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Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Four-Year Results

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Partnered Pavement Research Program (PPRC) Contract Strategic Plan Element 4.27:
Fourth-Year Field Evaluation of Tire/Pavement Noise, IRI, Macrotexture and Surface Condition of Flexible Pavements

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Abstract: The work presented in this report is a summary of a series of research projects, whose central purpose is to support the Caltrans Quieter Pavement Research Program, which has as its goals and objectives the identification of quieter, smoother, safer, and more durable pavement surfaces. The research has been carried out as Partnered Pavement Research Center Strategic Plan Elements (PPRC SPEs) 4.16, 4.19, and 4.27.

In the study documented in this report, field data regarding tire/pavement noise, surface condition, ride quality, and macrotexture were collected over four consecutive years from pavements in California placed with open-graded and other asphaltic mixes. The four-year data were analyzed to evaluate the durability and effectiveness of open-graded mixes in reducing noise compared to other asphalt surfaces, including dense- and gap-graded mixes, and to evaluate the pavement characteristics that affect tire/pavement noise. The analysis in this report is a supplement and update to two previous studies on the first three years of data collected, which are detailed in two separate reports prepared as part of PPRC SPE 4.16 and PPRC SPE 4.19, the previous phases of the Quieter Pavement Research Program, and documented in the reports for Partnered Pavement Research Center Strategic Plan Elements 4.16 and 4.19 for the first and second, and third years, respectively.

Conclusions are made regarding the performance of open-graded mixes and rubberized mixes (RAC-G), comparisons are made with dense-graded mixes (DGAC), and the effects of variables affecting tire/pavement noise are examined.

Keywords: asphalt concrete, decibel (dB), noise, absorption, macrotexture, microtexture, open-graded, gap-graded, dense-graded, onboard sound intensity, permeability, flexible pavement

Proposals for implementation: No proposals for implementation are presented in this report.

Related documents:

- Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphaltic Pavement Surface Types: First- and Second-Year Results, by A. Ongel, J. Harvey, E. Kohler, Q. Lu, and B. Steven. February 2008. (UCPRC-RR-2007-03). Report prepared by UCPRC for the Caltrans Department of Research and Innovation.
- *Summary Report*: Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphalt Pavement Surface Types: First- and Second-Year Results, by A. Ongel, J.T. Harvey, E. Kohler, Q. Lu, B.D. Steven, and C.L. Monismith. August 2008. (UCPRC-SR-2008-01). Report prepared by UCPRC for the Caltrans Department of Research and Innovation.
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- State of the Practice in 2006 for Open-graded Asphalt Mix Design, by A. Ongel, J. Harvey, and E. Kohler. December 2007. (UCPRC-TM-2008-07). Technical memorandum prepared by UCPRC for the Caltrans Department of Research and Innovation.
- Temperature Influence on Road Traffic Noise: Californian OBSI Measurement Study, by H. Bendtsen, Q. Lu, and E. Kohler. May 2010. (UCPRC-RP-2010-02). Report for Caltrans by the Danish Road Institute, Road Directorate, and University of California Pavement Research Center.
- Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Three-Year Results, by Q. Lu, E. Kohler, J. Harvey, and A. Ongel. January 2009. (UCPRC-RR-2009-01). Report prepared by UCPRC for the Caltrans Department of Research and Innovation.
- Work Plan for Project 4.27, “Fourth Year of Noise and Smoothness Monitoring of Flexible Pavements,” (UCPRC-WP-2008-16). Work plan prepared by UCPRC for the Caltrans Department of Research and Innovation.

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PROJECT OBJECTIVES

The research presented in this report is part of the California Department of Transportation (Caltrans) Quieter Pavement Research (QPR) Work Plan, whose central purpose is to support the Caltrans Quieter Pavement Research Program. This program's goals and objectives are to identify quieter, safer, and more durable asphalt pavement surfaces.

The purpose of the project presented in this report, which is part of Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.27, is to perform a fourth year of measurement of tire/pavement noise, surface condition, ride quality, and macrotexture of 74 flexible pavement sections, and to provide an updated preliminary table of estimated design lives for different treatments with respect to the variables measured.

PPRC SPE 4.27 has the following objectives:

- Objective 1: To perform a fourth year of collection of OBSI and IRI data from existing flexible pavement test sections.
- Objective 2: To upgrade the noise car.
- Objective 3: To collect additional information on existing test sections to help explain changes observed in OBSI and IRI. This additional information consists of surface macrotexture and surface distresses (cracking, rutting, etc.).
- Objective 4: To combine the new data with the existing three-year performance history in order to determine rates of change for noise and smoothness of asphalt-surfaced sections.
- Objective 5: To report updated trends for noise (OBSI) and smoothness (IRI), and to model them where applicable.
- Objective 6: To develop an updated preliminary table of expected lives for flexible pavement surfaces.

This report documents the work completed for all these objectives.

EXECUTIVE SUMMARY

Background and Purpose

California Department of Transportation (Caltrans) employs a variety of strategies and materials for maintaining and rehabilitating the state's highways pavements. Since the smoothness and quietness of pavements are receiving increased attention and importance, as they affect quality of life issues for highway users and neighboring residents, Caltrans has sought to identify the lives of the strategies and materials, and those of new candidates, that can maintain roadway smoothness and quietness for the longest time. To accomplish this, the Department established the Quieter Pavement Research (QPR) Program.

The Caltrans QPR program is intended to examine the impact of quieter pavements on traffic noise levels and to establish which pavement characteristics have the greatest impact on tire/pavement noise. The program also aims to identify surface treatments, materials, and construction methods that will result in quieter pavements that are also safe, durable, and cost-effective. The information gathered as part of the Caltrans QPR program will be used to develop quieter-pavement design features and specifications for noise abatement throughout the state. The QPR program includes several studies to evaluate the acoustic properties of pavements and the role that pavement surface characteristics play in relation to tire/pavement noise levels.

The QPR Work Plan includes research on both asphalt and concrete pavement surfaces. For the flexible (asphalt-surfaced) pavement part of the QPR study, Caltrans previously identified a need for research into the acoustics, friction, and performance of asphalt pavement surfaces, and in November 2004 initiated Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.16 as a response. Among its other objectives, PPRC SPE 4.16 developed preliminary performance estimates for current Caltrans asphalt surfaces—including DGAC, OGAC, RAC-G, and RAC-O as part of a factorial experiment—and a number of experimental asphalt surfaces with respect to tire/pavement noise, permeability, macrotexture, microtexture, smoothness, and surface distress development. (*Note*: The technical names for these mixes have changed in the new Section 39 of the Caltrans Standard Specifications. However, in this report the names in use at the start of PPRC SPE 4.16 have been maintained for consistency among all the reports and technical memoranda generated by the quieter pavement studies). The results of PPRC SPE 4.16 warranted a continuation of field monitoring of tire/pavement noise and other surface properties on the same asphalt pavements; a third year of measurements was begun in September 2007 and completed as PPRC SPE 4.19—titled "Third Year Field Evaluation of Tire/Pavement Noise, IRI, crotexture, and Surface Condition of Flexible Pavements." The study was further continued in PPRC SPE 4.27, titled "Fourth Year of Noise and Smoothness Monitoring of Flexible Pavements," in 2008/2009. This report summarizes the results from the fourth-year study, combining the data from all four years' measurements.

Objectives

The purpose of PPRC SPE 4.27 is to perform a fourth year of measurement of tire/pavement noise, surface condition, ride quality, and macrotexture of up to 74 flexible pavement sections in order to improve performance estimates for identifying more durable, smoother, and quieter asphalt pavement surface types.

Following are the objectives of PPRC SPE 4.27:

1. To perform a fourth year of collection of OBSI and IRI data from existing flexible pavement test sections.
2. To upgrade the noise car.
3. To collect additional information on existing test sections to help explain changes observed in OBSI and IRI. This additional information consists of surface macrotexture and surface distresses (cracking, rutting, etc.).
4. To combine the new data with the existing three-year performance history in order to determine rates of change for noise and smoothness of asphalt-surfaced sections.
5. To report updated trends for noise (OBSI) and smoothness (IRI), and to model them where applicable.
6. To develop an updated preliminary table of expected lives for flexible pavement surfaces.

Scope of the Report

This report documents the work completed for all of the objectives and is organized as follows:

- Chapter 1 presents the background of the study, its objectives, and the performance parameters for pavement surfaces.
- Chapter 2 provides a summary of the analysis results of the ride-quality data in terms of the International Roughness Index (IRI).
- Chapter 3 presents a summary of the analysis results of the macrotexture data in terms of Mean Profile Depth (MPD).
- Chapter 4 presents a summary of the analysis results of the condition survey data for bleeding, rutting, raveling, transverse/reflective cracking, and wheelpath cracking.
- Chapter 5 presents a summary of the analysis results of On-board Sound Intensity (OBSI) data.
- Chapter 6 presents a summary of the analysis results of the four-year data collected on the Environmental Sections (ES).
- Chapter 7 presents an overall evaluation of the performance models developed in this study, and an assessment of the life spans of the different surface mixes for different conditions and failure criteria based on the models.
- Chapter 8 lists the conclusions from the analyses and includes preliminary recommendations.
- Appendices describe detailed analysis work and provide additional information in support of the conclusions in Chapter 8.

The data presented in this report includes the four years of data collection, and is included in a relational database that will be delivered to Caltrans separately. Specific data in the database includes:

- Microtexture data collected for the first two years and macrotexture data for all four years as these affect skid resistance;
- Permeability data collected for the first two years, and in the fourth year for some of the sections.
- Ride quality data in terms of International Roughness Index (IRI) for all four years;
- On-board Sound Intensity (OBSI) data, a measure of tire/pavement noise for all four years;
- Sound intensity data for different frequencies for all four years;
- Surface distress data, including bleeding, rutting, raveling, transverse cracking, and cracking in the wheelpaths for all four years;
- Climate data; and
- Traffic data.

The analyses presented for each performance variable in Appendix A.2 through A.6 include a summary of descriptive statistics and, where the data is sufficient, statistical models. Appendices also provide a summary of the development of calibration equations for OBSI and detailed condition survey information.

Conclusions

The following conclusions were drawn from the results of the analysis of the four years of data. No new recommendations have been made.

Performance of Open-Graded Mixes

For newly paved overlays, OGAC and RAC-O open-graded mixes had lower tire/pavement noise than DGAC mixes by average levels of 2.7 dB(A) and 2.8 dB(A), respectively. For comparison, the average tire/pavement noise level on DGAC pavements was approximately 101.3 dB(A) for newly paved overlays, 102.0 dB(A) for pavements between one and three years old, and between 103 and 104 dB(A) for pavements older than three years.

After the OGAC and RAC-O pavements were exposed to traffic, this noise benefit generally diminished slightly for about five to seven years and then began to diminish more rapidly after seven years. RAC-O was quieter than OGAC and kept a noise-reduction benefit longer than OGAC.

For newly paved overlays, open-graded mixes had higher low-frequency noise and lower high-frequency noise than DGAC mixes. In the first four years after the open-graded mixes were exposed to traffic, high-frequency noise increased with age due to the reduction of surface permeability and air-void content under traffic, while low-frequency noise decreased with age, likely due to the reduction of surface roughness caused by further compaction under traffic. These opposing changes left the overall sound intensity nearly unchanged. For open-graded pavements older than three years, noise in the frequencies between 500 and 2,500 Hz increased with age, while noise in the frequencies over 2,500 Hz had only slight changes with age, generally decreasing.

The effect of Mean Profile Depth (MPD), a measure of pavement surface macrotexture**,** on noise is complex. Between the two open-graded mixes, MPD had lower initial values and increased more slowly on RAC-O pavements than on OGAC pavements. It appears that a higher MPD value did not significantly affect noise on OGAC and RAC-O pavements, although increasing MPD values increased noise on DGAC and RAC-G pavements.

Based on the condition survey for pavements less than 11 years old, for newly paved overlays transverse/reflective cracking is less significant on open-graded mixes than on dense- or gap-graded mixes. However once cracking appears on open-graded mixes it increases more rapidly with pavement age than on dense- or gap-graded mixes. It also appears that open-graded pavements experience less raveling than dense-graded mixes. There is no other significant difference between open- and dense-graded mixes in terms of pavement distresses. The data also reveal that bleeding tends to appear earlier on RAC-O mixes than on OGAC mixes.

Performance of RAC-G Mixes

Newly paved RAC-G mixes were quieter than an average DGAC mix by about 1.8 dB(A). Within a few years of the pavements' first exposure to traffic, the tire/pavement noise on RAC-G mixes approached the average noise level of similarly aged DGAC pavements. Among newly paved overlays, RAC-G mixes had higher low frequency noise and lower high frequency noise than DGAC mixes. In the first three years after the pavements were exposed to traffic, high frequency noise increased with age due to the reduction of air-void content under traffic, while low frequency noise (equal to or less than 1,000 Hz) was nearly unchanged with age. For RAC-G pavements older than three years, noise of all frequencies increased with age.

The IRI value on newly paved RAC-G mixes was lower than that on DGAC mixes and it did not increase with age as much as the IRI on DGAC pavements. RAC-G mixes had a permeability level as high as that of open-graded mixes in the first two years after construction, but under traffic the permeability decreased rapidly to the level of DGAC mixes in about four years. These facts explain the reasons for the initial low noise level and the rapid loss of the noise benefit of RAC-G mixes.

Based on the condition survey of pavements less than 11 years old, RAC-G pavement is more prone than other mixes to bleeding in terms of both the time of occurrence and the extent of distress. RAC-G pavements may exhibit less initial raveling than DGAC pavements, but the difference disappeared in two or three years. No other significant difference was observed between RAC-G and DGAC mixes in terms of pavement distresses.

Variables Affecting Tire/Pavement Noise

The findings from this fourth year of the study regarding variables affecting tire/pavement noise are generally consistent with the findings from analyses of the two-year and three-year data. That is, the tire/pavement noise was greatly influenced by surface mix type and mix properties, age, traffic volume, and the presence of distresses. Various mix types had different noise performances, and the overall noise level generally increased with traffic volume, pavement age, and the presence of pavement distresses. Overall noise level decreased with increased surface layer thickness and permeability (or air-void content).

For all mix types (DGAC, RAC-G, OGAC and RAC-O), the aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise. It must be noted that the conclusion regarding aggregate gradation is drawn from a data set that only contains nominal maximum aggregate size (NMAS) ranging from 9.5 to 19 mm, while most open-graded mixes were either 9.5 or 12.5 mm, and most of the RAC-G and DGAC mixes were either 12.5 or 19 mm.

Pavement surface macrotexture, in terms of MPD, is a significant factor for DGAC and RAC-G pavements, and a higher MPD value corresponds to a higher noise level. For OGAC and RAC-O pavements, MPD does not have a significant influence on noise level.

Performance of Experimental Mixes

Monitoring continued in the fourth year of a number of experimental test mixes placed in test sections by Caltrans and outside of the main factorial experiment. These sections are collectively referred to as the Environmental Sections (ES). These sections include open-graded and bituminous wearing course (BWC) sections on LA 138, a number of different mixes on Fresno 33, a European gap-graded mix on State Route 19, and a long-term open-graded section on I-80. Additional testing of a number of additional BWC sections begun in the third year was not performed in the fourth-year measurements, and was postponed to the fifth year.

The bituminous wearing course (BWC) mix placed on the LA 138 sections had a noise level comparable to that of DGAC mixes and distress development similar to current Caltrans open-graded mixes. The noise levels of the BWC mixes were generally higher than those of open-graded mixes of similar age. This indicates that the tire/pavement noise performance of the LA 138 BWC mix is not typical of that of the other BWC mixes placed in the state.

Based on the Fresno 33 (Firebaugh) sections it was observed that:

- RAC-G and RUMAC-GG mixes generally exhibit higher MPD and IRI values than Type G-MB, Type D-MB, and DGAC mixes. Increase of MPD and IRI with pavement age is much less significant on Type G-MB and Type D-MB mixes than on RAC-G, RUMAC-GG, and DGAC mixes. Increasing layer thickness did not reduce fatigue cracking or transverse cracking on the RAC-G mix. Increasing thickness may help reduce cracking of RUMAC-GG, Type G-MB, and Type D-MB.
- Although the Type G-MB mix had higher noise levels than the RAC-G mix soon after construction, the increase in noise with age was less significant on the Type G-MB mix than on the RAC-G mix and the Type D-MB mix.
- All the Fresno 33 test mixes were prone to bleeding in the first four years after construction, and bleeding remained into the fourth year on the Type G-MB and Type D-MB sections, while not being observed on the other sections.
- The Type D-MB mix was more resistant to cracking than the DGAC mix but it was also more susceptible to bleeding.
- The Type D-MB mix had a noise level similar to the DGAC mix soon after construction, but its noise level increased with age more than the noise level of the DGAC mix.
- After being open to traffic for four years, none of the test mixes (RAC-G, RUMAC-GG, Type G-MB, and Type D-MB) provided any noise-reduction benefit.

The European gap-graded (EU-GG) mix placed on LA 19 has performance characteristics (in terms of noise, roughness, and durability) very similar to those of gap-graded mixes (RAC-G) used in California, except it may retain its permeability longer.

After ten years of service, the Yolo 80 OGAC section still provides acceptable ride quality, but it has a noise level close to that of DGAC pavements.

CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
in.	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
AREA				
$in.^2$	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
VOLUME				
ft^3	cubic feet	0.028	cubic meters	m^3
MASS				
lb	pounds	0.454	kilograms	kg
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	C
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
$lbf/in.^2$	poundforce/square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
mm	millimeters	0.039	inches	in.
m	meters	3.28	feet	ft
AREA				
mm^2	square millimeters	0.0016	square inches	$in.^2$
m^2	square meters	10.764	square feet	ft^2
VOLUME				
m^3	cubic meters	35.314	cubic feet	ft^3
MASS				
kg	kilograms	2.202	pounds	lb
TEMPERATURE (exact degrees)				
C	Celsius	1.8C+32	Fahrenheit	F
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce/square inch	$lbf/in.^2$

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (revised March 2003).

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1 INTRODUCTION

1.1 Project Background

The California Department of Transportation (Caltrans) employs a variety of strategies and materials for maintaining and rehabilitating the state's highway pavements. Among the pavement characteristics addressed by maintenance or rehabilitation, pavement smoothness and quietness are important because they affect the quality of life of highway users and neighboring residents. To improve smoothness and quietness of the pavements on the state highway network, Caltrans has sought to identify the lives of current materials and strategies, and those of new candidates, in order to determine the most cost-effective approaches for maintaining roadway smoothness and quietness. To accomplish this, the Department established the Quieter Pavement Research (QPR) Program.

The Caltrans QPR program is intended to examine the impact of quieter pavements on traffic noise levels and to establish which pavement characteristics have the greatest impact on tire/pavement noise. The program also aims to identify surface treatments, materials, and construction methods that will result in quieter pavements that are also safe, durable, and cost-effective. The information gathered as part of the Caltrans QPR program will be used to develop quieter-pavement policies, design features, and specifications for noise abatement throughout the state.

The QPR program includes several studies to evaluate the acoustic properties of pavements and the role that pavement surface characteristics play relative to tire/pavement noise levels. The research presented in this report is part of one of these studies and is an element of the Caltrans Quieter Pavements Research (QPR) Work Plan.

The QPR Work Plan includes research on both asphalt and concrete pavement surfaces. For the flexible (asphalt-surfaced) pavement part of the QPR study, Caltrans previously identified a need for research into the acoustics, friction, and performance of asphalt pavement surfaces, and in November 2004 initiated Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.16 as a response. Among its other objectives, PPRC SPE 4.16 developed preliminary performance estimates for current Caltrans asphalt surfaces—including DGAC, OGAC, RAC-G, and RAC-O as part of a factorial experiment—and for a number of experimental asphalt surfaces with respect to tire/pavement noise, permeability, macrotexture, microtexture, smoothness, and surface distress development. (*Note*: The technical names for these mixes have changed in the new Section 39 of the Caltrans Standard Specifications. In this report, the names in use at the start of PPRC SPE 4.16 have been maintained for consistency among all the reports and technical memoranda generated by the quieter pavement studies.) PPRC SPE 4.16 included two years of field measurement of tire/pavement noise and other surface properties of asphalt pavements, and laboratory testing of field cores. The results of data collection, modeling, and performance predictions in the first two years, as summarized in References *(1)* and *(2)*, warranted a continuation of field monitoring of tire/pavement noise and other surface properties on the same asphalt pavements included in the PPRC SPE 4.16 study. Therefore, PPRC SPE 4.19, titled "Third Year Field Evaluation of Tire/Pavement Noise, IRI, Macrotexture, and Surface Condition of Flexible Pavements," was initiated in September 2007. Those analysis results, including updated performance estimates from the third year of measurements on most of the pavement sections included in the PPRC SPE 4.16 project, combined with the first two years of data, were summarized in Reference *(3)*. The study was further continued in 2008 and 2009 under PPRC SPE 4.27, titled "Fourth Year of Noise and Smoothness Monitoring of Flexible Pavements." This current report summarizes the results from the fourth year study, combining the data from all four years of measurements.

1.2 Project Purpose and Objectives

The purpose of PPRC SPE 4.27 was to perform a fourth year of measurement of tire/pavement noise, surface condition, ride quality, and macrotexture of up to 74 flexible pavement sections in order to improve performance estimates so that more durable, smoother, and quieter pavement types could be identified.

PPRC SPE 4.27 had these objectives:

1. To perform a fourth year of collection of OBSI and IRI data from existing flexible pavement test sections.
2. To upgrade the noise car.
3. To collect additional information on existing test sections to help explain changes observed in OBSI and IRI. This additional information consists of surface macrotexture and surface distresses (cracking, rutting, etc.).
4. To combine the new data with the existing three-year performance history in order to determine rates of change for noise and smoothness of asphalt-surfaced sections.
5. To report updated trends for noise (OBSI) and smoothness (IRI), and to model them where applicable.
6. To develop an updated preliminary table of expected lives for flexible pavement surfaces.

1.3 Experiment Factorial for Fourth-Year Measurements

As part of PPRC SPE 4.16, a factorial was developed for current Caltrans asphalt surfaces including DGAC, RAC-G, OGAC, and RAC-O. (As noted earlier, although the names of materials were changed in the new Standard Specifications Section 39, the earlier names are used in this report to maintain consistency with earlier reports. The current names for these materials are HMA, RHMA-G, OGAC and RHMA-O.) The factorial includes 51 sections referred to as the *Quieter Pavement* (QP) sections, which were selected based on climate region (rainfall), traffic (Average Daily Truck Traffic [ADTT]), and years since construction at the time of the initial measurement (referred to as *Age Category* and grouped at the time of the first year of measurements into: less than one year, one to four years, or four to eight years). In addition, several sections identified in other projects and 23 sections with new materials and their associated control sections, referred to as the *Environmental Sections* (ES), were also tested. Appendix B.1 shows specific test section information.

These sections have been tested for four years. The first two years of data included the following:

- Coring, condition survey, permeability, and friction (microtexture) tests performed within traffic closures;
- Profile and tire/pavement noise measurements performed at highway speeds with the instrumented noise car, and
- Mix property testing on cores performed in the laboratory.

The third-year data included condition surveys conducted from the highway shoulder, and profile and tire/pavement noise measurements performed at highway speeds. The fourth-year data included condition surveys performed from the shoulders, profile and tire/pavement noise measurements performed at highway speeds, and coring and permeability tests performed within traffic closures on 31 sections.

Detailed descriptions of project testing methodologies, definitions, and background can be found in Reference *(2)*. Most of the same data collection methodologies were continued in the third and fourth years. However, in the third and fourth years, two Standard Reference Test Tires (SRTT) were used for all noise measurements rather than the Aquatred tires used for the first two years of measurement. All measurements from the first two years with the Aquatred tires were converted to equivalent noise levels measured with one specific SRTT tire using correction equations developed by the UCPRC as part of this project. In addition, for the fourth year measurements the noise data analyzer was changed from a Larson-Davis unit to a Harmonie unit, which introduced some small changes on certain frequencies. Correction equations were developed and applied to the data from the previous years to convert all measurements to the Harmonie analyzer. Details of the correction equations are shown in Appendix B.2. Air density adjustments were applied to all data from all four years using correction equations documented in Reference *(2)*.

A few pavement sections had maintenance or rehabilitation treatment by the third or fourth year and were dropped from the survey. Table 1.1 shows the number of sections surveyed for various performance measures in the four years. Tables B.1.1 and B.1.2 in Appendix B.1 detail which sections were included each year for OBSI testing and for coring in the fourth survey year.

Table 1.1: Number of Sections with Valid Measurements in Four Years

	Year 1 (Phase 1)	Year 2 (Phase 2)	Year 3 (Phase 3)	Year 4 (Phase 4)
Tire/Pavement Noise (OBSI-California)*	76	71	65	62
Roughness (ASTM E1926)	78	71	69	67
Macrotexture (ASTM E1845)	77	72	60	67
Friction (ASTM E303)	83	73	0	0
Air-void Content/Aggregate Gradation**	83/83	73/73	0/0	27/0
Permeability (NCAT falling head)	78	73	0	31
Pavement Distresses**	84	84	73	72

* ASTM and AASHTO test methods currently being standardized based in part on California experience (ASTM WK26025 - New Practice for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity [OBSI] Method; AASHTO TP 76 EN-Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity [OBSI] Method).
** See Reference *(2)* for method description.

1.4 Scope of this Report

Chapters 2 through 5 of this report present results for the current Caltrans asphalt surfaces: DGAC, OGAC, RAC-G, and RAC-O. Chapter 2 presents results for the International Roughness Index (IRI). Chapter 3 presents results for Mean Profile Depth (MPD), which is a measure of surface macrotexture related to high-speed skid resistance and an indicator of raveling and bleeding. Chapter 4 presents the results for surface distresses, including bleeding, rutting, transverse cracking, raveling, and wheelpath cracking. Chapter 5 presents results for On-Board Sound Intensity (OBSI) measurements of tire/pavement noise. Chapter 6 presents an update of performance measures on the experimental test sections referred to as "Environmental Sections." Chapter 7 presents an update of the PPRC SPE 4.19 estimates of pavement life based on new regression equations for each of the performance measures presented in the appendices. A summary of conclusions and recommendations appears in Chapter 8. The details of data presentation, analysis, and modeling are given in the appendices.

2 SURFACE PROFILE RESULTS: IRI

International Roughness Index (IRI) was measured in four consecutive years to evaluate the change in the surface roughness of asphalt pavements. The IRI measurements were collected in both the left and right wheelpaths. The average of the two wheelpath measurements along the whole length of each pavement section was used in the analysis.

Figure 2.1 shows the average IRI measured in four consecutive years for individual pavement sections for four mix types in both the factorial experiment (QP) and the Environmental Sections (ES): DGAC, OGAC, RAC-G, and RAC-O. The first data point for each section is shown at the age of the section when the first measurement was taken, with Year Zero defined as the year of construction. The plots are shown with metric units (m/km) with a note showing conversion to U.S. standard units (in./mi). The study was initiated using metric units, and all data has continued to be recorded in metric units.

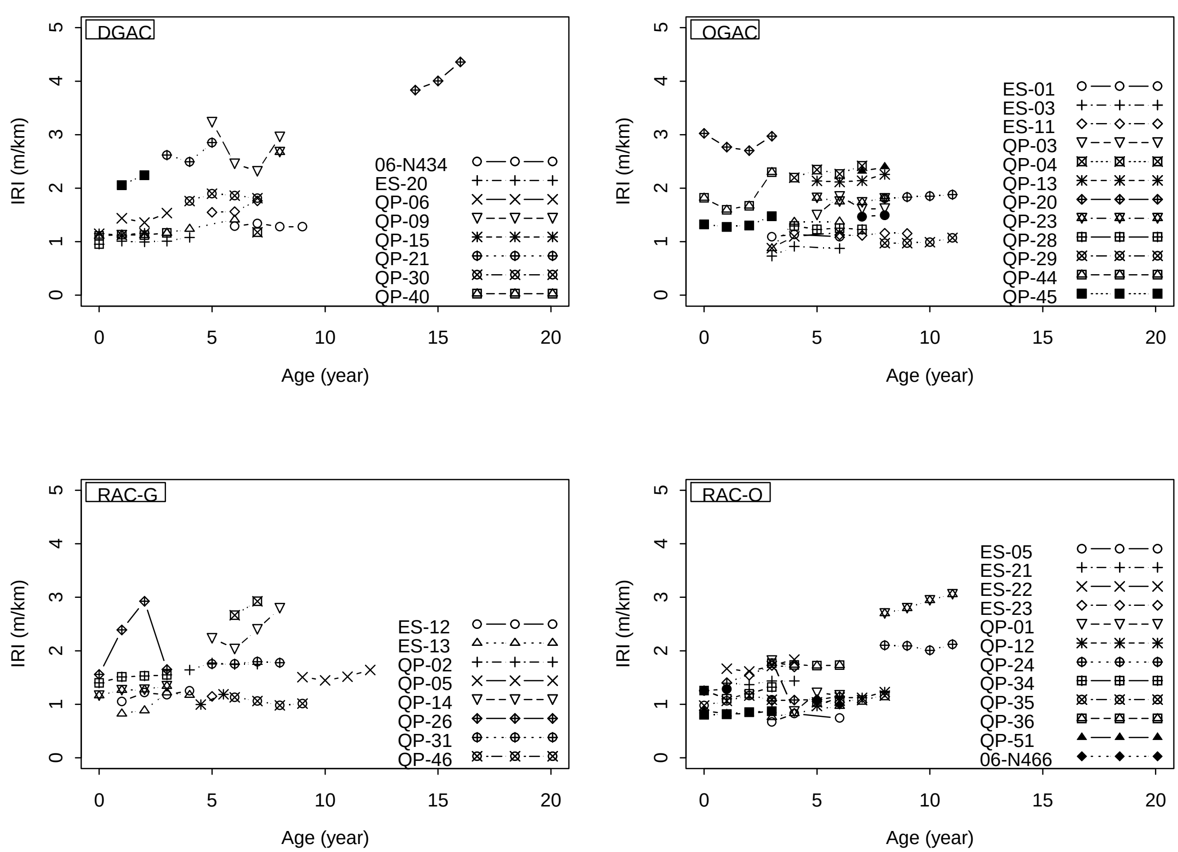

Figure 2.1: IRI trends over four years for each pavement section.
(*Note:* 1 m/km = 63 in./mi; 2 m/km = 127 in./mi; 3 m/km = 190 in./mi.)

Details of both descriptive and statistical analyses are presented in Appendix A.2. The following findings were obtained regarding roughness:

1. The IRI models for DGAC and RAC-G have R^2 above 0.65, while the OGAC and RAC-O models have R^2 below 0.45.
2. Except for an old DGAC pavement, all sections are smoother than the Caltrans Pavement Management System IRI trigger criterion of 3.6 m/km (224 in./mi).
3. Rubberized open-graded mixes have lower initial IRI values than non-rubberized open-graded mixes; rubberized gap-graded mixes have lower initial IRI values than non-rubberized dense-graded mixes.
4. The surface mix types OGAC, RAC-G, and RAC-O all have lower initial IRI than DGAC, but only OGAC and RAC-O are statistically significantly different from DGAC. Monitoring over four years indicates that IRI increases with age on DGAC, RAC-G, and RAC-O pavements, but that age does not have a statistically significant effect on the increase of IRI on OGAC pavements.
5. Open-graded pavements (OGAC and RAC-O) are smoother in high temperature regions than in low temperature regions.
6. The IRI of OGAC pavements increases with increasing MPD. The monitoring performed to date shows that traffic volume significantly affects IRI only on RAC-G pavements, with higher traffic volumes leading to higher IRI values.

3 SURFACE MACROTEXTURE RESULTS: MEAN PROFILE DEPTH

Macrotexture was measured by UCPRC using the same profilometer and was reported in terms of mean profile depth (MPD) and root mean square (RMS) of profile deviations. Because MPD and RMS are highly correlated, only MPD is analyzed in this report.

Figure 3.1 shows the average MPD measured in four consecutive years for individual pavement sections for four mix types: DGAC, OGAC, RAC-G, and RAC-O. It was expected that MPD would increase with pavement age, as pavements deteriorate with time, particularly in the form of increased raveling. The plots in Figure 3.1 confirmed this expectation.

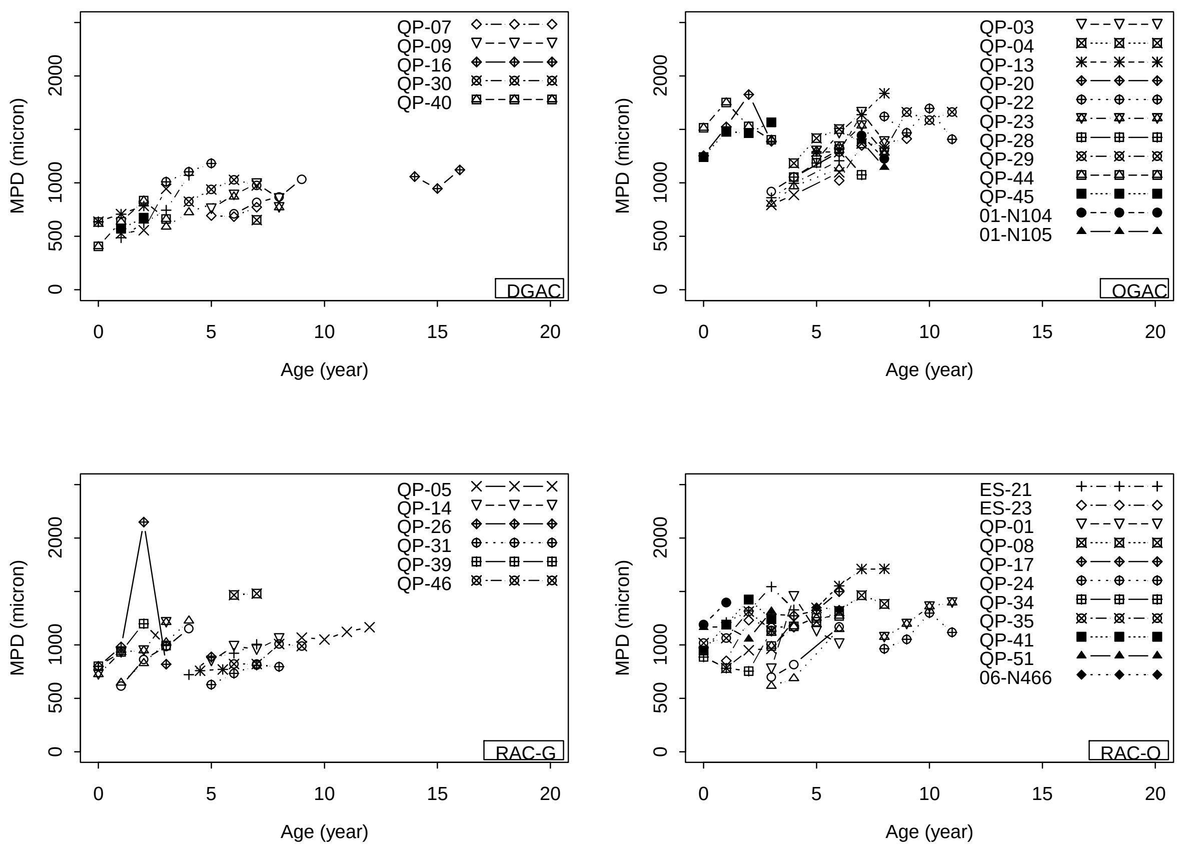

Figure 3.1: MPD trend over four years for each pavement section.

Details of both descriptive and statistical analyses are presented in Appendix A.3. The following findings were obtained regarding macrotexture:

1. RAC-G mixes have higher MPD values than dense-graded mixes, while open-graded mixes have higher MPD values than RAC-G mixes. Between the two open-graded mixes, RAC-O mixes have lower MPD values than OGAC mixes.
2. The R^2 for the RAC-G model is extremely low, probably because the RAC-G mixes show little change in macrotexture over the ages included in this study, indicating that they have not exhibited raveling. The R^2 of the models for the other three mixes are all above 0.50, and for the OGAC it is 0.75. The OGAC mix shows the greatest change in macrotexture over the ages included in this study, indicating that it has the highest propensity to ravel over time. MPD generally increases with pavement age. For open-graded mixes, the age effect on macrotexture is more prominent on non-rubberized pavements (OGAC) than on rubberized pavements (RAC-O). The growth rate (with age) of MPD is significantly higher on OGAC pavements than on DGAC, RAC-G, and RAC-O pavements. The growth rates of MPD of RAC-G and RAC-O pavements are not statistically different from those of DGAC pavements.
3. Within each mix type, air-void content has no significant effect on the value of MPD.
4. Fineness modulus is significant in affecting the macrotexture of open-graded pavements, including both OGAC and RAC-O, and dense-graded pavements (DGAC), and insignificant for RAC-G pavements. Generally the coarser the mix gradation is (i.e., higher fineness modulus), the larger the MPD.
5. The macrotexture of RAC-O pavements decreases with the number of high-temperature days.

4 SURFACE DISTRESS RESULTS

A condition survey of the pavement surface was performed on all pavement sections in each of the four years. During the first two years of the survey, the truck lane was temporarily closed and pavement conditions were measured, visually assessed, and recorded on site during the traffic closure. During the third-year survey, traffic lanes were not closed, and instead high-resolution digital photos were taken from the shoulder along the whole length of each section; pavement conditions were assessed afterwards based on pavement surface images. In the fourth-year survey, pavement conditions were also evaluated based on a set of high resolution digital photos taken from the shoulder for most of the sections; however, a supplemental on-site condition survey was conducted on 31 sections where the truck lane was closed for permeability measurement and coring. Information from both fourth-year approaches was combined and used for surface distress analysis.

A variety of flexible pavement distresses, consistent with the descriptions in the Caltrans *Office Manual* (part of the *Guide to the Investigation and Remediation of Distress in Flexible Pavements [4]*), were recorded. It must be noted that some distresses such as rutting could not be evaluated accurately solely with surface images. Because of the differences in the distress assessment methods in the first two years and in the third and fourth years, some distresses were recorded as less severe in the latter years than in the earlier ones. A basic assumption was made in post-processing the distress data that the third-year distress was not less than that of the second year and that the fourth-year distress was not less than that of the third-year. Any abnormalities that ran contrary to this assumption were corrected in the data analysis.

Five distress types, including bleeding, rutting, transverse/reflective cracking, raveling, and wheelpath cracking, were analyzed for four pavement types: DGAC, OGAC, RAC-G, and RAC-O. The numbers of sections included in the survey were 12, 17, 10, and 17 for DGAC, OGAC, RAC-G, and RAC-O pavements, respectively.

Details of the analysis are presented in Appendix A.4. Findings from the data from the four survey years, which are generally consistent with the findings from the data from the first three survey years, are summarized as follows:

1. The ability of the models to explain the results in the visual condition survey data is poor, as indicated by low R^2 values. The condition survey data is best used for a qualitative understanding of the relative performance of the different surface mixes.
2. Bleeding may appear two to four years after construction on all pavement types, and it tends to appear earlier on rubberized pavements than on non-rubberized pavements. Statistically, among the four mix types (DGAC, OGAC, RAC-G, and RAC-O), the bleeding performance of OGAC and RAC-O pavements is not significantly different from that of DGAC pavements, but RAC-G pavement is significantly (statistically) more prone to bleeding. Regression analysis indicates that bleeding increases with pavement age, number of wet and high-temperature days, and cumulative truck traffic, but decreases with number of freeze-thaw cycles.

3. Rutting may appear four to six years after construction on all pavement types, but only on a few pavement sections. DGAC pavements showed more rutting than other pavement types in all four survey years. Comparison of the rutting resistance of the four mixes, however, cannot be made without knowledge of the underlying layers.
4. Transverse/reflective cracks seem to initiate earlier and propagate faster on the rubberized asphalt pavements (RAC-G and RAC-O) than on the non-rubberized pavements (DGAC and OGAC). This is possibly because RAC-G and RAC-O mixes tend to be placed more often on pavements with a greater extent of existing cracking. Transverse/reflective cracking increased significantly from the first survey year to the second survey year for pavements overlaid with open-graded mixes (OGAC and RAC-O), but stayed relatively stable for pavements overlaid with DGAC and RAC-G mixes. Between the third and fourth survey years, the percentage of cracked sections also increased for RAC-G pavements, but did not change for DGAC pavements.
5. Statistical analysis shows that pavement age, surface mix type, overlay thickness, number of days with temperature greater than 30ºC, and cumulative truck traffic are significant in affecting transverse/reflective cracking. Crack length increases with age and cumulative truck traffic, but decreases with the thickness of surface layer and number of high-temperature days. Pavements overlaid with open-graded mixes tend to have less transverse/reflective cracking than dense- or gap-graded mixes.
6. Pavements overlaid with DGAC mixes seem to experience more raveling than pavements overlaid with other mixes (OGAC, RAC-G, and RAC-O) according to the visual survey results, which contradict the macrotexture (MPD) measurements that showed that OGAC has a faster increase in macrotexture that is usually caused by raveling. RAC-G pavements showed no raveling in the first survey year, but a significant increase in raveling in the next two years. Statistical analysis shows that mix type, fineness modulus, the number of days with temperature greater than 30ºC, and cumulative truck traffic are significant in affecting raveling. Pavement age is marginally significant. The estimated parameters indicate that raveling increases with pavement age, fineness modulus, number of high-temperature days, and cumulative truck traffic.
7. Fatigue cracking/reflective cracking in the wheelpaths, based on limited data, seems to initiate earlier on DGAC and RAC-G pavements than on open-graded pavements, while mixes with rubberized binder (RAC-G and RAC-O) seem to experience less fatigue cracking than mixes without rubber (DGAC and OGAC).
8. Regression analysis shows that pavement age, existence of underlying PCC slabs, and cumulative truck traffic are significant in affecting fatigue cracking. The estimated parameters indicate that fatigue cracking increases with pavement age and cumulative truck traffic. The existence of underlying PCC slabs increases the potential for fatigue cracking/reflective cracking in the wheelpath in the surface layer. Mix type is an insignificant factor, indicating there is no significant difference in the fatigue performance of the four surface mix types.

5 SOUND INTENSITY RESULTS

Tire/pavement noise was measured in all four survey years using the version of the On-board Sound Intensity method developed in California, OBSI-California. Since the OBSI-California method was under continuous improvement during the project, variations of the method exist between years. Specifically, two Aquatred 3 test tires (designated Aquatred 3 #1 and Aquatred 3 #2) were used in the first and second years, while two standard reference test tires (designated as SRTT #1 and SRTT #2) were used in the third and fourth years. A Larson-Davis real-time sound analyzer was used in the first three years, but was replaced with a Harmonie sound analyzer in the fourth year. Because these variations affected the measured OBSI values to varying degrees, calibration equations were developed based on a series of field experiments to standardize OBSI measurements. A summary of the field experiments and development of the calibration equations is presented in Appendix B.2. One thing to notice is that significant differences exist in OBSI values measured with the two standard reference test tires (SRTT #1 and SRTT #2), as illustrated in Figure 5.1.

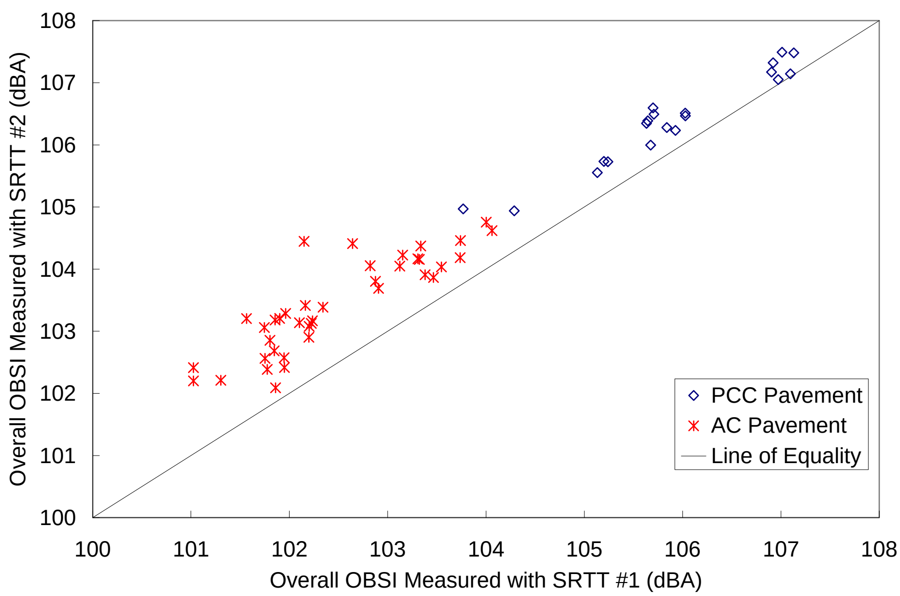

Figure 5.1: Comparison of overall OBSI values measured with SRTT #1 and SRTT #2.

With the developed calibration equations, all sound intensity measurements were calibrated to their equivalent values at a reference condition (60 mph test car speed, Harmonie equipment, and SRTT #1). In the two-year and three-year study reports *(2, 8),* OBSI values measured at a speed of 30 mph (48 km/h) on a few sections and were converted to their equivalent values at 60 mph (97 km/h) using calibration equations developed in the first two-year study report *(8)*. Given the small number of sections on which the test speed was 30 mph and potential large errors introduced during the calibration for speed, a decision was made by UCPRC and Caltrans that in the analysis of the four-year data, all the OBSI measurements at 30 mph would be excluded from the analysis. Pavement temperature corrections developed from the experiments were also excluded because the standard error of the calibration equation was large relative to the size of the temperature correction.

The same air-density correction equations used in the first two years were applied to the data to account for the differences caused by variations of air density (a function of air temperature, humidity, and altitude) *(2)*. Subsequent analysis and modeling were all based on the calibrated OBSI values corrected for tire type, analyzer, and air density.

Both the overall sound intensity and the sound intensities at one-third octave frequency bands were analyzed. Figure 5.2 shows the average overall OBSI values observed in the four survey years on each pavement section for the four mix types. Figure 5.3 shows box plots of overall OBSI over four years for different mix types for the three original age categories (less than one year, one to four years, greater than four years). Figure 5.4 shows the estimated cumulative distribution functions of overall OBSI for four mixes based on the data collected over four years. Figure 5.5 through Figure 5.7 show the sound intensity spectra averaged by mix type and age group in the four survey phases (i.e., four survey years). From the plots it can be seen that tire/pavement noise generally increases with pavement age for all surface mix types.

Regression analysis was conducted to determine the effects of mix properties, distresses, traffic, and weather conditions on sound intensity levels, and to develop prediction models for tire/pavement noise.

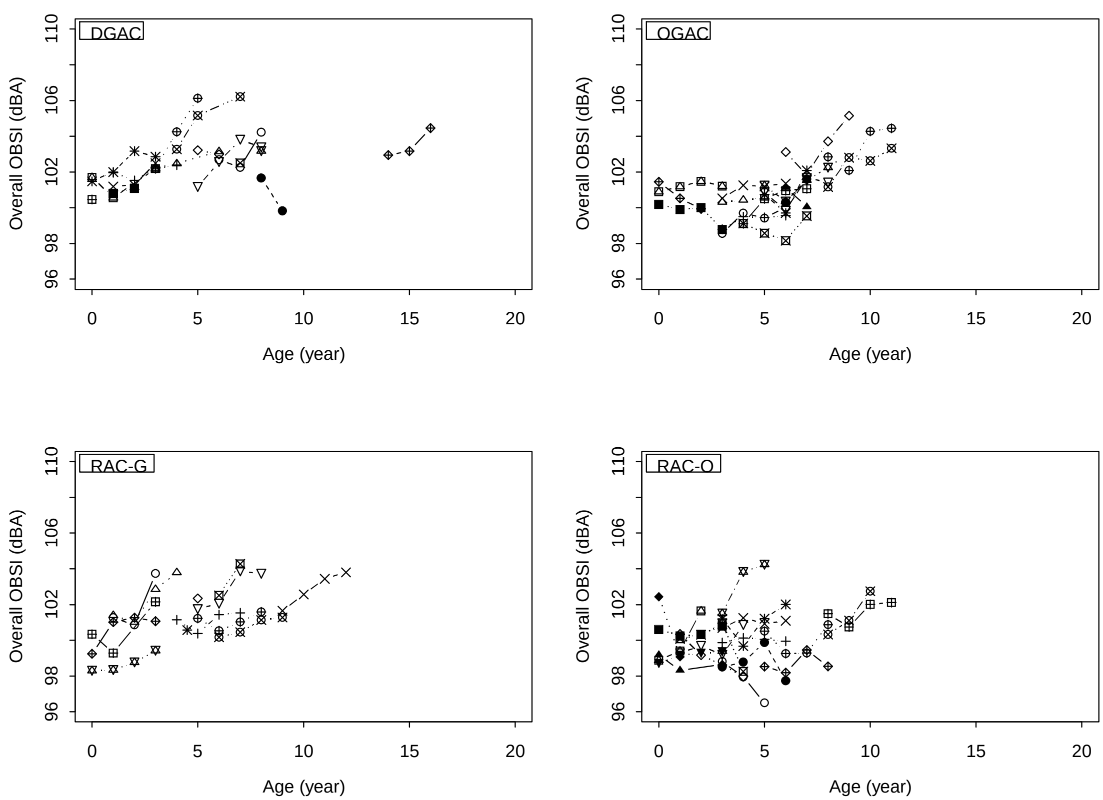

Figure 5.2: Trends of overall OBSI over four years for each pavement section.

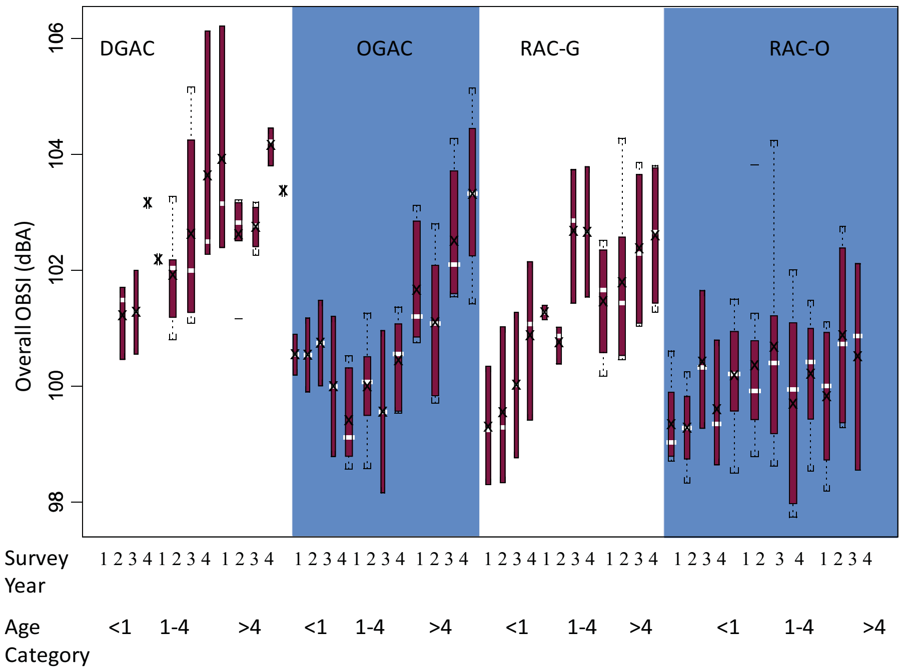

Figure 5.3: Comparison of overall OBSI values for different mix types for different initial age categories (Age Category) and for four years of data collection.

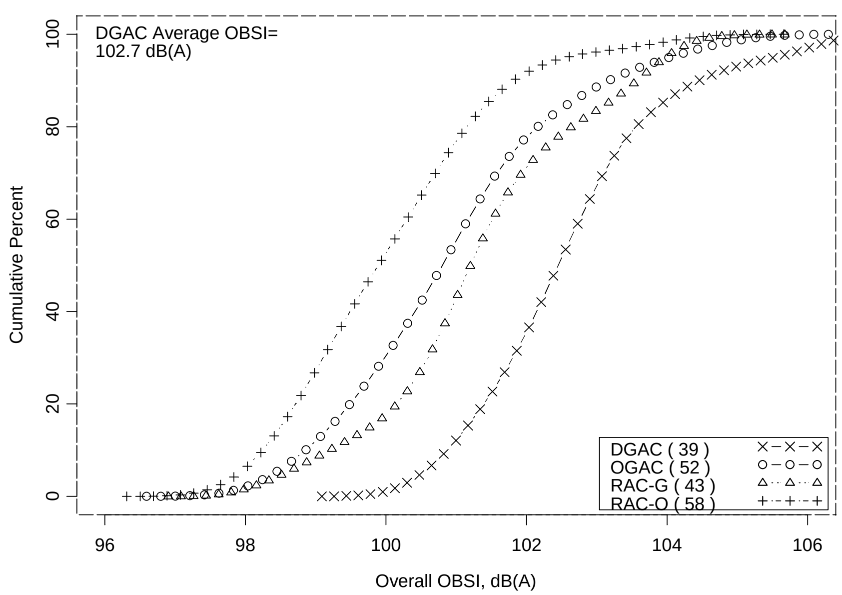

Figure 5.4: Estimated cumulative distribution function of overall OBSI of DGAC, OGAC, RAC-O, and RAC-G mixes from four years of data collection.
(Note: **the numbers in parentheses in the legends represent the sample size of each mix type.)**

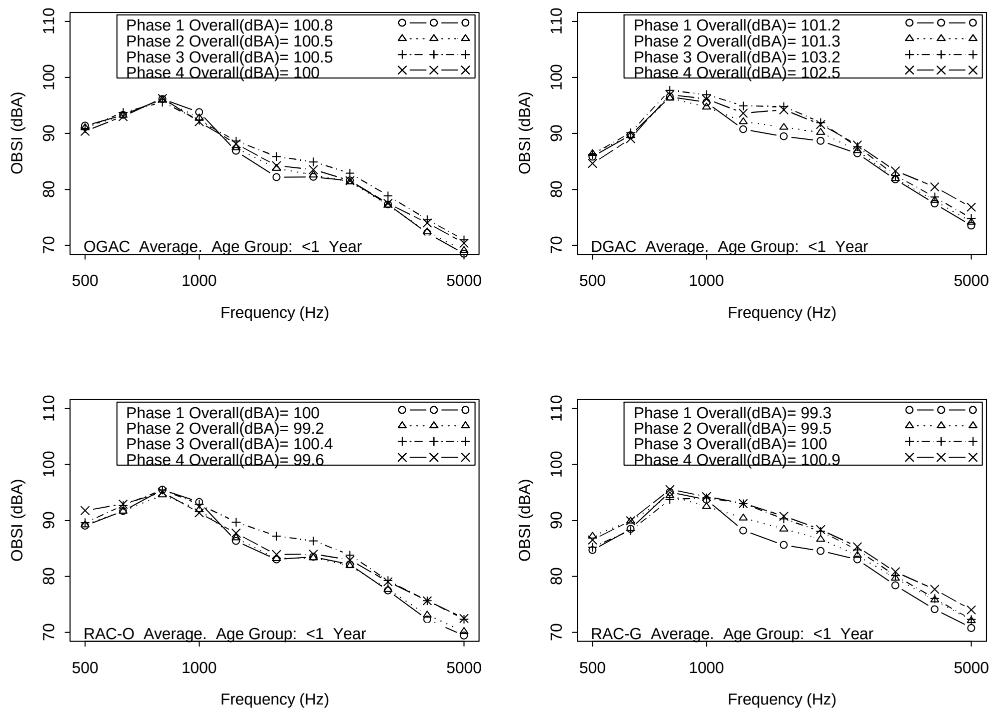

Figure 5.5: Average OBSI spectra for Age Group "<1 Year" in four survey phases (years).

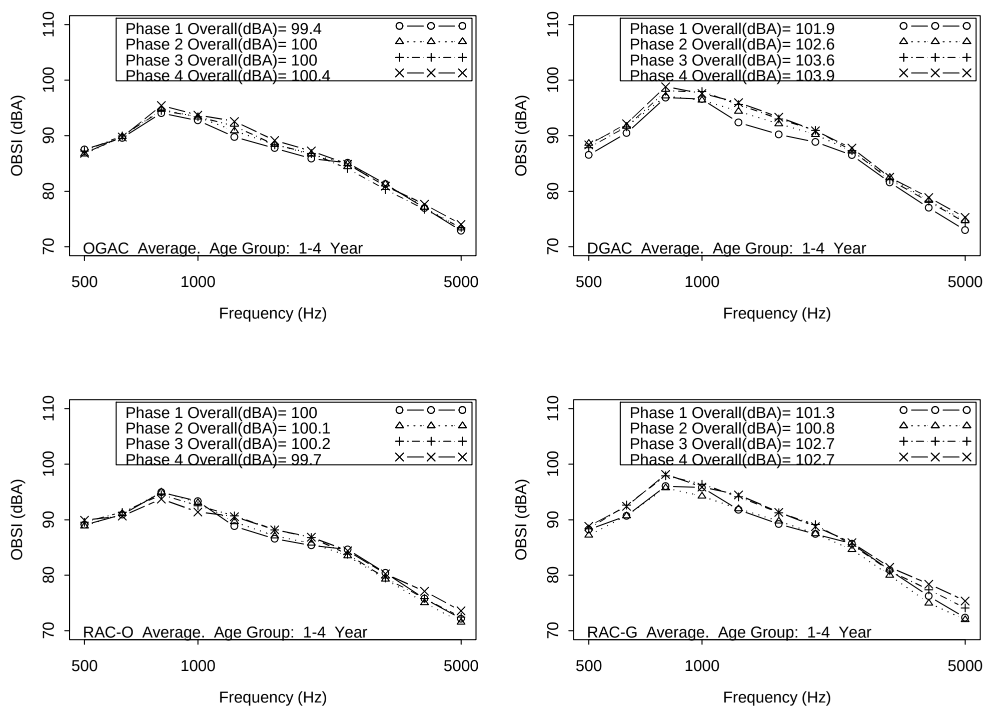

Figure 5.6: Average OBSI spectra for Age Group "1–4 Years" in four survey phases (years).

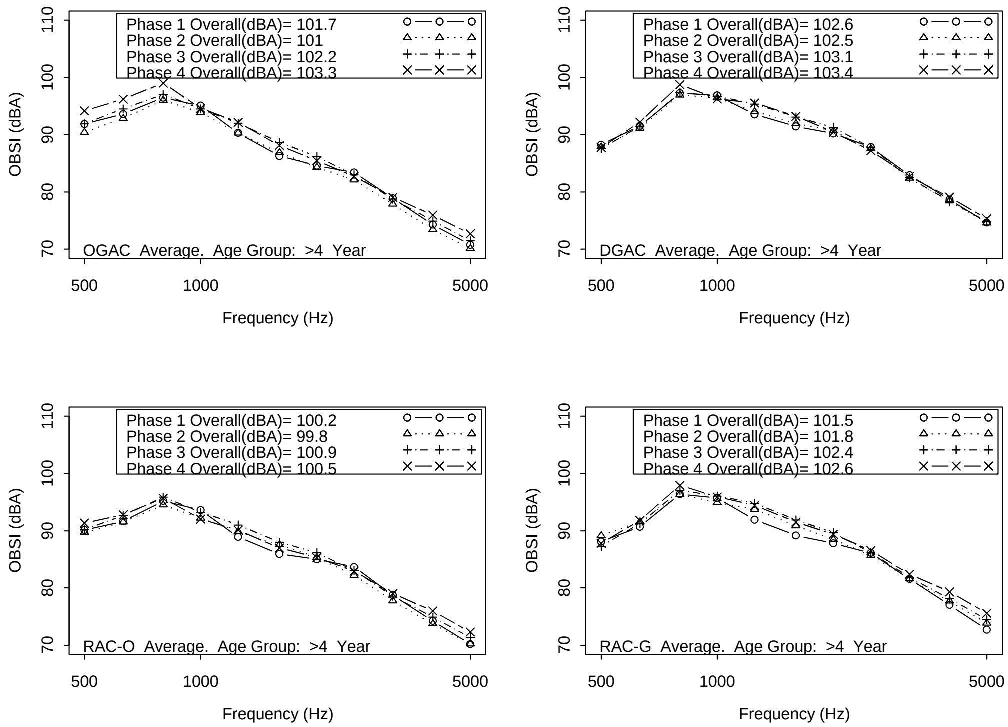

Figure 5.7: Average OBSI spectra for Age Group ">4 Years" in four survey phases (years).

Details of the analysis and modeling are presented in Appendix A.5, and the findings are summarized below. Models for all mixes combined and for each of the four mixes with their properties are included in Appendix A.5 for overall sound intensity and sound intensity at a number of one-third octave band frequencies.

The following findings were obtained regarding overall sound intensity:

1. Overall tire/pavement noise generally increases with pavement age. The average noise level on DGAC pavements is about 101.3 dB(A) for newly paved overlays, 102.0 dB(A) for pavements between one and three years old, and between 103 and 104 dB(A) for pavements older than three years. Based on statistical analysis, for newly paved overlays, the overall sound intensities measured on OGAC, RAC-G, and RAC-O pavements are lower than the values measured on the DGAC pavements. The average noise reductions (compared to DGAC pavements) for newly paved OGAC, RAC-G, and RAC-O mixes are about 2.7, 1.8, and 2.8 dB(A), respectively. After the pavements are exposed to traffic, the overall sound intensity measured on RAC-G pavements quickly approaches the typical value measured on DGAC pavements of similar ages. The overall sound intensity measured on the OGAC pavements does not change much for about five years and then increases quickly with pavement age. With a few exceptions, the overall sound intensity measured on the RAC-O pavements does not change much for about seven

years and then increases quickly with pavement age. The ranking (from best to worst) of the four mix types in terms of noise reduction is RAC-O, OGAC, RAC-G, and DGAC.

2. Multiple regression analysis on all mixes shows that overall sound intensity increases with increased raveling and rutting, and decreases with increased surface layer thickness. Multiple regression analysis on individual mix types shows that the in-situ permeability (or air-void content) is a significant factor on all mixes except RAC-O, and that higher permeability leads to a lower noise level. For all four mix types, the aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise. Pavement surface macrotexture (MPD) is a significant factor for DGAC and RAC-G pavements, and a higher MPD value corresponds to a higher noise level. Relative truck traffic volume is a significant factor that increases tire/pavement noise for OGAC mixes.

The following findings were obtained regarding sound intensity at one-third octave bands:

1. At low frequency levels (500 Hz and 630 Hz), sound intensities measured on OGAC and RAC-O pavements are generally higher than the values measured on DGAC and RAC-G pavements. At a frequency level of 800 Hz, the sound intensities measured on OGAC, RAC-G, and RAC-O pavements begin to become lower than those measured on DGAC pavements. For frequency levels equal to or over 1,000 Hz, the sound intensities measured on OGAC and RAC-O pavements are generally lower than those measured on RAC-G pavements.
2. For newly paved OGAC and RAC-O mixes (age less than or equal to one year), the sound intensities at frequencies higher than 1,000 Hz increase with age in the first four years, but the sound intensities at low frequencies (630 to 800 Hz) decrease with age. These two opposite changes make the overall sound intensity nearly unchanged. For newly paved DGAC and RAC-G mixes, the low frequency noise varies slightly with age in the first four years, while the sound intensities at frequencies over 1,000 Hz increase significantly with age.
3. For pavements with an initial age between 1 and 4 years, sound intensity increases slightly on both open-graded pavements (OGAC and RAC-O), and increases more significantly on DGAC and RAC-G pavements.
4. For the oldest pavements (initial age greater than 4 years), the increase of overall sound intensity with age is more significant on OGAC, RAC-G, and DGAC pavements than on RAC-O pavements. The increase of sound intensity with age mainly occurs at frequencies between 1,000 Hz and 2,000 Hz on RAC-G pavements; while for OGAC pavements, the increase of sound intensity with age mainly occurs at frequencies below 1,000 Hz.

The following findings were obtained regarding 500-Hz band sound intensity:

1. For newly paved overlays (age less than or equal to one year), OGAC and RAC-O pavements have a statistically higher 500-Hz noise level than DGAC pavements, while RAC-G pavements have statistically the same level of 500-Hz sound intensity as DGAC pavements. This indicates that for newly-placed mixes, open-graded pavements have rougher surfaces that contribute to more tire vibration than dense- and gap-graded pavements. For pavements with ages between four and seven years, there is no significant difference in 500-Hz sound intensity among the four mixes. For old pavements (older than seven years), OGAC pavements have higher 500-Hz sound intensity than the other three pavement types, which indicates that OGAC pavements experience more surface distresses that affect the surface smoothness than the other pavement types. Overall, the increase rate of 500-Hz sound intensity with age is lower on rubberized pavements (RAC-G and RAC-O) than on non-rubberized pavements (DGAC and OGAC).
2. Multiple regression analysis on all mixes shows that mix type, number of high-temperature days, truck traffic in the coring lane, and the existence of rutting significantly affect the 500-Hz band sound intensity. The 500-Hz band noise increases with pavement age, truck traffic volume, and the existence of rutting distress, but decreases with number of high-temperature days.
3. Multiple regression analysis on individual mix type shows that truck traffic volume is a significant factor that contributes to the increase of 500-Hz band noise for open-graded mixes, but not for dense- or gap-graded mixes. The traffic effect is more significant on the OGAC pavements than on the RAC-O pavements. For all pavements, the aggregate gradation variable (fineness modulus) does not seem to significantly affect the low-frequency noise.

The following findings were obtained regarding 1,000-Hz band sound intensity:

1. For newly paved sections, the 1,000-Hz sound intensity measured on open-graded pavements (OGAC and RAC-O) and gap-graded pavements (RAC-G) is lower than the values measured on dense-graded pavements (DGAC). After the pavements were exposed to traffic, OGAC and RAC-O pavements have similar noise-reducing properties for about three years, after which the OGAC pavements begin to reduce noise less than the RAC-O pavements, while all age groups of RAC-G pavements show decreased noise-reducing properties.
2. Multiple regression analysis on individual mix type shows that air-void content is an insignificant factor for all pavements. For 1,000-Hz sound intensity, the surface layer thickness is significant for OGAC and RAC-O pavements and insignificant for DGAC and RAC-G pavements. The estimated parameters indicate that a thicker open-graded surface layer corresponds to a lower noise level at 1,000 Hz. Pavement surface roughness (MPD) is a significant factor for all pavements, and a higher MPD value corresponds to a higher noise level on DGAC, OGAC, and RAC-G pavements, but a lower noise level

on RAC-O pavements. The aggregate gradation variable (fineness modulus) does not seem to significantly affect the tire/pavement noise for any of the mixes.

The following findings were obtained regarding 2,000 to 4,000-Hz band sound intensity:

1. For newly paved sections, the 2,000-Hz sound intensities measured on open-graded pavements (OGAC and RAC-O) and gap-graded pavements (RAC-G) are significantly lower than the values measured on dense-graded pavements (DGAC). The 2,000-Hz sound intensity increases at all pavement ages on DGAC and RAC-G pavements, but for the most part only in early ages on OGAC and RAC-O pavements.
2. For 2,000-Hz sound intensity, multiple regression analysis on individual mix types shows that air-void content is a significant factor for DGAC, OGAC, and RAC-G pavements, and is insignificant for RAC-O pavements. For 2,000-Hz sound intensity, MPD is significant for DGAC and RAC-G pavements, and higher MPD increases the 2,000-Hz noise on DGAC and RAC-G pavements. The aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise on any pavement type except RAC-O. For RAC-O pavements, a larger fineness modulus (coarser gradation) results in significantly lower tire/pavement noise in the 2,000-Hz band.
3. The 4,000-Hz sound intensity does not change significantly with pavement age on DGAC and RAC-O pavements. For OGAC pavements, the 4,000-Hz sound intensity increases with age for newly paved overlays but tends to stabilize or even decrease slightly with age for pavements older than four years. On RAC-G pavements, the 4,000-Hz sound intensity increases with pavement age for both newly paved and older pavements.
4. OGAC, RAC-G, and RAC-O pavements are all initially quieter than DGAC pavements in terms of 4,000-Hz band noise. For newly paved overlays, OGAC, RAC-G, and RAC-O exhibit similar noise-reducing properties. For pavements between three and seven years old, OGAC and RAC-O pavements still have similar noise-reducing properties, while RAC-G begins to perform worse than open-graded mixes. The relative performance of the three mixes remains unchanged for pavements older than seven years.
5. Multiple regression analysis results show that truck traffic volume is a significant factor for all pavements except OGAC. Air-void content is significant for DGAC and RAC-G pavements, and insignificant for the open-graded (OGAC and RAC-O) pavements. For all mixes, higher traffic volume and lower air-void content lead to higher 4,000-Hz band noise levels. The aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise on all pavement types except RAC-O pavements. Pavement surface macrotexture (MPD) is significant on both OGAC and RAC-O pavements, and higher MPD values lead to a lower 4,000-Hz noise level.

6 ENVIRONMENTAL SECTIONS RESULTS

Twenty-three environmental test sections (labeled "ES" in this study) were built by Caltrans to test pavement noise, durability, permeability, and friction performance trends for new types of surface mixes. They include new asphalt mixes—such as Type G-MB, Type D-MB, RUMAC-GG, and EU gap-graded mixes—and currently used mixes—OGAC, RAC-O, DGAC, and RAC-G—placed as controls at some locations. For more information, see Appendix B.1. Detailed descriptions of the mixes are included in the two-year noise study report *(2)*.

All the environmental test sections were tested during the fourth-year survey, except for the Bonded Wearing Courses (BWC) that was tested for the first time during the third-year study and which will be tested again in the fifth year. The four years of survey data were pooled to analyze the performance trends of several distresses. Details of the analysis are included in Appendix A.6, and the findings are summarized below:

- Based on the Fresno 33 sections, RAC-G and RUMAC-GG mixes generally exhibit higher MPD and IRI values than Type G-MB, Type D-MB, and DGAC mixes. Increases in MPD and IRI with pavement age are much less significant on Type G-MB and Type D-MB mixes than on RAC-G, RUMAC-GG, and DGAC mixes. Tire/pavement noise increased significantly in the third survey year on the RAC-G, RUMAC-G, and Type D-MB sections and remained relatively stable in the fourth survey year on all sections. Type G-MB was quieter than the RAC-G and Type D-MB mixes in the third survey year, but none of these mixes provided any noise reduction compared to the DGAC mix.
- All the Fresno 33 test mixes were prone to bleeding in the first four years after construction, and bleeding lasted longer on Type G-MB and Type D-MB sections.
- Increasing thickness does not reduce fatigue cracking or transverse cracking on the RAC-G mix. Increasing thickness may help reduce cracking of RUMAC-GG, Type G-MB, and Type D-MB.
- The performance of RAC-O mixes placed on PCC pavements, on the Sacramento 5 and San Mateo 280 sections, does not differ from that of RAC-O mixes primarily placed on asphalt pavements. The San Mateo 280 section performed better than the Sacramento 5 sections in terms of both noise and pavement distresses, possibly due to its thicker layer.
- From the LA 138 test sections, it was found that increasing the thickness of OGAC overlays does not increase durability or provide additional noise reduction as measured by the OBSI method (contradicting the proposed theory for San Mateo 280). Open-graded mixes have the lowest noise levels among all the mix types over the four survey years. The one BWC mix at LA 138 performed more like a DGAC mix than the open-graded mixes at the same site, although there was some critique from industry sources that this BWC was not representative of most BWC layers. Rubberized mixes may have slower distress propagation than non-rubberized mixes.

- The EU-GG mix performs similarly to the RAC-G mixes used in California, in terms of noise, roughness, and durability, although it may retain its permeability longer than RAC-G mixes.
- After ten years of service, the Yolo 80 section still provides acceptable ride quality, but it has a noise level close to that of DGAC pavements.

7 ESTIMATED PERFORMANCE OF DIFFERENT ASPHALT MIX TYPES BASED ON PERFORMANCE MODELS

The performance regression models developed as part of this study from the pooled four years of data collected, presented in Appendix A, were used to estimate the lifetimes of the different mixes with respect to the following performance criteria: roughness (IRI), tire/pavement noise (OBSI), and durability (bleeding, raveling, transverse/reflective cracking). These new models have improved prediction capability compared to the models from the first three years of data collection because of the additional observations. This chapter presents estimates of the time to failure for different mixes under different climate and traffic conditions using the respective regression models. The times to failure predicted from these new models are generally similar to the times to failure predicted from the models based on the three-year data.

The performance models developed from the first two years of data collection for permeability and friction (measured in terms of British Pendulum Number, BPN) for both open- and gap-graded mixes indicated these variables do not control the lifetime of the two mix types *(1, 2).* Instead, it was generally found to take nine or more years for the permeability of open- or gap-graded mixes to decrease to the level of dense-graded mixes. In addition, the friction model did not provide a good estimate of the lifetime of the mixes because of the absence of the variable *aggregate type.* In any case, friction was not found to be a problem for the California mixes evaluated in the two-year study *(1, 2)*, and since friction was not measured in the third and fourth survey years, the performance model is not updated for it. Since permeability was measured on about 33 sections in the fourth survey year, its performance model is updated with the new data and presented in Appendix B.3.2.

7.1 Prediction of IRI

In Appendix A.2, two regression models were estimated for roughness (IRI). The first one contains the mix type (categorical variable), environmental, and traffic factors as independent variables, while the second model contains mix property variables as independent variables. Both models can be used to estimate the average lifetime of each mix type, but the first model (Equation A.2.1) is easier to use because it does not need the mix characteristic inputs such as MPD and permeability.

Equation A.2.1 shows that the average annual rainfall, number of days with temperature higher than 30°C, truck traffic, and number of annual freeze-thaw cycles are statistically significant in affecting IRI. All these factors are continuous variables, which can be used to estimate the roughness of a pavement at any combination of values of these variables. In this section of this report, some typical values of the independent variables have been selected to estimate the time for a pavement to reach failure.

Two ten-year Traffic Index (TI) values, 9 and 12, were chosen to represent high and low traffic conditions, respectively. Using a statewide average truck factor of 1.17 ESALs per axle and a compound growth rate of 3 percent—which were estimated from Weigh-In-Motion data collected from 73 Caltrans WIM sites between 1991 and 2003 *(5)*—the two TI values correspond to 204 and 2,291 AADTT in the design lanes, and ten-year ESALs of 1.0 million and 11.2 million, respectively.

Values for the environmental factors have been selected to represent different climate conditions, as shown in Table 7.1. The typical climate data for the four climate conditions is averaged from climate data at the QP and ES sections in this study, grouped in the four environmental combinations. The climate data were obtained from the *Climatic Database for Integrated Model (CDIM)* software *(6).*

Table 7.1: Selection of Typical Environmental Regions

Environment	Average Annual Rainfall (mm)	Number of Days with Temperature Greater than 30°C	Annual Freeze-Thaw Cycles
Low Rainfall/ High Temperature	274	117	14
Moderate Rainfall/ Low Temperature	585	33	12
High Rainfall/ Moderate Temperature	1,444	68	32
Moderate Rainfall/ Moderate Temperature	719	68	7

An IRI value of 2.68 m/km (170 in./mi), which is the maximum acceptable value for roughness according to FHWA, has been selected as the threshold value for a pavement to reach failure. Table 7.2 shows the estimated age to reach this threshold value for each mix type in different traffic and climate combinations. It can be seen from the table that rubberized mixes retain "acceptable" riding smoothness longer than non-rubberized mixes, and that open-graded mixes retain acceptable riding smoothness longer than dense- or gap-graded mixes. It must be noted that IRI before overlay was unknown, and there may be some bias in these results if open-graded mixes are typically placed on smoother pavement while dense- and gap-graded mixes are placed on rougher and more damaged pavement. Roughness also increases more slowly on pavements in low rainfall/high temperature regions than in high rainfall/moderate temperature regions. Another observation is that higher truck traffic volume shortens pavement life by about one to two years in terms of roughness.

In general, all pavement types can retain an acceptable roughness for over ten years in various climate regions, as can be seen in Table 7.2, where all predicted lifetimes are greater than ten years. This conclusion is consistent with observations from the sections investigated, as discussed in Chapter 2. The longest life predicted by the model is 21 years for RAC-O for TI=9, Low Rainfall/High Temperature (South Coast).

Table 7.2: Predicted Lifetime[1] of Different Asphalt Mix Types with Respect to Roughness

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	>10	>>10	>>10	>>10
	Moderate Rainfall/ Low Temperature	>10	>10	>10	>>10
	High Rainfall/ Moderate Temperature	>10	>10	>10	>>10
	Moderate Rainfall/ Moderate Temperature	>10	>10	>10	>>10
Low Traffic (TI=9)	Low Rainfall/ High Temperature	>>10	>>10	>>10	>>>10
	Moderate Rainfall/ Low Temperature	>10	>10	>10	>>10
	High Rainfall/ Moderate Temperature	>10	>10	>10	>>10
	Moderate Rainfall/ Moderate Temperature	>10	>>10	>10	>>10

Note 1: Since the oldest sections in the sample are approximately 10 years old, calculated values greater than 10 years are shown as >10, values greater than 15 years are shown as >>10, and values greater than 20 years are shown as >>>10. Actual values predicted by all models with values greater than 10 years are shown in Table B.7.1 in Appendix B.7.

7.2 Prediction of Tire/Pavement Noise

In Appendix A.5, two regression models were estimated for the overall tire/pavement noise, which is represented by on-board sound intensity (OBSI). The first model (Equation A.5.2) contains the mix type, pavement distress, environmental, and traffic factors as independent variables, while the second model (Equation A.5.3 through Equation A.5.6) was estimated for each individual mix type to explore the effects on noise of mix property variables such as permeability, fineness modulus, MPD, and thickness. Both models are used to estimate pavement performance life in terms of noise. Results from the second model should be more accurate because they were estimated from individual mix data.

Equation A.5.2 shows that the overall OBSI is statistically significantly affected by pavement age, mix type, surface layer thickness, and the presence of raveling and rutting distresses. Environmental and traffic variables seem to have no significant effect. However, the raveling model (Equation A.4.3) shows that raveling is significantly affected by the number of days with temperature higher than 30°C and by cumulative truck traffic. So both environmental and traffic factors affect OBSI indirectly.

Equation A.5.2 includes the mix type, surface layer thickness, and the presence of raveling and rutting in the independent variable list. To apply this model, the surface layer thickness is assumed to be 60 mm, 30 mm, 40 mm, and 30 mm for the DGAC, OGAC, RAC-G, and RAC-O mixes, respectively. Rutting is assumed to be zero for all mixes since a rutting model has not been developed in this study and rutting is affected by the underlying layers. The percentage of pavement area with raveling is estimated based on Equation A.4.3. (Here the pavement area includes the wheelpath areas and the areas outside the wheelpaths.)

Pavement life for open- and gap-graded mixes in terms of noise is defined as the time for the OBSI to reach the level on a typical DGAC pavement with an age of one to three years, which is 102 dB(A).

The estimated ages for open- and gap-graded mixes are shown in Table 7.3 for different traffic and climate combinations. It can be seen from the table that RAC-O mixes retain lower tire/pavement noise longer than OGAC and RAC-G mixes under all traffic and climate conditions, while OGAC mixes can maintain lower tire/pavement noise longer than RAC-G mixes. The results also show that environmental factors have only a slight effect on the ability of OGAC and RAC-G mixes to remain quieter than DGAC mixes, according to the current model. Environmental factors do affect the development of raveling. However, this effect is too small to significantly affect the noise level before OGAC and RAC-G mixes reach failure. The effect of truck traffic level is apparent on the all mixes. High traffic volume promotes the development of raveling, which contributes to the increase of tire/pavement noise. It must be noted that the raveling model (Equation A.4.3) used here does not fit the raveling data well (the coefficient of determination, R^2, is only 0.38) because of the large variability in the data.

To exclude the use of pavement distress as the independent variable for tire/pavement noise prediction, the second model (Equation A.5.3 through Equation A.5.6) was used to predict the pavement life in terms of noise. The independent variables of this model include pavement age, permeability, fineness modulus, MPD, surface layer thickness, the number of days with temperature higher than 30°C, and AADTT in the coring lane. The same values of surface layer thickness used in the first model, and the same values of traffic and environmental variables used in Section 7.1 are used here. Both permeability and MPD change with pavement age. They are estimated from regression models developed previously (the regression model in Appendix B.2.3 for permeability, and Equation A.3.1 for MPD). The estimated ages for open- and gap-graded mixes are shown in Table 7.4.

It can be seen from Table 7.4 that the number of years to reach the equivalent noise level of a DGAC pavement with an age of one to three years is different for the various mixes (OGAC, RAC-G, and RAC-O), but not significantly different for various traffic and environmental conditions. The relative ranks of the three mixes remain the same as in the first model: With respect to the tire/pavement noise of DGAC mixes, RAC-O mixes remain quieter longer than OGAC mixes do, and OGAC mixes remain quieter than DGAC mixes for a longer time than RAC-G mixes do. The lifetime of RAC-O is longer than 15 years under various traffic and climate conditions, however this conclusion must be interpreted carefully because it is extrapolated from RAC-O pavement sections that are less than 11 years old. In the data set, only two RAC-O sections are between nine and eleven years old, and all the other RAC-O sections are less than eight years old. The estimated parameters of the regression model, therefore, were heavily weighted on the young RAC-O sections.

Table 7.3: Predicted Lifetime[1,2] of Different Asphalt Mix Types with Respect to Noise from First Model

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	–	7	4	>10
	Moderate Rainfall/ Low Temperature	–	6	4	>10
	High Rainfall/ Moderate Temperature	–	6	4	>10
	Moderate Rainfall/ Moderate Temperature	–	6	4	>10
Low Traffic (TI=9)	Low Rainfall/ High Temperature	–	7	5	>>>10
	Moderate Rainfall/ Low Temperature	–	7	4	>>>10
	High Rainfall/ Moderate Temperature	–	7	5	>>>10
	Moderate Rainfall/ Moderate Temperature	–	7	5	>>>10

Note 1: Since the oldest sections in the sample are approximately 10 years old, calculated values greater than 10 years are shown as >10, values greater than 15 years are shown as >>10, and values greater than 20 years are shown as >>>10. Actual values predicted by all models with values greater than 10 years are shown in Table B.7.2 in Appendix B.7.
Note 2: Years to reach average noise level of 1- to 3-year-old DGAC.

Table 7.4: Predicted Lifetime[1,2] of Different Asphalt Mix Types with Respect to Noise from Second Model

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	–	10	6	>>10
	Moderate Rainfall/ Low Temperature	–	>10	10	>>10
	High Rainfall/ Moderate Temperature	–	>10	8	>>10
	Moderate Rainfall/ Moderate Temperature	–	>10	8	>>10
Low Traffic (TI=9)	Low Rainfall/ High Temperature	–	>10	6	>>10
	Moderate Rainfall/ Low Temperature	–	>10	10	>>10
	High Rainfall/ Moderate Temperature	–	>10	8	>>10
	Moderate Rainfall/ Moderate Temperature	–	>10	8	>>10

Note 1: Since the oldest sections in the sample are approximately 10 years old, calculated values greater than 10 years are shown as >10, values greater than 15 years are shown as >>10, and values greater than 20 years are shown as >>>10. Actual values predicted by all models with values greater than 10 years are shown in Table B.7.3 in Appendix B.7.
Note 2: Years to reach average noise level of 1- to 3-year-old DGAC.

It must be emphasized that in this section the pavement life for open- and gap-graded mixes in terms of noise reduction is defined as the time it takes the OBSI to reach the level of a typical DGAC pavement with an age of one to three years. The values in Table 7.3 and Table 7.4 will increase if the noise level on a DGAC pavement with an age of over three years [approximately 103.5 dB(A)] is used as the criterion, and will decrease if the noise level on a newly paved DGAC surface is used as the criterion (about 101.3 dB(A)]. It also needs to be noted that even if the noise level on an OGAC pavement is numerically lower than that on a DGAC pavement, it may not be perceived by residents along the roadside because there is a minimum value in noise difference (generally around 2 to 3 dB[A]) that can be detected by human ears.

7.3 Prediction of Pavement Distresses

In Appendix A.4, regression models were developed for four distress types: bleeding, raveling, transverse/reflective cracking, and wheelpath cracking. Due to the small sample size and large variation in the data, however, these models generally do not fit the data well. The coefficient of determination, R^2, is generally smaller than 0.50. This section of this report will use these models to give an indication of how soon bleeding, raveling, and transverse/reflective cracking will occur on various asphalt surface mixes. Since the rut depths were estimated subjectively with large errors during measurement, no model was developed for rutting.

Wheelpath cracking (fatigue cracking) will not be discussed because it is dominated by the cracking patterns and other properties of underlying layers instead of the surface mix.

Equation A.4.1 shows that bleeding is statistically significantly affected by pavement age, mix type, environmental factors, and cumulative truck traffic. To apply this model, the fineness modulus is assumed as 4.3, 5.2, 5.0, and 5.2 for the DGAC, OGAC, RAC-G, and RAC-O mixes, respectively. Environmental and traffic variables use the same values as in Section 7.1.

Table 7.5 shows the estimated ages to occurrence of bleeding for different mixes. Here the occurrence of bleeding is defined as three percent of the pavement surface showing bleeding. It can be seen that bleeding occurs earlier on pavements with heavier truck traffic volumes. Among the four mixes, RAC-G is the most susceptible to bleeding distress. The estimated ages to occurrence of bleeding for the DGAC, OGAC, and RAC-O mixes are all higher than 10 years, indicating that bleeding is not a main distress concern on pavements with these mixes.

Table 7.5: Predicted Age[1] to Occurrence of Bleeding of Different Asphalt Mix Types

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	>10	>10	7	>10
	Moderate Rainfall/ Low Temperature	>>10	>10	8	>10
	High Rainfall/ Moderate Temperature	>10	>10	7	>10
	Moderate Rainfall/ Moderate Temperature	>10	>10	5	>10
Low Traffic (TI=9)	Low Rainfall/ High Temperature	>10	>10	7	>10
	Moderate Rainfall/ Low Temperature	>>10	>>10	9	>>10
	High Rainfall/ Moderate Temperature	>>10	>10	8	>10
	Moderate Rainfall/ Moderate Temperature	>10	>10	8	>10

Note 1: Since the oldest sections in the sample are approximately 10 years old, calculated values greater than 10 years are shown as >10, values greater than 15 years are shown as >>10, and values greater than 20 years are shown as >>>10. Actual values predicted by all models with values greater than 10 years are shown in Table B.7.4 in Appendix B.7.

Equation A.4.3 shows that raveling is significantly affected by mix type, fineness modulus, the number of days with temperature higher than 30°C, and cumulative truck traffic. To apply this model, the fineness modulus was assumed to be 4.3, 5.2, 5.0, and 5.2 for the DGAC, OGAC, RAC-G, and RAC-O mixes, respectively. Environmental and traffic variables used the same values as in Section 8.1.

Table 7.6 shows the estimated ages to occurrence of raveling for the different mixes. Here the occurrence of raveling is defined as five percent of the pavement surface showing raveling. It can be seen that raveling occurs earlier on pavements with heavier truck traffic volumes. Among the four environmental conditions, raveling occurs earliest for the high rainfall/moderate temperature conditions. There is no significant difference among the four mixes in terms of the age to raveling.

Equation A.4.2 shows that transverse/reflective cracking is significantly affected by pavement age, mix type, surface layer thickness, the number of days with temperature higher than 30°C, and cumulative truck traffic. To apply this model, the surface layer thickness was assumed as 60 mm, 30 mm, 40 mm, and 30 mm for the DGAC, OGAC, RAC-G, and RAC-O mixes, respectively. Environmental and traffic variables used the same values as in Section 7.1. It was also assumed that the underlying AC layer is cracked with a thickness of 177 mm for all mixes, and that there are no PCC slabs underneath.

Table 7.7 shows the estimated ages to occurrence of transverse/reflective cracking for the different mixes. Here the occurrence of cracking is defined as 5 m of transverse/reflective cracks occurring on a 150 m-long section. It can be seen that transverse/reflective cracking occurs earlier on pavements with heavier truck traffic volumes.

Among the four climate variable combinations, transverse/reflective cracking occurs earliest in the region with moderate rainfall/low temperature. Table 7.7 also shows that transverse/reflective cracking occurs earlier in rubberized mixes than in non-rubberized mixes. This is possibly due to the bias in the sample data, in which RAC-G and RAC-O mixes tend to typically be placed on pavements with a greater extent of cracking than are DGAC and OGAC mixes.

Table 7.6: Predicted Age[1] to Occurrence of Raveling of Different Asphalt Mix Types

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	>10	>10	10	>10
	Moderate Rainfall/ Low Temperature	>10	>10	>10	>10
	High Rainfall/ Moderate Temperature	>10	>10	10	>10
	Moderate Rainfall/ Moderate Temperature	>10	>10	>10	>10
Low Traffic (TI=9)	Low Rainfall/ High Temperature	>>>10	>>>10	>>>10	>>>10
	Moderate Rainfall/ Low Temperature	>>>10	>>>10	>>>10	>>>10
	High Rainfall/ Moderate Temperature	>>>10	>>>10	>>>10	>>>10
	Moderate Rainfall/ Moderate Temperature	>>>10	>>>10	>>>10	>>>10

Note 1: Since the oldest sections in the sample are approximately 10 years old, calculated values greater than 10 years are shown as >10, values greater than 15 years are shown as >>10, and values greater than 20 years are shown as >>>10. Actual values predicted by all models with values greater than 10 years are shown in Table B.7.5 in Appendix B.7.

Table 7.7: Predicted Age[1] to Occurrence of Transverse/Reflective Cracking of Different Asphalt Mix Types

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	4	5	3	4
	Moderate Rainfall/ Low Temperature	2	3	1	2
	High Rainfall/ Moderate Temperature	3	4	2	3
	Moderate Rainfall/ Moderate Temperature	3	4	2	3
Low Traffic (TI=9)	Low Rainfall/ High Temperature	8	9	6	8
	Moderate Rainfall/ Low Temperature	4	7	2	4
	High Rainfall/ Moderate Temperature	6	8	4	6
	Moderate Rainfall/ Moderate Temperature	6	7	3	5

Note 1: Since the oldest sections in the sample are approximately 10 years old, calculated values greater than 10 years are shown as >10, values greater than 15 years are shown as >>10, and values greater than 20 years are shown as >>>10.

7.4 Summary

This chapter estimated the lifetime of various asphalt mixes in terms of roughness, tire/pavement noise, and occurrence of bleeding, raveling, and transverse/reflective cracking. It can be seen that for non-rubberized OGAC mixes, the controlling performance indices are noise and the occurrence of transverse/reflective cracking, while roughness, and the occurrence of bleeding and raveling are not of primary concern. For RAC-G mixes, the controlling performance indices include noise and the occurrence of bleeding and transverse/reflective cracking. For RAC-O mixes, the controlling performance index is the occurrence of transverse/reflective cracking.

8 CONCLUSIONS

The work presented in this report is part of on-going research. The central purpose of this research is to support the Caltrans Quieter Pavement Research Program, which has as its goals the identification of quieter, smoother, safer, and more durable pavement surfaces.

This study compares four consecutive years of pooled field data gathered on California pavements with open-graded (OGAC, RAC-O) and other asphaltic mix (RAC-G) surfaces with data collected on conventional dense-graded asphalt concrete (DGAC). Categories of data include tire/pavement noise, surface condition, ride quality, and macrotexture. The four years of data were analyzed in this report with the following objectives:

1. To evaluate the durability and effectiveness of the OGAC, RAC-O, and RAC-G asphalt mix types in reducing noise, as measured with the On-board Sound Intensity (OBSI) method.
2. To evaluate the pavement characteristics that affect tire/pavement noise.
3. To evaluate the changes in the following pavement performance parameters over time and to develop equations for estimating future performance:
   - Smoothness, in terms of International Roughness Index (IRI)
   - Macrotexture, in terms of mean profile depth (MPD)
   - Surface distress condition, with respect to bleeding, rutting, raveling, transverse/reflective cracking, and wheelpath cracking

8.1 Performance of Open-Graded Mixes

For newly paved overlays, the OGAC and RAC-O open-graded mixes had lower tire/pavement noise than the DGAC mix by average levels of 2.7 dB(A) and 2.8 dB(A), respectively. For comparison, the average tire/pavement noise level is approximately 101.3 dB(A) for newly paved DGAC overlays.

After the pavements are exposed to traffic, this noise benefit generally diminishes slightly for about five to seven years, and then begins to diminish more rapidly after seven years. RAC-O is quieter than OGAC and keeps a noise-reduction benefit longer than OGAC.

For newly paved overlays, open-graded mixes had higher low-frequency noise and lower high-frequency noise than dense-graded mixes. In the first four years after the open-graded mixes were exposed to traffic, high-frequency noise increased with age due to the reduction of surface permeability and air-void content under traffic, while low-frequency noise decreased with age, likely due to the reduction of surface roughness caused by further compaction under traffic. These opposing changes left the overall sound intensity nearly unchanged.

For open-graded pavements older than three years, noise in the frequencies between 500 and 2,500 Hz increased with age, while noise in the frequencies over 2,500 Hz decreased slightly with age.

Among the two open-graded mixes, MPD had lower initial values and increased more slowly on RAC-O pavements than on OGAC pavements. The effect of MPD on noise is complex. It appears that a higher MPD value increased noise on DGAC and RAC-G pavements, but did not significantly affect noise on OGAC and RAC-O pavements.

Based on the condition survey for pavements less than eleven years old, for newly paved overlays transverse/reflective cracking was less significant on open-graded mixes than on dense- or gap-graded mixes. However once the cracking appeared on open-graded mixes it increased more rapidly with pavement age than on dense- or gap-graded mixes. It also appears that open-graded pavements experienced less raveling than dense-graded mixes. There was no other significant difference between open- and dense-graded mixes in terms of pavement distresses. The data also reveal that bleeding tends to appear earlier on RAC-O mixes than on OGAC mixes.

8.2 Performance of RAC-G Mixes

The newly paved RAC-G mixes were quieter than an average newly paved DGAC mix by about 1.8 dB(A). Within a few years after the pavements were exposed to traffic, the tire/pavement noise on RAC-G mixes approached the average noise level of DGAC pavements of similar ages. Among newly paved overlays, RAC-G mixes had higher low frequency noise and lower high frequency noise than DGAC mixes. In the first three years after the pavements were exposed to traffic, high frequency noise increased with age due to the reduction of surface permeability and air-void content under traffic, while low frequency noise (equal to or less than 1,000 Hz) was nearly unchanged with age. For RAC-G pavements older than three years, noise of all frequencies increased with age.

The IRI value on newly paved RAC-G mixes was lower than that on DGAC mixes and it did not increase with age as much as the IRI on DGAC pavements. RAC-G mixes had a permeability level as high as that of open-graded mixes in the first two years after construction, but under traffic the permeability decreased rapidly to the level of DGAC mixes in about four years. These facts explain the reasons for the initial low noise level and the rapid loss of the noise benefit of RAC-G mixes.

Based on the condition survey of pavements less than eleven years old, RAC-G pavement is more prone than other mixes to bleeding in terms of both the time of occurrence and the extent of distress. Transverse/reflective cracks seem to initiate earlier and propagate faster on rubberized pavements than on non-rubberized pavements, but this is possibly because rubberized mixes tend to be placed more often on pavements with a greater extent of cracking, which biases the comparison. RAC-G pavements may exhibit less initial raveling than DGAC pavements, but the difference quickly disappears in two or three years. No other significant difference was observed between RAC-G and DGAC mixes in terms of pavement distresses.

8.3 Variables Affecting Tire/Pavement Noise

The findings from this fourth year of the study regarding variables affecting tire/pavement noise are generally consistent with the findings from analysis of the two-year and three-year data *(2, 3)*. That is, the tire/pavement noise is greatly influenced by surface mix type and mix properties, age, traffic volume, and the presence of distresses. Various mix types have different noise performances, and the overall noise level generally increases with traffic volume, pavement age, and the presence of pavement distresses. Overall noise level decreases with increased surface layer thickness and permeability (or air-void content).

For all mix types (DGAC, RAC-G, OGAC and RAC-O), the aggregate gradation variable (fineness modulus) did not seem to significantly affect tire/pavement noise. It must be noted that the conclusion regarding aggregate gradation is drawn from a data set that only contains NMAS ranging from 9.5 mm to 19 mm, while most open-graded mixes are either 9.5 or 12.5 mm, and most RAC-G and DGAC mixes are either 12.5 or 19 mm.

Pavement surface macrotexture (MPD) was a significant factor for DGAC and RAC-G pavements, and a higher MPD value corresponded to a higher noise level. For OGAC and RAC-O pavements, MPD did not have a significant influence on noise level.

8.4 Performance of Experimental Mixes

The bituminous wearing course (BWC) mix placed on the LA 138 sections had a noise level comparable to that of DGAC mixes and similar distress development as current Caltrans open-graded mixes. The noise levels of the BWC mixes were generally higher than those of open-graded mixes of similar age. This indicates that the tire/pavement noise performance of the LA 138 BWC mix was not typical of that of other BWC mixes placed in the state that were tested in the third year and will be tested again in the fifth year.

Based on the Fresno 33 (Firebaugh) sections it was observed that:

- RAC-G and RUMAC-GG mixes generally exhibited higher MPD and IRI values than Type G-MB, Type D-MB, and DGAC mixes. Increase of MPD and IRI with pavement age was much less significant on Type G-MB and Type D-MB mixes than on RAC-G, RUMAC-GG, and DGAC mixes. Increasing layer thickness did not reduce fatigue cracking or transverse cracking on the RAC-G mix. Increasing thickness may help reduce cracking of RUMAC-GG, Type G-MB, and Type D-MB.

- Although the Type G-MB mix had higher noise levels than the RAC-G mix soon after construction, the increase in noise with age was less significant on the Type G-MB mix than on the RAC-G mix and the Type D-MB mix.
- All the Fresno 33 test mixes were prone to bleeding in the first four years after construction, and bleeding remained longer on Type G-MB and Type D-MB sections.
- The Type D-MB mix was more resistant to cracking than the DGAC mix but it was also more susceptible to bleeding.
- The Type D-MB mix had a noise level similar to the DGAC mix soon after construction, but its noise level increased with age more than the noise level of the DGAC mix.
- After opening to traffic for four years, none of the test mixes—RAC-G, RUMAC-GG, Type G-MB, and Type D-MB—provided any noise reduction benefit compared with DGAC.

The European gap-graded (EU-GG) mix placed on LA 19 has performance characteristics (in terms of noise, roughness, and durability) very similar to those of gap-graded mixes (RAC-G) used in California, except it may retain its permeability longer.

After ten years of service, the Yolo 80 OGAC section still provides acceptable ride quality, but it has a noise level close to that of DGAC pavements.

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APPENDICES

Appendix A: Details of Four-Year Data Presentation and Analysis

A.1: Introduction

This appendix presents the details of data plotting and analysis based on the pool of four-year measurement data, including International Roughness Index (IRI), Mean Profile Depth (MPD), surface distresses (bleeding, rutting, transverse cracking, raveling, and wheelpath cracking), and On-board Sound Intensity (OBSI) measurements of tire/pavement noise. The appendix also includes estimation of pavement life based on new regression equations for each of the performance measures.

A.2: Surface Profile Results and Analysis: IRI

The analysis of the IRI answers these questions:

- What pavement characteristics affect IRI?
    - Are initial IRI and IRI changes with time different for rubberized and non-rubberized mixes?
    - Are initial IRI and IRI changes with time different for open-graded and dense-graded mixes?
- How do traffic and climate affect IRI?

A.2.1: Descriptive Analysis

Figure 2.1 shows the average IRI measured in four consecutive years for individual pavement sections of four mix types, DGAC, OGAC, RAC-G, and RAC-O. It should be noted that the IRI values at the time the overlays were constructed or soon thereafter are unknown except for those sections that were tested soon after construction. It should also be noted that the original condition of the pavement layers beneath the overlays is unknown.

The figure legends list sections that showed a decrease of IRI with age. Small reductions in IRI with age can be attributed to measurement errors. However, a couple of sections show a significant decrease in IRI, specifically QP-09 (DGAC), QP-26 (RAC-G), and QP-20 (OGAC). Section QP-09 has a large patch in the middle; Section QP-26 showed good surface condition in the fourth survey year; and Section QP-20 is located on a steep hill. It is uncertain why the IRI decreased on these sections, and their changes may be due either to difficulties in measurement (such as problems retracing the earlier wheelpath) or to road maintenance. These three sections are treated as outliers and will be removed from the subsequent analysis.

It can be seen from Figure 2.1 that IRI increased with age for many pavement sections. This is expected because pavement conditions deteriorate with age due to traffic and environmental effects. However, some sections, particularly OGAC sections, showed little change in IRI in the four-year survey period. For newly placed

OGAC pavements, IRI reduced in the first three years after being opened to traffic, possibly due to additional compaction from traffic, then began to increase in the fourth year.

Figure A.1 is a box plot that shows the variation in IRI values for different mix types, including two F-mixes, across all four years of measurement. In all of the box plots shown in this report the white bar is the median value, the "x" is the mean value, the upper and lower edges of the purple box are the 75th and 25th percentiles respectively, and the upper and lower brackets are the upper and lower extreme values respectively.

According to the plot, except for the OGAC-F mixes, the average IRI values of the different mixes are close to each other, and most of the sections have acceptable IRI values based on the FHWA criteria of 170 in./mi (2.4 m/km) *(1)*. However, one DGAC pavement shows high IRI values (>3.6 m/km) that would trigger Caltrans maintenance action. From Figure 2.1 it can be seen that this is an old pavement that was 14 years old at the beginning of the survey.

Figure A.2 shows the IRI values for different mix types for the three initial age categories of less than one year, one to four years, and greater than four years. It can be seen that IRI values increase with age for RAC-O and DGAC mixes but show no trend for OGAC and RAC-G mixes.

Figure A.3 shows the time trend of IRI across the four years of data collection for different mix types for the three initial three age categories. As the figure shows, IRI generally increases with time. For newly paved mixes (Age Category "<1 year"), IRI varied insignificantly for DGAC, OGAC, and RAC-O in the first four years. On the other hand, RAC-G showed a significant increase in IRI in the first three years after construction. From Figure 2.1 it can be seen that this is due to the rapid increase in IRI on one pavement section. This section is QP-26, which is located on Highway 280 in Santa Clara County in Caltrans District 4. The reason for the rapid increase in IRI at this section is unknown. This section also showed a rapid increase in macrotexture (Mean Profile Depth [MPD] increased from 800 microns in the first year to 2,150 microns in the third year after construction) and observations of raveling and segregation in the third year. Cores from this section taken within a year of construction showed measured air-void contents of approximately 9 percent, which indicates that insufficient compaction might have caused the rapid IRI increase. If QP-26 is excluded, IRI also varied insignificantly for RAC-G in the first three years. In the fourth year, Section QP-26 showed good surface condition and low MPD and IRI values, indicating maintenance action was taken between the third and fourth survey years. The corresponding box plot therefore showed a significant reduction in IRI in the fourth year for RAC-G mix.

(Note: IRI values have been reported in m/km since data collection began. For reference, some critical IRI values are shown below in inches per mile *(2):*

Criteria	in./mi	m/km
FHWA "very good" maximum value	60	0.95
FHWA "good" maximum value	94	1.48
FHWA "fair" for Interstates maximum value	119	1.88
FHWA "fair" for non-Interstates and "mediocre" for Interstate maximum values	170	2.68
FHWA "mediocre" for non-Interstate maximum value	220	3.47
Caltrans rigid pavement PMS prioritization trigger	213	3.36
Caltrans flexible pavement PMS prioritization trigger	224	3.54

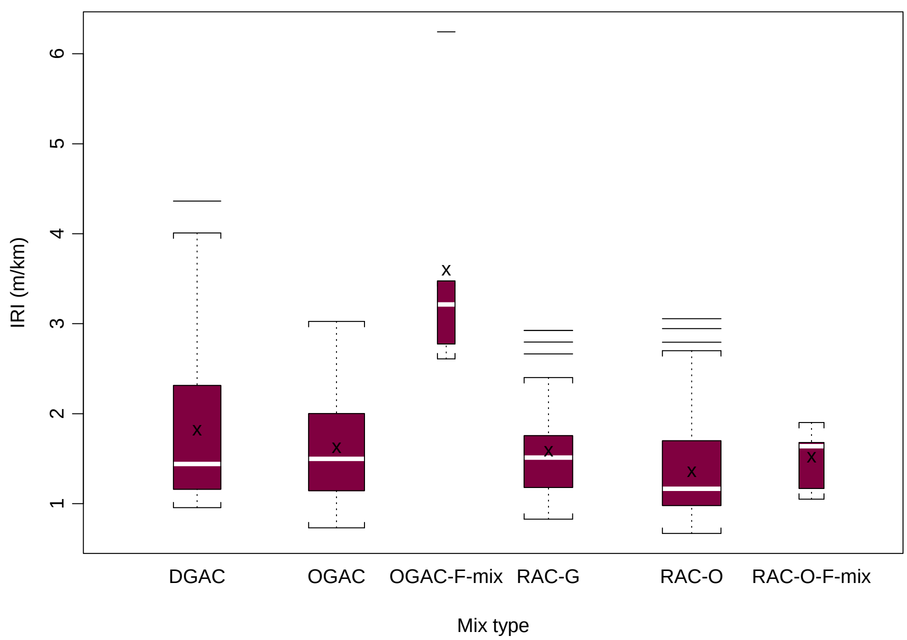


Figure A.1: Variation in IRI values for different mix types for all four years of pooled data and all initial ages.
(Note: 1 m/km = 63 in./mi; 2 m/km = 127 in./mi; 3 m/km = 190 in./mi)

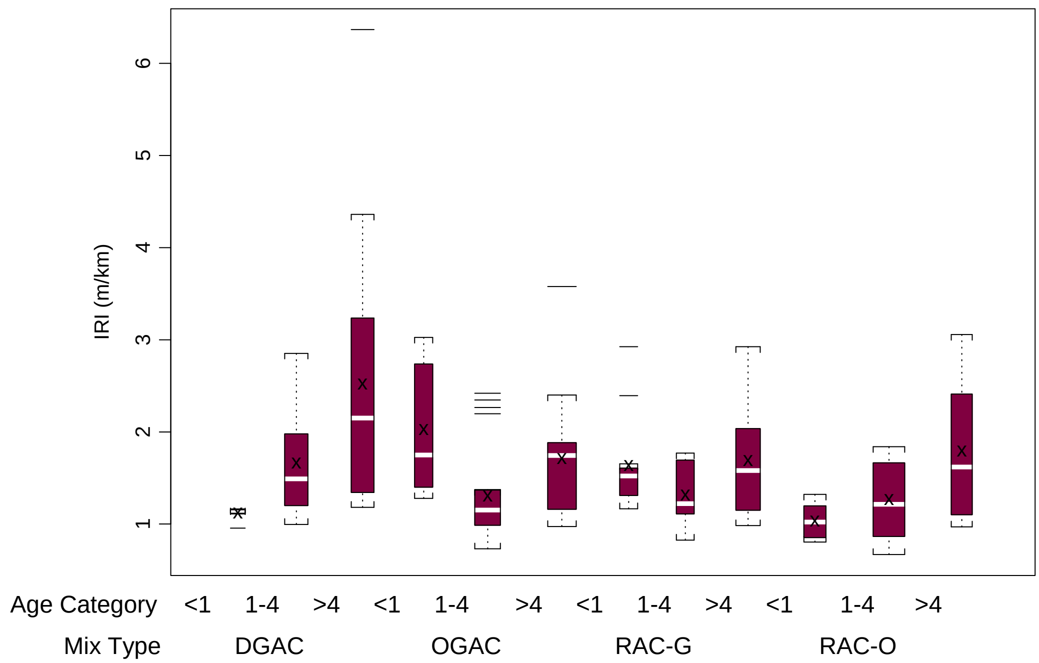


Figure A.2: Variation in IRI values for different mix types for different initial ages (Age category in years) for all four years of pooled data.
(Note: 1 m/km = 63 in./mi; 2 m/km = 127 in./mi; 3 m/km = 190 in./mi)

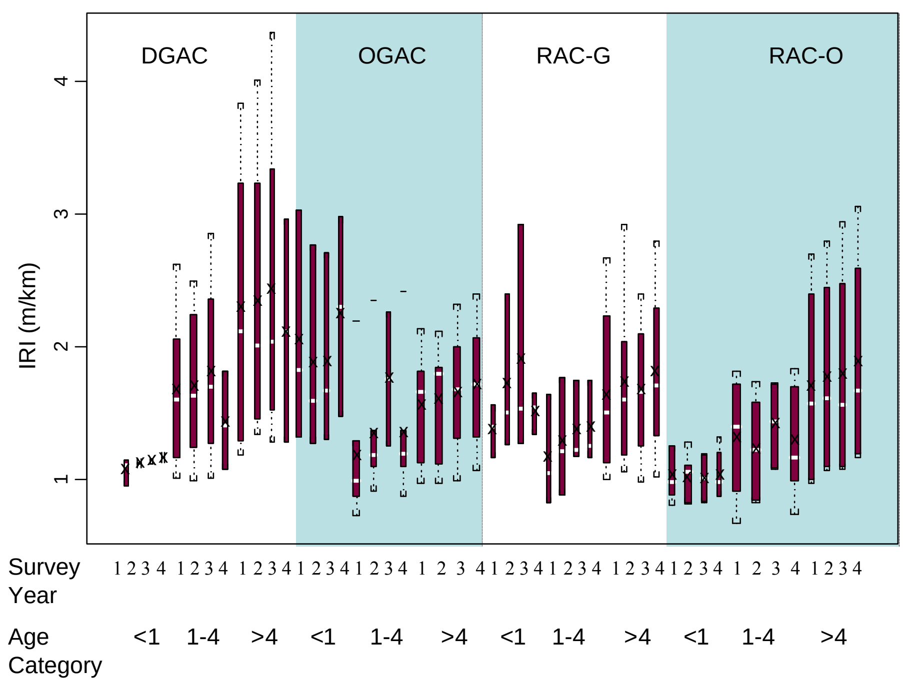


Figure A.3: Comparison of IRI values for different mix types at different ages for four years of data collection.
(Note: 1 m/km = 63 in./mi; 2 m/km = 127 in./mi; 3 m/km = 190 in./mi)

A.2.2: Regression Analysis

Regression analysis was performed to evaluate the effects of traffic, climate, distresses, and pavement materials on IRI values. First, a single variable regression analysis was conducted to prescreen significant factors to be included in a multiple regression model. Estimates of the coefficient of the explanatory variable and the constant term along with their P-values and the coefficient of determination (R^2) for each model are given in Table A.1. The P-values less than 0.05, indicating highly significant variables, are shown in bold type.

The results in Table A.1 show that IRI tends to be significantly affected by the presence of distresses and environmental factors. The signs of the estimated coefficients indicate that the greater the distresses (fatigue cracking, raveling, rutting, and bleeding) and rainfall, the higher the IRI. These are expected. High temperature days, on the other hand, seem to reduce IRI. This may be due to higher temperatures making it easier to obtain smoothness at the time of construction or some initial compaction of the mixes by trafficking after construction. Table A.1 also shows that rubberized binder tends to reduce IRI.

Table A.1: Regression Analysis of Single-Variable Models for IRI

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	9.913E-02	**<0.001**	1.020	0.236
2	Air-void Content (%)	-7.523E-03	0.337	1.589	0.004
3	Mix Type	-3.308E-01	**0.006**	1.800	0.078
4	Rubber Inclusion	-2.169E-01	**0.010**	1.615	0.031
5	MPD (micron)	2.281E-04	0.122	1.277	0.012
6	Presence of Fatigue Cracking	3.616E-01	**0.001**	1.437	0.051
7	Presence of Raveling	2.578E-01	**0.006**	1.427	0.036
8	Presence of Rutting	7.880E-01	**<0.001**	1.401	0.183
9	Presence of Transverse Cracking	1.696E-01	0.052	1.434	0.018
10	Presence of Bleeding	2.944E-01	**0.006**	1.444	0.036
11	Average Annual Rainfall (mm)	1.128E-04	0.222	1.435	0.007
12	Age*Average Annual Rainfall (mm)	1.630E-04	**<0.001**	1.097	0.290
13	Average Annual Wet Days	1.017E-03	0.252	1.428	0.006
14	Age*Average Annual Wet Days	1.010E-03	**<0.001**	1.170	0.214
15	Average Annual Max. Daily Air Temp (ºC)	-7.651E-02	**<0.001**	3.277	0.098
16	Annual Number of Days >30ºC	-3.790E-03	**<0.001**	1.812	0.100
17	Annual Degree-Days >30ºC	-1.072E-04	**<0.001**	1.805	0.102
18	Annual FT Cycles	-6.533E-03	**0.039**	1.589	0.020
19	Annual AADTT per Coring Lane	-1.924E-05	0.476	1.525	0.002
20	Annual ESALs per Coring Lane	-6.496E-08	0.209	1.537	0.008

Based on the results in Table A.1, multiple regression analysis was conducted to account for the effect of various factors simultaneously. First a pair-wise correlation analysis was performed to avoid highly-correlated variables in the same model. It was found that air-void content and MPD are highly correlated. MPD is also partly determined by the maximum aggregate size in the mix. Average Annual Maximum Daily Air Temperature is highly correlated with Annual Number of Days >30°C and Annual Degree-Days >30°C. Annual AADTT per Coring Lane is highly correlated with Annual ESALs per Coring Lane. In the multiple regression analysis, only one variable in each highly correlated variable pair was considered.

Preliminary analysis revealed that the error terms from multiple regression have non-constant variance, so a reciprocal square-root transformation (Y' = $1/\sqrt{IRI}$) was applied to the dependent variable, IRI, to stabilize the variance of the error terms.

Because mix properties are highly affected by mix type (e.g., higher air-void contents in open-graded mixes than in dense- and gap-graded mixes), it is not appropriate to incorporate both mix property variables (e.g., air-void content) and mix type in the same model. To determine the effects of mix type and mix properties on IRI, separate regression models were proposed.

In the first model, only the mix type (categorical variable) and environmental and traffic factors are included as the independent variables, while mix property variables are excluded. The regression equation, Equation A.2.1, is

$$\begin{aligned} 1/\sqrt{IRI}\,(m/km) &= 0.884208 - 0.020064 \times Age(year) + 0.052834 \times ind\,(MixTypeOGAC) + 0.033662 \times ind\,(MixTypeRAC-G) \\ &+ 0.103240 \times ind\,(MixTypeRAC-O) - 0.000069 \times AverageAnnualRainfall(mm) + 0.000580 \times NumberOfDays > 30C \\ &- 0.000012 \times AADTTinCoringLane + 0.001810 \times AnnualFTCycles \end{aligned} \quad \textbf{(A.2.1)}$$

where $ind(\cdot)$ is an indicator function, 1 if a variable in parenthesis is true and 0 if it is false. The coefficient of the $ind(\cdot)$ function represents the difference in the effects of other mix types and DGAC. The estimated values and P-values of the parameters are shown below, with variables that are significant at the 95 percent confidence interval shown in bold type.

	Value	Std. Error	t value	P-value
(Intercept)	0.884208	0.039806	22.2129	<0.0001
Age	-0.020064	0.003098	-6.4761	<0.0001
MixTypeOGAC	0.052834	0.025145	2.1012	0.0369
MixTypeRAC-G	0.033662	0.026930	1.2500	0.2128
MixTypeRAC-O	0.103240	0.023977	4.3058	<0.0001
AvgAnnualRainfall	-0.000069	0.000025	-2.7869	0.0058
NoDaysTempGT30	0.000580	0.000192	3.0215	0.0028
AADTTCoringLane	-0.000012	0.000006	-2.0119	0.0456
AnnualFTCycles	0.001810	0.000743	2.4367	0.0157

Residual standard error: 0.1229 on 203 degrees of freedom; Multiple R-Squared: 0.35.

Overall, this model with the pooled data for all four mix types does not do a very good job of predicting IRI, as indicated by the R^2 of 0.35. It can be seen that at the 95 percent confidence level, age (Age), mix type (MixTypeOGAC, MixTypeRAC-O), average annual rainfall (AvgAnnualRainfall), number of days greater than 30ºC (NoDaysTempGT30), AADTT per Coring Lane (AADTTCoringLane), and annual freeze-thaw cycles (AnnualFTCycles) significantly affect IRI. The IRI increases with age and average annual rainfall, but decreases with the number of days greater than 30ºC and annual freeze-thaw cycles. Among the three pavement types, OGAC, RAC-G, and RAC-O, all have lower initial IRI than DGAC, but only OGAC and RAC-O are statistically significantly different than DGAC. Initially, the interaction terms between age and mix type were included in the model but none of them were statistically significant, which indicates that the growth rate of IRI is not statistically different among the four pavement types.

In the second model, the mix type variables are replaced with mix property variables and the model is estimated for each mix type separately. The regression equations, Equation A.2.2 through Equation A.2.5, are shown below.

For DGAC pavements:

$$\begin{aligned}1/\sqrt{IRI}\,(m/km) &= 0.843451 - 0.016616\times Age(year) - 0.000143\times MPD - 0.00524\times \log(Permeability)(cm/\sec)\\ &-0.000062\times AverageAnnualRainfall(mm) + 0.001090\times NumberOfDays > 30C\\ &+0.0000002\times AADTTinCoringLane + 0.004192\times AnnualFTCycles\end{aligned} \quad \textbf{(A.2.2)}$$

	Value	Std. Error	t value	P-value
(Intercept)	0.843451	0.102690	8.2135	<0.0001
Age	-0.016616	0.005796	-2.8670	0.0070
MPD	-0.000143	0.000108	-1.3222	0.1947
logPerm	-0.005424	0.010063	-0.5390	0.5933
AvgAnnualRainfall	-0.000062	0.000036	-1.6925	0.0994
NoDaysTempGT30	0.001090	0.000337	3.2349	0.0027
AADTTCoringLane	0.000002	0.000010	0.1560	0.8769
AnnualFTCycles	0.004192	0.001730	2.4233	0.0207

Residual standard error: 0.0961 on 35 degrees of freedom; Multiple R-Squared: 0.68.

For OGAC pavements:

$$\begin{aligned}1/\sqrt{IRI}\,(m/km) &= 0.880751 + 0.018568\times Age(year) - 0.000246\times MPD\,(micron) + 0.004061\times \log(Permeability)(cm/\sec)\\ &+0.000115\times AverageAnnualRainfall(mm) + 0.001346\times NumberOfDays > 30C - 0.0000001\times AADTTinCoringLane\\ &+0.002605\times AnnualFTCycles\end{aligned} \quad \textbf{(A.2.3)}$$

	Value	Std. Error	t value	P-value
(Intercept)	0.880751	0.129281	6.8127	<0.0001
Age	0.018568	0.009792	1.8964	0.0645
MPD	-0.000246	0.000080	-3.0678	0.0037
logPerm	0.004061	0.009371	0.4334	0.6669
AvgAnnualRainfall	0.000115	0.000108	1.0678	0.2914
NoDaysTempGT30	0.001346	0.000491	2.7387	0.0089
AADTTCoringLane	-0.000001	0.000017	-0.0827	0.9344
AnnualFTCycles	0.002605	0.001825	1.4276	0.1605

Residual standard error: 0.1066 on 44 degrees of freedom; Multiple R-Squared: 0.44.

For RAC-G pavements:

$$1/\sqrt{IRI}\,(m/km) = 1.132704 - 0.020914 \times Age(year) - 0.000125 \times MPD(micron) - 0.011731 \times \log(Permeability)(cm/\sec) \\ -0.000090 \times AverageAnnualRainfall(mm) - 0.000155 \times NumberOfDays > 30C \\ -0.000068 \times AADTTinCoringLane - 0.001772 \times AnnualFTCycles \quad \textbf{(A.2.4)}$$

	Value	Std. Error	t value	P-value
(Intercept)	1.132704	0.077367	14.6406	<0.0001
Age	-0.020914	0.008323	-2.5129	0.0172
MPD	-0.000125	0.000077	-1.6217	0.1147
logPerm	-0.011731	0.007175	-1.6351	0.1118
AvgAnnualRainfall	-0.000090	0.000046	-1.9767	0.0567
NoDaysTempGT30	-0.000155	0.000389	-0.3980	0.6933
AADTTCoringLane	-0.000068	0.000018	-3.8681	0.0005
AnnualFTCycles	-0.001772	0.001544	-1.1474	0.2597

Residual standard error: 0.0794 on 32 degrees of freedom; Multiple R-Squared: 0.67.

For RAC-O pavements:

$$1/\sqrt{IRI}\,(m/km) = 0.835255 - 0.029043 \times Age(year) + 0.000075 \times MPD(micron) + 0.001935 \times \log(Permeability)(cm/\sec) \\ +0.000043 \times AverageAnnualRainfall(mm) + 0.001169 \times NumberOfDays > 30C \\ -0.000007 \times AADTTinCoringLane + 0.000127 \times AnnualFTCycles \quad \textbf{(A.2.5)}$$

	Value	Std. Error	t value	P-value
(Intercept)	0.835255	0.137195	6.0881	<0.0001
Age	-0.029043	0.007593	-3.8252	0.0003
MPD	0.000075	0.000090	0.8397	0.4045
logPerm	0.001935	0.011187	0.1730	0.8633
AvgAnnualRainfall	0.000043	0.000053	0.8258	0.4123
NoDaysTempGT30	0.001169	0.000431	2.7139	0.0087
AADTTCoringLane	-0.000007	0.000011	-0.6386	0.5256
AnnualFTCycles	0.000127	0.001298	0.0980	0.9222

Residual standard error: 0.1312 on 58 degrees of freedom; Multiple R-Squared: 0.35.

The IRI models for DGAC and RAC-G have R^2 above 0.65, while the OGAC and RAC-O models have R^2 below 0.45. The results show that for DGAC and RAC-O pavements, age and number of days greater than 30ºC are significant at the 95 percent confidence level. For OGAC pavements, IRI increases with MPD, but does not change significantly with age. IRI on open-graded pavements (OGAC and RAC-O) decreases with the number of days greater than 30ºC, indicating that open-graded pavements are smoother in high temperature regions than in low temperature regions. Traffic volume is a significant variable for RAC-G pavements. Higher traffic volume leads to higher IRI values although it is not a significant variable except for RAC-G.

A.2.3: Summary of Findings

The following findings were obtained regarding roughness:

1. The IRI models for DGAC and RAC-G have R^2 above 0.65, while the OGAC and RAC-O models have R^2 below 0.45.
2. Except for an old DGAC pavement, all sections are smoother than the Caltrans Pavement Management System IRI trigger criterion of 3.6 m/km (224 in./mi).
3. Rubberized open-graded mixes have lower initial IRI values than non-rubberized open-graded mixes; rubberized gap-graded mixes have lower initial IRI values than non-rubberized dense-graded mixes.
4. The surface types OGAC, RAC-G, and RAC-O all have lower initial IRI than DGAC, but only OGAC and RAC-O are statistically significantly different from DGAC. Monitoring over four years indicates that IRI increases with age on DGAC, RAC-G, and RAC-O pavements, but that age does not have a statistically significant effect on increasing IRI on OGAC pavements.
5. Open-graded pavements (OGAC and RAC-O) are smoother in high temperature regions than in low temperature regions.
6. The IRI of OGAC pavements increases with increasing MPD. The monitoring performed to date shows that traffic volume significantly affects IRI only on RAC-G pavements, with higher traffic volumes showing higher IRI values.

A.3: Surface Profile Analysis: Mean Profile Depth

The analysis of the MPD answers these questions:

- What pavement characteristics affect MPD?
    - Are initial MPD and change of MPD with time different for rubberized and non-rubberized mixes?
    - Are the initial MPD and MPD progression different for open-graded and dense-graded mixes?
- How do traffic and climate affect MPD?

The hypotheses regarding the effects of the explanatory variables on MPD are discussed in Reference *(1).*

A.3.1: Descriptive Analysis

Figure 3.1 shows the average MPD measured in four consecutive years for individual pavement sections for four mix types: DGAC, OGAC, RAC-G, and RAC-O. Some of the sections, whose numbers are listed in the legend, showed lower MPDs in the later years but the differences were small and can be attributed to measurement errors or other random variations. A few sections, however, show significantly different MPD values. These sections include the three OGAC pavements that were newly paved at the start of the study, QP-20, QP-44, and

QP-45, and a RAC-G pavement (QP-26). The three newly paved OGAC sections all showed significantly high initial MPD values. As noted earlier, Section QP-20 is located on a steep hill and may have experienced compaction problems during construction that led to the high MPD. QP-44 is on I-80 in District 3 in Placer County where both annual rainfall and traffic volume are very high. A pavement condition survey conducted one year after construction revealed a very rough texture with only angular coarse aggregates exposed on the surface. Although QP-45, which is on I-80 in District 3 in Yolo County, also has high traffic volume the reason for the high initial MPD values remains unclear. Lastly, QP-26 showed a rapid increase in macrotexture (MPD increased from 800 microns in the first year after construction to 2,150 microns in the third year) and the distresses raveling and segregation in the third year, and a significant drop of MPD and improvement of surface conditions in the fourth year, likely due to some maintenance and rehabilitation activities taken between the third and the fourth survey years. As discussed earlier (A.2.1: Descriptive Analysis), the mix design and/or compaction for this section might not have been sufficient. Consequently, these four sections are treated as outliers and will be removed from the statistical analysis.

Figure A.4 shows the variation in MPD values for different mix types, including two F-mixes, based on the four-year survey data. The information conveyed in the plots is the similar to that in the plot based on the data collected in the first three years *(3)*. The two F-mixes have the highest MPD. The RAC-G mixes have higher MPD values than the dense-graded mixes, while the open-graded mixes have higher MPD values than the RAC-G mixes. Among the two open-graded mixes, RAC-O mixes have lower MPD values than OGAC mixes.

Figure A.5 shows the time trend of MPD in four years for different mix types for three age categories. As the figure shows, MPD generally increases with pavement age for the same pavement section. Except for the four outlier pavement sections, this increase trend is also obvious among different pavement sections of the same mix type.

<u>A.3.2: Regression Analysis</u>

Regression analysis was performed to evaluate the effects of traffic, climate, distresses, and pavement materials on MPD values. First, a single-variable regression analysis was conducted to prescreen significant factors to be included in a multiple regression model. Estimates of the coefficient of the explanatory variable and the constant term along with their P-values and the coefficient of determination (R^2) for each model are given in Table A.2. The P-values less than 0.05 are shown in bold type. Descriptions of the variables are provided in References *(1,3)*.

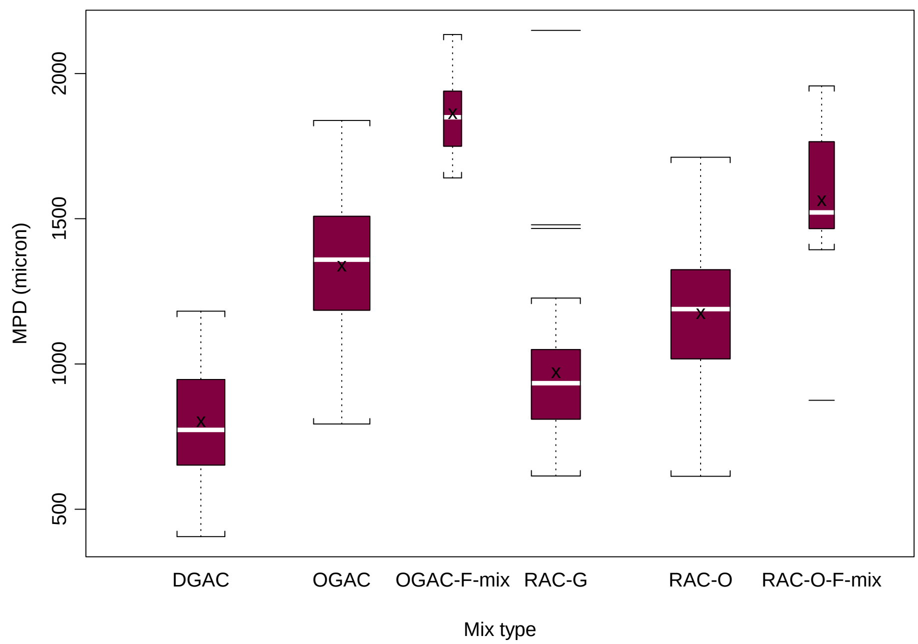


Figure A.4: Variation in MPD values for different mix types for pooled data for all four years and all initial ages.

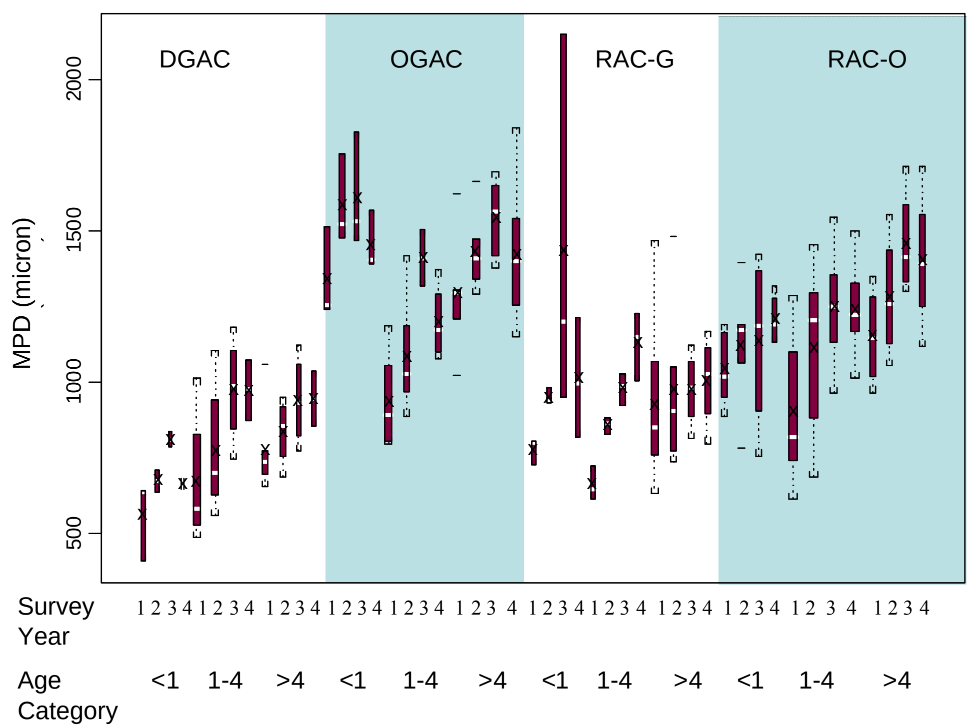


Figure A.5: Comparison of MPD values for different mix types for different initial age categories (Age Category) and for four years of data collection.

Table A.2: Regression Analysis of Single-Variable Models for MPD

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	3.579E+01	**<0.001**	886.040	0.139
2	Air-void Content (%)	3.668E+01	**<0.001**	645.479	0.472
3	Mix Type	5.083E+02	**<0.001**	786.003	0.426
4	Rubber Inclusion	4.289E+01	0.306	1045.561	0.005
5	Fineness Modulus	3.834E+02	**<0.001**	-827.064	0.349
6	NMAS (mm)	-4.440E+01	**<0.001**	1639.136	0.135
7	C_u	-1.115E+01	**<0.001**	1310.084	0.339
8	C_c	1.308E+01	0.218	1031.432	0.008
9	BPN	-1.574E-01	0.922	1078.208	0.000
10	Surface Thickness (mm)	-6.399E+00	**<0.001**	1324.946	0.169
11	IRI (m/km)	4.334E+01	0.193	1003.368	0.009
12	Presence of Rutting	1.459E+02	**0.017**	1047.426	0.029
13	Presence of Bleeding	1.597E+02	**0.001**	1030.935	0.052
14	Average Annual Rainfall (mm)	5.043E-03	0.910	1065.296	0.000
15	Average Annual Wet Days	4.895E-01	0.259	1033.023	0.006
16	Average Annual Max. Daily Air Temp (ºC)	-6.122E+00	0.466	1209.679	0.003
17	Annual Number of Days >30ºC	-5.595E-01	0.178	1112.375	0.009
18	Annual Degree-Days >30ºC	-1.513E-02	0.195	1109.343	0.008
19	Annual FT Cycles	8.094E-01	0.596	1057.097	0.001
20	Annual AADTT per Coring Lane	2.975E-03	0.818	1064.537	0.000

The results in Table A.2 show that MPD tends to be significantly affected by mix property variables, including air-void content, fineness modulus, nominal maximum aggregate size (NMAS), and aggregate coefficient of uniformity (C_u). According to the estimated coefficients, increasing air-void content and fineness modulus increases macrotexture, and increasing NMAS and C_u reduces macrotexture. A decrease of macrotexture with an increase of NMAS is unexpected. This is likely due to pooling of dense- and open-graded mixes and the effect of other uncontrolled factors in the single-variable model. Also, macrotexture seems to be smaller on thicker surface layers, probably due to better compaction of thicker layers. Higher temperature (in terms of both Average Annual Max. Daily Air Temp (ºC) and Annual Number of Days >30ºC) tends to reduce macrotexture, which likely is due to easier aggregate reorientation and further mix compaction at high temperatures. Heavier daily traffic volume tends to increase macrotexture, which is most likely due to removal of fines around the larger stones in the surface, resulting in raveling.

Based on the results in Table A.2, multiple regression analysis was conducted to account for the effect of various factors simultaneously. Highly correlated independent variables are mutually excluded from the modeling. Two separate regression models were proposed to determine the effects of mix type and mix properties on MPD.

In the first model, only the mix type (categorical variable) and environmental and traffic factors are included as the independent variables, while mix property variables are excluded. The regression equation, Equation A.3.1, is

$$\begin{aligned} MPD(micron) &= 761.1793 + 22.2964 \times Age(year) + 46.6012 \times ind(MixTypeOGAC) + 198.6066 \times ind(MixTypeRAC-G) \\ &+ 369.3836 \times ind(MixTypeRAC-O) - 6.3082 \times NMAS(mm) + 0.6019 \times Thickness(mm) - 0.4721 \times NumberOfDays > 30C \\ &+ 0.0026 \times AADTTinCoringLane + 67.1500 \times Age \times ind(MixTypeOGAC) - 5.2977 \times Age \times ind(MixTypeRAC-G) \\ &+ 9.4071 \times Age \times ind(MixTypeRAC-O) \end{aligned} \quad \textbf{(A.3.1)}$$

where $ind(\cdot)$ is an indicator function, 1 if a variable in parenthesis is true and 0 if it is false. The estimated values and P-values of the parameters are shown below.

	Value	Std. Error	t value	P-value
(Intercept)	761.1793	133.6918	5.6935	0.0000
Age	22.2964	8.0787	2.7599	0.0064
MixTypeOGAC	46.6012	108.0843	0.4312	0.6668
MixTypeRAC-G	198.6066	77.4069	2.5657	0.0111
MixTypeRAC-O	369.3836	75.0738	4.9203	0.0000
NMAS	-6.3082	6.8590	-0.9197	0.3589
Thickness	0.6019	0.9596	0.6273	0.5312
NoDaysTempGT30	-0.4721	0.2962	-1.5939	0.1126
AADTTCoringLane	0.0026	0.0092	0.2804	0.7795
AgeMixTypeOGAC	67.1500	16.3789	4.0998	0.0001
AgeMixTypeRAC-G	-5.2977	13.0044	-0.4074	0.6842
AgeMixTypeRAC-O	9.4071	11.7475	0.8008	0.4243

Residual standard error: 193.5 on 188 degrees of freedom; Multiple R-Squared: 0.5926.

The R^2 is 0.59, which is low but indicates some ability of the combined mix type model to explain MPD. It can be seen that at the 95 percent confidence level, age (Age) and mix type (MixTypeRAC-G, MixTypeRAC-O) significantly affect macrotexture. MPD increases with age. Among the three pavement types, OGAC, RAC-G, and RAC-O, all have higher initial MPD than DGAC, but OGAC is statistically insignificantly different from DGAC. This is likely due to the removal of the three newly paved OGAC pavement sections from the analysis. P-values for the interaction terms between age and mix type showed that the growth rate (with age) of MPD of OGAC pavements is significantly higher than that of DGAC pavements. The growth rates of MPD of RAC-G and RAC-O pavements are not statistically different from those of DGAC pavements.

In the second model, the mix type variables are replaced with mix property variables and the model is estimated for each mix type separately. The regression equations, Equation A.3.2 through Equation A.3.5, are:

For DGAC pavements:

$$MPD(micron) = -401.6160 - 11.3743 \times AirVoid(\%) + 27.3989 \times Age(year) + 380.3184 \times FinenessModulus$$
$$-22.7317 \times NMAS(mm) - 3.0461 \times Thickness(mm) + 0.2828 \times NumberOfDays > 30C$$
$$-0.0276 \times AADTTinCoringLane \quad \textbf{(A.3.2)}$$

	Value	Std. Error	t value	P-value
(Intercept)	-401.6160	499.2565	-0.8044	0.4266
AirVoid	-11.3743	11.0045	-1.0336	0.3084
Age	27.3989	7.0737	3.8734	0.0004
FinenessModulus	380.3184	149.8658	2.5377	0.0158
NMAS	-22.7317	10.5426	-2.1562	0.0380
Thickness	-3.0461	1.4316	-2.1277	0.0405
NoDaysTempGT30	0.2828	0.5351	0.5284	0.6005
AADTTCoringLane	-0.0276	0.0154	-1.8005	0.0804

Residual standard error: 144.3 on 35 degrees of freedom; Multiple R-Squared: 0.511.

For OGAC pavements:

$$MPD(micron) = -815.2128 + 3.6423 \times AirVoid(\%) + 87.2194 \times Age(year) + 277.9719 \times FinenessModulus$$
$$+7.8040 \times NMAS(mm) - 0.8408 \times Thickness(mm) + 0.1055 \times NumberOfDays > 30C$$
$$-0.0319 \times AADTTinCoringLane \quad \textbf{(A.3.3)}$$

	Value	Std. Error	t value	P-value
(Intercept)	-815.2128	478.0237	-1.7054	0.0959
AirVoid	3.6423	12.7704	0.2852	0.7770
Age	87.2194	14.1546	6.1619	<0.0001
FinenessModulus	277.9719	129.9876	2.1384	0.0386
NMAS	7.8040	20.5752	0.3793	0.7065
Thickness	-0.8408	2.0561	-0.4089	0.6848
NoDaysTempGT30	0.1055	0.4674	0.2258	0.8225
AADTTCoringLane	-0.0319	0.0238	-1.3404	0.1877

Residual standard error: 137.5 on 40 degrees of freedom; Multiple R-Squared: 0.747.

For RAC-G pavements:

$$MPD(micron) = -622.8650 + 6.5056 \times AirVoid(\%) + 33.9267 \times Age(year) + 286.3112 \times FinenessModulus$$
$$-13.8687 \times NMAS(mm) + 0.4202 \times Thickness(mm) + 1.4864 \times NumberOfDays > 30C$$
$$-0.0389 \times AADTTinCoringLane \quad \textbf{(A.3.4)}$$

	Value	Std. Error	t value	P-value
(Intercept)	-622.8650	988.9887	-0.6298	0.5333
AirVoid	6.5056	21.0890	0.3085	0.7597
Age	33.9267	14.6677	2.3130	0.0273
FinenessModulus	286.3112	220.7961	1.2967	0.2040
NMAS	-13.8687	18.5049	-0.7495	0.4591
Thickness	0.4202	3.0200	0.1391	0.8902
NoDaysTempGT30	1.4864	0.7832	1.8979	0.0668
AADTTCoringLane	-0.0389	0.0372	-1.0466	0.3031

Residual standard error: 191.6 on 32 degrees of freedom; Multiple R-Squared: 0.2473.

For RAC-O pavements:

$$MPD(micron) = 684.5893 - 7.4871 \times AirVoid(\%) + 19.6358 \times Age(year) + 424.9033 \times FinenessModulus$$
$$-152.8162 \times NMAS(mm) + 8.2288 \times Thickness(mm) - 1.1919 \times NumberOfDays > 30C \quad \textbf{(A.3.5)}$$
$$+0.0059 \times AADTTinCoringLane$$

	Value	Std. Error	t value	P-value
(Intercept)	684.5893	628.8429	1.0886	0.2808
AirVoid	-7.4871	9.0311	-0.8290	0.4105
Age	19.6358	7.5137	2.6133	0.0114
FinenessModulus	424.9033	138.6280	3.0651	0.0033
NMAS	-152.8162	25.1081	-6.0863	0.0000
Thickness	8.2288	2.7913	2.9480	0.0046
NoDaysTempGT30	-1.1919	0.4905	-2.4300	0.0182
AADTTCoringLane	0.0059	0.0120	0.4932	0.6237

Residual standard error: 155.4 on 58 degrees of freedom; Multiple R-Squared: 0.6224.

The R^2 for the RAC-G model is extremely low, probably because the RAC-G mixes show little change in macrotexture over the ages included in this study. This indicates that the RAC-G mixes show little tendency to ravel. The R^2 of the models for the other three mixes are all above 0.50, and for the OGAC it is 0.75. The OGAC mix shows the greatest change in macrotexture over the ages included in this study, indicating that it has the highest propensity to ravel over time. The results show that within each mix type, air-void content (AirVoid) has no significant effect on the value of MPD. Fineness modulus (FinenessModulus) is significant in affecting the macrotexture of open-graded pavements, including both OGAC and RAC-O, and DGAC pavements, and is insignificant for RAC-G pavements. Generally, macrotexture increases with fineness modulus, with increasing fineness modulus indicating a coarser gradation. Layer thickness (Thickness) is significant on DGAC and RAC-O pavements. Thicker DGAC layers have lower macrotexture, probably due to better compaction of thicker layers; while thicker RAC-O layers have higher macrotexture. Higher temperature duration, in terms of number of days with air temperature greater than 30ºC (NoDaysTempGT30), is a significant factor on RAC-O pavements but not on the other types of pavement. The effect of pavement age on macrotexture is statistically significant for all four mix types, and more significant (in terms of practical significance) on non-rubberized open-graded pavements (OGAC) than on rubberized open-graded pavements (RAC-O).

A.3.3: Summary of Findings

The following findings were obtained regarding macrotexture:

1. Among all the mixes investigated, F-mixes have the highest MPD. RAC-G mixes have higher MPD values than the dense-graded mixes, while open-graded mixes have higher MPD values than RAC-G mixes. Among the two open-graded mixes, RAC-O mixes have lower MPD values than OGAC mixes.

2. The R^2 for the RAC-G model is extremely low, probably because the RAC-G mixes show little change in macrotexture over the ages included in this study, indicating that they have not exhibited raveling. The R^2 of the models for the other three mixes are all above 0.50, and for the OGAC it is 0.75. The OGAC mix shows the greatest change in macrotexture over the ages included in this study, indicating that it has the highest propensity to ravel over time.
3. MPD generally increases with pavement age. For open-graded mixes, the age effect on macrotexture is more prominent on non-rubberized pavements (OGAC) than on rubberized pavements (RAC-O). The growth rate (with age) of MPD is significantly higher on OGAC pavements than on DGAC, RAC-G, and RAC-O pavements. The growth rates of MPD of RAC-G and RAC-O pavements are not statistically different from those of DGAC pavements.
4. Within each mix type, air-void content has no significant effect on the value of MPD.
5. Fineness modulus is significant in affecting the macrotexture of open-graded pavements, including both OGAC and RAC-O, and dense-graded pavements (DGAC), and insignificant for RAC-G pavements. Generally the coarser the mix gradation is (i.e., higher fineness modulus), the larger the MPD.
6. Layer thickness is only significant on DGAC and RAC-O pavements. Thicker DGAC layers have lower macrotexture, while thicker RAC-O layers have higher macrotexture.
7. The macrotexture of RAC-O pavements decreases with the number of high temperature days.

A.4: Surface Distress Analysis

The evaluation of distresses answers these questions:

- Do the initiation and progression of distresses differ for different mixes?
- How do traffic and climate affect distress initiation and progression?

It must be noted that the distresses present on the underlying pavement surface at the time of construction of the overlays are unknown. The current condition of the pavement layers beneath the overlays is also unknown.

A.4.1: Bleeding

In the survey, bleeding is reported in terms of severity—low, medium, and high—and extent, expressed as the percentage of the total area with bleeding, including the wheelpath areas and the areas outside the wheelpaths. In the analysis for this study, three percent of the test section area with bleeding was selected as the threshold for the start of bleeding.

A.4.1.1: Descriptive Analysis

Figure A.6 shows the percentage of bleeding area measured in four consecutive years for individual pavement sections of four mix types: DGAC, OGAC, RAC-G, and RAC-O. In this figure, bleeding includes all three severity levels (low, medium, and high). The figure shows that bleeding may appear two to four years after construction on all pavement types, and it tends to appear earlier on rubberized pavements than on non-rubberized ones. Among the four mix types, RAC-G pavements seem to be most susceptible to bleeding in terms of both the time of occurrence and the extent of distress. For some sections, the bleeding distress in the third or fourth survey year is at the same level as in the second survey year. This is likely due to the assumption (i.e., distress does not decrease with age) made in handling the survey data.

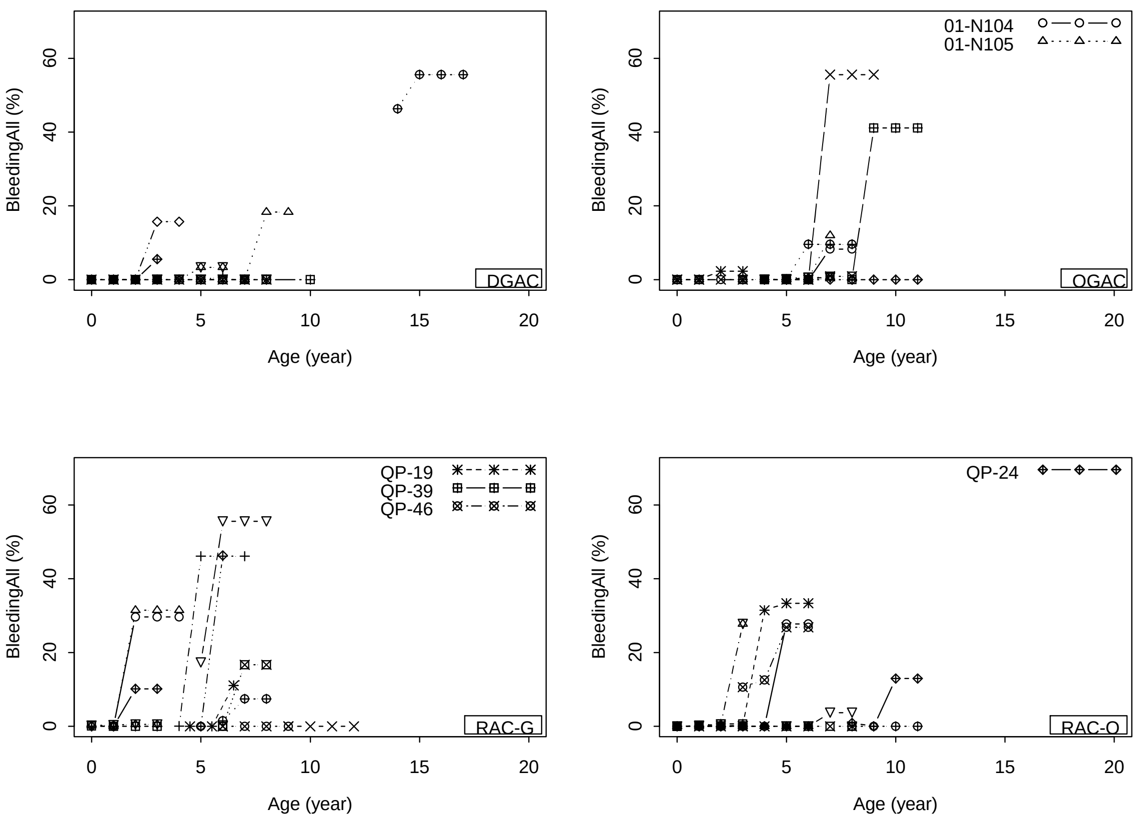


Figure A.6: Bleeding development trend over four years for each pavement section.

Figure A.7 shows the percentage of sections with bleeding over four consecutive years for the four pavement types: DGAC, OGAC, RAC-G, and RAC-O. It can be seen that bleeding develops with pavement age, and RAC-G pavements show the most bleeding in all four years among the four pavement types. In the third and fourth survey years, the difference in extent of bleeding between OGAC and RAC-O is not significant.

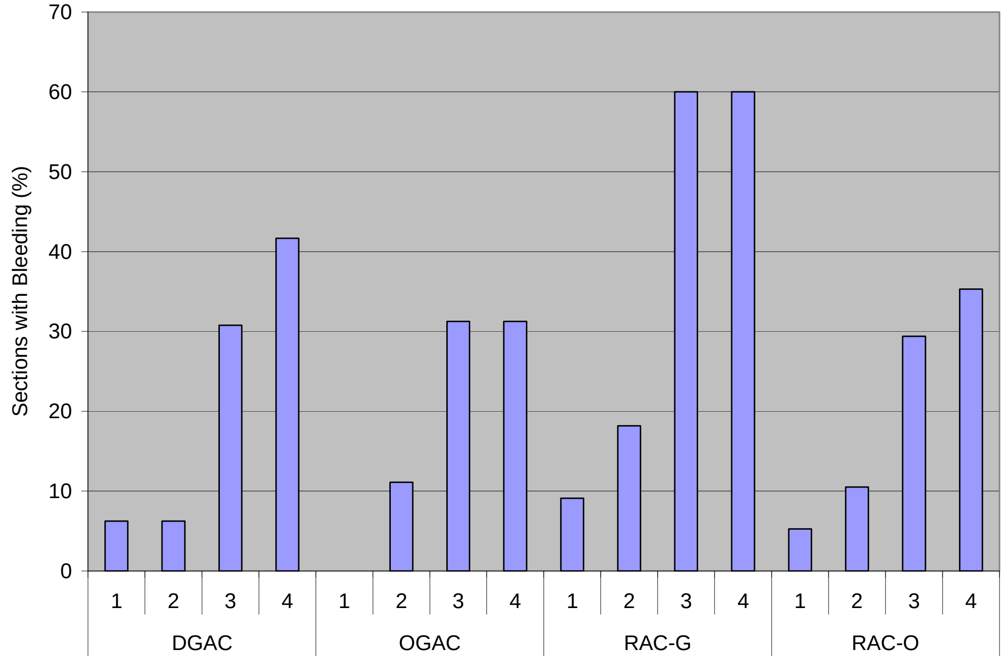


Figure A.7: Percentage of pavement sections of the four mix types with at least 3 percent of their area showing bleeding for each of the four measured years.

A.4.1.2: Regression Analysis

Regression analysis was performed to evaluate the effects of traffic, climate, and mix type on bleeding. The percentage of pavement surface area with bleeding is selected as the response variable. Table A.3 shows the results of the single-variable regression analysis. Based on a 95 percent confidence level, Age, C_c (coefficient of curvature), annual average rainfall, cumulative wet days, and annual freeze-thaw cycles are significant factors. Mix type, air-void content and other mix properties, and traffic volume are all insignificant. The R^2 value, however, is very small for every model, indicating a poor fitting of the single-variable regression model.

Based on the results in Table A.3, multiple regression analysis was conducted to account for the effect of various factors simultaneously. The regression equation, Equation A.4.1, is

$$\begin{aligned} Bleeding(\%) = \frac{1}{540}[&-6.36646 + 1.36635\times Age(year) + 3.01842\times ind(MixTypeOGAC) + 12.35834\times ind(MixTypeRAC-G) \\ &+2.61354\times ind(MixTypeRAC-O) - 1.57241\times FinenessModulus + 0.00184\times AverageAnnualRainfall(mm) \\ &+0.05298\times AverageAnnualWetDays + 0.06897\times NumberOfDays > 30C - 0.21083\times AnnualFTCycles \\ &+281.75212\times CumulativeAADTTinCoringLane(10e6)] \end{aligned} \quad \textbf{(A.4.1)}$$

where $ind(\cdot)$ is an indicator function, 1 if a variable in parenthesis is true and 0 if it is false.

Table A.3: Regression Analysis of Single-Variable Models for Bleeding

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	1.162E+00	**<0.001**	-0.082	0.082
2	Air-void Content (%)	7.481E-02	0.616	4.922	0.001
3	Mix Type	1.944E+00	0.385	3.324	0.064
4	Rubber Inclusion	2.818E+00	0.088	4.359	0.012
5	Fineness Modulus	3.631E-01	0.850	4.138	<0.001
6	NMAS (mm)	-8.962E-02	0.784	6.860	<0.001
7	C_u	5.481E-03	0.923	5.817	<0.001
8	C_c	2.211E+00	**<0.001**	-1.607	0.114
9	Surface Thickness (mm)	-1.208E-01	**0.007**	10.458	0.031
10	Average Annual Rainfall (mm)	-4.650E-03	**0.010**	8.565	0.028
11	Age * Average Annual Rainfall (mm)	4.211E-04	0.245	4.557	0.006
12	Average Annual Wet Days	-2.947E-03	0.858	5.938	<0.001
13	Age * Average Annual Wet Days	1.072E-02	**<0.001**	1.988	0.057
14	Average Annual Max. Daily Air Temp (ºC)	5.466E-01	0.092	-6.835	0.012
15	Annual Number of Days >30ºC	3.040E-02	0.062	3.349	0.015
16	Annual Degree-Days >30ºC	8.341E-04	0.068	3.475	0.014
17	Annual FT Cycles	-1.815E-01	**0.005**	8.088	0.033
18	Annual AADTT per Coring Lane	7.276E-04	0.189	4.867	0.007

The estimated coefficients of the independent variables and corresponding P-values are shown below:

	Value	Std. Error	t value	P-value
(Intercept)	-6.366464	13.481869	-0.4722	0.6372
Age	1.366346	0.264543	5.1649	<0.0001
MixTypeOGAC	3.018418	3.470409	0.8698	0.3854
MixTypeRAC-G	12.358344	3.196654	3.8660	0.0001
MixTypeRAC-O	2.613542	3.359854	0.7779	0.4375
FinenessModulus	-1.572412	2.970015	-0.5294	0.5971
AvgAnnualRainfall	0.001838	0.002212	0.8308	0.4070
AvgAnnualWetDays	0.052975	0.017891	2.9610	0.0034
NoDaysTempGT30	0.068970	0.018230	3.7833	0.0002
AnnualFTCycles	-0.210826	0.066052	-3.1918	0.0016
Age*AADTTCoringLane	281.752115	97.338105	2.8946	0.0042

Residual standard error: 11.13 on 214 degrees of freedom; Multiple R-Squared: 0.28.

The results are the same as those obtained from the survey data from the first three years *(3)*. The R^2 of the model is extremely low. Specifically, the results show that at the 95 percent confidence level, age (Age), pavement type (MixTypeRAC-G), average annual wet days (AvgAnnualWetDays), number of days with temperature greater than 30ºC (NoDaysTempGT30), annual freeze-thaw cycles (AnnualFTCycles), and cumulative truck traffic (Age*AADTTCoringLane) are significant in affecting bleeding. Bleeding area increases with age, number of wet days, number of high-temperature days, and cumulative truck traffic, but decreases with the number of freeze-thaw cycles. Higher freeze-thaw cycles indicates that the pavement is in a colder region, where bleeding is less likely to occur. Among the four pavement types, OGAC and RAC-O pavements are not significantly different from DGAC pavement, but RAC-G pavement is significantly (statistically) more prone to bleeding.

A.4.2: Rutting

In the first two-year survey, the maximum rut depth at every 25 m of the test section was recorded in millimeters, and rut depth was measured across the wheelpaths with a straight-edge ruler. In the third-year survey, there was an unsuccessful attempt to assess rut depth from photographs of the surface taken from the shoulder. In the fourth-year survey, rut depth was evaluated visually onsite for 31 sections, and was evaluated based on photographs for the rest of the sections. The data obtained in the third and fourth years, therefore, are unreliable, and the corresponding analysis only gives a general idea of the rutting distress on these pavements. In the analysis, a maximum of a 3-mm rut present on at least 25 m of the total section (125 or 150 m) was assumed as the threshold for the occurrence of rutting.

A.4.2.1: Descriptive Analysis

Figure A.8 shows the rut depths measured in four consecutive years (essentially the first two years of measurement) for individual pavement sections of four mix types: DGAC, OGAC, RAC-G, and RAC-O. The figure shows that rutting may appear four to six years after construction on all pavement types, but it only appeared on a few pavement sections. Because OGAC, RAC-G, and RAC-O are typically constructed as thin overlays, rutting on these pavements is significantly affected by the mix properties of the underlying layers. Therefore, comparison of the rutting resistance of the four mixes cannot be made without knowledge of the underlying layers.

Figure A.9 shows the percentage of sections with rutting in four consecutive survey years. It can be seen that rutting develops with pavement age, and that DGAC pavements show more rutting than other pavement types in all four years.

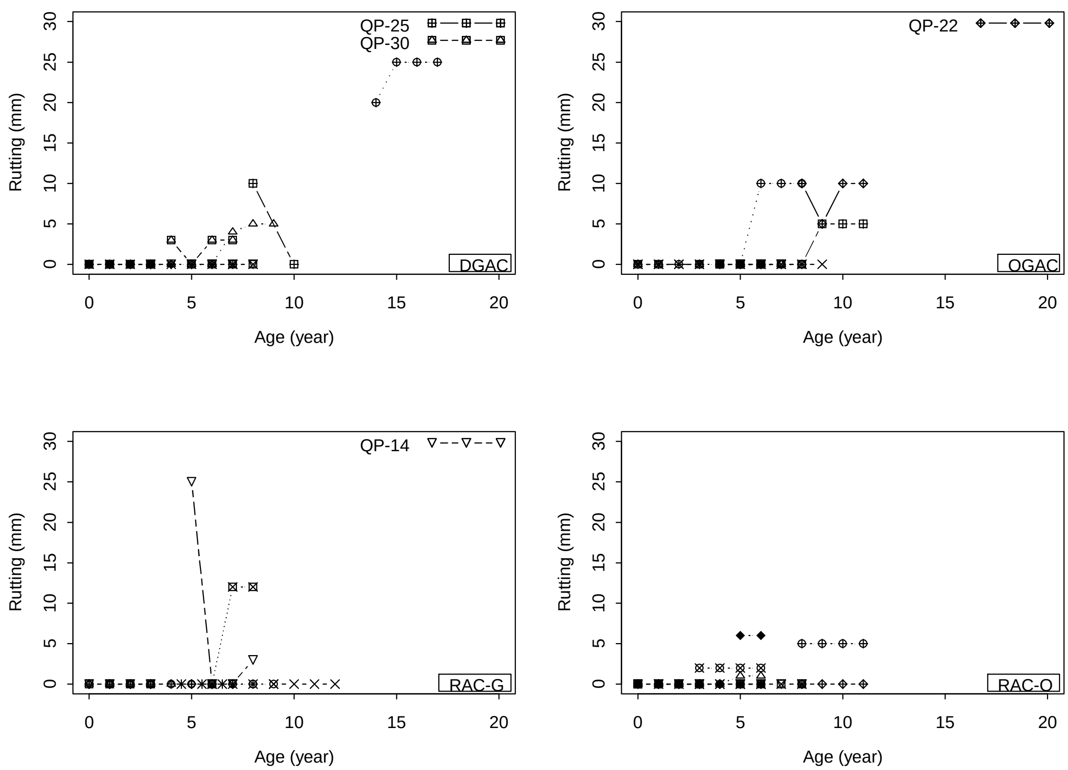


Figure A.8: Rutting development trend over four years for each pavement section.

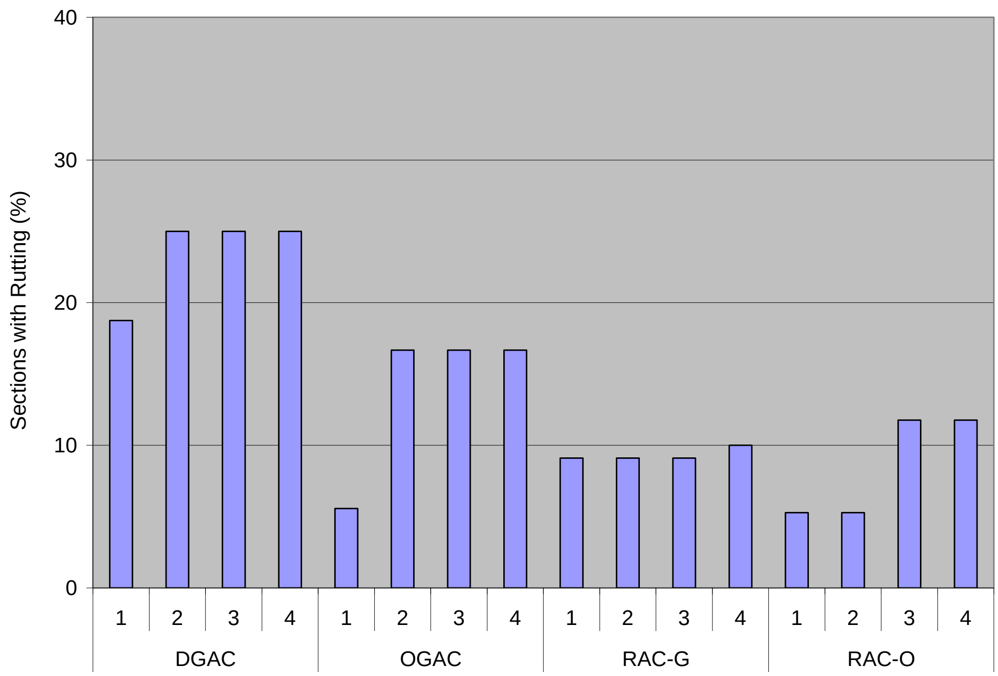


Figure A.9: Percentage of pavement sections with rutting of at least 3 mm on at least 25 m of a 150-m long section in four years of measurement for four mix types.

A.4.2.2: Regression Analysis

Because the number of sections with rutting is small and the rut depth data in the third and fourth years are rough estimates, no regression analysis was performed on the rutting data.

A.4.3: Transverse/Reflective Cracking

Because all the sections investigated in this study are overlays on AC or PCC pavements and it is difficult to distinguish the thermal and reflective cracking mechanisms based only on surface condition observations, the analysis in this study combines thermal cracking and reflective cracking as one distress type.

A.4.3.1: Descriptive Analysis

In the condition survey, the number and length of transverse/reflective cracks were recorded for each of three severity levels (low, medium, and high) for each 25-m subsection. The average length of transverse/reflective cracking (at all severity levels) per unit length of pavement is shown in Figure A.10 for four survey years for four pavement types.

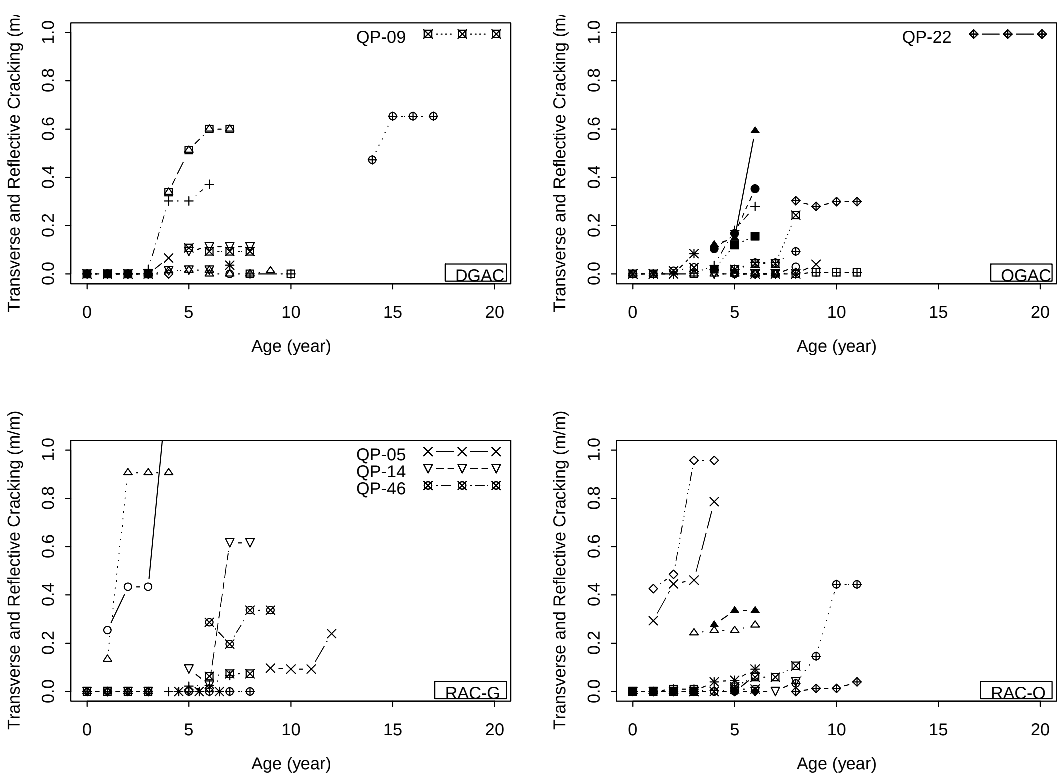


Figure A.10: Transverse/reflective cracking development trends over four years for each pavement section.

It can be seen that transverse/reflective cracking generally propagates with pavement age, and once cracking occurs, it propagates quickly with age. The transverse/reflective cracks seem to initiate earlier and propagate faster on the rubberized asphalt pavements (RAC-G and RAC-O) than on the non-rubberized pavements (DGAC and OGAC). As pointed out in the two-year noise study report *(1),* the increased cracking in the rubber mixes may be biased by the condition of the underlying pavements because RAC-G and RAC-O mixes tend to be placed more often on pavements with a greater extent of existing cracking.

A 5-m total transverse crack length out of 125 or 150 m was assumed as the threshold of transverse/reflective cracking. With this threshold, Figure A.11 shows the percentage of sections with transverse and reflective cracking in the four consecutive survey years. It can be seen that the percentage of sections with transverse/reflective cracking increased significantly from the first survey year to the second survey year for pavements overlaid with open-graded mixes (OGAC and RAC-O), but stayed relatively stable for pavements overlaid with DGAC and RAC-G mixes. From the third survey year to the fourth survey year, the percentage of cracked sections increased for OGAC, RAC-G, and RAC-O pavements, but did not change for DGAC pavements.

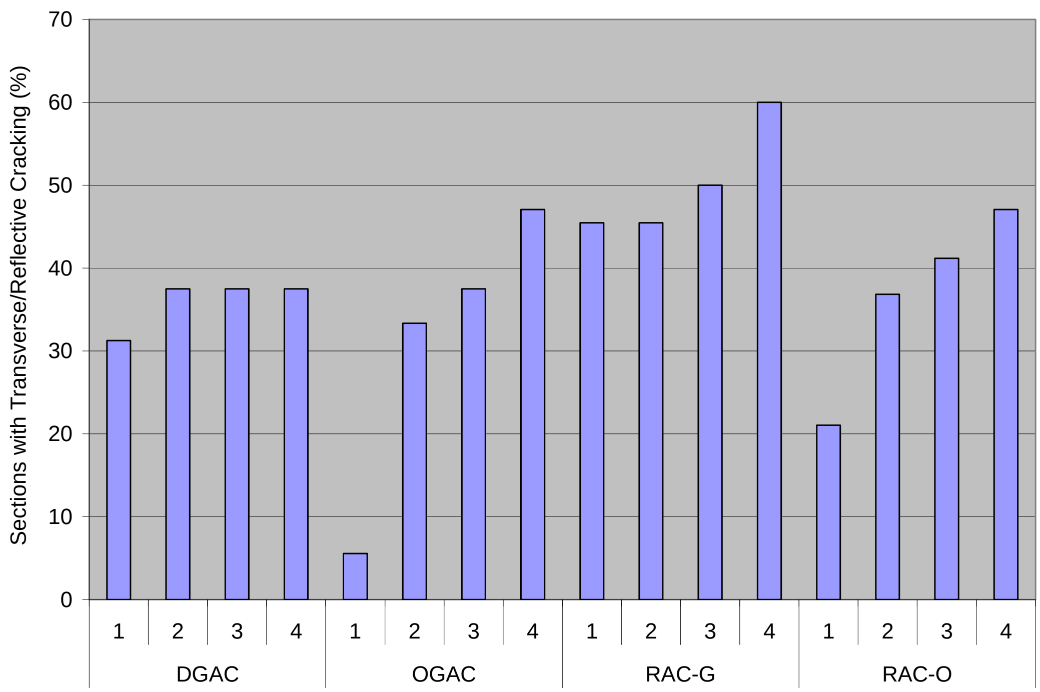


Figure A.11: Percentage of pavement sections with 5 m of transverse/reflective cracking in 125 or 150 m section in four years for four mix types.

A.4.3.2: Regression Analysis

In the regression analysis, the total length of the cracks (at all severity levels) was selected as the response variable. Results of the single-variable regression analysis are given in Table A.4. To account for the effects of underlying layers, the following variables were included in the analysis: the presence of a PCC underlayer (determined from coring), thickness of the layer underneath the surface, and the presence of cracking in the layer underneath the surface.

Table A.4: Regression Analysis of Single-Variable Models for Transverse/Reflective Cracking

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	1.393E-02	**0.002**	0.049	0.040
2	Air-void Content (%)	-2.201E-03	0.391	0.145	0.003
3	Mix Type	-4.812E-02	0.219	0.113	0.038
4	Rubber Inclusion	6.338E-02	**0.026**	0.088	0.021
5	Fineness Modulus	-7.558E-02	**0.021**	0.497	0.023
6	PCC Below (1–yes)	1.454E-01	**0.004**	0.062	0.056
7	Underneath Layer Thickness (mm)	-1.835E-04	0.491	0.105	0.003
8	Cracking in Underneath Layer (1–yes)	-2.412E-02	0.388	0.089	0.005
9	Surface Thickness (mm)	-3.346E-04	0.668	0.131	0.001
10	Average Annual Rainfall (mm)	-1.156E-04	**<0.001**	0.189	0.059
11	Age * Average Annual Rainfall (mm)	-3.860E-07	0.951	0.119	<0.001
12	Average Annual Wet Days	-1.095E-03	**<0.001**	0.202	0.064
13	Age*Average Annual Wet Days	2.332E-05	0.647	0.110	0.001
14	Average Annual Max. Daily Air Temp (ºC)	2.029E-02	**<0.001**	-0.348	0.057
15	Annual Number of Days >30ºC	1.154E-03	**<0.001**	0.029	0.072
16	Annual Degree-Days >30ºC	3.208E-05	**<0.001**	0.032	0.071
17	Annual FT Cycles	-2.968E-03	**0.008**	0.157	0.030
18	Annual AADTT per Coring Lane	1.400E-05	0.142	0.102	0.009

Results of the single-variable regression analysis on the data collected over the four survey years are similar to the results based on the first three-years' survey data *(3).* That is, transverse/reflective cracking may be significantly affected by pavement age, aggregate gradation (in terms of Fineness Modulus), the existence of underlying PCC slabs, rainfall, high temperature days, and freeze-thaw cycles.

Based on the results in Table A.4, multiple regression analysis was conducted to account for the effect of various factors simultaneously. The regression equation appears as Equation A.4.2:

$$Transverse/ReflectiveCracking(m/m) = 0.248493 + 0.006219 \times AirVoid(\%) + 0.018452 \times Age(year)$$
$$-0.208476 \times ind(MixTypeOGAC) - 0.054494 \times ind(MixTypeRAC-G) - 0.169545 \times ind(MixTypeRAC-O)$$
$$+0.008560 \times ind(PCCBelow) + 0.024418 \times ind(CrackBelow) - 0.003883 \times SurfaceThickness(mm)$$
$$-0.000401 \times UnderlyingThickness(mm) + 0.000016 \times AverageAnnualRainfall(mm) - 0.000178 \times AverageAnnualWetDays$$
$$-0.000940 \times NumberOfDays > 30C - 0.000701 \times AnnualFTCycles + 8.525797 \times CumulativeAADTTinCoringLane(10e6) \quad \textbf{(A.4.2)}$$

where $ind(\cdot)$ is an indicator function, 1 if a variable in parenthesis is true and 0 if it is false. The estimated coefficients of the independent variables and corresponding P-values are shown below:

	Value	Std. Error	t value	P-value
(Intercept)	0.248493	0.093064	2.6701	0.0086
AirVoid	0.006219	0.003251	1.9127	0.0580
Age	0.018452	0.003703	4.9833	<0.0001
MixTypeOGAC	-0.208476	0.049404	-4.2199	<0.0001
MixTypeRAC-G	-0.054494	0.034507	-1.5792	0.1167
MixTypeRAC-O	-0.169545	0.044711	-3.7920	0.0002
PCCBelow	0.008560	0.043502	0.1968	0.8443
CrackBelow	0.024418	0.029497	0.8278	0.4093
Thickness	-0.003883	0.000977	-3.9742	0.0001
UnderlyingThickness	-0.000401	0.000309	-1.2986	0.1964
AvgAnnualRainfall	0.000016	0.000028	0.5811	0.5622
AvgAnnualWetDays	-0.000178	0.000219	-0.8133	0.4175
NoDaysTempGT30	-0.000940	0.000319	-2.9491	0.0038
AnnualFTCycles	-0.000710	0.000957	-0.7418	0.4596
Age*AADTTCoringLane	8.525797	3.064105	2.7825	0.0062

Residual standard error: 0.1208 on 129 degrees of freedom; Multiple R-Squared: 0.51.

The results are also similar to the results based on the three-year data, and the R^2 is just above 0.50. At the 95 percent confidence level, age (Age), pavement type (MixTypeOGAC, MixTypeRAC-O), overlay thickness (Thickness), number of days with temperature greater than 30ºC (NoDaysTempGT30), and cumulative truck traffic (Age*AADTTCoringLane) are significant in affecting transverse/reflective cracking. The crack length increases with age and cumulative truck traffic, but decreases with the thickness of surface layer and number of high-temperature days. Pavements overlaid with open-graded mixes tend to have fewer transverse/reflective cracks than dense- or gap-graded mixes. This is probably because the high air-void contents in open-graded mixes hinder crack propagation in the mixes. Based on the data available in this study, the conditions of the underlying layer (existence of a PCC underlayer [PCCBelow], the layer thickness underneath [UnderlyingThickness], and cracking of the layer underneath [CrackBelow]) do not have a significant effect on the transverse/reflective cracking in the surface layer in the multiple regression model. This is likely due to the high bias in the data sample. Most of the sections investigated have asphalt concrete as underlying layers, and only about eight percent of sections have a PCC underlayer. It should be noted that in the single variable regression model the existence of PCC below is significant.

A.4.4: Raveling

In the condition survey, raveling was evaluated as the areas of raveling at three severity levels (low, moderate, and high) based on the definitions in the Caltrans *Office Manual (4).*

A.4.4.1 Descriptive Analysis

Figure A.12 shows the percentage of area with raveling (at all three severity levels) over the four survey years for the four pavement types. It can be seen from the plots that raveling may occur on all types of pavements, and in general, raveling starts earlier on DGAC and RAC-G pavements than on open-graded pavements. Pavements overlaid with DGAC mixes seem to experience more raveling than pavements overlaid with other mixes (OGAC, RAC-G, and RAC-O), according to the visual survey. This contradicts the measured MPD data, which indicated that OGAC showed faster increases in macrotexture, usually caused by raveling. Raveling observed in the fourth survey year does not seem to be worse than that observed in the third survey year.

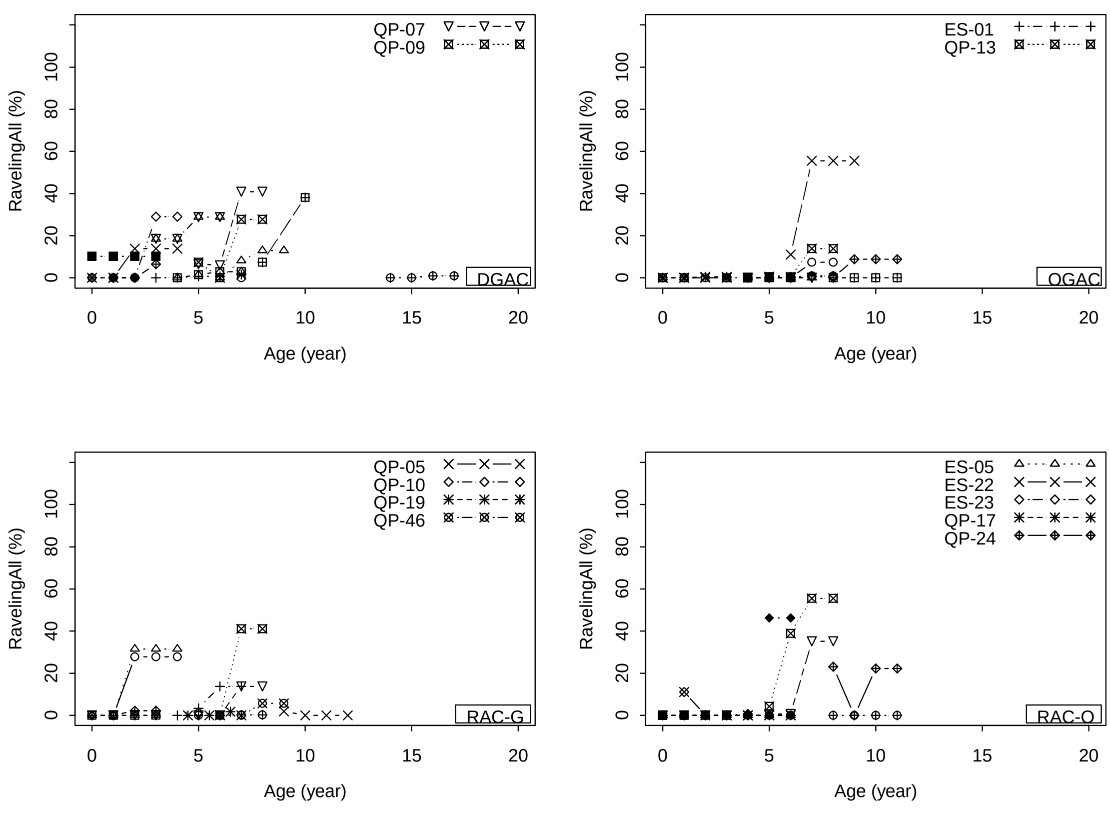


Figure A.12: Raveling development trends over four years for each pavement section.

The presence of raveling on five percent or more of the total area of a section was selected as the threshold for the start of raveling for this analysis. Figure A.13 shows the percentage of sections with raveling over four consecutive survey years for four pavement types. It can be seen that the DGAC pavements experience the most raveling in all four years. RAC-G pavements showed no raveling in the first survey year, but significant increases of raveling in the second and third survey years. Raveling in the open-graded pavements (OGAC and RAC-O) is less significant than that in the DGAC and RAC-G pavements.

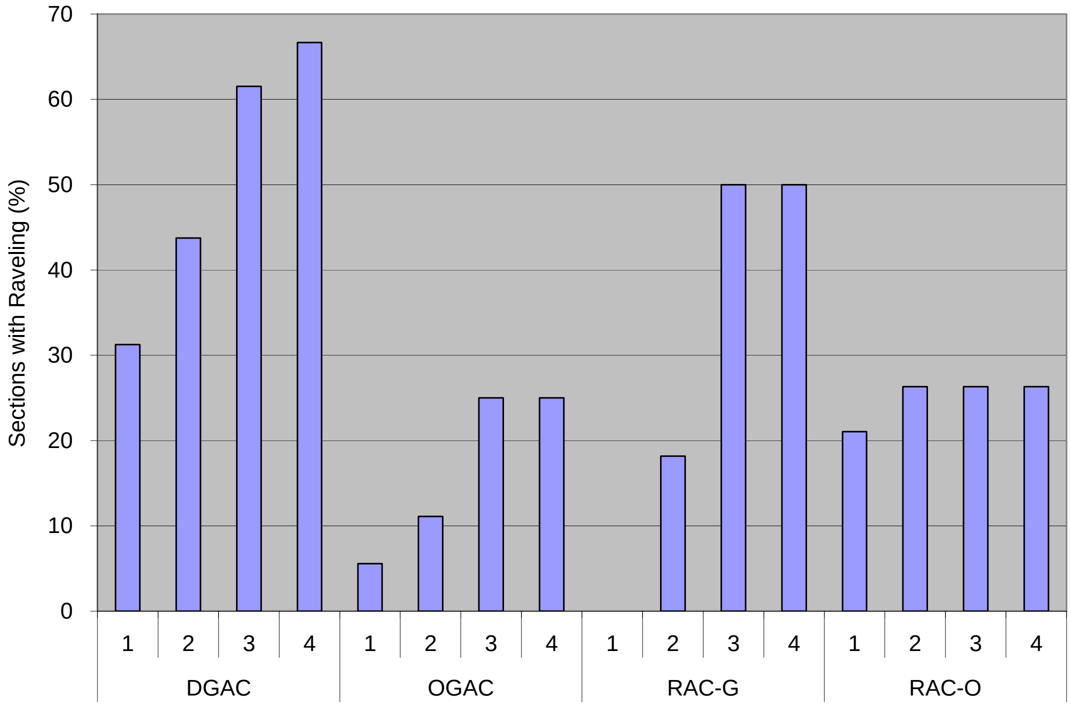


Figure A.13: Percentage of pavement sections with at least 5 percent of area with raveling for each of four years of measurement for four mix types.

A.4.4.2: Regression Analysis

In the regression analysis, surface area with raveling (at all severity levels) was selected as the response variable. Results of the single-variable regression analysis, as given in Table A.5, indicate that raveling may be significantly affected by pavement age, NMAS, average annual wet days, high temperature days, and cumulative truck traffic.

Table A.5: Regression Analysis of Single-Variable Models for Raveling

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	7.686E-01	**0.003**	2.349	0.036
2	Air-void Content (%)	-1.372E-01	0.356	7.852	0.004
3	Mix Type	-4.722E+00	**0.040**	8.618	0.018
4	Rubber Inclusion	1.702E-01	0.918	6.102	<0.001
5	Fineness Modulus	-1.041E+00	0.587	11.578	0.001
6	NMAS (mm)	7.516E-01	**0.020**	-3.429	0.023
7	C_u	1.053E-01	0.060	4.189	0.016
8	C_c	-1.263E-01	0.773	6.860	<0.001
9	Surface Thickness (mm)	2.440E-02	0.588	5.226	0.001
10	Average Annual Rainfall(mm)	-3.869E-03	**0.032**	8.556	0.020
11	Age*Average Annual Rainfall(mm)	-1.565E-05	0.965	6.227	<0.001
12	Average Annual Wet Days	-4.640E-02	**0.004**	9.710	0.034
13	Age*Average Annual Wet Days	4.290E-05	0.988	6.169	<0.001
14	Average Annual Max. Daily Air Temp (ºC)	6.476E-01	**0.045**	-8.685	0.017
15	Annual Number of Days > 30ºC	3.885E-02	**0.016**	3.161	0.024
16	Annual Degree-Days > 30ºC	1.103E-03	**0.015**	3.223	0.025
17	Annual FT Cycles	3.062E-02	0.637	5.783	0.001
18	Annual AADTT per Coring Lane	3.139E-03	**<0.001**	2.526	0.138

Based on the results in Table A.5, multiple regression analysis was conducted to account for the effect of various factors simultaneously. The regression equation, Equation A.4.3, is:

$$\begin{aligned} Raveling(\%) = \frac{1}{540}[&-26.88784 + 0.37531 \times Age(year) - 7.51581 \times ind(MixTypeOGAC) - 3.28724 \times ind(MixTypeRAC-G) \\ &-6.47839 \times ind(MixTypeRAC-O) + 5.44893 \times FinenessModulus + 0.00209 \times AverageAnnualRainfall(mm) \\ &-0.00541 \times AverageAnnualWetDays + 0.03870 \times NumberOfDays > 30C + 0.07563 \times AnnualFTCycles \\ &+723.76829 \times CumulativeAADTTinCoringLane(10e6)] \end{aligned} \quad \textbf{(A.4.3)}$$

where $ind(\cdot)$ is an indicator function, 1 if a variable in parenthesis is true and 0 if it is false. The estimated coefficients of the independent variables and corresponding P-values are shown below:

	Value	Std. Error	t value	P-value
(Intercept)	-30.373786	12.537363	-2.4227	0.0162
Age	0.435822	0.246010	1.7716	0.0779
MixTypeOGAC	-9.242846	3.227281	-2.8640	0.0046
MixTypeRAC-G	-4.457340	2.972705	-1.4994	0.1352
MixTypeRAC-O	-8.246686	3.124471	-2.6394	0.0089
FinenessModulus	6.400725	2.761944	2.3175	0.0214
AvgAnnualRainfall	0.001457	0.002057	0.7080	0.4797
AvgAnnualWetDays	-0.005231	0.016638	-0.3144	0.7535
NoDaysTempGT30	0.038132	0.016953	2.2492	0.0255
AnnualFTCycles	0.085029	0.061424	1.3843	0.1677
AgeAADTTCoringLane	794.220941	90.518840	8.7741	<0.0001

Residual standard error: 10.35 on 215 degrees of freedom; Multiple R-Squared: 0.38.

The R^2 is very low for this model. The results show that at the 95 percent confidence level, mix type (MixTypeOGAC, MixTypeRAC-O), fineness modulus (FinenessModulus), the number of days with temperature greater than 30ºC (NoDaysTempGT30), and cumulative truck traffic (Age*AADTTCoringLane) are significant in affecting raveling. At the 90 percent confidence level, pavement age becomes significant. The estimated parameters indicate that raveling increases with pavement age, fineness modulus, number of high temperature days, and cumulative truck traffic. Open-graded mixes (OGAC and RAC-O) are significantly less prone to raveling than DGAC mixes, according to the visual observations.

A.4.5: Wheelpath (Fatigue) Cracking

In the condition survey, all the cracks in the wheelpath were recorded as fatigue cracks, whether they were caused by reflection of underlying cracks or not. No data is available to determine whether they were caused by reflective or new fatigue cracking. Fatigue cracking was evaluated as the areas of cracking at three severity levels (low, moderate, and high) based on the definitions in the Caltrans *Office Manual (4),* and extent as the percent of wheelpath with cracking.

A.4.5.1: Descriptive Analysis

Figure A.14 shows the percentage of area with fatigue cracking (at all three severity levels) in the four survey years for four surface mix types. The plots show that fatigue cracking may occur on all types of pavements, and in general it increases with pavement age. Limited data indicate that fatigue cracking seems to initiate earlier on DGAC and RAC-G pavements than on open-graded pavements.

The presence of fatigue cracking on five percent or more of the wheelpaths was selected as the threshold for the start of fatigue cracking for this analysis. Figure A.15 shows the percentage of sections with fatigue cracking in the four survey years. It can be seen that the DGAC pavements experienced the most fatigue cracking in all four years. Fatigue cracking in the open-graded pavements (OGAC and RAC-O) was less significant than that in the DGAC and RAC-G pavements, while mixes with rubberized binder (RAC-G and RAC-O) seemed to experience less fatigue cracking than mixes without rubber (DGAC and OGAC).

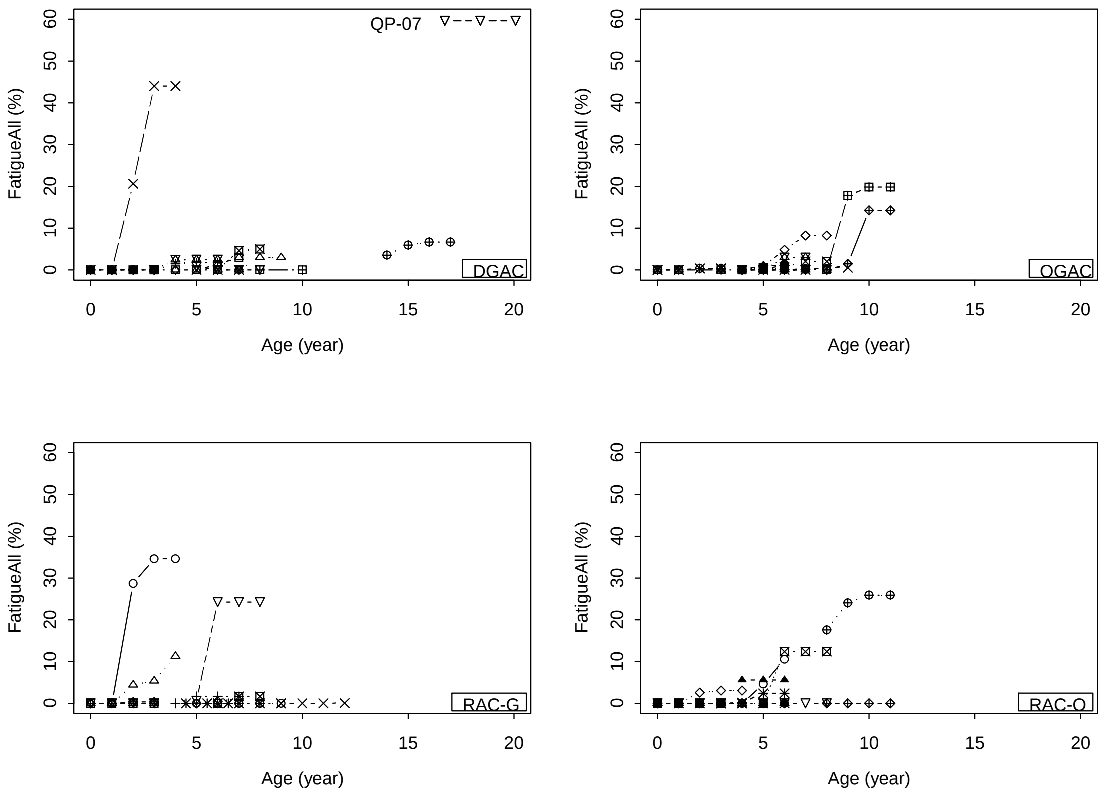


Figure A.14: Development trends for fatigue cracking over four years for each pavement section.

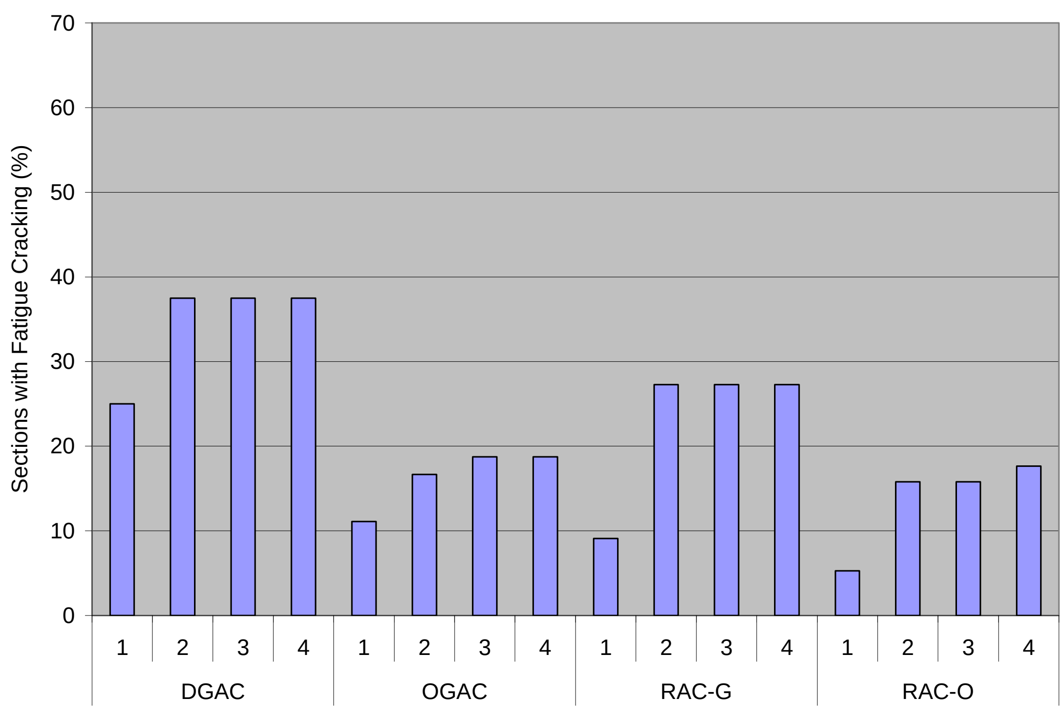


Figure A.15: Percentage of pavement sections with at least 5 percent of wheelpaths with fatigue cracking for each of the four years measured.

A.4.5.2: Statistical Analysis

Regression analysis was performed to evaluate the effects of traffic, climate, and mix properties on fatigue cracking. The percent of the wheelpaths with fatigue cracking (at all severity levels) was selected as the response variable. As a common statistical method for service life analysis, survival analysis was performed here to further analyze the factors affecting fatigue cracking.

Regression Analysis

Results of the single-variable regression analysis, shown in Table A.6, indicate that fatigue cracking may be significantly affected by pavement age, the existence of underlying PCC slabs, cumulative rainfall, and the number of high-temperature days.

Table A.6: Regression Analysis of Single-Variable Models for Fatigue Cracking

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	4.741E-01	**0.002**	0.503	0.041
2	Air-void Content (%)	-2.046E-02	0.812	3.142	<0.001
3	Mix Type	-9.811E-01	0.459	2.958	0.014
4	Rubber Inclusion	9.008E-01	0.345	2.435	0.004
5	Fineness Modulus	-7.495E-01	0.500	6.670	0.002
6	PCC Below (1 -yes)	6.532E+00	**<0.001**	2.016	0.080
7	Underneath Layer Thickness (mm)	2.168E-02	**0.029**	-1.321	0.032
8	Cracking in Underneath Layer (1 -yes)	-2.049E+00	**0.049**	3.843	0.026
9	Surface Thickness (mm)	4.473E-02	0.085	1.112	0.013
10	Average Annual Rainfall (mm)	-2.794E-03	**0.007**	4.581	0.031
11	Age*Average Annual Rainfall (mm)	2.223E-04	0.287	2.257	0.005
12	Average Annual Wet Days	-2.266E-02	**0.016**	4.590	0.024
13	Age*Average Annual Wet Days	2.787E-03	0.101	1.899	0.012
14	Average Annual Maximum Daily Air Temp (°C)	6.293E-01	**0.001**	-11.580	0.049
15	Annual Number of Days >30°C	3.423E-02	**<0.001**	0.205	0.057
16	Annual Degree-Days >30°C	9.546E-04	**<0.001**	0.305	0.056
17	Annual FT Cycles	-3.403E-02	0.364	3.313	0.004
18	Annual AADTT per Coring Lane	-3.804E-05	0.905	2.912	<0.00

Based on the results in Table A.6, multiple regression analysis was conducted to account for the effect of various factors simultaneously. The regression equation, Equation A.4.4, is:

$$
\begin{aligned}
FatigueCracking(\%) = {} & \frac{1}{540}[-8.174691 + 0.725556 \times Age + 2.128561 \times ind(MixTypeOGAC) + 1.864865 \times ind(MixTypeRAC-G) \\
& + 2.434264 \times ind(MixTypeRAC-O) + 5.412817 \times ind(underlyingPCC) + 0.127399 \times ind(CrackingBelow) + 0.001157 \times Thickness \\
& 0.001055 \times AverageAnnualRainfall + 0.012810 \times AverageAnnualWetDays + 0.022295 \times NumberOfDays > 30C \\
& + 0.007326 \times AnnualFTCycles + 323.812878 \times CumulativeAADTTinCoringLane(10e6)]
\end{aligned} \quad \textbf{(A.4.4)}
$$

where $ind(\cdot)$ is an indicator function, 1 if a variable in parenthesis is true and 0 if it is false. The estimated coefficients of the independent variables and corresponding P-values are shown below:

	Value	Std. Error	t value	P-value
(Intercept)	-8.174691	3.715051	-2.2004	0.0295
Age	0.725556	0.153081	4.7397	<0.0001
MixTypeOGAC	2.128561	1.566440	1.3589	0.1765
MixTypeRAC-G	1.864865	1.386471	1.3450	0.1809
MixTypeRAC-O	2.434264	1.560146	1.5603	0.1211
PCCBelow	5.412817	1.801673	3.0043	0.0032
CrackBelow	0.127399	1.171458	0.1088	0.9136
Thickness	0.001157	0.040120	0.0288	0.9770
AvgAnnualRainfall	0.001055	0.001166	0.9048	0.3672
AvgAnnualWetDays	0.012810	0.009020	1.4202	0.1579
NoDaysTempGT30	0.022295	0.012969	1.7191	0.0879
AnnualFTCycles	0.007326	0.039288	0.1865	0.8524
AgeAADTTCoringLane	323.812878	125.829842	2.5734	0.0112

Residual standard error: 5.010 on 133 degrees of freedom; Multiple R-Squared: 0.38.

As with the other visual survey models, the R^2 is very low. The results are similar to those based on three-year survey data. That is, at the 95 percent confidence level, pavement age (Age), the existence of underlying PCC slabs (PCCBelow), and cumulative truck traffic (Age*AADTTCoringLane) are significant in affecting fatigue cracking. The estimated parameters indicate that fatigue cracking increases with pavement age and cumulative truck traffic. The existence of underlying PCC slabs increases the potential of fatigue cracking in the surface layer. This is probably because the fatigue cracking defined in this study consists of all types of cracking in the wheelpath, which includes reflective cracks from old PCC slabs. At the 95 percent confidence level, pavement type (MixTypeOGAC, MixTypeRAC-G, MixTypeRAC-O) is an insignificant factor, indicating there is no significant difference in the fatigue performance of the four mix types.

<u>Survival Analysis</u>

Survival analysis was used to model crack initiation. A brief introduction of survival analysis was included in the two-year noise study report *(1)*.

The Cox (proportional hazard) regression model was developed using the four-year condition surveys from 57 sections. The dependent variable is the cumulative ESALs to failure. Failure is defined as five percent of the wheelpaths showing fatigue cracking (at all three severity levels: low, moderate, high). The coefficients of the explanatory variables and the p-values, as well as the p-value of Wald tests from single-variable Cox regression analysis are shown in Table A.7. It can be seen that no variable is significant at the 95 percent confidence level.

Table A.7: Single-Variable Cox Regression Model for Wheelpath Crack Initiation

Model Number	Variable Name	Coefficient	P-value	Wald Test p-value
1	Air-void Content (%)	-0.0303336	0.586	0.586
2	Mix Type (DGAC-RAC-O)	0.726087	0.430	
	Mix Type (OGAC-RAC-O)	0.434080	0.637	
	Mix Type (RAC-G-RAC-O)	1.610398	0.081	0.319
3	Rubber Inclusion	0.079731	0.897	0.897
4	Fineness Modulus	-0.380461	0.510	0.510
5	Underneath Layer Thickness (mm)	-0.012871	0.241	0.241
6	Cracking in Underneath Layer (1 -yes)	0.094490	0.925	0.925
7	Surface Thickness (mm)	-0.10754	0.113	0.113
8	Average Annual Rainfall (mm)	-0.001725	0.284	0.284
9	Average Annual Wet Days	-0.003825	0.703	0.703
10	Average Annual Max. Daily Air Temp (ºC)	-0.019684	0.876	0.876
11	Annual Number of Days >30ºC	-0.288458	0.266	0.266
12	Annual Degree-Days >30ºC	0.0000170	0.925	0.925
13	Annual FT Cycles	0.002868	0.900	0.900

A multiple-variable Cox regression analysis also revealed that no variable is significant in affecting the fatigue cracking in asphalt overlays.

A.4.6: Summary of Findings

Findings from the data collected over four survey years are generally the same as the findings from the data collected over the first three years. A brief summary of findings regarding pavement distresses is given below.

1. The ability of the models to explain the results in the visual condition survey data is poor, as indicated by low R^2 values. The condition survey data is best used for qualitative understanding of the relative performance of the different surface mixes.
2. Bleeding may appear two to four years after construction on all pavement types, and it tends to appear earlier on rubberized pavements than on non-rubberized pavements. Statistically, among the four mix types (DGAC, OGAC, RAC-G, and RAC-O), the bleeding performance of OGAC and RAC-O pavements is not significantly different from that of DGAC pavements, but RAC-G pavement is significantly (statistically) more prone to bleeding. Regression analysis indicates that bleeding increases with pavement age, number of wet and high-temperature days, and cumulative truck traffic, but decreases with the number of freeze-thaw cycles.
3. Rutting may appear four to six years after construction on all pavement types, but only on a few pavement sections. DGAC pavements showed more rutting than other pavement types in all four survey years. Comparison of the rutting resistance of the four mixes, however, cannot be made without knowledge of the underlying layers.

4. Transverse/reflective cracks seem to initiate earlier and propagate faster on the rubberized asphalt pavements (RAC-G and RAC-O) than on the non-rubberized pavements (DGAC and OGAC). This is possibly because RAC-G and RAC-O mixes tend to be placed more often on pavements with a greater extent of existing cracking. Transverse/reflective cracking increased significantly from the first survey year to the second survey year for pavements overlaid with open-graded mixes (OGAC and RAC-O), but stayed relatively stable for pavements overlaid with DGAC and RAC-G mixes. Between the third survey year and the fourth survey year, the percentage of cracked sections also increased for RAC-G pavements but did not change for DGAC pavements.
5. Statistical analysis shows that pavement age, pavement type, overlay thickness, number of days with temperature greater than 30ºC, and cumulative truck traffic are significant in affecting transverse/reflective cracking. Crack length increases with age and cumulative truck traffic, but decreases with the thickness of surface layer and number of high-temperature days. Pavements overlaid with open-graded mixes tend to have less transverse/reflective cracking than dense- or gap-graded mixes.
6. Pavements overlaid with DGAC mixes seem to experience more raveling than pavements overlaid with other mixes (OGAC, RAC-G, and RAC-O). RAC-G pavements showed no raveling in the first survey year, but a significant increase in raveling in the next two years. Statistical analysis shows that mix type, fineness modulus, the number of days with temperature greater than 30ºC, and cumulative truck traffic are significant in affecting raveling. Pavement age is marginally significant. The estimated parameters indicate that raveling increases with pavement age, fineness modulus, number of high temperature days, and cumulative truck traffic. Open-graded mixes (OGAC and RAC-O) are significantly less prone to raveling than DGAC mixes according to the visual survey results, which contradict the macrotexture (MPD) measurements that showed that OGAC has a faster increase in macrotexture which is usually caused by raveling.
7. Fatigue cracking/reflective cracking in the wheelpaths, based on limited data, seems to initiate earlier on DGAC and RAC-G pavements than on open-graded pavements, while mixes with rubberized binder (RAC-G and RAC-O) seem to experience less fatigue cracking than mixes without rubber (DGAC and OGAC).
8. Regression analysis shows that pavement age, existence of underlying PCC slabs, and cumulative truck traffic are significant in affecting fatigue cracking. The estimated parameters indicate that fatigue cracking increases with pavement age and cumulative truck traffic. The existence of underlying PCC slabs increases the potential for fatigue cracking/reflective cracking in the wheelpath in the surface layer. Mix type is an insignificant factor, indicating there is no significant difference in the fatigue performance of the four surface mix types.

A.5: Sound Intensity Analysis

The On-board Sound Intensity (OBSI) results are given in terms of spectral content in one-third octave bands. Summation of the one-third octave band noise levels gives the overall A-weighted sound intensity levels. Analysis in this chapter first focuses on the overall sound intensity, and then on the one-third octave band noise levels in several typical frequency bands. Among the questions answered by this analysis are these:

- What is the trend with time for overall OBSI?
  - How do the mixes rank with respect to OBSI, initially and with time?
  - How is the change with time different for each mix type?
  - What variables affect OBSI for each mix type?
- What are the answers to the questions above for different ranges of frequency of OBSI?

It is generally considered that the tire vibration noise–generating mechanism is mostly responsible for low frequency noise (800 Hz and below), and that the air-pumping mechanism is mostly responsible for high frequency noise (2,000 Hz and higher frequencies). The 800 and 1,000 Hz frequencies, which often have the highest sound intensity due to the nature of tire/pavement noise and weighting for human perception through the A-weighted scale, are generally considered to be predominantly influenced by tire tread, with some lesser influence from both pavement-related mechanisms. Therefore, variables that increase tire vibration, such as increased macrotexture, roughness, distresses, and NMAS, would generally be expected to increase low frequency noise; while variables that mitigate the air-pumping mechanism, such as increased air-voids, would be expected to decrease high frequency noise. Overall noise levels are influenced by the combined effects of the different frequencies *(5)*. The hypotheses regarding the effects of the explanatory variables on noise have been discussed in the analysis of the first three-years of data *(1,3),* but will be revisited in more detail in this report based on the four-year data.

<u>A.5.1: Conversion of Sound Intensity for Temperature, Speed, Air Density, Equipment, Tire</u>

Sound intensity measurements may be affected by temperature, test car speed, type of test tire, type of sound analyzer, and air density.

In the analysis of the data from the first three years *(1, 3),* the pavement temperature correction was not applied because the calibration equations were unavailable at that time and it was believed that the pavement temperature effect on noise is small. In the fourth year of this study, the effect of pavement temperature was analyzed explicitly and addressed in a separate report *(5),* and it was verified that the pavement temperature correction is small (about –0.018 dB per increase of one degree Celsius for general asphalt pavements). For this reason, the pavement temperature correction was not used in the analysis of the four years of data in this report.

In general, sound intensity measurements were conducted at a speed of 60 mph (96 km/h). However, due to constraints imposed by road geometry and traffic conditions, in some cases pavement sections were tested at either 30 mph (50 km/h) or 35 mph (56 km/h). In the analysis of the data collected in the first three years, the 35-mph measurements were converted to the equivalent 60-mph measurements using an empirical equation as described in the two-year noise study report *(1),* while the 30-mph measurements (on QP-48 and QP-49 sections) were discarded due to the lack of conversion equations. In this report, both the 30-mph and 35-mph measurements were removed from the analysis based an agreement reached between UCPRC and Caltrans.

In the analysis of the data collected over the first two years, sound intensities measured with an Aquatred 3 tire were used *(1).* In the analysis of the three-year data, sound intensity data obtained in the first two years were converted to equivalent SRTT measurements, using a set of correlation equations developed by simple linear regression analysis from both the Aquatred 3 #2 tire and SRTT #1 tire (used late in the second year for that project) measurements on 24 QP pavement sections. These converted measurements were combined with the third-year SRTT #1 measurements for analysis in the third-year report *(3).* In this report, the fourth-year data, which were collected with the SRTT #2 tire, are converted to SRTT #1 data, using a set of newly developed correction equations described in Appendix B.2: Development of Calibration Equations for Pavement Temperature, Test Tire, Speed, and Analyzer Equipment.

In the fourth survey year, the Larson-Davis real-time sound analyzer was replaced with a Harmonie sound analyzer, which caused significant differences in the measured sound intensity levels. The previous Larson-Davis results were converted to Harmonie results before further analysis.

As discussed above, several varying factors were involved in the measurement of OBSI over the four years. While calibration equations have been developed and applied for some factors, these equations were typically developed under certain specific conditions without consideration of interactions between factors. To improve the calibration equations on a broader range, two factorial experiments were conducted in the field in mid-2010 using the Aquatred 3 #3 tire and the SRTT #3 tire, and from these experiments comprehensive correction equations were developed for the SRTT #3 tire. Significant differences between different SRTT tires were then detected when the new correction equations were applied to the fourth-year data. Several additional experiments were conducted using four SRTT tires (SRTT #1, SRTT #2, SRTT #3, and SRTT #4) on both asphalt pavements and concrete pavements to develop the calibration equations between SRTT tires. A summary of the experiments and results is included in Appendix B.2.

After all the sound intensity measurements were calibrated to their equivalent values at reference conditions (60-mph vehicle speed, Harmonie equipment, and SRTT #1), the same air-density correction equations as those used in the first three years were applied to the data to account for the differences caused by variations of air density (a function of air temperature, humidity, and altitude) *(1).*

A.5.2: Evaluation of Overall Sound Intensity

The overall A-weighted sound intensity levels are calculated by summing sound intensity levels at each frequency using Equation (A.5.1):

$$\text{Overall OBSI (dBA)} = 10 \times \log \sum_{i} 10^{f_i/10} \qquad \textbf{(A.5.1)}$$

where f_i is the A-weighted sound intensity level at each one-third octave frequency, dB(A). The frequencies included in the analysis in this study are between 500 and 5,000 Hz.

A.5.2.1: Descriptive Analysis

It can be seen from Figure 5.2 that the OBSI values in the fourth survey year are generally higher than those in the third survey year. The trends of OBSI with time on various surface mixes are the same as those observed from the three-year data analysis. As stated in Reference *(3):*

> *the overall tire/pavement noise generally increases with pavement age. For newly paved overlays, the overall sound intensities measured on OGAC, RAC-G, and RAC-O pavements are lower than the values measured on the DGAC pavements. After the pavements were exposed to traffic, the overall sound intensity measured on RAC-G pavements quickly approached the representative value measured on DGAC pavements of similar ages. The overall sound intensity measured on the OGAC pavements appears to remain stable for about five years and then increases quickly with pavement age. With a few exceptions, the overall sound intensity measured on the RAC-O pavements appears to remain stable for about seven years and then increases quickly with pavement age. Based on these observations, the rank of the four mix types (from best to worst) in terms of noise is RAC-O, OGAC, RAC-G, and DGAC.*

Figure 5.2 shows that there are a few pavement sections on which the measured sound intensity dropped significantly in the subsequent survey years. The potential reasons have been discussed in the three-year data analysis report *(3).*

Figure 5.3 shows the box plots of overall OBSI over four years for different mix types for the three original age categories. As the figure shows, sound intensity generally increases with pavement age for the same pavement section. Overall, the increased rate of sound intensity is the lowest on RAC-O pavements, which means that RAC-O pavements remain quieter than DGAC pavements longer than do OGAC pavements. As pointed out in the three-year data analysis report *(3),* "quieter" or "noise reduction" is defined for this study as the difference between the tire/pavement noise of each mix type other than DGAC compared to the average noise level of DGAC.

Figure A.16 shows the estimated cumulative distribution function (CDF) of noise reduction for both the OGAC and RAC-O types of open-graded mixes and RAC-G mixes compared to the average noise levels of DGAC mixes in six age groups: less than or equal to one year, between one and three years, between three and five years, between five and seven years, between seven and nine years, and greater than nine years. The CDF curves were estimated using a kernel density estimation technique that smoothes the curves. The numbers in parentheses in the legends represent the sample size of each mix type. All four years of observations were aggregated to create the plots. As can be seen, the sample sizes are different among the different mixes and age groups. The average noise level of DGAC mixes in each age group, as shown in the legend, are 101.3 dB(A) for newly paved overlays, 102.0 dB(A) for pavements with an age between one and three years old, and varies between 103.3 and 103.6 dB(A) for pavements older than three years.

A positive value in Figure A.16 indicates reduction in noise levels compared to the average DGAC mix noise level. The figure shows that, with the exception of a few outliers, the noise change is generally between 2 dB(A) increase and 6 dB(A) reduction.

For newly paved overlays (age less than or equal to one year), RAC-G and RAC-O pavements seem to be quieter than OGAC pavements. If at least a 3 dB(A) noise reduction is required for a surface to be considered noise-reducing, only 10 percent of RAC-G and RAC-O pavements are noise-reducing and, based on a small sample size, OGAC pavements are not noise reducing, compared to DGAC pavements of the same ages.

For pavements with an age between one and three years, OGAC and RAC-O pavements have similar noise-reducing ability (about 30 percent of pavements are at least 3 dB[A] quieter than average DGAC pavement of the same ages), while at this age RAC-G pavements begin to lose their noise-reducing properties.

For pavements with an age between three and five years, with one outlier in the RAC-O pavements (Section QP-17), OGAC and RAC-O pavements still have similar noise-reducing ability, which is better than RAC-G pavements. About 70 percent of RAC-O and OGAC pavements and 20 percent of RAC-G pavements in this age range are at least 3 dB(A) quieter than the average DGAC pavement with the same age. The reason for the increased percentage of noise-reducing pavements is that the referenced DGAC pavements become much noisier with age (103.5 dB[A] in the three-to-five year age range versus 101.3 dB[A] at less than one year).

For pavements with an age between five and nine years, OGAC pavements begin to lose their noise-reducing properties and become similar to RAC-G pavements, while RAC-O pavements still remain "noise-reducing."

The corresponding plots for pavements that are older than nine years are not discussed in detail here because the sample size is very small for all mixes. One general trend, however, is that RAC-O pavements remain the best performers among the four mixes in terms of noise reduction.

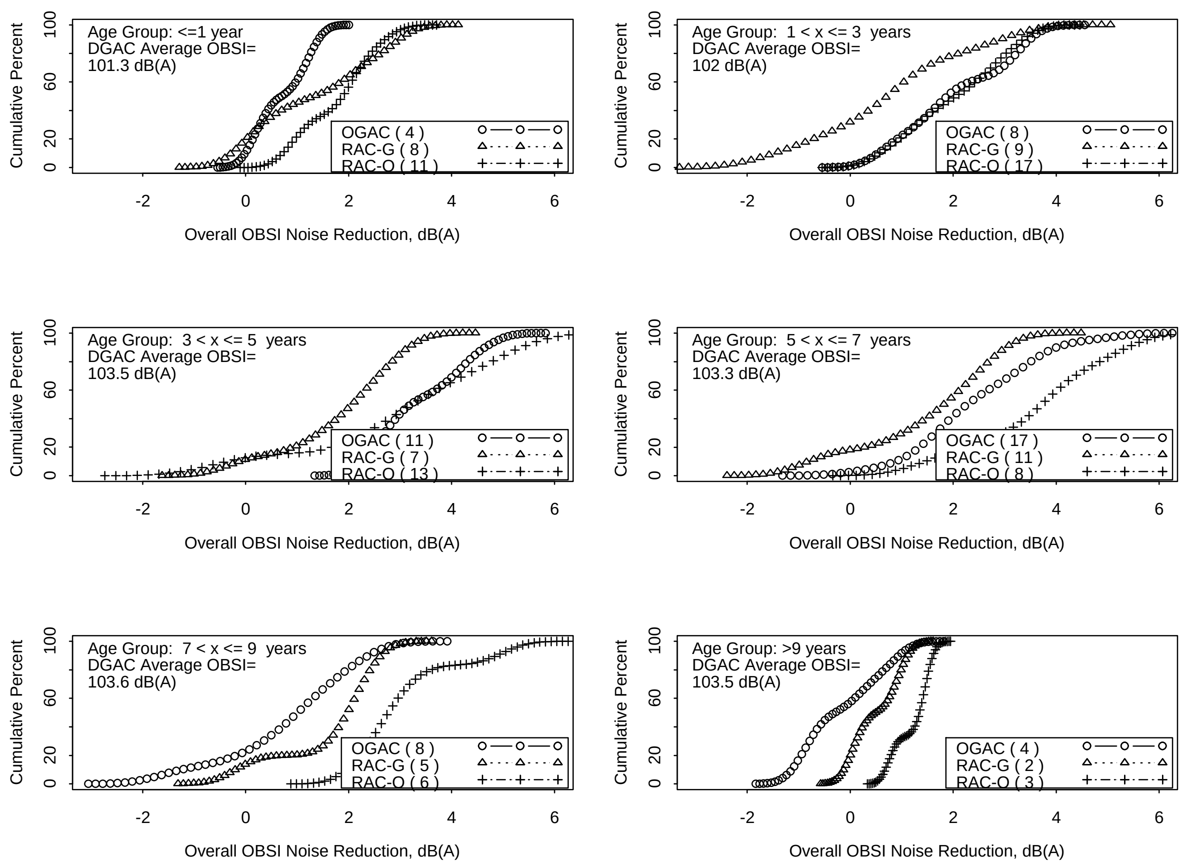


Figure A.16: Estimated cumulative distribution functions of noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups of pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.)

A.5.2.2 Regression Analysis

Regression analysis was conducted to determine the effects of mix properties, distresses, traffic, and weather conditions on sound intensity levels, and to develop prediction models for tire/pavement noise. A single-variable regression analysis was first conducted to check the correlation between the dependent variable and each independent variable, and then a multiple regression model was estimated to consider the effects of various variables simultaneously.

Air-void content and permeability are important mix variables that affect tire/pavement noise, so they should be included in the noise prediction models. Both variables were measured in the first two survey years *(1),* but not in the third year *(3).* In the fourth year, about half of the pavement sections were measured for air-void content and in-situ permeability. Appendix B.3 shows the trend lines and box plots of the two variables. It can be observed that generally both air-void content and logarithm of permeability decrease linearly with time for all mixes. Based on these observations, the missing third-year and/or fourth-year data were estimated by linear extrapolation or simple linear regression from the available two-year or three-year data.

Multiple linear regression analysis was conducted to determine the effects of various variables on sound intensity levels and to construct prediction models for tire/pavement noise. A few pavement sections, as specified in the three-year data analysis report *(3),* were excluded from the data set used for the statistical analysis because they were either outliers or contained erroneous measurements in one year.

To determine the effects of mix type and mix properties on tire/pavement noise, separate regression models were proposed. In the first model, only the mix type (categorical variable) and environmental and traffic factors are included as the independent variables, while mix property variables other than NMAS are excluded. The regression equation appears below as Equation A.5.2:

$$\begin{aligned}&Overall\ Sound\ Intensity(dBA) = 102.502 + 0.1217 \times Age(year) - 2.7261 \times ind(MixTypeOGAC) - 1.6732 \times ind(MixTypeRAC-G)\\&-2.7697 \times ind(MixTypeRAC-O) - 0.0210 \times Thickness(mm) - 0.003262 \times NumberOfDays > 30C\\&+0.00000243 \times AADTinCoringLane + 0.7070 \times ind(PresenceofRaveling) + 0.7468 \times ind(PresenceofRutting)\\&+0.1318 \times Age \times ind(MixTypeOGAC) + 0.0878 \times Age \times ind(MixTypeRAC-G) - 0.0481 \times Age \times ind(MixTypeRAC-O)\end{aligned} \quad \textbf{(A.5.2)}$$

where $ind(\cdot)$ is an indicator function, 1 if a variable in parenthesis is true and 0 if it is false. The estimated values and P-values of the parameters are shown below:

	Value	Std. Error	t value	P-value
(Intercept)	102.5020	0.5181	197.8490	<0.0001
Age	0.1217	0.0537	2.2653	0.0246
MixTypeOGAC	-2.7261	0.5360	-5.0864	<0.0001
MixTypeRAC-G	-1.6732	0.4493	-3.7242	0.0003
MixTypeRAC-O	-2.7697	0.4540	-6.1003	<0.0001
Thickness	-0.0210	0.0057	-3.7087	0.0003
NoDaysTempGT30	0.003262	0.001991	1.6387	0.1030
AADTperLane	0.00000243	0.00001446	0.1681	0.8667
Raveling	0.7070	0.2115	3.3428	0.0010
Rutting	0.7468	0.3103	2.4072	0.0170
AgeMixTypeOGAC	0.1318	0.0819	1.6090	0.1093
AgeMixTypeRAC-G	0.0878	0.0788	1.1137	0.2668
AgeMixTypeRAC-O	-0.0481	0.0766	-0.6283	0.5306

Residual standard error: 1.160 on 187 degrees of freedom; Multiple R-Squared: 0.58.

The R^2 shows that the model explains approximately 58 percent of the variation in the dependent variable. The estimation results are very similar to the results based on the data collected over the first three years *(3),* only with slight changes in the values of the estimated parameters. Specifically, at the 95 percent confidence level, age (Age), mix type (MixTypeOGAC, MixTypeRAC-G, MixTypeRAC-O), surface layer thickness (Thickness), and existence of raveling (Raveling) significantly affect the overall sound intensity. All three surface mix types, OGAC, RAC-G, and RAC-O, have lower initial overall sound intensity than DGAC. The average noise reductions (compared to new DGAC pavements) for newly paved OGAC, RAC-G, and RAC-O mixes are about 2.7, 1.8, and 2.8 dB(A), respectively.

In the second model, the mix type variables are replaced with mix property variables and the model is estimated for each mix type separately. The regression equations appear as Equation A.5.3 through Equation A.5.6:

<u>For DGAC pavements</u>

$$\begin{aligned} &Overall\ Sound\ Intensity(dBA) = 99.3934 - 0.3004 \times \log(Permeability)(cm/\sec) + 0.03512 \times Age(year) - 0.7708 \times FinenessModulus \\ &+ 0.004036 \times MPD + 0.001539 \times Thickness(mm) + 0.001804 \times NumberOfDays > 30C + 0.000058 \times AADTTinCoringLane \end{aligned} \quad \textbf{(A.5.3)}$$

	Value	Std. Error	t value	P-value
(Intercept)	99.3934	3.3595	29.5856	<0.0001
log(Permeability)	-0.3004	0.1202	-2.4990	0.0180
Age	0.03512	0.0492	0.7135	0.4809
FinenessModulus	-0.7708	0.7368	-1.0461	0.3036
MPD	0.004036	0.0010	3.9558	0.0004
Thickness	0.001539	0.0077	0.1989	0.8437
NoDaysTempGT30	0.001804	0.0033	0.5461	0.5889
AADTTCoringLane	0.00005800	0.0000	1.7253	0.0944

Residual standard error: 0.869 on 31 degrees of freedom; Multiple R-Squared: 0.67.

For OGAC pavements

$$Overall\ Sound\ Intensity(dBA)=101.45303\text{-}0.17798\times\log(permeability)(cm/\sec)+0.34784\times Age(year)-0.89906\times FinenessModulus$$
$$+0.00035\times MPD(micron)-0.00936\times Thickness(mm)+0.00357\times NumberOfDays>30C+0.000104\times AADTTinCoringLane \quad \textbf{(A.5.4)}$$

	Value	Std. Error	t value	P-value
(Intercept)	101.45303	3.13633	32.3476	<0.0001
log(Permeability)	-0.17798	0.10375	-1.7154	0.0933
Age	0.34784	0.06281	5.5380	<0.0001
FinenessModulus	-0.89906	0.55918	-1.6078	0.1150
MPD	0.00035	0.00073	0.4797	0.6338
Thickness	-0.00936	0.01053	-0.8887	0.3790
NoDaysTempGT30	0.00357	0.00349	1.0242	0.3113
AADTTCoringLane	0.000104	0.00002	4.2702	0.0001

Residual standard error: 0.8798 on 30 degrees of freedom; Multiple R-Squared: 0.73.

For RAC-G pavements

$$Overall\ Sound\ Intensity(dBA)=95.13176\text{-}0.29595\times\log(permeability)(cm/\sec)+0.21296\times Age(year)+0.05397\times FinenessModulus$$
$$+0.00159\times MPD(micron)+0.00805\times Thickness(mm)+0.01327\times NumberOfDays>30C+(2.8e-5)\times AADTTinCoringLane \quad \textbf{(A.5.5)}$$

	Value	Std. Error	t value	P-value
(Intercept)	95.13176	4.65032	20.4570	<0.0001
log(Permeability)	-0.29595	0.09927	-2.9812	0.0053
Age	0.21296	0.06385	3.3355	0.0021
FinenessModulus	0.05397	0.91976	0.0587	0.9536
MPD	0.00159	0.00057	2.7980	0.0084
Thickness	0.00805	0.01215	0.6622	0.5123
NoDaysTempGT30	0.01327	0.00328	4.0451	0.0003
AADTTCoringLane	0.000028	0.00002	1.2126	0.2336

Residual standard error: 0.9462 on 34 degrees of freedom; Multiple R-Squared: 0.68.

For RAC-O pavements

$$Overall\ Sound\ Intensity(dBA)=107.61178\text{-}+0.03748\times\log(permeability)(cm/\sec)+0.20822\times Age(year)-1.01597\times FinenessModulus$$
$$-0.00080\times MPD(micron)-0.06961\times Thickness(mm)-0.00113\times NumberOfDays>30C-(0.8e-6)\times AADTTinCoringLane \quad \textbf{(A.5.6)}$$

	Value	Std. Error	t value	P-value
(Intercept)	107.61178	6.08119	17.6958	<0.0001
log(Permeability)	0.03748	0.22189	0.1689	0.8666
Age	0.20822	0.10205	2.0404	0.0469
FinenessModulus	-1.01597	0.99307	-1.0231	0.3115
MPD	-0.00080	0.00085	-0.9421	0.3510
Thickness	-0.06961	0.02987	-2.3301	0.0241
NoDaysTempGT30	-0.00113	0.00298	-0.3811	0.7048
AADTperCoringLane	-0.0000008	0.00003	-0.0284	0.9775

Residual standard error: 0.9481 on 47 degrees of freedom; Multiple R-Squared: 0.44.

The R^2 for the individual mix models are all above 0.67 and better than that of the combined model, except for the RAC-O mix model. The results show that the overall sound intensity increases with pavement age for all four mix types except DGAC. At the 95 percent confidence level, the in-situ permeability (log[Permeability]) is a significant factor for all mixes except RAC-O. For all the other mixes, higher permeability leads to lower noise levels. The surface layer thickness (Thickness) is significant only for RAC-O, possibly due to the fact that for other mix types the thicknesses were typically very similar. Pavement surface macrotexture (MPD) is a significant factor for DGAC and RAC-G pavements, and a higher MPD value corresponds to a higher noise level. For OGAC and RAC-O pavements, MPD does not have a significant influence on noise level.

For all mix types, the aggregate gradation variable (FinenessModulus) does not seem to significantly affect tire/pavement noise. Truck traffic volume (AADTperCoringLane) is a significant factor that increases tire/pavement noise for OGAC mixes. For RAC-G mixes, high temperature days (NoDaysTempGT30) is significant and the estimated coefficient (0.01327) indicates that tire/pavement noise increases when the number of high temperature days increases.

A.5.3 Evaluation of Sound Intensity Levels at One-Third Octave Frequency Bands

Sound intensity was analyzed at each one-third octave frequency band. The frequencies included in the analysis are between 500 and 5,000 Hz, including 500, 630, 800, 1,000, 1,250, 1,600, 2,000, 2,500, 3,150, 4,000, and 5,000 Hz. In this report, detailed statistical analysis was performed for four typical frequency levels: 500, 1,000, 2,000, and 4,000 Hz. Data at other frequency levels are presented in less detail.

Reference *(1)* presents a detailed description of the expected effects of different tire/pavement noise–producing mechanisms on each one-third octave frequency.

A.5.3.1 Change of OBSI Spectra with Age

Figure 5.5 through Figure 5.7 show the sound intensity spectra averaged by mix type and age group in the four survey phases (i.e., four survey years). For more information, see Appendix B.5: Sound Intensity Spectra Measured in Four Years for Each Pavement Section.

From Figure 5.5, it can be seen that for newly paved overlays, the overall sound intensity changed little in the first four years on both open-graded pavements (OGAC and RAC-O). For DGAC and RAC-G pavements, the overall sound intensity increased slightly in the first two years, increased significantly in the third year, and remained relatively unchanged in the fourth year. The spectra show that for OGAC and RAC-O pavements, the sound intensities at the frequencies higher than 1,000 Hz did increase with age in the first four years, but the sound intensities at low frequencies (630 to 800 Hz) decreased with age. These two opposite changes make the overall sound intensity nearly unchanged. Decrease of the low frequency noise indicates that the surface of open-graded pavements became smoother in the first four years, which is possibly due to the further compaction action of traffic. The increase of high frequency noise indicates that the air-void content (or permeability) of open-graded pavements decreases in the first four years, which is also due to traffic action. For DGAC and RAC-G pavements, the low-frequency noise changed slightly with age in the first four years, while the sound intensities at frequencies over 1,000 Hz increased significantly with age. This indicates that the air-void content of DGAC and RAC-G pavements decreased significantly in the first four years.

Figure 5.6 shows that for pavements with an age between one and four years at the start of the study, the overall sound intensity increased slightly on both open-graded pavements (OGAC and RAC-O), and increased more significantly on the DGAC and RAC-G pavements. Figure 5.7 shows that for old pavements ("Age Group: >4 years"), the increase of overall sound intensity with age is comparable on OGAC, RAC-G, and DGAC pavements, while the increase is insignificant on RAC-O pavements. The spectra show that for RAC-G pavements the overall sound intensity increased significantly at frequencies between 1,000 Hz and 2,000 Hz, indicating a reduction of permeable air voids, while for OGAC pavements, the overall sound intensity increased significantly at frequencies below 1,000 Hz, indicating a significant increase in surface roughness.

A.5.3.2 Descriptive Analysis of Sound Intensity Data for All One-Third Octave Bands

Figure A.17 through Figure A.27 show the four-year measurements of sound intensity at each one-third octave frequency band for the four mix types: DGAC, OGAC, RAC-G, and RAC-O. Sound intensity generally increases with pavement age at most frequency levels. Opposite trends, however, also exist in the plots, which show a lower sound intensity level in the subsequent survey years. Potential reasons for the reduction of noise may include measurement error, change of measurement conditions that are not accounted for (e.g., different seasons, different tire temperatures), change of pavement conditions, and other random effects. The potential reasons that several pavement sections showed significant reductions in overall sound intensity in subsequent years were discussed in detail in Reference *(3)*.

Figure A.17 and Figure A.18 show that at low frequency levels (500 Hz and 630 Hz), sound intensities measured on OGAC and RAC-O pavements are generally higher than the values measured on DGAC and RAC-G pavements. This is because tire/pavement noise at low frequencies is dominated by tire vibration, which is significantly affected by the macrotexture of pavement surfaces. Figure A.19 shows that at a frequency level of 800 Hz, the sound intensities measured on OGAC, RAC-G, and RAC-O pavements begin to become lower than those measured on DGAC pavements. This trend becomes much clearer at higher frequency levels, as shown in Figure A.20 through Figure A.27. The figures also show that for frequency levels equal to or larger than 1,000 Hz, the sound intensities measured on OGAC and RAC-O pavements are generally lower than that measured on RAC-G pavements. This is primarily because the two open-graded pavements have higher air-void contents than the gap-graded pavements, which can reduce the tire/pavement noise caused by the air-pumping mechanism.

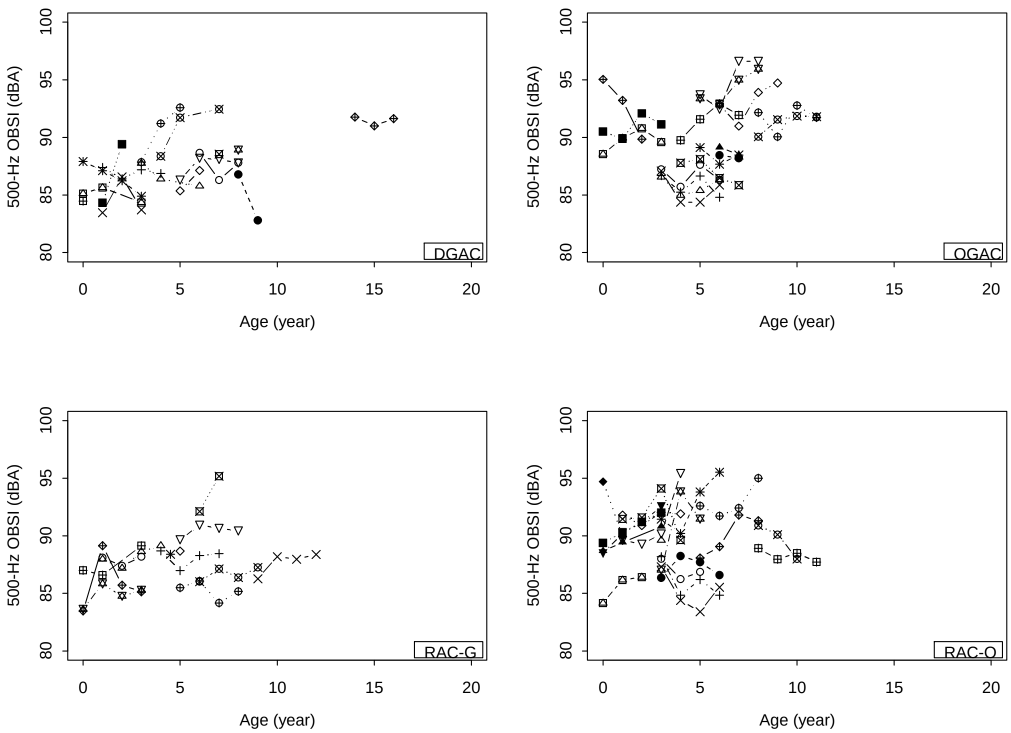


Figure A.17: Sound intensity at 500 Hz over four years for each pavement section.

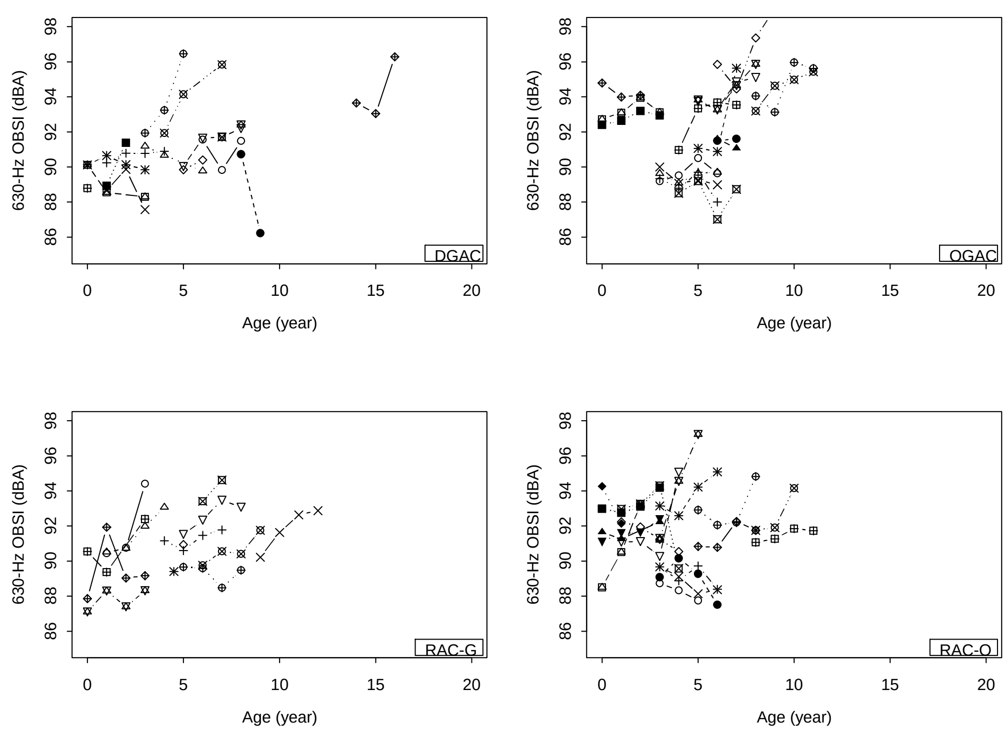


Figure A.18: Sound intensity at 630 Hz over four years for each pavement section.

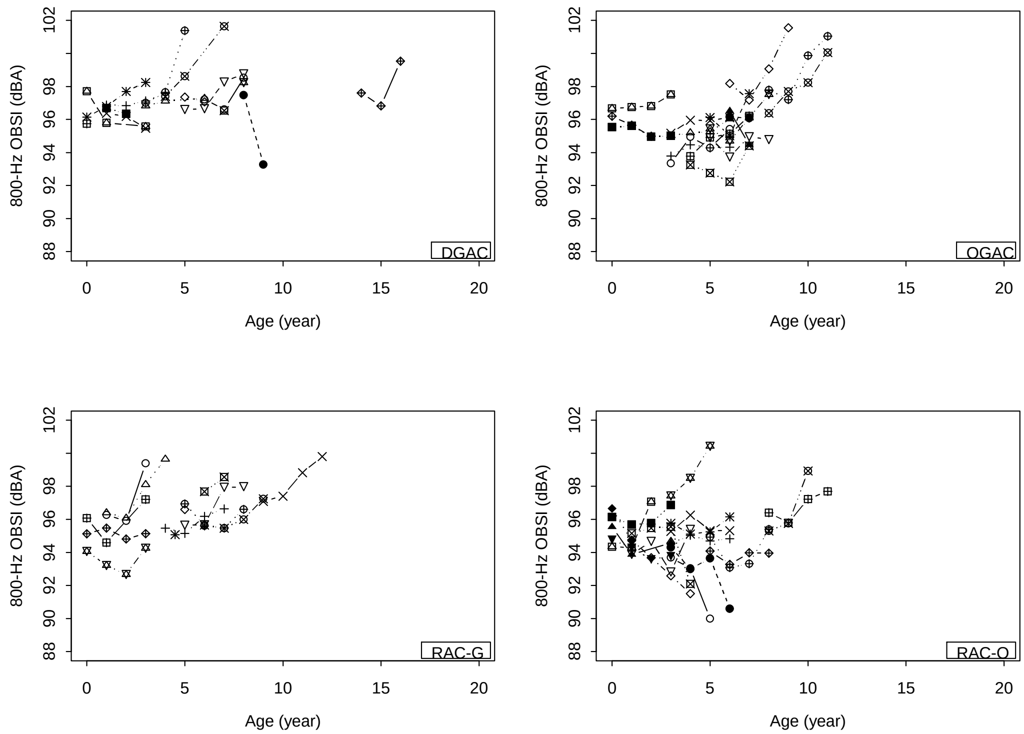


Figure A.19: Sound intensity at 800 Hz over four years for each pavement section.

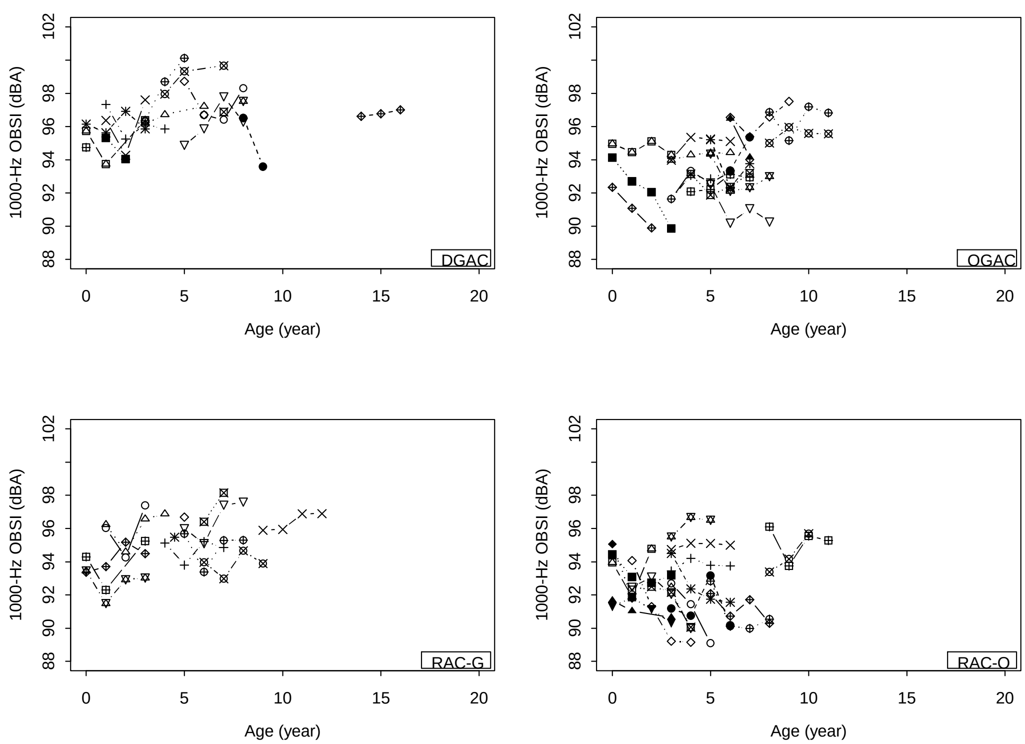


Figure A.20: Sound intensity at 1,000 Hz over four years for each pavement section.

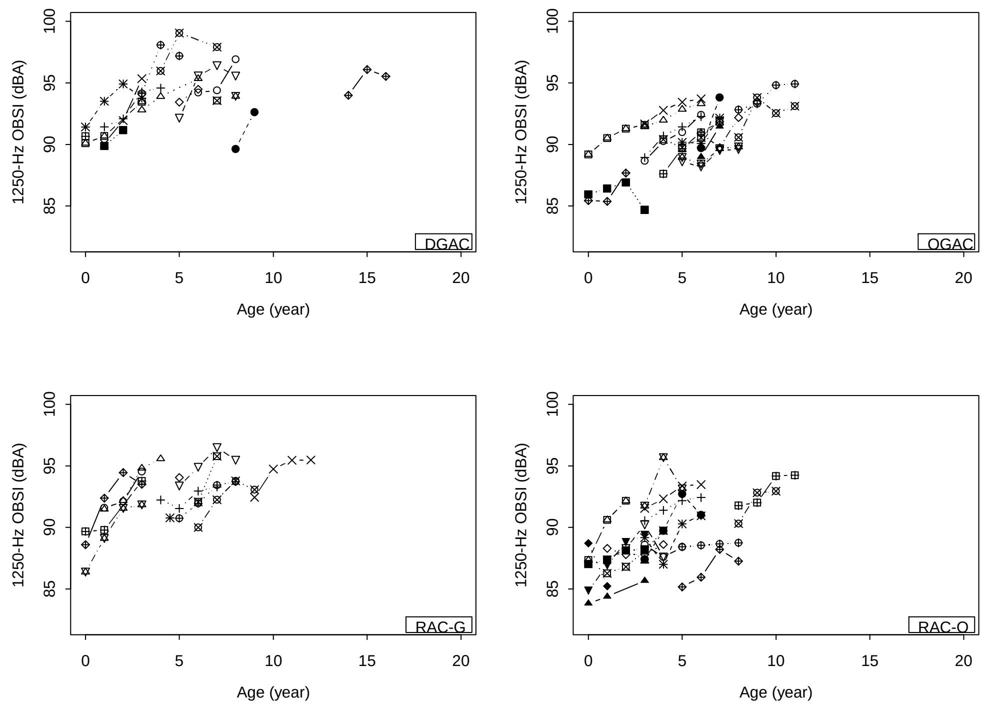


Figure A.21: Sound intensity at 1,250 Hz over four years for each pavement section.

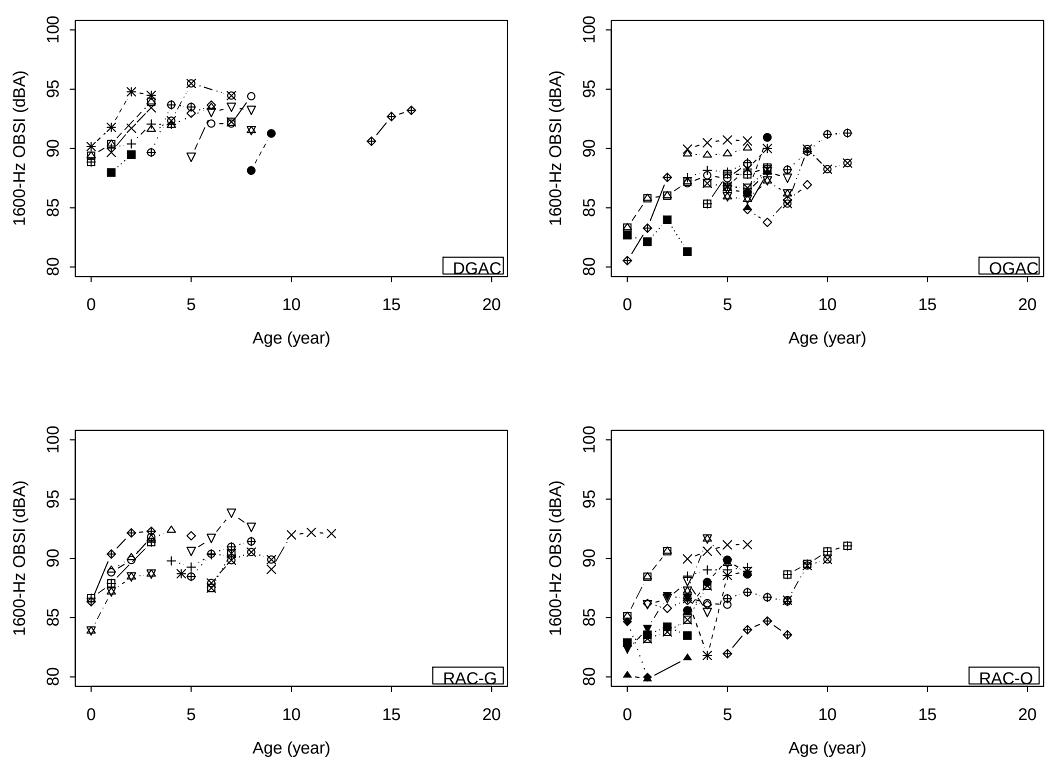


Figure A.22: Sound intensity at 1,600 Hz over four years for each pavement section.

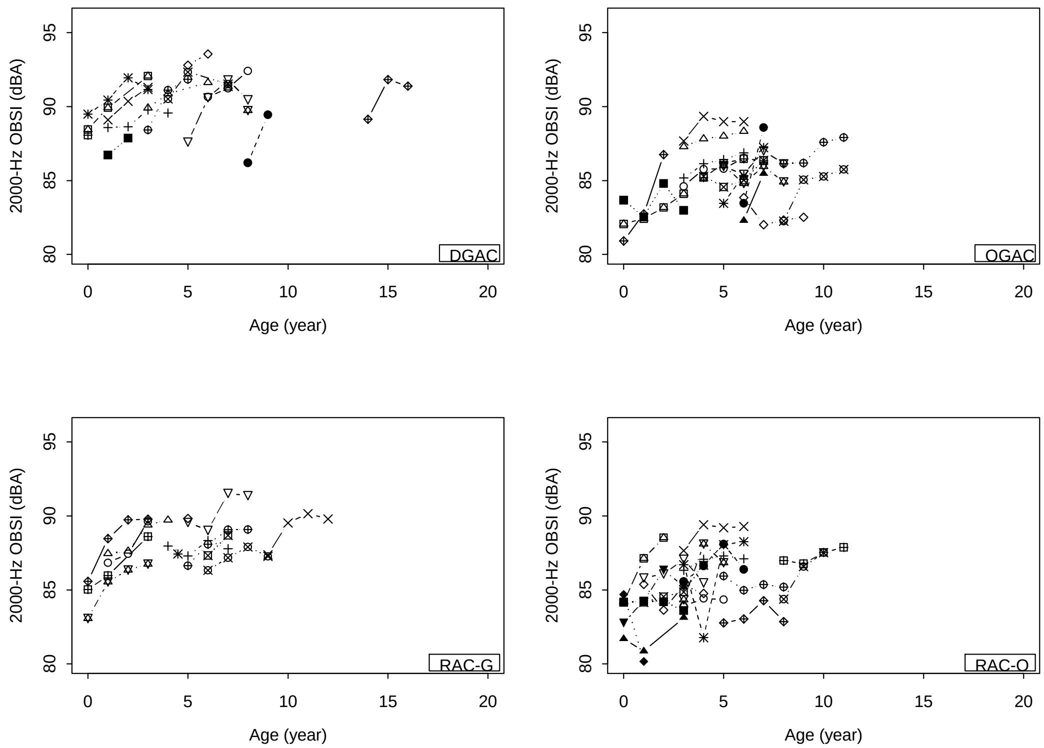


Figure A.23: Sound intensity at 2,000 Hz over four years for each pavement section.

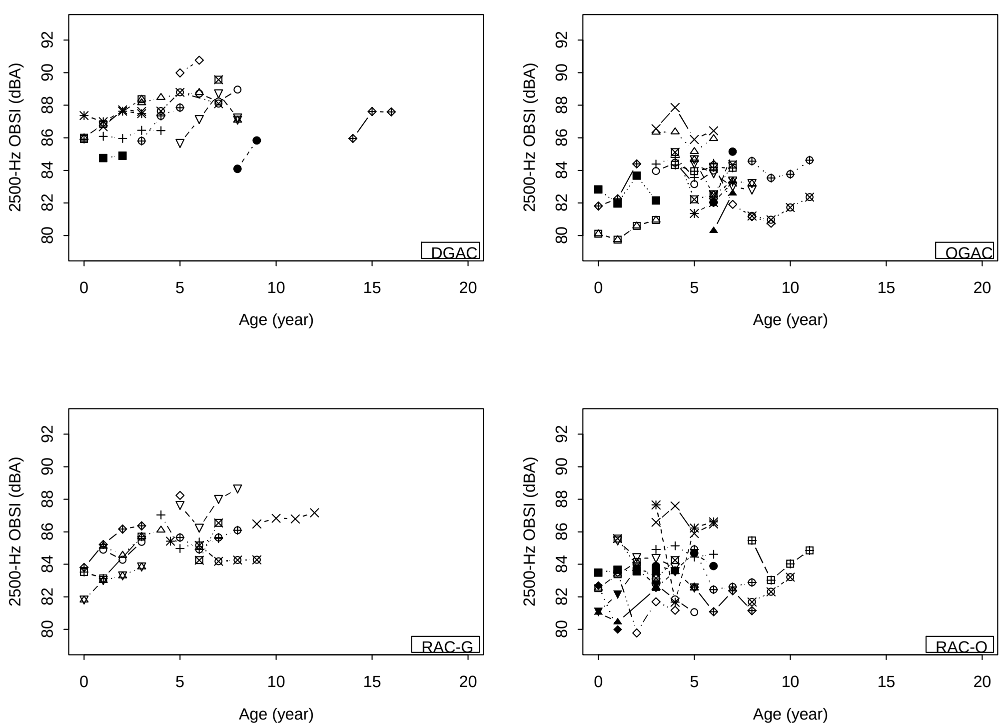


Figure A.24: Sound intensity at 2,500 Hz over four years for each pavement section.

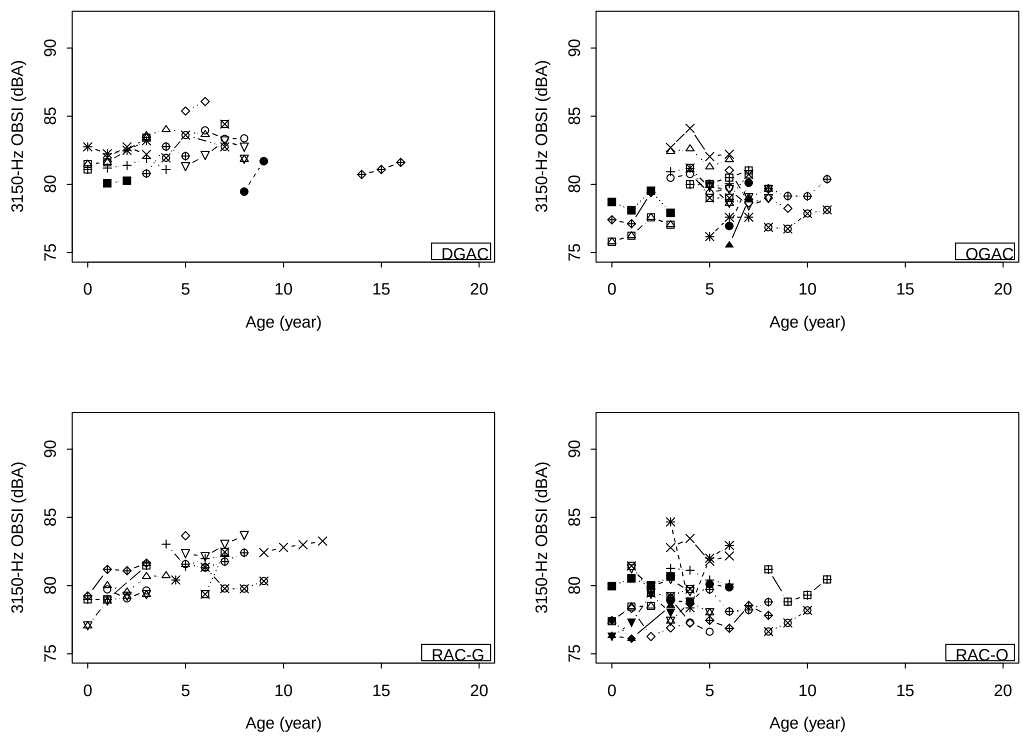


Figure A.25: Sound intensity at 3,150 Hz over four years for each pavement section.

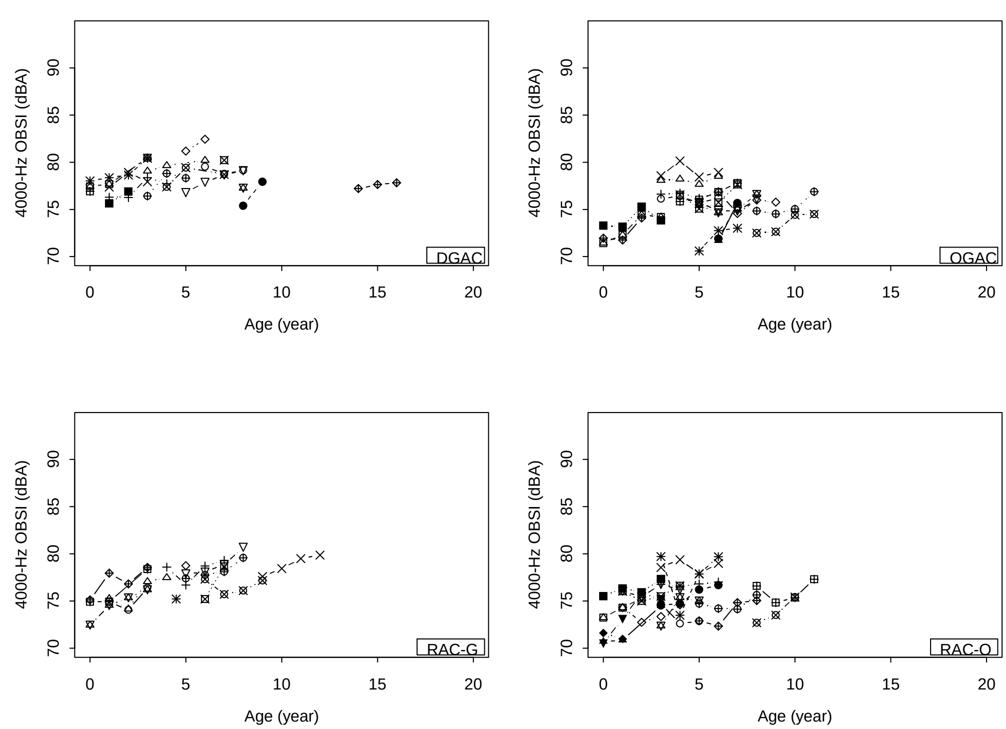


Figure A.26: Sound intensity at 4,000 Hz over four years for each pavement section.

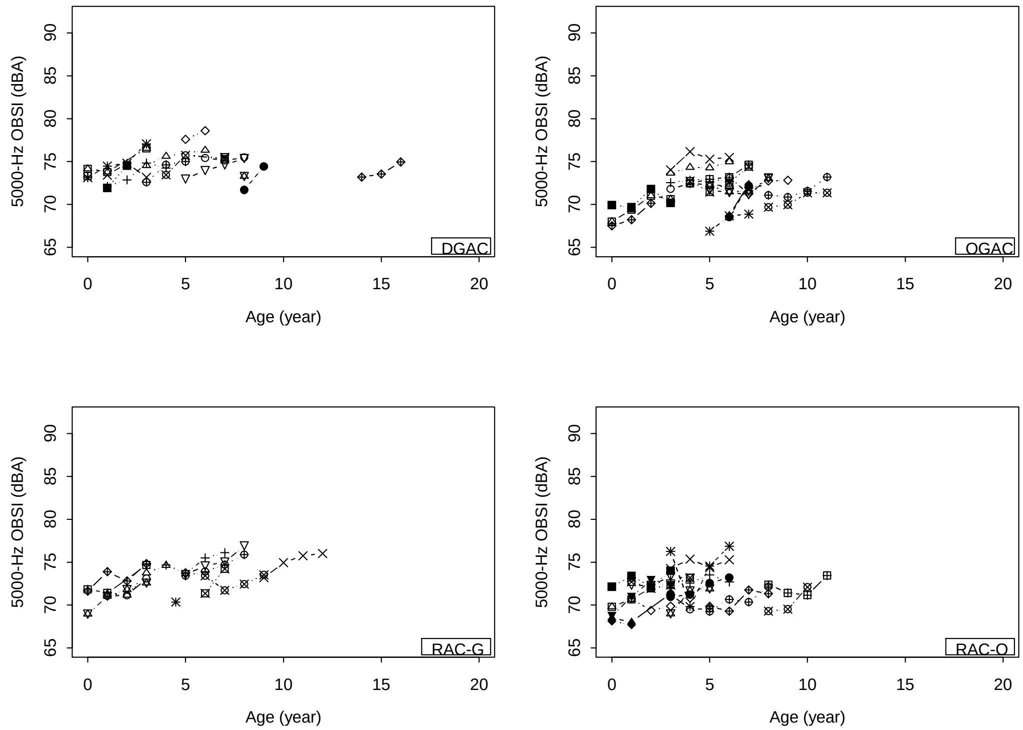


Figure A.27: Sound intensity at 5,000 Hz over four years for each pavement section.

A.5.3.3 Evaluation of Sound Intensity at 500 Hz One-Third Octave Band

A.5.3.3.1 Descriptive Analysis

Figure A.17 shows the 500-Hz OBSI values observed on each pavement section of the four mix types in the four survey years. For newly paved sections, 500-Hz sound intensities measured on open-graded pavements (OGAC and RAC-O) are generally higher than the values measured on dense- or gap-graded pavements (DGAC and RAC-G). This indicates that for newly placed mixes, open-graded pavements have rougher surfaces that contribute to more tire vibration than dense- and gap-graded pavements. For pavements with an age between four and seven years, there seems to be no significant difference in 500-Hz sound intensity among the four mixes. For old pavements (more than seven years), OGAC pavements seem to have higher 500-Hz sound intensity than the other three pavement types. This indicates that OGAC pavements experience more surface distresses that affect surface smoothness than the other pavement types. Variation of 500-Hz sound intensity among different pavement sections seems to be higher on RAC-O pavements than on other pavement types. This indicates that different RAC-O pavements have significantly different surface smoothness.

Figure A.28 shows the box plots of 500-Hz OBSI in four years for different mix types for three age categories. As the figure shows, sound intensity generally increases with pavement age for the same pavement section. Except for a few cases, this increasing trend is also obvious among different pavement sections of the same mix type. Overall, the rate of increase of sound intensity is lower on rubberized pavements (RAC-G and RAC-O) than on non-rubberized pavements (DGAC and OGAC).

Figure A.29 shows the estimated cumulative distribution function of 500-Hz noise reduction for both the OGAC and RAC-O types of open-graded mixes and RAC-G mixes compared to the average 500-Hz noise levels of DGAC mixes in six age groups. The average 500-Hz noise level on DGAC pavements, as shown in the legend, is about 85.7 dB(A) for newly paved overlays, between 88.1 and 88.6 dB(A) for pavements with an age between three and nine years, and approximately 91.5 dB(A) for pavements older than nine years.

A negative value in Figure A.29 indicates an increase in noise levels compared to the average DGAC mix noise level. The figure shows that the noise change varies over a wide range for open-graded mixes, from –10 dB(A) to 5 dB(A), and it varies in a narrower range for RAC-G pavements.

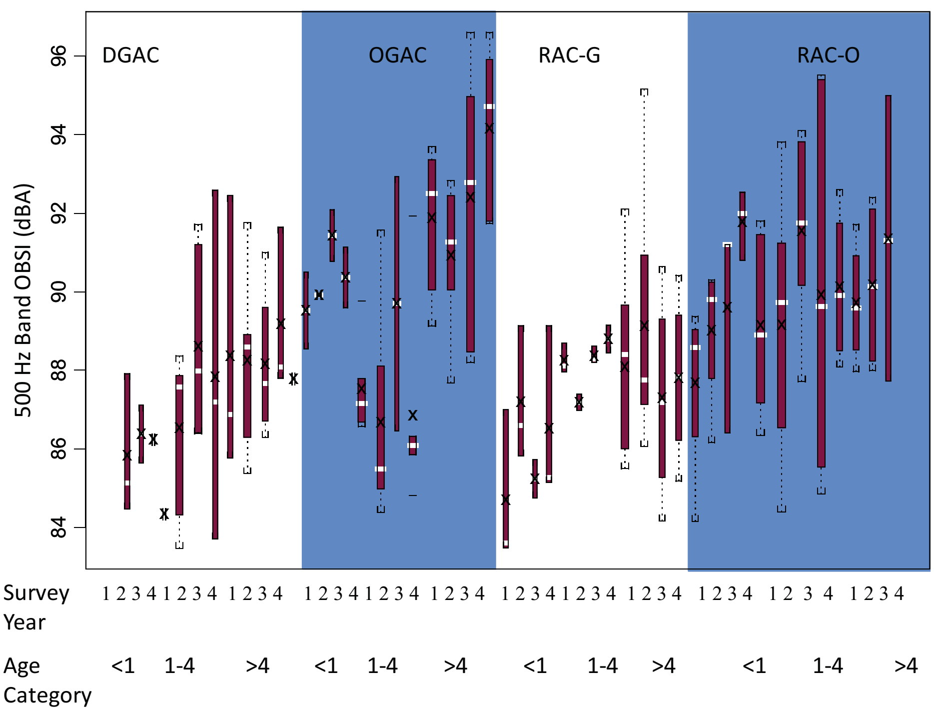


Figure A.28: Sound intensity at 500 Hz for different initial age categories (Age Category) and for four years of data collection.

For newly paved overlays (age less than or equal to one year), RAC-G pavements seem to have 500-Hz noise levels similar to DGAC pavements, while the open-graded pavements are significantly noisier than the DGAC pavements. Approximately 80 percent of RAC-O and 90 percent of OGAC pavements are at least 3 dB(A) noisier than DGAC pavements.

Among pavements with an age between one and three years, about 10 percent of the RAC-G, 40 percent of the OGAC, and 60 percent of the RAC-O are at least 3 dB(A) noisier than DGAC pavements.

For pavements with an age between four and seven years, if the mix with small sample sizes (RAC-G in the age group three to five years) is excluded, the median of the noise reduction distribution curve is generally around 0 dB(A) for all mixes, which indicates that in the age group three to seven years, the four mixes have similar 500-Hz noise levels.

For pavements with an age between seven and nine years, both OGAC and RAC-O mixes are noisier than DGAC, while RAC-G is generally quieter than DGAC.

The corresponding plots for pavements with an age greater than nine years are not discussed in detail here because the sample size is very small for all mixes. One general trend, however, is that OGAC pavements became the noisiest (in 500-Hz frequency band) among the four mixes.

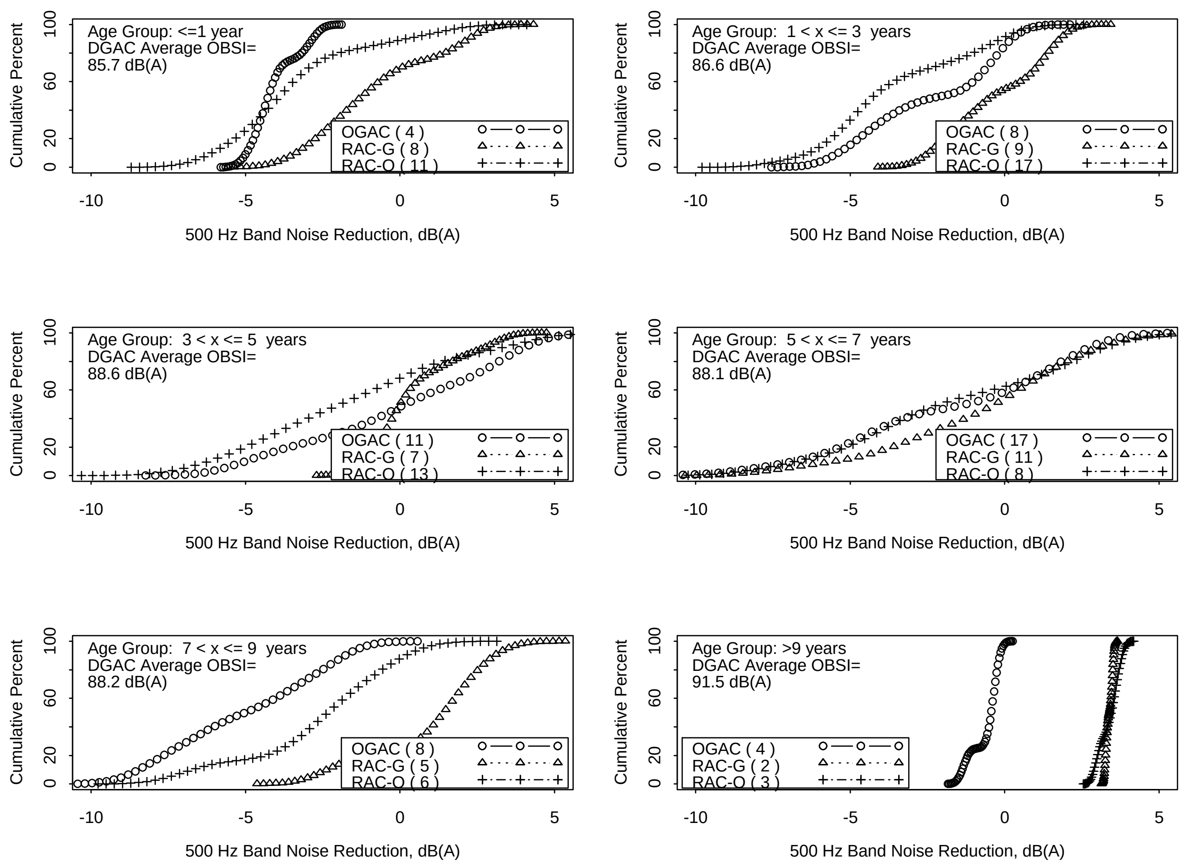


Figure A.29: Estimated cumulative distribution function of 500-Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups of pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.)

A.5.3.1.2 Statistical Analysis

A single-variable regression analysis was first conducted to check the correlation between the dependent variable and each independent variable, and then a multiple regression model was estimated to consider the effects of all variables simultaneously. To determine the effects of mix type and mix properties on tire/pavement noise, separate regression models were proposed.

In the first model, only the mix type (categorical variable) and environmental and traffic factors are included as the independent variables, while mix property variables are excluded. The regression equation appears as Equation A.5.7:

$$\begin{aligned}&500Hz\ Sound\ Intensity(dBA)=87.2794+0.1504\times Age(year)+2.5116\times ind(MixTypeOGAC)+0.3243\times ind(MixTypeRAC-G)\\&+1.6924\times ind(MixTypeRAC-O)-0.0133\times Thickness(mm)-0.0148\times NumberOfDays>30C\\&+0.0007091\times AADTTinCoringLane+0.4566\times ind(PresenceofRaveling)+1.6218\times ind(PresenceofRutting)\end{aligned} \quad \textbf{(A.5.7)}$$

where $ind(\cdot)$ is an indicator function, 1 if a variable in parenthesis is true and 0 if it is false. The estimated values and P-values of the parameters are shown below:

	Value	Std. Error	t value	P-value
(Intercept)	87.2794	0.8628	101.1630	<0.0001
Age	0.1504	0.0665	2.2617	0.0248
MixTypeOGAC	2.5116	0.5551	4.5245	<0.0001
MixTypeRAC-G	0.3243	0.5378	0.6030	0.5473
MixTypeRAC-O	1.6924	0.5847	2.8945	0.0042
Thickness	-0.0133	0.0110	-1.2117	0.2271
NoDaysTempGT30	-0.0148	0.0033	-4.5268	<0.0001
AADTTCoringLane	0.0007091	0.0001	5.7512	<0.0001
Raveling	0.4566	0.4043	1.1295	0.2601
Rutting	1.6218	0.5876	2.7603	0.0063

Residual standard error: 2.29 on 190 degrees of freedom; Multiple R-Squared: 0.42.

It can be seen that at the 95 percent confidence level, age (Age), mix type (MixTypeOGAC, MixTypeRAC-O), number of days with air temperature greater than 30°C (NoDaysTempGT30), truck traffic in the coring lane (AADTTCoringLane), and the existence of rutting (Rutting) significantly affect the 500-Hz band sound intensity. The 500-Hz band noise increases with pavement age, truck traffic volume, and the existence of rutting distress, but decreases with number of days with air temperature greater than 30°C. Among the four pavement types, OGAC and RAC-O pavements have a statistically higher 500-Hz noise level than DGAC pavements, while RAC-G pavements have statistically the same 500-Hz noise level as DGAC pavements. The interaction terms between age and mix type are statistically insignificant, although they are not shown in the model above. This indicates that the growth rate of overall sound intensity is not statistically different among the four pavement types.

In the second model, the mix type variables are replaced with mix property variables and the model is estimated for each mix type separately. The regression equations appear as Equation A.5.8 through Equation A.5.11:

For DGAC pavements

$$500Hz\ Sound\ \ Intensity(dBA)\text{=}84.2628\text{+}0.4054\times AirVoid(\%)+0.1147\times Age(year)-0.8866\times FinenessModulus$$
$$+0.005274\times MPD+0.0115\times Thickness(mm)-0.004897\times NumberOfDays>30C-0.0000313\times AADTTinCoringLane \quad \textbf{(A.5.8)}$$

	Value	Std. Error	t value	P-value
(Intercept)	84.2628	5.2192	16.1449	<0.0001
AirVoid	0.4054	0.1351	3.0016	0.0053
Age	0.1147	0.1005	1.1417	0.2623
FinenessModulus	-0.8866	1.2876	-0.6885	0.4962
MPD	0.005274	0.0019	2.7636	0.0095
Thickness	0.01150	0.0158	0.7287	0.4716
NoDaysTempGT30	-0.004897	0.0065	-0.7520	0.4577
AADTTCoringLane	0.00003130	0.0002	0.1497	0.8819

Residual standard error: 1.672 on 31 degrees of freedom; Multiple R-Squared: 0.61.

For OGAC pavements

$$500Hz\ Sound\ \ Intensity(dBA)\text{=}102.0372\text{+}0.3834\times AirVoid(\%)+0.1353\times Age(year)-3.1022\times FinenessModulus-0.0004184\times MPD(micron)$$
$$+0.01718\times Thickness(mm)-0.04123\times NumberOfDays>30C+0.001176\times AADTTinCoringLane \quad \textbf{(A.5.9)}$$

	Value	Std. Error	t value	P-value
(Intercept)	102.0372	6.1613	16.5611	<0.0001
AirVoid	0.3834	0.1564	2.4520	0.0182
Age	0.1353	0.1082	1.2507	0.2177
FinenessModulus	-3.1022	1.4886	-2.0839	0.0430
MPD	-0.0004184	0.0016	-0.2686	0.7895
Thickness	0.01718	0.0271	0.6341	0.5293
NoDaysTempGT30	-0.04123	0.0062	-6.6152	<0.0001
AADTTCoringLane	0.001176	0.0003	3.9882	0.0002

Residual standard error: 1.808 on 44 degrees of freedom; Multiple R-Squared: 0.73.

For RAC-G pavements

$$500Hz\ Sound\ \ Intensity(dBA)\text{=}81.9368\text{-}0.02213\times AirVoid(\%)+0.2013\times Age(year)+0.3396\times FinenessModulus+0.002542\times MPD(micron)$$
$$-0.02589\times Thickness(mm)+0.01573\times NumberOfDays>30C+0.0006195\times AADTTinCoringLane \quad \textbf{(A.5.10)}$$

	Value	Std. Error	t value	P-value
(Intercept)	81.9368	8.2459	9.9367	<0.0001
AirVoid	0.02213	0.1762	0.1256	0.9008
Age	0.2013	0.1155	1.7435	0.0903
FinenessModulus	0.3396	1.8383	0.1847	0.8545
MPD	0.002542	0.0011	2.2649	0.0300
Thickness	-0.02589	0.0276	-0.9378	0.3550
NoDaysTempGT30	0.01573	0.0060	2.6246	0.0129
AADTTCoringLane	0.0006195	0.0003	1.8184	0.0778

Residual standard error: 1.853 on 34 degrees of freedom; Multiple R-Squared: 0.46.

For RAC-O pavements

$$500Hz\ Sound\ Intensity(dBA)=69.3494+0.0587\times AirVoid(\%)-0.0110\times Age(year)+2.91\times FinenessModulus+0.003399\times MPD(micron) -0.00375\times Thickness(mm)-0.003824\times NumberOfDays>30C+0.0004704\times AADTTinCoringLane \quad \textbf{(A.5.11)}$$

	Value	Std. Error	t value	P-value
(Intercept)	69.3494	9.7660	7.1011	<0.0001
AirVoid	0.0587	0.1389	0.4223	0.6746
Age	-0.0110	0.1240	-0.0891	0.9294
FinenessModulus	2.9100	2.1369	1.3618	0.1794
MPD	0.003399	0.0015	2.2186	0.0311
Thickness	-0.003750	0.0374	-0.1003	0.9205
NoDaysTempGT30	-0.003824	0.0067	-0.5718	0.5700
AADTTCoringLane	0.0004704	0.0002	2.7367	0.0086

Residual standard error: 2.085 on 50 degrees of freedom; Multiple R-Squared: 0.50.

All four models show large variance in the residual errors, which indicates that the data used in the analysis have high inherent variability. At a 95 percent confidence level, age (Age) is insignificant on all pavements. Truck traffic volume (AADTTCoringLane) is a significant factor that contributes to the increase of 500-Hz band noise for open-graded mixes, but not for dense- or gap-graded mixes. The estimated coefficients (0.0012 for OGAC versus 0.0005 for RAC-O) indicate that the traffic effect is more significant on the OGAC pavements than on the RAC-O pavements. This suggests that the inclusion of rubber in the open-graded mixes reduces distresses that are related to surface smoothness, and therefore extends their noise-reducing life.

For DGAC and OGAC pavements, air-void content (AirVoid) is statistically significant at the 95 percent confidence level. The estimated coefficient indicates that higher air-void content increases 500-Hz band noise.

For all pavements except OGAC, the aggregate gradation variable (FinenessModulus) does not seem to significantly affect the low-frequency noise. The number of days with air temperature greater than 30°C (NoDaysTempGT30) is a statistically significant variable for OGAC and RAC-G. More high-temperature days tend to result in lower low-frequency noise on OGAC pavements, but greater low-frequency noise on RAC-G pavements.

For DGAC, RAC-G and RAC-O pavements, MPD is a statistically significant variable. A higher MPD value (i.e., coarser gradation) tends to increase low-frequency noise. Truck traffic volume is significant on the open-graded pavements (OGAC and RAC-O). The estimated coefficient of AADTT in the coring lane (AADTTCoringLane) indicates that higher truck traffic volume leads to higher low-frequency noise.

A.5.3.4 Evaluation of Sound Intensity at 1,000 Hz One-Third Octave Band

A.5.3.4.1 Descriptive Analysis

Figure A.20 shows the 1,000-Hz OBSI values observed in the four survey years on each pavement section of the four mix types. Generally the 1,000-Hz sound intensity also increases with pavement age. For newly paved overlays, the 1,000-Hz sound intensities measured on open-graded pavements (OGAC and RAC-O) and gap-graded pavements (RAC-G) are lower than the values measured on dense-graded pavements (DGAC). This is because the open- and gap-graded pavements have higher air-void content than the dense-graded pavements, and the 1,000-Hz noise is influenced by both the air-pumping and tire vibration mechanisms.

Figure A.30 shows the box plots of 1,000-Hz OBSI for four years of measurement for different mix types for the three initial age categories. As the figure shows, sound intensity generally increases with pavement age. Other than a few exceptions, this increase trend is also obvious among different pavement sections of the same mix type. Overall, the increase rate of sound intensity is lowest on RAC-O pavements, which means that RAC-O pavements retain their noise-reducing properties longer than OGAC pavements.

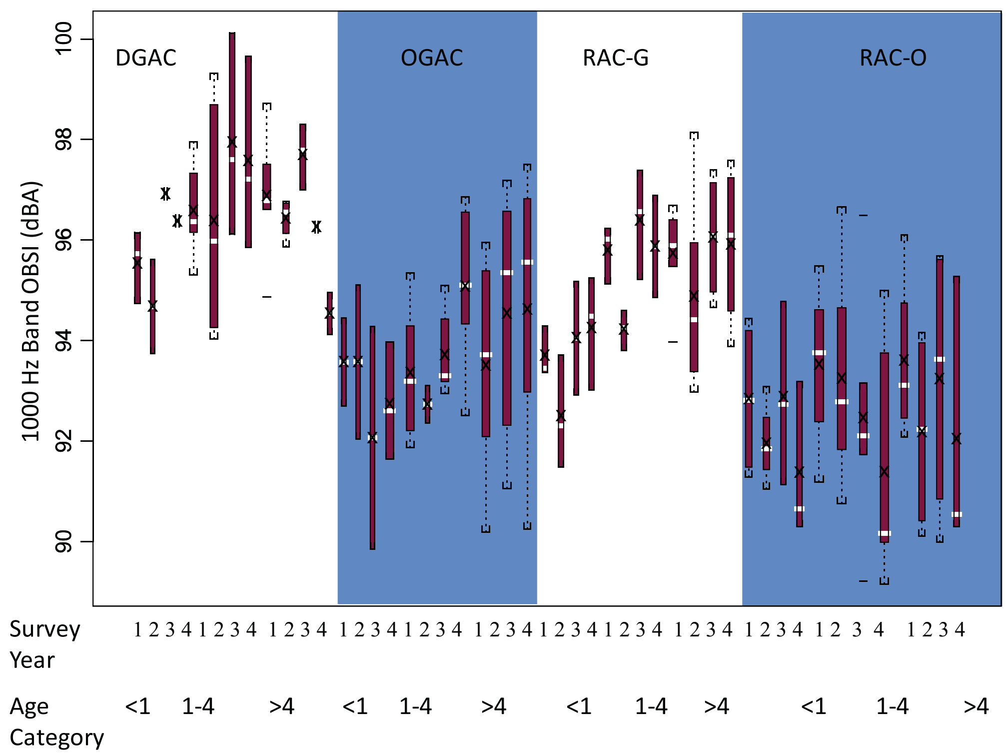


Figure A.30: Sound intensity at 1,000 Hz for different initial age categories (Age Category) and for four years of data collection.

Figure A.31 shows the estimated cumulative distribution function of 1,000-Hz noise reduction for both the OGAC and RAC-O types of open-graded mixes and the RAC-G mixes compared to the average 1,000-Hz noise levels of DGAC mixes in six age groups. The average 1,000-Hz noise level on DGAC pavements, as shown in the legend, is approximately 95.6 dB(A) for newly paved overlays, around 96 and 98 dB(A) for pavements with an age between three and nine years, and approximately 96.8 dB(A) for pavements older than nine years.

A negative value in Figure A.31 indicates an increase in noise levels compared to the average DGAC mix noise level. The figure shows that except for pavements older than nine years (for which the sample sizes of all types of pavements are too small to give representative conclusions), OGAC, RAC-G, and RAC-O pavements are all generally quieter than DGAC pavements in terms of 1,000-Hz band noise.

For pavements younger than nine years, the figure shows that with the exception of a few outliers the noise reduction is generally between 0 and 8 dB(A) for open-graded pavements, and between –2 and 5 dB(A) for RAC-G pavements.

For newly paved overlays (age less than or equal to one year), OGAC and RAC-G pavements seem to have similar noise-reducing properties, while RAC-O pavements reduce noise the most. If at least a 3 dB(A) noise reduction is required for a surface to be considered noise-reducing, about 10 percent of OGAC and 20 percent of RAC-G pavements are noise-reducing, but about 70 percent of RAC-O pavements are noise-reducing compared with DGAC of the same age.

For pavements with an age between one and three years, OGAC and RAC-O pavements have similar noise-reducing properties (about 70 percent of the pavements are at least 3 dB[A] quieter than average DGAC pavement), while RAC-G pavements begin to lose their noise-reducing property.

For pavements with an age between three and five years, OGAC and RAC-O pavements still have similar noise-reducing properties, which are better than RAC-G pavements. About 80 percent of RAC-O and OGAC pavements and 20 percent of RAC-G pavements are at least 3 dB(A) quieter than the average DGAC pavement.

For pavements with an age between five and nine years, RAC-O, OGAC, and RAC-G pavements show different noise-reducing properties, with RAC-O the best and RAC-G the worst. The corresponding plots for pavements with ages greater than nine years are not discussed in detail here because the sample size is very small for all mixes. One general trend, however, is that the rank of the three mixes (RAC-O, OGAC, and RAC-G, best to worst) remains unchanged in terms of noise reduction in the 1,000-Hz band compared to DGAC mixes.

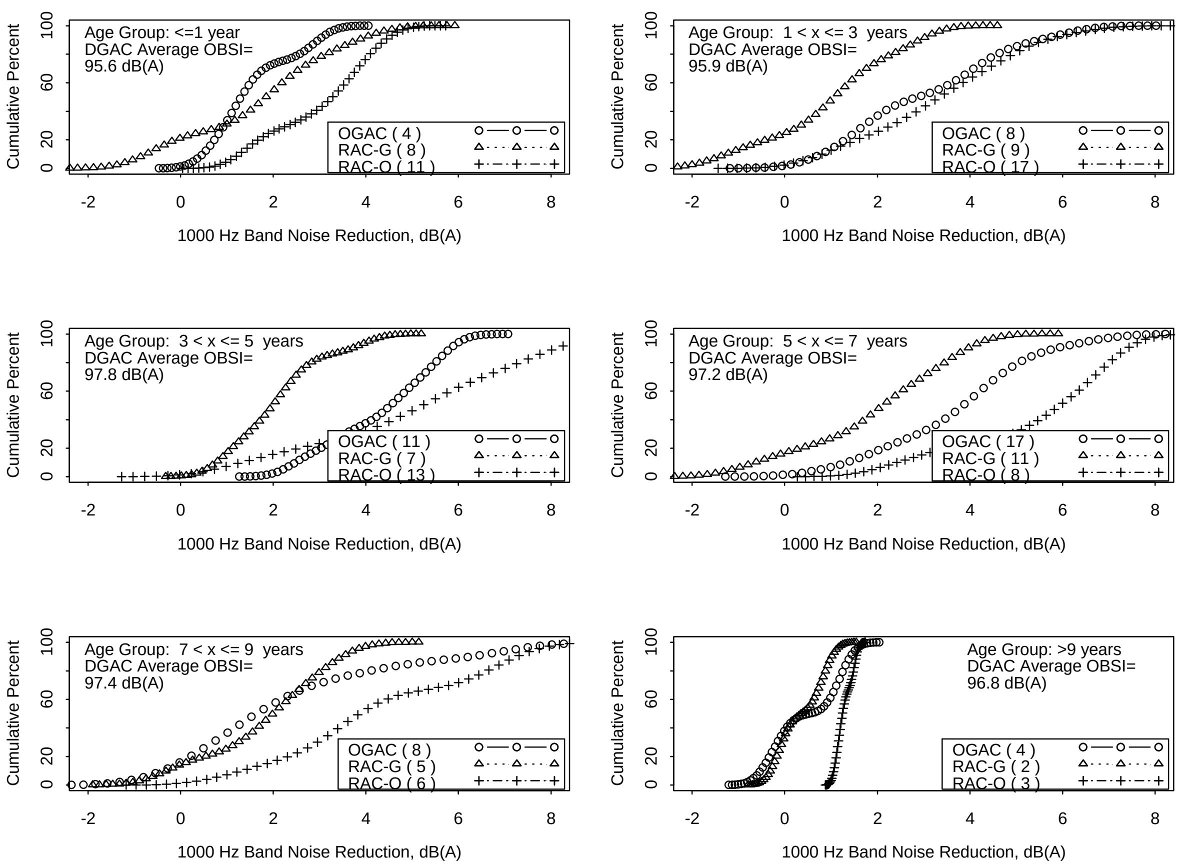


Figure A.31: Estimated cumulative distribution function of 1,000-Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups of pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.)

A.5.3.4.2 Statistical Analysis

Multiple regression analysis was conducted to account for the effects of various variables simultaneously. Two separate regression models were proposed. In the first model, only the mix type and environmental and traffic factors are included as independent variables, while mix property variables are excluded. The regression equation appears as Equation A.5.12:

$$\begin{aligned}&1000Hz\ Sound\ Intensity(dBA) = 96.8894 + 0.0851\times Age(year) - 3.3883\times ind(MixTypeOGAC) - 1.6191\times ind(MixTypeRAC-G)\\&-4.6108\times ind(MixTypeRAC-O) - 0.02987\times Thickness(mm) + 0.009264\times NumberOfDays > 30C\\&-0.0000994\times AADTTinCoringLane + 0.5396\times ind(PresenceofRaveling) + 0.9389\times ind(PresenceofRutting)\end{aligned} \quad \textbf{(A.5.12)}$$

where $ind(\cdot)$ is an indicator function, 1 if a variable in parenthesis is true and 0 if it is false. The estimated values and P-values of the parameters are shown below:

	Value	Std. Error	t value	P-value
(Intercept)	96.8894	0.5652	171.4177	<0.0001
Age	0.08510	0.0436	1.9540	0.0500
MixTypeOGAC	-3.3883	0.3637	-9.3171	<0.0001
MixTypeRAC-G	-1.6191	0.3524	-4.5948	<0.0001
MixTypeRAC-O	-4.6108	0.3831	-12.0368	<0.0001
Thickness	-0.02987	0.0072	-4.1533	<0.0001
NoDaysTempGT30	0.009264	0.0021	4.3132	<0.0001
AADTTCoringLane	-0.00009940	0.0001	-1.2309	0.2199
Raveling	0.5396	0.2648	2.0374	0.0430
Rutting	0.9389	0.3849	2.4391	0.0156

Residual standard error: 1.506 on 190 degrees of freedom; Multiple R-Squared: 0.58.

This regression model is similar to the multiple regression model for the overall sound intensity (Equation A.5.2), which makes sense since this is generally the dominant frequency in the A-weighted spectrum. At the 95 percent confidence level, age (Age), mix type (MixTypeOGAC, MixTypeRAC-G, MixTypeRAC-O), surface layer thickness (Thickness), number of days with air temperature greater than 30°C (NoDaysTempGT30), and the existence of raveling (Raveling) or rutting (Rutting) significantly affect the 1,000-Hz sound intensity. The 1,000-Hz sound intensity increases with pavement age and the existence of raveling and rutting distresses, but decreases with the surface layer thickness. Among the three pavement types, OGAC, RAC-G, and RAC-O, all have lower initial 1,000-Hz sound intensity than DGAC. The average noise reductions (compared to DGAC pavements) for newly paved OGAC, RAC-G, and RAC-O mixes are about 3.4, 1.6, and 4.6 dB(A), respectively.

The interaction terms between age and mix type are statistically insignificant, so they were not included in the model above. This indicates that the overall growth rate of 1,000-Hz sound intensity is not statistically different among the four pavement types.

In the second model, the mix type variables are replaced with mix property variables and the model is estimated for each mix type separately. The regression equations appear as Equation A.5.13 through Equation A.5.16:

For DGAC pavements

$$1000Hz\ Sound\ Intensity(dBA)=95.0882-0.03286\times AirVoid(\%)-0.02189\times Age(year)-0.3604\times FinenessModulus$$
$$+0.00475\times MPD-0.01423\times Thickness(mm)+0.002341\times NumberOfDays>30C+0.0002593\times AADTTinCoringLane \quad \textbf{(A.5.13)}$$

	Value	Std. Error	t value	P-value
(Intercept)	95.0882	3.7561	25.3159	<0.0001
AirVoid	-0.03286	0.0972	-0.3381	0.7376
Age	-0.02189	0.0723	-0.3028	0.7641
FinenessModulus	-0.3604	0.9267	-0.3889	0.7000
MPD	0.004749	0.0014	3.4583	0.0016
Thickness	-0.01423	0.0114	-1.2536	0.2194
NoDaysTempGT30	0.002341	0.0047	0.4995	0.6210
AADTTCoringLane	0.0002593	0.0002	1.7248	0.0945

Residual standard error: 1.202 on 31 degrees of freedom; Multiple R-Squared: 0.45.

For OGAC pavements

$$1000Hz\ Sound\ Intensity(dBA)=101.2464-0.1008\times AirVoid(\%)+0.2108\times Age(year)-1.7488\times FinenessModulus+0.001337\times MPD(micron)$$
$$-0.02946\times Thickness(mm)+0.008114\times NumberOfDays>30C+0.0007337\times AADTTinCoringLane \quad \textbf{(A.5.14)}$$

	Value	Std. Error	t value	P-value
(Intercept)	101.2464	4.5324	22.3385	<0.0001
AirVoid	-0.10077	0.1150	-0.8761	0.3857
Age	0.2108	0.0796	2.6482	0.0112
FinenessModulus	-1.7488	1.0951	-1.5970	0.1174
MPD	0.001337	0.0011	1.1664	0.2497
Thickness	-0.02946	0.0199	-1.4780	0.1465
NoDaysTempGT30	0.008114	0.0046	1.7696	0.0837
AADTTCoringLane	0.0007337	0.0002	3.3813	0.0015

Residual standard error: 1.330 on 44 degrees of freedom; Multiple R-Squared: 0.56.

For RAC-G pavements

$$1000Hz\ Sound\ Intensity(dBA)=88.0852-0.1687\times AirVoid(\%)+0.2147\times Age(year)+1.2802\times FinenessModulus+0.00099\times MPD(micron)$$
$$-0.02087\times Thickness(mm)+0.01186\times NumberOfDays>30C-0.0002996\times AADTTinCoringLane \quad \textbf{(A.5.15)}$$

	Value	Std. Error	t value	P-value
(Intercept)	88.0852	5.2210	16.8714	<0.0001
AirVoid	-0.1687	0.1115	-1.5126	0.1396
Age	0.2147	0.0731	2.9362	0.0059
FinenessModulus	1.2802	1.1640	1.0999	0.2791
MPD	0.0009893	0.0007	1.3922	0.1729
Thickness	-0.02087	0.0175	-1.1940	0.2407
NoDaysTempGT30	0.01186	0.0038	3.1248	0.0036
AADTTCoringLane	0.0002996	0.0002	1.3890	0.1739

Residual standard error: 1.173 on 34 degrees of freedom; Multiple R-Squared: 0.53.

For RAC-O pavements

$$1000Hz\ Sound\ Intensity(dBA)=110.1519+0.1353\times AirVoid(\%)+0.22\times Age(year)-2.503\times FinenessModulus-0.0027\times MPD(micron)$$
$$-0.129\times Thickness(mm)-0.001803\times NumberOfDays>30C-0.0002137\times AADTTinCoringLane \quad \textbf{(A.5.16)}$$

	Value	Std. Error	t value	P-value
(Intercept)	110.1519	6.2111	17.7346	<0.0001
AirVoid	0.1353	0.0884	1.5308	0.1321
Age	0.2200	0.0789	2.7891	0.0075
FinenessModulus	-2.5030	1.3591	-1.8417	0.0714
MPD	-0.002677	0.0010	-2.7474	0.0083
Thickness	-0.1290	0.0238	-5.4283	<0.0001
NoDaysTempGT30	-0.001803	0.0043	-0.4239	0.6735
AADTTCoringLane	-0.0002137	0.0001	-1.9551	0.0562

Residual standard error: 1.326 on 50 degrees of freedom; Multiple R-Squared: 0.59.

The R^2 values are all less than 0.60, indicating that there is an explanatory variable other than the traffic, climate, and pavement variables considered here. The results show that at a 95 percent confidence level, age (Age) is significant for all pavement surface types except DGAC, for which age is significant at a 90 percent confidence level. The estimated parameters indicate that the 1,000-Hz sound intensity increases with pavement age for all four mix types. Air-void content (AirVoid) is insignificant for all pavements. The surface layer thickness (Thickness) is significant for OGAC and RAC-O pavements and insignificant for DGAC and RAC-G pavements. The estimated parameters indicate that a thicker open-graded surface layer corresponds to a lower noise level at 1,000 Hz. Pavement surface roughness (MPD) is a significant factor for all pavements, and a higher MPD value corresponds to a higher noise level on DGAC, OGAC, and RAC-G pavements, but a lower noise level on RAC-O pavements.

The aggregate gradation variable (FinenessModulus) does not seem to significantly affect tire/pavement noise for all mixes.

Truck traffic volume (AADTTCoringLane) is a significant factor that increases tire/pavement noise only for OGAC pavements.

A.5.3.5 Evaluation of Sound Intensity at 2,000 Hz One-Third Octave Band

A.5.3.5.1 Descriptive Analysis

Figure A.23 shows the 2,000-Hz OBSI values observed in the four survey years on each pavement section of the four mix types. Generally the 2,000-Hz sound intensity also increases with pavement age, but the increase trend is more significant on OGAC, RAC-G, and RAC-O pavements than on DGAC pavements. For newly paved surfaces, the 2,000-Hz sound intensity measured on open-graded surfaces (OGAC and RAC-O) and gap-graded surfaces (RAC-G) is significantly lower than the values measured on dense-graded surfaces (DGAC).

Figure A.32 shows the box plots of 2,000-Hz OBSI in four years for different mix types for three age categories. As the figure shows, sound intensity generally increases with pavement age for the same pavement sections. For DGAC and RAC-G pavements, noise increase occurs at all pavement ages, while for OGAC and RAC-O pavements, noise increases mainly occur for newly paved overlays.

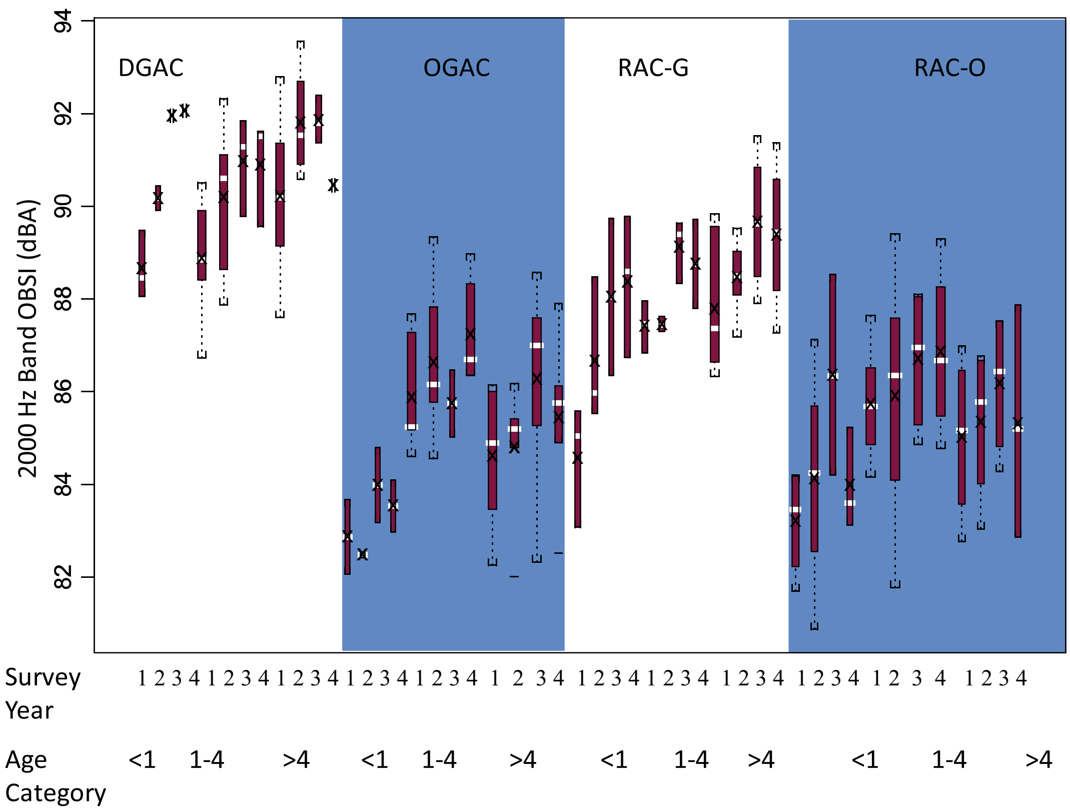


Figure A.32: Sound intensity at 2,000 Hz for different initial age categories (Age Category) and for four years of data collection.

Figure A.33 shows the estimated cumulative distribution function of 2,000-Hz noise reduction for both the OGAC and RAC-O types of open-graded mixes and the RAC-G mixes compared to the average 2,000-Hz noise levels of DGAC mixes in six age groups. The average 2,000-Hz noise level on DGAC pavements, as shown in the legend, is approximately 88.8 dB(A) for newly paved overlays, between 90.8 and 91.5 dB(A) for pavements with ages between three and nine years, and approximately 90.8 dB(A) for pavements older than nine years.

A positive value in Figure A.33 indicates reduction in noise levels compared to the average DGAC mix noise level. The figure shows that OGAC, RAC-G, and RAC-O pavements are all quieter than the DGAC pavements in terms of the 2,000-Hz band noise. With the exceptions of a few outliers, the noise reduction is generally between 0 and 9 dB(A) for open-graded pavements, and between –1 and 6 dB(A) for RAC-G pavements.

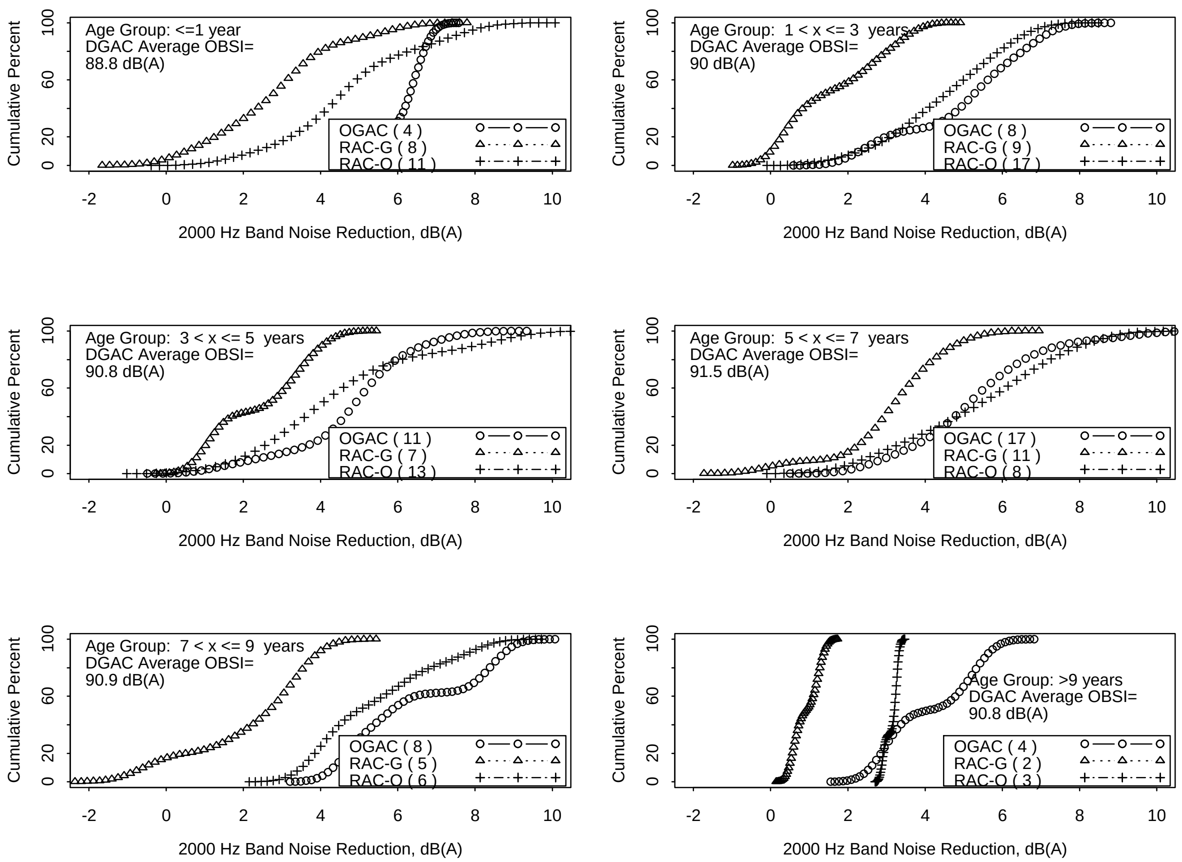


Figure A.33: Estimated cumulative distribution function of 2,000-Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups of pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.)

For newly paved overlays (age less than or equal to one year), OGAC pavements have better noise-reducing properties than RAC-O pavements, which themselves have better noise-reducing properties than RAC-G pavements. If at least a 3 dB(A) noise reduction is required for a surface to be considered a noise-reducing one, all OGAC pavements, 80 percent of RAC-O pavements, and 50 percent of RAC-G pavements are noise-reducing.

For pavements with ages between one and three years, OGAC and RAC-O pavements have similar noise-reducing ability—about 80 percent are at least 3 dB(A) quieter than average DGAC pavement—while only 20 percent of RAC-G pavements are at least 3 dB(A) quieter than the average DGAC pavement.

For pavements with ages between three and nine years, the relative performances (in terms of reducing noise in the 2,000-Hz band) of OGAC, RAC-G, and RAC-O pavements are similar to those of pavements with ages between one and three years.

The corresponding plots for pavements older than nine years are not discussed in detail here because the sample size is very small for all mixes. One general trend, however, is that RAC-G pavements always provide the least noise reduction in the 2,000-Hz band.

A.5.3.5.2 Statistical Analysis

Multiple regression analysis was conducted to account for the effects of different variables simultaneously. Two separate regression models were proposed. In the first model, only the mix type and environmental and traffic factors are included as independent variables, while mix property variables are excluded. The regression equation appears as Equation A.5.17:

$$\begin{aligned} &2000Hz\ Sound\ Intensity(dBA) = 88.4773 + 0.2365 \times Age(year) - 5.0649 \times ind(MixTypeOGAC) - 2.2618 \times ind(MixTypeRAC-G) \\ &-4.5265 \times ind(MixTypeRAC-O) + 0.006326 \times Thickness(mm) + 0.006398 \times NumberOfDays > 30C \\ &-0.0000343 \times AADTTinCoringLane - 0.01805 \times ind(PresenceofRaveling) + 0.1933 \times ind(PresenceofRutting) \end{aligned} \quad \textbf{(A.5.17)}$$

where $ind(\cdot)$ is an indicator function, 1 if a variable in parenthesis is true and 0 if it is false. The estimated values and P-values of the parameters are shown below:

	Value	Std. Error	t value	P-value
(Intercept)	88.4773	0.6287	140.7393	<0.0001
Age	0.2365	0.0484	4.8818	<0.0001
MixTypeOGAC	-5.0649	0.4045	-12.5219	<0.0001
MixTypeRAC-G	-2.2618	0.3919	-5.7712	<0.0001
MixTypeRAC-O	-4.5265	0.4261	-10.6243	<0.0001
Thickness	0.006326	0.0080	0.7908	0.4301
NoDaysTempGT30	0.006398	0.0024	2.6785	0.0080
AADTTCoringLane	-0.00003430	0.0001	-0.3819	0.7030
Raveling	-0.01806	0.2946	-0.0613	0.9512
Rutting	0.1933	0.4281	0.4515	0.6522

Residual standard error: 1.675 on 190 degrees of freedom; Multiple R-Squared: 0.62.

This regression model is similar to the multiple regression models for the overall sound intensity (Equation A.5.2) and 1,000-Hz sound intensity (Equation A.5.12), except that surface layer thickness, rutting, and raveling are not significant variables in this model. Raveling and rutting are not expected to be significant at 2,000 Hz and higher frequencies because they primarily affect the tire vibration mechanism, which does not influence these frequencies. At the 95 percent confidence level, age (Age), mix type (MixTypeOGAC, MixTypeRAC-G, MixTypeRAC-O), and number of days with air temperature greater than 30°C (NoDaysTempGT30) significantly affect the 2,000-Hz sound intensity. The 2,000-Hz sound intensity increases with pavement age. All three pavement types, OGAC, RAC-G, and RAC-O, have lower initial 2,000-Hz sound intensity than DGAC. The average noise reductions (compared to DGAC pavements) for newly paved OGAC, RAC-G, and RAC-O mixes are about 5.1, 2.3, and 4.5 dB(A), respectively. The interaction terms between age and mix type are statistically insignificant, so they were not included in the model above. This indicates that the overall growth rate of 2,000-Hz sound intensity is not statistically different among the four pavement types.

In the second model, the mix type variables are replaced with mix property variables and the model is estimated for each mix type separately. The regression equations appear as Equation A.5.18 through Equation A.5.21:

For DGAC pavements

$$2000Hz\ Sound\ Intensity(dBA) = 91.0135 - 0.3558 \times AirVoid(\%) + 0.1435 \times Age(year) - 0.1156 \times FinenessModulus + 0.002755 \times MPD - 0.0303 \times Thickness(mm) + 0.002906 \times NumberOfDays > 30C + 0.0003513 \times AADTTinCoringLane \quad \textbf{(A.5.18)}$$

	Value	Std. Error	t value	P-value
(Intercept)	91.0135	3.2950	27.6216	<0.0001
AirVoid	-0.3558	0.0853	-4.1725	0.0002
Age	0.1435	0.0634	2.2617	0.0309
FinenessModulus	-0.1156	0.8129	-0.1422	0.8879
MPD	0.002755	0.0012	2.2867	0.0292
Thickness	-0.03030	0.0100	-3.0426	0.0047
NoDaysTempGT30	0.002906	0.0041	0.7067	0.4850
AADTTCoringLane	0.0003513	0.0001	2.6634	0.0122

Residual standard error: 1.055 on 31 degrees of freedom; Multiple R-Squared: 0.64.

For OGAC pavements

$$2000Hz\ Sound\ Intensity(dBA) = 86.4649 - 0.2801 \times AirVoid(\%) + 0.2564 \times Age(year) + 0.4968 \times FinenessModulus + 0.0000319 \times MPD(micron) - 0.004864 \times Thickness(mm) - 0.002611 \times NumberOfDays > 30C - 0.000854 \times AADTTinCoringLane \quad \textbf{(A.5.19)}$$

	Value	Std. Error	t value	P-value
(Intercept)	86.4649	3.9952	21.6423	0.0000
AirVoid	-0.2801	0.1014	-2.7627	0.0083
Age	0.2564	0.0702	3.6537	0.0007
FinenessModulus	0.4968	0.9653	0.5146	0.6094
MPD	0.0000319	0.0010	0.0316	0.9749
Thickness	0.004864	0.0176	0.2768	0.7832
NoDaysTempGT30	-0.002611	0.0040	-0.6460	0.5216
AADTTCoringLane	-0.000854	0.0002	-4.4648	0.0001

Residual standard error: 1.172 on 44 degrees of freedom; Multiple R-Squared: 0.66.

For RAC-G pavements

$$2000Hz\ Sound\ \ Intensity(dBA)\text{=}82.2329\text{-}0.4428\times AirVoid(\%)+0.1756\times Age(year)+1.7447\times FinenessModulus+0.001228\times MPD(micron)$$
$$-0.04397\times Thickness(mm)+0.00297\times NumberOfDays>30C+0.0008367\times AADTTinCoringLane \quad \textbf{(A.5.20)}$$

	Value	Std. Error	t value	P-value
(Intercept)	82.2329	4.2948	19.1471	<0.0001
AirVoid	-0.4428	0.0918	-4.8259	<0.0001
Age	0.1756	0.0601	2.9191	0.0062
FinenessModulus	1.7447	0.9575	1.8222	0.0772
MPD	0.001228	0.0006	2.1017	0.0431
Thickness	-0.04397	0.0144	-3.0578	0.0043
NoDaysTempGT30	0.002970	0.0031	0.9514	0.3481
AADTTCoringLane	0.0008367	0.0002	4.7155	<0.0001

Residual standard error: 0.965 on 34 degrees of freedom; Multiple R-Squared: 0.74.

For RAC-O pavements

$$2000Hz\ Sound\ \ Intensity(dBA)\text{=}113.3108\text{-}0.0347\times AirVoid(\%)+0.4076\times Age(year)-5.1684\times FinenessModulus-0.001842\times MPD(micron)$$
$$-0.00238\times Thickness(mm)-0.002091\times NumberOfDays>30C+0.0001462\times AADTTinCoringLane \quad \textbf{(A.5.21)}$$

	Value	Std. Error	t value	P-value
(Intercept)	113.3108	6.0639	18.6862	<0.0001
AirVoid	-0.0347	0.0863	-0.4027	0.6889
Age	0.4076	0.0770	5.2939	<0.0001
FinenessModulus	-5.1684	1.3268	-3.8953	0.0003
MPD	-0.001842	0.0010	-1.9361	0.0585
Thickness	-0.002380	0.0232	-0.1026	0.9187
NoDaysTempGT30	-0.002091	0.0042	-0.5035	0.6168
AADTTCoringLane	0.0001462	0.0001	1.3694	0.1770

Residual standard error: 1.295 on 50 degrees of freedom; Multiple R-Squared: 0.61.

The results show that the 2,000-Hz sound intensity decreases with the increase of air-void content for all four mix types except that air-void content is a statistically insignificant factor for RAC-O mixes. At the 95 percent confidence level, pavement age (Age) is a significant factor for all mix types. The surface layer thickness (Thickness) is significant for DGAC and RAC-G pavements, but insignificant for OGAC and RAC-O pavements. Generally, thicker surface layer corresponds to lower 2,000-Hz sound intensity. Truck traffic volume (AADTTCoringLane) is a significant factor that increases tire/pavement noise for three of the four mix types, the exception being RAC-O. Surface macrotexture (MPD) is significant for DGAC and RAC-G pavements, and higher MPD increases the 2,000-Hz noise on DGAC and RAC-G pavements.

The aggregate gradation variable (FinenessModulus) does not seem to significantly affect tire/pavement noise on any pavement type except RAC-O. For RAC-O pavements, a larger fineness modulus (coarser gradation) results in significantly lower tire/pavement noise in the 2,000-Hz band.

A.5.3.6: Evaluation of Sound Intensity at 4,000 Hz One-Third Octave Band

A.5.3.6.1: Descriptive Analysis

Figure A.26 shows the 4,000-Hz OBSI values observed on each pavement section of the four mix types for the four survey years. Overall, it appears that the 4,000-Hz sound intensity band does not change significantly with pavement age on DGAC and RAC-O pavements. For OGAC pavements, the 4,000-Hz sound intensity increases with age for newly paved overlays, but tends to stabilize or even decrease slightly with age for pavements older than four years. On RAC-G pavements, the 4,000-Hz sound intensity increases with pavement age for both newly paved and older pavements.

Figure A.34 shows the box plots of 4,000-Hz OBSI in four years for different mix types for three age categories. As the figure shows, 4,000-Hz band sound intensity generally increases with age for the same pavement section. For DGAC and RAC-G mixes, older pavements generally exhibited higher 4,000-Hz band sound intensity than younger pavements. For the two open-graded mixes (OGAC and RAC-O), however, older pavements may exhibit lower 4,000-Hz band sound intensity than younger pavements.

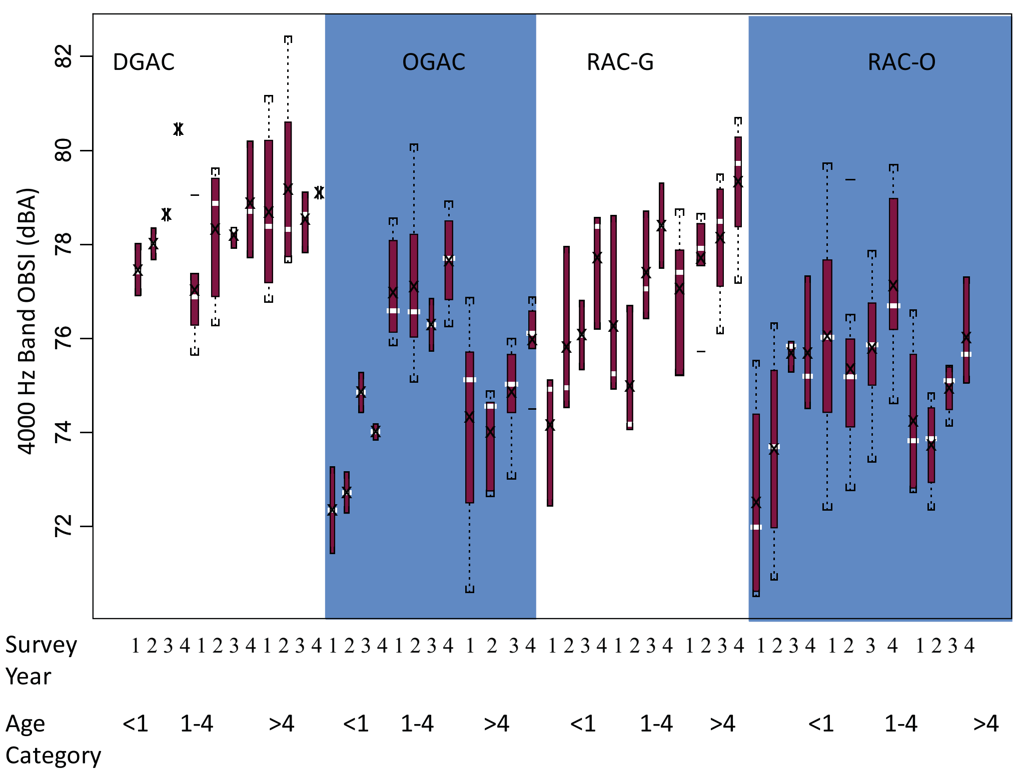


Figure A.34: Sound intensity at 4,000 Hz for different initial age categories (Age Category) and for four years of data collection.

Figure A.35 shows the estimated cumulative distribution function of 4,000-Hz noise reduction for OGAC, RAC-O, and RAC-G pavements compared to the average 4,000-Hz noise levels of DGAC pavements in six age groups. The average 4,000-Hz noise level on DGAC pavements, as shown in the legend, is about 77.2 dB(A) for newly paved overlays (Age Category ≤ 1 year), between approximately 78.0 and 80.0 dB(A) for pavements with ages between three and nine years, and around 77.5 dB(A) for pavements older than nine years. This indicates that the 4,000-Hz noise level on DGAC pavements does not change significantly with age.

A positive value in Figure A.35 indicates reduction in noise levels compared to the average DGAC mix noise level. The figure shows that the open-graded (OGAC and RAC-O) pavements are all quieter than the DGAC pavements in terms of 4,000-Hz band noise. RAC-G pavements with an age between 0 and 7 years also exhibited lower 4,000-Hz band noise, but RAC-G pavements with an age greater than 7 years exhibited similar or even higher 4,000-Hz band noise compared to DGAC pavements. With the exceptions of a few outliers, the noise reduction is generally between 0 and 7 dB(A) for open-graded pavements and between –2 and 5 dB(A) for RAC-G pavements.

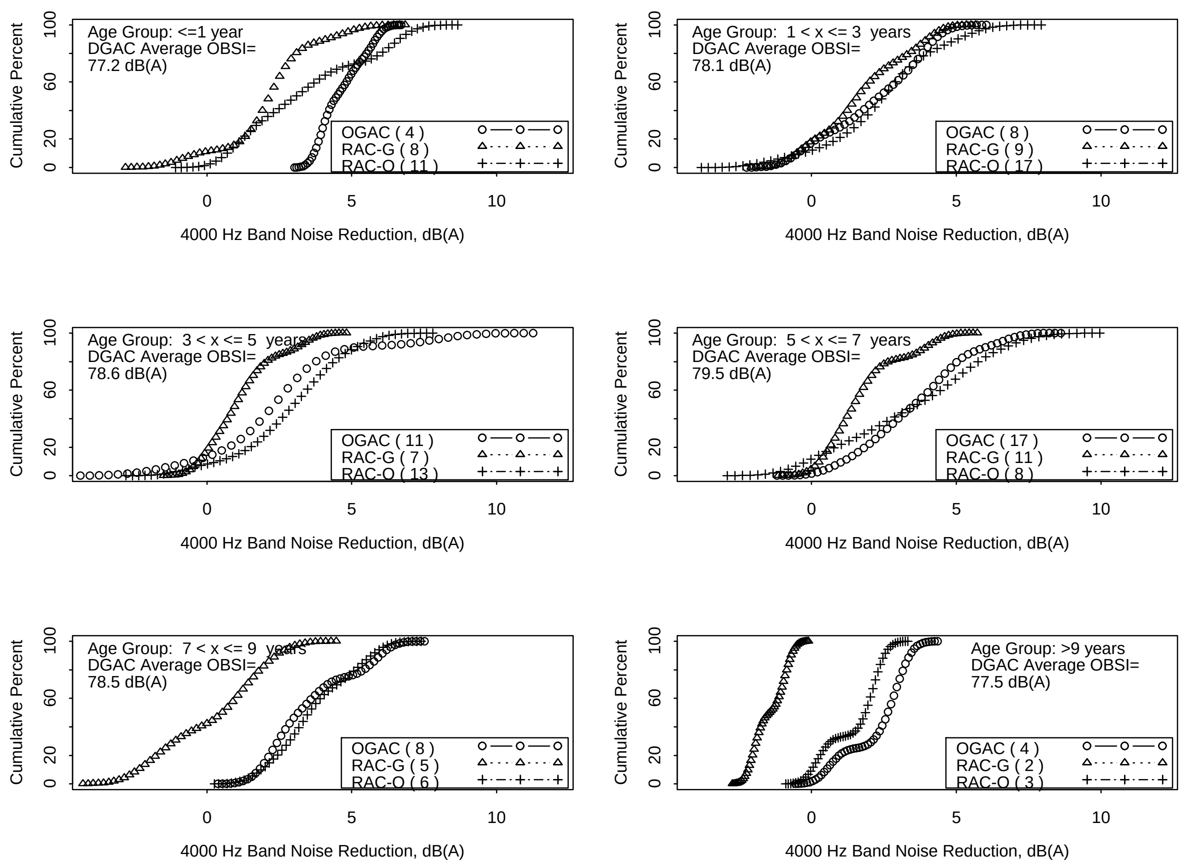


Figure A.35: Estimated cumulative distribution function of 4,000-Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups of pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.)

For newly paved overlays (age between one and three years), the three mix types, OGAC, RAC-G, and RAC-O, exhibit similar noise-reducing properties. Approximately 30 to 60 percent of pavements of each mix type are at least 3 dB(A) quieter than the corresponding DGAC pavements.

For pavements with ages between three and seven years, OGAC and RAC-O pavements still have similar noise-reducing properties, while RAC-G begins to perform worse than open-graded mixes. The relative performance of the three mixes remains unchanged for pavements older than seven years.

A.5.3.6.2 Statistical Analysis

Multiple regression analysis was conducted to account for the effects of various variables simultaneously. Two separate regression models were proposed. In the first model, only the mix type and environmental and traffic factors are included as independent variables, while mix property variables are excluded. The regression equation appears as Equation A.5.22:

$$\begin{aligned}&4000Hz\ Sound\ Intensity(dBA)=76.087+0.08891\times Age(year)-3.08242\times ind(MixTypeOGAC)-3.01463\times ind(MixTypeRAC-G)\\&-3.8021\times ind(MixTypeRAC-O)+0.0223\times Thickness(mm)+0.005744\times NumberOfDays>30C\\&+0.0003854\times AADTTinCoringLane-0.4782\times ind(PresenceofRaveling)-0.07188\times Age\times ind(MixTypeOGAC)\\&+0.4155\times Age\times ind(MixTypeRAC-G)+0.181\times Age\times ind(MixTypeRAC-O)\end{aligned} \quad \textbf{(A.5.22)}$$

where $ind(\cdot)$ is an indicator function, 1 if a variable in parenthesis is true and 0 if it is false. The estimated values and P-values of the parameters are shown below:

	Value	Std. Error	t value	P-value
(Intercept)	76.0870	0.6691	113.7080	<0.0001
Age	0.08891	0.0703	1.2645	0.2076
MixTypeOGAC	-3.08242	0.7369	-4.1829	<0.0001
MixTypeRAC-G	-3.01463	0.6378	-4.7264	<0.0001
MixTypeRAC-O	-3.8021	0.6640	-5.7261	<0.0001
Thickness	0.02230	0.0078	2.8688	0.0046
NoDaysTempGT30	0.005744	0.0024	2.4007	0.0173
AADTTCoringLane	0.0003854	0.0001	4.2352	<0.0001
Raveling	-0.4782	0.3048	-1.5688	0.1184
Age*MixTypeOGAC	0.07188	0.1153	0.6235	0.5337
Age*MixTypeRAC-G	0.4155	0.1087	3.8223	0.0002
Age*MixTypeRAC-O	0.1810	0.1109	1.6310	0.1046

Residual standard error: 1.654 on 188 degrees of freedom; Multiple R-Squared: 0.48.

This regression model is similar to the multiple regression models for 2,000-Hz sound intensity (Equation A.5.17), with the exception that truck traffic volume (AADTTCoringLane) and surface layer thickness (Thickness) are significant variables in this model, and pavement age (Age) is only significant for RAC-G pavements. The 4,000-Hz sound intensity increases with pavement age only for RAC-G pavements. Among the three pavement types, OGAC, RAC-G, and RAC-O, all have lower initial 4,000-Hz sound intensity than DGAC. The average noise reductions (compared to DGAC pavements) for newly paved OGAC, RAC-G, and RAC-O mixes are about 3.1, 3.0, and 3.8 dB(A), respectively. The 4,000-Hz sound intensity also increases with truck traffic volume (AADTTCoringLane) and surface layer thickness (Thickness).

In the second model, the mix type variables are replaced with mix property variables and the model is estimated for each mix type separately. The regression equations appear as Equation A.5.23 through Equation A.5.26:

For DGAC pavements

$$4000Hz\ Sound\ \ Intensity(dBA) = 81.1844 - 0.3791\times AirVoid(\%) + 0.1173\times Age(year) - 0.262\times FinenessModulus + 0.0005502\times MPD - 0.02786\times Thickness(mm) + 0.004968\times NumberOfDays > 30C + 0.000428\times AADTTinCoringLane \quad \textbf{(A.5.23)}$$

	Value	Std. Error	t value	P-value
(Intercept)	81.1844	2.5980	31.2489	<0.0001
AirVoid	-0.3791	0.0672	-5.6380	<0.0001
Age	0.1173	0.0500	2.3451	0.0256
FinenessModulus	-0.2620	0.6410	-0.4088	0.6855
MPD	0.0005502	0.0009	0.5792	0.5666
Thickness	-0.02786	0.0079	-3.5475	0.0013
NoDaysTempGT30	0.004968	0.0032	1.5327	0.1355
AADTTCoringLane	0.0004280	0.0001	4.1157	0.0003

Residual standard error: 0.832 on 31 degrees of freedom; Multiple R-Squared: 0.72.

For OGAC pavements

$$4000Hz\ Sound\ \ Intensity(dBA) = 83.3492 - 0.1338\times AirVoid(\%) + 0.2186\times Age(year) - 0.818\times FinenessModulus - 0.003119\times MPD(micron) + 0.0476\times Thickness(mm) - 0.00707\times NumberOfDays > 30C + 0.0002137\times AADTTinCoringLane \quad \textbf{(A.5.24)}$$

	Value	Std. Error	t value	P-value
(Intercept)	83.3492	3.7686	22.1170	<0.0001
AirVoid	-0.1338	0.0956	-1.3991	0.1688
Age	0.2186	0.0662	3.3022	0.0019
FinenessModulus	-0.8180	0.9105	-0.8984	0.3738
MPD	-0.003119	0.0010	-3.2738	0.0021
Thickness	0.04760	0.0166	2.8716	0.0063
NoDaysTempGT30	-0.007065	0.0038	-1.8531	0.0706
AADTTCoringLane	0.0002137	0.0002	1.1845	0.2426

Residual standard error: 1.106 on 44 degrees of freedom; Multiple R-Squared: 0.73.

For RAC-G pavements

$$4000Hz\ Sound\ \ Intensity(dBA) = 71.4188 - 0.3287\times AirVoid(\%) + 0.2986\times Age(year) + 1.6033\times FinenessModulus - 0.0000889\times MPD(micron) - 0.02513\times Thickness(mm) - 0.0105\times NumberOfDays > 30C + 0.0009311\times AADTTinCoringLane \quad \textbf{(A.5.25)}$$

	Value	Std. Error	t value	P-value
(Intercept)	71.4188	4.7958	14.8921	<0.0001
AirVoid	-0.3287	0.1025	-3.2080	0.0029
Age	0.2986	0.0672	4.4456	0.0001
FinenessModulus	1.6033	1.0692	1.4996	0.1429
MPD	0.00008890	0.0007	0.1362	0.8925
Thickness	-0.02513	0.0161	-1.5648	0.1269
NoDaysTempGT30	-0.01050	0.0035	-3.0112	0.0049
AADTTCoringLane	0.0009311	0.0002	4.6989	<0.0001

Residual standard error: 1.077 on 34 degrees of freedom; Multiple R-Squared: 0.72.

For RAC-O pavements

$$4000Hz\ Sound\ Intensity(dBA)=96.4906-0.078\times AirVoid(\%)+0.4055\times Age(year)-4.0257\times FinenessModulus$$
$$-0.002913\times MPD(micron)+0.02507\times Thickness(mm)+0.004834\times NumberOfDays>30C+0.0006428\times AADTTinCoringLane \quad \textbf{(A.5.26)}$$

	Value	Std. Error	t value	P-value
(Intercept)	96.4906	5.6653	17.0318	<0.0001
AirVoid	-0.0780	0.0806	-0.9678	0.3378
Age	0.4055	0.0719	5.6365	<0.0001
FinenessModulus	-4.0257	1.2396	-3.2476	0.0021
MPD	-0.002913	0.0009	-3.2777	0.0019
Thickness	0.02507	0.0217	1.1563	0.2530
NoDaysTempGT30	0.004834	0.0039	1.2460	0.2186
AADTTCoringLane	0.0006428	0.0001	6.4469	<0.0001

Residual standard error: 1.209 on 50 degrees of freedom; Multiple R-Squared: 0.70.

The results show that at a 95 percent confidence level, truck traffic volume (AADTTCoringLane) is a significant factor for three of the four pavements, with the exception of OGAC: Higher traffic volume leads to a higher 4,000-Hz noise level. Air-void content (AirVoid) is significant for DGAC and RAC-G pavements, and insignificant for the open-graded (OGAC and RAC-O) pavements. For all mixes, however, the estimated parameters indicate that higher air-void contents result in lower 4,000-Hz noise. Pavement age (Age) is a significant factor for all pavements. The estimated coefficients indicate that the 4,000-Hz sound intensity increases with pavement age.

The aggregate gradation variable (FinenessModulus) does not seem to significantly affect tire/pavement noise on any of the pavement types except RAC-O.

Pavement surface macrotexture (MPD) is significant on both OGAC and RAC-O pavements, and the estimated coefficients indicate that higher MPD values lead to a lower 4,000-Hz noise level.

A.5.3.7: Sound Intensity at Other One-Third Octave Bands

The variation trends of sound intensities at other one-third octave bands are similar to the trends of sound intensities at their adjacent frequency bands, 500, 1,000, 2,000, and 4,000 Hz, which have been analyzed in the previous sections. Therefore, statistical analysis was not performed on these data to avoid repetitive work. For more information on these see Appendix B.4: Box Plots and Cumulative Distribution of Noise Reduction for Sound Intensity at Other Frequency Bands.

A.5.4: Summary of Findings

The following findings were obtained regarding overall sound intensity:

1. Overall tire/pavement noise generally increases with pavement age. The average noise level on DGAC pavements was about 101.3 dB(A) for newly paved overlays, 102.0 dB(A) for pavements between one and three years old, and between 103 and 104 dB(A) for pavements older than three years. Based on statistical analysis, for newly paved overlays, the overall sound intensities measured on OGAC, RAC-G, and RAC-O pavements were lower than the values measured on the DGAC pavements. The average noise reductions (compared to DGAC pavements) for newly paved OGAC, RAC-G, and RAC-O mixes were about 2.7, 1.8, and 2.8 dB(A), respectively. After the pavements were exposed to traffic, the overall sound intensity measured on RAC-G pavements quickly approached the typical values measured on DGAC pavements of similar ages. The overall sound intensity measured on the OGAC pavements did not change much for about five years and then increased quickly with pavement age. With a few exceptions, the overall sound intensity measured on the RAC-O pavements did not change much for about seven years and then increased quickly with pavement age. The ranking (from best to worst) of the four mix types in terms of noise reduction is RAC-O, OGAC, RAC-G, and DGAC.
2. Multiple regression analysis on all mixes shows that overall sound intensity increases with increased raveling and rutting, and decreases with the increased surface layer thickness. Multiple regression analysis on individual mix types shows that the in-situ permeability (or air-void content) is a significant factor on all mixes except RAC-O, and higher permeability leads to a lower noise level. For all four mix types, the aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise. Pavement surface macrotexture (MPD) is a significant factor for DGAC and RAC-G pavements, and a higher MPD value corresponds to a higher noise level. Relative truck traffic volume is a significant factor that increases tire/pavement noise for OGAC mixes.

The following findings were obtained regarding sound intensity at one-third octave bands:

1. At low-frequency levels (500 Hz and 630 Hz), sound intensities measured on OGAC and RAC-O pavements were generally higher than the values measured on DGAC and RAC-G pavements. At a

frequency level of 800 Hz, the sound intensities measured on OGAC, RAC-G, and RAC-O pavements began to become lower than those measured on DGAC pavements. For frequency levels equal to or over 1,000 Hz, the sound intensities measured on OGAC and RAC-O pavements were generally lower than those measured on RAC-G pavements.

2. For newly paved OGAC and RAC-O mixes, the sound intensities at frequencies higher than 1,000 Hz increased with age in the first four years, but the sound intensities at low frequencies (630 to 800 Hz) decreased with age. These two opposite changes make the overall sound intensity nearly unchanged. For newly paved DGAC and RAC-G mixes, the low frequency noise changed slightly with age in the first four years, while the sound intensities at frequencies over 1,000 Hz increased significantly with age.
3. For pavements with an initial age between 1 and 4 years, sound intensity increased slightly on both open-graded pavements (OGAC and RAC-O), and increased more significantly on DGAC and RAC-G pavements.
4. For the oldest pavements (initial age greater than four years), the increase of overall sound intensity with age was comparable on OGAC, RAC-G, and DGAC pavements, while the increase was insignificant on RAC-O pavements. The increase of sound intensity with age mainly occurred at frequencies between 1,000 Hz and 2,000 Hz on RAC-G pavements; while for OGAC pavements, the increase of sound intensity with age mainly occurred at frequencies below 1,000 Hz.

The following findings were obtained regarding 500 Hz-band sound intensity:

1. For newly paved overlays (age less than or equal to one year), OGAC and RAC-O pavements have a statistically higher 500-Hz noise level than DGAC pavements, while RAC-G pavements have statistically the same level of 500-Hz sound intensity as DGAC pavements. This indicates that for newly-placed mixes, open-graded pavements have rougher surfaces that contribute to more tire vibration than dense- and gap-graded pavements. For pavements with ages between four and seven years, there is no significant difference in 500-Hz sound intensity among the four mixes. For old pavements (older than seven years), OGAC pavements have higher 500-Hz sound intensity than the other three pavement types, which indicates that OGAC pavements experienced more surface distresses that affected the surface smoothness than the other pavement types. Overall, the increase rate of 500-Hz sound intensity with age was lower on rubberized pavements (RAC-G and RAC-O) than on non-rubberized pavements (DGAC and OGAC).
2. Multiple regression analysis on all mixes shows that mix type, number of high temperature days, truck traffic in the coring lane, and the existence of rutting significantly affect the 500 Hz-band sound intensity. The 500 Hz-band noise increases with pavement age, truck traffic volume, and the existence of rutting distress, but decreases with number of high temperature days.

3. Multiple regression analysis on individual mix type shows that truck traffic volume is a significant factor that contributes to the increase of 500 Hz-band noise for open-graded mixes, but not for dense- or gap-graded mixes. The traffic effect is more significant on the OGAC pavements than on the RAC-O pavements. For all pavements, the aggregate gradation variable (fineness modulus) does not seem to significantly affect the low-frequency noise.

The following findings were obtained regarding 1,000 Hz-band sound intensities:

1. For newly paved sections, the 1,000-Hz sound intensity measured on open-graded pavements (OGAC and RAC-O) and gap-graded pavements (RAC-G) was lower than the values measured on dense-graded pavements (DGAC). After the pavements were exposed to traffic, OGAC and RAC-O pavements had similar noise-reducing properties for about three years, then OGAC pavements began to reduce less noise than RAC-O pavements; RAC-G pavements began to lose their noise-reducing properties for all age groups.
2. Multiple regression analysis on individual mix type shows that air-void content is an insignificant factor for all pavements. For 1,000-Hz sound intensity, the surface layer thickness is significant for OGAC and RAC-O pavements and insignificant for DGAC and RAC-G pavements. The estimated parameters indicate that a thicker open-graded surface layer corresponds to a lower noise level at 1,000 Hz. Pavement surface roughness (MPD) is a significant factor for all pavements, and a higher MPD value corresponds to a higher noise level on DGAC, OGAC, and RAC-G pavements, but a lower noise level on RAC-O pavements. The aggregate gradation variable (fineness modulus) does not seem to significantly affect the tire/pavement noise for any of the mixes.

The following findings were obtained regarding 2,000 to 4,000 Hz-band sound intensity:

1. For newly paved sections, the 2,000-Hz sound intensities measured on open-graded pavements (OGAC and RAC-O) and gap-graded pavements (RAC-G) were significantly lower than the values measured on dense-graded pavements (DGAC). The 2,000-Hz sound intensity increased at all pavement ages on DGAC and RAC-G pavements, but only mainly in early ages on OGAC and RAC-O pavements.
2. For 2,000-Hz sound intensity, multiple regression analysis on individual mix type shows that air-void content is a significant factor for DGAC, OGAC, and RAC-G pavements and insignificant for RAC-O pavements. For 2,000-Hz sound intensity, MPD is significant for DGAC and RAC-G pavements, and higher MPD increases the 2,000-Hz noise on DGAC and RAC-G pavements. The aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise on any pavement type except RAC-O. For RAC-O pavements, a larger fineness modulus (coarser gradation) results in significantly lower tire/pavement noise in the 2,000-Hz band.

3. The 4,000-Hz sound intensity did not change significantly with pavement age on DGAC and RAC-O pavements. For OGAC pavements, the 4,000-Hz sound intensity increased with age for newly paved overlays, but tended to stabilize or even decrease slightly with age for pavements older than four years. On RAC-G pavements, the 4,000-Hz sound intensity increased with pavement age for both newly paved and older pavements.
4. OGAC, RAC-G, and RAC-O pavements were all initially quieter than DGAC pavements in terms of 4,000 Hz-band noise. For newly paved overlays, OGAC, RAC-G, and RAC-O exhibited similar noise-reducing properties. For pavements between three and seven years old, OGAC and RAC-O pavements still had similar noise-reducing properties, while RAC-G began to perform worse than open-graded mixes. The relative performance of the three mixes remained unchanged for pavements older than seven years.
5. Multiple regression analysis results show that truck traffic volume is a significant factor for all pavements except OGAC. Air-void content is significant for DGAC and RAC-G pavements and insignificant for the open-graded (OGAC and RAC-O) pavements. For all mixes, higher traffic volume and lower air-void content lead to a higher 4,000-Hz noise level. The aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise on all pavement types except RAC-O pavements. Pavement surface macrotexture (MPD) is significant on both OGAC and RAC-O pavements, and higher MPD values lead to a lower 4,000-Hz noise level.

A.6 Environmental Sections Analysis

All the environmental test sections (ES sections) were tested during the four-year survey. This section presents an analysis of the performance trends of the different mixes at each site.

A.6.1 Fresno 33 Sections

The Fresno 33 site includes nine test sections with five different surfacing mixes—RAC-G, Type G-MB, Type D-MB, RUMAC-GG, and DGAC—in the northbound direction of State Route 33 near the town of Firebaugh in District 6. Except for the DGAC control surface, all the sections were placed with both 45-mm and 90-mm thicknesses to evaluate the effects of thickness on pavement performance. All sections have a nominal maximum aggregate size (NMAS) of 19 mm. The test sections were one year old during the first-year measurements. All the gap-graded mixes have the same aggregate gradations; the DGAC mix has a slightly finer dense gradation than the Type D-MB mix. The MB mixes generally have lower stiffnesses than the other mix types at 20°C, and the DGAC mix has the highest stiffness.

Roughness, noise, and surface condition for the different mixes over four years were analyzed and compared for different thicknesses and different mixes. The results answer these questions:

- How does the performance of dry- (RUMAC-GG) and terminal-process rubber (MB) compare to wet-process asphalt rubber (RAC-G) and dense-graded asphalt concrete (DGAC) under the same traffic and climate with respect to noise, roughness, and distress?
- How does increased thickness affect the cracking performance of rubberized mixes?

Figure A.36 shows the four-year MPD values for the Fresno 33 sections. The figure shows that the RAC-G mixes have higher MPD values than the RUMAC-GG and Type G-MB mixes, and that the MPD values of Type D-MB and DGAC mixes are close to each other. Except for one outlier, all sections show an increase in macrotexture values with age. This increase is probably due to an increase in distresses, mostly raveling, under traffic.

Figure A.37 shows the four-year IRI values for the Fresno 33 sections. The figure shows that the RAC-G and RUMAC-GG mixes have higher IRI values than other mixes. The 45-mm Type G-MB section showed the lowest IRI values in the four survey years. IRI generally increased slightly with age in the four survey years for all sections except the 45-mm RAC-G mix, which showed a marked increase from the second to the third year.

Figure A.38 shows the four-year overall sound intensity levels for the Fresno 33 sections. The figure shows that the noise level increased significantly from the second survey year to the third survey year on the RAC-G, RUMAC-G, and Type D-MB sections, and only changed slightly on the Type G-MB and DGAC sections. The DGAC section has the lowest noise level in the third and fourth survey years. The four-year noise spectra, as shown in Appendix B.5, reveals that the noise increases occurred across all frequencies, particularly for RAC-G and Type D-MB mixes. This indicates that the increase of overall noise is caused by both an increase in the surface roughness that causes more tire vibration (at low frequencies) and a decrease in the air-void content that causes more air-pumping (at high frequencies). For the DGAC mix, the low-frequency noise increase seems to be less significant than for the other mixes, likely due to less surface distress on the DGAC pavement.

Based on the sound intensity analysis, Type G-MB performed better than the RAC-G and Type D-MB mixes in the third and fourth survey years (i.e., fourth and fifth years after opening to traffic), but none of the new mixes had lower tire/pavement noise compared to the DGAC mix.

The four-year condition survey data, as shown in Appendix B.7, shows that after serving for two years, all the mixes except the DGAC mix showed bleeding. The bleeding did not become worse in the third survey year. In the fourth survey year, bleeding still existed on Type G-MB and Type D-MB sections, but was not observed on other sections. Instead, polished aggregates were observed on RUMAC-GG sections in the fourth survey year.

All the mixes except Type G-MB and DGAC show raveling in the second survey year. Raveling appeared on the DGAC section in the third survey year. In the fourth survey year, raveling was not obvious on any section.

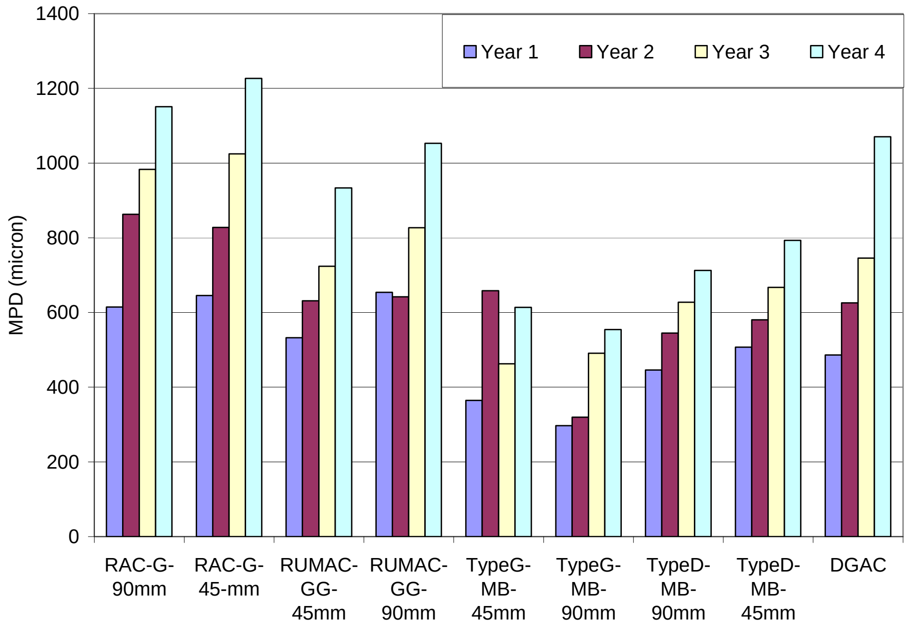


Figure A.36: Four-year MPD values for Fresno 33 sections.

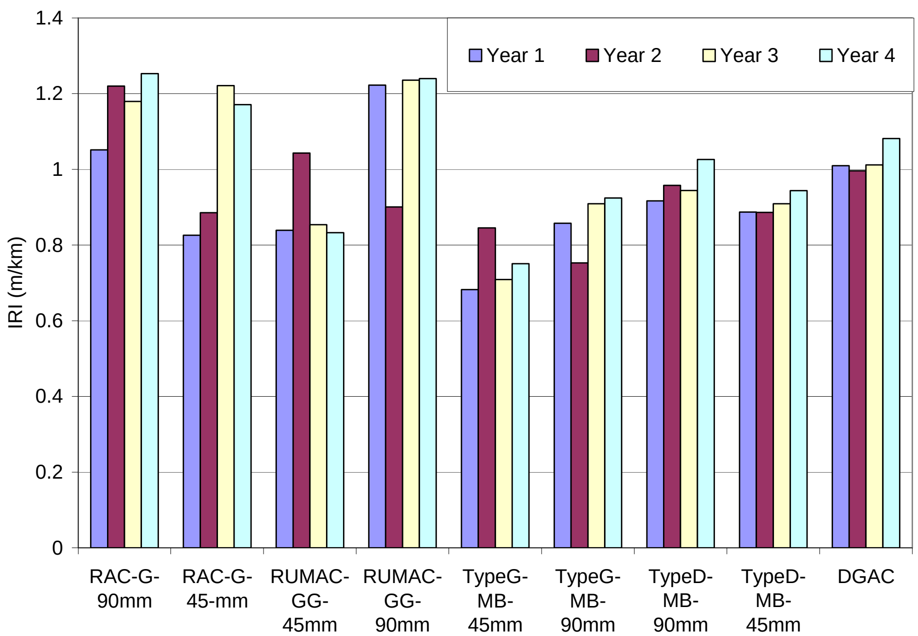


Figure A.37: Four-year IRI values for Fresno 33 sections.
(Note: 1 m/km = 63 in./mi)

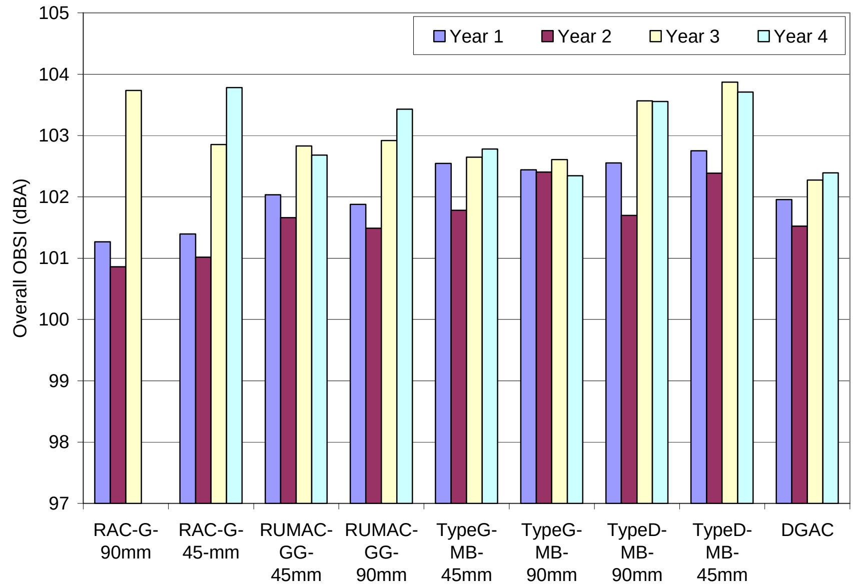


Figure A.38: Four-year overall OBSI values for Fresno 33 sections.

Among all the mixes, the 90-mm RUMAC-GG and 90-mm Type D-MB mixes performed the best in the second survey year as they showed only bleeding. Fatigue cracking began to show up in the second survey year on the 45-mm and 90-mm RAC-G, 45-mm and 90-mm Type G-MB, 45-mm Type D-MB, and 90-mm DGAC sections, and progressed in the third and fourth survey years on the RAC-G and DGAC sections, but not on the Type G-MB and Type D-MB sections. In the third survey year, transverse cracking and short fatigue cracking began to appear on the 90-mm RUMAC-GG section, while the 90-mm Type D-MB still only showed bleeding. In the fourth survey year, edge and longitudinal cracking occurred and transverse cracking progressed on the 90-mm RUMAC-GG section. The 90-mm Type D-MB showed bleeding and a small area of patching. Slight longitudinal and transverse cracking began to develop on the 45-mm Type D-MB section.

Increasing thickness did not reduce fatigue cracking or transverse cracking on the RAC-G mix in the fourth survey year. Increasing thickness may help reduce the cracking for RUMAC-GG, Type D-MB, and Type G-MB.

A.6.2 Sacramento 5 and San Mateo 280 Sections

The Sacramento 5 and San Mateo 280 sites consist of thin RAC-O overlays placed on jointed PCC. The Sacramento 5 sections (same overlay in two directions of travel) have thicknesses around 30 mm, and the San Mateo 280 section has a thickness of 40 mm. The Sacramento 5 site was evaluated for both the northbound (NB) and southbound (SB) directions, while San Mateo 280 was evaluated only for the northbound direction. The Sacramento 5 sections were one year old and the San Mateo section was three years old during the first-year measurements. Both sites have an NMAS of 12.5 mm.

Roughness, noise, and surface condition for different mixes over four years were analyzed and compared for the northbound and southbound directions for the Sacramento 5 sections. The results answer the following questions:

- How does the performance of the Sacramento 5 and San Mateo 280 sections, which are overlays of PCC, compare to the performance of RAC-O mixes that are placed over asphalt pavement?
- Are there any differences between the performance in the northbound and southbound directions of the Sacramento 5 sections?

It was known from the data collected in the first two years that the permeability/air-void content in the northbound direction of the Sacramento 5 sections is greater than that in the southbound direction. The San Mateo 280 section has lower air-void content but much higher permeability values than the Sacramento 5 sections *(1)*.

Figure A.39 shows the four-year IRI values for the Sacramento 5 and San Mateo 280 sites. Both sites have "acceptable" ride quality based on overall FHWA criteria (IRI values less than 2.68 m/km [170 in./mi]), and are considered "fair" for Interstate highways by FHWA (less than 1.88 m/km [119 in./mi]) *(2)*. Analysis of the data collected in the first two years showed that both the Sacramento 5 and San Mateo 280 sites have higher IRI values than the majority of the Quieter Pavement (QP) sections, probably due to the cracked PCC underneath, which have a high IRI value *(1)*. Figure A.39 shows that IRI generally increased with pavement age on all three sections, and the increase rate was more significant on the two Sacramento 5 sections than on the San Mateo 280 section.

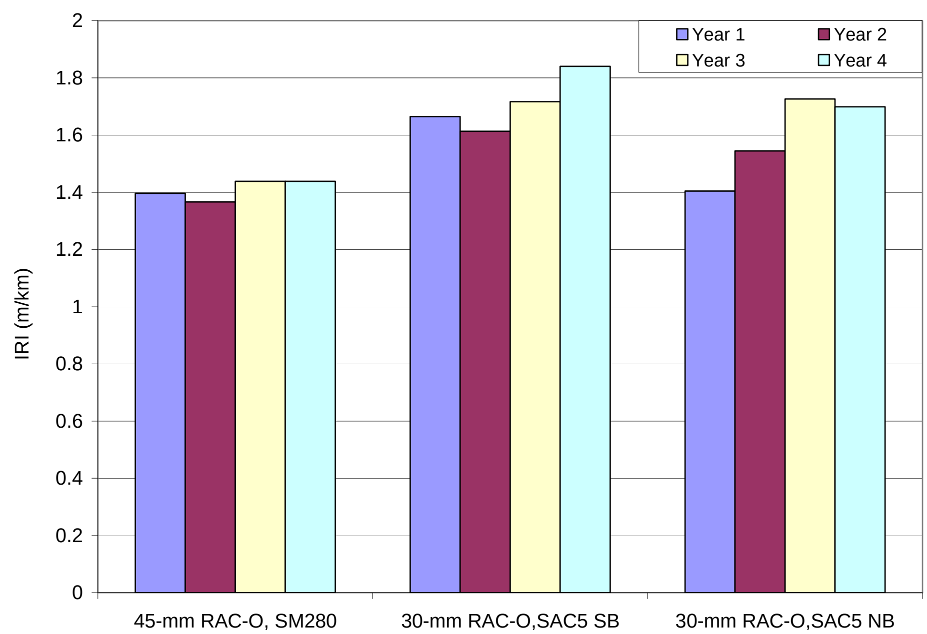


Figure A.39: Four-year IRI values for Sacramento 5 and San Mateo 280 sections. (Note: 1 m/km = 63 in./mi.)

Figure A.40 shows the four-year MPD values for the Sacramento 5 and San Mateo 280 sites. The figures show that the MPD values in the northbound direction are much higher than in the southbound direction in the second and third years for the Sacramento 5 sections, which is probably due to higher air-void content and more distresses. In the fourth survey year, however, the MPD values are similar in both directions. The San Mateo 280 section has higher MPD than both Sacramento 5 directions, which is consistent with the fact that the San Mateo 280 section has higher permeability values than the Sacramento 5 sections.

Figure A.41 shows the four-year overall sound intensity levels for the Sacramento 5 and San Mateo 280 sections. According to the figure, the northbound section of the Sacramento 5 site has higher noise levels than the southbound section in the first three survey years, which is likely due to the higher MPD values and more reflective cracking (which will be discussed below) in the northbound section. In the fourth survey year, the northbound section of the Sacramento 5 site showed a significant reduction in the overall sound intensity. The sound intensity spectra revealed that in the fourth survey year, the noise levels in low frequency bands (500, 630, and 800 Hz) were significantly lower on the Sacramento 5 northbound section than on the southbound section. The reason is unknown, and further investigation is needed. There is a continuous reduction in the noise levels of the San Mateo 280 section. The reason is unknown.

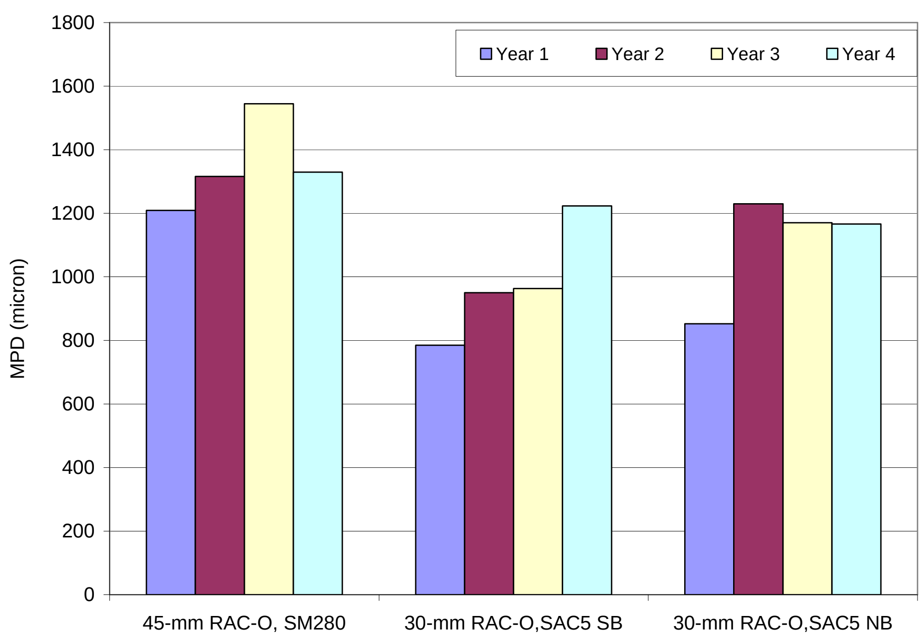


Figure A.40 Four-year MPD values for Sacramento 5 and San Mateo 280 sections.

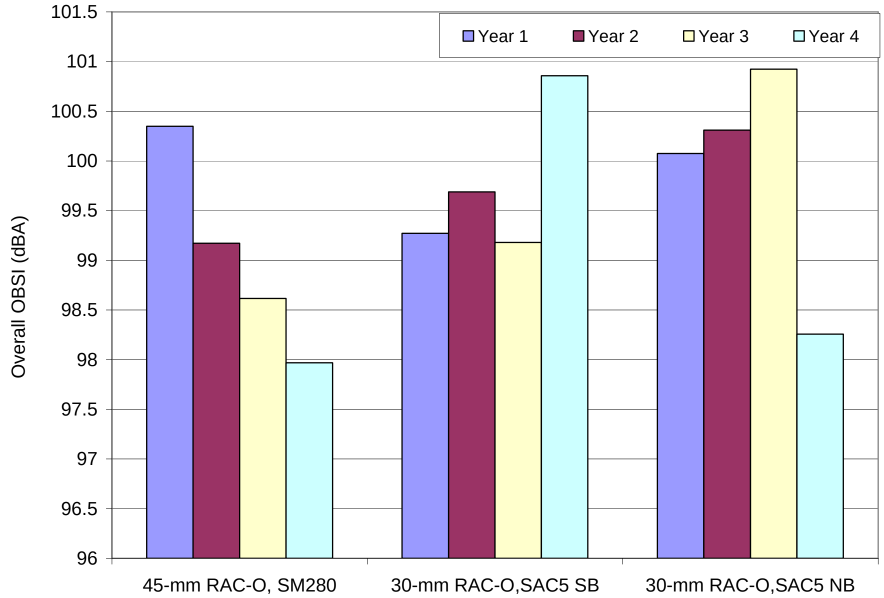


Figure A.41: Four-year overall OBSI values for Sacramento 5 and San Mateo 280 sections.

According to the condition survey (Appendix B.7), both directions of the Sacramento 5 site showed reflective cracking in the first year. The amount of cracking increased with pavement age, and there was more cracking in terms of the severity of cracks in the northbound direction than in the southbound direction. For the San Mateo 280 site, no distresses were recorded for the first year and the section showed minor raveling, and transverse and longitudinal cracking in the next three years. There was no reflective cracking on this section in the fourth survey year.

In summary, the performance of RAC-O mixes used on the Sacramento 5 and San Mateo 280 sections does not differ from that of RAC-O mixes primarily placed on asphalt pavements. The San Mateo 280 section performed better than the Sacramento 5 sections in terms of both noise and pavement distresses. The thicker overlay (45 mm instead of 30 mm) on the San Mateo 280 section may contribute to its better performance.

A.6.3 LA 138 Sections

The LA 138 site includes four mix types—OGAC, RAC-O, Bituminous Wearing Course (BWC), and DGAC—which were placed in both the eastbound and westbound lanes. Measurements were taken on the nine test sections: on the eastbound (EB) and westbound (WB) OGAC, RAC-O, and BWC sections, and on the westbound DGAC mix. All the mixes have an NMAS of 12.5 mm. The test sections were three years old during the first-year measurements. OGAC was placed in 75- and 30-mm thicknesses in different sections to determine the effect of thickness on noise and distress development. All other sections were placed at a thickness of 30 mm.

Roughness, noise, and surface condition for the different mixes were collected over four years and analyzed to compare the effects of different thicknesses and different mixes. The analysis helps answer these questions:

- Does thickness affect noise levels and distress development?
- How does the performance of open-graded and BWC mixes compare to the performance of the DGAC mix on the control section?

It was known from the first two years of data that most of the LA 138 open-graded mixes have much lower than typical air-void contents. The permeability of these OGAC and RAC-O mixes is also lower than the average permeability of other OGAC and RAC-O mixes in the same age category. The eastbound sections have higher air-void content and permeability values than the westbound sections, which may be due to compaction differences during construction as well as to the difference in truck traffic volumes in the two directions *(1)*.

Figure A.42 shows the four-year IRI values for the LA 138 sections. It can be seen that RAC-O mixes have the lowest IRI values. In the first year of measurements, all sections provided "good" ride according to the FHWA criteria for non-Interstate highways of less than 1.50 m/km (95 in./mi) *(1)*. IRI changed slightly with age on all sections except for the 75-mm OGAC westbound section. In the third and fourth survey years, IRI values generally increased slightly or were similar to the values in the previous years.

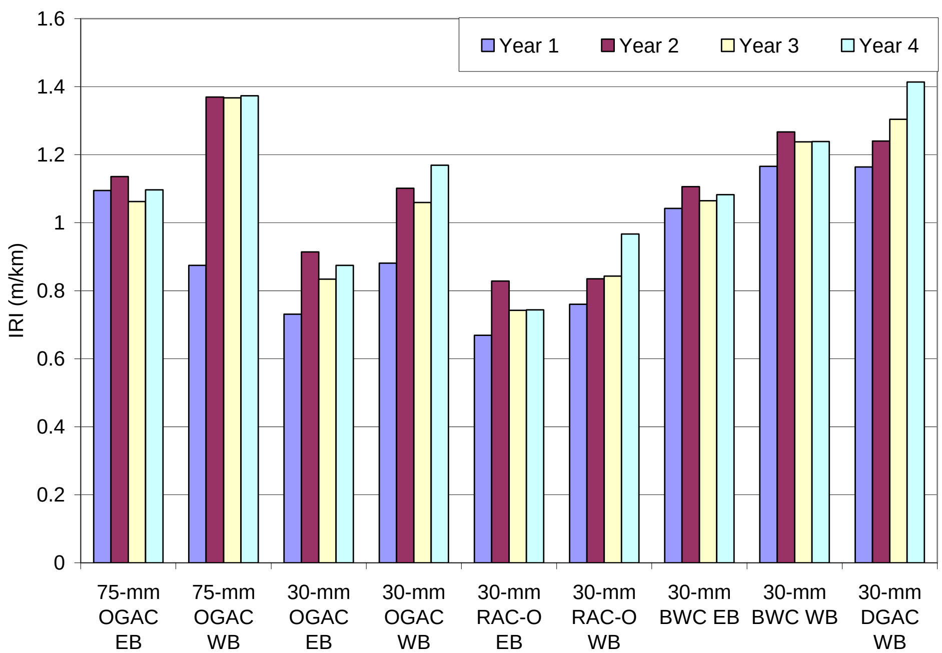


Figure A.42: Four-year IRI values for the LA 138 sections.

The third-year MPD was not measured on the LA 138 sections. Based on the previous two years of measurement, it was found that open-graded mixes have higher MPD values than the BWC and dense-graded mixes. RAC-O mixes have the smallest MPD values among open-graded mixes. MPD increased in the second year for all sections. As shown in Figure A.43, in the fourth survey year, MPD increased significantly on all sections, and RAC-O mixes exhibited MPD values similar to other open-graded mixes.

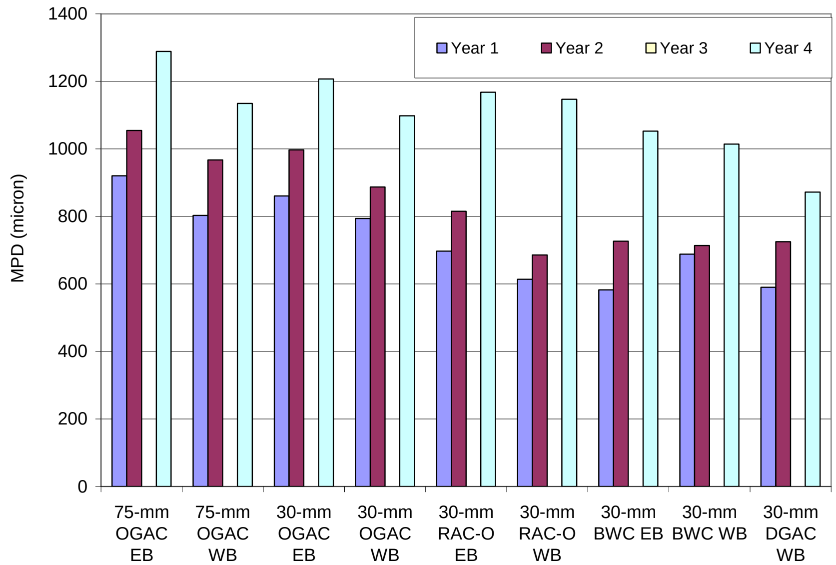


Figure A.43: Four-year MPD values for the LA 138 sections.

Figure A.44 shows the four-year overall sound intensity levels for the LA 138 sections. There are errors in the third-year measurements on the DGAC and westbound BWC sections, so the data for these two sections are not included. The figure shows that the westbound open-graded mixes have higher noise levels than the eastbound mixes. The lower noise levels of the eastbound sections can be explained by the higher air-void content of these mixes compared to those of the westbound sections *(1).*

DGAC and BWC mixes have the highest noise levels and OGAC mixes have the lowest. The difference in noise between the 75-mm OGAC and the 30-mm OGAC is less than 1 dB(A) for both directions. The overall noise levels increased about 1 dB(A) from the first survey year to the second on most OGAC and RAC-O sections. The noise increase was less significant in the following two survey years.

Because the first-year condition survey was conducted only on the eastbound sections for open-graded and BWC mixes, the comparison of distress development trends was made only on the eastbound sections. The four-year distress data for each eastbound section are given in Appendix B.7.

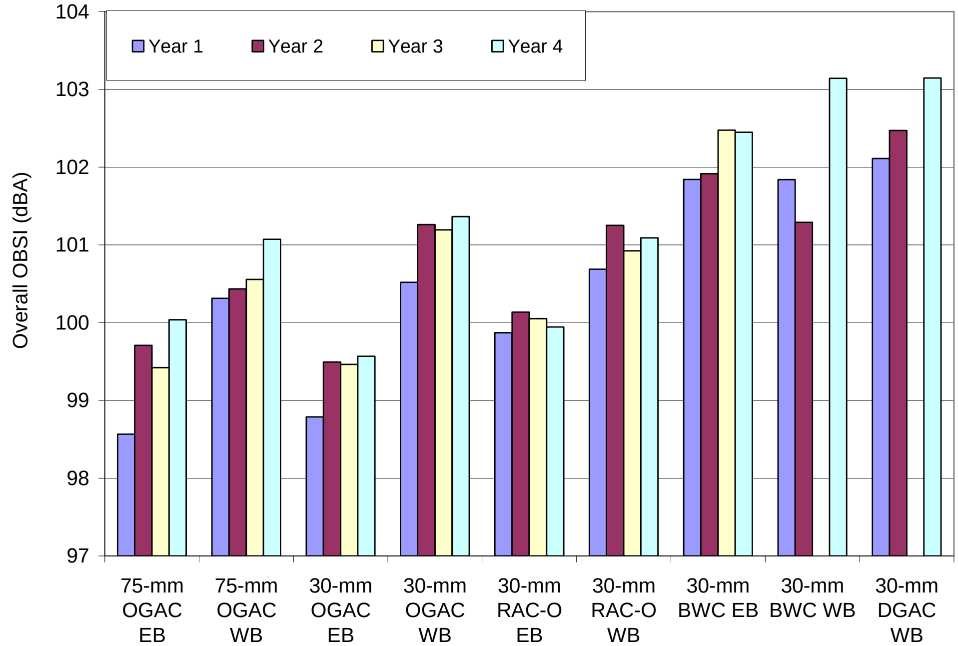


Figure A.44: Four-year overall OBSI values for LA 138 sections.

Transverse cracking appeared to be the major distress on all the eastbound sections. Small areas of fatigue cracking occurred on the westbound DGAC section in the second survey year and on the OGAC sections and BWC section in the fourth survey year. The number and length of transverse cracks increased from the first survey year to the second survey year on all sections. Transverse cracking developed between the second survey year and the fourth survey year on all the OGAC sections, but not on the RAC-O section. The BWC section began to show segregation/raveling in the third survey year.

In summary, increased thickness was not found to increase durability or to provide any noise reduction as measured by the OBSI method. Open-graded mixes have the lowest noise levels among all mix types in the four survey years. BWC mixes have noise performance closer to that of the DGAC mixes than to open-graded mixes, although there was some critique from industry sources that this BWC was not representative of most BWC layers. Rubberized mixes may have slower distress propagation.

A.6.4 LA 19 Sections

The LA 19 section has a European gap-graded (EU-GG) mix as a surface layer. It was less than a year old when the first-year measurements were conducted.

It was known from the first two years of data that EU-GG retains its permeability longer than Caltrans RAC-G mixes *(1)*. Figure A.45 shows the four-year IRI values for the LA 19 section. It can be seen that the IRI on the EU-GG mix is in the same range as on the RAC-G mixes; that it is somewhat less than the mean and median values across RAC-G mixes less than one year old when data collection began (as shown in Figure A.3); and that it has not changed significantly with pavement age over the four survey years, and even decreased in the fourth survey year.

Figure A.46 shows the four-year MPD values for the LA 19 section. The MPD on the EU-GG mix is in the same range of most older RAC-G mixes (as shown in Figure A.5), and it increased slightly from the second to the fourth survey year. Figure A.47 shows the overall OBSI measured in four years on the LA 19 section. *(Note*: The third year data is missing.) It can be seen from the plot that the EU-GG mix has initial noise levels close to those of the RAC-G mixes, and the noise did not increase in the four survey years. The condition survey revealed no distresses in the first year, bleeding in the second survey year (of an area of 150 m^2), minor raveling and transverse cracking in the third survey year, and one more transverse crack in the fourth survey year.

In summary, the EU-GG mix performs similarly to the RAC-G mixes used in California in terms of noise, roughness, and durability, although it may retain its permeability longer.

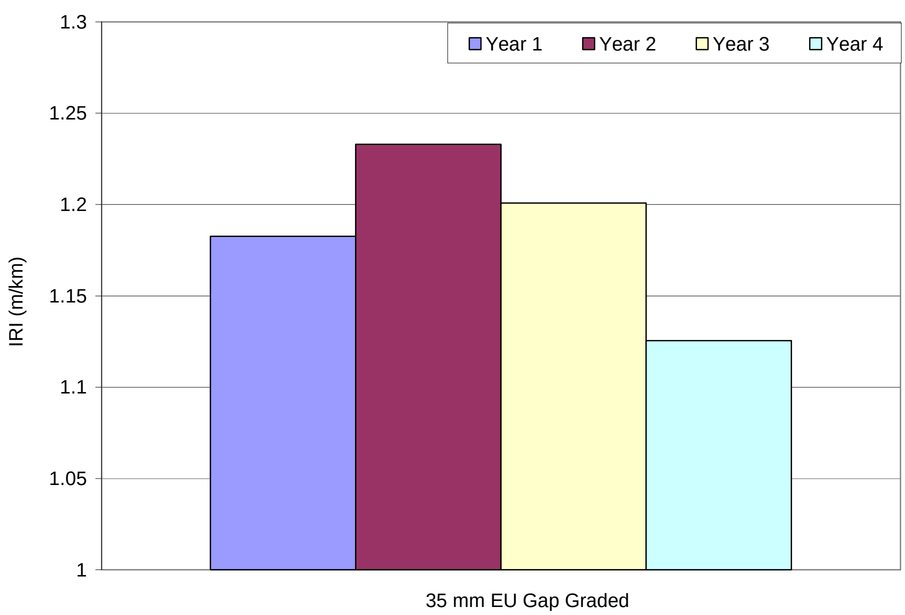


Figure A.45: Four-year IRI values for the LA 19 section.

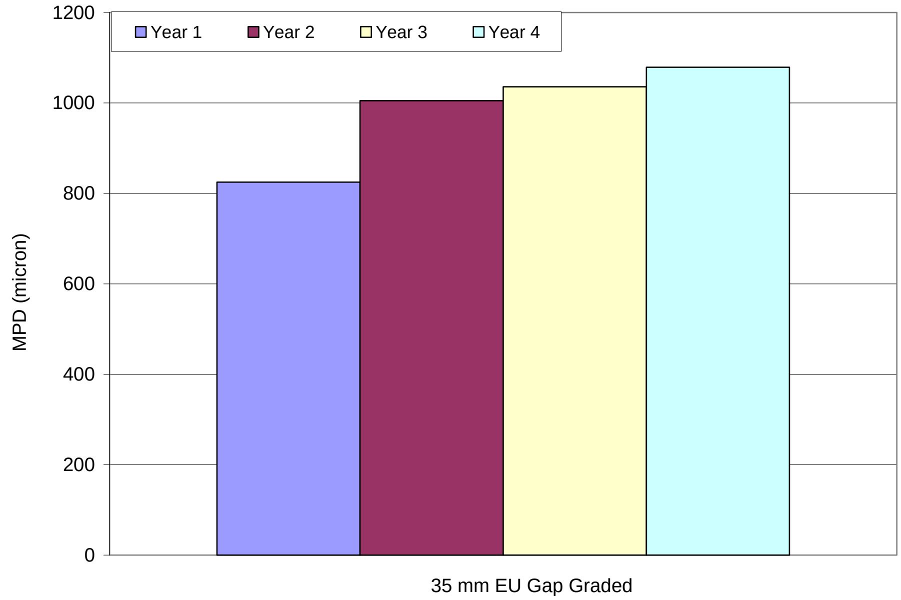


Figure A.46: Four-year MPD values for the LA 19 section.

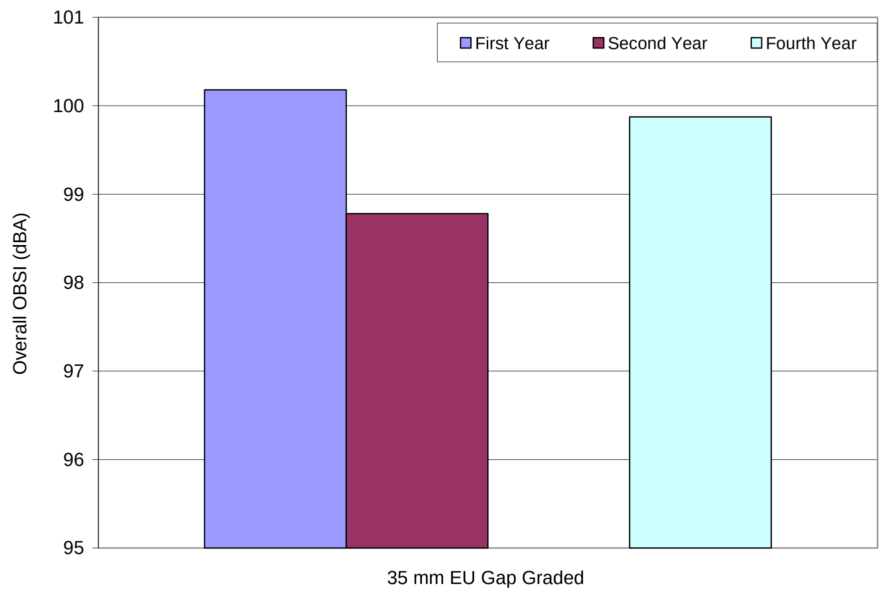


Figure A.47: Four-year overall OBSI values for the LA 19 section.

<u>A.6.5 Yolo 80 Section</u>

The Yolo 80 section has a 20-mm OGAC surface layer. It was seven years old in the first year of measurements.

It was known from the first two years of data collection that this section has higher air-void content but lower permeability than the average OGAC mix *(1)*.

Figure A.48 shows the four-year IRI values for the Yolo 80 section. The figure shows that the IRI values increased slightly in the third and fourth survey years, but that overall the section has good ride quality over the four survey years. Figure A.49 shows the four-year MPD values for the Yolo 80 section. The figure shows MPD values of 1,000, 1,350, 1,375, and 1,413 microns in the four survey years. The increase in MPD in the second year is probably due to an increase of raveling on the pavement surface, which will be discussed later.

Figure A.50 shows the four-year overall noise levels for the Yolo 80 section. It can be seen that this section has an overall sound intensity of around 102 dB(A) for the first two survey years and of approximately 104 and 105 dB(A) in the third and fourth survey years, which are higher than other open-graded mixes tested. The noise spectra of this section shows that the increase of noise mainly occurred at frequencies lower than 1,500 Hz. This indicates that the increase of noise was probably caused by increased roughness (see Figure A.48) and reduction of permeability, which is reduced from a value of 0.036 cm/s in the first survey year to a value of 0.009 cm/s in the fourth survey year.

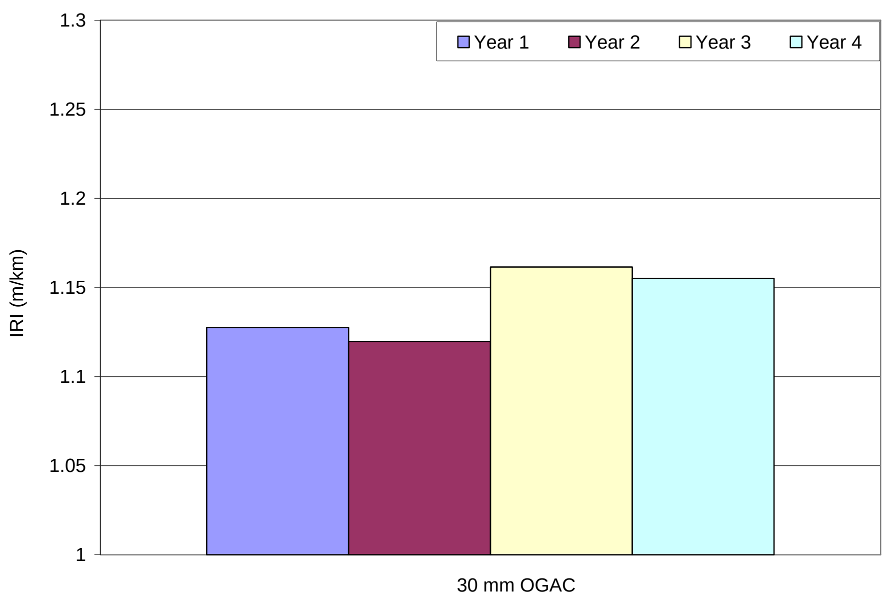


Figure A.48: Four-year IRI values for the Yolo 80 section.

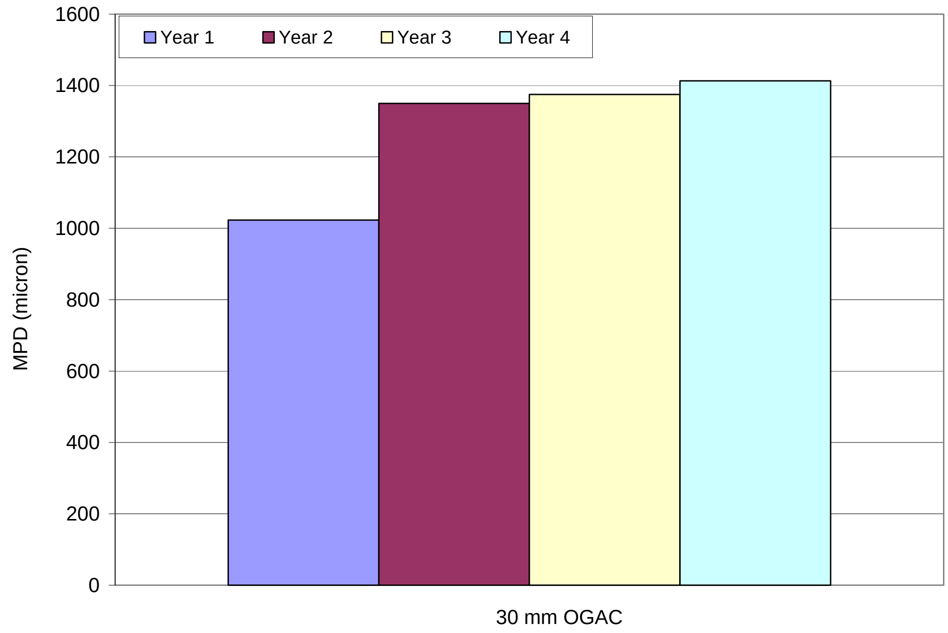


Figure A.49: Four-year MPD values for the Yolo 80 section.

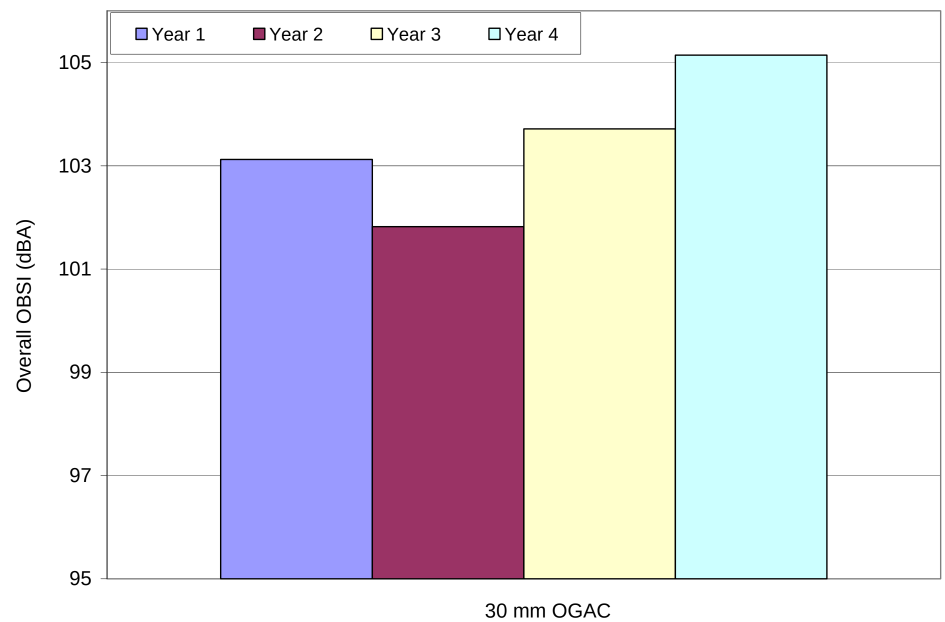


Figure A.50: Four-year overall OBSI values for the Yolo 80 section.

The condition survey revealed 60 m^2 raveling in the first survey year, 300 m^2 raveling and 300 m^2 bleeding in the second and third survey years, minor fatigue cracking in the third survey year, and one minor transverse crack in the fourth survey year.

In summary, the Yolo 80 section still provides acceptable ride quality after ten years in service, but it has a noise level close to that of DGAC pavements.

A.6.6 Summary

The following observations were obtained from the environmental noise monitoring site (ES) sections:

- Based on the Fresno 33 sections, RAC-G and RUMAC-GG mixes generally exhibit higher MPD and IRI values than Type G-MB, Type D-MB, and DGAC mixes. Increase of MPD and IRI with pavement age is much less significant on Type G-MB and Type D-MB mixes than on RAC-G, RUMAC-GG, and DGAC mixes. Tire/pavement noise increased significantly in the third survey year on the RAC-G, RUMAC-G, and Type D-MB sections and kept relatively stable in the fourth survey year on all sections. Type G-MB was quieter than the RAC-G and Type D-MB mixes in the third survey year, but none of these mixes provided any noise reduction compared to the DGAC mix.
- All the Fresno 33 test mixes were prone to bleeding in the first four years after construction, and bleeding remained longer on Type G-MB and Type D-MB sections.
- Increasing thickness does not reduce fatigue cracking or transverse cracking on the RAC-G mix. Increasing thickness may help reduce cracking of RUMAC-GG, Type G-MB, and Type D-MB.
- The performance of RAC-O mixes placed on PCC pavements (on the Sacramento 5 and San Mateo 280 sections) did not differ from that of RAC-O mixes primarily placed on asphalt pavements. The San Mateo 280 section performed better than the Sacramento 5 sections in terms of both noise and pavement distresses, possibly due to its thicker layer.
- From the LA 138 test sections, it was found that increasing the thickness of OGAC overlays does not increase durability or provide additional noise reduction as measured by the OBSI method. Open-graded mixes have the lowest noise levels among all the mix types over the four survey years. BWC mixes perform more similarly to DGAC mixes than to open-graded mixes (although there was some critique from industry sources that this BWC was not representative of most BWC layers). Rubberized mixes may have slower distress propagation than non-rubberized mixes.
- The EU-GG mix performed similarly to the RAC-G mixes used in California in terms of noise, roughness, and durability, although it may retain its permeability longer than RAC-G mixes.
- After ten years of service, the Yolo 80 section still provides acceptable ride quality, but it has a noise level close to that of DGAC pavements.

A.7 References

1. Ongel, A., J. Harvey, E. Kohler, Q. Lu, and B. Steven (2008). *Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphaltic Pavement Surface Types: First- and Second-Year Results*. UCPRC-RR-2007-03, University of California Pavement Research Center, California.
2. FHWA (1999). "Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance Report." U.S. Department of Transportation.
3. Lu, Q., E. Kohler, J. Harvey, and A. Ongel (2009). *Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Three-Year Results*. UCPRC-RR-2009-01, University of California Pavement Research Center, California.
4. California Department of Transportation (Caltrans) (2002). "Guide to the Investigation and Remediation of Distress in Flexible Pavements: Office Manual." Caltrans Flexible Pavement Materials Program, Caltrans, Sacramento, California.
5. Bendtsen, H., E. Kohler, and Q. Lu (2009). *Temperature Influence on Road Traffic Noise: A Californian OBSI Measurement Study*. Danish Road Directorate/Road Institute, DRI report.

Appendix B: Test Section Lists, Calibration of Noise Results for Conditions and Equipment, Data Plots, Spectra and Condition Survey Data, and Details of Regression Predictions

Appendix B.1: List of Test Sections Included in the Study

B.1.1 List of Quiet Pavement (QP) Factorial Experiment Sections

Mix Type	Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	2006 AADT on the Coring Lane	Survey Year of Dropout for OBSI Test*	Coring in the Fourth Year
Open-graded Asphalt Concrete (OGAC) (conventional and polymer-modified)	Less than 1 year old	High	High	03-PLA-80-1.4/2.6	QP-44	<1	19,250	0	Yes
			Low	NA		–	–		
		Low	High	03-Yol-80-0.0/0.4	QP-45	<1	20,833	0	
			Low	05-SCR-152-7.6/8.0	QP-20	<1	3,050	0	Yes
	1 to 4 years old	High	High	04-Mrn-101-0.0/2.5	QP-28	4	13,625	0	Yes
			Low	04-Son-121-3.4/7.3	QP-4	4	8,230	0	
		Low	High	04-SCl-237-R3.8/7.10	QP-23	5	15,639	0	
			Low	08-SBd-38-S0.0/R5.0	QP-13	5	4,733	0	
	5 to 8 years old	High	High	04-Mrn-37-12.1/14.4	QP-3	5	8,482	0	Yes
			Low	01-MEN-1-0.1/15.2	01-N103 01-N104 01-N105	5	1,450	1 4 4	Yes
		Low	High	04-SCl-237-R1.0/2.3	QP-22	8	15,148	0	Yes
			Low	03-Sac-16-6.9/20.7	QP-29	8	6,367	0	Yes

***** Note: This column indicates the survey year when the section was excluded from OBSI testing because it was resurfaced or for another reason. The “0” entry means that the section was tested for OBSI in all four survey years.

Mix Type	Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	2006 AADT on the Coring Lane	Survey Year of Dropout for OBSI Test*	Coring in the Fourth Year
Rubberized Open-graded Asphalt Concrete (RAC-O)	Less than 1 year old	High	High	03-Pla-80-14.3/33.3	QP-51	<1	14,167	0	Yes
			Low	01-MEN-20-R37.9/43.0	QP-41	<1	5,200	0	
				01-LAK-29-R37.3/R37.6	QP-42	<1	5,850	3	
		Low	High	06-TUL-99-42.0/47.0	QP-35	<1	10,400	0	Yes
			Low	06-TUL-63-19.8/R30.1	QP-34	<1	3,325	0	
	1 to 4 years old	High	High	03-Sac-50-16.10/17.30	QP-8	5	17,694	0	
			Low	10-Ama-49-14.7/17.6	QP-17	3	4,060	0	Yes
		Low	High	07-LA-710-6.8/9.7	QP-1	3	19,208	0	Yes
				04-CC-680-23.9/24.9	QP-36	3	17,107	0	
			Low	06-Tul-65-21/29	06-N466 06-N467 06-N468	3	4,919	4 2 1	
	5 to 8 years old	High	High	No sections found to fit this cell	-	-	-		
			Low	04-Nap-128-5.1/7.4	QP-32	8	1,353	0	Yes
		Low	High	04-SCl-85-1.9/4.7	QP-24	8	16,986	0	Yes
			Low	08-SBD-58-R0.0/5.3	QP-12	5	6,497	0	Yes

***** Note: This column indicates the survey year when the section was excluded from OBSI testing because it was resurfaced or for another reason. The "0" entry means that the section was tested for OBSI in all four survey years.

Mix Type	Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	2006 AADT on the Coring Lane	Survey Year of Dropout for OBSI Test*	Coring in the Fourth Year
Rubberized Gap-graded Asphalt Concrete (RAC-G)	Less than 1 year old	High	High	No sections found to fit this cell	-	-	-		
			Low	01-MEN-20-R37.9/43.0	QP-39	<1	5,200	0	Yes
		Low	High	04-SCl-280-R0.0/R2.7	QP-26	<1	25,667	0	Yes
			Low	06-TUL-63-19.8/R30.1	QP-33	<1	4,800	0	
	1 to 4 years old	High	High	04-Mrn-101-18.9/23.1	QP-2	4	2,100	0	Yes
			Low	04-Son-1-0.0/8.4	QP-31	5	2,250	0	
		Low	High	08-Riv-15-33.8/38.4	QP-14	5	19,528	0	Yes
			Low	05-SLO-46-R10.8/R22.0	QP-19	4.5	3,233	3	
	5 to 8 years old	High	High	04-Mrn-101-2.5/8.5	QP-5	9	20,925	0	
			Low	10-Cal-4-0/18.8	QP-18	6	2,211	3	
		Low	High	11-SD-8-0.8/1.9	QP-46	6	26,607	0	
			Low	07-Ven-34-4.3/6.3	QP-10	5	8,007	2	

***** Note: This column indicates the survey year when the section was excluded from OBSI testing because it was resurfaced or for another reason. The "0" entry means that the section was tested for OBSI in all four survey years.

Mix Type	Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	2006 AADT on the Coring Lane	Survey Year of Dropout for OBSI Test*	Coring in the Fourth Year
Dense-graded Asphalt Concrete (DGAC)	Less than 1 year old	High	High	03-Pla-80-14.3/33.3	QP-27	<1	8,333	2	
			Low	01-MEN-20-R37.9/43.0	QP-40	<1	5,200	0	
		Low	High	06-FRE-99-10.7/15.9	QP-6	<1	15,500	4	
			Low	07-LA-138-60.2/61.6	QP-15	<1	7,750	0	
	1 to 4 years old	High	High	03-ED-50-17.3/18.3	QP-21	3	12,969	4	
			Low	03-ED-50-18.5/20.3	QP-30	4	6,385	0	
		Low	High	06-KER-99 29.5/31.0	QP-7	5	10,417	3	
			Low	04-SOL-113-0.1/18.0	QP-43	1	2,750	3	
	5 to 8 years old	High	High	04-SM-280-9.6/10.8	QP-9	5	10,986	0	
			Low	01-Men-1-20.8/38.7	01-N114	7	813	4	
					01-N121	7	581	1	
		Low	High	04-Ala-92-6.6/8.8	QP-16	14	6,744	4	
			Low	06-KER-65-R0.0/2.9	06-N434	6	3,107	4	
					06-N436	6	4,950	1	
				07-LA-60 R25.4/R30.5	QP-11	7	29,818	2	
				04-CC-680-23.9/24.9	QP-25	8	18,071	2	

* Note: This column indicates the survey year when the section was excluded from OBSI testing because it was resurfaced or for another reason. The "0" entry means that the section was tested for OBSI in all four survey years.

Mix Type		Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	2006 AADT on the Coring Lane	Survey Year of Dropout for OBSI Test	Coring in the Fourth Year
F-mixes	RAC Binder	Less than 1 year old	High	Low	01-Men-101-37.4/38.8	QP-52	1	4,000	0	
		1 to 4 years old	High	Low	01-Men-101-50.8/ 51.5	QP-47	3	5,081	0	
					01-HUM-101-111.1/111.5	QP-50	4	2,130	4	
	Conven-tional Binder	5 to 8 years old	High	Low	01-Men-20-21.19/21.69	QP-48	8	1,289	0	
					01-Men-20-22.18 /22.68	QP-49	8	1,289	0	

B.1.2 List of Caltrans Environmental Noise Monitoring Site (ES) Sections

Site Name	Site Location	Mix Types, Design Thicknesses, and Site ID*	Construction Date	Survey Year of Dropout for OBSI Test **	Coring in the Fourth Year
Los Angeles 138 (LA 138)	07-LA-138/ PM 16.0-21.0	OGAC, 75 mm (ES-1, ES-2) OGAC, 30 mm (ES-3, ES-4) RAC-O, 30 mm (ES-5, ES-6) BWC, 30 mm (ES-7, ES-8) DGAC, 30 mm (ES-9)	Spring 2002	0 0 0 0 0	Yes Yes Yes
Los Angeles 19 (LA 19)	07-LA-19/ PM 3.4	European gap-graded, 30 mm (ES-10)	May 2005	0	Yes
Yolo 80	03-Yolo-80/ PM 2.9-5.8	OGAC, 20 mm (ES-11)	Summer 1998	0	Yes
Fresno 33 (Fre 33)	06-Fre-33/ PM 70.9-75.08	RAC-G, 45 mm (ES-13) RAC-G, 90 mm (ES-12) RUMAC-GG, 45 mm (ES-14) RUMAC-GG, 90 mm (ES-15) Type G-MB, 45 mm (ES-16) Type G-MB, 90 mm (ES-17) Type D-MB, 45 mm (ES-19) Type D-MB, 90 mm (ES-18) DGAC, 90 mm (ES-20)	Summer 2004	0 0 0 0 0 0 0 0 0	Yes Yes
San Mateo 280 (SM 280)	04-SM-280/ PM R0.0-R5.6	RAC-O, 45 mm (ES-21)	Fall 2002	0	Yes
Sacramento 5 (Sac 5)	03-Sac-5/ PM 17.2-17.9 North and southbound directions	RAC-O, 30 mm (ES-22, ES-23)	Summer 2004	0	Yes

***** Note:

OGAC: Open-graded asphalt concrete
RAC-O: Rubberized open-graded asphalt concrete
BWC: Bonded wearing course
RAC-G: Rubberized gap-graded asphalt concrete (wet process)
RUMAC-GG: Rubber-modified asphalt concrete (dry process, a local-government specification)
Type D-MB: Dense-graded rubberized asphalt concrete (terminal blend)
Type G-MB: Gap-graded rubberized asphalt concrete (terminal blend)
DGAC: Dense-graded asphalt concrete

******Note: This column indicates the survey year when the section was excluded from OBSI testing because it was resurfaced or for another reason. The “0” entry means that the section was tested for OBSI in all four survey years.

Appendix B.2: Development of Calibration Equations for Pavement Temperature, Test Tire, Speed, and Analyzer Equipment

B.2.1 Introduction

To investigate the combined effects of test tire, speed, sound analyzer equipment, and pavement temperature on on-board sound intensity (OBSI) measured near the tire/pavement interface, two factorial experiments were conducted on several pavement sections around Los Angeles and Davis, California, during May and June 2010.

The first experiment was conducted on seven pavement sections (ODR-N, ODR-S, RD105-N, RD105-S, RD32a-E, RD32a-W1, and RD32a-W2) near Davis, California, during late May through early June. On each section, OBSI was measured with three repetitions at all factor-level combinations of four variables: test tire (Aquatred 3 #3, SRTT #3), speed (35 mph, 60 mph), sound analyzer equipment (Larson-Davis, Harmonie), and pavement temperature (low [early morning], high [noon]). Pavement temperature varied among all the measurements between 18°C and 44°C.

The second experiment was conducted on nine experimental test sections on State Route 138 in Los Angeles County (see Table B.1.2) during mid-June 2010. On each section, OBSI was measured with three repetitions at all factor-level combinations of three variables: test tire (Aquatred 3 #3, SRTT #3), speed (35 mph, 60 mph), and pavement temperature (low [early morning], high [noon]). Pavement temperature among all the measurements varied between 13°C and 52°C. The same sound analyzer equipment, Harmonie was used for all measurements.

Results of the above two factorial experiments were analyzed and applied to the four-year sound intensity data to convert them to reference conditions. An unexpectedly large increase in sound intensity measured in the fourth year of testing of the QP and ES sections was discovered after data calibration. Because a different SRTT (SRTT #2) was used in the fourth year than in the third year (SRTT #1), it was suspected that significant differences exist among the various SRTT tires. Several additional experiments were then conducted in late 2010 and early 2011 to develop calibration equations among the different SRTT tires that had been used in the UCPRC noise studies. Four tires (SRTT #1, SRTT #2, SRTT #3, and SRTT #4) were included in these experiments that were conducted on both asphalt and concrete pavements. In these additional experiments, calibration between analyzers (Larson-Davis and Harmonie) was also further investigated using different tires on both AC and PCC pavements.

Table B.2.1 summarizes the experiments undertaken to develop calibration equations. In this table, the first two experiments are the two factorial experiments; experiment numbers 3 through 5 are additional experiments for calibrating among the various SRTT tires; and experiment numbers 6 through 9 are additional experiments for calibration between the Larson-Davis and Harmonie analyzers.

Table B.2.1: Summary of Experiments for Development of Calibration Equations

No.	Plan ID	Year	Section Set	Plan Description	Notes
1	Calibration_2010_ Davis	2010	Davis Calibration Sections (AC and PCC)	Full factorial on tire type, speed, pavement temperature, and analyzer	Used SRTT #3 and Aquatred 3 #3
2	Calibration_2010_ LA138	2010	LA 138 Sections (AC)	Same as Calibration_2010_Davis except no analyzer effect	Used SRTT #3 and Aquatred 3 #3
3	Tire_2010_Davis	2010	Davis Calibration Sections (AC and PCC)	Develop correlation between SRTT #1, #2, #3, and #4	It is believed that SRTT #A = SRTT #1 and SRTT #B = SRTT #2 based on the fact that SRTT #B is noisier and harder than #A.
4	Tire_2010_Local_ PCC	2010	Davis nearby PCC Sections	Same as Tire_2010_Davis except on PCC sections	Using SRTT #A, #B, #3, and #4
5	Tire_2010_ LA 138	2010	LA 138 Sections (AC)	Same as Tire_2010_Davis except on different sections	Using SRTT #A, #B, #3, and #4
6	Analyzer_2010_ LA138	2010	LA 138 Sections (AC)	Use both Harmonie and Larson-Davis to test LA 138 again to establish analyzer correction	Using SRTT #3
7	Analyzer_2010_ Firebaugh	2010	Firebaugh Sections (AC)	Use both Harmonie and Larson-Davis to test Firebaugh sections again to establish analyzer correction	Using SRTT #4
8	Calibration_2010_ Davis_Extra	2010	Davis RD32a Sections (PCC)	Extra runs not included in Calibration_2010_Davis because pavement temperature was not the lowest; use both Harmonie and Larson-Davis.	Marked as Low temp but really was not the lowest one. Using Aquatred 3 #3.
9	Analyzer_2011_ Local_PCC	2011	Davis nearby PCC Sections	Use both Harmonie and Larson-Davis to test nearby PCC Sections	Using SRTT #3

B.2.2 Analysis and Modeling of the Two Factorial Experiment Results

Since the second experiment only includes one sound analyzer (Harmonie), combining the measurements from both experiments creates an unbalanced data set, which will pose severe problems in estimating the effect of the sound analyzer equipment. An analysis of variance (ANOVA) was first conducted on the data from the first experiment to identify significant factors among all main effects and second-order interaction terms. Once the significant (at the 95% confidence level in this study) factors were determined, a linear regression analysis was performed to estimate the parameter corresponding to each significant factor. The estimation results are shown in Table B.2.2. As can be seen, the interactions between equipment and other variables (speed, tire, and pavement temperature) are generally insignificant for OBSI at all one-third octave frequency bands, except the 4,000 Hz and 5,000 Hz frequency bands where the effect of equipment type interacts with the effect of speed level (35 mph or 60 mph).

Excluding the data measured with Larson-Davis sound analyzer, a pool of both experiments' data is balanced (i.e., same number of observations at all factor level combinations). An ANOVA on this data set further identified significant factors on a wider range of pavement sections. The identified significant variables and corresponding estimated parameters from linear regression analysis are shown in Table B.2.3. The estimated parameters (coefficients) in Table B.2.2 and Table B.2.3 can be used to calibrate OBSI measurements to equivalent values under certain reference conditions. Calibration based on these models, however, assumes a constant difference between two levels of one factor. For example, for 400-Hz OBSI, Table B.2.2a shows that the Harmonie analyzer always gives a value -2.240157 dB(A) lower than the value measured with Larson-Davis analyzer, no matter how large the 400-Hz OBSI is. This assumption is not necessary true, and may therefore introduce large errors in the calibrated data.

Another approach is then suggested to calibrate the OBSI data: Based on the statistical significance identified in the ANOVA for each main effect and interaction term, a simple linear regression is performed on paired observations for each significant factor. In this approach, the calibration is conducted sequentially based on the simple linear regression results. Specifically, the original OBSI data are calibrated to a reference condition (e.g., SRTT #1, Larson-Davis equipment, 60 mph, and 25ºC pavement temperature) following these steps:

1. Calibrate for air density following the procedure in Reference *(1)* of Appendix A.
2. Calibrate for type of test tire (Aquatred 3 #2 versus SRTT #1) using the equations in Reference *(3)* of Appendix A.
3. Calibrate for type of sound analyzer equipment using the parameters in Table B.2.4. Figure B.2.1 shows the comparison of overall OBSI values measured with the Larson-Davis Analyzer and the Harmonie Analyzer on AC and PCC Pavements. It can be seen that the correlation is not significantly affected by

pavement surface type. Therefore, the data from both pavement types were combined to estimate the calibration parameters presented in Table B.2.4.

4. Calibrate for test vehicle speed using the parameters in Table B.2.5.
5. Calibrate for pavement temperature using the parameters in Table B.2.6.

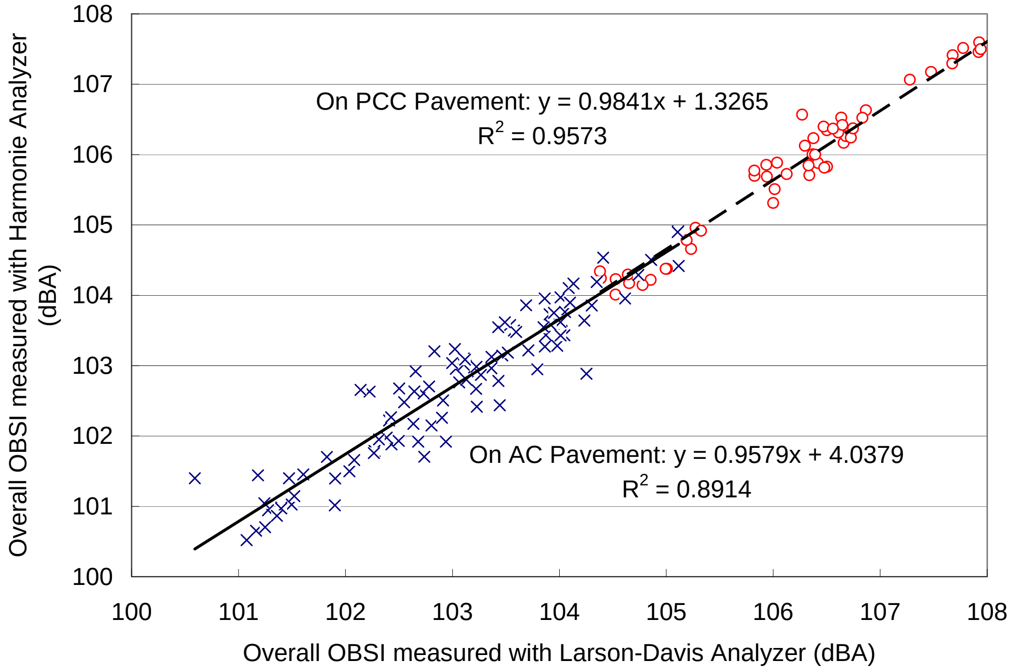


Figure B.2.1: Comparison of overall OBSI measured with Larson-Davis Analyzer and Harmonie Analyzer on AC and PCC Pavements.

Table B.2.2a: Regression Estimation Results for 400 Hz – 800 Hz OBSI Data Based on Davis Experiment

Variable	400 Hz		500 Hz		630 Hz		800 Hz	
	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
Intercept	87.267489	<2e-16	90.8568	<2e-16	94.69849	<2e-16	100.7043	<2e-16
Equipment_Harmonie	-2.240157	<2e-16	-1.76316	6.01E-11	-1.97258	4.71E-14	-0.89028	1.81E-05
Tire_Aquatred	3.441456	1.52E-05	2.49052	6.52E-11	2.09021	0.0187	0.85159	4.26E-05
Speed_35mph	-5.819413	<2e-16	-6.06326	<2e-16	-6.61749	<2e-16	-7.59271	<2e-16
Temperature	-0.003208	0.8479	-0.03714	0.0125	-0.02147	0.2551	-0.02945	0.0115
Equipment_Harmonie*Tire_Aquatred								
Equipment_Harmonie*Speed_35mph								
Equipment_Harmonie*Temperature								
Tire_Aquatred*Speed_35mph			1.18606	0.0237				
Tire_Aquatred*Temperature	-0.053363	0.0354			-0.05303	0.0635		
Speed_35mph*Temperature								
Residual Standard Error	2.129 on 366 DF		2.505 on 366 DF		2.4 on 366 DF		1.963 on 367 DF	
R-square	0.7042		0.6338		0.6808		0.7961	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is

$$\text{400 Hz OBSI } (\text{dBA}) = 87.267489 - 2.240157 \times Equipment\_Harmonie + 3.441456 \times Tire\_Aquatred$$
$$-5.819413 \times Speed\_35mph - 0.003208 \times Temperature(C) - 0.053363 \times Tire\_Aquatred \times Speed\_35mph$$

where,
if Harmonie equipment is used, "Equipment_Harmonie"=1; if Larson-Davis equipment is used, "Equipment_Harmonie"=0;
if Aquatred 3 #3 tire is used, "Tire_Aquatred"=1; if SRTT #3 tire is used, "Tire_Aquatred"=0;
if Speed is 35 mph, "Speed_35mph"=1; if Speed is 60 mph, "Speed_35mph"=0.
Temperature is a continuous variable with a unit of degree-Celsius.

Table B.2.2b: Regression Estimation Results for 1,000 Hz – 2,000 Hz OBSI Data Based on Davis Experiment

Variable	1,000 Hz		1,250 Hz		1,600 Hz		2,000 Hz	
	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
Intercept	98.306697	<2e-16	97.49826	<2e-16	97.00729	< 2E-16	94.306573	<2e-16
Equipment_Harmonie	-1.368448	<2e-16	-1.71652	<2e-16	-1.662404	< 2E-16	-1.727353	<2e-16
Tire_Aquatred	3.172145	1.23E-11	1.07264	5.48E-10	1.43064	< 2E-16	0.699508	<2e-16
Speed_35mph	-8.096755	<2e-16	-8.9182	<2e-16	-9.150354	< 2E-16	-9.073492	<2e-16
Temperature	0.002638	0.7847	-0.02116	0.00181	-0.039613	< 2E-16	-0.042667	<2e-16
Equipment_Harmonie*Tire_Aquatred								
Equipment_Harmonie*Speed_35mph								
Equipment_Harmonie*Temperature								
Tire_Aquatred*Speed_35mph			0.63043	0.00825				
Tire_Aquatred*Temperature	-0.029658	0.0428						
Speed_35mph*Temperature								
Residual Standard Error	1.229 on 366 DF		1.139 on 366 DF		0.7367 on 367 DF		0.7042 on 367 DF	
R-square	0.9244		0.939		0.9765		0.9778	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is :

$$\text{400 Hz OBSI }(\text{dBA}) = 87.267489 - 2.240157 \times Equipment\_Harmonie + 3.441456 \times Tire\_Aquatred$$
$$-5.819413 \times Speed\_35mph - 0.003208 \times Temperature(C) - 0.053363 \times Tire\_Aquatred \times Speed\_35mph$$

where,

if Harmonie equipment is used, "Equipment_Harmonie"=1; if Larson-Davis equipment is used, "Equipment_Harmonie"=0;
if Aquatred 3 #3 tire is used, "Tire_Aquatred"=1; if SRTT #3 tire is used, "Tire_Aquatred"=0;
if Speed is 35 mph, "Speed_35mph"=1; if Speed is 60 mph, "Speed_35mph"=0.
Temperature is a continuous variable with a unit of degree-Celsius.

Table B.2.2c: Regression Estimation Results for 2,500 Hz – 5,000 Hz OBSI Data Based on Davis Experiment

Variable	2,500 Hz		3,150 Hz		4,000 Hz		5,000 Hz	
	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
Intercept	90.790525	<2e-16	85.83699	<2e-16	82.466918	<2e-16	80.43229	<2e-16
Equipment_Harmonie	-1.737763	<2e-16	-1.675705	<2e-16	-2.103915	<2e-16	-3.086838	<2e-16
Tire_Aquatred	0.021032	0.788	1.330337	<2e-16	1.95939	<2e-16	1.441034	<2e-16
Speed_35mph	-8.953544	<2e-16	-8.666086	<2e-16	-9.295093	<2e-16	-9.858498	<2e-16
Temperature	-0.043341	<2e-16	-0.046889	5.80E-15	-0.044409	1.01E-12	-0.055617	<2e-16
Equipment_Harmonie*Tire_Aquatred								
Equipment_Harmonie*Speed_35mph					0.339816	0.024158	0.564247	0.000736
Equipment_Harmonie*Temperature								
Tire_Aquatred*Speed_35mph			0.431137	0.00305	0.591399	0.000103	0.723893	1.79E-05
Tire_Aquatred*Temperature								
Speed_35mph*Temperature			-0.020828	0.0106	-0.016768	0.049223		
Residual Standard Error	0.745 on 367 DF		0.6906 on 365 DF		0.7191 on 364 DF		0.7991 on 365 DF	
R-square	0.9744		0.9792		0.9794		0.9746	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is:

$$\text{400 Hz OBSI }(\text{dBA}) = 87.267489 - 2.240157 \times Equipment\_Harmonie + 3.441456 \times Tire\_Aquatred$$
$$-5.819413 \times Speed\_35mph - 0.003208 \times Temperature(C) - 0.053363 \times Tire\_Aquatred \times Speed\_35mph$$

where,
if Harmonie equipment is used, “Equipment_Harmonie”=1; if Larson-Davis equipment is used, “Equipment_Harmonie”=0;
if Aquatred 3 #3 tire is used, “Tire_Aquatred”=1; if SRTT #3 tire is used, “Tire_Aquatred”=0;
if Speed is 35 mph, “Speed_35mph”=1; if Speed is 60 mph, “Speed_35mph”=0.
Temperature is a continuous variable with a unit of degree-Celsius.

Table B.2.2d: Regression Estimation Results for Overall OBSI Based on Davis Experiment

Variable	Overall	
	Coefficient	P-value
Intercept	105.983549	<2e-16
Equipment_Harmonie	-1.414839	<2e-16
Tire_Aquatred	1.391065	<2e-16
Speed_35mph	-7.926374	<2e-16
Temperature	-0.027389	0.00138
Equipment_Harmonie*Tire_Aquatred		
Equipment_Harmonie*Speed_35mph		
Equipment_Harmonie*Temperature		
Tire_Aquatred*Speed_35mph		
Tire_Aquatred*Temperature		
Speed_35mph*Temperature		
Residual Standard Error	1.438 on 367	
R-square	0.8914	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is:

$$\text{400 Hz OBSI }(\text{dBA}) = 87.267489 - 2.240157 \times Equipment\_Harmonie + 3.441456 \times Tire\_Aquatred$$
$$-5.819413 \times Speed\_35mph - 0.003208 \times Temperature(C) - 0.053363 \times Tire\_Aquatred \times Speed\_35mph$$

where,

if Harmonie equipment is used, “Equipment_Harmonie”=1; if Larson-Davis equipment is used, “Equipment_Harmonie”=0;

if Aquatred 3 #3 tire is used, “Tire_Aquatred”=1; if SRTT #3 tire is used, “Tire_Aquatred”=0;

if Speed is 35 mph, “Speed_35mph”=1; if Speed is 60 mph, “Speed_35mph”=0.

Temperature is a continuous variable with a unit of degree-Celsius.

Table B.2.3a: Regression Estimation Results for 400 Hz – 800 Hz OBSI Data Measured with Harmonie Analyzer

Parameter	400 Hz		500 Hz		630 Hz		800 Hz	
	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
Intercept	85.00795	<2e-16	87.67398	<2e-16	91.88879	<2e-16	97.55541	<2e-16
Tire_Aquatred	0.999419	0.000778	2.342435	7.56E-13	0.467116	0.0341	0.761535	0.000614
Speed_35mph	-6.02908	<2e-16	-5.30661	<2e-16	-5.74776	<2e-16	-7.00157	<2e-16
Temperature	-0.03758	1.68E-06	-0.04989	3.81E-09	-0.05635	1.78E-11	-0.01837	0.02509
Tire_Aquatred*Speed_35mph	1.155647	0.005887	1.424581	0.00155				
Tire_Aquatred*Temperature								
Speed_35mph*Temperature								
Residual Standard Error	2.09 on 397 DF		2.238 on 397 DF		2.201 on 398 DF		2.209 on 398 DF	
R-square	0.6586		0.6214		0.6497		0.7207	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is:

$$\text{400 Hz OBSI } (\text{dBA}) = 85.00795 + 0.999419 \times Tire\_Aquatred - 6.02908 \times Speed\_35mph$$
$$-0.03758 \times Temperature(C) + 1.155647 \times Tire\_Aquatred \times Speed\_35mph$$

where,

if Harmonie equipment is used, “Equipment_Harmonie”=1; if Larson-Davis equipment is used, “Equipment_Harmonie”=0;

if Aquatred 3 #3 tire is used, “Tire_Aquatred”=1; if SRTT #3 tire is used, “Tire_Aquatred”=0;

if Speed is 35 mph, “Speed_35mph”=1; if Speed is 60 mph, “Speed_35mph”=0.

Temperature is a continuous variable with a unit of degree-Celsius.

Table B.2.3b: Regression Estimation Results for 1,000 Hz – 2,000 Hz OBSI Data Measured with Harmonie Analyzer

Parameter	1,000 Hz		1,250 Hz		1,600 Hz		2,000 Hz	
	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
Intercept	96.10816	<2e-16	94.85625	<2e-16	93.8864	<2e-16	91.0258	<2e-16
Tire_Aquatred	2.11134	<2e-16	1.145633	1.38E-09	1.765192	<2e-16	0.869567	7.92E-08
Speed_35mph	-7.51168	<2e-16	-8.25975	<2e-16	-8.42221	<2e-16	-8.48323	<2e-16
Temperature	-0.02141	0.000923	-0.03106	3.83E-10	-0.05345	<2e-16	-0.04327	1.14E-12
Tire_Aquatred*Speed_35mph			0.607719	0.0204				
Tire_Aquatred*Temperature								
Speed_35mph*Temperature								
Residual Standard Error	1.734 on 398 DF		1.31 on 397 DF		1.66 on 398 DF		1.59 on 398 DF	
R-square	0.8372		0.907		0.8753		0.8807	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is:

$$\text{400 Hz OBSI }(\text{dBA}) = 85.00795 + 0.999419 \times Tire\_Aquatred - 6.02908 \times Speed\_35mph$$
$$-0.03758 \times Temperature(C) + 1.155647 \times Tire\_Aquatred \times Speed\_35mph$$

where,
if Harmonie equipment is used, “Equipment_Harmonie”=1; if Larson-Davis equipment is used, “Equipment_Harmonie”=0;
if Aquatred 3 #3 tire is used, “Tire_Aquatred”=1; if SRTT #3 tire is used, “Tire_Aquatred”=0;
if Speed is 35 mph, “Speed_35mph”=1; if Speed is 60 mph, “Speed_35mph”=0.
Temperature is a continuous variable with a unit of degree-Celsius.

Table B.2.3c: Regression Estimation Results for 2,500 Hz – 5,000 Hz OBSI Data Measured with Harmonie Analyzer

Parameter	2,500 Hz		3,150 Hz		4,000 Hz		5,000 Hz	
	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
Intercept	87.79607	<2e-16	83.47042	<2e-16	79.40459	<2e-16	76.78138	<2e-16
Tire_Aquatred	0.458477	0.000222	1.568983	<2e-16	2.788376	<2e-16	1.594221	<2e-16
Speed_35mph	-8.59103	<2e-16	-8.6599	<2e-16	-11.2491	<2e-16	-9.20009	<2e-16
Temperature	-0.04172	<2e-16	-0.04798	<2e-16	-0.03468	2.41E-06	-0.06215	<2e-16
Tire_Aquatred*Speed_35mph			0.540814	0.00316	0.767649	0.000711	0.69554	0.0032
Tire_Aquatred*Temperature					-0.02329	0.005445		
Speed_35mph*Temperature			-0.0156	0.02122	0.059899	3.31E-12		
Residual Standard Error	1.232 on 398 DF		0.912 on 396 DF		1.127 on 395 DF		1.174 on 397 DF	
R-square	0.9261		0.9625		0.947		0.9396	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is:

$$\text{400 Hz OBSI }(\text{dBA}) = 85.00795 + 0.999419 \times Tire\_Aquatred - 6.02908 \times Speed\_35mph$$
$$-0.03758 \times Temperature(C) + 1.155647 \times Tire\_Aquatred \times Speed\_35mph$$

where,
if Harmonie equipment is used, “Equipment_Harmonie”=1; if Larson-Davis equipment is used, “Equipment_Harmonie”=0;
if Aquatred 3 #3 tire is used, “Tire_Aquatred”=1; if SRTT #3 tire is used, “Tire_Aquatred”=0;
if Speed is 35 mph, “Speed_35mph”=1; if Speed is 60 mph, “Speed_35mph”=0.
Temperature is a continuous variable with a unit of degree-Celsius.

Table B.2.3d: Regression Estimation Results for Overall OBSI Measured with Harmonie Analyzer

Parameter	Overall	
	Coefficient	**P-value**
Intercept	102.9963	<2e-16
Tire_Aquatred	1.381321	2.35E-14
Speed_35mph	-7.29377	<2e-16
Temperature	-0.03091	2.39E-06
Tire_Aquatred*Speed_35mph		
Tire_Aquatred*Temperature		
Speed_35mph*Temperature		
Residual Standard Error	1.746 on 398 DF	
R-square	0.8221	

Notes: 1. Empty cell means the corresponding variable (factor) is statistically insignificant in ANOVA.

2. The regression model is $OBSI(dBA) = \sum Variable \times Coefficient$.

For example, for the 400 Hz frequency band, the regression model is:

$$\text{400 Hz OBSI } (\text{dBA}) = 85.00795 + 0.999419 \times Tire\_Aquatred - 6.02908 \times Speed\_35mph$$
$$-0.03758 \times Temperature(C) + 1.155647 \times Tire\_Aquatred \times Speed\_35mph$$

where,

if Harmonie equipment is used, “Equipment_Harmonie”=1; if Larson-Davis equipment is used, “Equipment_Harmonie”=0;

if Aquatred 3 #3 tire is used, “Tire_Aquatred”=1; if SRTT #3 tire is used, “Tire_Aquatred”=0;

if Speed is 35 mph, “Speed_35mph”=1; if Speed is 60 mph, “Speed_35mph”=0.

Temperature is a continuous variable with a unit of degree-Celsius.

Table B.2.4: Calibration Parameters for Sound Analyzer Equipment

One-Third Octave Band	Speed (mph)	Slope*	Intercept	R^2
400	-	0.9765	4.1048	0.964
500	-	0.9978	1.8798	0.987
630	-	1.0257	-0.4471	0.988
800	-	1.0213	-1.2074	0.989
1,000	-	1.0235	-0.8917	0.992
1,250	-	1.0112	0.6458	0.993
1,600	-	1.0148	0.2472	0.993
2,000	-	1.0212	-0.2081	0.993
2,500	-	1.0116	0.6869	0.994
3,150	-	1.0163	0.2721	0.992
4,000	35	0.9176	7.4976	0.929
4,000	60	0.8552	13.624	0.913
5,000	35	0.9237	7.5707	0.908
5,000	60	0.8294	16.035	0.860
Overall	-	1.0178	-0.427	0.994

**Note:* The calibration equation is (OBSI with Larson-Davis) = (OBSI with Harmonie)*Slope+Intercept

Table B.2.5a: Speed Calibration Parameters for SRTT #3

One-Third Octave Band	Slope*	Intercept	R^2
400	1.0099	5.2385	0.666
500	1.3718	-24.806	0.864
630	1.3400	-23.451	0.889
800	1.2410	-15.036	0.838
1,000	1.2892	-17.766	0.946
1,250	1.2831	-15.955	0.900
1,600	1.2545	-12.98	0.926
2,000	1.1516	-3.7188	0.945
2,500	1.0141	7.7036	0.919
3,150	0.9146	15.498	0.884
4,000	0.7622	26.134	0.587
5,000	1.0054	9.056	0.918
Overall	1.3058	-21.718	0.943

**Note:* The calibration equation is (OBSI at 60 mph) = (OBSI at 35 mph)*Slope+Intercept

Table B.2.5b: Speed Calibration Parameters for Aquatred 3 #3 Tire

One-Third Octave Band	Slope*	Intercept	R^2
400	1.309	-20.005	0.832
500	1.6516	-51.565	0.855
630	1.3977	-27.653	0.914
800	1.1847	-9.3743	0.884
1,000	1.2825	-18.04	0.948
1,250	1.3663	-24.397	0.918
1,600	1.2428	-12.199	0.932
2,000	1.2647	-13.257	0.926
2,500	1.1197	-0.8175	0.893
3,150	0.9275	14.195	0.871
4,000	0.8633	18.752	0.679
5,000	1.0329	6.4302	0.930
Overall	1.313	-22.801	0.961

**Note:* The calibration equation is (OBSI at 60 mph) = (OBSI at 35 mph)*Slope+Intercept

Table B.2.6: Pavement Temperature Calibration Parameters

	SRTT #3, 60 mph	Aquatred 3 #3, 60 mph	SRTT #3 or Aquatred 3 #3, 35 mph
One-Third Octave Band	Slope	Slope	Slope
400	-0.03758	-0.03758	-0.03758
500	-0.04989	-0.04989	-0.04989
630	-0.05635	-0.05635	-0.05635
800	-0.01837	-0.01837	-0.01837
1,000	-0.02141	-0.02141	-0.02141
1,250	-0.03106	-0.03106	-0.03106
1,600	-0.05345	-0.05345	-0.05345
2,000	-0.04327	-0.04327	-0.04327
2,500	-0.04172	-0.04172	-0.04172
3,150	-0.04798	-0.04798	-0.06358
4,000	-0.03468	-0.05797	0.001929
5,000	-0.06215	-0.06215	-0.06215
Overall	-0.03091	-0.03091	-0.03091

**Note:* The calibration equation is (OBSI at 25ºC) = (OBSI at other temperature in Celsius)+(25 minus other temperature in Celsius)*Slope

B.2.3 Analysis and Modeling of the Additional Experiment Results

Experiments No. 3 through No. 5 in Table B.2.1 were conducted to investigate the relationship between four SRTT tires (SRTT #A [#1], SRTT #B [#2], SRTT #3, and SRTT #4). SRTT #1 was used in the second and third years of measurement of OBSI on AC pavements, while SRTT #2 was used in the fourth year data collection, and SRTT #3 and SRTT #4 were used in the fifth year data collection on AC pavements. SRTT #2, SRTT #3, and SRTT #4 were also used to collect the OBSI data on PCC pavements in the first, second, and third years, respectively. Experiments numbers 3 through 5 included both AC and PCC sections, and used only the Harmonie analyzer to process noise data. Figure B.2.2 and Figure B.2.3 show comparisons of overall OBSI values measured with different SRTT tires on AC pavement and PCC pavement, respectively. It can be seen that the values measured with SRTT #2 are significantly different from the values measured with other SRTT tires.

Simple linear regression analysis was conducted for various pairs of SRTT tires, for AC sections only, and for PCC sections only. The results are summarized in Table B.2.7.

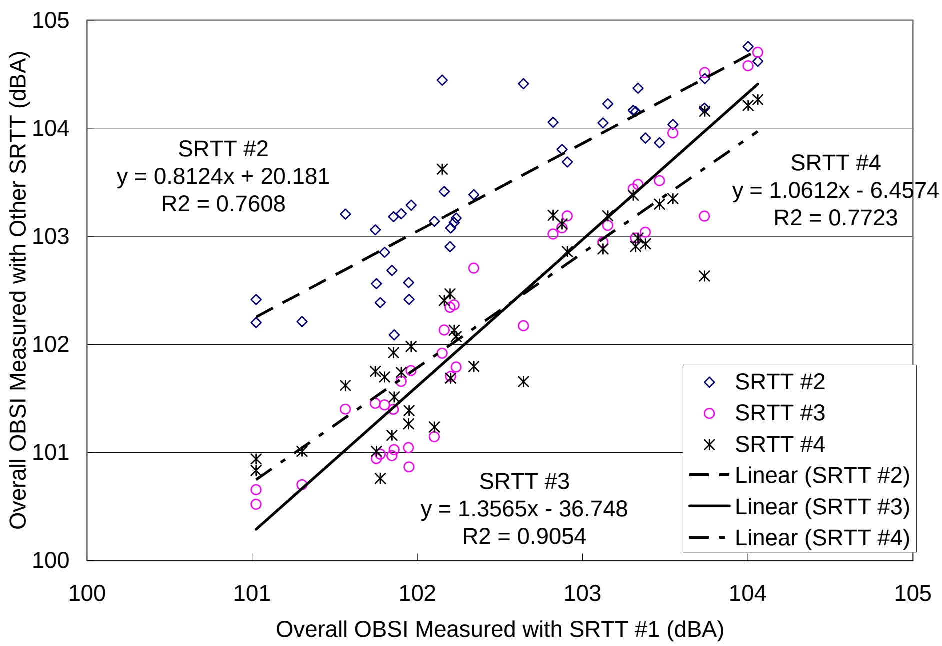


Figure B.2.2: Comparison of overall OBSI measured with various SRTT tires on AC pavements.

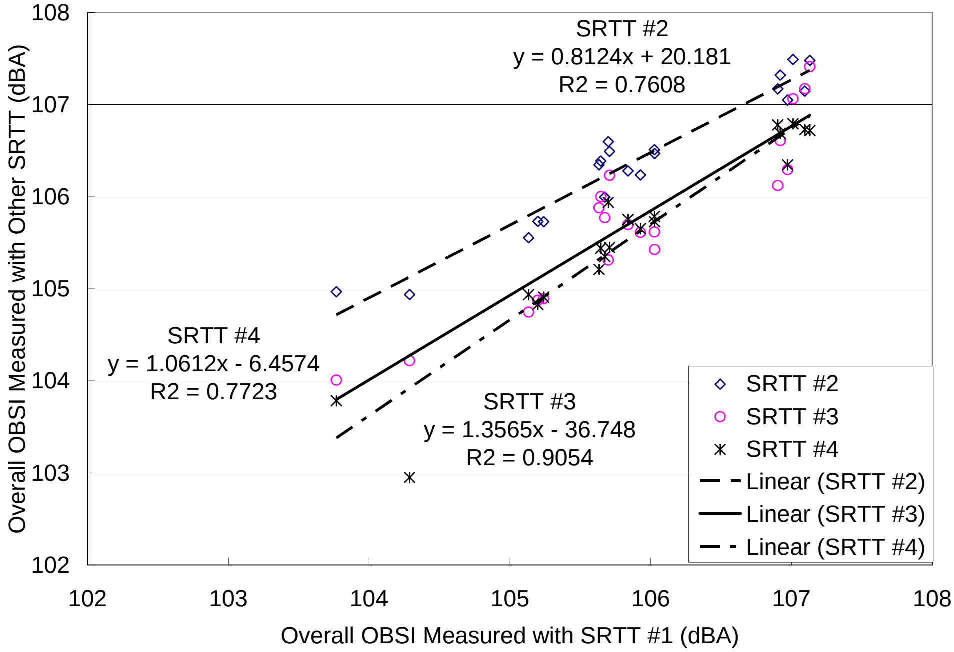


Figure B.2.3: Comparison of overall OBSI measured with various SRTT tires on PCC pavements.

Table B.2.7a: SRTT Tire Calibration Parameters on AC Pavements

	SRTT #1 to SRTT #3			SRTT #2 to SRTT #3		
Frequency	**Intercept**	**Slope**	**R^2**	**Intercept**	**Slope**	**R^2**
400	60.7380	0.2636	0.08	66.5322	0.1959	0.04
500	3.6808	0.9528	0.64	22.2986	0.7327	0.36
630	-0.8985	1.0042	0.76	2.0400	0.9682	0.52
800	-21.9632	1.2231	0.90	-22.5924	1.2230	0.75
1,000	-21.9966	1.2296	0.86	-18.6739	1.1755	0.64
1,250	-6.6236	1.0674	0.68	10.3488	0.8770	0.44
1,600	-44.2338	1.4727	0.93	-53.8537	1.5593	0.91
2,000	-30.5374	1.3346	0.93	-23.2965	1.2397	0.94
2,500	-31.8006	1.3660	0.83	-19.4132	1.2104	0.90
3,150	-32.1054	1.3894	0.77	-26.0760	1.3040	0.80
4,000	-31.8360	1.4004	0.84	-19.8023	1.2397	0.84
5,000	-35.0003	1.4565	0.86	-19.3382	1.2451	0.80
Overall	-36.7482	1.3565	0.91	-37.3630	1.3499	0.78
	SRTT #4 to SRTT #3			**SRTT #2 to SRTT #1**		
Frequency	**Intercept**	**Slope**	**R^2**	**Intercept**	**Slope**	**R^2**
400	43.0797	0.4731	0.14	25.2230	0.7044	0.50
500	23.6078	0.7210	0.41	24.4337	0.7125	0.48
630	2.3692	0.9617	0.59	14.8822	0.8323	0.51
800	-0.9392	1.0053	0.77	6.0426	0.9328	0.73
1,000	-9.7246	1.1063	0.88	-0.9962	0.9940	0.81
1,250	8.8142	0.9105	0.72	16.1836	0.8186	0.65
1,600	-9.9530	1.1095	0.97	-2.4799	1.0157	0.90
2,000	-20.0984	1.2268	0.98	8.0316	0.9005	0.95
2,500	-14.9727	1.1750	0.97	16.6884	0.7994	0.88
3,150	-12.1375	1.1458	0.87	16.4124	0.7935	0.75
4,000	-13.3360	1.1646	0.91	16.9545	0.7799	0.78
5,000	-10.8424	1.1343	0.90	17.4375	0.7670	0.75
Overall	-10.3478	1.1009	0.87	5.6130	0.9365	0.76

Table B.2.7b: SRTT Tire Calibration Parameters on PCC Pavements

	SRTT #1 to SRTT #3			SRTT #2 to SRTT #3		
Frequency	**Intercept**	**Slope**	**R^2**	**Intercept**	**Slope**	**R^2**
400	-5.2795	1.0498	0.72	20.4138	0.7668	0.30
500	24.3890	0.7274	0.80	14.5457	0.8347	0.89
630	14.2176	0.8452	0.85	11.2100	0.8787	0.87
800	13.9783	0.8591	0.93	12.1956	0.8756	0.87
1,000	1.0015	0.9900	0.92	13.8438	0.8519	0.60
1,250	1.0296	0.9876	0.92	-0.2586	0.9924	0.93
1,600	-10.0633	1.1053	0.93	-17.2125	1.1725	0.94
2,000	-1.1616	1.0119	0.90	-13.8908	1.1358	0.95
2,500	-0.7452	1.0103	0.89	-3.6465	1.0320	0.92
3,150	-11.9573	1.1430	0.92	-17.8493	1.2046	0.95
4,000	-8.3923	1.1006	0.91	-12.4682	1.1471	0.94
5,000	-2.0791	1.0259	0.89	-6.1325	1.0781	0.93
Overall	8.5215	0.9182	0.85	-15.7817	1.1423	0.87
	SRTT #4 to SRTT #3			**SRTT #2 to SRTT #1**		
Frequency	**Intercept**	**Slope**	**R^2**	**Intercept**	**Slope**	**R^2**
400	-12.2495	1.1304	0.78	12.9152	0.8641	0.58
500	13.4721	0.8488	0.87	-4.8252	1.0516	0.93
630	12.5982	0.8612	0.85	-0.1345	1.0032	0.96
800	16.5470	0.8337	0.89	-3.6086	1.0344	0.95
1,000	20.7023	0.7930	0.82	12.8477	0.8618	0.65
1,250	3.1057	0.9725	0.91	2.3379	0.9677	0.94
1,600	7.5161	0.9300	0.90	-3.6609	1.0318	0.95
2,000	5.7929	0.9478	0.91	-6.1668	1.0549	0.93
2,500	4.0057	0.9621	0.89	2.1505	0.9663	0.92
3,150	-6.1946	1.0789	0.94	-1.3482	1.0095	0.95
4,000	-3.9044	1.0504	0.94	-0.4646	1.0028	0.96
5,000	2.3119	0.9741	0.93	0.9657	0.9886	0.92
Overall	20.8671	0.8039	0.77	-20.5446	1.1884	0.94

Experiment numbers 6 through 9 in Table B.2.1 were conducted to investigate the relationship between the Larson-Davis and Harmonie analyzers. Both AC and PCC pavements and several tires were included in the experiments. It is believed that the calibration between analyzer equipment types is independent of pavement type and tire type, which is partially verified by the results of the factorial experiments No. 1 and No. 2 in Table B.2.1. Simple linear regression analysis was conducted on the data from the four experiments. The results are summarized in Table B.2.8.

Table B.2.8: Equipment Calibration Parameters on AC and PCC Pavements

Frequency	Intercept	Slope	R^2
400	14.0606	0.8298	0.67
500	0.5176	0.9901	0.95
630	1.3928	0.9792	0.95
800	5.0341	0.9451	0.95
1000	-0.2779	0.9997	0.97
1250	3.6008	0.9597	0.95
1600	2.2686	0.9735	0.97
2000	1.7017	0.9797	0.96
2500	1.3379	0.9835	0.95
3150	1.9084	0.9763	0.92
4000	2.3261	0.9694	0.92
5000	4.3423	0.9402	0.89
Overall	2.1918	0.9758	0.97

Note: OBSI(Harmonie)=OBSI(Larson-Davis)*Slope+Intercept

B.2.4 Calibration of OBSI Data for This Report

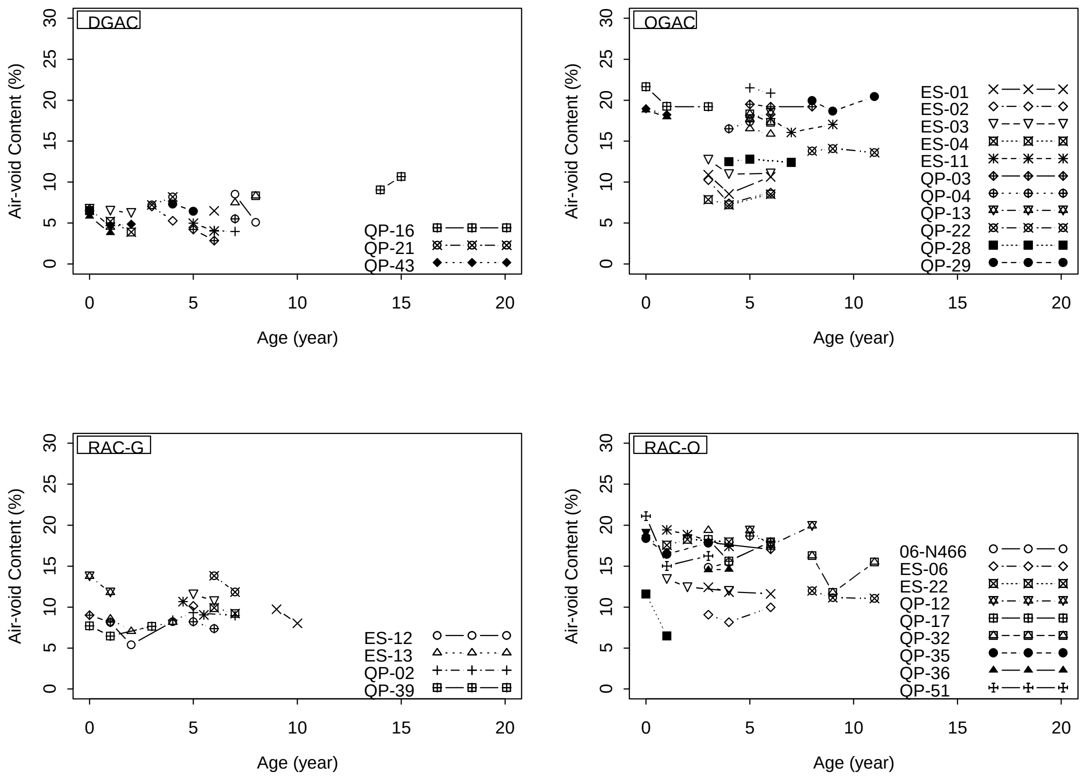
After reviewing the first three-year data analysis report and the calibration equations developed in this section, Caltrans and UCPRC reached an agreement regarding how to handle the calibration of OBSI data for the four-year analysis report. It was agreed that the following steps would be taken:

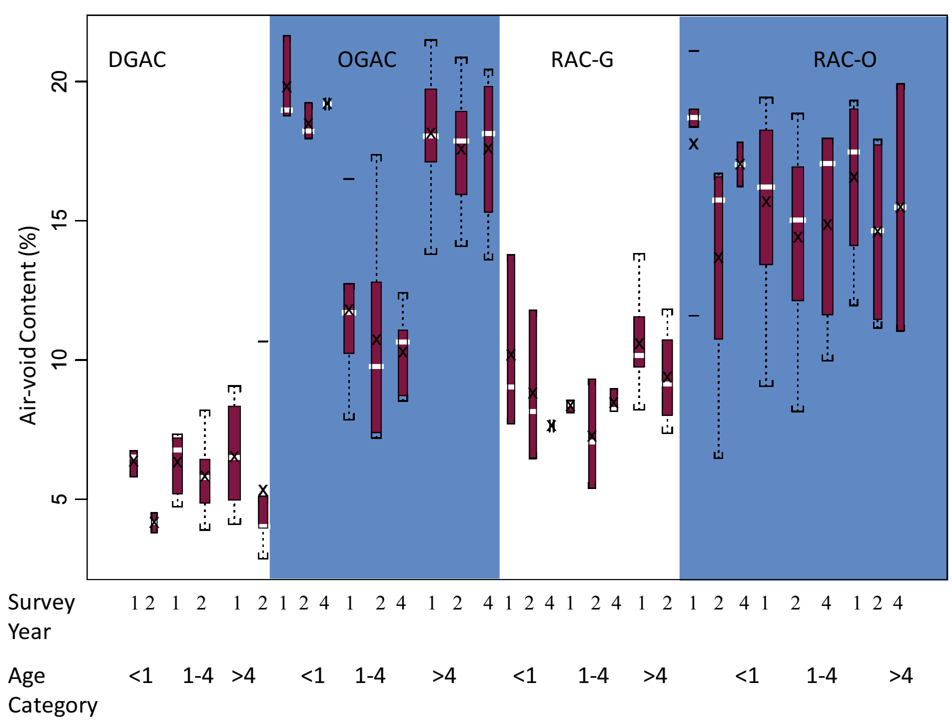
1. Disregard calibration for pavement temperature;
2. Remove all OBSI data measured at a test car speed other than 60 mph;
3. Calibrate the first three years of AC data from Larson-Davis to Harmonie equipment using the parameters in Table B.2.6b;
4. Calibrate the fourth-year data from SRTT #2 to SRTT #1 using parameters in Table B.2.6a;
5. Calibrate the first two years of AC data from Aquatred 3 #2 tire to SRTT #1 using equations developed in Reference *(3)* of Appendix A;
6. Calibrate all data for air density following the procedure in Reference *(1)* of Appendix A.

The reference conditions for OBSI data in this report are 60 mph test car speed, SRTT #1 tire, and Harmonie analyzer.

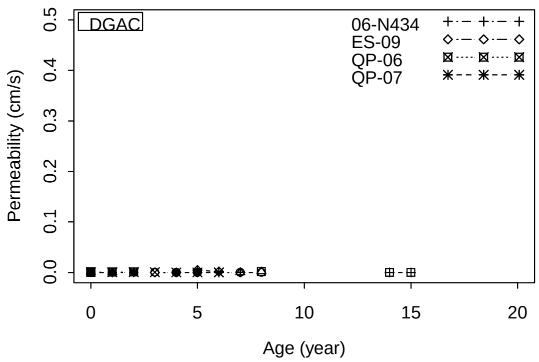
Appendix B.3: Plots of Air-Void Content and Permeability

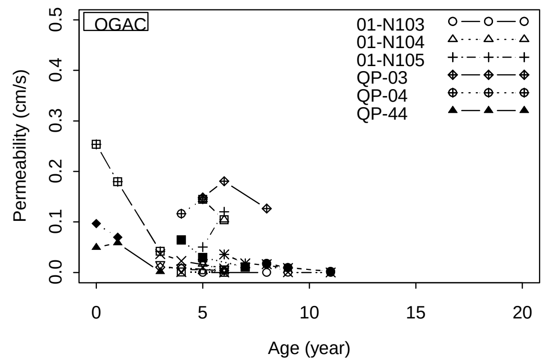
B.3.1 Trend Lines and Box Plots of Air-Void Content

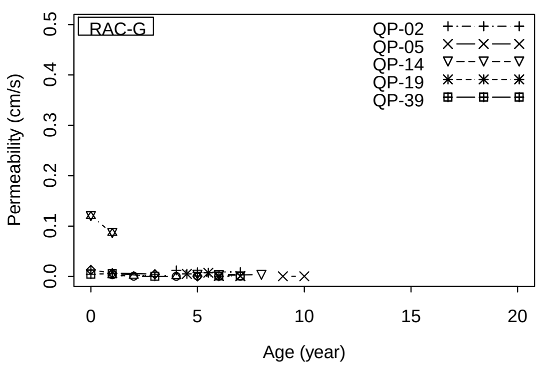


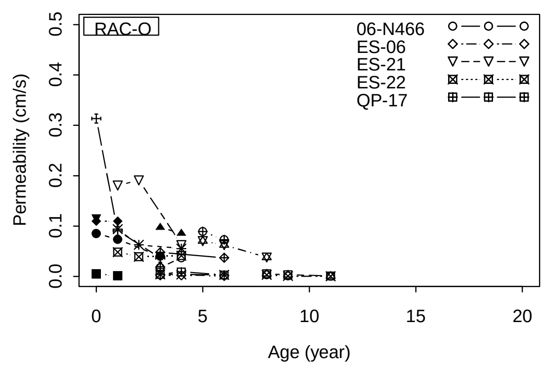


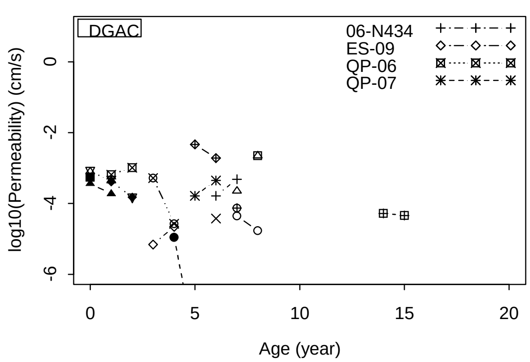
B.3.2 Trend Lines, Box Plots, and Regression Analysis of Permeability

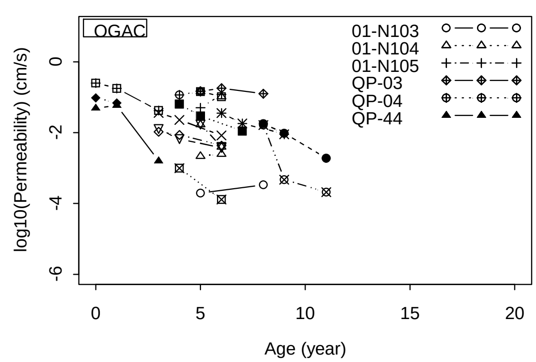


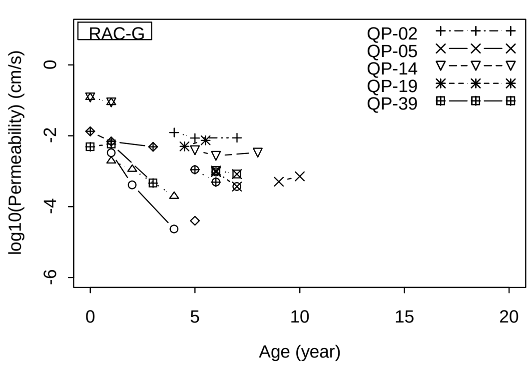


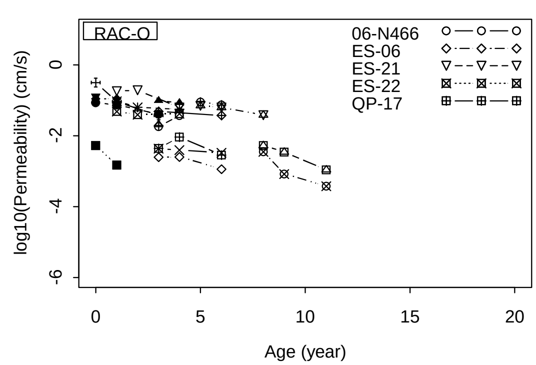


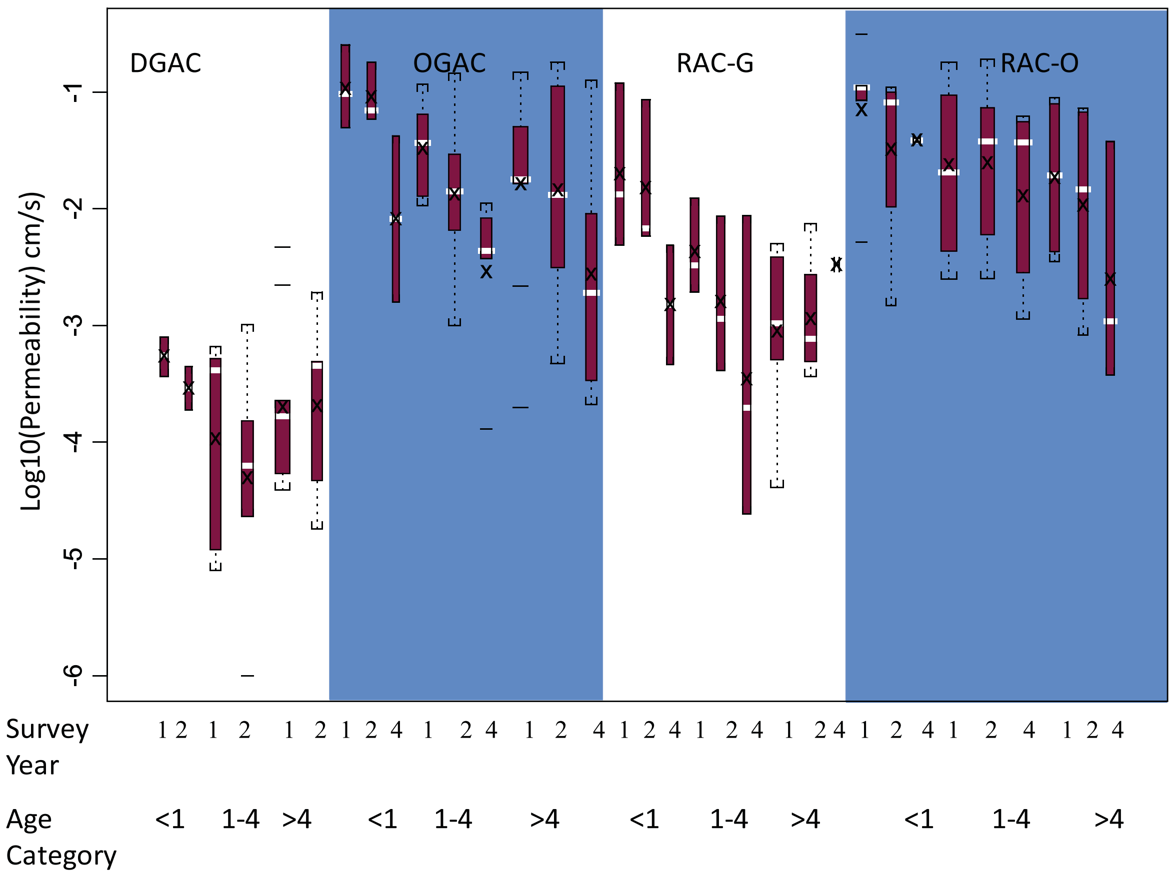












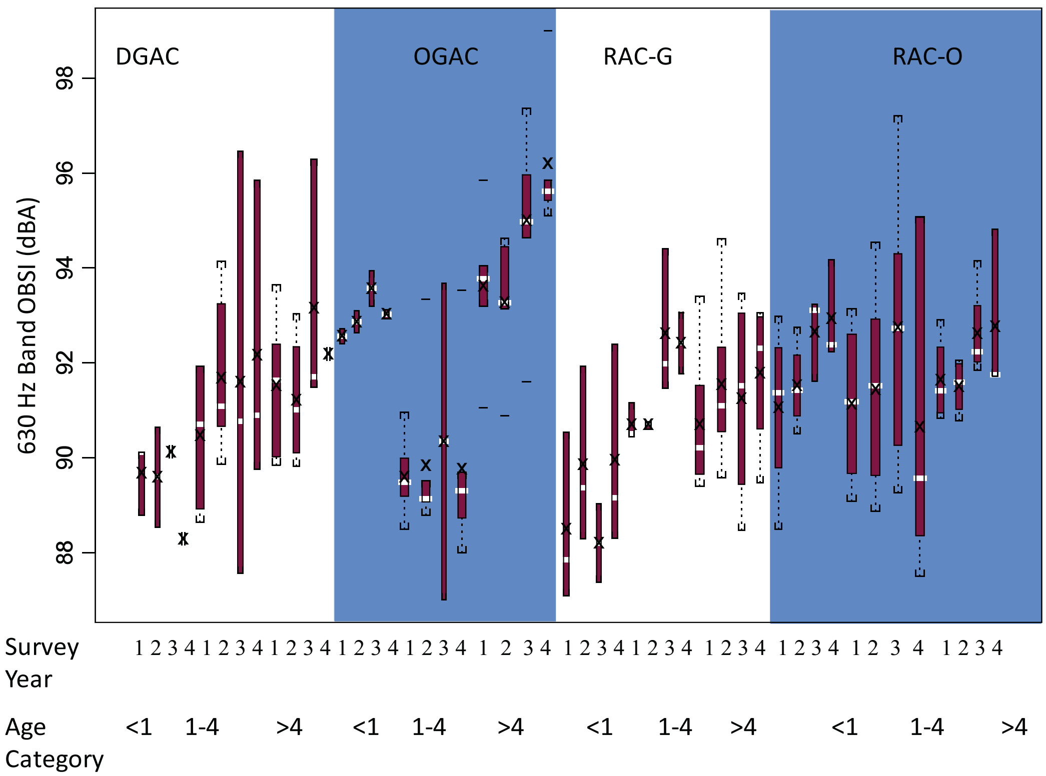
Multiple linear regression model:

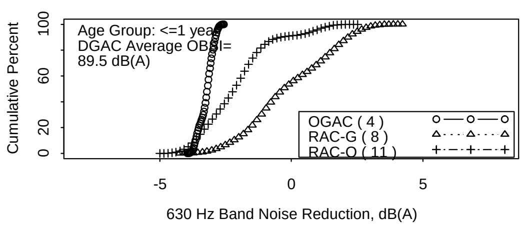
$$\log(Permeability[cm/s]) = -13.6863 - 0.2147 \times Age(year) + 1.4809 \times ind(OGAC) + 0.1943 \times ind(RAC-G) + 1.5398 \times ind(RAC-O) + 0.1696 \times AirVoid(\%) + 1.2788 \times FinenessModulus$$

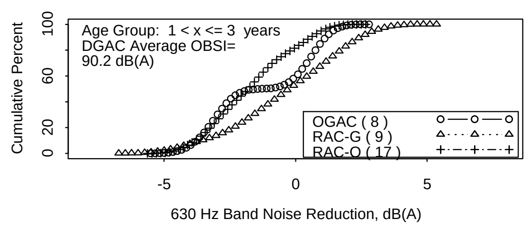
	Value	Std. Error	t value	P-value
(Intercept)	-13.6863	1.9798	-6.9131	<0.0001
Age	-0.2147	0.0373	-5.7536	<0.0001
PvmntTypeOGAC	1.4809	0.5255	2.8182	0.0054
PvmntTypeRAC-G	0.1943	0.4708	0.4128	0.6802
PvmntTypeRAC-O	1.5398	0.5214	2.9530	0.0036
AirVoid	0.1696	0.0380	4.4575	<0.0001
FinenessModulus	1.2788	0.4703	2.7189	0.0072

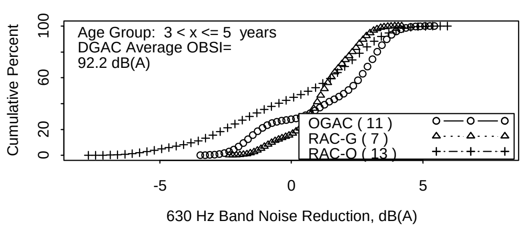
Residual standard error: 1.594 on 180 degrees of freedom; Multiple R-Squared: 0.65.

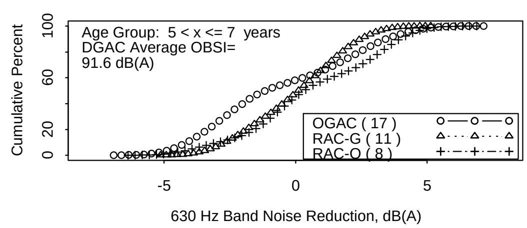
Appendix B.4: Box Plots and Cumulative Distribution of Noise Reduction for Sound Intensity at Other Frequency Bands

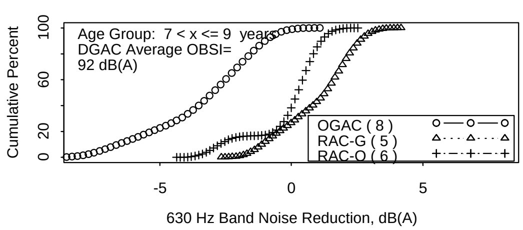


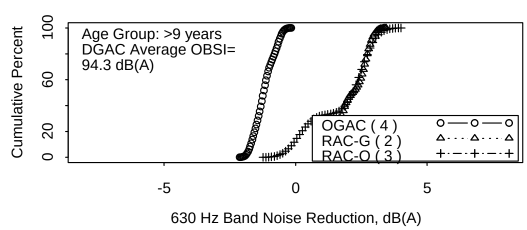


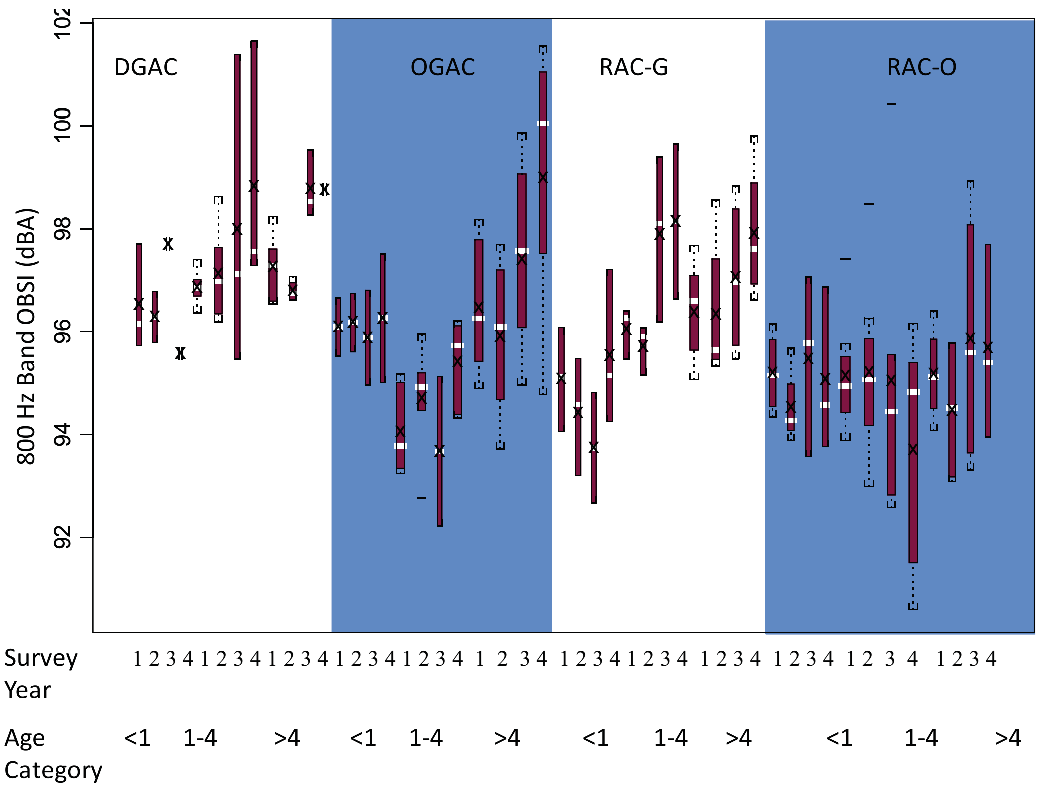


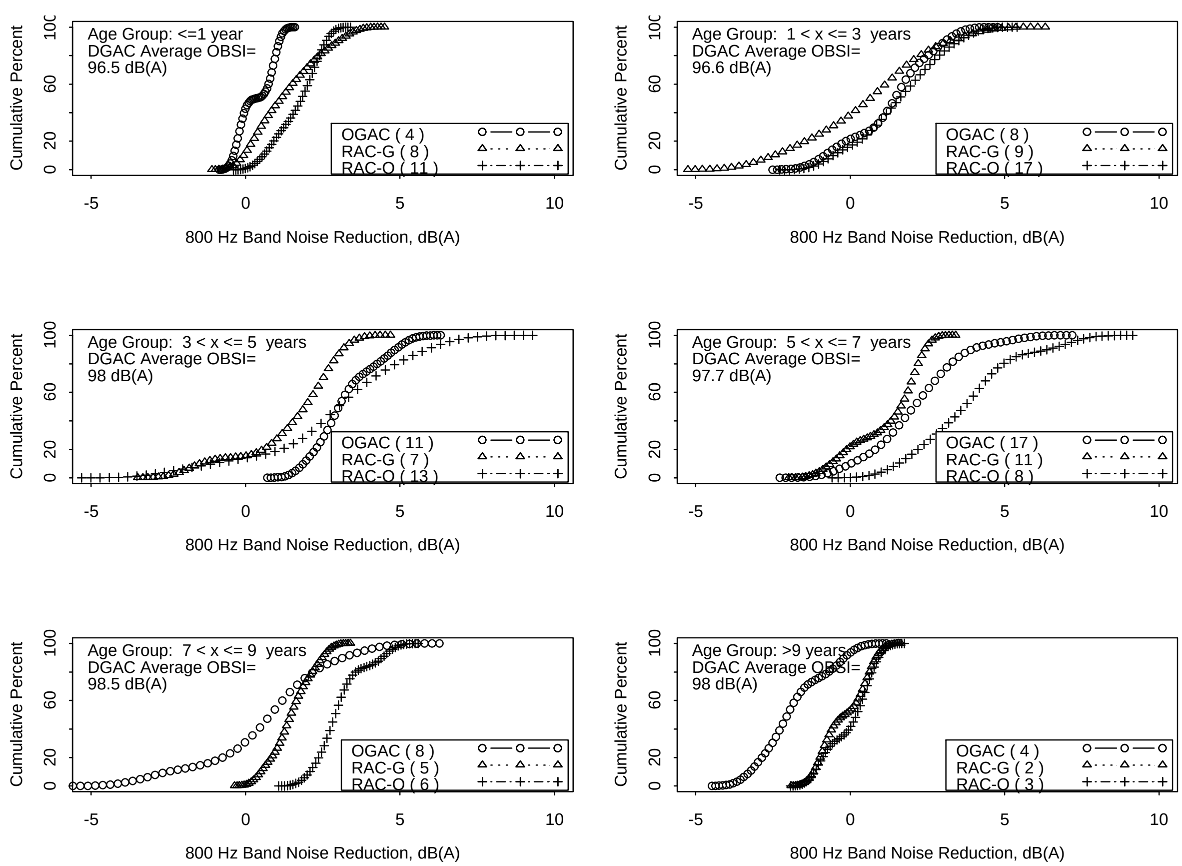


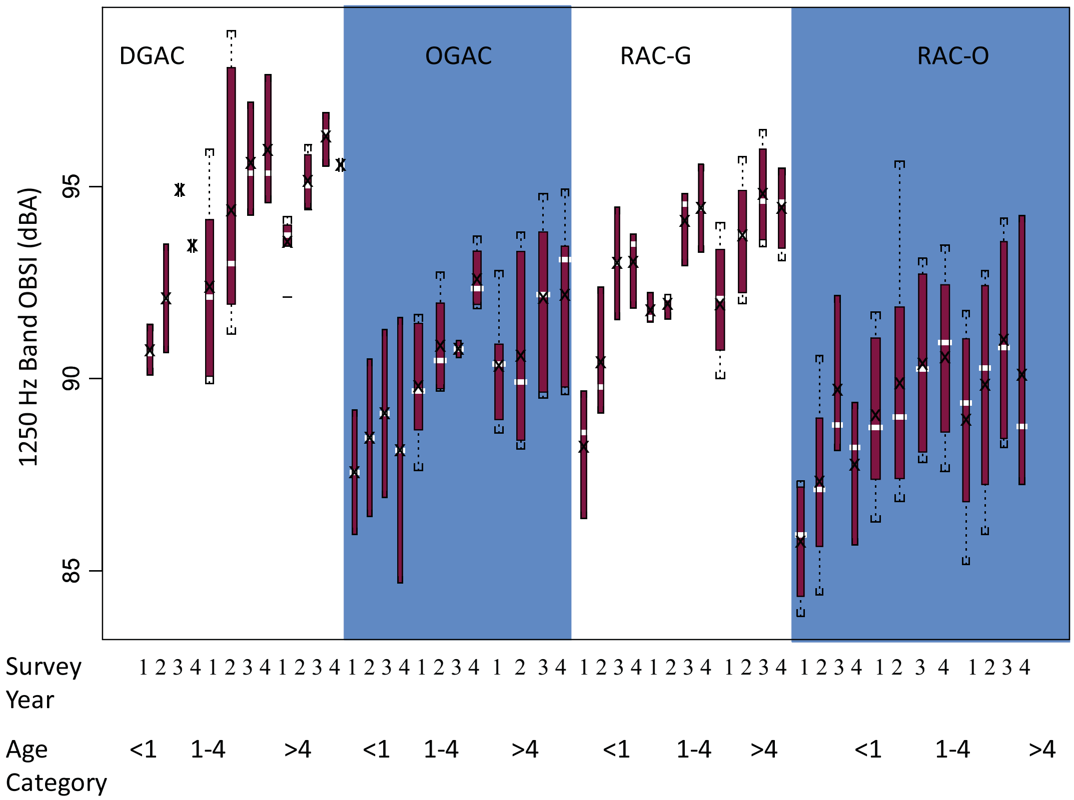


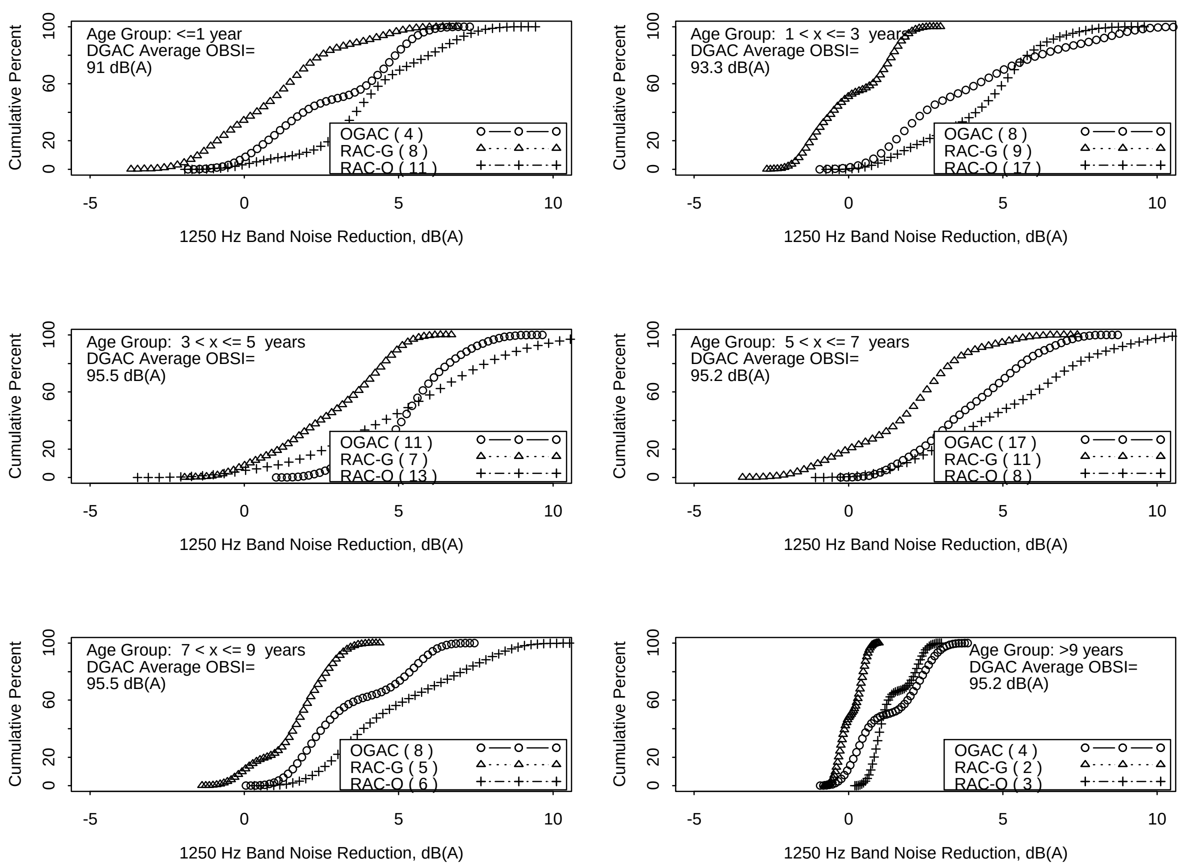


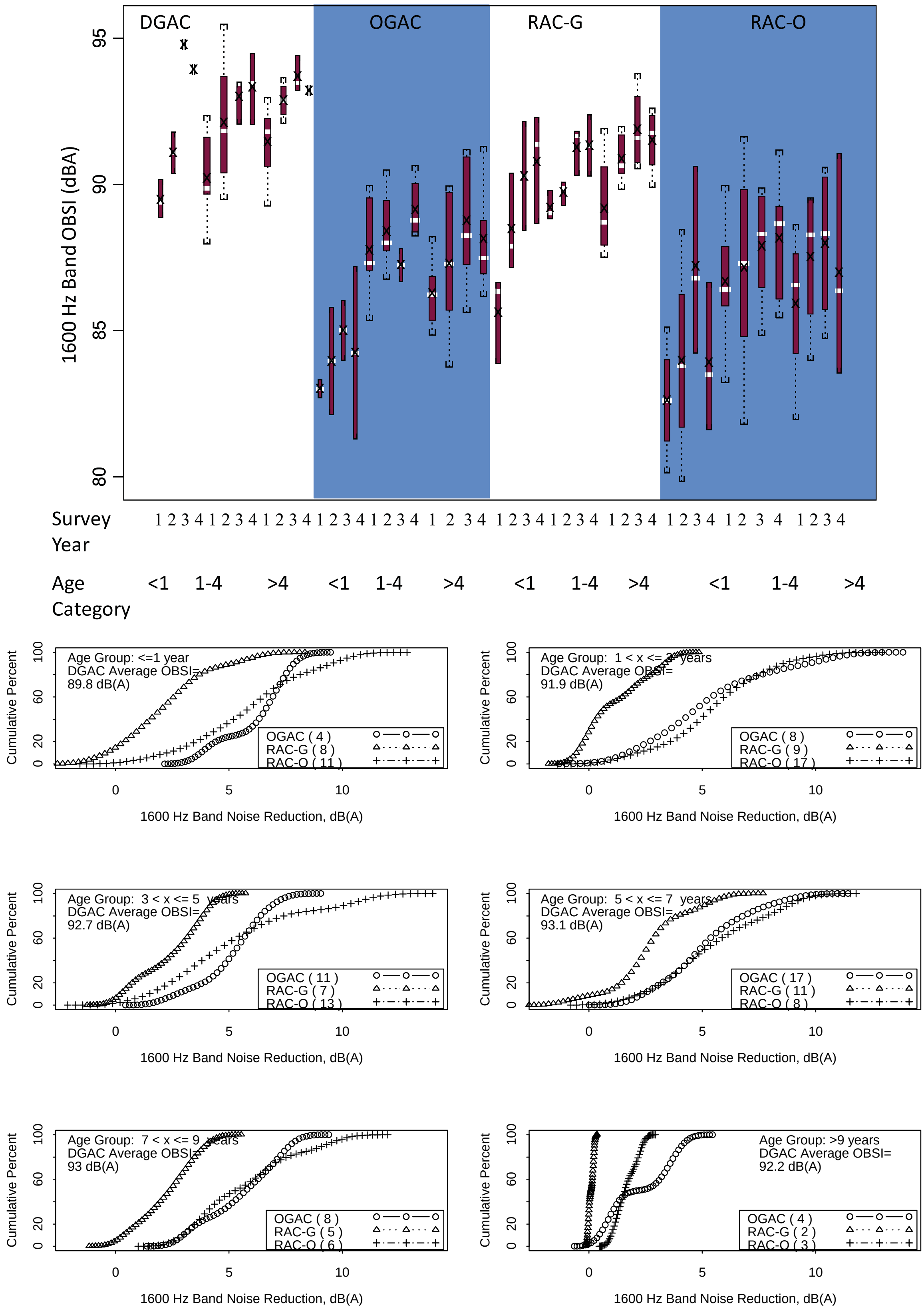



800 Hz Band OBSI (dBA)
92
94
96
98
100
102
DGAC
OGAC
RAC-G
RAC-O
Survey Year
1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
Age Category
<1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

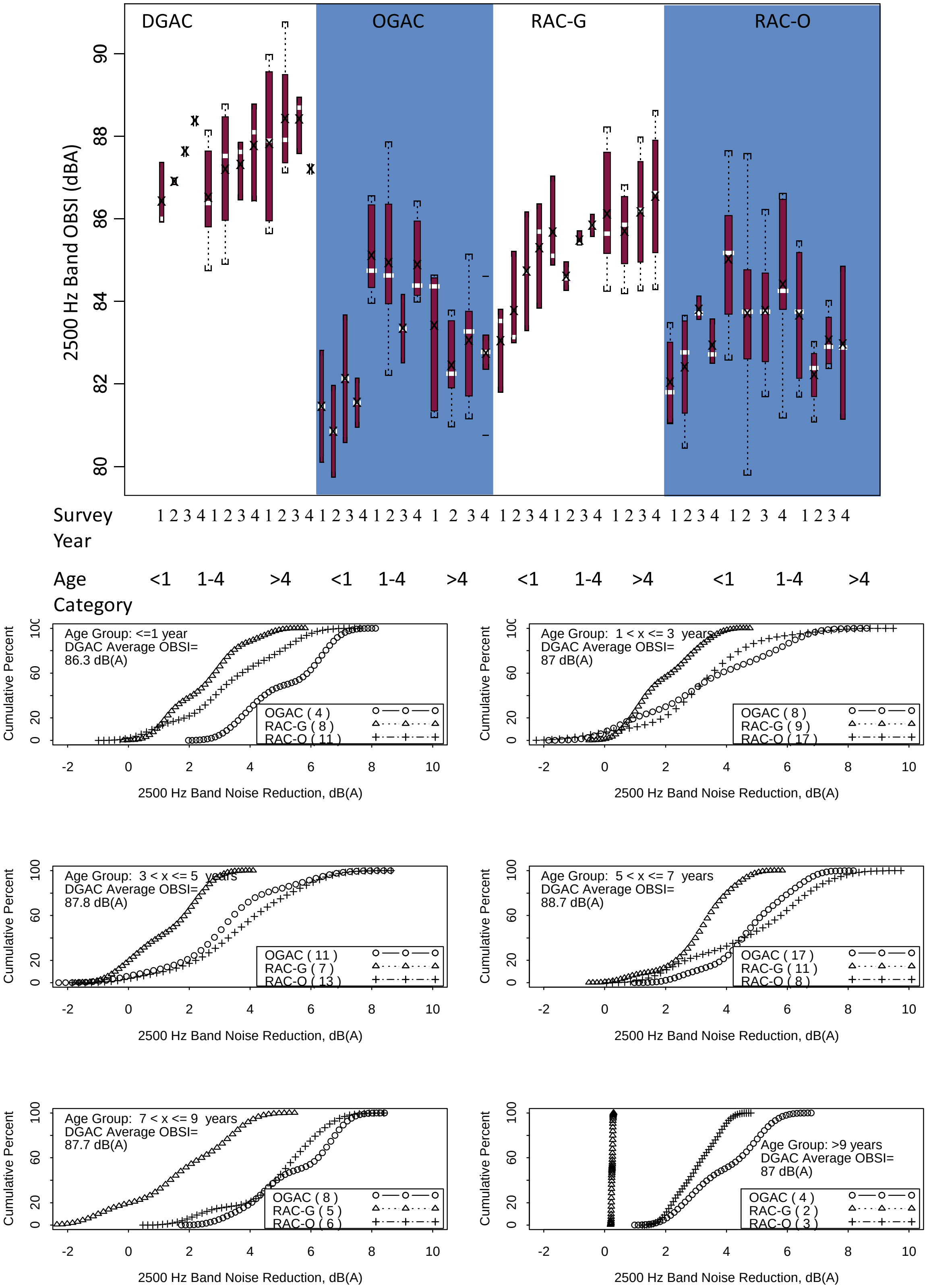

Age Group: <=1 year
DGAC Average OBSI=
96.5 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
96.6 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
98 dB(A)
OGAC (11)
RAC-G (7)
RAC-O (13)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
97.7 dB(A)
OGAC (17)
RAC-G (11)
RAC-O (8)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
98.5 dB(A)
OGAC (8)
RAC-G (5)
RAC-O (6)
Age Group: >9 years
DGAC Average OBSI=
98 dB(A)
OGAC (4)
RAC-G (2)
RAC-O (3)
Cumulative Percent
800 Hz Band Noise Reduction, dB(A)
-5
0
5
10


DGAC
OGAC
RAC-G
RAC-O
1250 Hz Band OBSI (dBA)
85
90
95
Survey Year
1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
Age Category
<1 1-4 >4 <1 1-4 >4 <1 1-4 >4 <1 1-4 >4

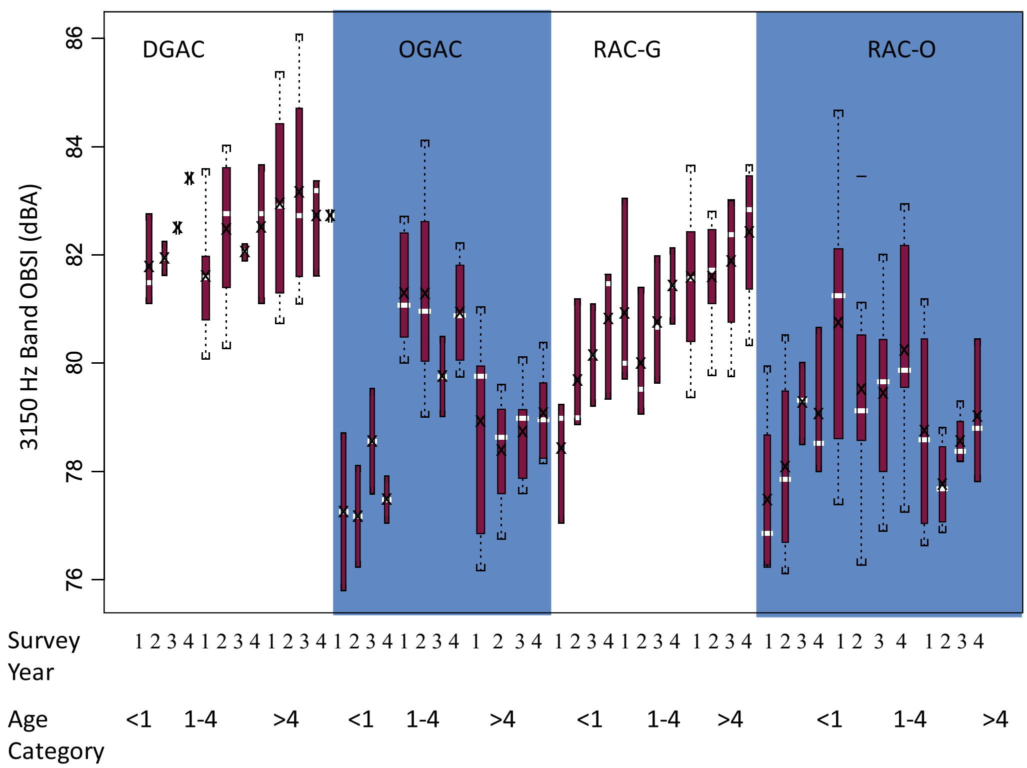

Age Group: <=1 year
DGAC Average OBSI=
91 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
93.3 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
95.5 dB(A)
OGAC (11)
RAC-G (7)
RAC-O (13)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
95.2 dB(A)
OGAC (17)
RAC-G (11)
RAC-O (8)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
95.5 dB(A)
OGAC (8)
RAC-G (5)
RAC-O (6)
Age Group: >9 years
DGAC Average OBSI=
95.2 dB(A)
OGAC (4)
RAC-G (2)
RAC-O (3)
Cumulative Percent
0 20 60 100
-5 0 5 10
1250 Hz Band Noise Reduction, dB(A)



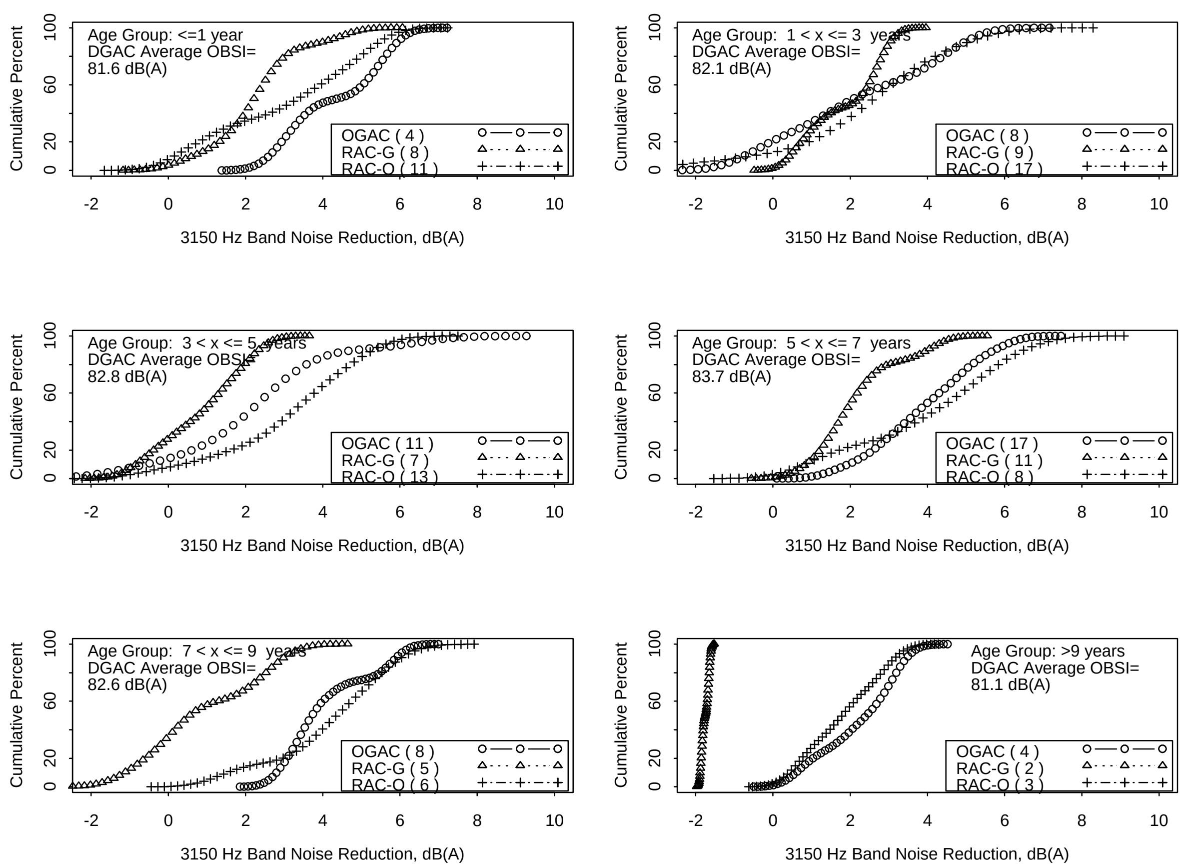
DGAC
OGAC
RAC-G
RAC-O
1600 Hz Band OBSI (dBA)
80
85
90
95
Survey Year
1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
Age Category
<1
1-4
>4
<1
1-4
>4
<1
1-4
>4
<1
1-4
>4
Age Group: <=1 year
DGAC Average OBSI=
89.8 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
91.9 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
92.7 dB(A)
OGAC (11)
RAC-G (7)
RAC-O (13)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
93.1 dB(A)
OGAC (17)
RAC-G (11)
RAC-O (8)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
93 dB(A)
OGAC (8)
RAC-G (5)
RAC-O (6)
Age Group: >9 years
DGAC Average OBSI=
92.2 dB(A)
OGAC (4)
RAC-G (2)
RAC-O (3)
Cumulative Percent
0
20
60
100
0
5
10
1600 Hz Band Noise Reduction, dB(A)



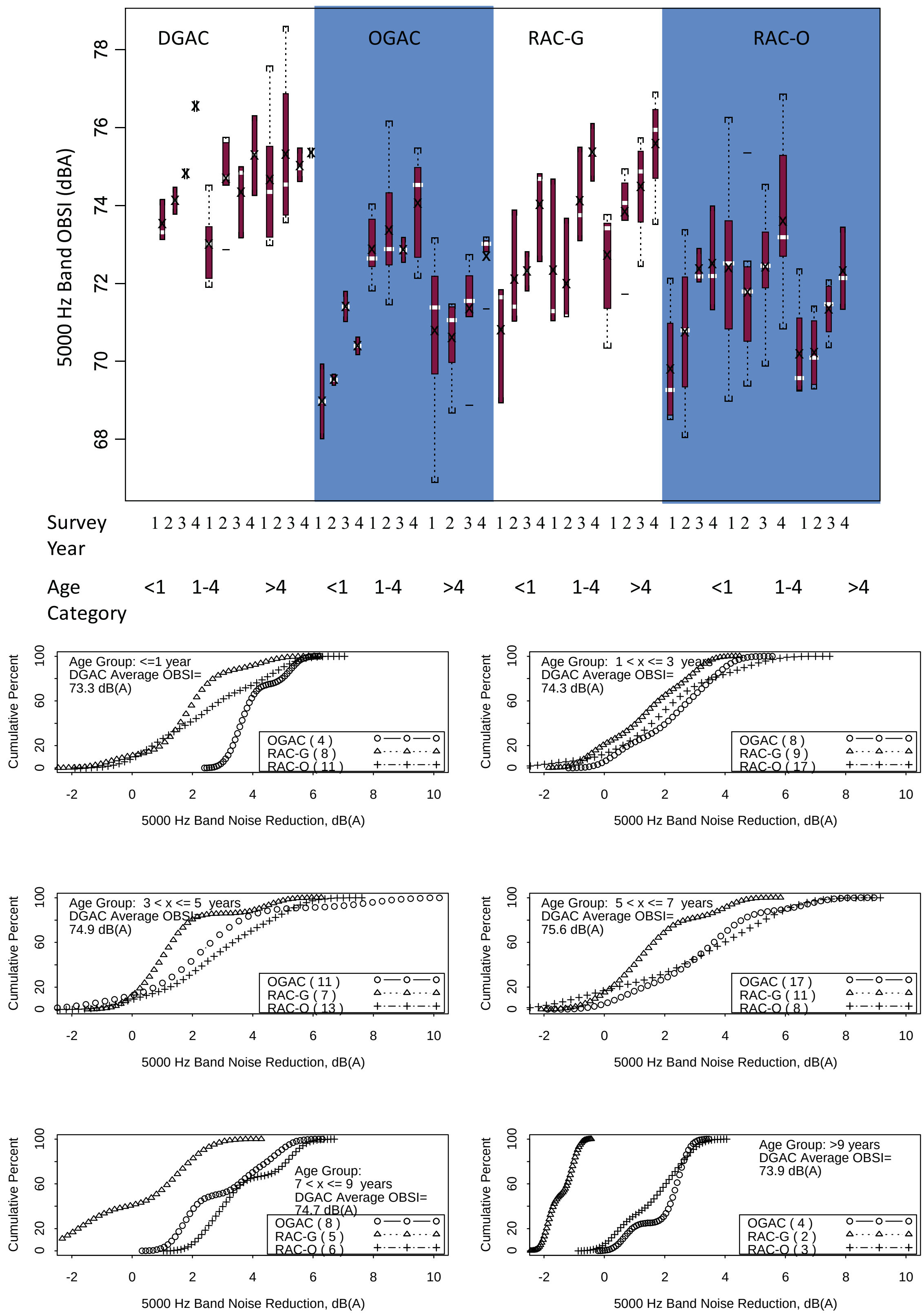
DGAC
OGAC
RAC-G
RAC-O
2500 Hz Band OBSI (dBA)
Survey Year
Age Category
<1
1-4
>4
Age Group: <=1 year
DGAC Average OBSI= 86.3 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI= 87 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Age Group: 3 < x <= 5 years
DGAC Average OBSI= 87.8 dB(A)
OGAC (11)
RAC-G (7)
RAC-O (13)
Age Group: 5 < x <= 7 years
DGAC Average OBSI= 88.7 dB(A)
OGAC (17)
RAC-G (11)
RAC-O (8)
Age Group: 7 < x <= 9 years
DGAC Average OBSI= 87.7 dB(A)
OGAC (8)
RAC-G (5)
RAC-O (6)
Age Group: >9 years
DGAC Average OBSI= 87 dB(A)
OGAC (4)
RAC-G (2)
RAC-O (3)
Cumulative Percent
2500 Hz Band Noise Reduction, dB(A)



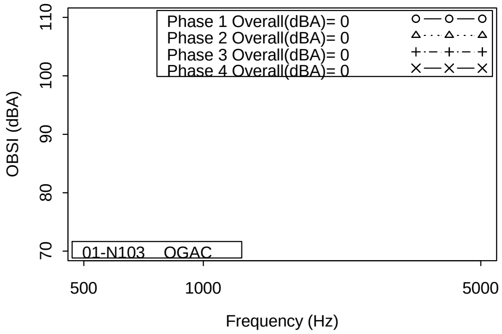
3150 Hz Band OBSI (dBA)
DGAC
OGAC
RAC-G
RAC-O
Survey Year
Age Category
<1
1-4
>4

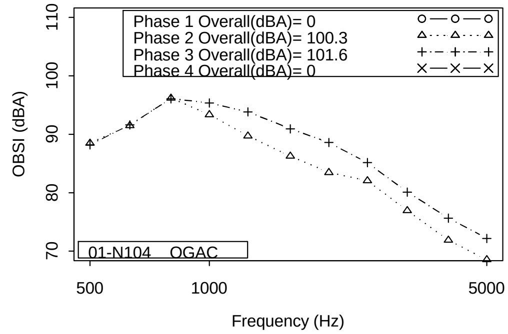


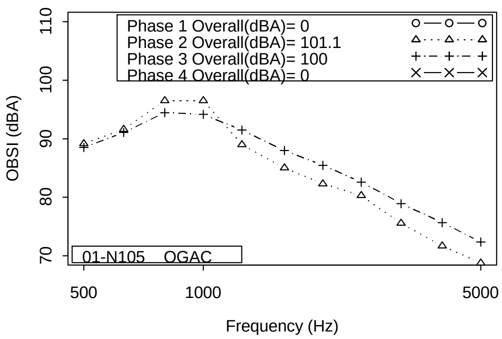
Cumulative Percent
3150 Hz Band Noise Reduction, dB(A)
Age Group: <=1 year
DGAC Average OBSI= 81.6 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI= 82.1 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Age Group: 3 < x <= 5 years
DGAC Average OBSI= 82.8 dB(A)
OGAC (11)
RAC-G (7)
RAC-O (13)
Age Group: 5 < x <= 7 years
DGAC Average OBSI= 83.7 dB(A)
OGAC (17)
RAC-G (11)
RAC-O (8)
Age Group: 7 < x <= 9 years
DGAC Average OBSI= 82.6 dB(A)
OGAC (8)
RAC-G (5)
RAC-O (6)
Age Group: >9 years
DGAC Average OBSI= 81.1 dB(A)
OGAC (4)
RAC-G (2)
RAC-O (3)

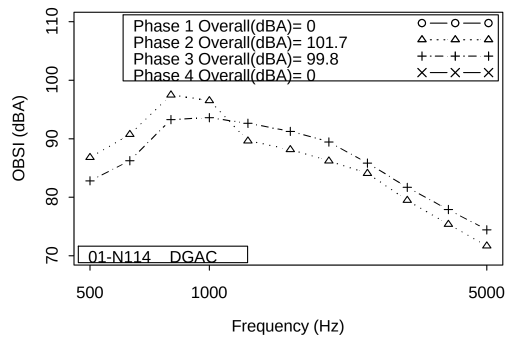

DGAC
OGAC
RAC-G
RAC-O
5000 Hz Band OBSI (dBA)
Survey Year
Age Category
<1
1-4
>4
Age Group: <=1 year
DGAC Average OBSI= 73.3 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI= 74.3 dB(A)
OGAC (8)
RAC-G (9)
RAC-O (17)
Age Group: 3 < x <= 5 years
DGAC Average OBSI= 74.9 dB(A)
OGAC (11)
RAC-G (7)
RAC-O (13)
Age Group: 5 < x <= 7 years
DGAC Average OBSI= 75.6 dB(A)
OGAC (17)
RAC-G (11)
RAC-O (8)
Age Group: 7 < x <= 9 years
DGAC Average OBSI= 74.7 dB(A)
OGAC (8)
RAC-G (5)
RAC-O (6)
Age Group: >9 years
DGAC Average OBSI= 73.9 dB(A)
OGAC (4)
RAC-G (2)
RAC-O (3)
Cumulative Percent
5000 Hz Band Noise Reduction, dB(A)

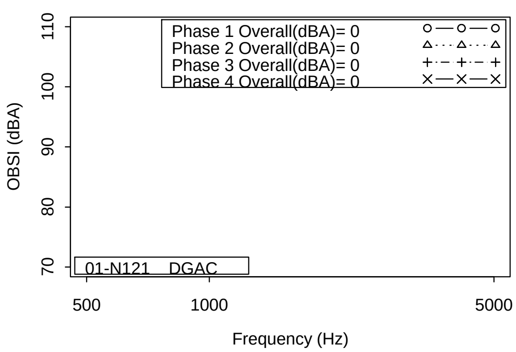
Appendix B.5: Sound Intensity Spectra Measured in Four Years for Each Pavement Section

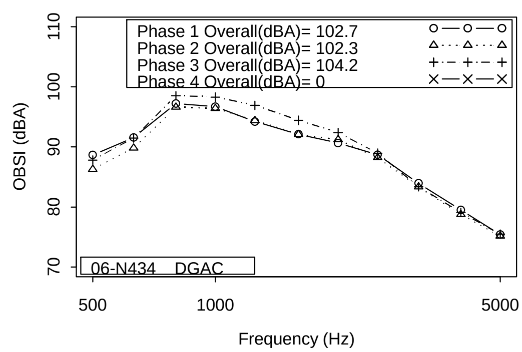


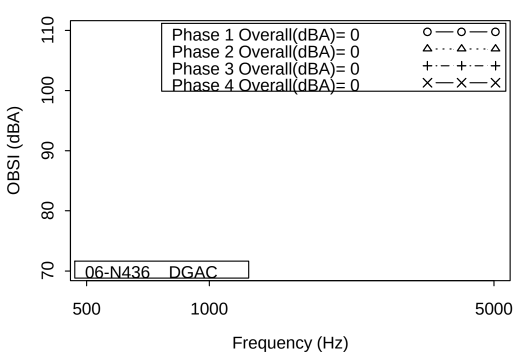


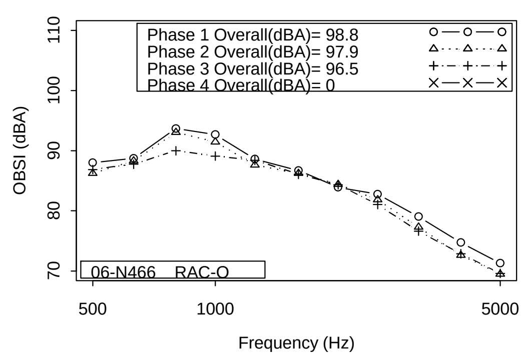


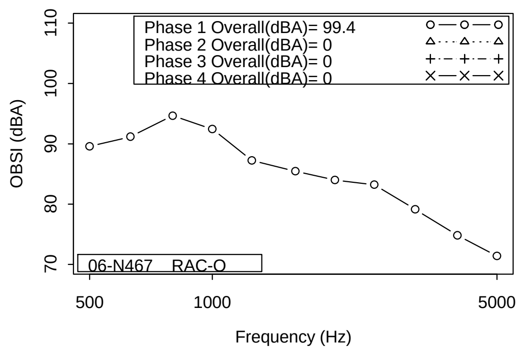


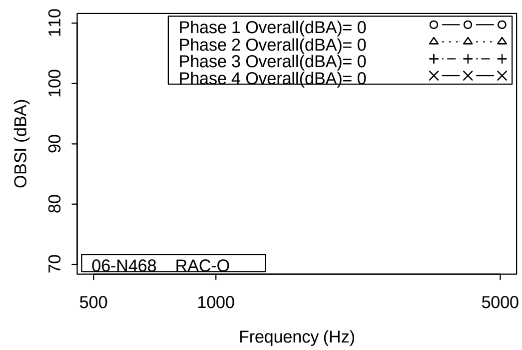


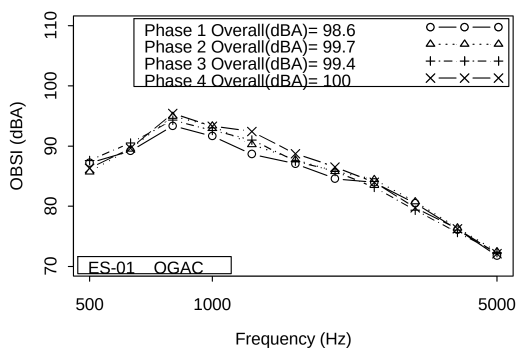


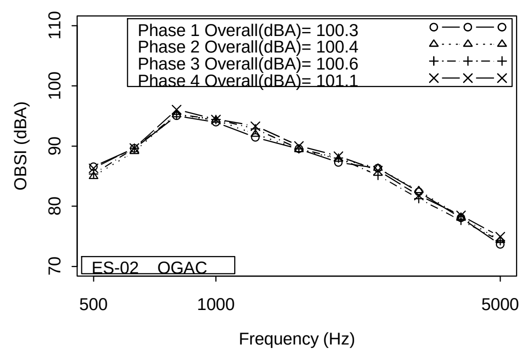


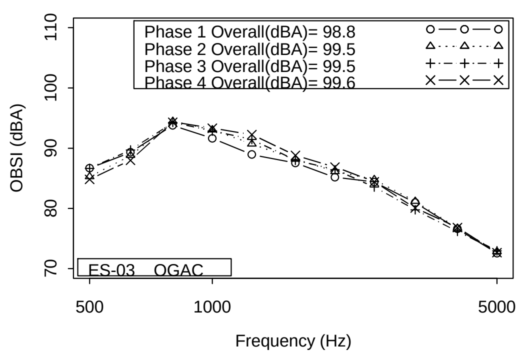


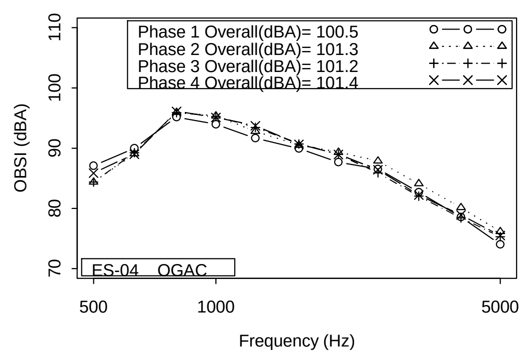

Phase 1 Overall(dBA)= 99.4
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
06-N467 RAC-O
OBSI (dBA)
Frequency (Hz)

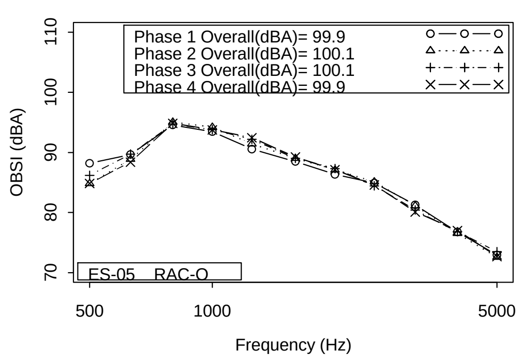

Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
06-N468 RAC-O
OBSI (dBA)
Frequency (Hz)

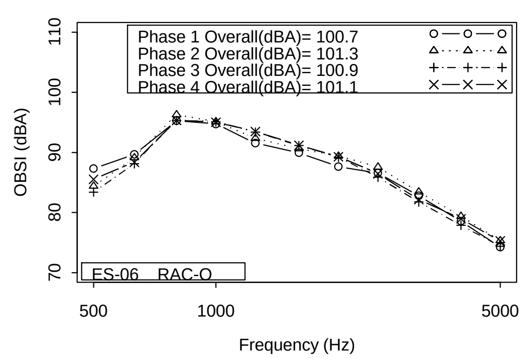

Phase 1 Overall(dBA)= 98.6
Phase 2 Overall(dBA)= 99.7
Phase 3 Overall(dBA)= 99.4
Phase 4 Overall(dBA)= 100
ES-01 OGAC
OBSI (dBA)
Frequency (Hz)

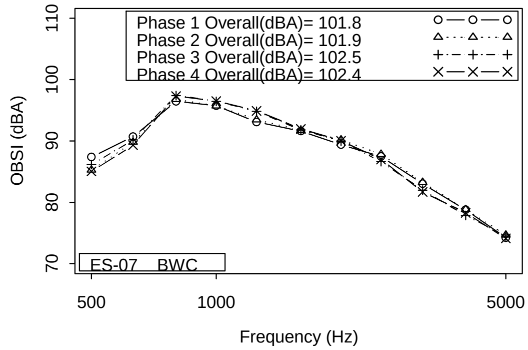

Phase 1 Overall(dBA)= 100.3
Phase 2 Overall(dBA)= 100.4
Phase 3 Overall(dBA)= 100.6
Phase 4 Overall(dBA)= 101.1
ES-02 OGAC
OBSI (dBA)
Frequency (Hz)

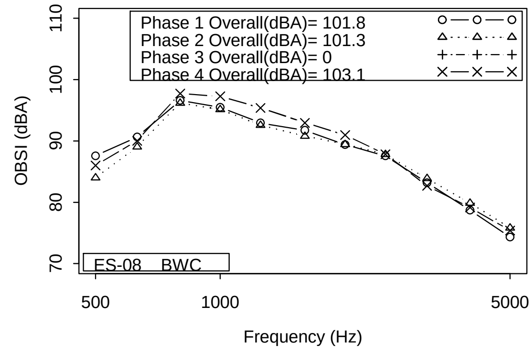

Phase 1 Overall(dBA)= 98.8
Phase 2 Overall(dBA)= 99.5
Phase 3 Overall(dBA)= 99.5
Phase 4 Overall(dBA)= 99.6
ES-03 OGAC
OBSI (dBA)
Frequency (Hz)

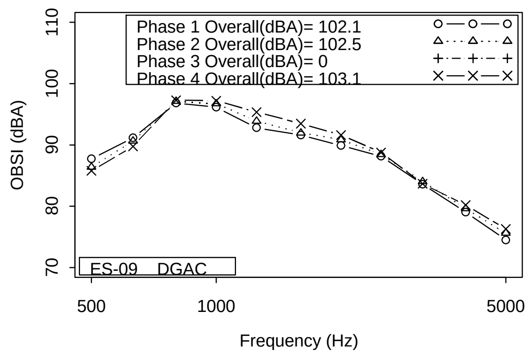

Phase 1 Overall(dBA)= 100.5
Phase 2 Overall(dBA)= 101.3
Phase 3 Overall(dBA)= 101.2
Phase 4 Overall(dBA)= 101.4
ES-04 OGAC
OBSI (dBA)
Frequency (Hz)

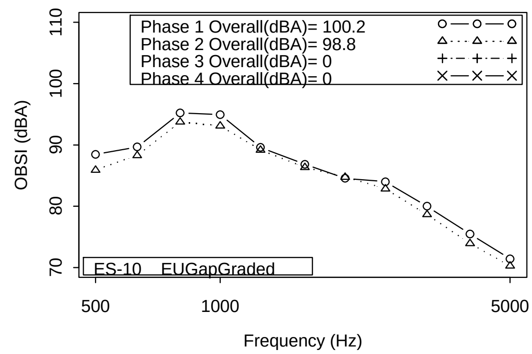

Phase 1 Overall(dBA)= 99.9
Phase 2 Overall(dBA)= 100.1
Phase 3 Overall(dBA)= 100.1
Phase 4 Overall(dBA)= 99.9
ES-05 RAC-O
OBSI (dBA)
Frequency (Hz)

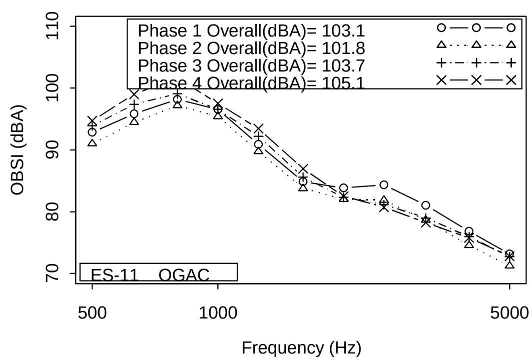

Phase 1 Overall(dBA)= 100.7
Phase 2 Overall(dBA)= 101.3
Phase 3 Overall(dBA)= 100.9
Phase 4 Overall(dBA)= 101.1
ES-06 RAC-O
OBSI (dBA)
Frequency (Hz)

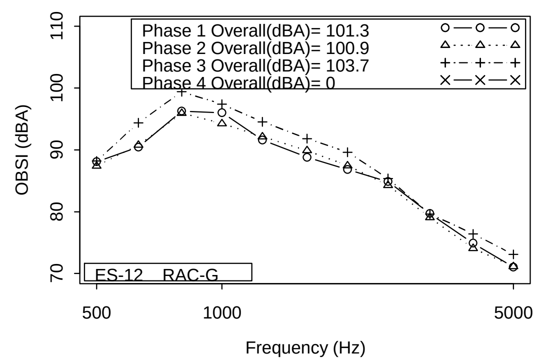

Phase 1 Overall(dBA)= 101.8
Phase 2 Overall(dBA)= 101.9
Phase 3 Overall(dBA)= 102.5
Phase 4 Overall(dBA)= 102.4
ES-07 BWC
OBSI (dBA)
Frequency (Hz)

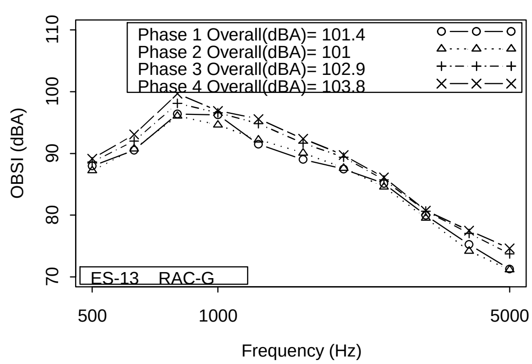

Phase 1 Overall(dBA)= 101.8
Phase 2 Overall(dBA)= 101.3
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 103.1
ES-08 BWC
OBSI (dBA)
Frequency (Hz)

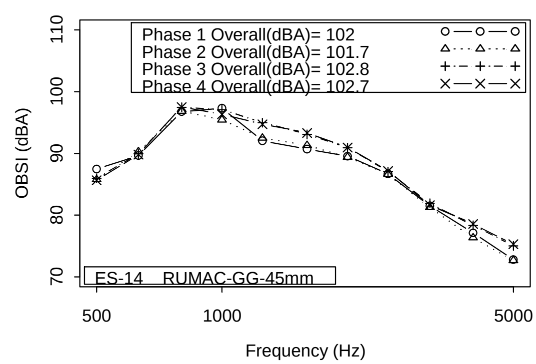

Phase 1 Overall(dBA)= 102.1
Phase 2 Overall(dBA)= 102.5
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 103.1
ES-09 DGAC
OBSI (dBA)
Frequency (Hz)

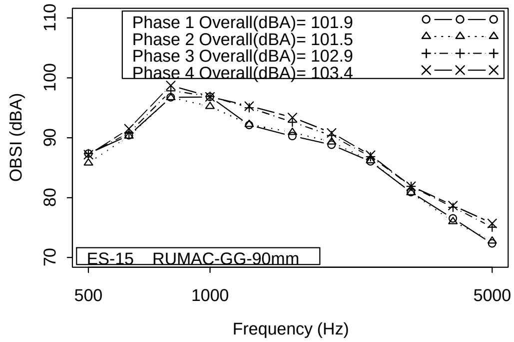

Phase 1 Overall(dBA)= 100.2
Phase 2 Overall(dBA)= 98.8
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
ES-10 EUGapGraded
OBSI (dBA)
Frequency (Hz)

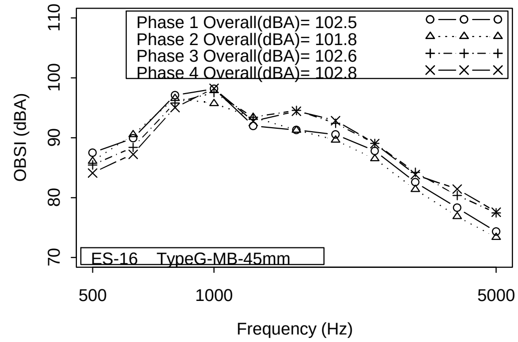

Phase 1 Overall(dBA)= 103.1
Phase 2 Overall(dBA)= 101.8
Phase 3 Overall(dBA)= 103.7
Phase 4 Overall(dBA)= 105.1
ES-11 OGAC
OBSI (dBA)
Frequency (Hz)

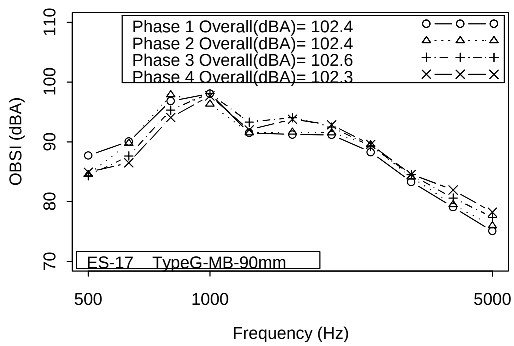

Phase 1 Overall(dBA)= 101.3
Phase 2 Overall(dBA)= 100.9
Phase 3 Overall(dBA)= 103.7
Phase 4 Overall(dBA)= 0
ES-12 RAC-G
OBSI (dBA)
Frequency (Hz)

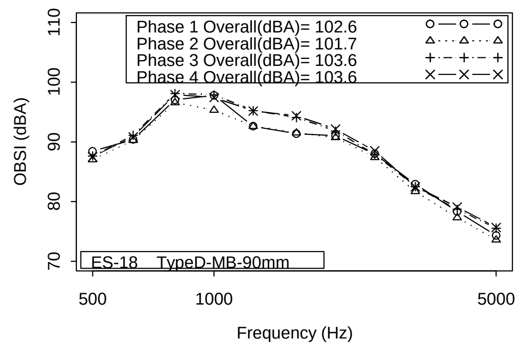

Phase 1 Overall(dBA)= 101.4
Phase 2 Overall(dBA)= 101
Phase 3 Overall(dBA)= 102.9
Phase 4 Overall(dBA)= 103.8
ES-13 RAC-G
OBSI (dBA)
Frequency (Hz)

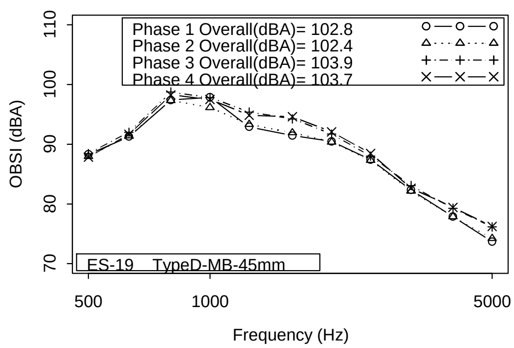

Phase 1 Overall(dBA)= 102
Phase 2 Overall(dBA)= 101.7
Phase 3 Overall(dBA)= 102.8
Phase 4 Overall(dBA)= 102.7
ES-14 RUMAC-GG-45mm
OBSI (dBA)
Frequency (Hz)

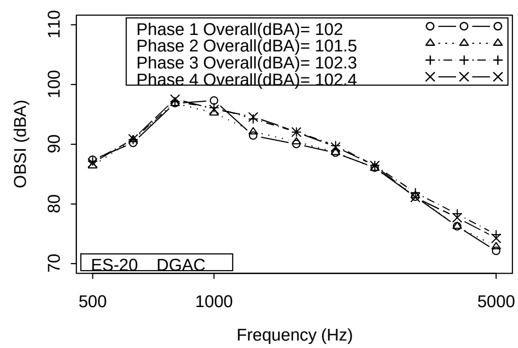

Phase 1 Overall(dBA)= 101.9
Phase 2 Overall(dBA)= 101.5
Phase 3 Overall(dBA)= 102.9
Phase 4 Overall(dBA)= 103.4
ES-15 RUMAC-GG-90mm
OBSI (dBA)
Frequency (Hz)

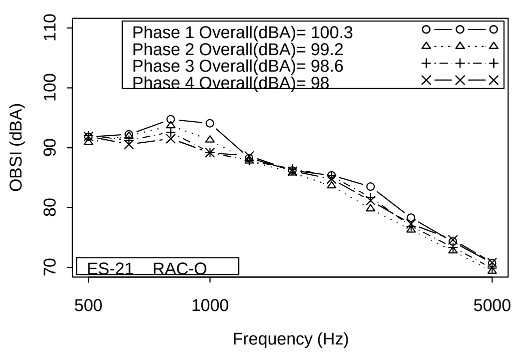

Phase 1 Overall(dBA)= 102.5
Phase 2 Overall(dBA)= 101.8
Phase 3 Overall(dBA)= 102.6
Phase 4 Overall(dBA)= 102.8
ES-16 TypeG-MB-45mm
OBSI (dBA)
Frequency (Hz)

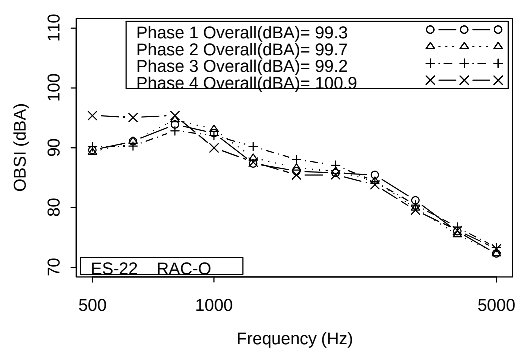

Phase 1 Overall(dBA)= 102.4
Phase 2 Overall(dBA)= 102.4
Phase 3 Overall(dBA)= 102.6
Phase 4 Overall(dBA)= 102.3
ES-17 TypeG-MB-90mm
OBSI (dBA)
Frequency (Hz)

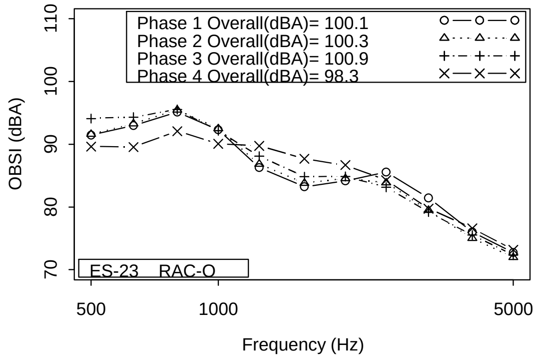

Phase 1 Overall(dBA)= 102.6
Phase 2 Overall(dBA)= 101.7
Phase 3 Overall(dBA)= 103.6
Phase 4 Overall(dBA)= 103.6
ES-18 TypeD-MB-90mm
OBSI (dBA)
Frequency (Hz)

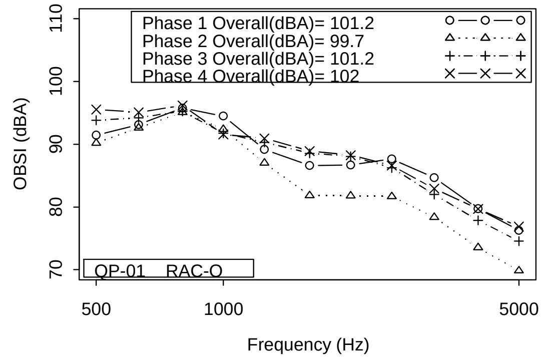

Phase 1 Overall(dBA)= 102.8
Phase 2 Overall(dBA)= 102.4
Phase 3 Overall(dBA)= 103.9
Phase 4 Overall(dBA)= 103.7
ES-19 TypeD-MB-45mm
OBSI (dBA)
Frequency (Hz)

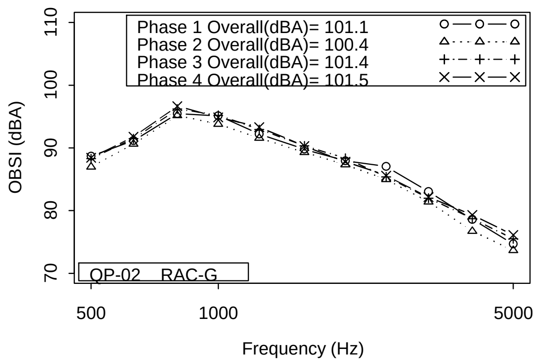

Phase 1 Overall(dBA)= 102
Phase 2 Overall(dBA)= 101.5
Phase 3 Overall(dBA)= 102.3
Phase 4 Overall(dBA)= 102.4
ES-20 DGAC
OBSI (dBA)
Frequency (Hz)

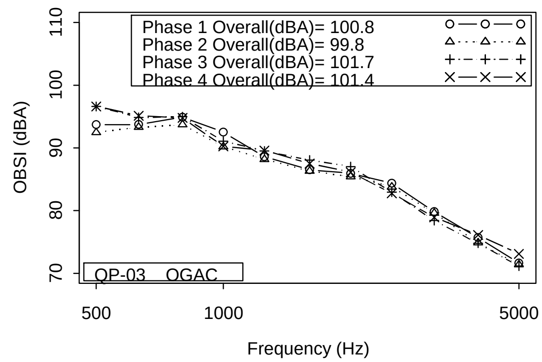

Phase 1 Overall(dBA)= 100.3
Phase 2 Overall(dBA)= 99.2
Phase 3 Overall(dBA)= 98.6
Phase 4 Overall(dBA)= 98
ES-21 RAC-O
OBSI (dBA)
Frequency (Hz)

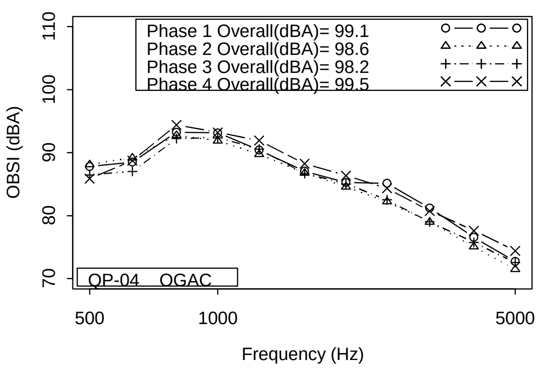

Phase 1 Overall(dBA)= 99.3
Phase 2 Overall(dBA)= 99.7
Phase 3 Overall(dBA)= 99.2
Phase 4 Overall(dBA)= 100.9
ES-22 RAC-O
OBSI (dBA)
Frequency (Hz)

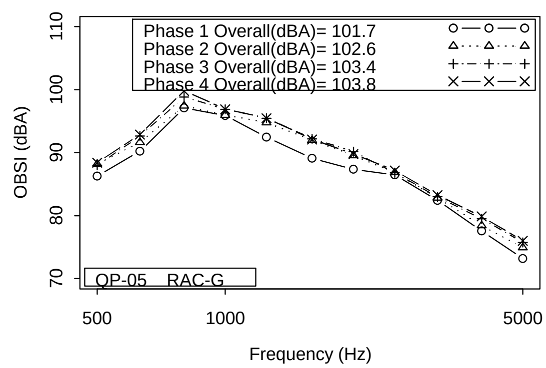

Phase 1 Overall(dBA)= 100.1
Phase 2 Overall(dBA)= 100.3
Phase 3 Overall(dBA)= 100.9
Phase 4 Overall(dBA)= 98.3
ES-23 RAC-O
OBSI (dBA)
Frequency (Hz)

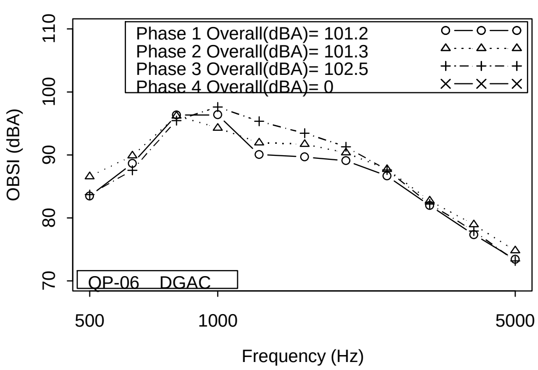

Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 99.7
Phase 3 Overall(dBA)= 101.2
Phase 4 Overall(dBA)= 102
QP-01 RAC-O
OBSI (dBA)
Frequency (Hz)

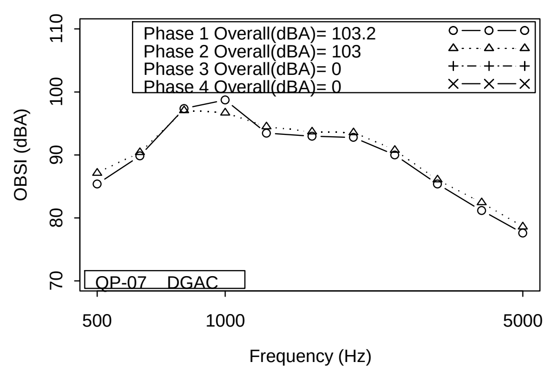

Phase 1 Overall(dBA)= 101.1
Phase 2 Overall(dBA)= 100.4
Phase 3 Overall(dBA)= 101.4
Phase 4 Overall(dBA)= 101.5
QP-02 RAC-G
OBSI (dBA)
Frequency (Hz)

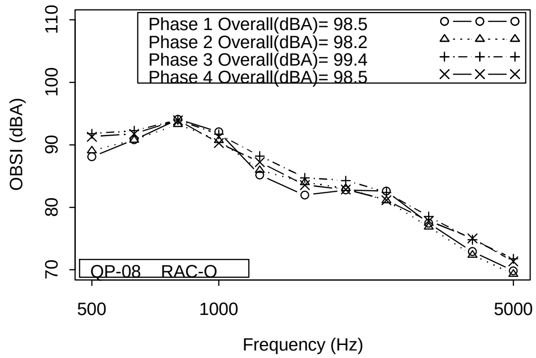

Phase 1 Overall(dBA)= 100.8
Phase 2 Overall(dBA)= 99.8
Phase 3 Overall(dBA)= 101.7
Phase 4 Overall(dBA)= 101.4
QP-03 OGAC
OBSI (dBA)
Frequency (Hz)

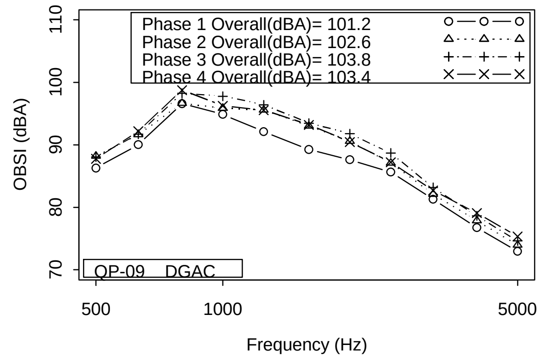

Phase 1 Overall(dBA)= 99.1
Phase 2 Overall(dBA)= 98.6
Phase 3 Overall(dBA)= 98.2
Phase 4 Overall(dBA)= 99.5
QP-04 OGAC
OBSI (dBA)
Frequency (Hz)

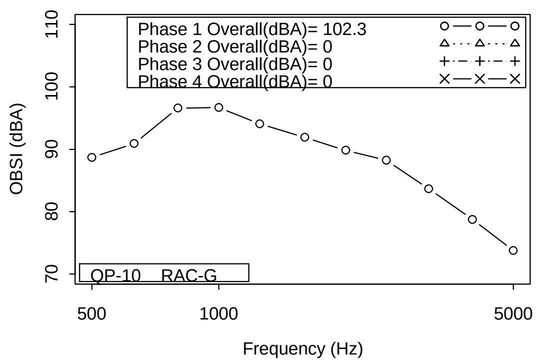

Phase 1 Overall(dBA)= 101.7
Phase 2 Overall(dBA)= 102.6
Phase 3 Overall(dBA)= 103.4
Phase 4 Overall(dBA)= 103.8
QP-05 RAC-G
OBSI (dBA)
Frequency (Hz)

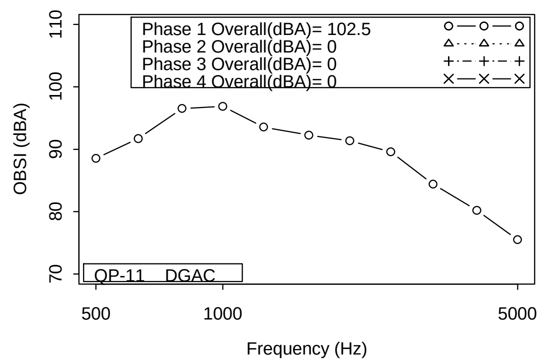

Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 101.3
Phase 3 Overall(dBA)= 102.5
Phase 4 Overall(dBA)= 0
QP-06 DGAC
OBSI (dBA)
Frequency (Hz)

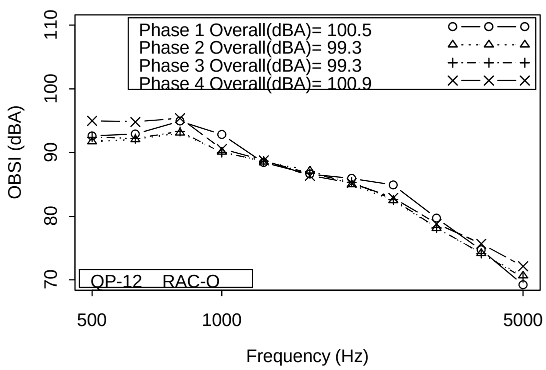

Phase 1 Overall(dBA)= 103.2
Phase 2 Overall(dBA)= 103
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
QP-07 DGAC
OBSI (dBA)
Frequency (Hz)

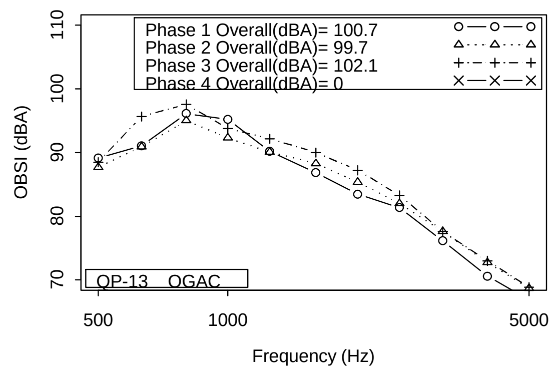

Phase 1 Overall(dBA)= 98.5
Phase 2 Overall(dBA)= 98.2
Phase 3 Overall(dBA)= 99.4
Phase 4 Overall(dBA)= 98.5
OBSI (dBA)
Frequency (Hz)
QP-08 RAC-O

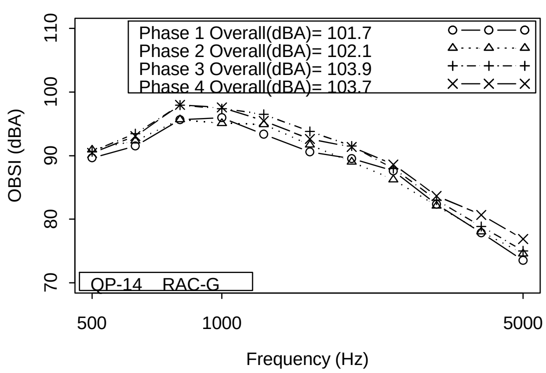

Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 102.6
Phase 3 Overall(dBA)= 103.8
Phase 4 Overall(dBA)= 103.4
OBSI (dBA)
Frequency (Hz)
QP-09 DGAC

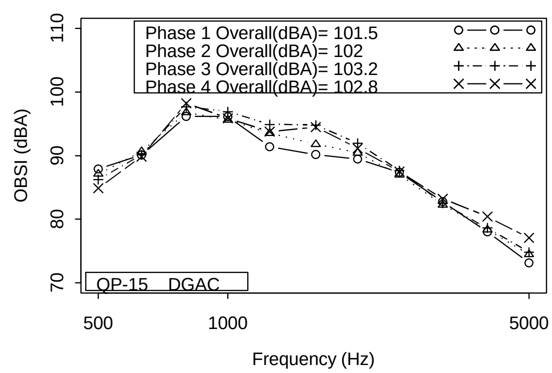

Phase 1 Overall(dBA)= 102.3
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
OBSI (dBA)
Frequency (Hz)
QP-10 RAC-G

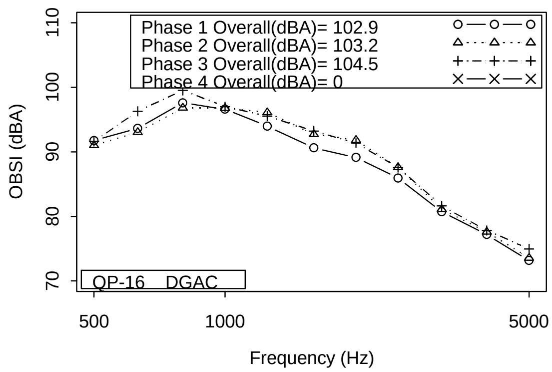

Phase 1 Overall(dBA)= 102.5
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
OBSI (dBA)
Frequency (Hz)
QP-11 DGAC

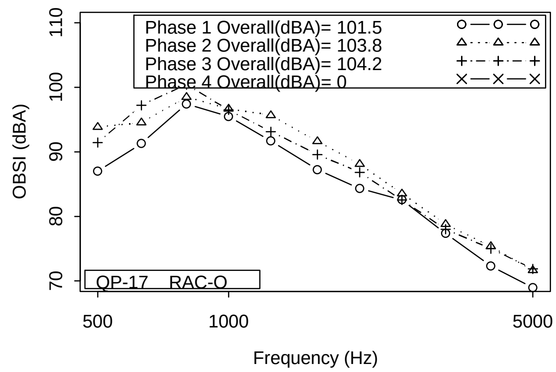

Phase 1 Overall(dBA)= 100.5
Phase 2 Overall(dBA)= 99.3
Phase 3 Overall(dBA)= 99.3
Phase 4 Overall(dBA)= 100.9
OBSI (dBA)
Frequency (Hz)
QP-12 RAC-O

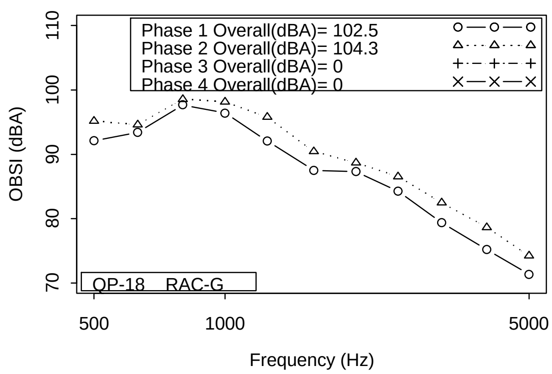

Phase 1 Overall(dBA)= 100.7
Phase 2 Overall(dBA)= 99.7
Phase 3 Overall(dBA)= 102.1
Phase 4 Overall(dBA)= 0
OBSI (dBA)
Frequency (Hz)
QP-13 OGAC

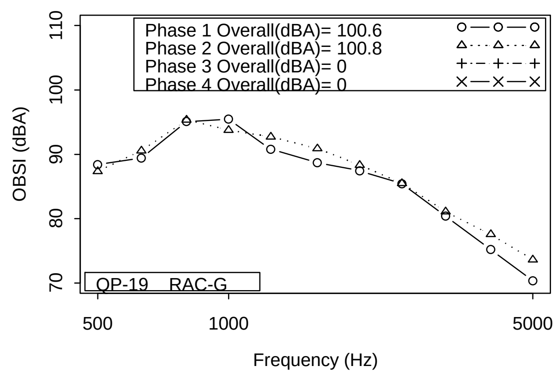

Phase 1 Overall(dBA)= 101.7
Phase 2 Overall(dBA)= 102.1
Phase 3 Overall(dBA)= 103.9
Phase 4 Overall(dBA)= 103.7
OBSI (dBA)
Frequency (Hz)
QP-14 RAC-G

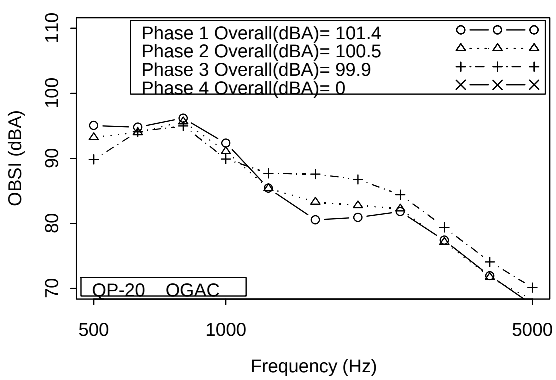

Phase 1 Overall(dBA)= 101.5
Phase 2 Overall(dBA)= 102
Phase 3 Overall(dBA)= 103.2
Phase 4 Overall(dBA)= 102.8
OBSI (dBA)
Frequency (Hz)
QP-15 DGAC

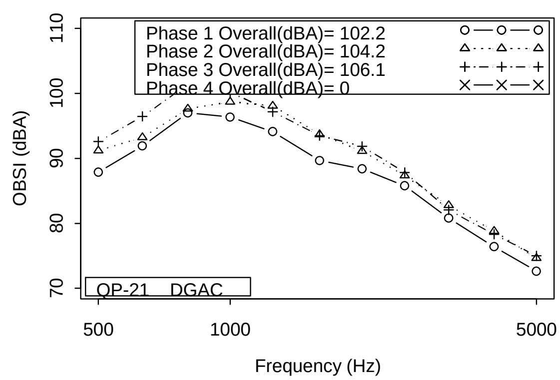

Phase 1 Overall(dBA)= 102.9
Phase 2 Overall(dBA)= 103.2
Phase 3 Overall(dBA)= 104.5
Phase 4 Overall(dBA)= 0
QP-16 DGAC
OBSI (dBA)
Frequency (Hz)

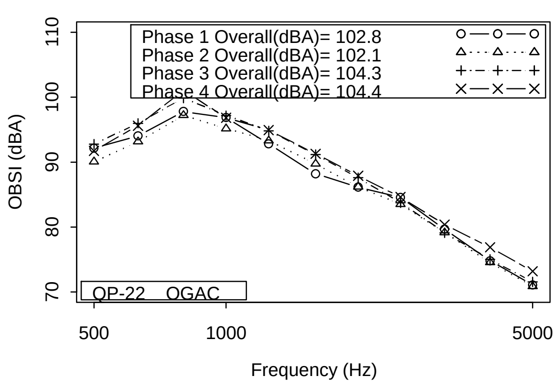

Phase 1 Overall(dBA)= 101.5
Phase 2 Overall(dBA)= 103.8
Phase 3 Overall(dBA)= 104.2
Phase 4 Overall(dBA)= 0
QP-17 RAC-O
OBSI (dBA)
Frequency (Hz)

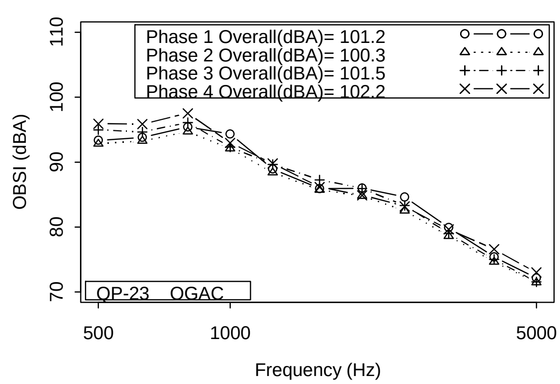

Phase 1 Overall(dBA)= 102.5
Phase 2 Overall(dBA)= 104.3
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
QP-18 RAC-G
OBSI (dBA)
Frequency (Hz)

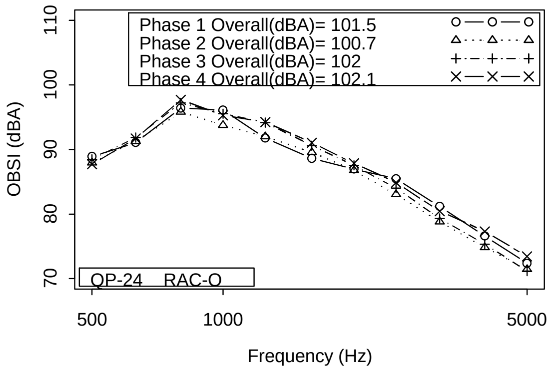

Phase 1 Overall(dBA)= 100.6
Phase 2 Overall(dBA)= 100.8
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
QP-19 RAC-G
OBSI (dBA)
Frequency (Hz)

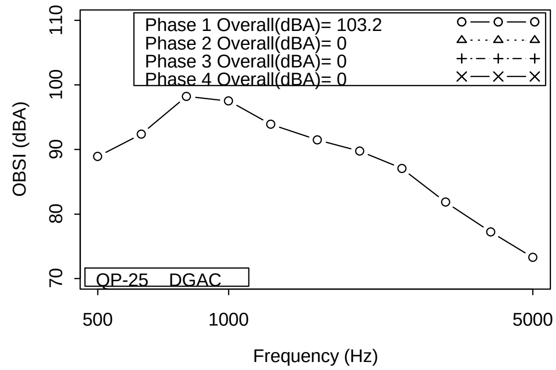

Phase 1 Overall(dBA)= 101.4
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 99.9
Phase 4 Overall(dBA)= 0
QP-20 OGAC
OBSI (dBA)
Frequency (Hz)

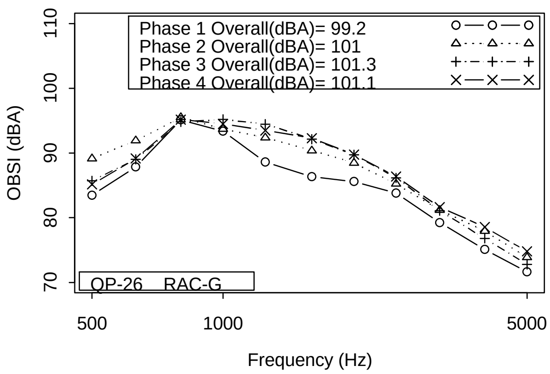

Phase 1 Overall(dBA)= 102.2
Phase 2 Overall(dBA)= 104.2
Phase 3 Overall(dBA)= 106.1
Phase 4 Overall(dBA)= 0
QP-21 DGAC
OBSI (dBA)
Frequency (Hz)

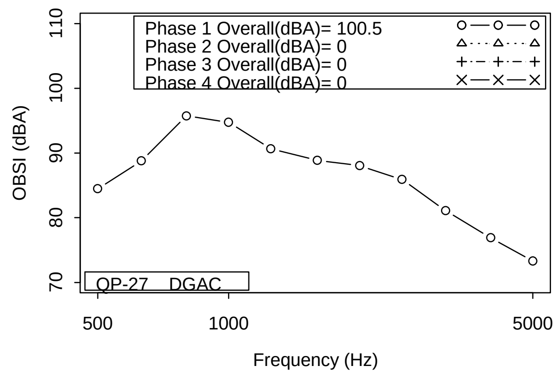

Phase 1 Overall(dBA)= 102.8
Phase 2 Overall(dBA)= 102.1
Phase 3 Overall(dBA)= 104.3
Phase 4 Overall(dBA)= 104.4
QP-22 OGAC
OBSI (dBA)
Frequency (Hz)

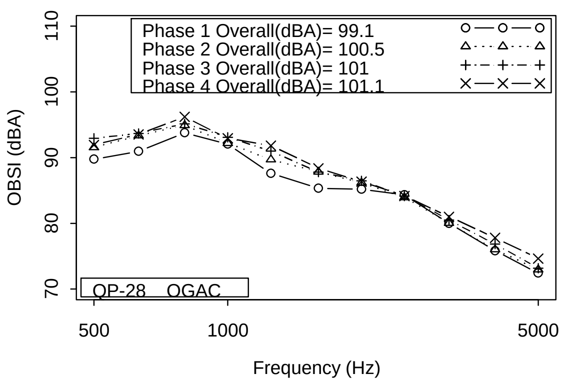

Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 100.3
Phase 3 Overall(dBA)= 101.5
Phase 4 Overall(dBA)= 102.2
QP-23 OGAC
OBSI (dBA)
Frequency (Hz)

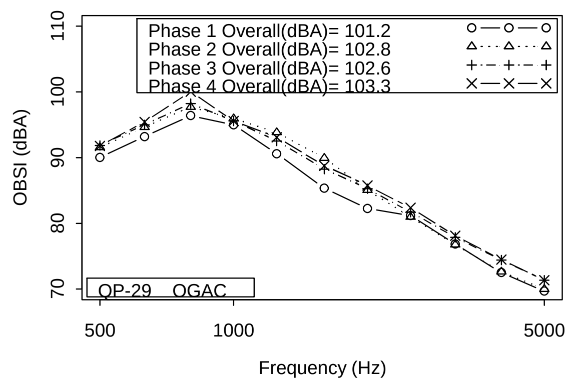

Phase 1 Overall(dBA)= 101.5
Phase 2 Overall(dBA)= 100.7
Phase 3 Overall(dBA)= 102
Phase 4 Overall(dBA)= 102.1
OP-24 RAC-O
OBSI (dBA)
Frequency (Hz)

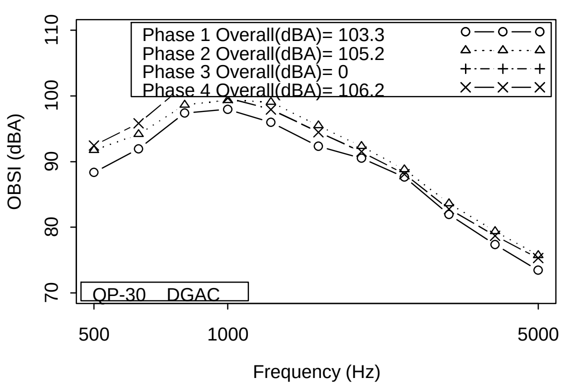

Phase 1 Overall(dBA)= 103.2
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
OP-25 DGAC
OBSI (dBA)
Frequency (Hz)

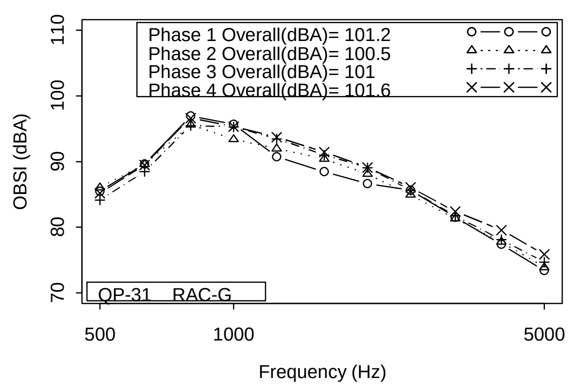

Phase 1 Overall(dBA)= 99.2
Phase 2 Overall(dBA)= 101
Phase 3 Overall(dBA)= 101.3
Phase 4 Overall(dBA)= 101.1
OP-26 RAC-G
OBSI (dBA)
Frequency (Hz)

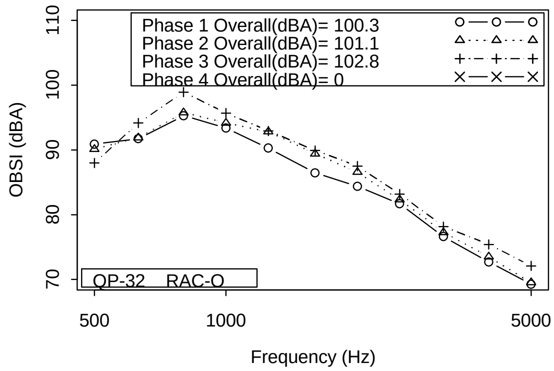

Phase 1 Overall(dBA)= 100.5
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
OP-27 DGAC
OBSI (dBA)
Frequency (Hz)

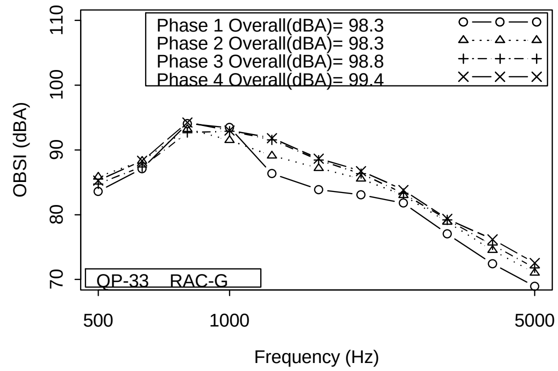

Phase 1 Overall(dBA)= 99.1
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 101
Phase 4 Overall(dBA)= 101.1
OP-28 OGAC
OBSI (dBA)
Frequency (Hz)

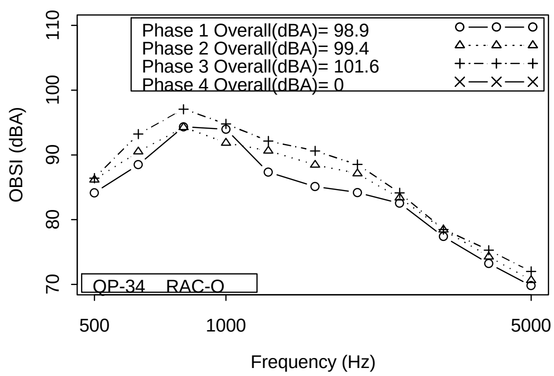

Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 102.8
Phase 3 Overall(dBA)= 102.6
Phase 4 Overall(dBA)= 103.3
OP-29 OGAC
OBSI (dBA)
Frequency (Hz)

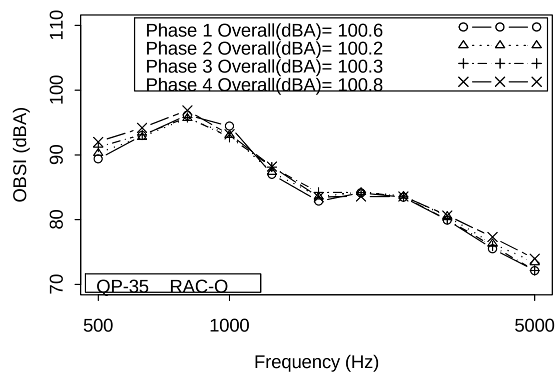

Phase 1 Overall(dBA)= 103.3
Phase 2 Overall(dBA)= 105.2
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 106.2
OP-30 DGAC
OBSI (dBA)
Frequency (Hz)

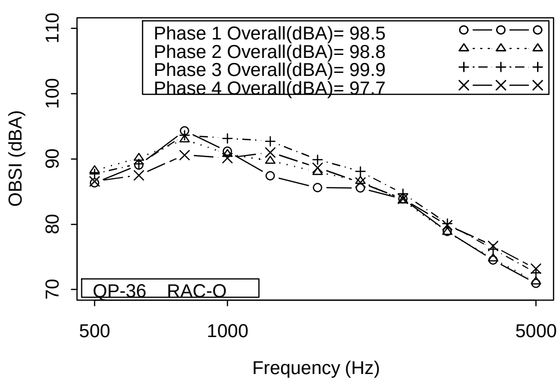

Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 101
Phase 4 Overall(dBA)= 101.6
OP-31 RAC-G
OBSI (dBA)
Frequency (Hz)

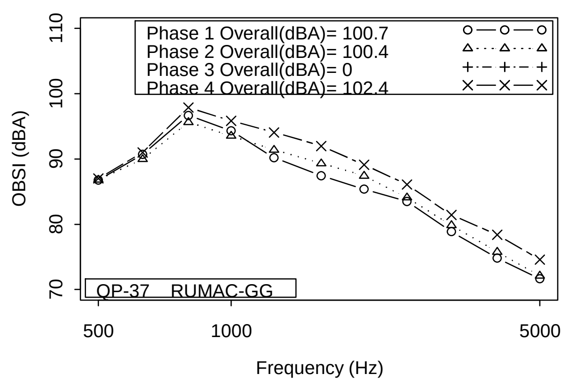

Phase 1 Overall(dBA)= 100.3
Phase 2 Overall(dBA)= 101.1
Phase 3 Overall(dBA)= 102.8
Phase 4 Overall(dBA)= 0
QP-32 RAC-O
OBSI (dBA)
Frequency (Hz)

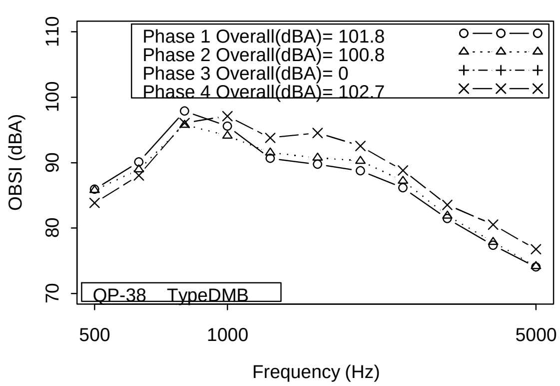

Phase 1 Overall(dBA)= 98.3
Phase 2 Overall(dBA)= 98.3
Phase 3 Overall(dBA)= 98.8
Phase 4 Overall(dBA)= 99.4
QP-33 RAC-G
OBSI (dBA)
Frequency (Hz)

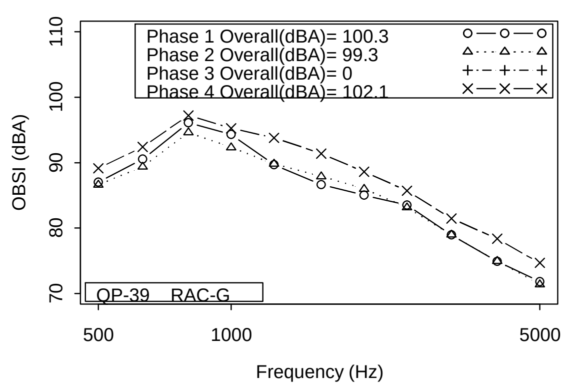

Phase 1 Overall(dBA)= 98.9
Phase 2 Overall(dBA)= 99.4
Phase 3 Overall(dBA)= 101.6
Phase 4 Overall(dBA)= 0
QP-34 RAC-O
OBSI (dBA)
Frequency (Hz)

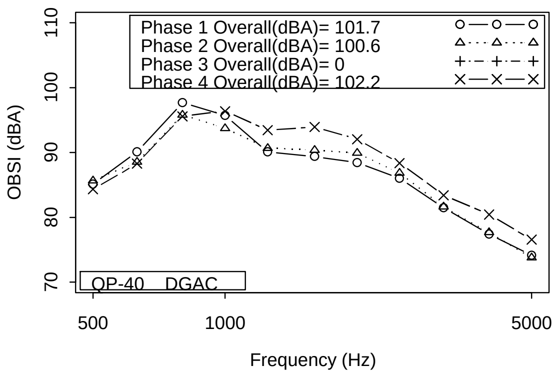

Phase 1 Overall(dBA)= 100.6
Phase 2 Overall(dBA)= 100.2
Phase 3 Overall(dBA)= 100.3
Phase 4 Overall(dBA)= 100.8
QP-35 RAC-O
OBSI (dBA)
Frequency (Hz)

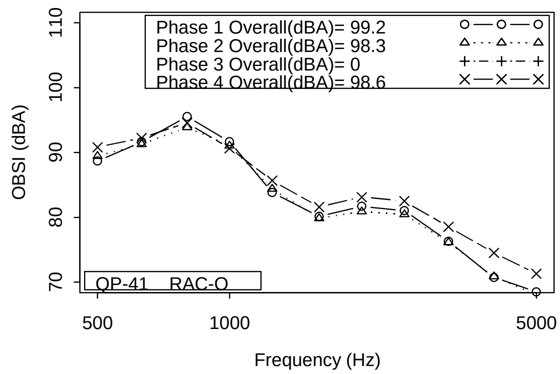

Phase 1 Overall(dBA)= 98.5
Phase 2 Overall(dBA)= 98.8
Phase 3 Overall(dBA)= 99.9
Phase 4 Overall(dBA)= 97.7
QP-36 RAC-O
OBSI (dBA)
Frequency (Hz)

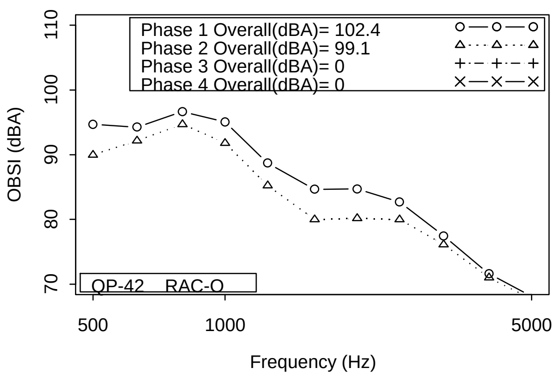

Phase 1 Overall(dBA)= 100.7
Phase 2 Overall(dBA)= 100.4
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 102.4
QP-37 RUMAC-GG
OBSI (dBA)
Frequency (Hz)

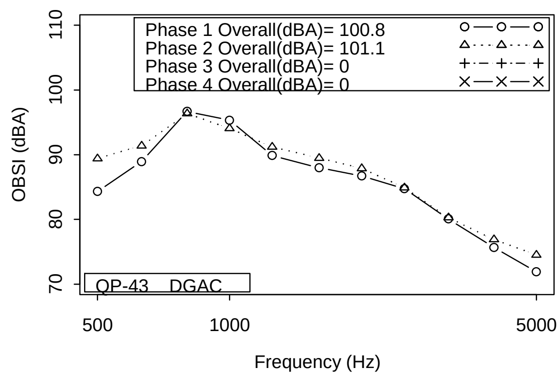

Phase 1 Overall(dBA)= 101.8
Phase 2 Overall(dBA)= 100.8
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 102.7
QP-38 TypeDMB
OBSI (dBA)
Frequency (Hz)

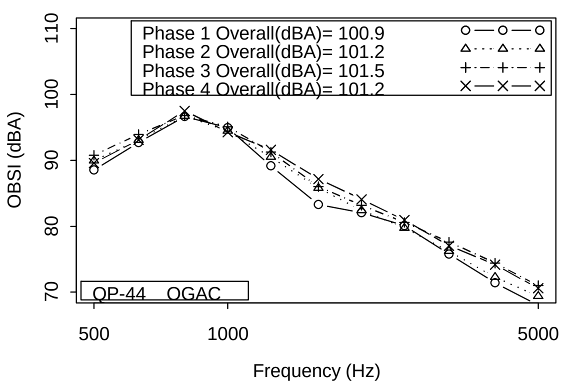

Phase 1 Overall(dBA)= 100.3
Phase 2 Overall(dBA)= 99.3
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 102.1
QP-39 RAC-G
OBSI (dBA)
Frequency (Hz)

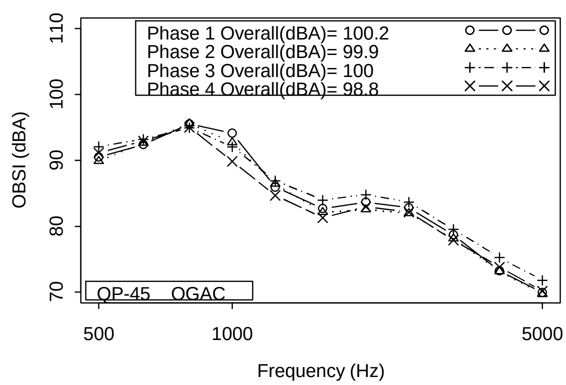

Phase 1 Overall(dBA)= 101.7
Phase 2 Overall(dBA)= 100.6
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 102.2
QP-40 DGAC
OBSI (dBA)
Frequency (Hz)

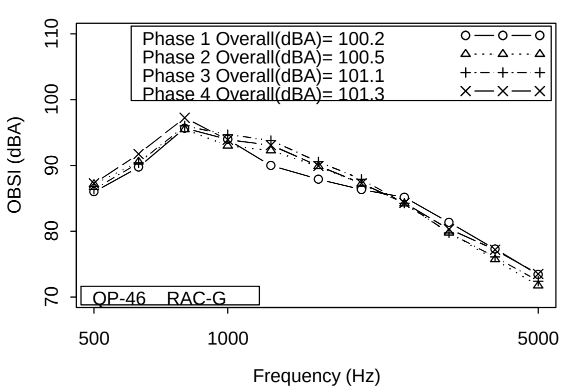

Phase 1 Overall(dBA)= 99.2
Phase 2 Overall(dBA)= 98.3
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 98.6
QP-41 RAC-O
OBSI (dBA)
Frequency (Hz)

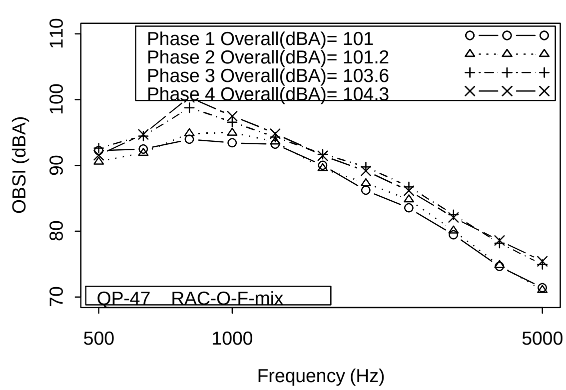

Phase 1 Overall(dBA)= 102.4
Phase 2 Overall(dBA)= 99.1
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
QP-42 RAC-O
OBSI (dBA)
Frequency (Hz)

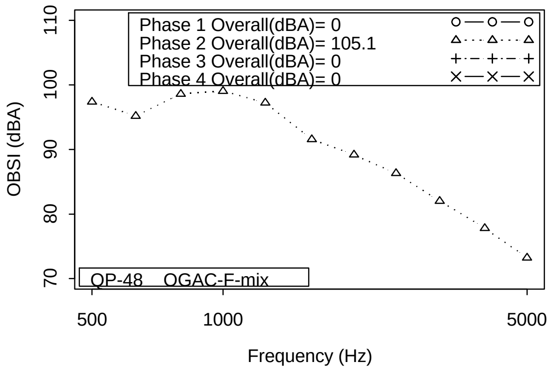

Phase 1 Overall(dBA)= 100.8
Phase 2 Overall(dBA)= 101.1
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
QP-43 DGAC
OBSI (dBA)
Frequency (Hz)

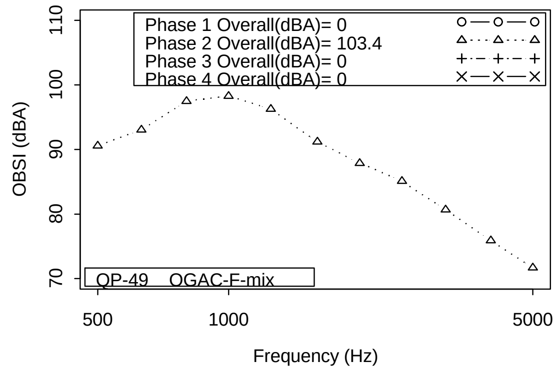

Phase 1 Overall(dBA)= 100.9
Phase 2 Overall(dBA)= 101.2
Phase 3 Overall(dBA)= 101.5
Phase 4 Overall(dBA)= 101.2
QP-44 OGAC
OBSI (dBA)
Frequency (Hz)

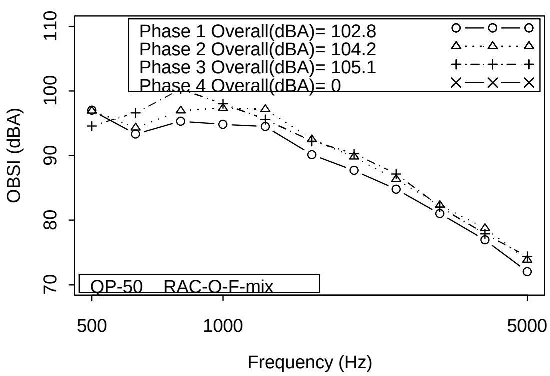

Phase 1 Overall(dBA)= 100.2
Phase 2 Overall(dBA)= 99.9
Phase 3 Overall(dBA)= 100
Phase 4 Overall(dBA)= 98.8
QP-45 OGAC
OBSI (dBA)
Frequency (Hz)

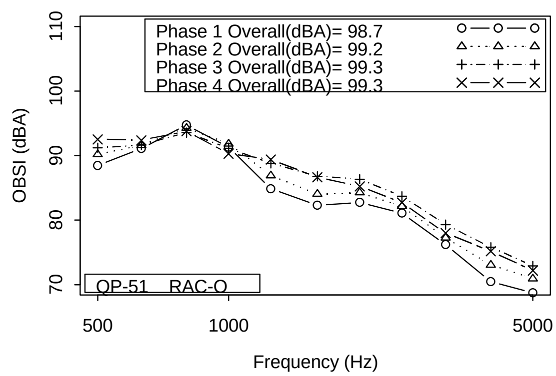

Phase 1 Overall(dBA)= 100.2
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 101.1
Phase 4 Overall(dBA)= 101.3
QP-46 RAC-G
OBSI (dBA)
Frequency (Hz)

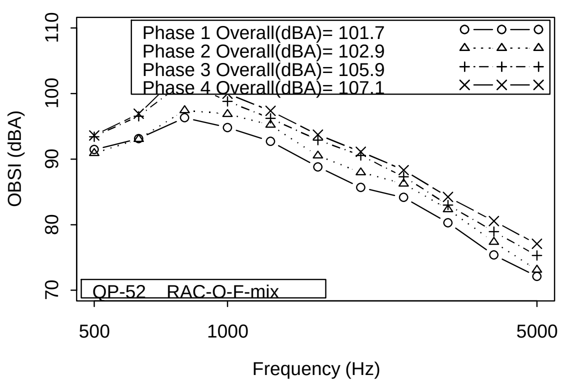

Phase 1 Overall(dBA)= 101
Phase 2 Overall(dBA)= 101.2
Phase 3 Overall(dBA)= 103.6
Phase 4 Overall(dBA)= 104.3
QP-47 RAC-O-F-mix
OBSI (dBA)
Frequency (Hz)


Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 105.1
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
QP-48 OGAC-F-mix
OBSI (dBA)
Frequency (Hz)


Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 103.4
Phase 3 Overall(dBA)= 0
Phase 4 Overall(dBA)= 0
QP-49 OGAC-F-mix
OBSI (dBA)
Frequency (Hz)


Phase 1 Overall(dBA)= 102.8
Phase 2 Overall(dBA)= 104.2
Phase 3 Overall(dBA)= 105.1
Phase 4 Overall(dBA)= 0
QP-50 RAC-O-F-mix
OBSI (dBA)
Frequency (Hz)


Phase 1 Overall(dBA)= 98.7
Phase 2 Overall(dBA)= 99.2
Phase 3 Overall(dBA)= 99.3
Phase 4 Overall(dBA)= 99.3
QP-51 RAC-O
OBSI (dBA)
Frequency (Hz)


Phase 1 Overall(dBA)= 101.7
Phase 2 Overall(dBA)= 102.9
Phase 3 Overall(dBA)= 105.9
Phase 4 Overall(dBA)= 107.1
QP-52 RAC-O-F-mix
OBSI (dBA)
Frequency (Hz)

Appendix B.6: Condition Survey of Environmental Noise Monitoring Site Sections (ES) for Four Years

Site Name	Mix Types	First-Year	Second-Year	Third-Year	Fourth-Year
Los Angeles 138 (LA 138)	OGAC, 75 mm Eastbound(ES-1)	1 low-severity transverse crack with a length of 0.6 m; 0.5 m^2 raveling	2 low-severity transverse cracks with a length of 5.4 m	7 low-severity transverse cracks with a length of 23.6 m; 1 med-severity transverse crack with a length of 3.6 m	14 low-severity transverse cracks with a length of 42 m; 0.1 m^2 segregation; 0.3 m^2 low-severity raveling; and 0.5 m low-severity fatigue crack
	OGAC, 30 mm Eastbound (ES-3)	No distresses	6 low-severity transverse cracks with a length of 7 m	3% area with polished aggregates; 7 low-severity transverse cracks with a length of 23.6 m; 1 med-severity transverse crack with a length of 1.6 m	18 low-severity transverse cracks with a length of 53 m; 7 m low-severity fatigue crack
	RAC-O, 30 mm Eastbound (ES-5)	10 low-severity transverse cracks with a length of 36 m; 0.5 m^2 raveling	10 low-severity transverse cracks with a length of 38 m	10 low-severity reflective/transverse cracks with a length of 34.4 m; 1 mm rutting	10 low-severity transverse cracks with a length of 34.5 m; 2.6 m low-severity longitudinal crack
	BWC, 30 mm Eastbound (ES-7)	8 low-severity transverse cracks with a length of 27 m; 9 medium-severity transverse cracks with a length of 33 m	13 medium-severity transverse cracks with a length of 48 m	0.5% area with polished aggregates; 13 medium-severity transverse cracks with a length of 48 m; 23.3 m^2 segregation	12% (220 m^2) area with polished aggregates; 1 low severity transverse crack with a length of 3.7 m; 12 med-severity transverse cracks with a total length of 41.1 m
	DGAC, 30 mm Westbound (ES-9)	1 low-severity transverse crack with a length of 3 m	14 medium-severity transverse cracks with a length of 45.4 m; 5.4-m low-severity and 2.5 m^2 medium-severity fatigue cracking	14 medium-severity transverse cracks with a length of 45 m; 5.4-m low-severity and 4 m^2 medium-severity fatigue cracking; 4 m^2 raveling	3 medium-severity transverse cracks with a length of 9.4 m; 13 low-severity transverse cracks with a length of 46.4 m; 3.5 m low-severity fatigue cracking and 1.5 m^2 medium-severity fatigue cracking; 0.1 m^2 raveling
Los Angeles 19 (LA 19)	European Gap-Graded mix, 30 mm (ES-10)	No distresses	150 m^2 bleeding	150 m^2 low bleeding; 1 m^2 raveling; 1 low-severity transverse crack with a length of 1 m	0.13 m^2 low bleeding; 0.13 m^2 raveling; 2 low-severity transverse crack with a length of 4 m

Site Name	Mix Types	First-Year	Second-Year	Third-Year	Fourth-Year
Yolo 80	OGAC, 20 mm (ES-11)	60 m^2 raveling	300 m^2 raveling; 300 m^2 bleeding	300 m^2 medium-severity raveling; 300 m^2 low-severity bleeding; 3-m low-severity fatigue crack; 1 low-severity pothole of 0.2 m^2;	1 low-severity transverse crack with a length of 3 m; 1 m^2 low-severity raveling; 0.01 m^2 low-severity bleeding
Fresno 33 (Fre 33)	RAC-G, 45 mm (ES-13)	1.3-m longitudinal crack; 10 low-severity transverse cracks with a total length of 20 m	47-m longitudinal cracking; 9-m low-severity and 15 m^2 medium-severity fatigue cracking; 51 low-severity transverse cracks with a total length of 136 m; 170 m^2 raveling; 170 m^2 bleeding	57-m longitudinal cracking; 9-m low-severity and 25 m^2 medium-severity fatigue cracking; 51 low-severity transverse cracks with a total length of 136 m; 170 m^2 medium raveling; 170 m^2 low bleeding; 21 low severity patching with area of 4.7 m^2	3 m^2 medium-severity edge cracking; 29-m low-severity and 32 m^2 medium-severity fatigue cracking; 45 medium-severity transverse cracks with a total length of 129 m; 0.2 m^2 low bleeding; 9 m^2 segregation; two locations showing pumping
	RAC-G, 90 mm (ES-12)	11 low-severity transverse cracks with a total length of 24 m; 6 medium-severity transverse cracks with a total length of 15 m; 0.04 m^2 raveling	150-m low-severity and 5 m^2 medium-severity fatigue cracking; 33 medium-severity transverse cracks with a total length of 65 m; 150 m^2 raveling; 160 m^2 bleeding	150-m low-severity and 37 m^2 medium-severity fatigue cracking; 33 medium-severity transverse cracks with a total length of 65 m; 150 m^2 medium raveling; 160 m^2 medium bleeding	97 m^2 medium-severity fatigue cracking; 10 low-severity transverse cracks with a total length of 24 m; 72 medium-severity transverse cracks with a total length of 172 m
	RUMAC-GG, 45 mm (ES-14)	39 low-severity transverse cracks with a total length of 111 m; one medium-severity transverse crack with a length of 3.35 m	150-m medium-severity longitudinal cracking; 45 medium-severity transverse cracks with a total length of 135 m; 180 m^2 raveling; 180 m^2 bleeding	150-m medium-severity longitudinal cracking; 45 medium-severity transverse cracks with a total length of 135 m; 180 m^2 medium raveling; 180 m^2 medium bleeding	27 m^2 low-severity and 75 m^2 medium-severity edge cracking; 75 m^2 area of polished aggregates; 19 medium-severity transverse cracks with a total length of 55.5 m; 21 low-severity transverse cracks with a total length of 53 m

Site Name	Mix Types	First-Year	Second-Year	Third-Year	Fourth-Year
	RUMAC-GG, 90 mm (ES-15)	No distresses	150 m^2 bleeding	150 m^2 medium bleeding; 1-m low-severity edge cracking; 2 m^2 med-severity fatigue cracking; 3-m low severity longitudinal cracking; 10 low-severity transverse cracks with a length of 18 m	5-m low-severity edge cracking; 0.1-m low severity fatigue cracking; 50-m low severity longitudinal cracking; 28 m^2 polished aggregates; 1 low-severity reflective crack with a length of 3.7 m; 17 low-severity transverse cracks with a length of 31 m
	Type G-MB, 45 mm (ES-16)	210 m^2 bleeding	3-m low-severity and 15 m^2 medium-severity fatigue cracking; 210 m^2 bleeding	15 m^2 medium-severity fatigue cracking; 210 m^2 medium bleeding; 18 low-severity transverse cracks with a length of 59 m	149 m^2 medium bleeding; 6 low-severity transverse cracks with a length of 7 m
	Type G-MB, 90 mm (ES-17)	154 m^2 bleeding	12.5 m^2 fatigue cracking; 245 m^2 bleeding	12.5 m^2 fatigue cracking; 300 m^2 medium bleeding; 25 m^2 high-severity bleeding; 0.2 m^2 delamination	132 m^2, 70 m^2 and 8 m^2 low, medium, and high-severity bleeding
	Type D-MB, 45 mm (ES-19)	40 m^2 bleeding	1-m low-severity and 8 m^2 medium-severity fatigue cracking; 32 m^2 raveling; 345 m^2 bleeding	8 m^2 medium-severity fatigue cracking; 36 m^2 medium raveling; 345 m^2 low bleeding; 1 low-severity transverse crack with a length of 2 m	3 m low-severity longitudinal cracking; 115 and 20 m^2 low and medium-severity bleeding; 1 low-severity transverse crack with a length of 0.5 m
	Type D-MB, 90 mm (ES-18)	2 m^2 bleeding	300 m^2 bleeding	300 m^2 medium bleeding; 1 m^2 low-severity bleeding; 19 patches with an area of 1.9 m^2	32 m^2 medium bleeding; 140 m^2 low-severity bleeding; 2 patches with an area of 0.3 m^2
	DGAC, 90 mm (ES-20)	No distresses	83-m low-severity and 28.5 m^2 medium-severity fatigue cracking	205-m low-severity and 32.5 m^2 medium-severity fatigue cracking; 32 m^2 medium raveling	15.5-m low-severity and 2.5 m^2 medium-severity fatigue cracking; 93 m low-severity longitudinal crack; 7 low-severity transverse cracks with a total length of 10 m

Site Name	Mix Types	First-Year	Second-Year	Third-Year	Fourth-Year
San Mateo 280 (SM 280)	RAC-O, 45 mm (ES-21)	No distresses	0.1 m^2 raveling	0.25 m^2 medium-severity raveling	1 low-severity transverse crack with a length of 0.5 m; 0.01 m^2 medium-severity raveling; 4 m low-severity longitudinal crack; 0.1 m^2 area with low-severity bleeding
Sacramento 5 (Sac 5)	OGAC, 30 mm Northbound (ES-23)	18 low-severity reflective cracks with a total length of 51 m; 3 medium-severity reflective cracks with a total length of 13 m	6 low-severity reflective cracks with a total length of 21.6 m; 7 medium-severity reflective cracks with a total length of 22.5 m; 8 high-severity reflective cracks with a total length of 28.8 m; 14-m low-severity fatigue cracking	2 low-severity reflective cracks with a total length of 7.2 m; 17 medium-severity reflective cracks with a total length of 62.1 m; 14 high-severity reflective cracks with a total length of 50.4 m; 14-m low severity fatigue cracking	4 m^2 low-severity raveling; 4 low-severity reflective cracks with a total length of 14 m; 11 medium-severity reflective cracks with a total length of 40.4 m; 17 high-severity reflective cracks with a total length of 63 m
	OGAC, 30 mm Southbound (ES-22)	18 low-severity reflective cracks with a total length of 44 m; 60 m^2 raveling	17 low-severity reflective cracks with a total length of 63.2 m; 1 medium-severity reflective crack with a total length of 3.7 m	21 low-severity reflective cracks with a total length of 65.5 m; 1 medium-severity reflective crack with a total length of 3.7 m	85 m and 63 m low and medium severity edge cracking; 0.2 m^2 raveling; 15 low-severity reflective cracks with a total length of 49 m; 20 medium-severity reflective cracks with a total length of 69 m

Appendix B.7: Actual Values Predicted by Regression Models for Chapter 7

Table B.7.1: Predicted Lifetime of Different Asphalt Mix Types with Respect to Roughness

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	15	18	17	20
	Moderate Rainfall/ Low Temperature	12	14	13	17
	High Rainfall/ Moderate Temperature	11	14	13	17
	Moderate Rainfall/ Moderate Temperature	12	14	13	17
Low Traffic (TI=9)	Low Rainfall/ High Temperature	16	19	18	22
	Moderate Rainfall/ Low Temperature	13	15	15	18
	High Rainfall/ Moderate Temperature	13	15	14	18
	Moderate Rainfall/ Moderate Temperature	13	16	15	18

Table B.7.2: Predicted Lifetime of Different Asphalt Mix Types with Respect to Noise from First Model

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	-	7	4	12
	Moderate Rainfall/ Low Temperature	-	6	4	14
	High Rainfall/ Moderate Temperature	-	6	4	12
	Moderate Rainfall/ Moderate Temperature	-	6	4	13
Low Traffic (TI=9)	Low Rainfall/ High Temperature	-	7	5	25
	Moderate Rainfall/ Low Temperature	-	7	4	24
	High Rainfall/ Moderate Temperature	-	7	5	24
	Moderate Rainfall/ Moderate Temperature	-	7	5	24

Table B.7.3: Predicted Lifetime of Different Asphalt Mix Types with Respect to Noise from Second Model

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	-	10	6	17
	Moderate Rainfall/ Low Temperature	-	11	10	17
	High Rainfall/ Moderate Temperature	-	11	8	17
	Moderate Rainfall/ Moderate Temperature	-	11	8	17
Low Traffic (TI=9)	Low Rainfall/ High Temperature	-	11	6	17
	Moderate Rainfall/ Low Temperature	-	12	10	17
	High Rainfall/ Moderate Temperature	-	11	8	17
	Moderate Rainfall/ Moderate Temperature	-	11	8	17

Table B.7.4: Predicted Age to Occurrence of Bleeding of Different Asphalt Mix Types

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	15	14	7	14
	Moderate Rainfall/ Low Temperature	16	15	8	15
	High Rainfall/ Moderate Temperature	15	14	7	14
	Moderate Rainfall/ Moderate Temperature	13	12	5	12
Low Traffic (TI=9)	Low Rainfall/ High Temperature	15	14	7	14
	Moderate Rainfall/ Low Temperature	17	16	9	16
	High Rainfall/ Moderate Temperature	16	15	8	15
	Moderate Rainfall/ Moderate Temperature	15	14	8	14

Table B.7.5: Predicted Age to Occurrence of Raveling of Different Asphalt Mix Types

Traffic	Climate	DGAC	OGAC	RAC-G	RAC-O
High Traffic (TI=12)	Low Rainfall/ High Temperature	11	12	10	11
	Moderate Rainfall/ Low Temperature	12	13	12	13
	High Rainfall/ Moderate Temperature	11	11	10	11
	Moderate Rainfall/ Moderate Temperature	11	13	11	12
Low Traffic (TI=9)	Low Rainfall/ High Temperature	>20	>20	>20	>20
	Moderate Rainfall/ Low Temperature	>20	>20	>20	>20
	High Rainfall/ Moderate Temperature	>20	>20	>20	>20
	Moderate Rainfall/ Moderate Temperature	>20	>20	>20	>20