORING AGENCY NAME AND ADDRESS Washington State Department of Transportation Transportation Building, MS 7370 Olympia, Washington 98504-7370		13. TYPE OF REPORT AND PERIOD COVERED Final Report 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

This is the final report of a study of the way in which tire/road noise changes as the pavement ages and wears. Measurements of the levels of noise generated at the tire/road-surface interface were made on sections of a variety of asphaltic and concrete compositions ranging in age from newly laid to 29 years. Data from these measurements are presented in graphical form showing levels and trends of levels with time. While the measurements made in this study do not portray the noise levels at the roadside, they do rank order the source noise levels of the various surfaces devoid of the noise absorption characteristics of the surface. An interpretation of the data is provided to assist highway planners, designers, or environmental engineers. As an add-on to the main study, a comparison of the noise from studded tires and non-studded tires of the same tread design was made for a variety of roadway surface types.

17. KEY WORDS Noise, tire noise, tire/road noise, noise measurement, road noise, trailers, roadway aging, roadway wear, studded tires		18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616	
19. SECURITY CLASSIF. (of this report) None	20. SECURITY CLASSIF. (of this page) None	21. NO. OF PAGES 38	22. PRICE

Final Report

Tire Noise - Effects of Roadway Wear - II
Agreement GC8719, Task 3

THE EFFECT OF ROADWAY WEAR ON TIRE NOISE

by

James D. Chalupnfk, Professor
Department of Mechanical Engineering, FU-10
University of Washington
Seattle, WAshington 98195

and

Donald S. Anderson, Acoustical Engineer
Environmental and Special Services
WSDOT District #1
15700 Dayton Avenue North
Seattle, Washington 98133

Washington State Transportation Center (TRAC)
University of Washington, JE-10
The Corbet Building, Suite 204
4507 University Way N.E.
Seattle, Washington 98105

Washington State Department of Transportation
Technical Monitor
Donald S. Anderson, Acoustical Engineer

Prepared for

Washington State Transportation Commission
Department of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

August 1992

DISCLAIMER

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

This is the final report of a study of the way in which tire/road noise changes as the pavement ages and wears. Measurements of the levels of noise generated at the tire/road-surface interface were made on sections of a variety of asphaltic and concrete compositions ranging in age from newly laid to 29 years. Data from these measurements are presented in graphical form showing levels and trends of levels with time. While the measurements made in this study do not portray the noise levels at the roadside, they do rank order the source noise levels of the various surfaces devoid of the noise absorption characteristics of the surface. An interpretation of the data is provided to assist highway planners, designers, or environmental engineers. As an add-on to the main study, a comparison of the noise from studded tires and non-studded tires of the same tread design was made for a variety of roadway surface types.

BACKGROUND

Studies of the noise generated by the interaction of tires with the road surface are numerous. Typically, these studies have been aimed at evaluating the effect produced by varying one of the following:

- the tire design and
- the road surface texture.

Researchers have taken several approaches to gathering the information for these studies. The two most favored methods are (1) the trailer method, which uses microphones mounted near the tire/road contact patch, and (2) the statistical passby (SPB) method in which noise generated by the traffic passing a designated point is measured near the roadside. For automobiles, most of the noise is produced by the interaction of tires with the roadway surface; for this reason, SPB measurements are considered by some to be studies of tire noise.

Typical of the work performed using trailer method are the studies by Sandberg and Ejsmont (1, 2, 3), Tatsushita (4), Steven (5), Springborn (6), and Breyer (7). Measurements of tire/road noise made at the side of the road have been made by von Meier (8, 9, 10), Samuels (11), Kragh (12, 13), and Vale (14).

The literature lacks sufficient information concerning the effects of pavement wear on noise levels. To fill this information gap, earlier studies were undertaken by the University of Washington (UW) and the Washington State Department of Transportation (WSDOT). The main purpose of these investigations was to learn more about the effects of wear and aging of the roadway surface on tire noise. The authors have used the trailer method successfully over a period of several years to study how noise generated at the tire/road interface is affected by the aging of roadway surfaces (15, 16, 17, 18). Forty-one roadway sections were studied in the earlier works, which included several cases involving each of the following materials:

- high-density portland cement concrete,
- latex-modified portland cement concrete,
- portland cement concrete,
- Class "D" open-graded asphalt cement pavement,
- polyester fiber asphalt cement pavement,
- Class "B" asphalt cement pavement, and
- rubber-modified asphalt cement pavement (Plus-Ride asphalt).

In the earlier studies performed by the University of Washington's Sound and Vibration Research Laboratory and the Environmental Engineering Department of District #1 of the Washington State Department of Transportation, the 41 surfaces that were selected were all freshly laid when the study began. Changes in the noise characteristics generated by these surfaces were tracked over two 2-year contract periods. Researchers recognized that the four years represented only a small portion of the expected life span of the portland cement concrete pavements. At the time that the study was undertaken, it was believed that the useful life span of asphalt cement pavements was on the order of seven years;* thus, the initial study covered over half the expected life span of these surfaces.

Researchers realized that it was unlikely that the study would continue for the lifetime of the portland cement concrete sections started in the earlier study. A new strategy was proposed for completing the study in a reasonable time frame. Portland cement concrete sections of the Washington state highway system that ranged in age from 6 to 28 years would be combined with the sections from the original study, thus extending the ages of PCCP surfaces studied to cover their expected life spans. The study was funded, and the material presented herein is derived from that study.

---

* At the time of this report, materials specialists at District #1 of the Washington State Department of Transportation estimated that the life spans of asphaltic pavements range from 5 years for rubber-modified ACP to 12.5 years for Class B ACP.

TERMINOLOGY

Acoustical Definitions

Some acoustical terms referenced in this report may be unfamiliar to the reader. A list of definitions follows.

Noise — any *unwanted sound.*

Hertz (Hz) — the unit of frequency. One Hz is equal to one cycle per second. The unit was named to honor Heinrich Hertz, who conducted research in the area of pitch (and frequency) discrimination.

Newton (N) — the force required to accelerate one kilogram at a rate of one meter per second per second. One Newton is equivalent to about 0.225 pound force (about the weight of a Washington Delicious apple). The unit was named in honor of Sir Isaac Newton, who performed fundamental research in the area of particle dynamics.

Sound pressure — the root-mean-square (rms) value of the fluctuations in the atmospheric pressure in the (human) audible range of approximately 20 Hz to 20,000 Hz. The unit of sound pressure is the Pascal, abbreviated Pa. This unit is equal to the force of one Newton equally distributed over an area of one square meter, roughly 0.000145 psi. It was named in honor of Blasius Pascal, who performed historical work research involving hydraulic pressure.

Decibel (dB) — one-tenth of a Bel, the unit used to compare the powers (or energies) of two signals. In acoustics, the signals are the sound pressure levels of two sources. The Bel is the logarithm of the ratio of two power-related quantities; thus, the decibel is ten times that ratio. In acoustics, the acoustical power is proportional to the sound pressure squared; hence, in acoustics, the decibel is 20 times the logarithm of the measured pressure to some reference pressure. Mathematically, in acoustics, the decibel is $20 \log(p/p_{ref})$, where p_{ref} is taken to be the threshold of hearing for the average listener at 1,000 Hz under free field conditions. Because the decibel is derived from the Bel, which in turn was named to honor Alexander Graham Bell, it is abbreviated "dB."

Sound pressure level* **(SPL)** — the root-mean-square (rms) value of the fluctuations in the atmospheric pressure in the (human) audible range of approximately 20 Hz to 20,000 Hz *expressed in decibels* relative to the threshold of hearing for the average listener at 1,000 Hz under free field conditions. Sound pressure level, SPL, may be modified by an additional descriptor indicating a frequency weighting factor that is applied to the measurement (see below).

Sound level meter (SLM) — an instrument that measures sound pressure and displays the results in decibel units. Erroneously, but frequently, referred to as a "decibel meter."

A-weighted sound pressure level (dBA) — sound pressure level measured by a system or instrument (e.g., an SLM) that weights sounds at different frequencies in such a way as to mimic the human response to sounds. For instance, humans are less sensitive to sounds at low frequencies in the audible range; therefore, the contributions of sounds at low frequencies are "attenuated" by the A-weighting system. The system is usually an electrical circuit built into a sound level meter.

A-weighted noise level — A-weighted sound pressure level of an unwanted sound.

Octave — in music, a span of eight diatonic notes in pitch. (Written "8va" in musical shorthand.) In acoustics, one tone is an octave above another if its frequency is twice that of the other. Mathematically, two tones are an octave apart if ratio of the frequencies of the tones is two to the first power. Two octaves are represented by a ratio of two to the second power, and so forth. Human response to pitch is approximately logarithmic; thus, the human perceives an octave between two notes as approximately the same, regardless of where the two notes occur in the audible range. Because the octave is a human subjective metric, it is used in evaluating the unwantedness of noises in the field of psychoacoustics. Ten octave bands cover the audible range for humans.

One-third octave (1/3 8va) — one-third of an octave, or two raised to the one-third power (26 percent). Acoustical engineers recognize that one octave is a rather broad range in frequencies, so the audible band has been subdivided into thirty 1/3 octave bands in order to better understand the nature of noises.

---

* In acoustics, the use of the word "level" implies that the quantity is expressed in power-related logarithmic units, usually decibels.

1/1 (1/3) Octave band	a band of frequencies 1/1 (1/3) octave wide, identified by the geometric mean frequency of the band. The 1/1 octave band center frequencies in the audible range are 31.5, 63, 125, 250, 500, 1,000, 2,000, 4,000, 8,000, and 16,000 Hz. The 1/3 octave band center frequencies in the audible range are 25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1.0k, 1.25k, 1.6k, 2.0k, 2.5k, 3.15k, 4.0k, 5.0k, 6.3k, 8.0k, 10.0k, 12.5k, 16.0k, and 20.0k Hz.
1/1 (1/3) Octave band level	the sound pressure level of a given sound in a given 1/1 (1/3) octave band.
1/3 Octave band format	a format in which the 1/3 octave band levels are plotted against the corresponding 1/3 octave band center frequency. Since the values of these frequencies represent a geometric progression, they are equally spaced when plotted to a logarithmic scale.

Highway Surface Materials Definitions

Researchers working on this project studied highway surfaces made of a number of different material types. They are listed, with their abbreviations, below.

PCCP	Portland cement concrete pavement. Recently, the highway construction industry has started using a number of additives to impart certain characteristics to the concrete used in highway and major roadway surfaces. Prior to approximately 1980, little distinction was made between these concretes.
LMPCCP	Latex-modified portland cement concrete pavement. A popular formulation of portland cement to which liquid latex has been added.
HDPCCP	High-density portland cement concrete pavement.
ACP	Asphalt cement pavement. This abbreviation is frequently used with a modifier that designates aggregate size, among other characteristics.
BACP	Class B asphalt cement pavement.
DACPOG	Open-graded class D asphalt cement pavement. Open-graded, or porous asphalt, sometimes called drainage asphalt, is a formulation of asphalt cement that contains voids that permit water to drain from the surface.
PMACP	Asphalt cement pavement to which polyester fibers have been added.
RMACP	Asphalt cement pavement to which pulverized rubber has been added. Also known as "Plus-Ride pavement."

OBJECTIVE

The long term objective of this study was to measure the A-weighted levels and examine the spectra of tire noise from selected pavement types as a function of time to determine how tire noise is affected by differences in the following variables:

- surface composition,
- surface wear, and
- surface roughness.

PROCEDURE

The ultimate goal of this project was to study the way in which the characteristics of tire/road noises change in relation to wear and aging of the road surface. Members of this research team had previously studied the relationship in early stages of the life spans of both portland cement concrete and asphaltic pavements. It became clear that it would be impractical to track developments of the same sections over their complete life spans, particularly in the case of the concrete pavements. Instead, researchers identified a number of sections that had been laid down at different times in the past. Of these, researchers selected 140 sections ranging in age from 7 to 29 years for study. Data from such a variety of pavement sections may not be as consistent as data from a fixed collection of sections, since undocumented changes, such as lane changes, which affect the acoustical performance of these surfaces, have often been made. However, this approach allowed the research team to complete the study within a reasonable period of time.

Inclusion of test sections used in earlier studies extended the period of intensive analysis of these surfaces to six years, which approaches the lifetime expectancy of some asphalt pavements. The additional test sections concentrated on enlarging the database on concrete pavements to include their acoustical performance in the later stages of their useful life.

This study also compares the level of noise generated by tires equipped with traction studs to that of similar tires without studs. Three sets of tires that were matched in pairs, with and without studs, were purchased for this portion of the study. Each pair represented a different type of tread design. One pair was typical of the "all weather type," one pair was judged to have "moderately aggressive" tread design, and one pair was judged to have an "aggressive" tread design. The aggressiveness rating scheme was purely subjective. The tires were purchased from a local vendor and mounted on wheels compatible with the test trailer.

The data were collected in two series conducted one year apart. A series consisted of a run over the same triangular course with each of the six tires. The course included pavements representative of the different types used in the other portion of this study.

TEST EQUIPMENT

Since the experimental procedures followed in this study were similar to those used in earlier research on tire noise performed by the Sound and Vibration Research Laboratory (SVRL) and WSDOT, researchers on this study chose to use the same equipment and instruments as well. This equipment included a specially instrumented 4- by 6-foot trailer that was purchased for the earlier studies and is used exclusively for tire noise studies at the SVRL. The instrumentation includes a microphone with a custom-designed mounting bracket that holds the microphone in a fixed position with respect to the tire tread patch. The trailer is loaded to simulate the weight of an intermediate-size passenger sedan. Pressure in the tire being tested was held constant and was measured before each run. Roadway temperature was measured at each of the test sections as part of the present study with a radiant infrared sensing thermometer.

The SVRL has over a half million dollars' worth of instruments for the measurement and analysis of sounds and mechanical vibrations. Data-recording instruments used in this study included microphones, accelerometers, and two instrumentation-quality, battery-powered tape recorders. The data were analyzed on a Hewlett-Packard system that included a Model 236 color computer and a Model 3561A dynamic signal analyzer. The latter is a fast fourier transform (FTT) analyzer, which analyzes the acoustical spectrum of signals recorded on tape recorders. The analyzer allows researchers to present data in 1/3 octave or narrow-band formats. Further data reduction can be performed on the 236 computer, which captures the data from the analyzer by means of an HPIB interface bus. The data were stored on diskette after analyzer processing.

ROAD SURFACE TESTS

Test Section Selection

Earlier work had been performed on a number of roadway sections of known history, so those sections were also used in this study. The roadway types represent most of the surface preparations currently used by WSDOT on highways in the state of Washington. They include sections with the following surface composition:

- portland cement concrete,
- latex-modified portland cement concrete,
- high density portland cement concrete,
- Class "D" ACP open-graded,
- polyester fiber ACP,
- Class "B" ACP, and
- rubber-modified ACP (Plus-Ride asphalt).

In all, 41 test sections were used in the previous studies; they covered a period of four years.

The present study was aimed at continuing this study for two additional years and, more importantly, investigating the behavior of portland cement concrete pavement (PCCP) during the latter portion of its lifetime. A period of six years covers a good portion of the expected lifetime of the asphalt concrete pavement (ACP) sections, but represents only a small portion of the lifetime of the PCCP sections.

After determining the locations of suitable PCCP sections throughout the state highway system, researchers decided that the most efficient way to collect the required data would be to use the section of interstate route I-5 (and I-205) between the borders of Canada and Oregon. One-hundred-and-forty sections were identified in all, from which data were gathered from 130. Pavement ages in this sample ranged from 7 to 29 years at the time of data collection. This covers most of the expected lifetime of typical PCCP sections, although the sections were not the same ones that were used in the original studies. For this reason, it was expected that the data from these sections would show more scatter than would the data from sections that were tracked in the original study.

Prior to about 1980, it was not common practice to differentiate between the various types of PCCP used in a given paving operation. For this reason, the test sections added in the present study have been given the single designation, "PCCP." The only high-density PCCP included in the study was in the sections on the West Seattle Bridge. For this reason, the data on these sections were included in the general classification "PCCP."

Studded Tire Test Route

The test sections with which the research team was familiar were scattered over a four-county area; for the sake of efficiency, researchers decided to select a more compact, closed-circuit route for the tire tests and measurements. They chose a route that constitutes a triangular circuit that runs south from the University of Washington on I-5 to Tacoma, then proceeds northeast on SR 18 to the junction with I-90, and then returns to Seattle. This route included sections representing all of the main surface types used by WSDOT, but the ages of the sections were not used as a criterion for selection in this portion of the study.

DATA ACQUISITION

Data for this project were collected on magnetic tape, which was labeled and saved for future reference. Data on the I-5/I-205 sections were gathered twice, once in the summer of 1989 and once in the summer of 1990. Data for the studded tire tests were also taken twice during this study. Data on the original sections were collected up until the summer of 1991 biannually. Including the original work, data for these sections were gathered a total of 13 times from the summer of 1985 to the summer of 1991.

Table 1 includes a list of the test sections used in the previous (and current) studies. Table 2 contains a similar list of the portland cement pavement sections especially added for this study.

Table 1. Compilation of the "Original" Roadway Test Sections Giving Location, Lane, and Pavement Type

No.	S.R.	Description	Lane	Pavement	1990 ADT All Lanes	Trucks %
1.		King County Airport	1 SB	BACP	N/A	N/A
2.		King County Airport	1 NB	BACP	N/A	N/A
3.	I-5	Puyallup R. to King Co.	2 SB	DACPOG	143,942	12
4.	I-5	Puyallup R. to King Co.	1 NB	DACPOG	143,942	12
5.	I-5	East T St.	3 SB	LMPCCP	150,372	12
6.	I-5	S.R. 167	3 SB	LMPCCP	150,372	12
7.	I-5	Portland Ave.	3 SB	LMPCCP	150,372	12
8.		West Seattle Bridge	1 WB	PCCP	92,200	12
9.		West Seattle Bridge	2 WB	PCCP	92,200	12
10.		West Seattle Bridge	1 EB	PCCP	92,200	12
11.		West Seattle Bridge	2 EB	PCCP	92,200	12
12.	I-5	Galer/Lakeview Viaduct	2 NB	LMPCCP	188,867	6
13.	I-5	Galer/Lakeview Viaduct	2 SB	LMPCCP	188,867	6
14.	I-5	Galer/Lakeview Viaduct	3 SB	LMPCCP	198,000	6
15.	I-5	Ship Canal Bridge	1 NB	LMPCCP	198,000	6
16.	I-5	Ship Canal Bridge	2 NB	LMPCCP	198,000	6
17.	I-5	Ship Canal Bridge	2 SB	LMPCCP	198,000	6
18.	I-5	Ship Canal Bridge	3 SB	LMPCCP	198,000	6
19.	I-5	Swamp Creek I/C	1 NB	BACP	126,300	6
20.	I-5	Swamp Creek I/C	2 NB	BACP	126,300	6
21.	I-5	Swamp Creek I/C	1 SB	BACP	126,300	6
22.	I-5	Swamp Creek I/C	2 SB	BACP	126,300	6
23.	I-5	Union Slough	1 NB	LMPCCP	120,000	5
24.	I-5	Union Slough	2 NB	LMPCCP	120,000	5
25.	I-5	Union Slough	1 SB	LMPCCP	120,000	5

Table 1. Compilation of the "Original" Roadway Test Sections Giving Location, Lane, and Pavement Type (Continued)

No.	S.R.	Description	Lane	Pavement	1990 ADT All Lanes	Trucks %
26.	I-5	Union Slough	3 SB	LMPCCP	120,000	5
27	I-5	Steamboat Slough	1 SB	LMPCCP	120,000	5
28.	I-5	Steamboat Slough	3 SB	LMPCCP	120,000	5
29.	I-5	Ebey Slough	1 SB	LMPCCP	120,000	5
30	I-5	Ebey Slough	3 SB	LMPCCP	120,000	5
31	530	Dahlgren Road	1 NB	BACP	3,350	12
32.	530	Dahlgren Rd.	1 SB	BACP	3,350	12
33.	530	Dahlgren Rd.	1 NB	PMACP	3,350	12
34.	530	Dahlgren Rd.	1 SB	PMACP	3,350	12
35.	530	Dahlgren Rd.	1 NB	RMACP	3,350	12
36.	530	Dahlgren Rd.	1 SB	RMACP	3,350	12
37.	I-405	Factoria HOV	HOV	BACP	89,900	0
38.	I-90	Asahel Curtis I/C	1 EB	PCCP	21,125	29
39.	I-90	Asahel Curtis I/C	2 EB	PCCP	21,125	29
40.	I-90	Snoqualmie Summit	3 EB	PCCP	20,600	29
41.	I-90	Snoqualmie Summit	4 EB	PCCP	20,600	29

Table 2. Sections of Old PCCP Used in the Current Study

Run	Dist. No.	S.R.	Beg. M.P.	End M.P.	Description	Compl. Date	Lane	ADT	Truck %
Seattle									
O1	1	5	168.34	167.70	Ship Canal	1964	2SB	181,700	6
O2	1	5	166.36	165.44	Viaduct	1967	1SB	177,225	6
O3	1	5	165.28	164.93	James St	1967	1SB	112,400	6
O4	1	5	162.68	162.36	End Median Left	1967	2SB	194,400	6
O5	1	5	162.24	161.68	Viaduct	1967	2SB	183,400	6
O6	1	5	161.54	160.16	Ramp	1967	2SB	165,050	6
O7	1	5	160.07	159.71	Fill	1967	2SB	157,500	6
O8	1	5	159.67	158.47	Military	1967	2SB	152,500	12
O9	1	5	158.47	156.68	S Norfolk	1969	2SB	157,500	12
O10	1	5	156.34	156.01	Duwamish	1969	2SB	165,750	12
O11	1	5	155.98	154.67	Interurban	1969	2SB	171,650	12
O12	1	5	154.50	154.16	Ramp	1969	2SB	171,650	12
O13	1	5	154.12	153.15	Klickitat	1969	2SB	171,650	12
O14	1	5	153.15	152.29	Uxing-S 178th	1966	2SB	154,462	12
O15	1	5	152.26	149.39	188th	1966	2SB	146,523	12
O16	1	5	149.17	147.67	SR 516	1962	2SB	146,523	12
O17	1	5	147.64	146.84	S 260th	1962	2SB	137,511	12
O18	1	5	146.81	146.47	S 272nd	1962	2SB	137,511	12
O19	1	5	146.43	145.82	Military	1962	2SB	137,511	12
O20	1	5	145.79	144.69	S 288th	1962	2SB	137,511	12
O21	1	5	144.65	142.81	Military	1962	2SB	137,511	12
O22	1	5	142.79	142.04	S 336	1962	2SB	137,511	12
O23	1	5	142.00	139.50	SR 18	1962	2SB	137,511	12
O24	3	5	134.87	134.10	Portland	1965	3SB	150,372	12
O25	3	5	133.70	132.88	Pacific	1966	2SB	150,372	12
O26	3	5	116.52	115.46	Median Xover Left	1969	2SB	70,300	22
O27	3	5	115.38	114.97	Slough	1969	2SB	70,300	22
O28	3	5	114.54	114.14	Nisqually	1969	2SB	62,500	22
O29	3	5	114.09	109.19	Mcallister Crk	1969	2SB	62,500	22
O30	3	5	50.01	48.01	End Of Section	1976	2SB	30,600	10
O31	3	5	47.97	45.44	Huntington	1976	2SB	30,600	10
O32	4	5	44.72	44.25	Start PCCP	1976	2SB	32,300	10
O33	4	5	19.82	18.37	N-Fk Lewis River	1970	2SB	41,354	10
O34	4	5	18.20	14.59	E-Fk Lewis River	1970	2SB	43,221	10
O35	4	5	14.59	13.73	Const JT Exit 14	1965	2SB	44,944	10
O36	4	5	13.73	9.53	End of On Ramp	1969	2SB	44,800	10
O37	4	5	9.51	7.98	SR 502	1969	2SB	38,700	10
O38	4	5	4.30	3.01	Start PCCP	1962	1SB	56,767	10
Vancouver, WA									

Table 2. Sections of Old PCCP Used in the Current Study (Continued)

Run	Dist. No.	S.R.	Beg. M.P.	End M.P.	Description	Compl. Date	Lane	ADT	Truck %
O39	4	5	3.01	4.31	Start PCCP	1962	1SB	56,767	10
O40	4	5	19.50	19.87	Start PCCP	1970	2SB	41,354	10
O41	4	205	37.16	36.08	EXIT 36	1976	1SB	28,300	9
O42	4	205	35.99	34.34	Salmon Creek	1976	1SB	36,700	9
O43	4	205	33.99	31.02	RR	1976	1SB	36,700	9
O44	4	205	31.02	29.82	S of 1st STR	1977	1SB	62,600	9
O45	4	205	29.79	27.54	Burton	1977	2SB	72,300	9
O46	4	205	27.54	27.09	Start of ACP	1982	2SB	82,000	9
Columbia River									
O47	4	205	27.09	27.53	Exit Sign	1982	2SB	82,000	9
O48	4	205	27.53	29.79	End of J-Curb	1977	2SB	72,300	9
O49	4	205	29.82	31.11	Burton	1977	2SB	62,600	9
O50	4	205	31.11	33.99	Warning Sign	1976	2SB	36,700	9
O51	4	205	34.34	35.99	St Johns	1976	1SB	36,700	9
O52	4	205	36.08	37.16	Salmon Creek	1976	1SB	25,500	9
O53	4	5	43.92	44.91	Start PCCP	1976	2NB	32,300	10
O54	4	5	45.77	46.14	"Hqs Rd. Exit 46"	1976	2NB	32,300	10
O55	4	5	46.41	47.97	"On Ramp 50 RT"	1976	2NB	32,300	10
O56	4	5	48.01	50.93	"On Ramp 50 RT"	1976	2NB	29,900	10
O57	3	5	108.81	109.14	After Sor-.1 mi	1969	2NB	91,693	22
O58	3	5	109.19	114.09	Martin	1969	2NB	62,500	22
O59	3	5	114.14	114.51	Mcallister	1969	2NB	62,500	22
O60	3	5	132.88	133.70	M	1966	2NB	150,372	12
O61	3	5	134.10	134.87	Pac Ave Uxing	1965	2NB	150,372	12
O62	1	5	139.50	142.00	Start PCCP	1962	2NB	137,511	12
O63	1	5	142.04	142.79	SR 18	1962	2NB	137,511	12
O64	1	5	142.82	144.65	S 336th	1962	2NB	137,511	12
O65	1	5	144.69	145.79	Military	1962	2NB	137,511	12
O66	1	5	145.82	146.44	S 288th	1962	2NB	137,511	12
O67	1	5	146.48	146.81	Military	1962	2NB	137,511	12
O68	1	5	146.84	147.64	S 272nd	1962	2NB	137,511	12
O69	1	5	147.67	149.17	S 260th	1962	2NB	146,523	12
O70	1	5	149.22	152.65	SR 516	1966	2NB	146,523	12
O71	1	5	152.65	153.65	"I-5 North"	1969	2NB	171,650	12
O72	1	5	153.74	154.40	Fill	1969	2NB	171,650	12
O73	1	5	154.67	155.98	Southcenter	1969	2NB	171,650	12
O74	1	5	156.01	156.34	Interurban	1969	2NB	165,570	12

Table 2. Sections of Old PCCP Used in the Current Study (Continued)

Run	Dist. No.	S.R.	Beg. M.P.	End M.P.	Description	Compl. Date	Lane	ADT	Truck %
O75	1	5	156.48	158.18	Start PCCP	1969	2NB	150,600	12
O76	1	5	158.47	159.67	S Norfolk	1967	2NB	152,500	12
O77	1	5	159.71	161.65	Military	1967	2NB	157,500	6
O78	1	5	161.68	162.19	S Lucile	1967	2NB	183,400	6
O79	1	5	162.36	162.68	Viaduct	1967	2NB	194,400	6
O80	1	5	164.94	165.32	King		2NB	112,400	6
O81	1	5	166.22	166.91	Olive Uxing		2NB	183,000	6
O82	1	5	167.67	168.34	Viaduct	1964	2NB	181,700	6
Seattle									
O83	1	5	169.18	170.25	Ship Canal	1965	2NB	185,300	6
O84	1	5	170.50	170.85	Ravenna	1963	2NB	167,100	6
O85	1	5	170.85	172.32	After 522 Uxing		2NB	171,066	6
O86	1	5	172.35	172.76	Ramp		2NB	161,600	6
O87	1	5	172.79	175.10	NE Northgate		3NB	171,066	6
O88	1	5	175.14	176.13	Start PCCP		3NB	161,600	5
O89	1	5	176.18	177.75	Start PCCP		3NB	168,166	5
O90	1	5	191.55	192.81	Lowell	1969	3NB	163,900	5
O91	1	5	193.26	193.63	RR		2NB	156,150	5
O92	1	5	194.05	194.81	Everett		2NB	119,300	5
O93	1	5	209.46	210.61	Stillquamish River	1976	2NB	120,000	5
O94	1	5	210.67	212.27	Pilchuck Creek.	1976	2NB	120,000	5
O95	1	5	215.08	216.77	300th NW	1976	2NB	51,517	5
O96	1	5	216.80	218.81	Dawson	1976	2NB	51,517	5
O97	1	5	218.81	219.82	Right On Ramp	1971	2NB	51,517	5
O98	1	5	231.80	233.33	Joe Leary Slough	1966	1NB	51,517	5
O99	1	5	233.68	234.04	Creek	1966	1NB	51,517	5
O100	1	5	234.08	240.02	Samish River	1966	1NB	26,200	14
O101	1	5	240.07	242.36	Colony	1966	1NB	26,200	14
O102	1	5	246.05	250.73	Start PCCP	1967	2NB	25,733	14
O103	1	5	250.77	252.06	SR 11	1967	1NB	24,200	13
O104	1	5	252.06	252.97	Uxing 36th	1961	1NB	24,800	13
O105	1	5	252.99	253.52	Lakeway	1961	1NB	26,550	13
O106	1	5	253.91	255.36	RR	1961		30,400	13

Table 2. Sections of Old PCCP Used in the Current Study (Continued)

Run	Dist. No.	S.R.	Beg. M.P.	End M.P.	Description	Compl. Date	Lane	ADT	Truck %
O107	1	5	255.43	256.21	Squalicum Crk	1961	1NB	36,650	13
O108	1	5	256.24	256.98	SR 539	1961	1NB	49,250	10
O109	1	5	261.91	262.21	"Blue Info"	1977	1NB	60,800	10
O110	1	5	262.21	262.91	Const jt	1968	1NB	52,000	10
O111	1	5	274.20	276.20	Uxing Bus. Rte	1966	1NB	26,300	10
Blaine									
O112	1	5	276.22	274.20	N Blaine	1966	1SB	21,637	10
O113	1	5	274.20	273.86	Uxing Bus. Rte	1964	1SB	17,800	10
O114	1	5	261.03	258.01	"Blue Info"	1977	1SB	36,500	10
O115	1	5	256.98	256.24	Northwest	1961	1SB	52,000	10
O116	1	5	256.21	255.43	SR 539	1961	1SB	60,800	10
O117	1	5	254.82	253.91	Uxing SR 542	1961	1SB	49,250	10
O118	1	5	253.52	252.99	Lincoln	1961	1SB	36,650	13
O119	1	5	252.97	252.07	Lakeway	1961	1SB	30,400	13
O120	1	5	248.01	246.11	Start PCCP	1967	1SB	24,800	13
O121	1	5	243.46	242.89	Start PCCP	1966	1SB	24,800	13
O122	1	5	242.86	242.38	Nulle	1966	1SB	24,200	13
O123	1	5	242.36	240.07	Friday Creek	1966	1SB	24,200	13
O124	1	5	240.02	234.08	Colony Rd	1966	1SB	25,733	14
O125	1	5	234.04	233.68	Samish River	1966	1SB	26,200	14
O126	1	5	233.35	231.80	N Blaine	1966	1SB	26,200	14
O127	1	5	218.81	218.30	"Exit Starbird Rd"	1976	2SB	51,517	5
O128	1	5	216.77	215.08	Dawson	1976	2SB	51,517	5
O129	1	5	215.05	212.69	300th NW	1976	2SB	51,517	5
O130	1	5	212.66	210.64	SR 532	1976	2SB	51,517	5
O131	1	5	210.59	209.71	Pilchuck Creek	1976	2SB	51,517	5
O132	1	5	194.81	194.05	Snohomish River	1969	2SB	120,000	5
O133	1	5	193.63	193.26	Pacific	1969	2SB	120,000	5
O134	1	5	192.81	192.35	RR	1969	2SB	119,300	5
O135	1	5	177.75	176.16	SR 104	1965	3SB	156,150	5
O136	1	5	176.13	175.14	NE 175th	1965	3SB	163,900	5
O137	1	5	175.11	172.79	NE 155th	1965	3SB	168,166	6
O138	1	5	172.76	170.85	NE Northgate	1965	3SB	167,100	6
O139	1	5	170.85	170.54	"Exit 171"	1963	2SB	167,100	6
O140	1	5	170.25	169.18	End Of Structure	1965	2SB	185,300	6
Seattle									

DATA ANALYSIS

After each data-gathering session, the data were reduced to 1/3 octave band format using a Hewlett-Packard Model 3561A dynamic signal analyzer and an HP 236 computer; the data were stored on magnetic disk media. Duplicate copies have been maintained to ensure that the information is available for future analysis.

The data are presented in 1/3 octave format to show the frequency distribution of the near field noise from the tire/road interface. Figure 1 illustrates an example. This information is summarized by an A-weighted noise level which is shown both graphically and numerically on the right side of the graph.

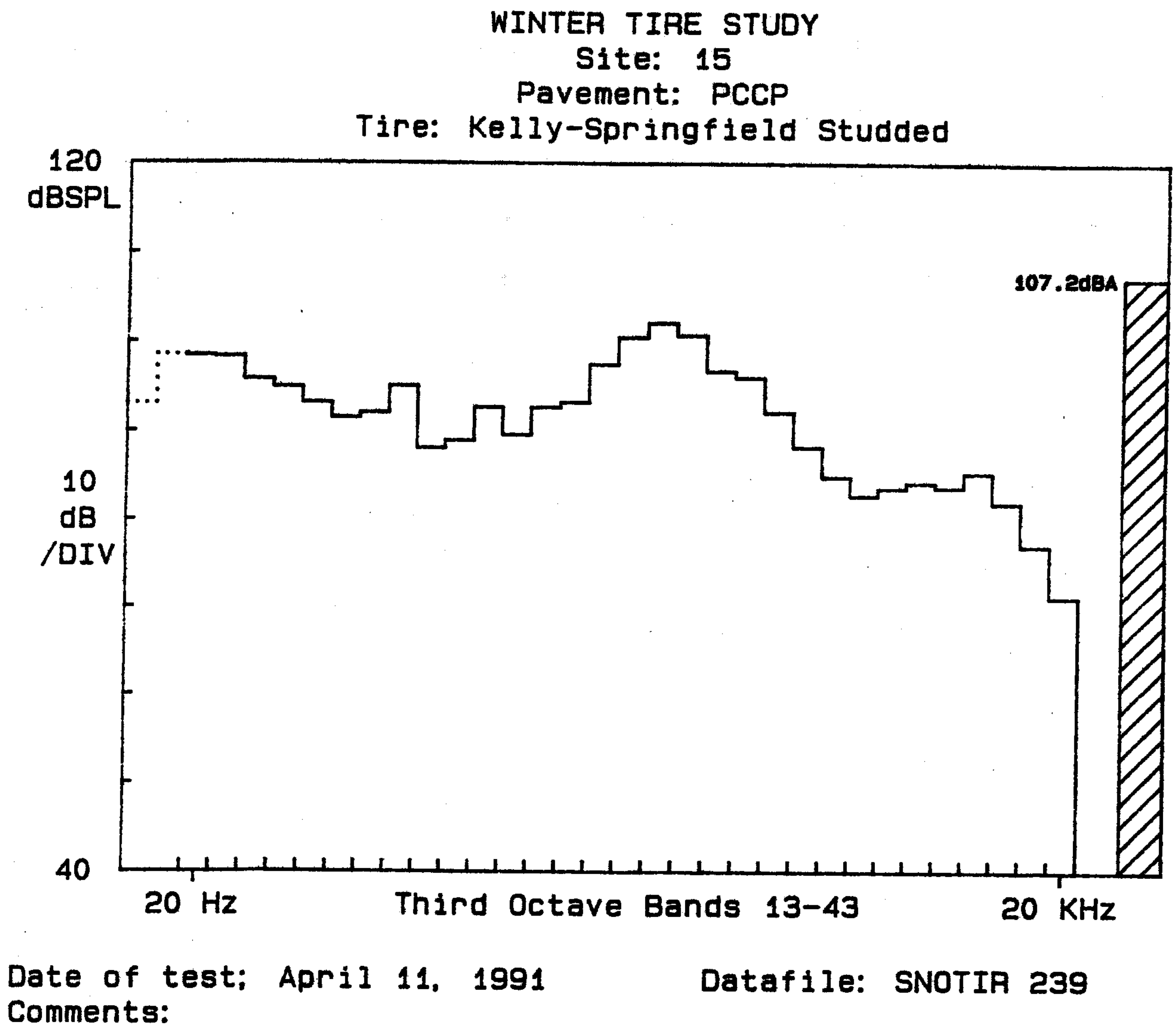

Figure 1. Data Sheet for Typical Studded Tire Data Gathering Run

FINDINGS

The results of this investigation are presented below. They are divided into three sections. Data for portland cement pavements are presented in the first section. The most important part of this section is the presentation of long-term data. Results for asphalt pavements are presented in the second section. These data are limited to the six years of this and previous studies. The third section contains the data from the studded tire portion of the investigation.

PCCP PAVEMENTS

Noise levels for portland cement concrete pavement (PCCP) are shown as a function of time over a pavement life up to 29 years in Figure 2. The data for sections ages 0 to 6 years are for those sections examined in the earlier studies. Those for ages 7 to 29 years are from the new sections evaluated in this current investigation.

Two sections of concrete pavement that were included in the earlier studies were exposed to significantly different climatic conditions, and as such, should be considered separately. These sections were located on I-90, in the Cascade Mountains. All other sections were located in the Puget Sound Basin.

The Asahel Curtis section is approximately halfway to the pass and is subject to frequent freeze-thaw cycles in the autumn and spring. The Snoqualmie Summit section, at the summit, is covered with snow for a good portion of the year and is also subject to freeze-thaw cycles in the autumn and spring. Traffic at Snoqualmie Summit was realigned three years after the initial study began, and the surfaces were dropped from the study at that time. Noise levels from these sections are illustrated for completeness in Figures 3 and 4.

Noise levels for latex-modified portland cement concrete pavement, LMPCCP, are shown in Figure 5. These data are for only those sections aged 0 to 6 years; and are for

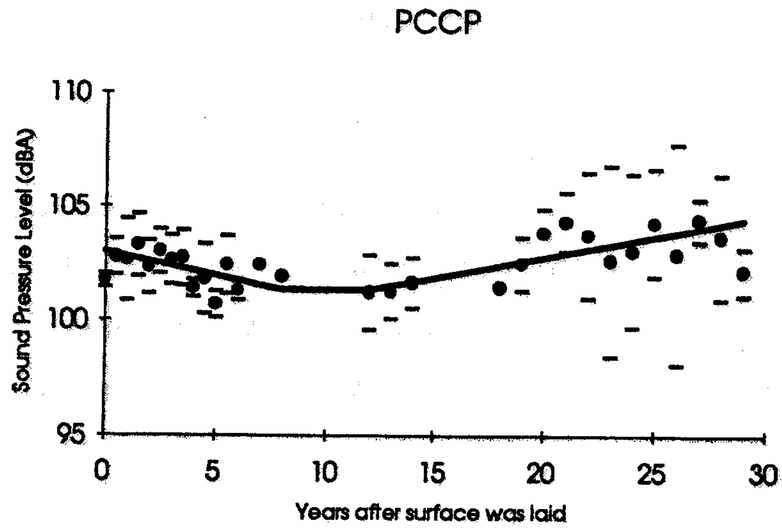

Figure 2. Noise Data for Portland Cement Concrete Pavements with Ages Ranging from Freshly Laid to 29 Years. These data represent 134 separate roadway sections. The dots mark the mean value; the bars mark the 90 percent confidence interval for the data.

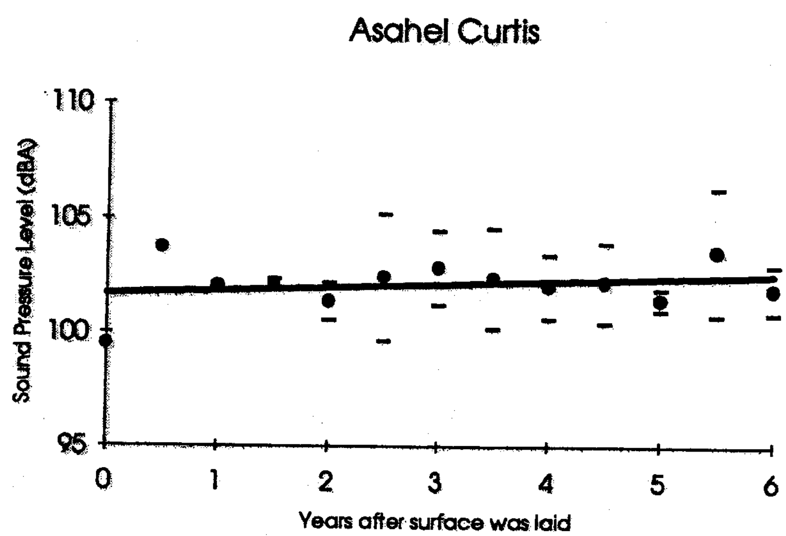

Figure 3. Noise Data for Portland Cement Concrete Pavement at Asahel Curtis Overcrossing Over a 6-year Period. The dots mark the mean value; the bars mark the 90 percent confidence interval for the data.

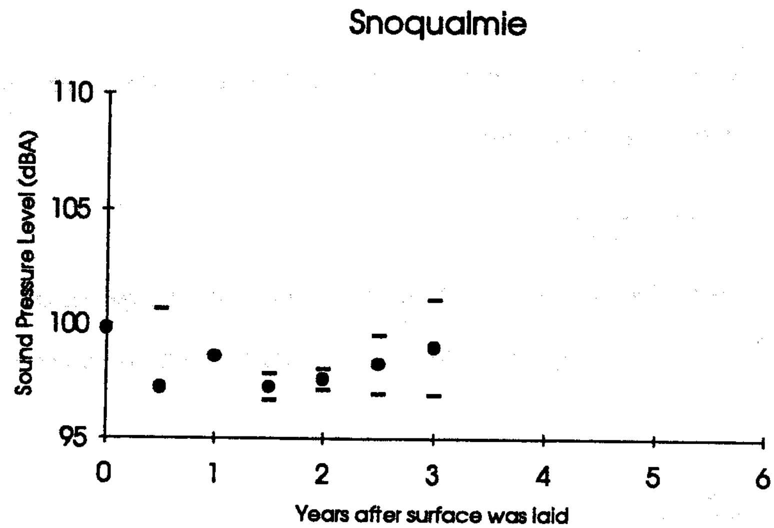

Figure 4. Noise Data for High-density Portland Cement Concrete Pavement at Snoqualmie Summit Over a 3-year Period. The dots mark the mean value; the bars mark the 90 percent confidence interval for the data.

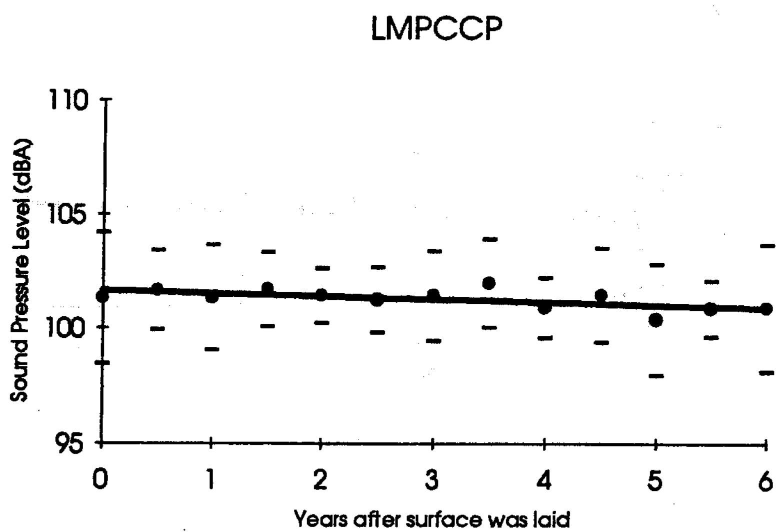

Figure 5. Noise Data for Latex-modified Portland Cement Concrete Pavements Over a 6-year Period. These data are for 18 separate roadway sections. The dots mark the mean value; the bars mark the 90 percent confidence interval for the data.

those sections used in the earlier studies. Among cement pavement types used in the initial studies, LMPCCP is the most common.

ASPHALT PAVEMENTS

All of the asphalt pavement data were collected on new pavement and tracked for a period of six years. The results from these measurements are presented in Figures 6 through 9.

STUDDED TIRES

Results from the studded tire tests are shown in Figure 10.

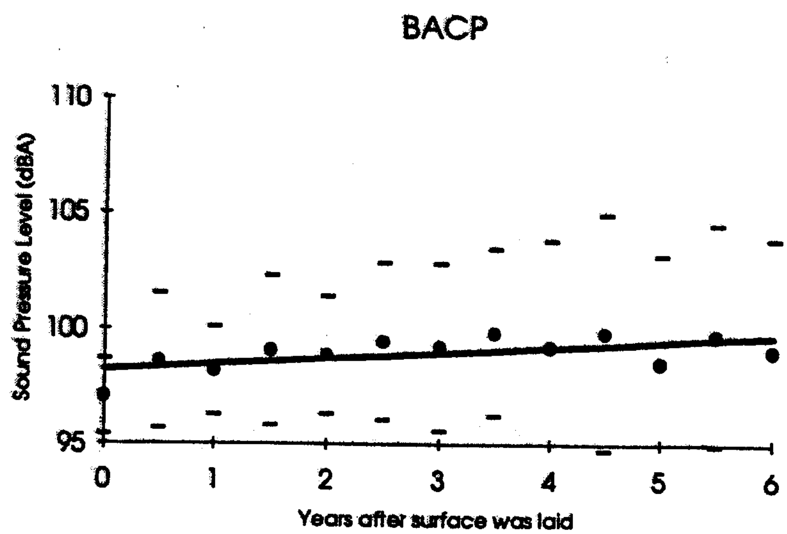

Figure 6. Noise Data for Class B Asphalt Pavements Over a 6-year Period. These data are for 8 separate roadway sections. The dots mark the mean value; the bars mark the 90 percent interval for the data.

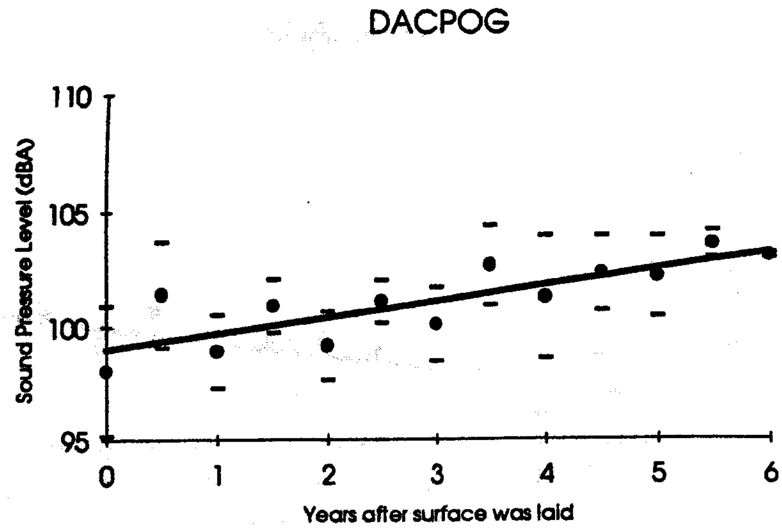

Figure 7. Noise Data for Class D Open-graded Pavement Over a 6-year Period. These data are for two roadway sections. The dots mark the mean value; the bars mark the 90 percent confidence interval for the data.

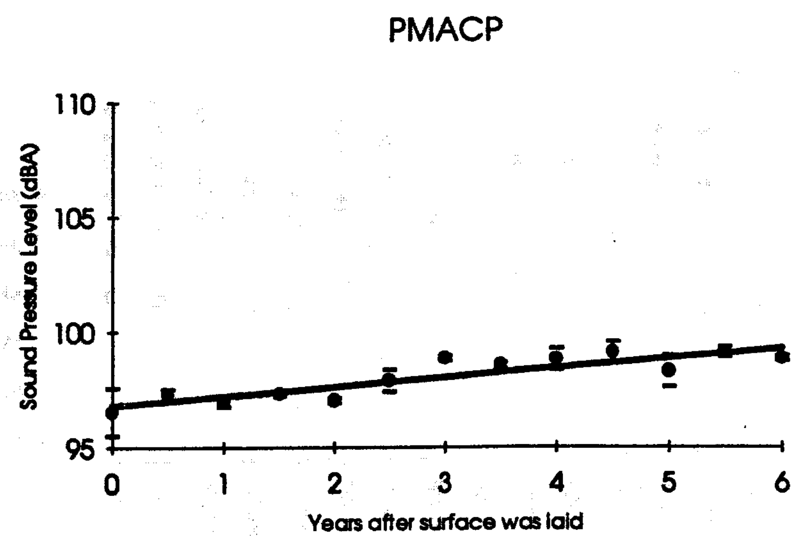

Figure 8. Noise Data for Polyester-modified Asphalt Pavement Over a 6-year Period. These data are for two roadway sections. The dots mark the mean value; the bars mark the 90 percent confidence interval for the data.

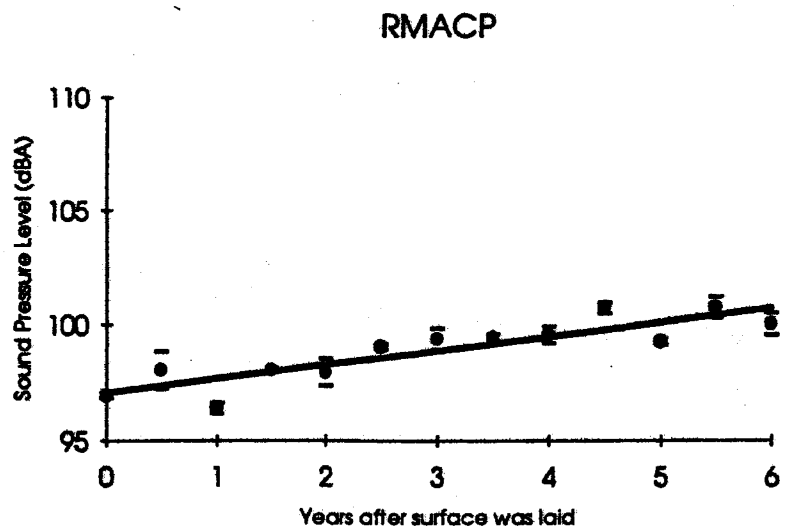

Figure 9. Noise Data for Rubber-modified Asphalt Pavements Over a 6-year Period. These data are for two roadway sections. The dots mark the mean value; the bars mark the 90 percent confidence interval for the data.

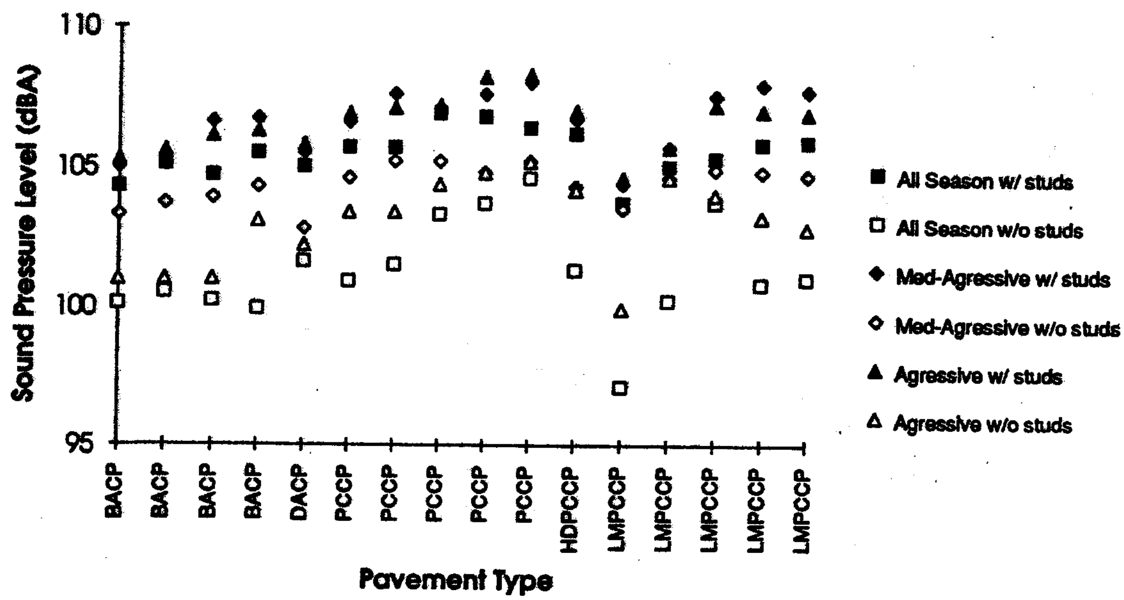

Figure 10. Data from the Studded Tire Tests Showing the Relative Differences in Noise from Studded and Non-studded Tires.

INTERPRETATION, APPRAISAL, AND APPLICATION

SURFACE WEAR

Based on the results of this study, it is apparent that noise generated at the tire/road interface of asphalt concrete pavement is less than portland cement concrete pavement in the initial phases of life span of these surfaces. Certain trends in the behavior of these surfaces can also be observed. Asphalt pavements appear to start out quieter, but the noise from these surfaces increases steadily from the beginning.

Concrete pavements start out somewhat noisier than asphalt pavements, but there is a period of approximately eight years during which the noise level decreases, reaching a minimum in the 8 to 12 year period. Beyond that, there is an increase in the noise generated by these surfaces. The reason for this behavior may be that traction enhancing treatments are applied to the cement concrete surfaces during the finishing process. At present, WSDOT texturizes pavement perpendicular to the centerline of the pavement with a comb. The comb is set to produce striations 0.015-foot deep, one-half inch apart. As the pavement ages, or wears, the irregularities in this treatment are worn down and smoothed, which reduces noise. Around the tenth year, the aggregate begins to emerge and from that point on, the surface gets rougher with time. On bridge decking, expansion joint hardware also becomes exposed, leading to slapping or popping noise at these junctures. (19)

An anomaly is observed in the two special cases mentioned earlier. The Asahel Curtis and Snoqualmie Summit sections were surfaced with portland cement concrete, but they behaved more like asphaltic surfaces. The starting noise level was lower than for other PCCP and there is even an increase in the noise level for the Snoqualmie Summit section data if the initial reading is disregarded. It will also be noted that there is more scatter in the data for these surfaces as a whole. As mentioned above, these surfaces are on I-90 near the summit of Snoqualmie Pass, and they are subject to frequent freeze-thaw cycling, chaining, sanding, etc., all of which might have affected their surface characteristics. While this might explain the increase in noise level, which we postulate is a manifestation of the aging process, it does not explain why the noise level was so low at the beginning of the test. This situation could be explained if the surfaces had not been provided with traction enhancing treatment when they were laid.

Seasonal variation in the noise generated by tires running on asphaltic surfaces is another phenomenon that can be seen in the data. This variation is particularly marked in the case of the open-graded Class D surfaces. The research team postulates that the asphalt softens with temperature, and that this leads to a cushioned ride for the tire, thus reducing the noise level during the summer. This phenomenon has been reported in private communications with other workers in the field of tire/road noise acoustics. Road surface temperatures were measured for the "original" test sections during this portion of the investigation. These measurements verify that surface temperatures during the summer runs were higher than those of the winter runs.

Transportation planners in Europe are showing substantial interest in "open-graded"* asphalt pavements, which are thought to have sound absorbing properties that are not easily detected with the trailer method of noise measurement. Because the microphone is positioned close to the source of the noise, the effects of propagation over the surface are not included in studies using this technique. Results of our research on this material are disappointing in that they show that this surface starts out slightly noisier and that the noise increases more rapidly with age. The seasonal variation mentioned above seems to be greater with this surface as well. Unfortunately, only one section of this interesting surface treatment was included in our study. This was a coincidence that was based on the point in time at which the research program was initiated. Only one section of DACPOG had been finished in the six-month period prior to the start of that study.

---

* Also known as "drainage," "pervious," or "porous" asphalt pavement.

Table 3 summarizes the information regarding tire noise and roadway surface age obtained from this study. The beginning noise levels are listed in the second column, under the heading "Starting Noise Level." The slope of the tire noise curve for the initial phase is listed in the third column. Noise levels after six years (eight years in the case of PCCP) are given in the fourth column. The research team was able to collect data on PCCP beyond six years in the extended study, as explained earlier, so the row containing the PCCP data, and only that row, is continued through the next four columns. The slope for the mid-life (from 8 to 12 years) portion of PCCP is zero, so the noise level after 12 years is about the same as at 8 years, as shown in columns five and six. Column seven gives the slope for aging (over 12-year-old) PCCP pavements, resulting in a final level after 29 years, listed in the last column. Because data were not collected for LMPCCP and the ACPs for the last four of these categories, those spaces in Table 3 are left blank.

The reader should bear in mind that extrapolation into these regions is risky; nonetheless, some observations can be made. One must keep in mind that the noise levels reported here are for a location only 20 centimeters from the tire patch. The noise level at the side of the roadway will be much lower for an individual tire. The noise for a normal passenger car is composed of the noise from four tires, two of which are partially shielded from the roadside observer, and from other sources that have not been included in the present study. Finally, *the ways in which the various pavement types affect the noise as it propagates from the tire patch to the roadside have not been included in this study*. This important issue is the subject of an investigation being conducted by the same WSDOT-UW research team that has conducted the study contained herein.

Highway planners, designers, and environmental engineers should be aware of the trends shown in Table 3 when selecting materials to be used in resurfacing applications in potentially noise-sensitive locations. It should be clearly understood that these data are

Table 3. Noise Performance of Pavement Types

Pavement Type	Starting Noise Level (dB)	Initial Slope 0-6 (8) years (dB/year)	6 (8*)-Year Noise Level (dB)	Mid-life Slope 8-12 years (dB/year)	12-Year Noise Level (dB)	Aging Slope 12-years (dB/year)	29-Year Noise Level (dB)
PCCP	103.0	-0.21	101.3	0	101.3*	0.18	104.5
LMPCCP	101.8	-0.13	101.1				
PCCP*	101.9	0.13	102.7				
BACP	98.4	0.24	99.9				
DACPOG	99.2	0.70	103.4				
PMACP	97.0	0.41	99.5				
RMACP	97.3	0.60	100.9				

* This is the I-90 section at Asahel-Curtis, which has been subject to numerous freeze-thaw cycles. Snoqualmie Summit data are not given because the data exist for only three years.

only for the noise generated by the interaction between the tires and the roadway surface. The data for the first six years are relatively accurate. Using the figures given in the table, one should be able to predict the performance of these surfaces to within 1.6 decibels at the 80 percent confidence level. Class BACP seems to show the greatest variation among these surfaces; it is assumed to be more dependent on traffic volume and mix than PCCPs.

The long-term data on PCCPs also show greater variation. This is not surprising in that the historical information regarding the test sections used in this study is sketchy. The 80 percent confidence interval for these surfaces is within 3.9 decibels of the levels predicted by the values given in Table 3.

It is beyond this study's scope to cover all of the factors that planners must weigh in making their choices, and ultimately, the decisions will be left to them; however, some observations can be made:

- ACPs start out quieter than PCCPs.
- The noise from ACPs increases with age, apparently until the end of service.
- Noise from PCCPs decreases with age for the first (approximately) eight years.

- ACPs will become noisier than PCCPs after about six to eight years of service.
- The initial noise levels of PCCPs are strongly dependent on the surface finishes applied to these materials.

STUDDED TIRES

When a car with studded tires goes by, one hears the clicking of the studs as they strike the pavement. These short duration impulses contain high-frequency components that are not present in the broad-band noise generated by a tire without studs. These clicks are easily detected by the listener, but it is a little more difficult to identify them unequivocally with the instruments commonly used for this purpose.

Noise from tires fitted with studs for traction enhancement is louder than noise from non-studded tires. The average increase in noise level for the sample tested in this study ranged from 2.2 to 4.2 decibels over 15 different surfaces. These data are summarized in Table 4.

It should be noted that the "medium-aggressive" tire is slightly noisier than its "aggressive" counterpart. This distinction was made by the vendor who sold the tires and was accepted by the research team as an "expert opinion." This observation does point out the importance of tread design for tire noise; however, the principle conclusion is that studded tires are noisier than non-studded tires of the same tread design.

Table 4. Summary of Studded Tire Data. Values are the average SPLs for fifteen roadway surfaces.

All-Season Tread		Medium-Aggressive Tread		Aggressive Tread	
Kelly w/studs dBA	Kelly w/o studs dBA	Bridgestone w/studs dBA	Bridgestone w/o studs dBA	Semperit w/studs dBA	Semperit w/o studs dBA
105.5	101.3	106.6	104.4	106.6	103.0

In Figure 11, noise levels from a studded and a non-studded tire of identical tread design are compared. The data are presented in 1/3 octave band format, which identifies the frequency (pitch) distribution of the noise components. Components in the mid- to upper-frequencies between 1,000 Hz and 4,000 Hz are more annoying than the lower frequencies. The figure shows that the noise from the studs falls in the range of high annoyance. This is illustrated in the figure, which shows the frequency distribution of the noise from studded and non-studded tires of the same tread design, in this case, a Kelly-Springfield "all weather" design. The shaded regions show the 1/3 octave bands in which the noise level from the studded version of the tire is higher than that of the non-studded version.

In addition to the increased noise that these tires produce in operation, they are also thought to accelerate wear of roadway surfaces, which leads in turn to increased noise in the community. Studded tires are an annoying source of noise; they are also costly because they necessitate more frequent roadway resurfacing.

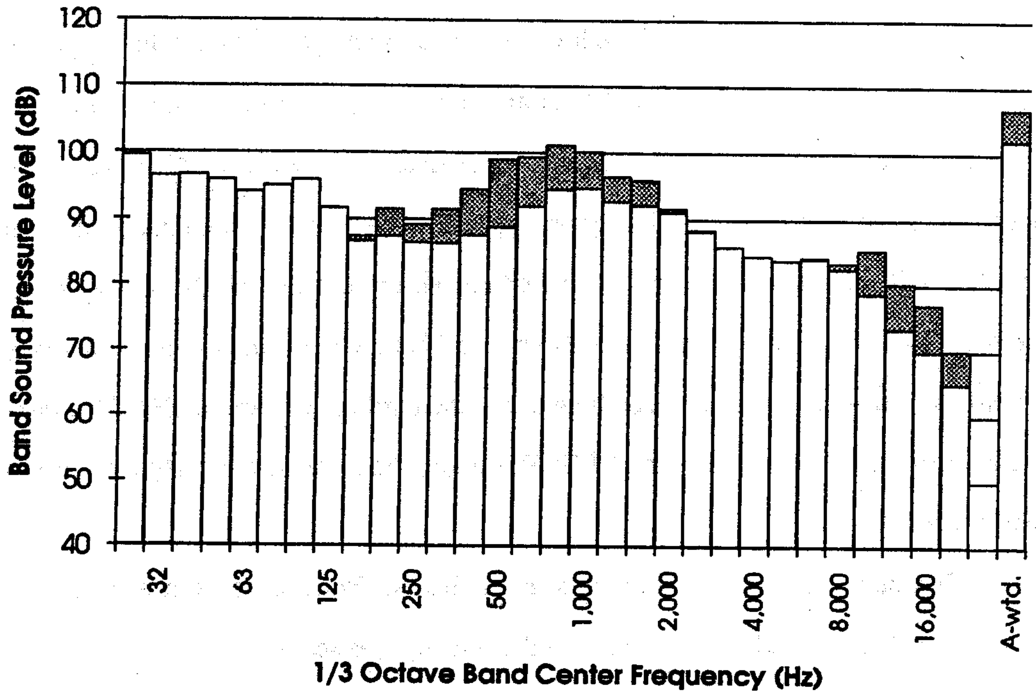

Figure 11. Third Octave Band Noise Comparison of a Tire With and Without Studs. The tire design in this case is a Kelly-Springfield "all-weather" design.

CONCLUSIONS

With regard to tire-generated noise, asphalt concrete pavements (ACPs) offer an advantage over portland cement concrete pavements in the first five or six years of service. They start out quieter, but their noise level increases with age. On the other hand, portland cement concrete pavements (PCCPs) usually start out noisier than ACPs, but their noise level decreases for the first eight years (approximately) of service. At about six to eight years, the noise levels from ACPs become greater than those of PCCPs, and it is assumed that they will continue to increase until taken out of service. Noise levels from PCCP surfaces level out in the period from about 8 to 12, at which time the noise level starts to increase as the aggregate is exposed by wear of the portland cement binder. The increase in this latter portion of the life span of PCCP is about the same as the early increase in noise level for ACP.

Studded tires are noisier than similar tires without studs. On average, they are about 2.2 to 4.2 dB louder when rated on the A-weighted scale.

REFERENCES

1. Ejsmont, J.A. and Sandberg, U., "Background Noise Estimation for Tire/Road Noise Measurements Using the Trailer Method," *VTI Meddelande 441A*, Swedish Road and Traffic Research Institute, Linköping, Sweden, 1985.

2. Sandberg, U. and Ejsmont, J.A., "Tire/Road Noise on Rubberized Asphalt and Cement Concrete Surfaces in Sweden," *VTI Meddelande 608A*, Swedish Road and Traffic Research Institute, Linköping, Sweden, 1990.

3. Ejsmont, J.A. and Sandberg, U., "Cornering Influence on Tire/Road Noise," *Proceedings of Inter-Noise 88*, Noise Control Foundation, P.O. Box 2469, Arlington Branch, Poughkeepsie, NY 12603 USA, vol. 3, 1988, pp. 1343-46.

4. Tatsushita, F., et al., "Application of Low Noise Pavement to Urban Arterial Road," *Proceedings of International Tire/Road Noise Conference, INTROC 90*, Gothenburg, Sweden, August 8-10, 1990, pp. 273-84.

5. Steven, H., "Investigations on a Measuring Method for the Tyre/Road Noise of Passenger Cars," *Proceedings of International Tire/Road Noise Conference, INTROC 90*, Gothenburg, Sweden, August 8-10, 1990, pp. 227-39.

6. Springborn, M., "Measurement of Tire/Road Noise and the Influence of the Road Surface," *Proceedings of International Tire/Road Noise Conference, INTROC 90*, Gothenburg, Sweden, August 8-10, 1990, pp. 145-55.

7. Bryer, G., "Low-Noise Road Surfaces in Austria," *Proceedings of International Tire/Road Noise Conference, INTROC 90*, Gothenburg, Sweden, August 8-10, 1990, pp. 75-82.

8. von Meier, A., "Acoustically Optimized Porous Road Surfaces, Recent Experiences and New Developments," *Proceedings of Inter-Noise 88*, Noise Control Foundation, P.O. Box 2469, Arlington Branch, Poughkeepsie, NY 12603 USA, vol. 3, 1988, pp. 1323-26.

9. von Meier, A., "A Poro-Elastic Road Surface for Traffic Noise Reduction," *Proceedings of Inter-Noise 85*, Noise Control Foundation, P.O. Box 2469, Arlington Branch, Poughkeepsie, NY 12603 USA, 1985.

10. von Meier, et al., "Noise Optimized Road Surfaces and further Improvements by Tyre Choice," *Proceedings of International Tire/Road Noise Conference, INTROC 90*, Gothenburg, Sweden, August 8-10, 1990, pp. 377-86.

11. Samuels, S., "Australian Road Surface Treatments to Minimize Tyre/Road Noise," *Proceedings of International Tire/Road Noise Conference,*

INTROC 90, Gothenburg, Sweden, August 8-10, 1990, pp. 91-101.

12. Kragh, J., "Traffic Noise Measurements at Asphaltic Road Surfaces," *Proceedings of International Tire/Road Noise Conference, INTROC 90*, Gothenburg, Sweden, August 8-10, 1990, pp. 103-114.

13. Kragh, J., "Measurements of Road Traffic Noise at Test Sections of a Road Near Niborg, 1988," (in Danish) Danish Acoustical Institute, Technical Report No. LI 850/88, 1988.

14. Vale, J. and Salta, A., "A Comparison between Transverse and Longitudinal Grooved Concrete Surfaces Regarding Tire/Road Noise," *Proceedings of International Tire/Road Noise Conference, INTROC 90*, Gothenburg, Sweden, August 8-10, 1990, pp. 115-122.

15. Chalupník, J. and Anderson, D., "Acoustic Characterization of Roadway Surfaces," Final Report of WSDOT Agreement Y2811 Task 35, September 10, 1987.

16. Chalupník, J. and Anderson, D., "Tire Noise -- Effect of Roadway Wear," Final Report of WSDOT Agreement GC8286 Task No. 5, February 20, 1990.

17. Chalupník, J. and Anderson, D., "Effects of Roadway Aging on Tire/Road Surface Noise," presented at the Transportation Research Board Committee A1F04 Summer Meeting, Transportation Related Noise and Vibration, Seattle, Washington, July 17-20, 1988, Seattle.

18. "Effects of Roadway Wear on Tire/Road Noise," *Proceedings of Inter-Noise 88*, Noise Control Foundation, P.O. Box 2469, Arlington Branch, Poughkeepsie, NY 12603 USA, vol. 3, 1988, pp. 1347-51.

19. "Noise Emission from Bridge Expansion Joint-Vehicle Interaction," Roadway Development Division, Washington State Highway Department, June 1976.