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

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Partnered Pavement Research Program (PPRC) Contract Strategic Plan Element 4.19:
Third 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 part of an on-going research project, whose central purpose is to support the Caltrans Quieter Pavement Research Program, that has as its goals and objectives the identification of quieter, smoother, safer and more durable pavement surfaces. The research has been carried out as part of Partnered Pavement Research Center Strategic Plan Element 4.19 (PPRC SPE 4.19).

In the study documented in this report, field data regarding tire/pavement noise, surface condition, ride quality, and macrotexture were collected over three consecutive years from pavements in California placed with open-graded and other asphaltic mixes. The three-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 a previous study on the first two years of data collected, which is detailed in a separate report prepared as part of PPRC SPE 4.16, the previous phase of the Quieter Pavement Research Program.

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. The report presents interim results that will be finalized after supplementation with data collected in 2009 as part of the fourth-year (PPRC SPE 4.27) of the study.

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 Aybike Ongel, John T. Harvey, Erwin Kohler, Qing Lu, Bruce D. Steven and Carl L. Monismith. August 2008. (UCPRC-SR-2008-01). Report prepared by UCPRC for the Caltrans Department of Research and Innovation.
- Acoustical Absorption of Open-Graded, Gap-Graded, and Dense-Graded Asphalt Pavements, by A. Ongel and E. Kohler. July 2007. (UCPRC-TM-2007-13) Report prepared by UCPRC for the Caltrans Department of Research and Innovation.
- 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) Report prepared by UCPRC for the Caltrans Department of Research and Innovation.
- Temperature Influence on Road Traffic Noise: Californian OBSI measurement study, by Hans Bendtsen, Qing Lu, and Erwin Kohler. Draft report for Caltrans by the Danish Road Institute, Road Directorate and University of California Pavement Research Center. 2009.
- Work Plan for project 4.19, "Third Year Field Evaluation of Tire/Pavement Noise, IRI, Macrotexture and Surface Condition of Flexible Pavements"

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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 the 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 University of California Pavement Research Center (UCPRC) is supporting the Caltrans Quieter Pavement Research Program by performing experiments under Partnered Pavement Research Center Strategic Plan Elements (PPRC SPEs) 4.16, 4.19, 4.27, and 4.29.

The purpose of the project discussed in this report, which is part of PPRC SPE 4.19, is to perform a third year of measurement of tire/pavement noise, surface condition, ride quality, and macrotexture of 74 flexible pavement sections to improve performance estimates for identification of the more durable, smoother, and quieter pavement types among current asphalt mixes used by Caltrans and several new types of mixes. The three years of data collected on the sections, including the first two years of data collected as part of PPRC SPE 4.16, will be used to provide a preliminary table of estimated design lives for different treatments with respect to the variables measured.

PPRC SPE 4.19 has the following objectives:

- Objective 1. To perform a third year of noise, smoothness, and distress monitoring of 4.16 sections;
- Objective 2. To conduct noise, smoothness, and distress monitoring on field sections with new types of mixes identified as having the potential to be the smoother, quieter, and more durable, or that perform under conditions not included in the previous testing;
- Objective 3. To develop pavement temperature corrections for OBSI data and upgrades to the instrumented noise car;
- Objective 4. To analyze the results and model them where applicable; and
- Objective 5. To develop a preliminary table of expected lives for flexible pavement surfaces;

This report documents the work completed for Objectives 1, 2, 4, and 5. The work completed as part of Objective 3 is documented in a separate report.

EXECUTIVE SUMMARY

Background and Purpose

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. Since the California Department of Transportation (Caltrans) employs a variety of strategies and materials for maintaining and rehabilitating the state's highways pavements, it has sought to identify the lives of those 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 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 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 in the areas of acoustics, friction, and performance of asphalt pavement surfaces. In response to that need, Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.16 was initiated in November 2004. 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 that the technical names for these mixes have changed in the new Section 39 of the Standard Specifications. The names in use at the start of PPRC SPE 4.16 have been maintained in this report for consistency with previous reports). Those performance estimates were based on data collected during field tests and laboratory testing of cores in the first two years of the study.

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. The purpose of PPRC SPE 4.19 is to perform a third year of measurement of tire/pavement noise, surface condition, ride quality and macrotexture of up to 74 flexible pavement sections to improve performance estimates for identification of the more durable, smoother, and quieter pavement types. Several new sections were also tested for the first time as part of this project.

The results presented in this report are updated performance estimates from the third year of measurements on most of the sections included in the PPRC SPE 4.16 project, combined with the first two years of data. As part of this project several new sections were also tested for the first time. In addition, the three years of data collected on the sections were used to provide a preliminary table of estimated design lives for different treatments with respect to the variables measured.

Objectives

The objectives of PPRC SPE 4.19 are:

1. To perform a third year of noise, smoothness and condition survey monitoring of PPRC SPE 4.16 sections. Following the PPRC SPE 4.19 work plan, noise, smoothness and macrotexture, and surface condition of each section were measured using the California On-board Sound Intensity (OBSI) method, laser profilometer, and visual condition survey (walking survey from the shoulder), respectively on the 74 sections included in PPRC SPE 4.16. (These comprised a factorial of current Caltrans asphalt surface mixes, referred to as “Quieter Pavement” or “QP” sections, and a number of experimental surfaces referred to as “Environmental” or “ES” sections.) Following the PPRC SPE 4.19 work plan, there were neither traffic closures in the scope of the third year of data collection nor were cores take for measurement of permeability, friction and air-voids.
2. To conduct noise, smoothness, and condition survey monitoring on new field sections identified as having the the potential to be more durable, smoother, and quieter, or that perform under conditions not included in the previous testing. The same methods mentioned in Objective 1 were used to evaluate sections not previously included in PPRC SPE 4.16, including asphalt and concrete surfaces. These included testing of additional bituminous wearing course (BWC)

sections beyond the one ES section on State Route 138 in Los Angeles County and evaluation of the Skidabrader™ on several concrete and asphalt surfaces.

3. To develop a pavement temperature correction for OBSI data and upgrades to the instrumented noise car. This objective involved measurement of some sections at various temperatures within a short period in order to quantify the effect of pavement temperature on noise levels and to determine correction formulas for normalizing OBSI measurements. A transition from a single sound intensity probe to double probes was done as part of this project, as were software developments and updates associated with improved data collection practices.
4. To analyze results and model them where applicable. This included analyzing the results of the measurements, investigating trends, and predicting durability, smoothness, and noise performance using the models.
5. To develop preliminary tables of expected lives for flexible pavement surfaces with respect to noise, smoothness, and durability.

Scope of the Report

This report documents the work completed for Objectives 1, 2, 4, and 5. The work completed as part of Objective 3 is documented in a separate report.

The measured results and the qualitative and statistical analyses from this testing program are documented in this report. The information is organized as follows:

- Chapter 1 presents the background of the study, its objectives, and the performance parameters for pavement surfaces.
- Chapter 2 provides an analysis of ride-quality data in terms of the International Roughness Index (IRI).
- Chapter 3 presents an analysis of the macrotexture data in terms of Mean Profile Depth (MPD).
- Chapter 4 presents an analysis of the condition survey data for bleeding, rutting, raveling, transverse/reflective cracking, and wheelpath cracking.
- Chapter 5 presents the On-board Sound Intensity (OBSI) data collected on the test sections.
- Chapter 6 presents an analysis of the third-year data collected on the Environmental (ES) sections (same data as in Chapters 2 through 5 for the QP sections).
- Chapter 7 presents the data collected on the new sections visited for the first time this year, including the BWC sections and the Skidabrader sections.

- Chapter 8 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 9 lists the conclusions from the analyses and includes preliminary recommendations.
- Appendices provide additional detailed information.

The data presented in this report includes the three 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 and macrotexture data that affect skid resistance;
- Ride quality in terms of International Roughness Index (IRI), including third year data;
- On-board Sound Intensity (OBSI), a measure of tire/pavement noise, including third year data;
- Sound intensity for different frequencies, including third year data;
- Surface distresses, including bleeding, rutting, raveling, transverse cracking, and cracking in the wheelpaths, including third year data;
- Climate data; and
- Traffic data.

The analyses presented for each performance variable in Chapters 2 through 5 include a summary of the expected trends from the literature, descriptive statistics, and where the data is sufficient, statistical models. Several appendices provide the data corrections used and detailed condition survey information. .

Conclusions

The following conclusions were drawn from the results of analysis of the three years of data and the testing of the new sections. No new recommendations were made.

Performance of Open-Graded Mixes

The average tire/pavement noise level on DGAC pavements is about 101.3 dB(A) for newly paved overlays, 102.4 dB(A) for pavements between one and three years old, and between 103 and 104 dB(A) for pavements older than three years.

Compared to the average noise level of a DGAC mix, the recently paved open-graded mixes are quieter by about 2.5 dB(A) for OGAC and by about 3.1 dB(A) for RAC-O. After the pavements are exposed to traffic, this noise benefit generally changes slightly for about five to seven years and then begins to diminish after seven years. RAC-O remains quieter longer than does OGAC.

For recently paved overlays, open-graded mixes have higher low frequency noise and lower high frequency noise than DGAC mixes. In the first three years after the open-graded mixes are exposed to traffic, high frequency noise increases with age due to the reduction of air-void content under traffic, while low frequency noise decreases with age, likely due to the reduction of surface roughness caused by further compaction under traffic. These opposing changes leave the overall sound intensity nearly unchanged. For open-graded pavements older than three years, noise in the frequencies between 500 and 2,500 Hz increases with age, while noise in the frequencies over 2,500 Hz changes slightly or diminishes with age.

Among the two open-graded mixes, MPD has lower initial values and increases 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 increases noise on OGAC pavements, but it does not significantly affect the noise on RAC-O pavements.

Based on the condition survey for pavements less than ten years old, for recently 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 it does 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 reveal no major difference in pavement distresses between OGAC and RAC-O mixes.

Performance of RAC-G Mixes

The newly paved RAC-G mixes are quieter in terms of tire/pavement noise by about 1.6 dB(A), compared to an average DGAC mix. Within a few years after the pavements are exposed to traffic, the tire/pavement noise on RAC-G mixes approaches the average noise level on DGAC pavements of similar ages. For newly paved overlays, RAC-G mixes have higher low frequency noise and lower high frequency noise than DGAC mixes. In the first three years after the pavements are exposed to traffic, high frequency noise increases with age due to the reduction of air-void content under traffic, while low frequency noise is nearly unchanged with age. For RAC-G pavements older than three years, noise of all frequencies increases with age.

The IRI value on newly paved RAC-G surfaces is lower than that for DGAC mixes, and it does not increase with age. The IRI on DGAC pavements, however, increases with age. RAC-G mixes have a permeability level as high as that of open-graded mixes in the first three years after construction, but under traffic the permeability decreases 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 for pavements less than ten 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 the rubberized pavements than on the nonrubberized pavements, but this is possibly because rubberized mixes tend to be placed more frequently on pavements with greater extent of cracking, which biases the comparison. There were no other significant differences between RAC-G and DGAC mixes in terms of pavement distresses.

Variables Affecting Tire/Pavement Noise

The findings from this third year of the study regarding variables affecting tire/pavement noise are generally consistent with the findings from the analysis on the two-year data. That is, 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. The overall noise level decreases with increasing surface layer thickness and permeability (or air-void content). For DGAC, RAC-G, and RAC-O pavements, the aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise. For OGAC pavements, however, a coarser gradation seems to significantly reduce 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, with most open-graded mixes either 9.5 or 12.5 mm, and most RAC-G and DGAC mixes either 12.5 or 19 mm.

At frequencies below 1,000 Hz, the aggregate gradation variable (fineness modulus) does not significantly affect the noise level for all pavements.

At frequencies above 1,000 Hz, higher macrotexture (MPD) values seem to significantly reduce the noise level on RAC-O mixes. On the other hand, higher macrotexture values increase the noise level of gap-graded mixes.

Performance of Experimental Mixes

The bituminous wearing course (BWC) mix placed on the LA 138 sections has a noise level comparable to that of DGAC mixes, and similar distress development as current Caltrans open-graded mixes. The noise levels of BWC mixes placed on the sections tested for the first time this year are similar to or lower than those of open-graded mixes of similar age. This indicates that the tire/pavement noise levels of the LA 138 BWC mix are not typical of other BWC mixes placed in the state.

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

- RUMAC-GG performed similarly to RAC-G in terms of tire/pavement noise and ride quality when placed in a thin (45 mm) or a thick (90 mm) lifts. However, RUMAC-GG was more crack resistant than RAC-G when placed in a thick lift (90 mm).
- Although the Type G-MB mix has higher noise levels than the RAC-G mix soon after construction, the increase in noise with age is less significant on the Type G-MB mix than on the RAC-G mix and the Type D-MB mix.
- The Type G-MB mix is more susceptible to bleeding than other mixes.
- The Type D-MB mix is more resistant to cracking than the DGAC mix but it is also more susceptible to bleeding.
- The Type D-MB mix has a noise level similar to the DGAC mix soon after construction, but its noise level increases 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) had noise levels as high as those of the DGAC mix.

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

Old concrete surfaces with burlap drag and longitudinally tined surface textures that were then retextured with Skidabrader technology showed slight decreases in noise of -0.5 and -0.1 dB(A), respectively. The results showed increases in noise on OGAC and DGAC surfaces that were similarly retextured of 1.3 and 0.8 dB(A), respectively.

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 smoothness and quietness of pavements are receiving increased attention and importance as they affect quality of life issues for highway users and neighboring residents. Since the California Department of Transportation (Caltrans) employs a variety of strategies and materials for maintaining and rehabilitating the state's highways pavements, it has sought to identify the lives of those 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 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 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 a number of experimental asphalt surfaces with respect to tire/pavement noise, permeability, macrotexture, microtexture, smoothness, and surface distress development. (Note that the technical names for these mixes have changed in the new Section 39 of the Standard Specifications. The names in use at the start of PPRC SPE 4.16 have been maintained in this report for consistency with previous reports). Those performance estimates were based on data collected during field tests and laboratory testing of cores in the first two years of the study. The results of the first two years of data collection, modeling, and performance predictions are summarized in Reference (1).

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. The results presented in this report are 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. Several new sections were also tested for the first time as part of this project.

1.2 Project Purpose and Objectives

The purpose of PPRC SPE 4.19 is to perform a third 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 the more durable, smoother, and quieter pavement types. The three years of data collected on the sections, including two years of data collected as part of PPRC SPE 4.16, were used to provide a preliminary table of estimated design lives for different treatments with respect to the variables measured.

The objectives of PPRC SPE 4.19 are:

Objective 1: To perform third year of noise, smoothness, and distress monitoring of PPRC SPE 4.16 sections.

In July 2007 the UCPRC completed field work on the second-year surface property monitoring of the PPRC SPE 4.16 sections. There were 74 sections monitored as part of PPRC SPE 4.16, comprised of a factorial of current Caltrans asphalt surface mixes, referred to as "Quieter Pavement" or "QP" sections, and a number of experimental surfaces referred to as "Environmental" or "ES" sections. The UCPRC conducted a third-year data collection campaign on these sections. Following the PPRC SPE 4.19 work plan, no cores were taken nor were there required traffic closures. Noise, smoothness and macrotexture, and surface condition of each section were measured using the California On-board Sound Intensity (OBSI) method, laser profilometer, and visual condition survey (walking survey from the shoulder), respectively.

Objective 2: To conduct noise, smoothness and distress monitoring on new field sections identified to have the potential to be more durable, smoother, and quieter, or that perform under conditions not included in the previous testing.

The same methods noted in Objective 1 were used to evaluate sections not previously included in PPRC SPE 4.16, including asphalt and concrete surfaces. An estimated maximum of 10 sections selected by Caltrans were to be included as part of this objective. In the case of new sections, measurements were to be conducted as much as scheduling allowed before and after construction.

Objective 3: To develop pavement a temperature correction for OBSI data and upgrades to the instrumented noise car.

This objective involved measuring some sections at various temperatures within a short time period in order to quantify the effect of pavement temperature on the noise levels and to determine correction formulas for normalizing OBSI measurements. The transition from a single sound intensity probes to double probes was to be done as part of this project, as well as any software development and updates associated with improved data collection practices.

Objective 4: To analyze the results and to model them where applicable.

Analyze results of the measurements, investigate trends, classify pavements with respect to durability, smoothness, and noise levels, and develop predictive models where possible to investigate trends and predict future performance. The database generated during PPRC SPE 4.16 was used in this part of the study, pooled with the third-year measurements.

Objective 5: To develop a preliminary table of expected lives for flexible pavement surfaces.

Analyze the results of Objective 4, and develop a preliminary table of estimated design lives for flexible pavement surfaces tested with respect to durability, smoothness, and noise levels. Traffic and climate condition effects on life were to be included in the table where data is available.

This report documents the work completed for Objectives 1, 2, 4, and 5. The work completed as part of Objective 3 is documented in a separate report.

1.3 Experiment Factorial for Third-Year Measurements

A factorial was developed for current Caltrans asphalt surfaces as part of PPRC SPE 4.16, including DGAC, RAC-G, OGAC, and RAC-O. (As noted earlier, although the names of materials have changed in the new Standard Specifications Section 39, the earlier names are used in this report to maintain consistency with earlier reports.) That 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). These sections have been tested for three years. The first two years of data included

- 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.

In addition, several sections identified in other projects and 23 sections with new materials and control sections, referred to as the Environmental Sections (ES) were also tested. Appendix A.1: List of Test Sections Included in the Study shows specific test section information.

Detailed project background for PPRC SPE 4.16—literature survey, experimental design, and data collection methodologies—can be found in the two-year noise study report, "Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphaltic Pavement Surface Types: First- and Second-Year Results." (2) Most of the same data collection methodologies were continued in the third year but on a smaller scale, and coring, permeability, and friction tests were not conducted. Also, in the third year a Standard Reference Test Tire (SRTT) was used for all noise measurements rather than the AquaTred tire used for the first two years of measurement. All measurements from the first two years with the AquaTred tire were converted to equivalent noise levels using the SRTT tire using a correlation developed by the UCPRC as part of this project. The details of the correlation are shown in Appendix A.2: Correlation Between Aquatred 3 Tire OBSI and SRTT OBSI. Air density adjustments were applied to all data from all three years.

Some pavement sections had failed by the third year and were dropped out from the survey. Table 1.1 shows the number of sections surveyed for various performance measures in the three years. A similar collection of data for the fourth-year is scheduled for spring 2009.

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

	Year 1 (Phase 1)	Year 2 (Phase 2)	Year 3 (Phase 3)
Tire/Pavement Noise (OBSI-California)*	76	71	65
Roughness (ASTM E 1926)	78	71	69
Macrotexture (ASTM E 1845)	77	72	60
Friction (ASTM E 303)	83	73	0
Air-void Content/Aggregate Gradation**	83	73	0
Permeability (NCAT falling head)	78	73	0
Pavement Distresses**	84	84	73

* ASTM and AASHTO methods currently being standardized based on California experience.
** See Reference (2) for method description.

1.4 Scope of this Report

Chapters 2, 3, 4, and 5 present results and analysis for the current Caltrans asphalt surfaces: DGAC, OGAC, RAC-G, and RAC-O. Chapters 2 present 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 also an indicator of raveling and bleeding. Chapter 4 presents the results and analysis of measurements of surface distresses, including bleeding, rutting, transverse cracking, raveling, and wheelpath cracking. Chapter 5 presents results and analysis of On-Board Sound Intensity (OBSI) measurements of tire/pavement noise. Findings are summarized at the end of each chapter. Chapter 6 presents an update of performance measures on the experimental test sections referred to as “Environmental Sections.” Chapter 7 presents results and analysis from OBSI and other performance measurements on asphalt and concrete surfaces included in the study for the first time in Year 3. Chapter 8 presents an update of the PPRC SPE 4.16 estimates of pavement life based on new regression equations for each of the performance measures presented in Chapters 2, 3, 4, and 5. A summary of conclusions and recommendations appears in Chapter 9.

2. SURFACE PROFILE RESULTS AND ANALYSIS: IRI

International Roughness Index (IRI) was measured in the third year to evaluate the change in surface roughness of asphalt pavements. The IRI measurements were collected every meter 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.

The analysis of the IRI answers two questions:

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

Hypotheses regarding the effects of the explanatory variables on IRI are discussed in Reference (2), and will be revisited in more detail at the conclusion of the fourth year of measurement, analysis, and modeling.

2.1 Descriptive Analysis

Figure 2.1 shows the average IRI measured in three consecutive years for individual pavement sections of four mix types: 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 One defined as the year of construction.

It should be noted that the IRI values at the time the overlays were constructed or soon thereafter is unknown except for those sections that were tested very soon after construction. It should also be noted that the current condition of the pavement layers beneath the overlays is not known.

Section IDs are listed in the figure legends. Some sections showed a decrease of IRI in the second or third survey year. 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) and QP-20 (OGAC). Section QP-09 has a large patch in the middle and section QP-20 is located on a steep hill. It is uncertain why the IRI decreased on these sections, either due to difficulty in measurement such as retracing the same wheelpath, or road maintenance. These two 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 three-year survey period.

Figure 2.2 is a box plot that shows the variation in IRI values for different mix types, including two F-mixes, across all three 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) (2). 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 2.3 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. This plot is similar to the plot based on the first two years' data (2). That is, IRI values increase with age for RAC-O and DGAC mixes but show no trend for OGAC and RAC-G mixes.

Figure 2.4 shows the time trend of IRI across the three years of data collection, with each year of measurement identified as "Phase ID," for different mix types for 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 three 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 the distresses 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.

(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 (3):

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

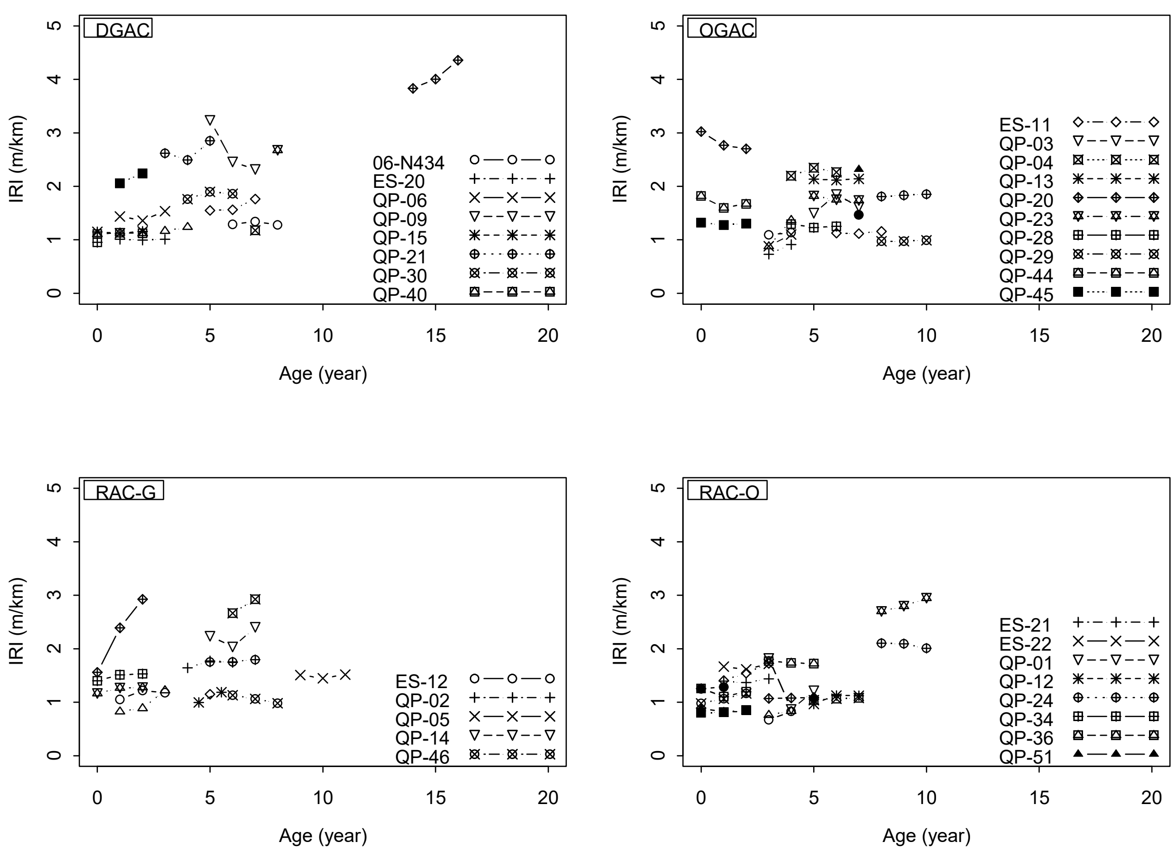

Figure 2.1: IRI trends over three years for each pavement section.

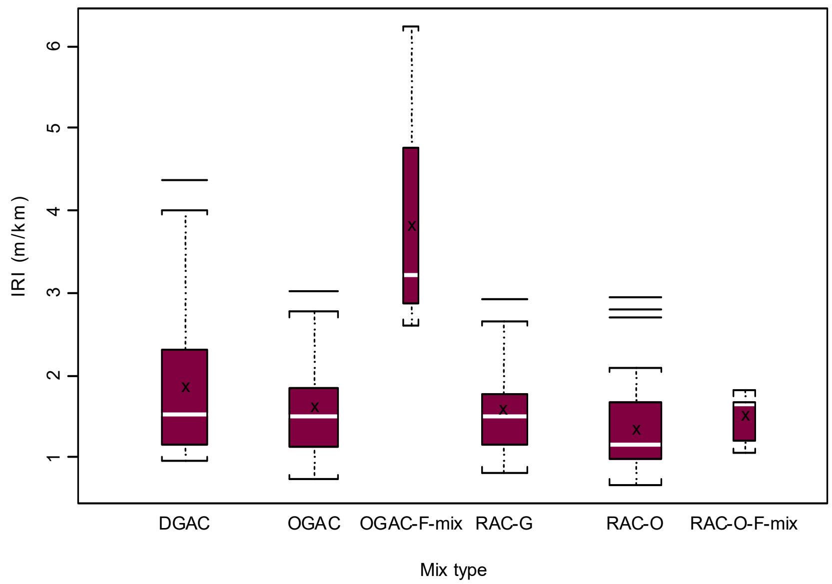

Figure 2.2: Variation in IRI values for different mix types for all three years of pooled data and all initial ages.

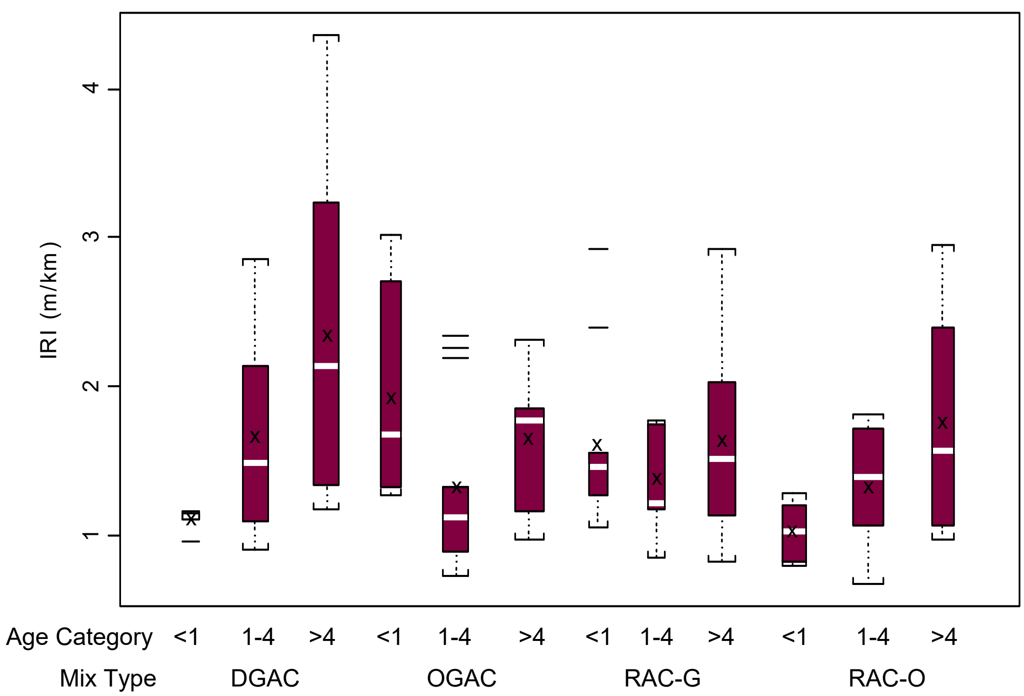

Figure 2.3: Variation in IRI values for different mix types for different initial ages (Age category in years) for all three years pooled data.

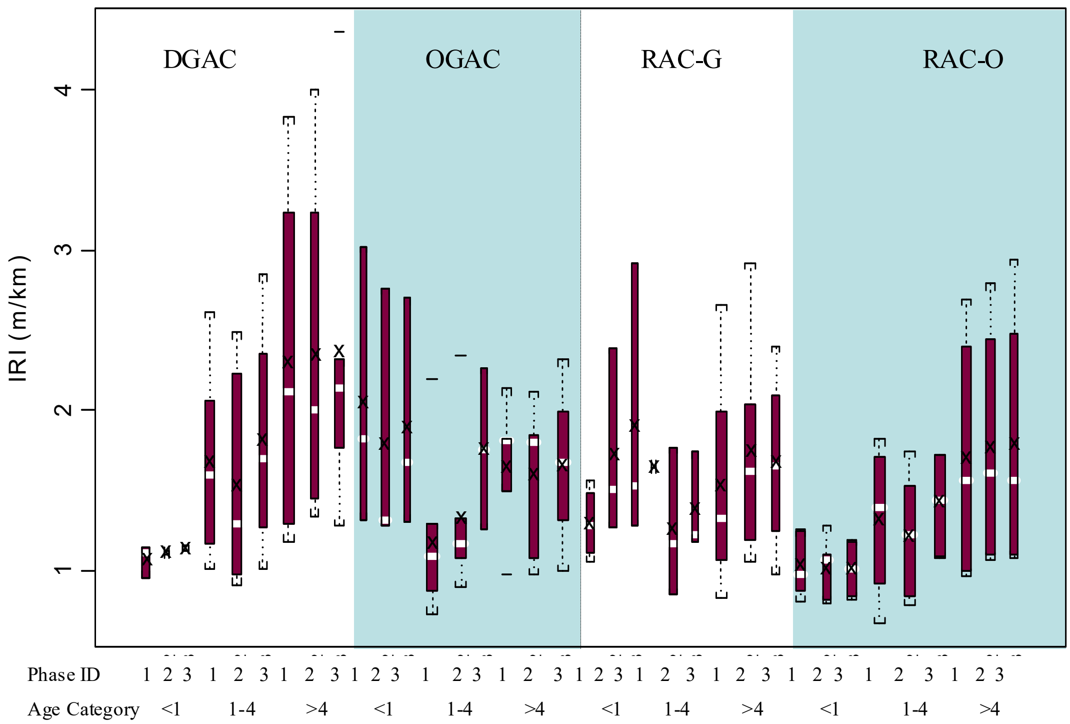

Figure 2.4: Comparison of IRI values for different mix types at different ages for first, second, and third years of data collection (Phase ID showing Years 1, 2, and 3).

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 2.1. The P-values less than 0.05, indicating highly significant variables, are shown in bold.

The results in Table 2.1 show that IRI tends to be significantly affected by 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. Table 2.1 also shows that the inclusion of rubber tends to reduce IRI.

Table 2.1: Regression Analysis of Single-Variable Models for IRI

Model Number	Variable Name	Coefficient	P-value	Constant Term	R2
1	Age (year)	0.113	**<0.001**	1.172	0.144
2	Air-void Content (%)	-0.00823	0.757	1.555	0.001
3	Mix Type	-0.387	0.076	1.783	0.074
4	Rubber Inclusion	-0.244	**0.018**	1.643	0.033
5	MPD (micron)	0.000285	**0.003**	1.057	0.054
6	Presence of Fatigue Cracking	0.441	**0.026**	1.473	0.031
7	Presence of Raveling	0.299	**0.013**	1.454	0.038
8	Presence of Rutting	0.911	**<0.001**	1.442	0.100
9	Presence of Transverse Cracking	0.188	0.546	1.497	0.002
10	Presence of Bleeding	0.439	**0.015**	1.472	0.036
11	Average Annual Rainfall (mm)	0.000131	0.051	1.397	0.023
12	Age*Average Annual Rainfall (mm)	0.000198	**<0.001**	1.151	0.259
13	Average Annual Wet Days	0.000862	**0.040**	1.371	0.025
14	Age*Average Annual Wet Days	0.00123	**<0.001**	1.219	0.180
15	Average Annual Max. Daily Air Temp (°C)	-0.0841	**<0.001**	3.735	0.155
16	Annual Number of Days >30°C	-0.00409	**<0.001**	1.879	0.141
17	Annual Degree-Days >30°C	-0.000116	**<0.001**	1.870	0.142
18	Annual FT Cycles	-0.00600	**0.034**	1.622	0.027
19	Annual AADTT per Coring Lane	-2.23e-5	0.297	1.563	0.007
20	Annual ESALs per Coring Lane	-6.91e-8	0.123	1.572	0.014

Based on the results in Table 2.1, 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. 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 will be considered.

Preliminary analysis revealed that the error terms from multiple regression have nonconstant 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 types (e.g., higher air-void contents in OGAC mixes than in DGAC 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 2.1, is

$$\begin{aligned} 1/\sqrt{IRI}\,(m/km) &= 0.889612 - 0.021589 \times Age(year) + 0.056035 \times ind\,(MixTypeOGAC) + 0.037902 \times ind\,(MixTypeRAC-G) \\ &+ 0.102960 \times ind\,(MixTypeRAC-O) - 0.000074 \times AverageAnnualRainfall(mm) + 0.000603 \times NumberOfDays > 30C \\ &- 0.000012 \times AADTTinCoringLane + 0.001576 \times AnnualFTCycles \end{aligned} \quad \textbf{(2.1)}$$

where $ind(\cdot)$ is an indicator function, 1 if the variable in the parentheses is true and 0 if 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)	0.889612	0.043695	20.3594	<0.0001
Age	-0.021589	0.003540	-6.0980	<0.0001
MixTypeOGAC	0.056035	0.028193	1.9875	0.0486
MixTypeRAC-G	0.037902	0.030027	1.2623	0.2087
MixTypeRAC-O	0.102960	0.026666	3.8611	0.0002
AvgAnnualRainfall	-0.000074	0.000028	-2.6733	0.0083
NoDaysTempGT30	0.000603	0.000218	2.7692	0.0063
AADTTCoringLane	-0.000012	0.000007	-1.7690	0.0788
AnnualFTCycles	0.001576	0.000819	1.9235	0.0562

Residual standard error: 0.1236 on 157 degrees of freedom; Multiple R-Squared: 0.38.

It can be seen that at the 95 percent confidence level, age, mix type, average annual rainfall, and number of days >30°C significantly affect IRI. IRI increases with Age and Average Annual Rainfall, but decreases with the Number of Days >30°C. 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 from 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, Mix Type variable is replaced with Mix Property variables and the model is estimated for each Mix Type separately. The regression equations, Equation 2.2 through Equation 2.5, are

For DGAC pavements:

$$1/\sqrt{IRI}\,(m/km) = 0.888563 - 0.01644 \times Age(year) - 0.000262 \times MPD - 0.014248 \times \log(Permeability)(cm/\sec) \\ -0.000064 \times AverageAnnualRainfall(mm) + 0.000718 \times NumberOfDays > 30C \\ +0.0000033 \times AADTTinCoringLane + 0.003385 \times AnnualFTCycles \quad \textbf{(2.2)}$$

	Value	Std. Error	t value	P-value
(Intercept)	0.888563	0.108166	8.2148	<0.0001
Age	-0.016440	0.006102	-2.6940	0.0116
MPD	-0.000262	0.000128	-2.0384	0.0507
logPerm	-0.014248	0.011623	-1.2259	0.2301
AvgAnnualRainfall	-0.000064	0.000038	-1.6820	0.1033
NoDaysTempGT30	0.000718	0.000396	1.8153	0.0798
AADTTCoringLane	0.0000033	0.000010	0.3254	0.7472
AnnualFTCycles	0.003385	0.001813	1.8674	0.0720

Residual standard error: 0.0959 on 29 degrees of freedom; Multiple R-Squared: 0.71.

For OGAC pavements:

$$1/\sqrt{IRI}\,(m/km) = 0.834436 + 0.022964 \times Age(year) - 0.000304 \times MPD\,(micron) - 0.006099 \times \log(Permeability)(cm/\sec) \\ +0.000231 \times AverageAnnualRainfall(mm) + 0.001301 \times NumberOfDays > 30C + 0.0000029 \times AADTTinCoringLane \\ +0.003270 \times AnnualFTCycles \quad \textbf{(2.3)}$$

	Value	Std. Error	t value	P-value
(Intercept)	0.834436	0.155224	5.3757	<0.0001
Age	0.022964	0.013217	1.7375	0.0925
MPD	-0.000304	0.000101	-3.0149	0.0052
logPerm	-0.006099	0.008093	-0.7536	0.4570
AvgAnnualRainfall	0.000231	0.000137	1.6831	0.1027
NoDaysTempGT30	0.001301	0.000558	2.3303	0.0267
AADTTCoringLane	0.0000029	0.000019	0.1512	0.8808
AnnualFTCycles	0.003270	0.002053	1.5930	0.1216

Residual standard error: 0.1058 on 30 degrees of freedom; Multiple R-Squared: 0.49.

For RAC-G pavements:

$$1/\sqrt{IRI}\,(m/km) = 1.165986 - 0.018908 \times Age(year) - 0.000178 \times MPD(micron) - 0.009595 \times \log(Permeability)(cm/\sec)$$
$$-0.000083 \times AverageAnnualRainfall(mm) - 0.00037 \times NumberOfDays > 30C$$
$$-0.0000697 \times AADTTinCoringLane - 0.001622 \times AnnualFTCycles \quad \textbf{(2.4)}$$

	Value	Std. Error	t value	P-value
(Intercept)	1.165986	0.090730	12.8511	<0.0001
Age	-0.018908	0.010672	-1.7717	0.0897
MPD	-0.000178	0.000097	-1.8360	0.0793
logPerm	-0.009595	0.008499	-1.1289	0.2706
AvgAnnualRainfall	-0.000083	0.000056	-1.4912	0.1495
NoDaysTempGT30	-0.000037	0.000476	-0.0769	0.9393
AADTTCoringLane	-0.0000697	0.000021	-3.3738	0.0026
AnnualFTCycles	-0.001622	0.001841	-0.8815	0.3872

Residual standard error: 0.08480 on 23 degrees of freedom; Multiple R-Squared: 0.67.

For RAC-O pavements:

$$1/\sqrt{IRI}\,(m/km) = 0.698788 - 0.036292 \times Age(year) + 0.000139 \times MPD(micron) - 0.012359 \times \log(Permeability)(cm/\sec)$$
$$+0.000051 \times AverageAnnualRainfall(mm) + 0.001275 \times NumberOfDays > 30C$$
$$-0.0000024 \times AADTTinCoringLane + 0.000269 \times AnnualFTCycles \quad \textbf{(2.5)}$$

	Value	Std. Error	t value	P-value
(Intercept)	0.698788	0.151179	4.6223	<0.0001
Age	-0.036292	0.009227	-3.9331	0.0003
MPD	0.000139	0.000103	1.3496	0.1846
logPerm	-0.012359	0.010380	-1.1907	0.2406
AvgAnnualRainfall	0.000051	0.000061	0.8365	0.4077
NoDaysTempGT30	0.001275	0.000506	2.5199	0.0157
AADTTCoringLane	-0.0000024	0.000012	-0.1947	0.8466
AnnualFTCycles	0.000269	0.001433	0.1878	0.8520

Residual standard error: 0.1317 on 41 degrees of freedom; Multiple R-Squared: 0.38.

The results show that for DGAC pavements, only age is significant at the 95 percent confidence level, while none of the mix, traffic, and environmental variables is significant. For RAC-O pavements, in addition to Age, Number of Days >30ºC is also significant. 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 >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.

2.3 Summary of Findings

The following findings were obtained regarding roughness:

1. 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).
2. Rubberized open-graded mixes have lower initial IRI values than nonrubberized open-graded mixes; rubberized gap-graded mixes have lower initial IRI values than nonrubberized dense-graded mixes.
3. 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 three 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.
4. Open-graded pavements (OGAC and RAC-O) are smoother in high temperature regions than in low temperature regions.
5. 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.

3. SURFACE PROFILE RESULTS AND ANALYSIS: MEAN PROFILE DEPTH

Macrotexture was measured in the third year, but microtexture was not because during the third-year survey time traffic was not closed.

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

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 nonrubberized 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) and will be revisited in more detail at the conclusion of the fourth year of measurement, analysis, and modeling.

3.1 Descriptive Analysis

Figure 3.1 shows the average MPD measured in three consecutive years for individual pavement sections of 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. 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 newly paved OGAC pavements: 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. As discussed earlier, 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.

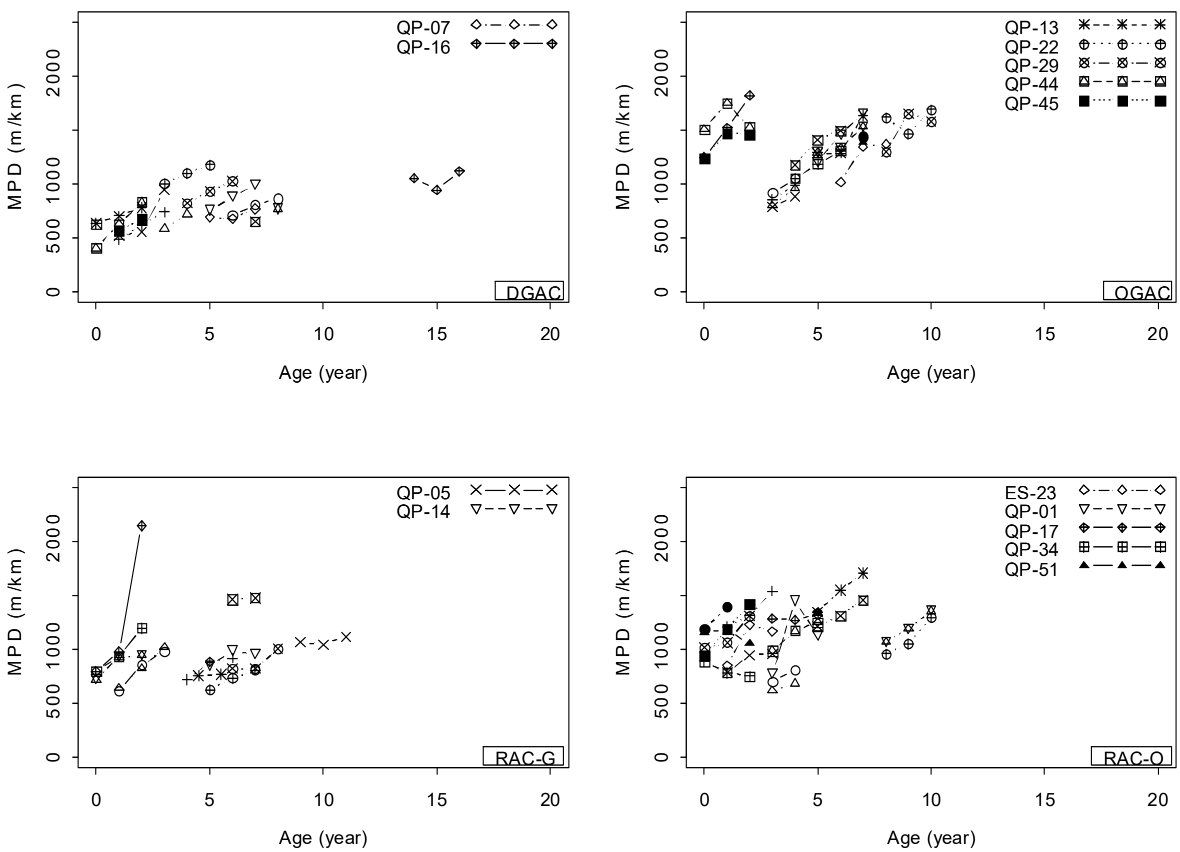

Figure 3.1: MPD trend over three years for each pavement section.

Figure 3.2 shows the variation in MPD values for different mix types, including two F-mixes, based on the three-year survey data. The information conveyed in the plots is the same as that in the plot based on the first two years' survey data (2). That is, 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 3.3 shows the time trend of MPD in three 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. Phase ID in the figure is the year of data collection, either 1, 2 or 3.

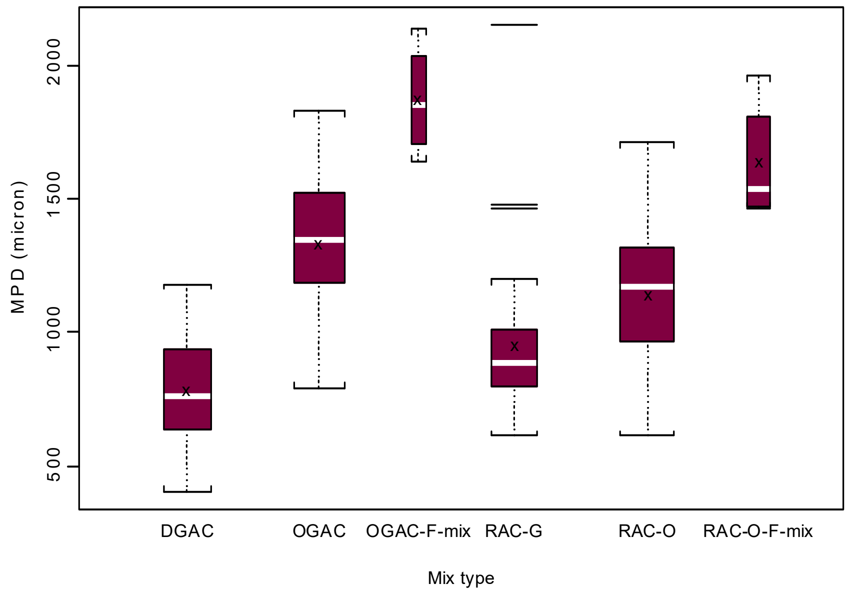

Figure 3.2: Variation in MPD values for different mix types for pooled data for all three years and all initial ages.

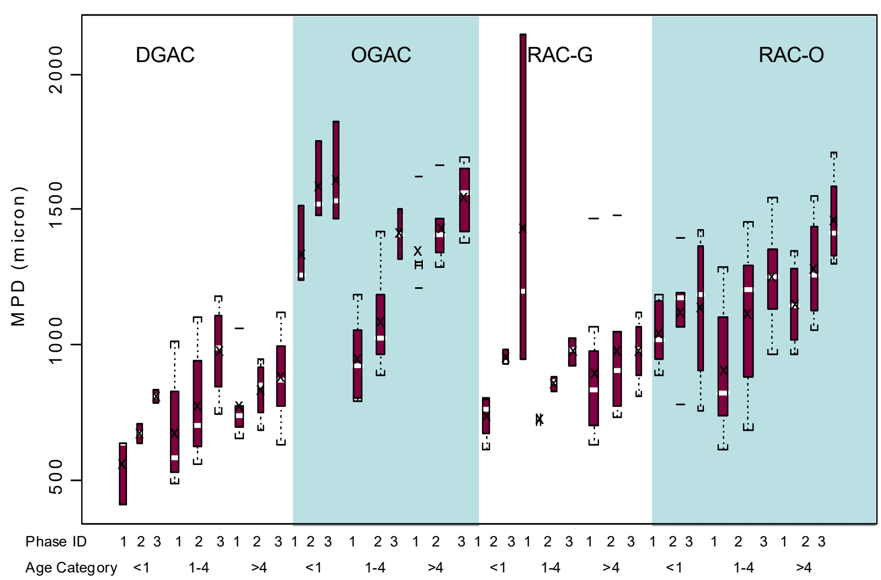

Figure 3.3: Comparison of MPD values for different mix types for different initial age categories (Age Category) and for first, second, and third years of data collection (Phase ID).

3.2 Regression Analysis

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 3.1. The P-values less than 0.05 are shown in bold.

Descriptions of the variables are provided in Reference (2). A few of the less common variables are described below.

C_c is the Coefficient of curvature. C_c = D30/D10 * D60, where D10 is the sieve size through which 10 percent of the aggregate passes (mm), D30 is the sieve size through which 30 percent of the aggregate passes (mm), and D60 is the sieve size through which 60 percent of the material passes (mm). C_u is the Coefficient of uniformity: C_u = D60/ D10. Fineness modulus is a measure of the uniformity of the aggregate gradation. The higher the fineness modulus, the coarser the asphalt mix (a higher percentage of coarse material) and the more uniform the gradation. Fineness Modulus is calculated as F.M. = (∑ percent material retained on each sieve) / 100.

Table 3.1: Regression Analysis of Single-Variable Models for MPD

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	38.073	**<0.001**	897.950	0.108
2	Air-void Content (%)	40.398	**<0.001**	576.863	0.473
3	Mix Type	572.389	**<0.001**	741.798	0.453
4	Rubber Inclusion	-17.816	0.732	1064.270	0.001
5	Fineness Modulus	446.849	**<0.001**	-1173.064	0.379
6	NMAS (mm)	-47.519	**<0.001**	1670.500	0.156
7	C_u	-12.334	**<0.001**	1310.232	0.361
8	C_c	7.839	0.564	1031.587	0.002
9	BPN	-1.482	0.587	1146.537	0.002
10	Surface Thickness (mm)	-7.935	**<0.001**	1360.557	0.173
11	IRI (m/km)	124.881	**0.019**	875.503	0.037
12	Presence of Rutting	156.453	0.061	1035.488	0.025
13	Presence of Bleeding	142.468	0.061	1033.051	0.025
14	Average Annual Rainfall (mm)	0.069	0.208	1012.951	0.011
15	Average Annual Wet Days	0.882	0.087	989.715	0.020
16	Average Annual Max. Daily Air Temp (ºC)	-21.335	**0.042**	1546.721	0.028
17	Annual Number of Days >30ºC	-1.046	**0.048**	1138.271	0.027
18	Annual Degree-Days >30ºC	-0.029	0.054	1133.514	0.025
19	Annual FT Cycles	0.712	0.696	1044.804	0.001
20	Annual AADTT per Coring Lane	0.00144	0.681	1046.206	0.001

The results in Table 3.1 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. An increase 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 maximum daily air temperature and the number of days with air temperature greater than 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.

Based on the results in Table 3.1, 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 3.1, is

$$\begin{aligned} MPD(micron) &= 838.2085 + 29.4579 \times Age(year) + 58.6352 \times ind(MixTypeOGAC) + 221.8027 \times ind(MixTypeRAC-G) \\ &+337.4369 \times ind(MixTypeRAC-O) - 6.1771 \times NMAS(mm) - 0.6911 \times Thickness(mm) - 1.0294 \times NumberOfDays > 30C \\ &+0.0042 \times AADTTinCoringLane + 68.0467 \times Age \times ind(MixTypeOGAC) - 19.0678 \times Age \times ind(MixTypeRAC-G) \\ &+8.6665 \times Age \times ind(MixTypeRAC-O) \end{aligned} \qquad \textbf{(3.1)}$$

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

	Value	Std. Error	t value	P-value
(Intercept)	838.2085	152.0913	5.5112	0.0000
Age	29.4279	14.1577	2.0786	0.0396
MixTypeOGAC	58.6352	126.1990	0.4646	0.6430
MixTypeRAC-G	221.8027	91.8216	2.4156	0.0171
MixTypeRAC-O	337.4369	87.7395	3.8459	0.0002
NMAS	-6.1771	7.7526	-0.7968	0.4270
Thickness	-0.6911	1.2638	-0.5469	0.5854
NoDaysTempGT30	-1.0294	0.3550	-2.8995	0.0044
AADTTCoringLane	0.0042	0.0109	0.3880	0.6987
AgeMixTypeOGAC	68.0467	23.0274	2.9550	0.0037
AgeMixTypeRAC-G	-19.0678	19.1255	-0.9970	0.3206
AgeMixTypeRAC-O	8.6665	18.4019	0.4710	0.6385

Residual standard error: 193.1 on 130 degrees of freedom; Multiple R-Squared: 0.6325.

It can be seen that at the 95 percent confidence level, age, mix type, and number of days >30^{o}C significantly affect macrotexture. MPD increases with age, but decreases with the number of days >30^{o}C. 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, Mix Type variable is replaced with Mix Property variables and the model is estimated for each mix type separately. The regression equations, Equation 3.2 through Equation 3.5, are:

For DGAC pavements:

$$
\begin{aligned}
MPD(micron) &= -93.7089 - 4.2910 \times AirVoid(\%) + 47.8933 \times Age(year) + 283.2136 \times FinenessModulus \\
&-9.9487 \times NMAS(mm) - 5.4209 \times Thickness(mm) - 0.7087 \times NumberOfDays > 30C \\
&-0.0402 \times AADTTinCoringLane
\end{aligned} \quad \textbf{(3.2)}
$$

	Value	Std. Error	t value	P-value
(Intercept)	-93.7089	529.8210	-0.1769	0.8612
AirVoid	-4.2910	15.7801	-0.2719	0.7882
Age	47.8933	13.0899	3.6588	0.0014
FinenessModulus	283.2136	156.2116	1.8130	0.0835
NMAS	-9.9487	10.1549	-0.9797	0.3379
Thickness	-5.4209	1.8722	-2.8955	0.0084
NoDaysTempGT30	-0.7087	0.6382	-1.1105	0.2788
AADTTCoringLane	-0.0402	0.0177	-2.2674	0.0335

Residual standard error: 133.1 on 22 degrees of freedom; Multiple R-Squared: 0.601.

For OGAC pavements:

$$MPD(micron) = -645.6240 - 0.4917 \times AirVoid(\%) + 103.6224 \times Age(year) + 274.1456 \times FinenessModulus$$
$$-1.9169 \times NMAS(mm) - 0.457 \times Thickness(mm) - 0.5966 \times NumberOfDays > 30C \quad \textbf{(3.3)}$$
$$-0.0089 \times AADTTinCoringLane$$

	Value	Std. Error	t value	P-value
(Intercept)	-645.6240	338.4451	-1.9076	0.0675
AirVoid	-0.4917	10.0302	-0.0490	0.9613
Age	103.6224	10.5024	9.8666	0.0000
FinenessModulus	274.1456	93.6918	2.9260	0.0070
NMAS	-1.9169	15.5844	-0.1230	0.9031
Thickness	-0.4570	1.5415	-0.2965	0.7692
NoDaysTempGT30	-0.5966	0.3698	-1.6131	0.1188
AADTTCoringLane	-0.0089	0.0171	-0.5201	0.6074

Residual standard error: 88.19 on 26 degrees of freedom; Multiple R-Squared: 0.9143.

For RAC-G pavements:

$$MPD(micron) = -622.7423 - 9.1326 \times AirVoid(\%) + 14.3359 \times Age(year) + 403.7994 \times FinenessModulus$$
$$-28.119 \times NMAS(mm) - 2.6337 \times Thickness(mm) - 0.7899 \times NumberOfDays > 30C \quad \textbf{(3.4)}$$
$$-0.0348 \times AADTTinCoringLane$$

	Value	Std. Error	t value	P-value
(Intercept)	-622.7423	1241.1985	-0.5017	0.6206
AirVoid	-9.1326	17.1338	-0.5330	0.5991
Age	14.3359	19.8725	0.7214	0.4779
FinenessModulus	403.7994	306.2677	1.3185	0.2003
NMAS	-28.1190	25.1487	-1.1181	0.2751
Thickness	-2.6337	3.1514	-0.8357	0.4119
NoDaysTempGT30	0.7899	0.9248	0.8541	0.4018
AADTTCoringLane	-0.0348	0.0442	-0.7874	0.4391

Residual standard error: 205.9 on 23 degrees of freedom; Multiple R-Squared: 0.2231.

For RAC-O pavements:

$$MPD(micron) = 358.6533 - 1.4151 \times AirVoid(\%) + 18.9136 \times Age(year) + 476.3388 \times FinenessModulus$$
$$-145.9686 \times NMAS(mm) + 5.2328 \times Thickness(mm) - 1.7772 \times NumberOfDays > 30C \quad \textbf{(3.5)}$$
$$+0.0048 \times AADTTinCoringLane$$

	Value	Std. Error	t value	P-value
(Intercept)	358.6533	827.2495	0.4335	0.6671
AirVoid	-1.4151	10.8988	-0.1298	0.8974
Age	18.9136	12.2301	1.5465	0.1303
FinenessModulus	476.3388	171.6864	2.7745	0.0085
NMAS	-145.9686	30.3248	-4.8135	<0.0001
Thickness	5.2328	3.8549	1.3574	0.1826
NoDaysTempGT30	-1.7772	0.6327	-2.8089	0.0078
AADTTCoringLane	0.0048	0.0145	0.3298	0.7434

Residual standard error: 167 on 38 degrees of freedom; Multiple R-Squared: 0.6447.

The results show that within each mix type, air-void content has no significant effect on the value of MPD. Fineness modulus is significant in affecting the macrotexture of open-graded pavements, including both OGAC and RAC-O, marginally significant in affecting the macrotexture of DGAC pavements, and insignificant for RAC-G pavements. Generally, macrotexture increases with fineness modulus, with increasing fineness modulus indicating a coarser gradation. Layer thickness is only significant on DGAC pavements. Thicker DGAC layers have lower macrotexture, probably due to better compaction of thicker layers. Higher temperature duration, in terms of number of days with air temperature greater than 30ºC, is a significant factor on RAC-O pavements but not on other types of pavement. The effect of pavement age on macrotexture is much more prominent (in terms of both statistical significance and practical significance) on nonrubberized pavements (DGAC and OGAC) than on rubberized pavements (RAC-G, and RAC-O).

3.3 Summary of Findings

The following findings were obtained regarding macrotexture:

1. Among all 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. MPD generally increases with pavement age. The age effect on macrotexture is much more prominent (in terms of both statistical significance and practical significance) on nonrubberized pavements (DGAC and OGAC) than on rubberized pavements (RAC-G, and RAC-O). The growth rate (with age) of MPD is significantly higher on OGAC pavements than on DGAC 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, marginally significant in affecting the macrotexture of DGAC pavements, and insignificant for RAC-G pavements. Generally the coarser the mix gradation is (i.e., higher fineness modulus), the larger the MPD.
5. Layer thickness is only significant on DGAC pavements. Thicker DGAC layers have lower macrotexture, probably due to better compaction of thicker layers.
6. The macrotexture of RAC-O pavements decreases with the number of high temperature days.

4. SURFACE DISTRESS RESULTS AND ANALYSIS

Traffic closures were not included in the scope of the the third-year survey. Therefore, pavement conditions were evaluated using a method different from the one used the previous two years. In the first two years' surveys, 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, high-resolution digital photos were taken from the shoulder along the whole length of each section, and pavement conditions were assessed afterwards, based on pavement surface images.

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 distress assessment in the first two years and the third year, some distresses were recorded as less severe in the third year than in the previous years. A basic assumption was made in post-processing the distress data that the third-year distress was no less than the second year.

In this report, six major 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 are 16, 18, 11, and 20 for DGAC, OGAC, RAC-G, and RAC-O pavements, respectively. 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?

The hypotheses regarding the effects of the explanatory variables on distress development are discussed in Reference (1), and will be revisited in more detail at the conclusion of the fourth year of measurement, analysis and modeling.

The distresses present on the pavement surface at the time of construction of the overlays is not known. The current condition of the pavement layers beneath the overlays is also not known.

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. In the analysis for this study, 3 percent of the test section area with bleeding was selected as the threshold for the start of bleeding.

4.1.1 Descriptive Analysis

Figure 4.1 shows the percentage of bleeding area measured in three 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 nonrubberized 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.

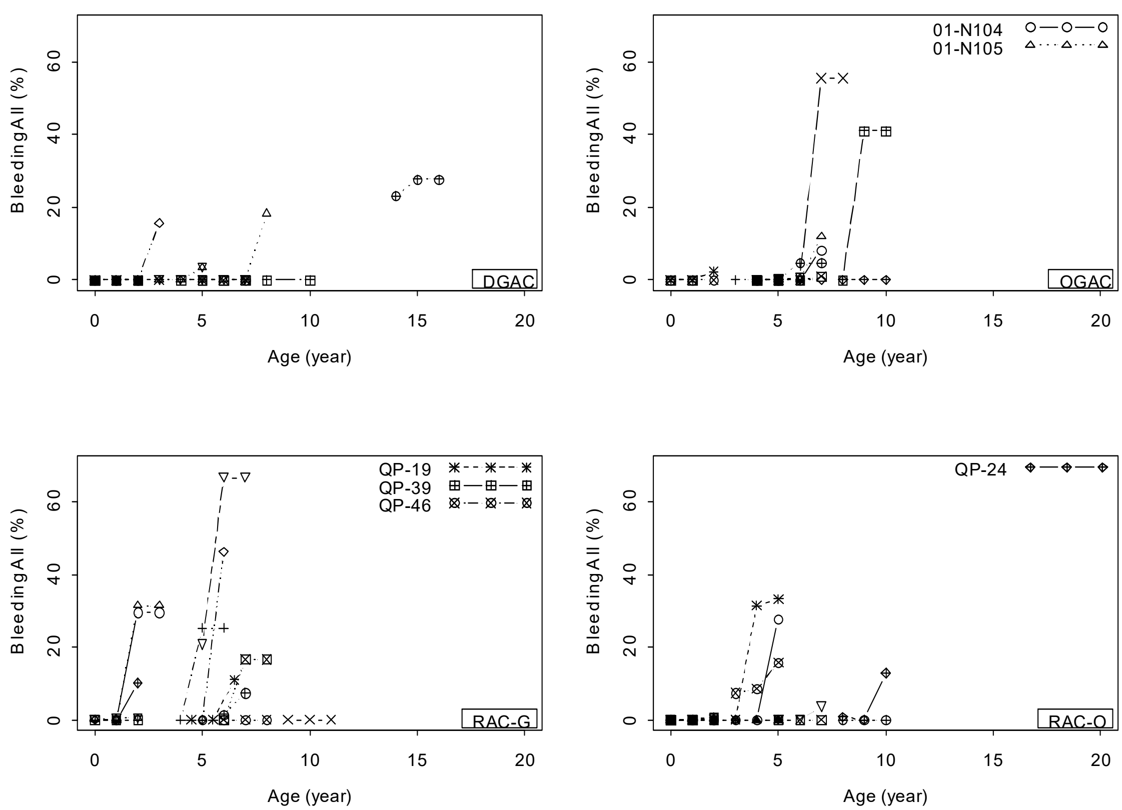

Figure 4.1: Bleeding development trend over three years for each pavement section.

Figure 4.2 shows the percentage of sections with bleeding over three 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 three years among the four pavement types.

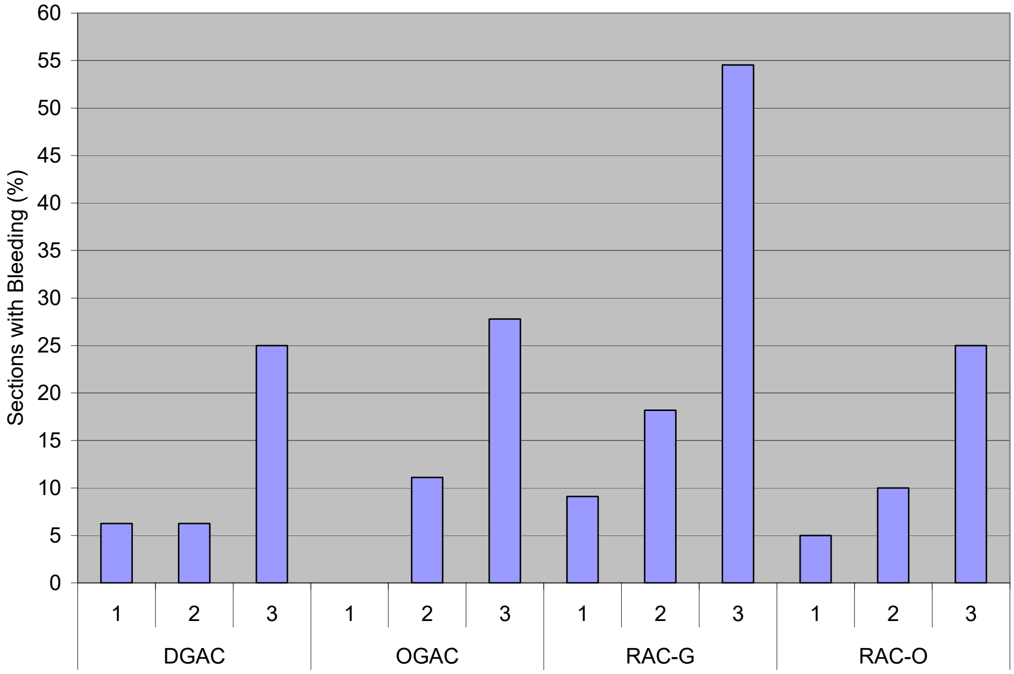

Figure 4.2: Percentage of pavement sections of the four mix types with at least 3 percent of their area showing bleeding for each of the three measured years.

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 4.1 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 4.1, multiple regression analysis was conducted to account for the effect of various factors simultaneously. The regression equation, Equation 4.1, is

$$\begin{aligned} Bleeding(\%) = & -8.31833 + 1.34027 \times Age(year) + 3.05324 \times ind(MixTypeOGAC) + 12.74202 \times ind(MixTypeRAC-G) \\ & +2.3931 \times ind(MixTypeRAC-O) - 1.1134 \times FinenessModulus + 0.00261 \times AverageAnnualRainfall(mm) \\ & +0.04448 \times AverageAnnualWetDays + 0.06624 \times NumberOfDays > 30C - 0.20956 \times AnnualFTCycles \\ & +331.3915 \times CumulativeAADTTinCoringLane(10e6) \end{aligned} \quad \textbf{(4.1)}$$

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

Table 4.1: Regression Analysis of Single-Variable Models for Bleeding

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	1.1707131	**<0.001**	-0.277	0.080
2	Air-void Content (%)	0.0097543	0.956	4.969	<0.001
3	Mix Type	2.1498328	0.399	2.601	0.074
4	Rubber Inclusion	2.7343317	0.148	3.710	0.012
5	Fineness Modulus	0.8046441	0.714	1.244	0.001
6	NMAS (mm)	-0.0514452	0.888	5.686	<0.001
7	C_u	-0.0155074	0.810	5.556	<0.001
8	C_c	1.9569111	**<0.001**	-1.458	0.090
9	Surface Thickness (mm)	-0.0644396	0.233	7.529	0.008
10	Average Annual Rainfall (mm)	-0.0042234	**0.042**	7.613	0.023
11	Age * Average Annual Rainfall (mm)	0.0005775	0.192	3.601	0.010
12	Average Annual Wet Days	-0.0077203	0.672	5.618	0.001
13	Age * Average Annual Wet Days	0.0108951	**0.002**	1.604	0.051
14	Average Annual Max. Daily Air Temp (ºC)	0.5352416	0.150	-7.258	0.012
15	Annual Number of Days >30ºC	0.0277209	0.139	2.884	0.012
16	Annual Degree-Days >30ºC	0.0007627	0.147	2.993	0.012
17	Annual FT Cycles	-0.1649969	**0.023**	7.203	0.029
18	Annual AADTT per Coring Lane	0.0000142	0.185	4.037	0.010

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

	Value	Std. Error	t value	P-value
(Intercept)	-8.31833	15.57583	-0.5341	0.5940
Age	1.34027	0.31703	4.2276	<0.0000
PvmntTypeOGAC	3.05324	3.99935	0.7634	0.4463
PvmntTypeRAC-G	12.74202	3.67548	3.4668	0.0007
PvmntTypeRAC-O	2.39310	3.87593	0.6174	0.5378
FinenessModulus	-1.11340	3.42440	-0.3251	0.7455
AvgAnnualRainfall	0.00261	0.00253	1.0319	0.3037
AvgAnnualWetDays	0.04448	0.01987	2.2388	0.0265
NoDaysTempGT30	0.06624	0.02138	3.0981	0.0023
AnnualFTCycles	-0.20956	0.07501	-2.7936	0.0058
Age*AADTTCoringLane	331.39150	124.13478	2.6696	0.0084

Residual standard error: 11.21 on 160 degrees of freedom; Multiple R-Squared: 0.28.

The results show that at the 95 percent confidence level, age, pavement type, average annual wet days, number of days with temperature greater than 30ºC, annual freeze-thaw cycles, and cumulative truck traffic 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 indicate 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.

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 following the 2000 Pavement Condition Survey (PCS), 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 the rut depth from photographs of the surface taken from the shoulder. For this reason, it is assumed that the rut depth in the third survey year was no less than those in the previous survey years. 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.

4.2.1 Descriptive Analysis

Figure 4.3 shows the rut depths measured in three 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 4.4 shows the percentage of sections with rutting in three consecutive survey years for the four pavement types: DGAC, OGAC, RAC-G, and RAC-O. It can be seen that rutting develops with pavement age, and that DGAC pavements show more rutting than other pavement types in all three years.

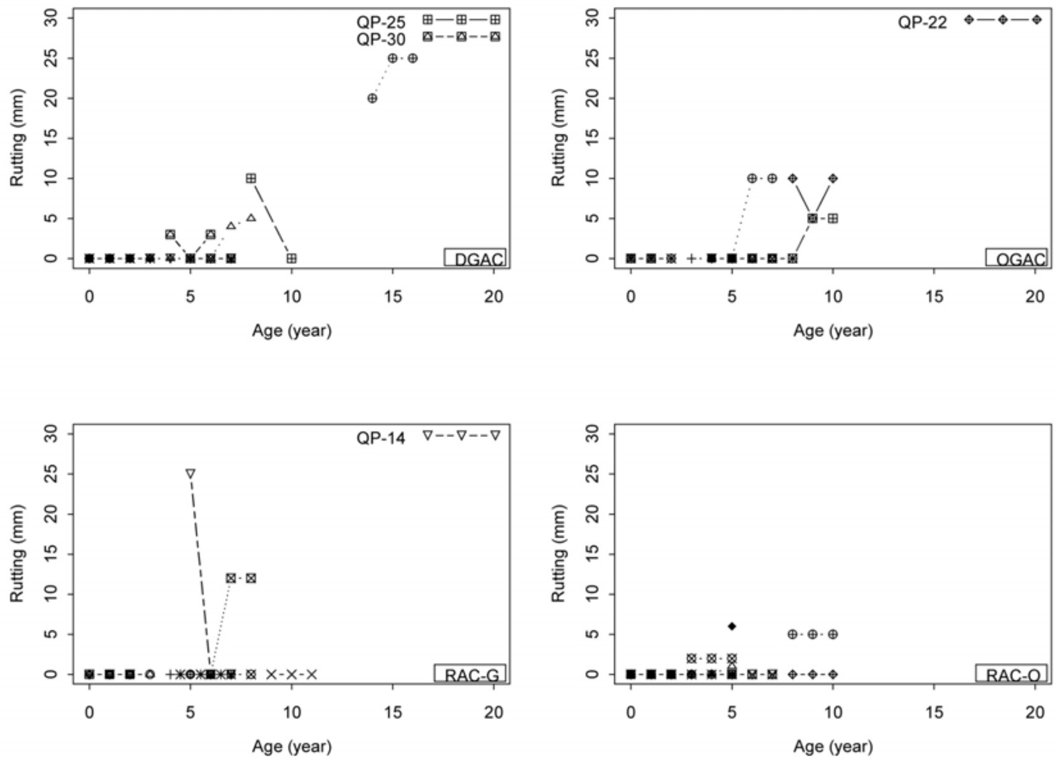

Figure 4.3: Rutting development trend in three years for each pavement section.

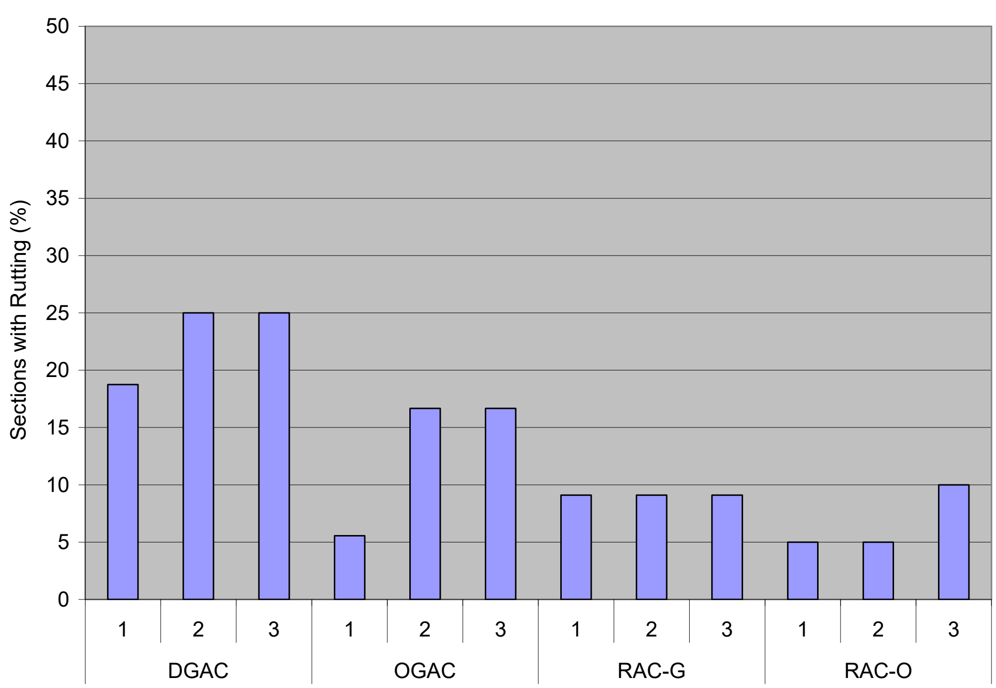

Figure 4.4: Percentage of pavement sections with rutting of at least 3 mm on at least 25 m of a 150 m long section in the first two years of measurement for four mix types.

4.2.2 Regression Analysis

Because the number of sections with rutting is small and the third-year data are rough estimates, no regression analysis was performed on the rutting data.

4.3 Transverse/Reflective Cracking

Because all the sections investigated in this study are overlays of AC or PCC 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.

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 4.5 for three survey years for four pavement types.

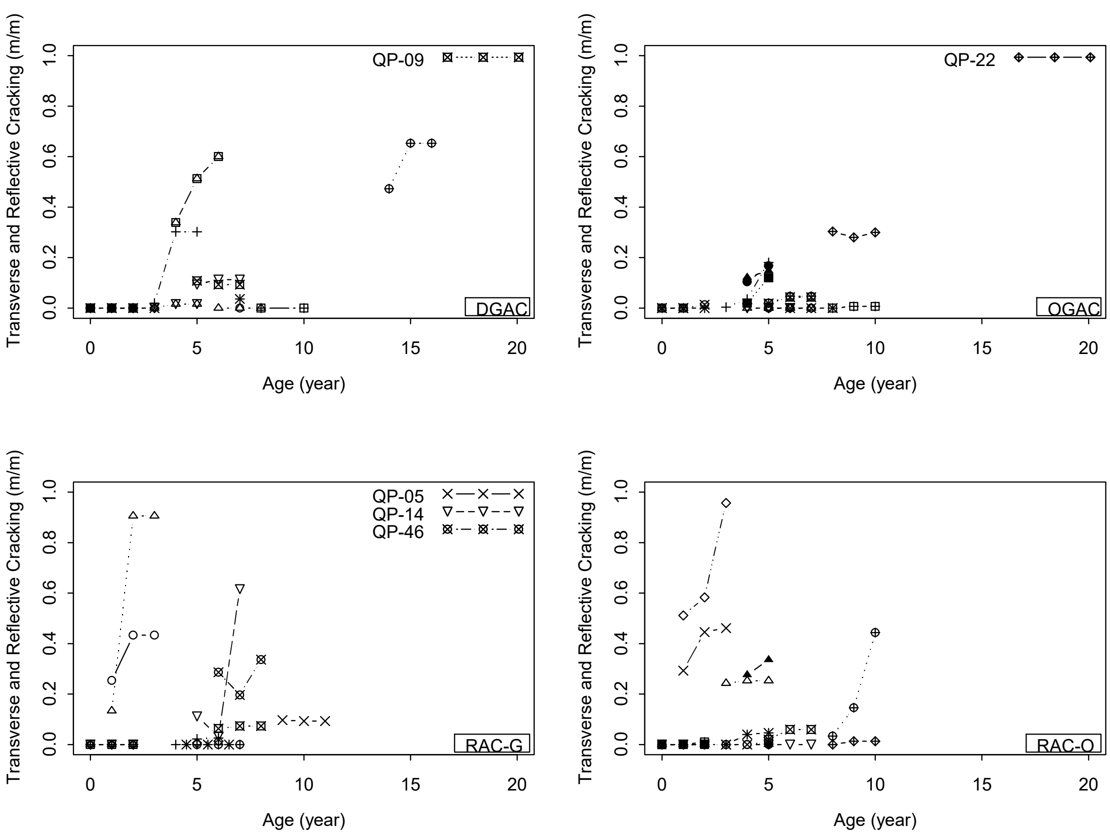

Figure 4.5: Transverse/reflective cracking development trends in three years for each pavement section.

It can be seen that transverse/reflective cracking generally propagates with pavement 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 nonrubberized pavements (DGAC and OGAC). As pointed out in the two-year noise study report (2), 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 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 4.6 shows the percentage of sections with transverse and reflective cracking in three consecutive survey years for the four pavement types: DGAC, OGAC, RAC-G, and RAC-O. 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 second survey year to the third survey year, the percentage of cracked sections does not change for any pavement type.

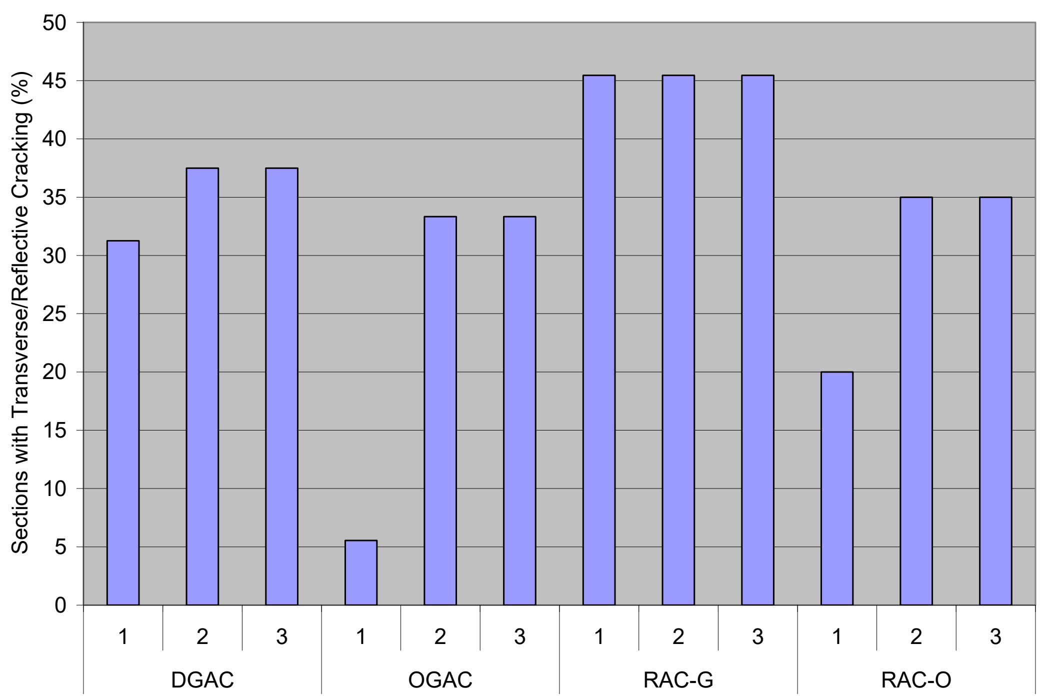

Figure 4.6: Percentage of pavement sections with 5 m of transverse/reflective cracking in 150 m section in three years for four mix types.

4.3.2 Statistical Analysis

Regression analysis was performed to evaluate the effects of traffic, climate, and mix properties on transverse/reflective cracking. The total length of the cracks (at all severity levels) was selected as the response variable. 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. Results of the single-variable regression analysis are given in Table 4.2. 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. The P-values less than 0.05 are shown in bold, indicating statistical significance at the 95 percent confidence interval.

Table 4.2: Regression Analysis of Single-Variable Models for Transverse/Reflective Cracking

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	0.0118358	**0.009**	0.043	0.037
2	Air-void Content (%)	-0.0031251	0.228	0.133	0.008
3	Mix Type	-0.0586000	0.128	0.101	0.038
4	Rubber Inclusion	0.0531253	0.057	0.071	0.020
5	Fineness Modulus	-0.0766643	**0.017**	0.479	0.033
6	PCC Below (1 -yes)	0.1147345	**0.025**	0.052	0.043
7	Underneath Layer Thickness (mm)	-0.0002376	0.392	0.103	0.006
8	Cracking in Underneath Layer (1 -yes)	-0.0165455	0.575	0.073	0.003
9	Surface Thickness (mm)	-0.0002858	0.721	0.107	0.001
10	Average Annual Rainfall (mm)	-0.0000898	**0.003**	0.151	0.048
11	Age * Average Annual Rainfall (mm)	0.0000030	0.649	0.089	0.001
12	Average Annual Wet Days	-0.0008404	**0.002**	0.161	0.055
13	Age*Average Annual Wet Days	0.0000450	0.399	0.082	0.004
14	Average Annual Max. Daily Air Temp (ºC)	0.0136164	**0.013**	-0.216	0.034
15	Annual Number of Days >30ºC	0.0007965	**0.004**	0.035	0.047
16	Annual Degree-Days >30ºC	0.0000221	**0.004**	0.038	0.045
17	Annual FT Cycles	-0.0025364	**0.018**	0.130	0.031
18	Annual AADTT per Coring Lane	0.0000146	0.126	0.079	0.013

Results of the single-variable regression analysis indicate that 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 4.2, multiple regression analysis was conducted to account for the effect of various factors simultaneously. The regression equation, Equation 4.2, is

$$\begin{aligned}&Transverse/ReflectiveCracking(m/m) = 0.271686 + 0.004845 \times AirVoid(\%) + 0.018047 \times Age(year)\\&-0.188134 \times ind(MixTypeOGAC) - 0.054069 \times ind(MixTypeRAC-G) - 0.136324 \times ind(MixTypeRAC-O)\\&-0.025383 \times ind(PCCBelow) + 0.018369 \times ind(CrackBelow) - 0.003510 \times SurfaceThickness(mm)\\&-0.000447 \times UnderlyingThickness(mm) + 0.000014 \times AverageAnnualRainfall(mm) - 0.000224 \times AverageAnnualWetDays\\&-0.001113 \times NumberOfDays > 30C - 0.000585 \times AnnualFTCycles + 8.170241 \times CumulativeAADTTinCoringLane(10e6)\end{aligned} \quad \textbf{(4.2)}$$

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

	Value	Std. Error	t value	P-value
(Intercept)	0.271686	0.104323	2.6043	0.0107
AirVoid	0.004845	0.003805	1.2734	0.2059
Age	0.018047	0.004194	4.3028	0.0000
PvmntTypeOGAC	-0.188134	0.054370	-3.4602	0.0008
PvmntTypeRAC-G	-0.054069	0.037564	-1.4394	0.1533
PvmntTypeRAC-O	-0.136324	0.047260	-2.8846	0.0048
PCCBelow	-0.025383	0.046622	-0.5445	0.5874
CrackBelow	0.018369	0.031515	0.5829	0.5613
Thickness	-0.003510	0.001063	-3.3007	0.0014
UnderlyingThickness	-0.000447	0.000325	-1.3771	0.1717
AvgAnnualRainfall	0.000014	0.000030	0.4716	0.6383
AvgAnnualWetDays	-0.000224	0.000230	-0.9762	0.3314
NoDaysTempGT30	-0.001113	0.000351	-3.1712	0.0020
AnnualFTCycles	-0.000585	0.000999	-0.5855	0.5596
Age*AADTTCoringLane	8.170241	3.549995	2.3015	0.0235

Residual standard error: 0.1153 on 97 degrees of freedom; Multiple R-Squared: 0.49.

The results show that at the 95 percent confidence level, age, pavement type, overlay thickness, number of days with temperature greater than 30ºC, and cumulative truck traffic 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 underlying layer (existence of PCC under layer, underneath layer thickness, and cracking of underneath layer) do not have a significant effect on the transverse/reflective cracking in the surface layer in the multiple variable regression. 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 the existence of PCC below is significant, and has an opposite sign than in the multiple variable regression.

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).

4.4.1 Descriptive Analysis

Figure 4.7 shows the percentage of area with raveling (at all three severity levels) in the three 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).

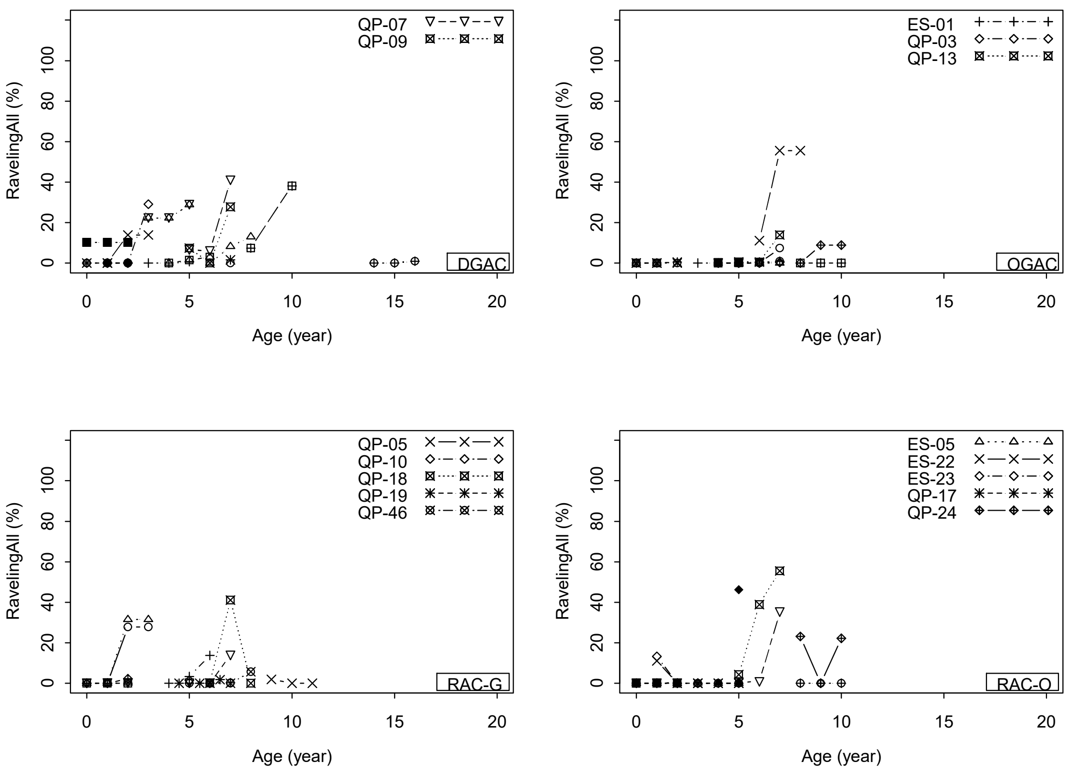

Figure 4.7: Raveling development trends over three years for each pavement section.

The presence of raveling on 5 percent or more of the total area of a section was selected as the threshold for the start of raveling for this analysis. If a section had 5 percent or more raveling, it was assumed that the section shows raveling. Figure 4.8 shows the percentage of sections with raveling in three consecutive survey years for the four pavement types: DGAC, OGAC, RAC-G, and RAC-O. It can be seen that the DGAC pavements experience the most raveling in all three 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.

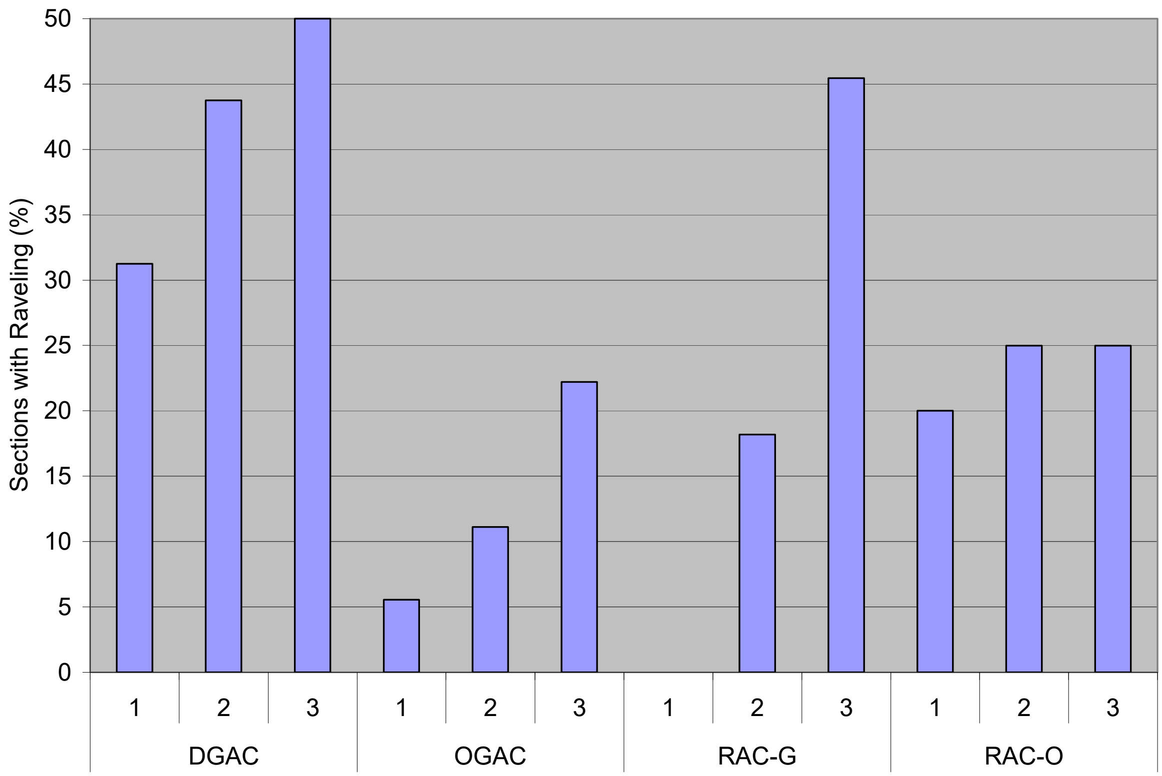

Figure 4.8: Percentage of pavement sections with at least 5 percent of area with raveling for each of three years of measurement for four mix types.

4.4.2 Statistical Analysis

Regression analysis was performed to evaluate the effects of traffic, climate, and mix properties on transverse/reflective cracking. The surface area with raveling (at all severity levels) was selected as the response variable. Results of the single-variable regression analysis are given in Table 4.3. The P-values less than 0.05 are shown in bold.

Results of the single-variable regression analysis indicate that raveling may be significantly affected by pavement age, NMAS, average annual wet days, high temperature days, and cumulative truck traffic.

Table 4.3: Regression Analysis of Single-Variable Models for Raveling

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	0.675437	**0.019**	2.216	0.031
2	Air-void Content (%)	-0.190704	0.242	7.517	0.008
3	Mix Type	-3.750916	0.125	7.196	0.014
4	Rubber Inclusion	0.031172	0.986	5.260	<0.001
5	Fineness Modulus	-0.717648	0.724	9.037	0.001
6	NMAS (mm)	0.692125	**0.040**	-3.630	0.024
7	C_u	0.088115	0.139	3.598	0.013
8	C_c	0.007133	0.988	5.464	<0.001
9	Surface Thickness (mm)	0.048421	0.335	3.392	0.005
10	Average Annual Rainfall(mm)	-0.002696	0.163	6.927	0.011
11	Age*Average Annual Rainfall(mm)	0.000144	0.727	4.919	0.001
12	Average Annual Wet Days	-0.038265	**0.023**	8.216	0.029
13	Age*Average Annual Wet Days	0.000622	0.853	5.079	<0.001
14	Average Annual Max. Daily Air Temp (ºC)	0.544350	0.115	-7.217	0.014
15	Annual Number of Days > 30ºC	0.036514	**0.035**	2.456	0.025
16	Annual Degree-Days > 30ºC	0.001030	**0.034**	2.531	0.025
17	Annual FT Cycles	0.047635	0.482	4.646	0.003
18	Annual AADTT per Coring Lane	0.002633	**<0.001**	2.235	0.109

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

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

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

	Value	Std. Error	t value	P-value
(Intercept)	-26.88784	14.10131	-1.9068	0.0583
Age	0.37531	0.28702	1.3076	0.1929
PvmntTypeOGAC	-7.51581	3.62075	-2.0758	0.0395
PvmntTypeRAC-G	-3.28724	3.32753	-0.9879	0.3247
PvmntTypeRAC-O	-6.47839	3.50901	-1.8462	0.0667
FinenessModulus	5.44893	3.10022	1.7576	0.0807
AvgAnnualRainfall	0.00209	0.00229	0.9132	0.3625
AvgAnnualWetDays	-0.00541	0.01799	-0.3008	0.7640
NoDaysTempGT30	0.03870	0.01936	1.9991	0.0473
AnnualFTCycles	0.07563	0.06791	1.1136	0.2671
AgeAADTTCoringLane	723.76829	112.38328	6.4402	<0.0000

Residual standard error: 10.16 on 160 degrees of freedom; Multiple R-Squared: 0.31.

The results show that at the 95 percent confidence level, the number of days with temperature greater than 30ºC and cumulative truck traffic are significant in affecting raveling. At the 90 percent confidence level, pavement age and fineness modulus become significant. The estimated parameters indicate that raveling increases with pavement age, fineness modulus, number of high temperature days, and cumulative truck traffic.

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 reflective 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).

4.5.1 Descriptive Analysis

Figure 4.9 shows the percentage of area with fatigue cracking (at all three severity levels) in the three survey years for the four pavement types. It can be seen from the plots 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.

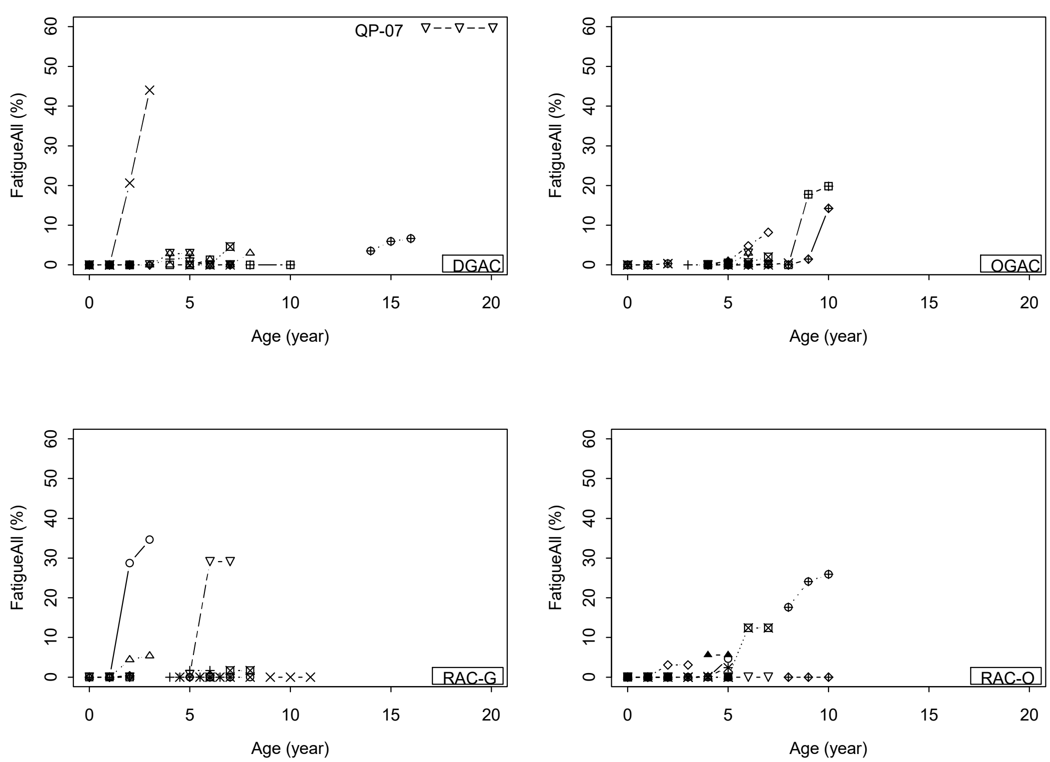

Figure 4.9: Development trends for fatigue cracking over three years for each pavement section.

The presence of fatigue cracking on 5 percent or more of the wheelpaths was selected as the threshold for the start of fatigue cracking for this analysis. If a section had 5 percent or more fatigue cracking, it was assumed that the section showed fatigue cracking. Figure 4.10 shows the percentage of sections with fatigue cracking in three consecutive survey years for the four pavement types: DGAC, OGAC, RAC-G, and RAC-O. It can be seen that the DGAC pavements experienced the most fatigue cracking in all three years. Fatigue cracking in the open-graded pavements (OGAC and RAC-O) was less significant than that in the DGAC and RAC-G pavements.

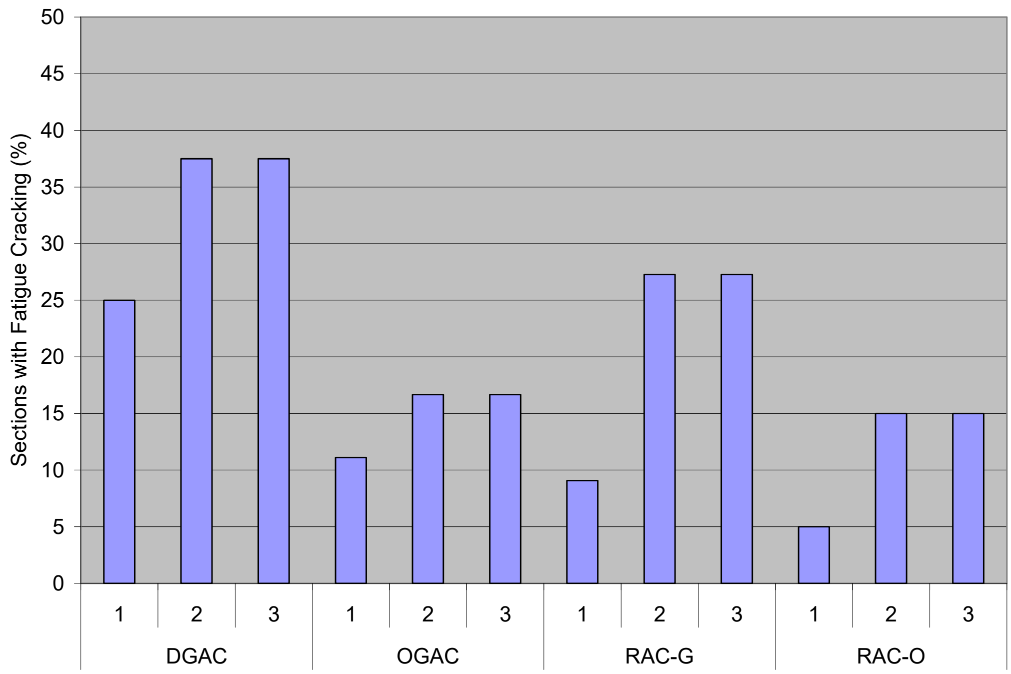

Figure 4.10: Percentage of pavement sections with at least 5 percent of wheelpaths with fatigue cracking for each of the three years measured.

4.5.2 Statistical Analysis

Both regression analysis and survival analysis were 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.

Regression Analysis

Results of the single-variable regression analysis are given in Table 4.4. The P-values less than 0.05 are shown in bold. Results in Table 4.4 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.

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

$$\begin{aligned}
&FatigueCracking(\%) = -7.1108 + 0.6729 \times Age + 1.6799 \times ind(MixTypeOGAC) + 2.2587 \times ind(MixTypeRAC - G) \\
&+2.4014 \times ind(MixTypeRAC - O) + 4.1988 \times ind(underlyingPCC) - 0.1159 \times ind(CrackingBelow) - 0.0026 \times Thickness \\
&0.0014 \times AverageAnnualRainfall + 0.0127 \times AverageAnnualWetDays + 0.0195 \times NumberOfDays > 30C \\
&-0.0034 \times AnnualFTCycles + 351.1 \times CumulativeAADTTinCoringLane(10e6)
\end{aligned} \tag{4.4}$$

Table 4.4: Regression Analysis of Single-Variable Models for Fatigue Cracking

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	0.439312	**0.0083**	0.4309	0.0388
2	Air-void Content (%)	-0.103554	0.2741	3.6329	0.0068
3	Mix Type	-0.672490	0.6349	2.2635	0.0141
4	Rubber Inclusion	1.048238	0.3043	1.9164	0.0060
5	Fineness Modulus	-0.371083	0.7542	4.3392	0.0006
6	PCC Below (1 -yes)	5.868801	**0.0042**	1.6991	0.0696
7	Underneath Layer Thickness (mm)	0.021019	0.0587	-1.5673	0.0310
8	Cracking in Underneath Layer (1 -yes)	-2.023936	0.0868	3.5060	0.0260
9	Surface Thickness (mm)	-0.053162	0.0675	4.4867	0.0188
10	Average Annual Rainfall (mm)	-0.002286	**0.0410**	3.8209	0.0234
11	Age*Average Annual Rainfall (mm)	0.000309	0.1956	1.6577	0.0094
12	Average Annual Wet Days	-0.018642	0.0570	3.8532	0.0203
13	Age*Average Annual Wet Days	0.003176	0.1019	1.4233	0.0150
14	Average Annual Maximum Daily Air Temp (°C)	0.543994	**0.0063**	-10.0633	0.0414
15	Annual Number of Days >30°C	0.028946	**0.0038**	0.1856	0.0463
16	Annual Degree-Days >30°C	0.000807	**0.0041**	0.2707	0.0455
17	Annual FT Cycles	-0.029643	0.4518	2.8115	0.0032
18	Annual AADTT per Coring Lane	0.000046	0.8961	2.3675	0.0001

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

	Value	Std. Error	t value	P-value
(Intercept)	-7.1108	4.4841	-1.5858	0.1159
Age	0.6729	0.1900	3.5408	0.0006
PvmntTypeOGAC	1.6799	1.8584	0.9039	0.3682
PvmntTypeRAC-G	2.2587	1.6517	1.3675	0.1745
PvmntTypeRAC-O	2.4014	1.8591	1.2917	0.1994
PCCBelow	4.1988	2.1203	1.9803	0.0500
CrackBelow	-0.1159	1.3834	-0.0838	0.9334
Thickness	-0.0026	0.0475	-0.0538	0.9572
AvgAnnualRainfall	0.0014	0.0014	0.9891	0.3250
AvgAnnualWetDays	0.0127	0.0104	1.2182	0.2260
NoDaysTempGT30	0.0195	0.0156	1.2488	0.2147
AnnualFTCycles	-0.0034	0.0451	-0.0761	0.9395
AgeAADTTCoringLane	351.1	159.6	2.1995	0.0301

Residual standard error: 5.246 on 100 degrees of freedom; Multiple R-Squared: 0.33.

The results show that at the 95 percent confidence level, pavement age, the 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 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 is an insignificant factor, indicating there is no significant difference in the fatigue performance of the four mix types.

Survival Analysis

Survival analysis was used to model the crack initiation. A brief introduction of survival analysis was included in the two-year noise study report (2).

The Cox (proportional hazard) regression model was developed using the three-year condition surveys from 59 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 4.5. It can be seen that no variable is significant at the 95 percent confidence level.

Table 4.5: Single-Variable Cox Regression Model for Wheelpath Crack Initiation

Model Number	Variable Name	Coefficient	P-value	Wald Test p-value
1	Air-void Content (%)	0.983	0.770	0.765
2	Mix Type (DGAC-RAC-O)	0.281	0.780	
	Mix Type (OGAC-RAC-O)	0.435	0.640	
	Mix Type (RAC-G-RAC-O)	1.566	0.094	0.322
3	Rubber Inclusion	0.259	0.690	0.686
4	Fineness Modulus	-0.0879	0.890	0.887
5	Underneath Layer Thickness (mm)	-0.0166	0.230	0.227
6	Cracking in Underneath Layer (1 -yes)	-0.596	0.630	0.627
7	Surface Thickness (mm)	-0.139	0.120	0.118
8	Average Annual Rainfall (mm)	-0.00203	0.280	0.276
9	Average Annual Wet Days	-0.0105	0.440	0.442
10	Average Annual Max. Daily Air Temp (ºC)	-0.00451	0.970	0.974
11	Annual Number of Days >30ºC	-0.278	0.310	0.306
12	Annual Degree-Days >30ºC	0.0000629	0.750	0.752
13	Annual FT Cycles	0.00637	0.780	0.778

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

4.6 Summary of Findings

Based on the data available in this study, the following findings were obtained regarding pavement distresses.

- Bleeding may appear two to four years after construction on all pavement types, and it tends to appear earlier on rubberized pavements than on nonrubberized 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. RAC-G pavements seem to be most susceptible to bleeding distress in terms of both the time of occurrence and the extent of distress. 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.
- 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 three survey years. Comparison of the rutting resistance of the four mixes, however, cannot be made without knowledge of the underlying layers.

- Transverse/reflective cracks seem to initiate earlier and propagate faster on the rubberized asphalt pavements (RAC-G and RAC-O) than on the nonrubberized 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. From the second survey year to the third survey year, the percentage of cracked sections did not change for any pavement type.
- 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.
- Raveling may occur on all types of pavements, and in general it 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). RAC-G pavements showed no raveling in the first survey year, but a significant increase in raveling in the second and third survey years.
- Statistical analysis shows that the number of days with temperature greater than 30ºC and cumulative truck traffic are significant in affecting raveling. Pavement age and fineness modulus are marginally significant. The estimated parameters indicate that raveling increases with pavement age, fineness modulus, number of high temperature days, and cumulative truck traffic.
- Fatigue cracking/reflective cracking in the wheelpaths 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. Fatigue cracking in the open-graded pavements (OGAC and RAC-O) is less significant than that in the DGAC and RAC-G pavements.
- Regression analysis shows that at the 95 percent confidence level, 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 mix types.

5. SOUND INTENSITY RESULTS AND ANALYSIS

The noise measurements in the third year were conducted similarly to those taken the previous two years (1), with one exception: The test tire was changed from the Aquatred 3 to a Standard Reference Test Tire (SRTT). Noise was measured using the version of the On-board Sound Intensity method developed in California (OBSI-California). The 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 will first focus on the overall sound intensity, and then on the one-third octave band noise levels in several typical frequency bands. Questions answered by this analysis include:

- What is the trend with time for overall OBSI?
  - How do the mixes rank with respect to OBSI, initially and with type?
  - 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?
- What do the answers for each frequency suggest about the mechanisms causing the noise?

The hypotheses regarding the effects of the explanatory variables on noise are discussed in Reference (1), and will be revisited in more detail at the conclusion of the fourth year of measurement, analysis and modeling. To very briefly summarize from that report, it is generally considered that the tire vibration noise–generating mechanism is mostly responsible for low frequency noise (500 Hz), and that the air-pumping mechanism is mostly responsible for high frequency noise (2,000 Hz and higher frequencies). The 1,000 Hz frequency, which often has the highest sound intensity due to the nature of tire/pavement noise and weighting for human perception through the A-weighted scale, is generally considered to be influenced by both 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)

All the noise levels presented in this report are A-weighted. The unit “dB(A)” is consequently used in this report and is sometimes written in the literature as “dBA.”

5.1 Conversion of Sound Intensity for Temperature, Speed, Air Density, Tire

Sound intensity measurements are highly affected by temperature, test car speed, air density, and type of test tire.

The effects of pavement temperature developed as part of this study are addressed in a separate memorandum. The temperature correction was not applied to these third-year results because the conversion was not available when these data were analyzed and it was found later that the pavement temperature correction is small (about –0.018 dB per increase of one degree Celsius). The temperature correction will be applied to all four years of data when the fourth-year measurements are completed in 2009.

In general, the sound intensity measurement was conducted at a speed of 60 mph (96 km/h). Under the constraints of road geometry and traffic condition, however, some pavement sections in this study were tested at a speed of 30 mph (50 km/h) or 35 mph (56 km/h). 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). The 30-mph measurements (on QP-48 and QP-49 sections) were discarded in the analysis because currently there is no conversion equation.

After all the sound intensity measurements were converted to their equivalent values at 60 mph, the same air-density correction equations as used in the previous 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) (1).

In the second-survey year, the sound intensities on 24 QP pavement sections were measured with both the Aquatred 3 tire and SRTT. The data were used to develop correlation equations to convert the previous two-year Aquatred 3 tire measurements to equivalent SRTT measurements. The 24 QP pavement sections include four mix types: DGAC, OGAC, RAC-G, and RAC-O. The correlation functions, however, were developed for a generic asphalt pavement because of the small sample size of pavement sections for each mix type. Simple linear regression analysis was used to develop the correlation functions, and the results are shown in A.2: Correlation Between Aquatred 3 Tire OBSI and SRTT OBSI. Results show that there are good correlations between the sound intensities measured with the two tire types in each of the one-third octave frequency bands. For the overall sound intensity, the coefficient of determination, R^2, is as high as 0.96. With those correlation functions, the sound intensities measured with the Aquatred 3 tires in the first two survey years were then converted to the equivalent SRTT measurements and combined with the third-year measurements made with the SRTT.

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 (5.1):

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

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.

5.2.1 Descriptive Analysis

Figure 5.1 shows the average overall OBSI values observed in the three survey years on each pavement section of the four mix types. It can be seen from the plots that 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 increase 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 increase 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 5.1 shows that there are a few pavement sections on which the measured sound intensity dropped significantly in the second or third survey years. These sections include: 01-N114 (DGAC), QP-20 (OGAC), 01-N105 (OGAC), QP-42 (RAC-O), and 06-N466 (RAC-O).

The overall OBSI value measured on Section 01-N114 in the third survey year was about 2 dB(A) lower than the value measured in the second survey year. The reason for the drop is not clear. It is possibly due to the combined effect of variations in pavement temperature (the measurement was taken in August in the second year and in May in the third year), use of different test tires (Aquatred 3) tire in the second year versus SRTT in the third year), and other random errors.

The overall OBSI value measured on Section QP-20 decreased with pavement age. As discussed earlier, Section QP-20 is located on a steep hill and may have experienced compaction problems during construction. This section had high MPD to begin with, and the measured MPD increased in the third year, which would generally result in increased rather than decreased noise. It is possible that the explanation is the difficulty of measuring OBSI on this section because the hill makes constant speed hard to maintain.

The overall OBSI value measured on Section 01-N105 in the third survey year was about 1 dB(A) lower than the value measured in the second year. The overall OBSI values measured on Section QP-42 in the second and third year were significantly lower than the value measured in the first year. This is because there were measurement errors in the first-year data collection on that particular section, which showed a particularly high sound intensity value (1).

The overall OBSI value measured on Section 06-N466 decreased with pavement age. This section was excluded from statistical analyses of noise. Probably this is due to different measurers in the three years (Illingworth and Rodkin in the first year, UCPRC in the second and third years), occurrence of bleeding in the third year, and variations in pavement temperature (the measurement was taken in September in the second year and in April in the third year). In this study, the effect of pavement temperature on measured sound intensity is not corrected. Another observation from Figure 5.1 is that the overall sound intensity measured on Section QP-17 (RAC-O) increased significantly with pavement age. This is possibly due to the occurrence of severe pavement distress (transverse cracking) in the second and third survey years.

Figure 5.2 shows the box plots of overall OBSI over three years for different mix types for the three original age categories (less than one year, one to four years, greater than four years). As the figure shows, sound intensity generally increases with pavement age for the same pavement section. With a few exceptions, this increasing trend is also obvious among different pavement sections of the same mix type. 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.

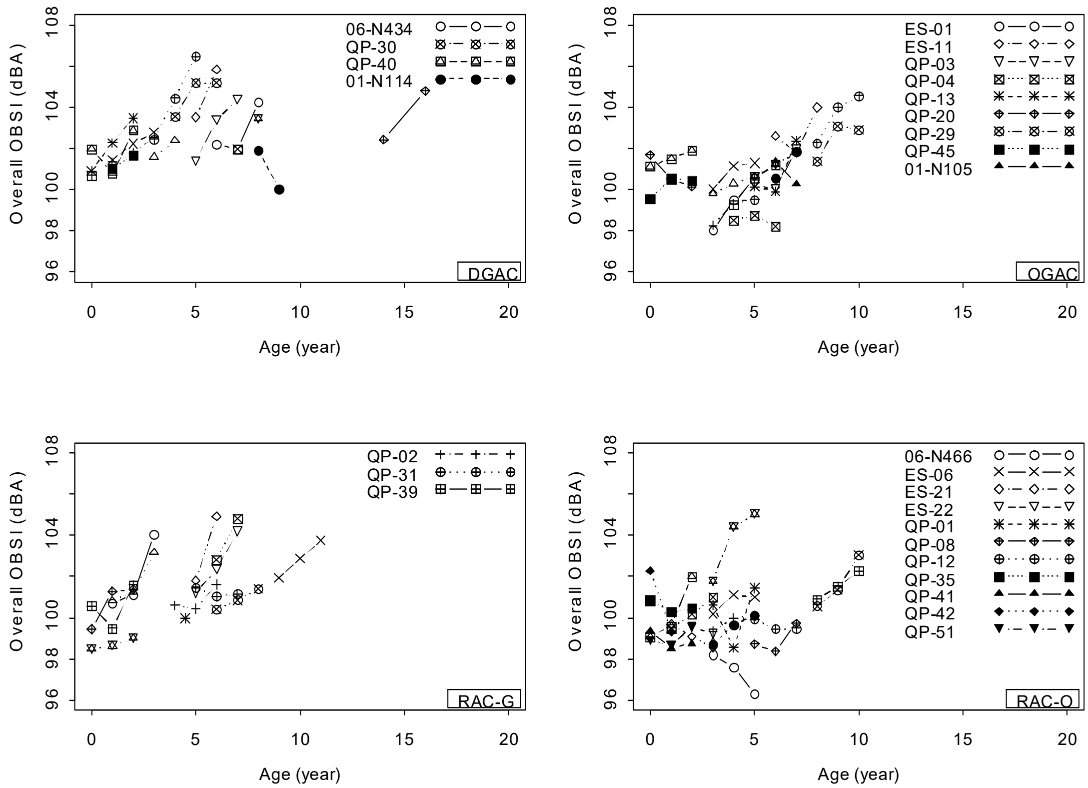

Figure 5.1: Development trends of overall OBSI over three years for each pavement section.

"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. The assumption is that an overlay will be placed, and that the decision to be made is which overlay mix type will produce the lowest noise and for how long, compared to the typical DGAC overlay. It should be noted that the definition of noise reduction used in this study—comparing to the tire/pavement noise levels of the most typical current overlay (DGAC)—is not the only definition of noise reduction. Some studies have defined noise reduction by comparing current noise levels on an overlay to noise levels on the damaged pavement prior to application of the overlay. Other studies have predicted the way-side noise levels of different alternatives using the Traffic Noise Model (TNM).

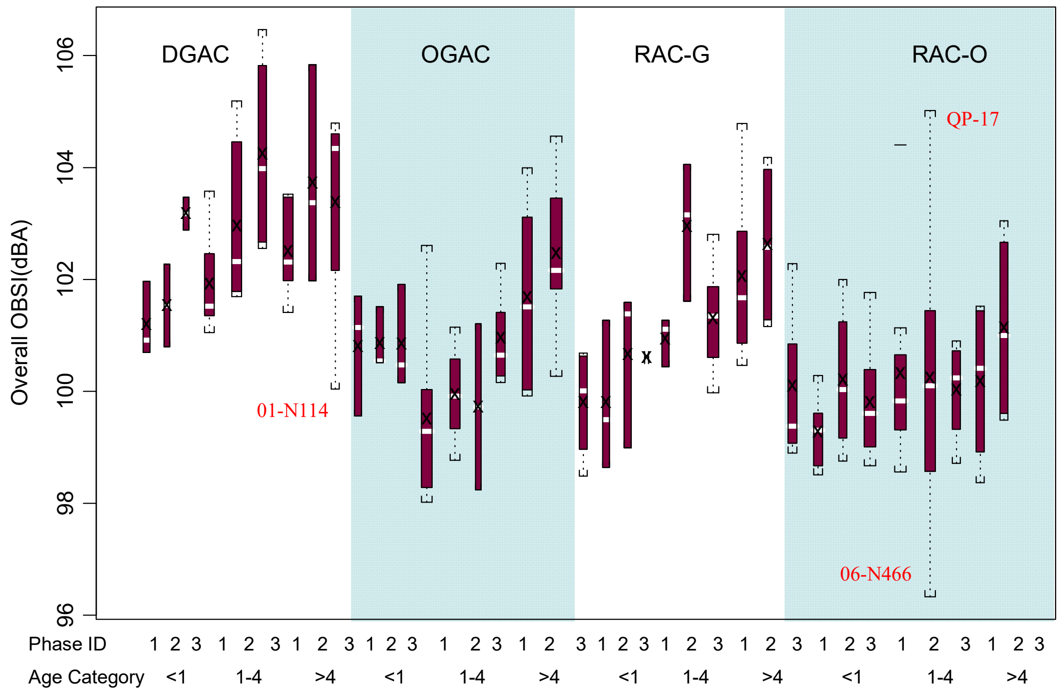

Figure 5.2: Comparison of overall OBSI values for different mix types for different initial age categories (Age Category) and for first, second, and third years of data collection (Phase ID).

Figure 5.3 shows the cumulative distribution function 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 numbers in parentheses in the legend represent the sample size of each mix type. All three-year observations were used to create the plots. As can be seen, the sample sizes are different among different mixes and age groups. The average noise level of DGAC mixes in each age group also appears in the legend, which shows that the average noise level on DGAC pavements is about 101.3 dB(A) for newly paved overlays, 102.4 dB(A) for pavements with an age between one and three years old, and varies between approximately 103 and 104 dB(A) for pavements older than three years.

A positive value in Figure 5.3 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 4 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. It has been suggested that to be considered "noise reducing," a pavement surface should lower traffic noise at least 3 dB(A) compared to conventional road surfaces without jeopardizing pavement safety and durability (5). This noise reduction level is partly based on the inability of humans to perceive a noise difference of much less than 2 dB(A). 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.

For pavements with an age between one and three years, OGAC and RAC-O pavements have similar noise-reducing ability [about 40 percent of pavements are at least 3 dB(A) quieter than average DGAC pavement], 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 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 80 percent of RAC-O and OGAC pavements and 50 percent of RAC-G pavements in this age range are at least 3 dB(A) quieter than the average DGAC pavement. The reason for the increased percentage of noise-reducing pavements is that the referenced DGAC pavements become much noisier with age [103.9 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 seven 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 seven 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.

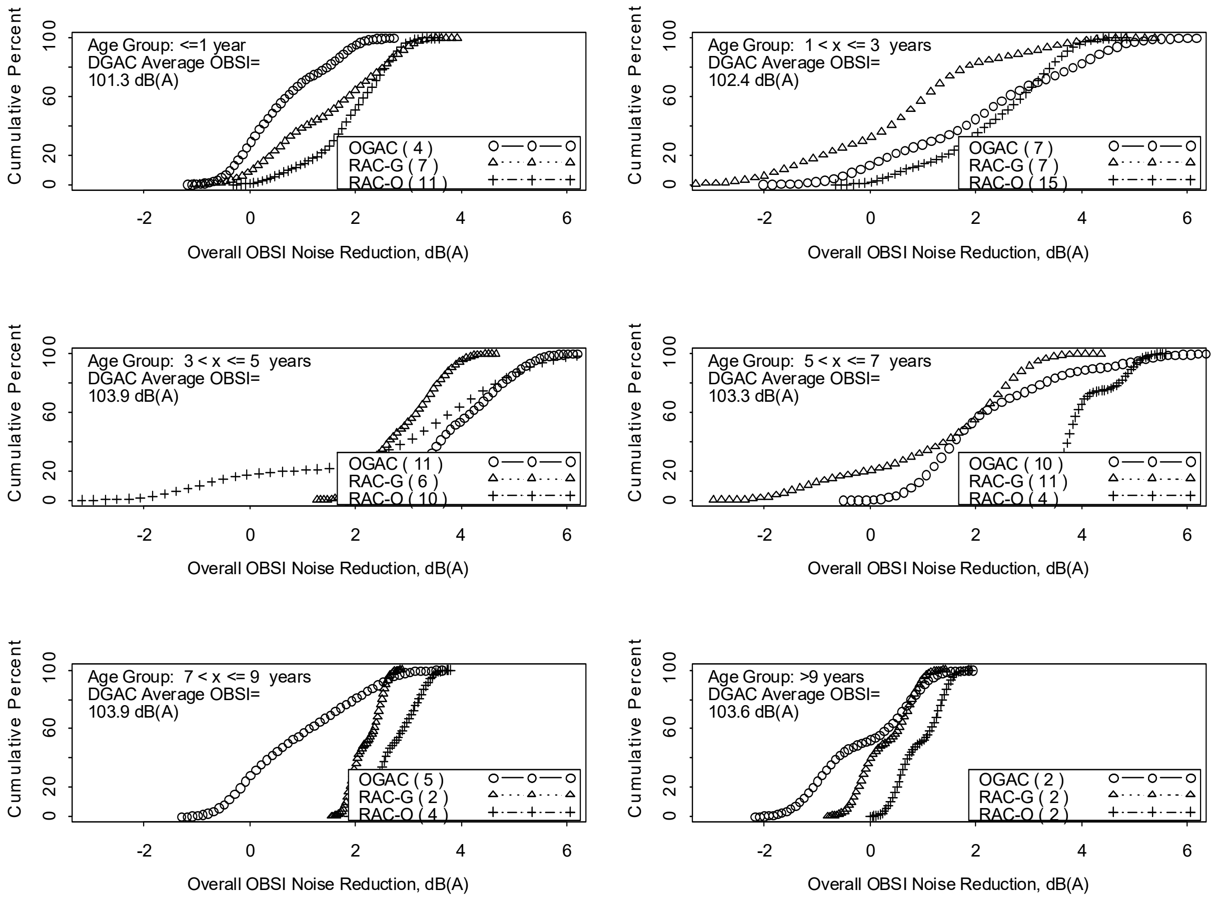

Figure 5.3: Cumulative distribution function of noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups of pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.)

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. 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.

In the third-year survey, air-void content, permeability, and friction (in terms of British Pendulum Number [BPN]) were not measured in the field. To use these variables in the regression analysis, the third-year data were extrapolated from the first two-year data. (See Appendix A.3: Box Plots of Air-Void Content, Permeability, and BPN.) It can be observed from the box plots that the air-void content generally decreases with time for all mixes, and the in-situ permeability decreases with time for OGAC, RAC-G, and RAC-O mixes. For RAC-G pavements, the in-situ permeability is comparable to that of open-graded pavements in the first three years after construction, but rapidly decreases to a near-zero level after four or five years. Surface friction (BPN) tends to increase slightly with pavement age. Based on these observations, linear extrapolation was applied to estimate the third-year values of air-void content, permeability, and BPN from the first two years' data.

A few pavement sections were excluded from the data set used for the statistical analysis because they were either outliers or contain erroneous measurements in one year: Sections QP-17, QP-20, QP-42, QP-30 (third-year), 01-N114, 01-N105, and 06-N466.

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 5.1. The P-values less than 0.05 are shown in bold.

Table 5.1: Regression Analysis of Single-Variable Models for Overall Sound Intensity

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	0.2510	**<0.001**	100.031	0.158
2	Air-void Content (%)	-0.1347	**<0.001**	102.669	0.159
3	Mix Type	-1.8942	**<0.001**	102.725	0.289
4	FinenessModulus	-1.7893	**<0.001**	110.006	0.174
5	NMAS (mm)	0.1025	0.061	99.784	0.020
6	C_u	0.0528	**<0.001**	100.026	0.187
7	C_c	0.0325	0.683	101.015	0.001
8	Rubber Inclusion	-1.0632	**<0.001**	101.646	0.086
9	IRI (m/km)	0.7505	**<0.001**	99.561	0.124
10	MPD (micron)	-9.95e-5	0.695	101.340	0.001
11	BPN	0.0019	0.919	101.011	<0.001
12	Surface Thickness (mm)	0.0006	0.931	101.075	0.000
13	Presence of Fatigue Cracking	1.4733	**<0.001**	100.892	0.087
14	Presence of Raveling	1.5373	**<0.001**	100.846	0.081
15	Presence of Transverse Cracking	0.9062	**0.003**	100.817	0.053
16	Presence of Bleeding	1.2014	**0.004**	100.956	0.049
17	Presence of Rutting	2.1100	**<0.001**	100.864	0.134
18	Permeability (cm/sec)	-13.5159	**<0.001**	101.584	0.179
19	Average Annual Rainfall (mm)	1.056e-4	0.653	101.022	0.001
20	Cumulative AADT in Coring Lane (×3.65e8)	10.1377	**<0.001**	100.667	0.083
21	Cumulative AADTT in Coring Lane(×3.65e8)	44.5435	**0.021**	100.899	0.030
22	Cumulative ESALs in Coring Lane(×3.65e8)	0.0720	0.063	100.962	0.020

The results in Table 5.1 show that the overall sound intensity level tends to be significantly affected by pavement age, air-void content, permeability, mix type, fineness modulus, C_u, existence of rubber, surface roughness, the presence of surface distresses, and cumulative traffic volume. The signs of the estimated coefficients indicate that the overall sound intensity increases with pavement age, surface roughness, cumulative traffic volume, and all types of distresses (fatigue cracking, raveling, transverse cracking, rutting, and bleeding), but overall sound intensity decreases with increasing air-void content, permeability, fineness modulus, permeability, and inclusion of rubber. These results are generally expected. Environmental factors are not significant in the single-variable regression analysis.

Based on the results in Table 5.1, multiple regression analysis was conducted to account for the effects of the important 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 other than NMAS are excluded. The regression equation, Equation 5.2, is

$$\begin{aligned}&Overall\ Sound\ Intensity(dBA) = 102.8169 + 0.1321 \times Age(year) - 2.5192 \times ind(MixTypeOGAC) - 1.6122 \times ind(MixTypeRAC-G)\\&-3.0692 \times ind(MixTypeRAC-O) - 0.0232 \times Thickness(mm) - 0.000552 \times NumberOfDays > 30C\\&+0.0000938 \times AADTinCoringLane + 0.7775 \times ind(PresenceofRaveling) + 0.6302 \times ind(PresenceofRutting)\\&+0.0971 \times Age \times ind(MixTypeOGAC) + 0.1023 \times Age \times ind(MixTypeRAC-G) - 0.0199 \times Age \times ind(MixTypeRAC-O)\end{aligned} \quad \textbf{(5.2)}$$

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

	Value	Std. Error	t value	P-value
(Intercept)	102.8169	0.5253	195.7370	0.0000
Age	0.1321	0.0668	1.9770	0.0499
PvmntTypeOGAC	-2.5192	0.6119	-4.1170	0.0001
PvmntTypeRAC-G	-1.6122	0.5139	-3.1371	0.0021
PvmntTypeRAC-O	-3.0692	0.5239	-5.8580	0.0000
Thickness	-0.0232	0.0067	-3.4450	0.0007
NoDaysTempGT30	-0.000552	0.002057	-0.2685	0.7887
AADTTCoringLane	0.0000938	0.0000775	1.2094	0.2284
Raveling	0.7775	0.2590	3.0020	0.0031
Rutting	0.6302	0.3800	1.6586	0.0993
Age*PvmntTypeOGAC	0.0971	0.1034	0.9386	0.3494
Age*PvmntTypeRAC-G	0.1023	0.0989	1.0348	0.3024
Age*PvmntTypeRAC-O	0.0199	0.0959	0.2073	0.8360

Residual standard error: 1.258 on 149 degrees of freedom; Multiple R-Squared: 0.57.

It can be seen that at the 95 percent confidence level, age, mix type, surface layer thickness, and existence of raveling significantly affect the overall sound intensity. The overall sound intensity increases with pavement age and the existence of raveling distress, but decreases with increasing surface layer thickness. With regard to the three pavement types, OGAC, RAC-G, and RAC-O, all have lower initial overall sound intensity than DGAC. The average noise reductions (compared to DGAC pavements) for newly paved OGAC, RAC-G, and RAC-O mixes are about 2.5, 1.6, and 3.1 dB(A), respectively.

The interaction terms between age and mix type are not statistically significant, which indicates that the growth rate of overall sound intensity is not statistically different among the four pavement types. This conclusion is different from the direct observations from Figure 5.1. This is mostly due to the constraints applied by the multiple regression analysis. The regression analysis assumes a linear increase of noise with age for all mixes, but Figure 5.1 indicates that the noise development on open-graded mixes is more likely piecewise linear. Use of different growth function forms for different mixes in the same regression model significantly increases the complexity of parameter estimation and result interpretation, which is not attempted in this report. Considering the total noise increase during the pavement life covered by the data set in this study (about 10 years), the estimated parameters of the interaction terms indicate that the noise increase is higher on OGAC and RAC-G pavements than on DGAC pavements, and the lowest on RAC-O pavements.

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

<u>For DGAC pavements</u>

$$\begin{aligned} &\mathit{Overall\ Sound\ Intensity}(dBA) = 100.17103 - 0.29648 \times \log(\mathit{Permeability})(cm/\sec) + 0.15973 \times \mathit{Age}(year) - 0.19016 \times \mathit{FinenessModulus} \\ &- 0.00609 \times \mathit{Thickness}(mm) - 0.000323 \times \mathit{NumberOfDays} > 30C + 0.0000563 \times \mathit{AADTTinCoringLane} \end{aligned} \quad \textbf{(5.3)}$$

	Value	Std. Error	t value	P-value
(Intercept)	100.17103	5.02810	19.9222	<0.0001
log(Permeability)	-0.29648	0.14931	-1.9857	0.0573
Age	0.15973	0.06275	2.5455	0.0169
FinenessModulus	-0.19016	1.08826	-0.1747	0.8626
Thickness	-0.00609	0.01172	-0.5199	0.6074
NoDaysTempGT30	0.000323	0.00504	0.0642	0.9493
AADTTCoringLane	0.0000563	0.0000489	1.1514	0.2597

Residual standard error: 1.251 on 27 degrees of freedom; Multiple R-Squared: 0.40.

For OGAC pavements

$$\begin{aligned}&\textit{Overall Sound Intensity}(dBA) = 103.66182 - 0.12505 \times \log(permeability)(cm/\sec) + 0.2826 \times Age(year) - 1.68612 \times FinenessModulus \\ &+ 0.00216 \times MPD(micron) - 0.0046 \times Thickness(mm) - 0.0046662 \times NumberOfDays > 30C + 0.0000992 \times AADTTinCoringLane\end{aligned} \quad \textbf{(5.4)}$$

	Value	Std. Error	t value	P-value
(Intercept)	103.66182	2.47136	41.9452	<0.0001
log(**Permeability**)	-0.12505	0.05681	-2.2012	0.0353
Age	0.28260	0.06374	4.4335	0.0001
FinenessModulus	-1.68612	0.46971	-3.5897	0.0011
MPD	0.00216	0.00074	2.9316	0.0063
Thickness	-0.006847	0.00945	-0.7242	0.4744
NoDaysTempGT30	0.0046662	0.0033011	1.4135	0.1675
AADTTCoringLane	0.0000992	0.0000218	4.5503	0.0001

Residual standard error: 0.6469 on 30 degrees of freedom; Multiple R-Squared: 0.88.

For RAC-G pavements

$$\begin{aligned}&\textit{Overall Sound Intensity}(dBA) = 96.90559 - 0.1895 \times \log(permeability)(cm/\sec) + 0.26596 \times Age(year) - 0.17105 \times FinenessModulus \\ &+ 0.00182 \times MPD(micron) + 0.007128 \times Thickness(mm) + 0.0116425 \times NumberOfDays > 30C + (6.8e-6) \times AADTTinCoringLane\end{aligned} \quad \textbf{(5.5)}$$

	Value	Std. Error	t value	P-value
(Intercept)	96.90559	4.99575	19.3976	<0.0001
log(Permeability)	-0.18950	0.09562	-1.9818	0.0582
Age	0.26596	0.07228	3.6798	0.0011
FinenessModulus	-0.17105	0.96815	-0.1767	0.8611
MPD	0.00182	0.00061	2.9565	0.0065
Thickness	0.007128	0.01333	0.5348	0.5973
NoDaysTempGT30	0.011642	3.77e-31	3.0912	0.0047
AADTTCoringLane	6.80e-6	2.52e-5	0.2714	0.7882

Residual standard error: 0.9744 on 26 degrees of freedom; Multiple R-Squared: 0.68.

For RAC-O pavements

$$\begin{aligned}&\textit{Overall Sound Intensity}(dBA) = 104.27101 - 0.07211 \times \log(permeability)(cm/\sec) + 0.2824 \times Age(year) - 0.6013 \times FinenessModulus \\ &- 0.00072 \times MPD(micron) - 0.044325 \times Thickness(mm) - 0.00257 \times NumberOfDays > 30C - 0.0000022 \times AADTTinCoringLane\end{aligned} \quad \textbf{(5.6)}$$

	Value	Std. Error	t value	P-value
(Intercept)	104.27101	4.14829	25.1359	<0.0001
log(Permeability)	-0.07211	0.07450	-0.9679	0.3397
Age	0.22824	0.06212	3.6740	0.0008
FinenessModulus	-0.60130	0.84510	-0.7115	0.4815
MPD	-0.00072	0.00074	-0.9812	0.3332
Thickness	-0.044325	0.02627	-1.6875	0.1004
NoDaysTempGT30	-0.00257	0.00312	-0.8215	0.4169
AADTperCoringLane	-0.00000220	0.0000248	-0.0893	0.9294

Residual standard error: 0.8415 on 34 degrees of freedom; Multiple R-Squared: 0.53.

The results show that the overall sound intensity increases with pavement age for all four mix types. At the 95 percent confidence level, the in-situ permeability is a significant factor for OGAC pavements. For DGAC and RAC-G pavements, permeability is significant at a 90 percent confidence level. Higher permeability leads to lower noise level for these mixes. The surface layer thickness is an insignificant factor for all mixes, possibly reflecting the fact that for a given mix type the thicknesses were typically very similar. Pavement surface macrotexture (MPD) is a significant factor for OGAC and RAC-G pavements, and a higher MPD value corresponds to a higher noise level. For DGAC pavements, MPD is highly correlated with age in the data set used for analysis, most likely due to increasing raveling, so it is not included in the model. For RAC-O pavements, MPD does not have a significant influence on noise level.

For DGAC, RAC-G, and RAC-O pavements, the aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise. Fineness modulus is significant for OGAC pavements. The signs of estimated parameters for fineness modulus show that coarser gradations reduce the tire/pavement noise for all pavements, which is only significant for OGAC.

Truck traffic volume is a significant factor that increases tire/pavement noise for OGAC mixes.

A number of other models are possible, and additional modeling will be performed after collection of the fourth year of data.

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

Sound intensity was analyzed at each one-third octave frequency. 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, statistical analysis were 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.

5.3.1 Change of OBSI Spectra with Age

Figure 5.4 through Figure 5.6 show the sound intensity spectra averaged by mix type and age group in the three survey phases (i.e., three survey years). For more information, see Appendix A.5: Sound Intensity

Spectra Measured in Three Years for Each Pavement Section and Appendix A.6: Close-up Photos of Pavements Included in This Study.

From Figure 5.4, it can be seen that for newly paved overlays, the overall sound intensity changed little in the first three 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, and then increased significantly in the third 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 three 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 three 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 three 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 three years, while the sound intensities in the frequency band between 1,000 Hz and 2,500 Hz increased significantly with age. This indicates that the air-void content of DGAC and RAC-G pavements decreased significantly in the first three years, while the surface smoothness did not change much. These observations are consistent with the observations on IRI (Figure 2.1) and air-void content (Appendix A.3: Box Plots of Air-Void Content, Permeability, and BPN).

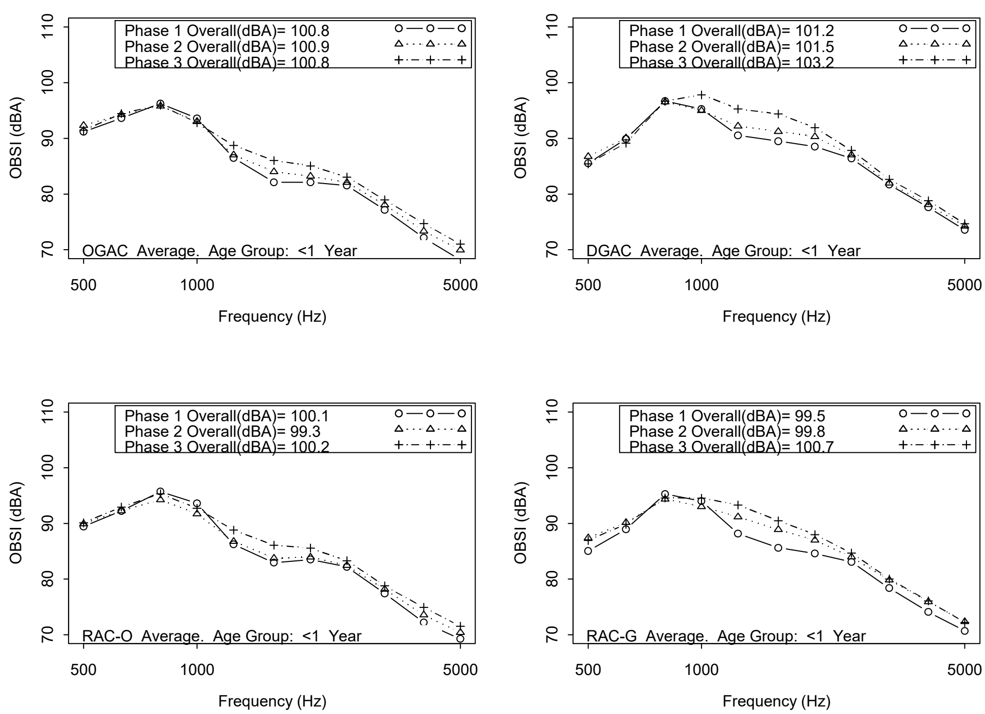

Figure 5.4: Average OBSI spectra for Age Group "<1 Year" in three survey phases (years).

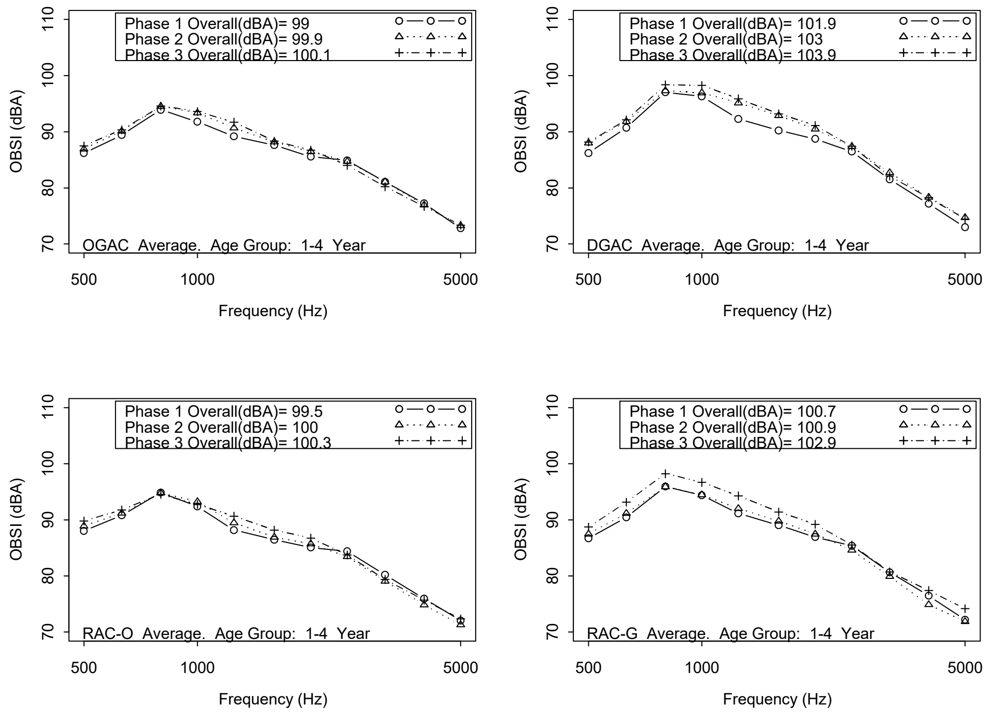

Figure 5.5: Average OBSI spectra for Age Group "1–4 Years" in three survey phases (years).

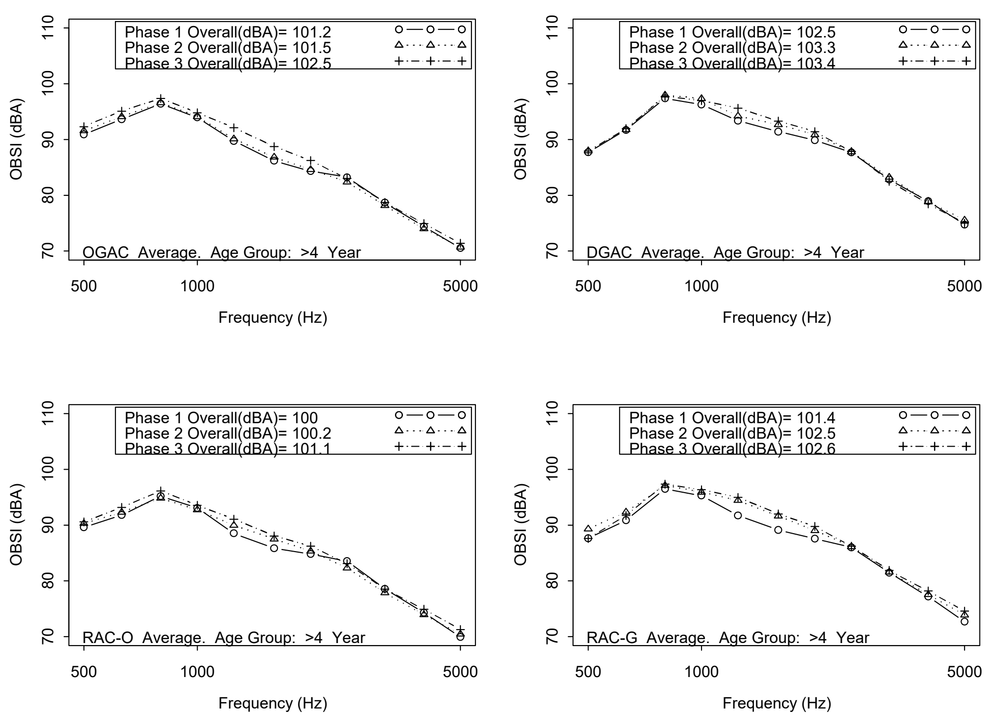

Figure 5.6: Average OBSI spectra for Age Group ">4 Years" in three survey phases (years).

Figure 5.5 shows that for pavements with an age between one and four years, the overall sound intensity increased slightly on both open-graded pavements (OGAC and RAC-O), and increased more significantly on DGAC and RAC-G pavements. The spectra show that for OGAC and RAC-O pavements, the sound intensity increased with age for frequencies lower than 2,500 Hz, and decreased slightly with age for frequencies higher than 2,500 Hz. For DGAC and RAC-G pavements, the sound intensity generally increased with age for all frequency levels.

Figure 5.6 shows that for old pavements ("age >4 years"), the increase of overall sound intensity with age is comparable on all of four pavement types. The spectra show that for OGAC, RAC-G, and RAC-O pavements, the increase of sound intensity with age mainly occurred at frequencies lower than 2,500 Hz, while for DGAC pavements, the increase of sound intensity with age mainly occurred at frequencies between 800 Hz and 2,500 Hz.

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

Figure 5.7 through Figure 5.17 show the three-year measurements of sound intensity at each one-third octave frequency band for the four mix types: DGAC, OGAC, RAC-G, and RAC-O. It can be seen from the plots that for the same pavement section 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 second or third survey year. Pavement sections showing a lower noise level in the later years are listed in the legend of each figure. There are many potential reasons for the reduction of noise: 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.

In Section 5.2.1, several pavement sections that showed significant reductions in the overall sound intensity in the second or third survey year were discussed for the potential causes. Here they are further studied at the individual frequency levels. For pavement sections 01-N114 and 01-N105, it can be seen that the sound intensities at low-frequency levels are lower in the second or third survey year than the values in the previous year (indicated by the section IDs in the figure legend), but the sound intensities at high-frequency levels are higher in later years than the previous year (indicated by the absence of the section IDs in the figure legend). This suggests that the reduction of the overall sound intensity on these pavement sections is primarily due to reduced tire vibration in the later years, which may result from the occurrence of bleeding (01-N105), and other changes that reduce macrotexture. For pavement Sections 06-N466 and QP-42, the sound intensity is less in the second or third year at all frequency levels (indicated by the presence of the section numbers in all the figure legends). As discussed in Section 5.2.1, the reason for the reduction is measurement error in the first-year data or different measurement methods. Pavement Section QP-17 (RAC-O) showed a significant increase of overall sound intensity in the second and third year (Figure 5.1). From Figure 5.7 through Figure 5.10 it can be seen that the increase is primarily at low frequency levels (500 to 1,000 Hz), not in the high frequency levels. This supports the conjecture in Section 5.2.1 that the cause of the significant increase in noise is the occurrence of severe pavement distress (transverse cracking).

Figure 5.7 and Figure 5.8 show that at low frequency levels (500 Hz and 630 Hz), sound intensities measured on OGAC, RAC-G, and RAC-O pavements are generally higher than the values measured on DGAC 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. As shown in Figure 3.1, OGAC, RAC-G, and RAC-O pavements have higher macrotexture (represented by MPD) than DGAC pavements, so they cause more tire vibration. Figure 5.9 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 5.10 through Figure 5.17. The figures also show that for frequency levels equal to or larger than 1,000 Hz, the sound intensity measured on OGAC and RAC-O pavements is 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.

Combining all the pavement sections in each mix type, it appears that the increase rate for sound intensity is similar at all frequency levels for DGAC pavements. For OGAC pavements, after excluding the three newly paved sections (which seem to be outliers), noise increase with pavement age is most significant at a frequency between 500 Hz and 2,500 Hz, and the noise at higher frequency levels does not seem to change significantly with pavement age. For RAC-G pavements, noise increase with pavement age seems to occur at all frequency levels. For RAC-O pavements, noise increase with pavement age seems to mainly occur at a frequency between 800 Hz and 2,500 Hz.

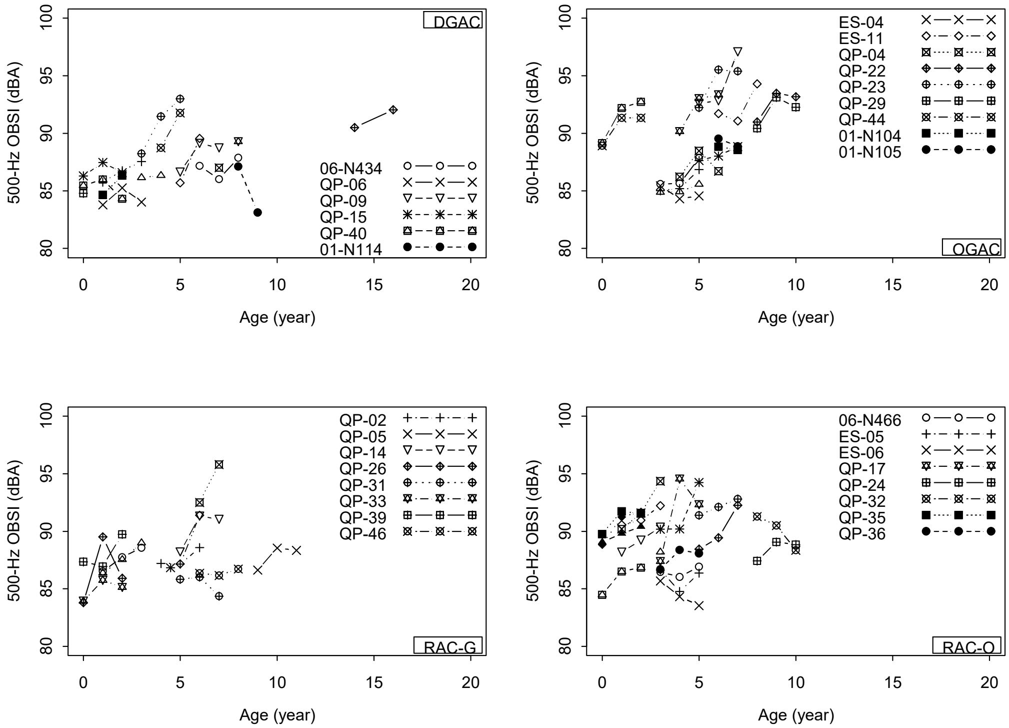

Figure 5.7: Sound intensity at 500 Hz over three years for each pavement section. (Note: Pavement sections showing a lower noise level in later years are listed in the legend of each figure.)

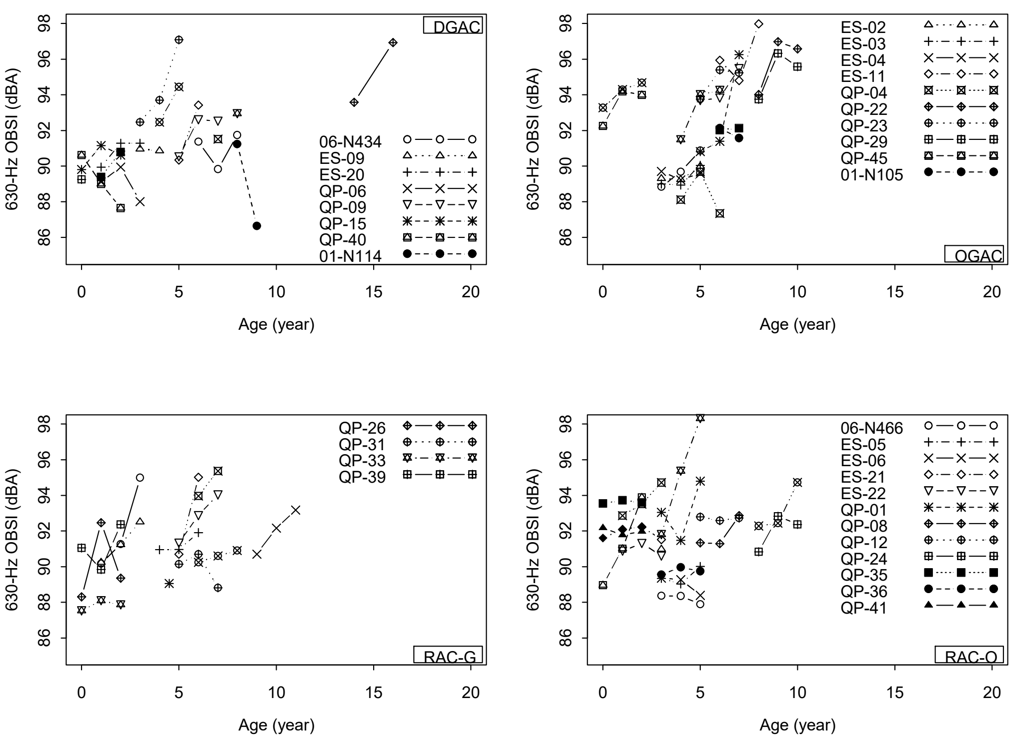

Figure 5.8: Sound intensity at 630 Hz over three years for each pavement section.

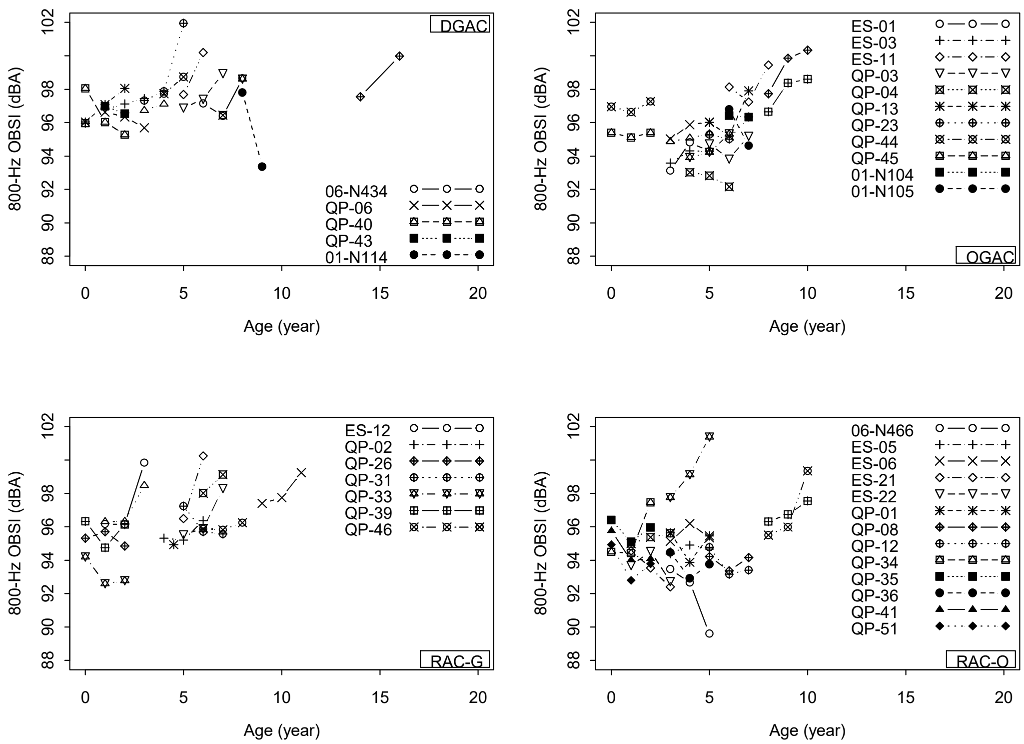

Figure 5.9: Sound intensity at 800 Hz over three years for each pavement section.

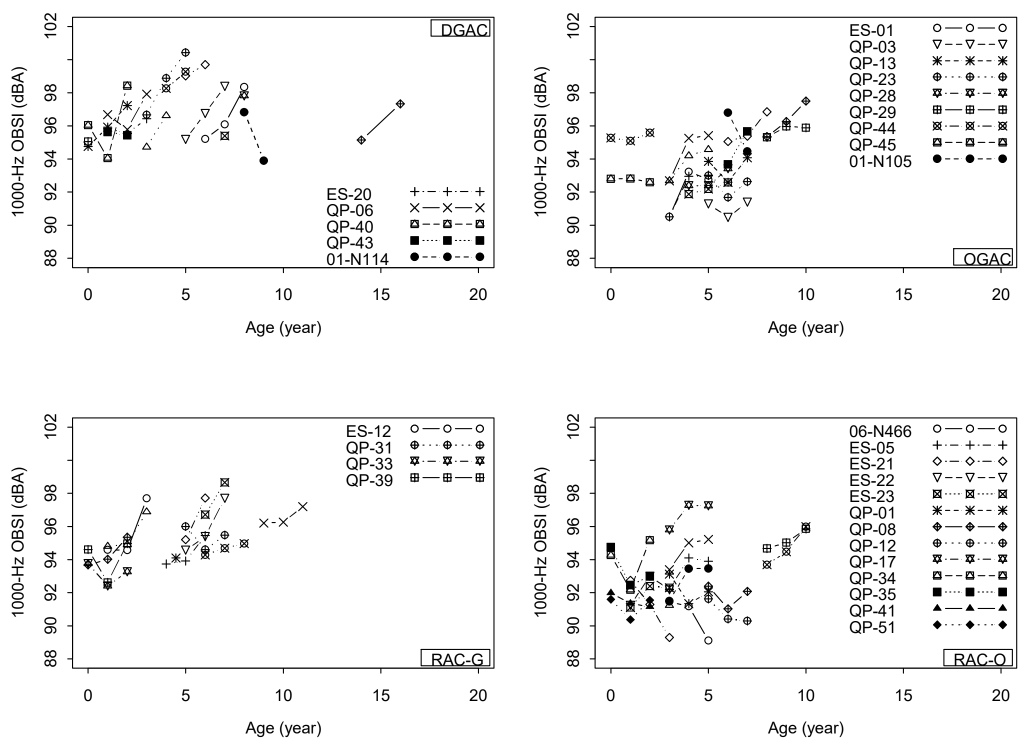

Figure 5.10: Sound intensity at 1,000 Hz over three years for each pavement section.

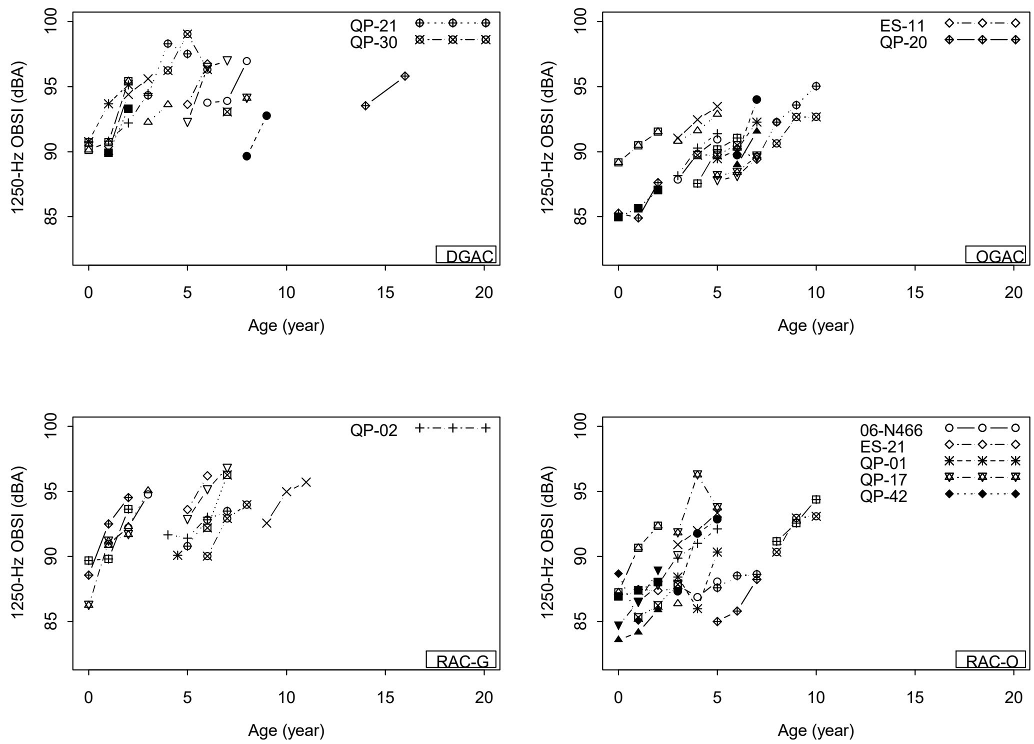

Figure 5.11: Sound intensity at 1,250 Hz over three years for each pavement section.

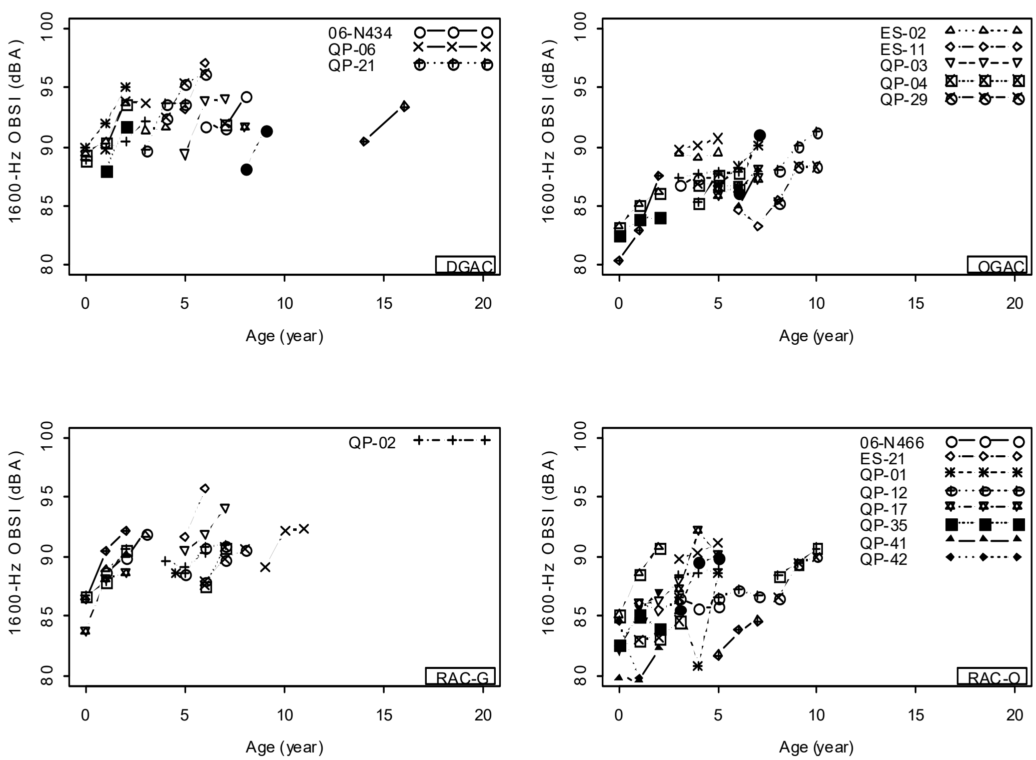

Figure 5.12: Sound intensity at 1,600 Hz over three years for each pavement section.

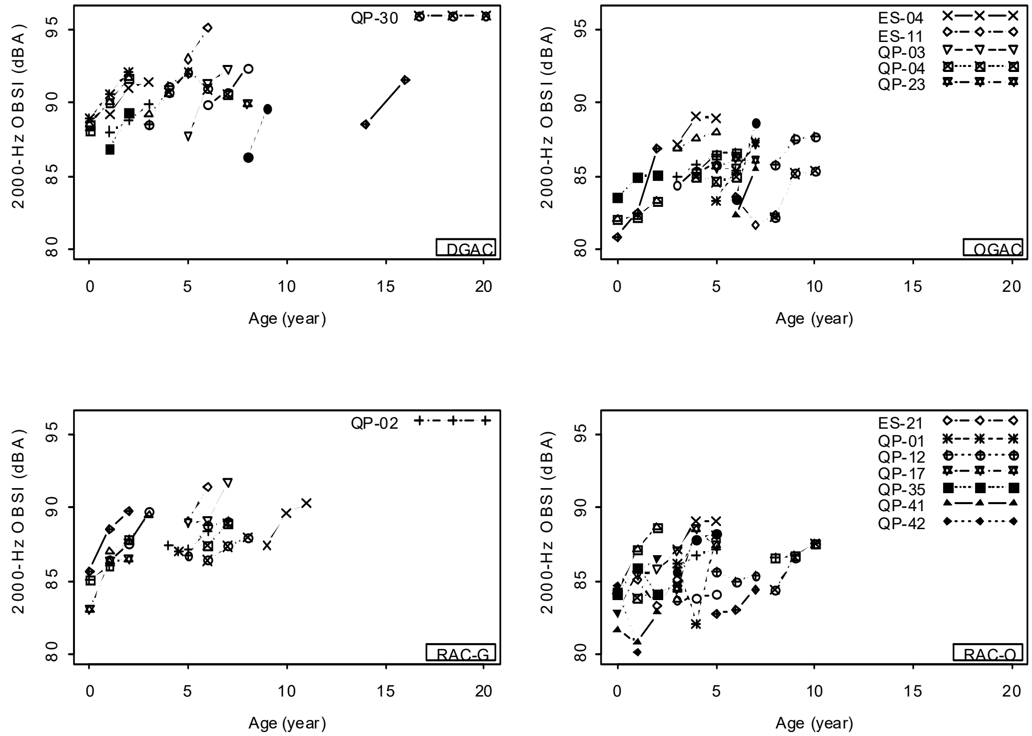

Figure 5.13: Sound intensity at 2,000 Hz over three years for each pavement section.

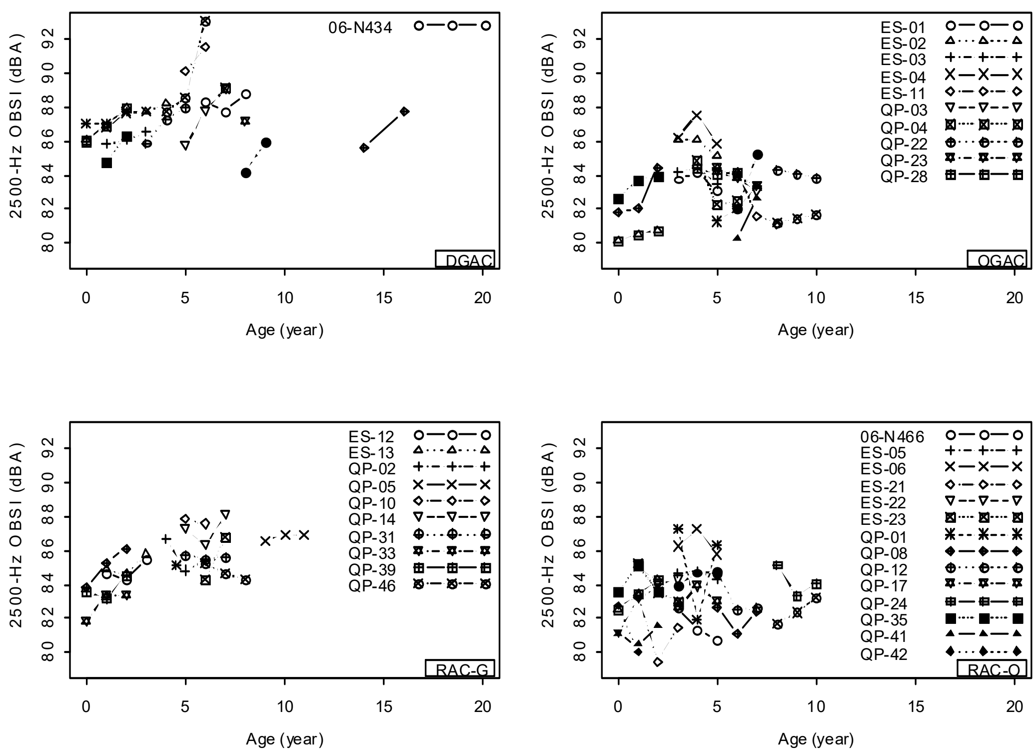

Figure 5.14: Sound intensity at 2,500 Hz over three years for each pavement section.

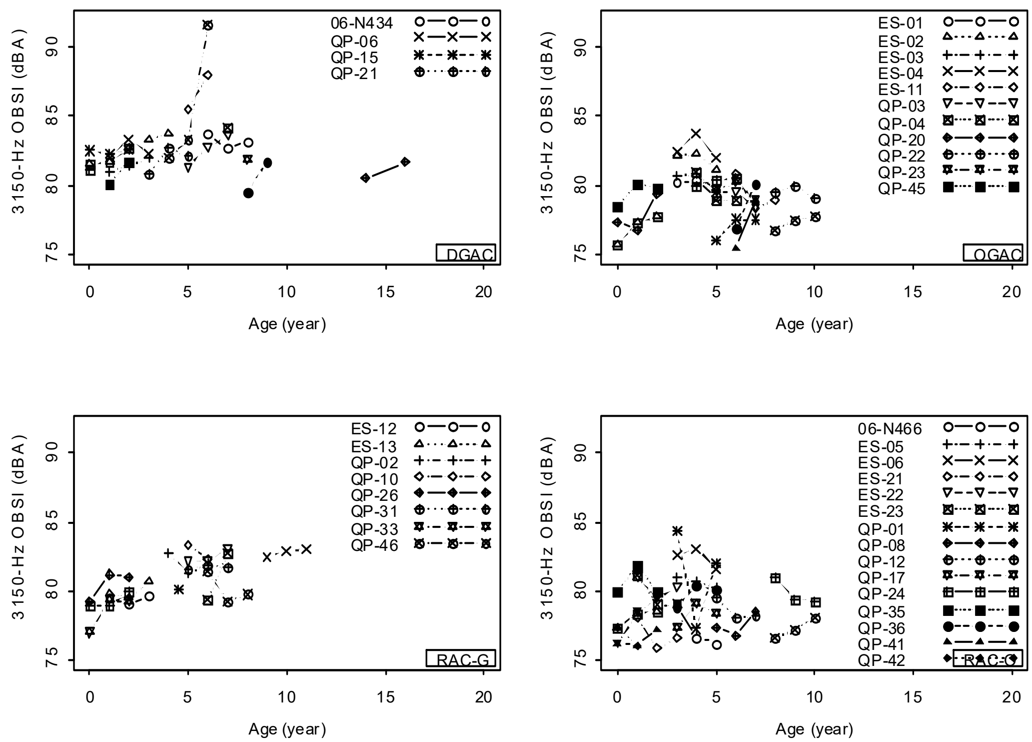

Figure 5.15: Sound intensity at 3,150 Hz over three years for each pavement section.

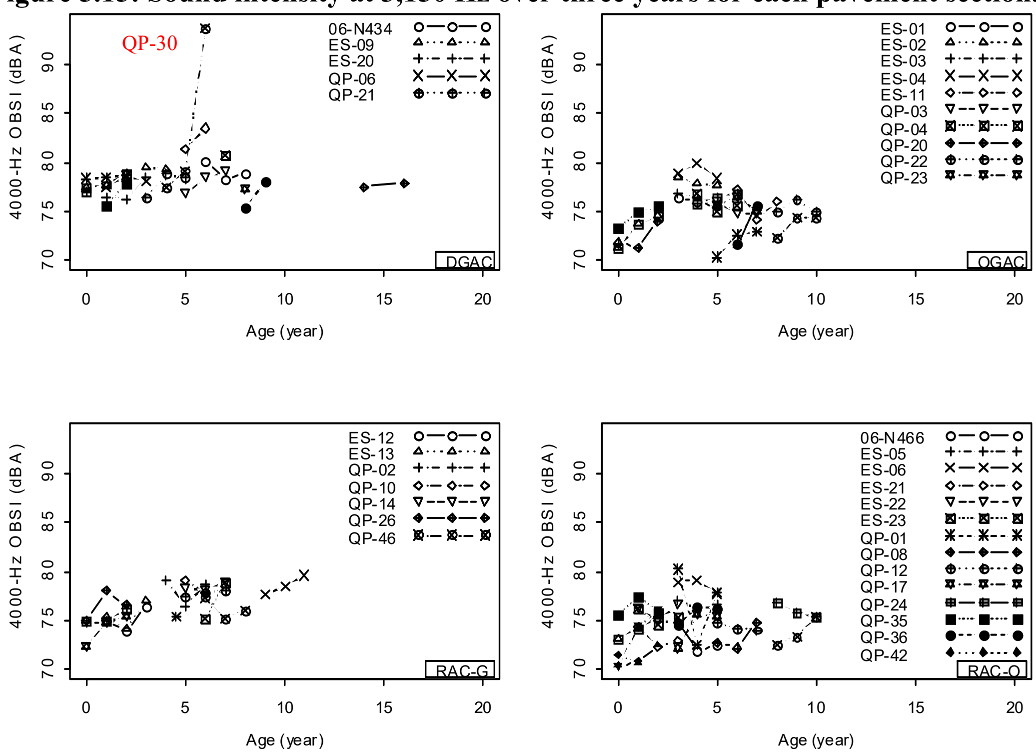

Figure 5.16: Sound intensity at 4,000 Hz over three years for each pavement section.

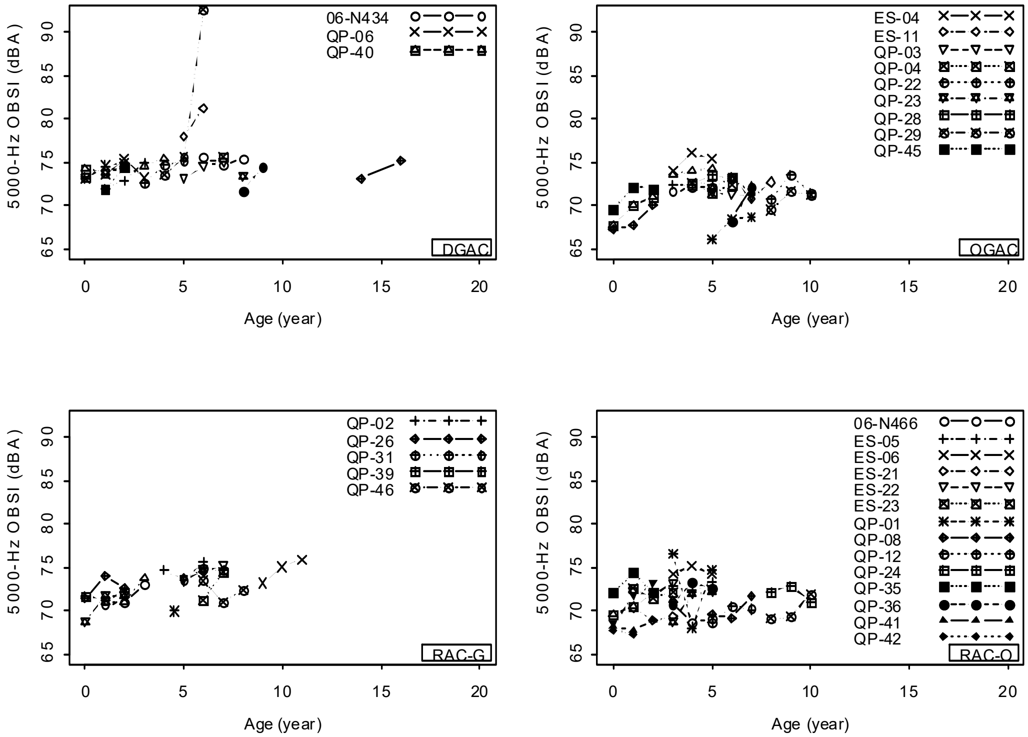

Figure 5.17: Sound intensity at 5,000 Hz over three years for each pavement section.

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

5.3.3.1 Descriptive Analysis

Figure 5.7 shows the 500-Hz OBSI values observed on each pavement section of the four mix types in the three survey years. As discussed earlier, sound intensity generally increases with pavement age. 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 the 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 5.18 shows the box plots of 500-Hz OBSI in three 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 increase trend is also obvious among different pavement sections of the same mix type. Overall, the increase rate of sound intensity is lower on rubberized pavements (RAC-G and RAC-O) than on nonrubberized pavements (DGAC and OGAC).

Figure 5.19 shows the cumulative distribution function of 500-Hz noise reduction for both 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 85.5 dB(A) for newly paved overlays, between 88 and 89 dB(A) for pavements with an age between three and nine years , and approximately 91.3 dB(A) for pavements older than nine years.

A negative value in Figure 5.19 indicates 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 –7 dB(A) to 3 dB(A), and it varies in a narrower range for RAC-G pavements.

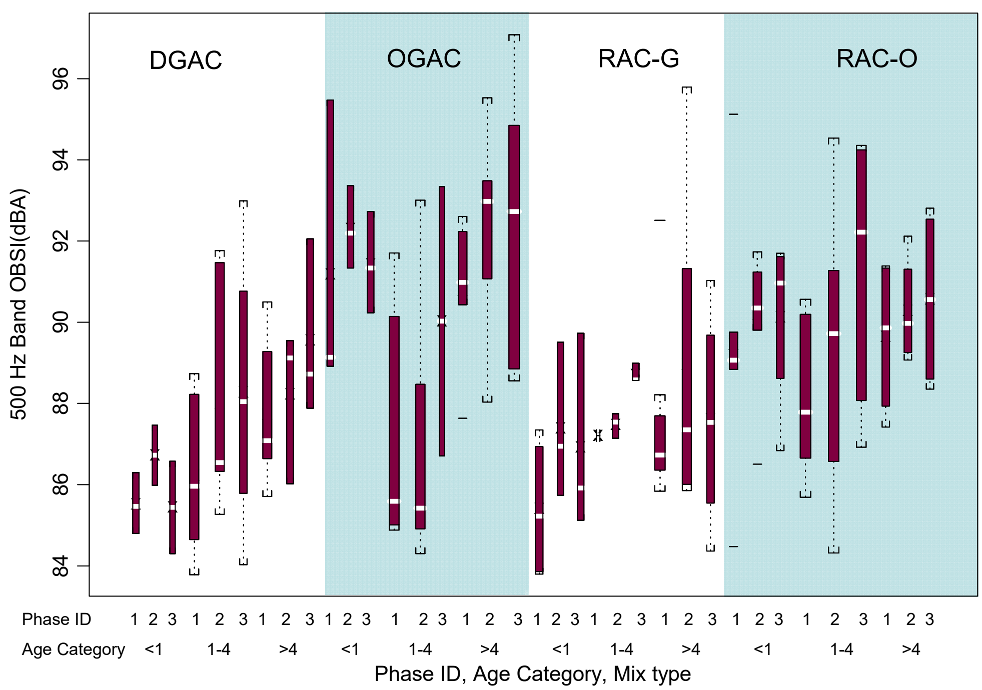

Figure 5.18: Sound intensity at 500 Hz for different initial age categories (Age Category) and for first, second, and third years of data collection (Phase ID).

For newly paved overlays (age less than or equal to one year old), RAC-G pavements seem to have similar 500-Hz noise level 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 20 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 three and seven years, if the mixes with small sample sizes (RAC-G in the age group three to five years, and RAC-O in the age group five to seven years) are 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.

The corresponding plots are not discussed in detail here for pavements with an age greater than seven years 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.

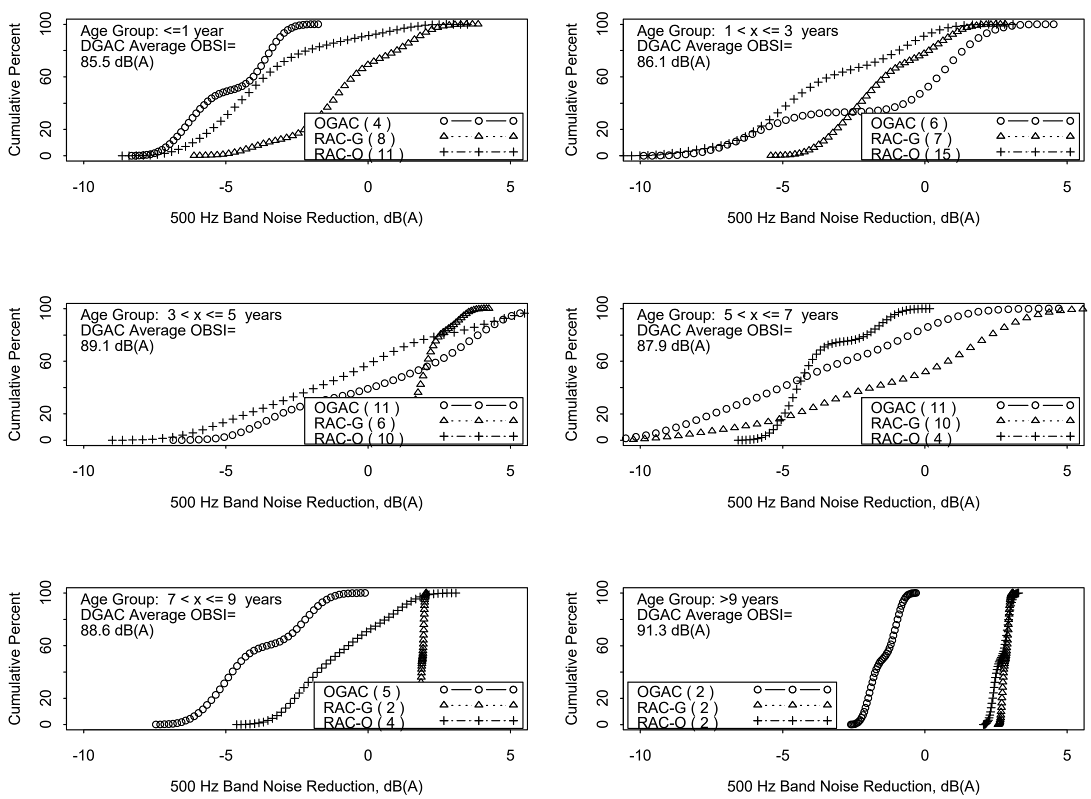

Figure 5.19: Cumulative distribution function of 500-Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups of pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.)

5.3.3.2 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.

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 single-variable regression model are given in Table 5.2. The P-values less than 0.05 are shown in bold.

The results in Table 5.2 show that the 500-Hz band sound intensity tends to be significantly affected by pavement age, air-void content, permeability, mix type, fineness modulus, NMAS, C_u, surface roughness, MPD, the presence of surface distresses including fatigue cracking and bleeding, annual rainfall, and cumulative traffic volume. The signs of the estimated coefficients indicate that the 500-Hz band sound intensity increases with pavement age, air-void content, permeability, fineness modulus (coarser gradation), surface roughness, MPD, cumulative traffic volume, annual rainfall, and surface distresses including fatigue cracking and bleeding, but decreases with NMAS, C_u, and surface layer thickness.

Table 5.2: Regression Analysis of Single-Variable Models for 500-Hz Band Sound Intensity

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	0.226	**0.003**	87.776	0.048
2	Air-void Content (%)	0.309	**<0.001**	85.144	0.306
3	Mix Type	2.624	**<0.001**	87.273	0.130
4	Fineness Modulus	2.768	**<0.001**	75.036	0.154
5	NMAS (mm)	-0.287	**0.001**	92.436	0.057
6	C_u	-0.073	**<0.001**	90.300	0.131
7	C_c	0.029	0.809	88.699	0.000
8	Rubber Inclusion	-0.030	0.948	88.768	0.000
9	IRI (m/km)	0.769	**0.012**	87.545	0.036
10	MPD (micron)	0.006	**<0.001**	82.269	0.433
11	BPN	-0.025	0.292	90.320	0.006
12	Surface Thickness (mm)	-0.062	**<0.001**	91.176	0.129
13	Presence of Fatigue Cracking	1.482	**0.017**	88.472	0.033
14	Presence of Raveling	0.947	0.071	88.465	0.019
15	Presence of Transverse Cracking	0.361	0.461	88.591	0.003
16	Presence of Bleeding	1.449	**0.018**	88.469	0.032
17	Presence of Rutting	2.645	**<0.001**	88.421	0.076
18	Permeability (cm/sec)	19.580	**<0.001**	88.048	0.138
19	Average Annual Rainfall (mm)	0.001	**0.049**	88.152	0.022
20	Cumulative AADT in Coring Lane (×3.65e8)	15.151	**0.001**	88.099	0.068
21	Cumulative AADTT in Coring Lane (×3.65e8)	120.702	**<0.001**	88.194	0.082
22	Cumulative ESALs in Coring Lane (×3.65e8)	0.210	**0.001**	88.335	0.062

Based on the results in Table 5.2, multiple regression analysis was conducted to account for 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, Equation 5.7, is:

$$\begin{aligned}&500Hz\ Sound\ Intensity(dBA)=87.8111+0.1394\times Age(year)+2.8639\times ind(MixTypeOGAC)+0.8116\times ind(MixTypeRAC-G)\\&+1.8097\times ind(MixTypeRAC-O)-0.0254\times Thickness(mm)-0.0192\times NumberOfDays>30C\\&+0.000657\times AADTTinCoringLane+0.9735\times ind(PresenceofRaveling)+1.8487\times ind(PresenceofRutting)\end{aligned} \quad \textbf{(5.7)}$$

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

	Value	Std. Error	t value	P-value
(Intercept)	87.8111	0.8595	102.1605	<0.0001
Age	0.1394	0.0735	1.8964	0.0598
PvmntTypeOGAC	2.8639	0.5733	4.9957	<0.0001
PvmntTypeRAC-G	0.8116	0.5593	1.4512	0.1488
PvmntTypeRAC-O	1.8097	0.5934	3.0494	0.0027
Thickness	-0.0254	0.0116	-2.1940	0.0298
NoDaysTempGT30	-0.0192	0.0035	-5.4171	<0.0001
AADTTCoringLane	0.000657	0.000131	5.0104	<0.0001
Raveling	0.9735	0.4369	2.2281	0.0273
Rutting	1.8487	0.6396	2.8905	0.0044

Residual standard error: 2.206 on 152 degrees of freedom; Multiple R-Squared: 0.48.

It can be seen that at the 95 percent confidence level, mix type, surface layer thickness, number of high temperature days, truck traffic in the coring lane, and existence of raveling and rutting significantly affect the 500-Hz band sound intensity. Pavement age is significant at 90 percent confidence level. The 500-Hz band noise increases with pavement age, truck traffic volume and the existence of raveling and rutting distress, but decreases with increasing surface layer thickness and number of high temperature days. 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 level of 500-Hz as DGAC pavements. The interaction terms between age and mix type are statistically insignificant, which 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. This conclusion is different from the direct observations from Figure 5.7 and is mostly due to the same reasons discussed in the analysis of overall sound intensity.

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

For DGAC pavements

$$500Hz\ Sound\ Intensity(dBA) = 83.7896 + 0.3471 \times AirVoid(\%) + 0.3125 \times Age(year) + 0.2393 \times FinenessModulus - 0.00653 \times Thickness(mm) - 0.00574 \times NumberOfDays > 30C + 0.0000494 \times AADTTinCoringLane \quad \mathbf{(5.8)}$$

	Value	Std. Error	t value	P-value
(Intercept)	83.7896	5.8335	14.3636	<0.0001
AirVoid	0.3471	0.1888	1.8389	0.0770
Age	0.3125	0.1001	3.1211	0.0043
FinenessModulus	0.2393	1.3922	0.1719	0.8648
Thickness	-0.00653	0.02025	-0.3227	0.7494
NoDaysTempGT30	-0.00574	0.00732	-0.7838	0.4400
AADTTCoringLane	0.0000494	0.0002206	0.2239	0.8245

Residual standard error: 1.795 on 27 degrees of freedom; Multiple R-Squared: 0.53.

For OGAC pavements

$$500Hz\ Sound\ Intensity(dBA) = 100.1266 + 0.3031 \times AirVoid(\%) + 0.1321 \times Age(year) - 3.2811 \times FinenessModulus + 0.0013 \times MPD(micron) + 0.0156 \times Thickness(mm) - 0.0409 \times NumberOfDays > 30C + 0.00102 \times AADTTinCoringLane \quad \mathbf{(5.9)}$$

	Value	Std. Error	t value	P-value
(Intercept)	100.1266	6.3945	15.6583	<0.0001
AirVoid	0.3031	0.1892	1.6018	0.1193
Age	0.1321	0.1279	1.0329	0.3096
FinenessModulus	-3.2811	1.6499	-1.9886	0.0556
MPD	0.00287	0.00173	1.6626	0.1065
Thickness	0.0156	0.0312	0.4990	0.6213
NoDaysTempGT30	-0.0409	0.0073	-5.5775	<0.0001
AADTTCoringLane	0.00102	0.00032	3.2096	0.0031

Residual standard error: 1.776 on 31 degrees of freedom; Multiple R-Squared: 0.79.

For RAC-G pavements

$$500Hz\ Sound\ Intensity(dBA) = 84.4227 - 0.0470 \times AirVoid(\%) + 0.2603 \times Age(year) - 0.3735 \times FinenessModulus + 0.0037 \times MPD(micron) + 0.00372 \times MPD(micron) + 0.0166 \times NumberOfDays > 30C + 0.000474 \times AADTTinCoringLane \quad \textbf{(5.10)}$$

	Value	Std. Error	t value	P-value
(Intercept)	84.4227	9.4402	8.9429	<0.0001
AirVoid	-0.0470	0.1641	-0.2861	0.7770
Age	0.2603	0.1326	1.9632	0.0604
FinenessModulus	-0.3735	1.9371	-0.1928	0.8486
MPD	0.00372	0.00127	2.9238	0.0071
Thickness	-0.0150	0.0270	-0.5546	0.5839
NoDaysTempGT30	0.0166	0.0074	2.2321	0.0344
AADTTCoringLane	0.000474	0.000416	1.1375	0.2657

Residual standard error: 1.9975 on 26 degrees of freedom; Multiple R-Squared: 0.47.

For RAC-O pavements

$$500Hz\ Sound\ Intensity(dBA) = 68.2087 - 0.0497 \times AirVoid(\%) - 0.0241 \times Age(year) + 3.3653 \times FinenessModulus + 0.0027 \times MPD(micron) - 0.0534 \times Thickness(mm) - 0.00338 \times NumberOfDays > 30C + 0.00041 \times AADTTinCoringLane \quad \textbf{(5.11)}$$

	Value	Std. Error	t value	P-value
(Intercept)	68.2087	9.2430	7.3795	<0.0001
AirVoid	-0.00497	0.1056	-0.0470	0.9627
Age	-0.0241	0.1182	-0.2037	0.8397
FinenessModulus	3.3653	2.0299	1.6579	0.1056
MPD	0.00451	0.00136	3.3265	0.0020
Thickness	-0.0534	0.0370	-1.4432	0.1572
NoDaysTempGT30	-0.00338	0.00661	-0.5117	0.6118
AADTTCoringLane	0.00041	0.00015	2.6605	0.0114

Residual standard error: 1.7501 on 38 degrees of freedom; Multiple R-Squared: 0.59.

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 slightly lower confidence level (i.e., 85 percent), the results show that the 500-Hz band sound intensity increases with pavement age for DGAC, OGAC, and RAC-G pavements, but not for RAC-O pavements. At a 95 percent confidence level, 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 estimated coefficients (0.0011 for OGAC versus 0.0004 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 pavements, air-void content is marginally significant (significant at the 90 percent confidence level). The estimated coefficient indicates that higher air-void content increases 500-Hz band noise.

For all pavements, the aggregate gradation variable (fineness modulus) does not seem to significantly affect the low-frequency noise. The number of high temperature days is a statistically significant variable. 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 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 indicates that higher truck traffic volume leads to higher low-frequency noise.

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

5.3.4.1 Descriptive Analysis

Figure 5.10 shows the 1,000-Hz OBSI values observed in the three survey years on each pavement section of the four mix types. Generally the 1,000-Hz sound intensity also increases with pavement age, but the increase trend is more significant on OGAC and RAC-G pavements than on DGAC and RAC-O pavements. For newly paved overlays, the 1,000-Hz the 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). 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 mechanism and the tire vibration mechanism.

Comparing Figure 5.10 to Figure 5.1, it can be seen that the variation trends of the 1,000-Hz sound intensity are very similar to those of the overall sound intensity. It can also be seen that the 1,000-Hz sound intensity measured on RAC-G pavements quickly approached the representative value measured on DGAC pavements of similar ages. The 1,000-Hz sound intensities measured on the OGAC pavements appear to only increase after about five years and then increase quickly with pavement age. With a few exceptions, the 1,000-Hz sound intensity measured on the RAC-O pavements appear to be stable for about seven years and then increase with pavement age.

Figure 5.20 shows the box plots of 1,000-Hz OBSI for three 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 the lowest on RAC-O pavements, which means that RAC-O pavements retain their noise-reducing properties longer than OGAC pavements.

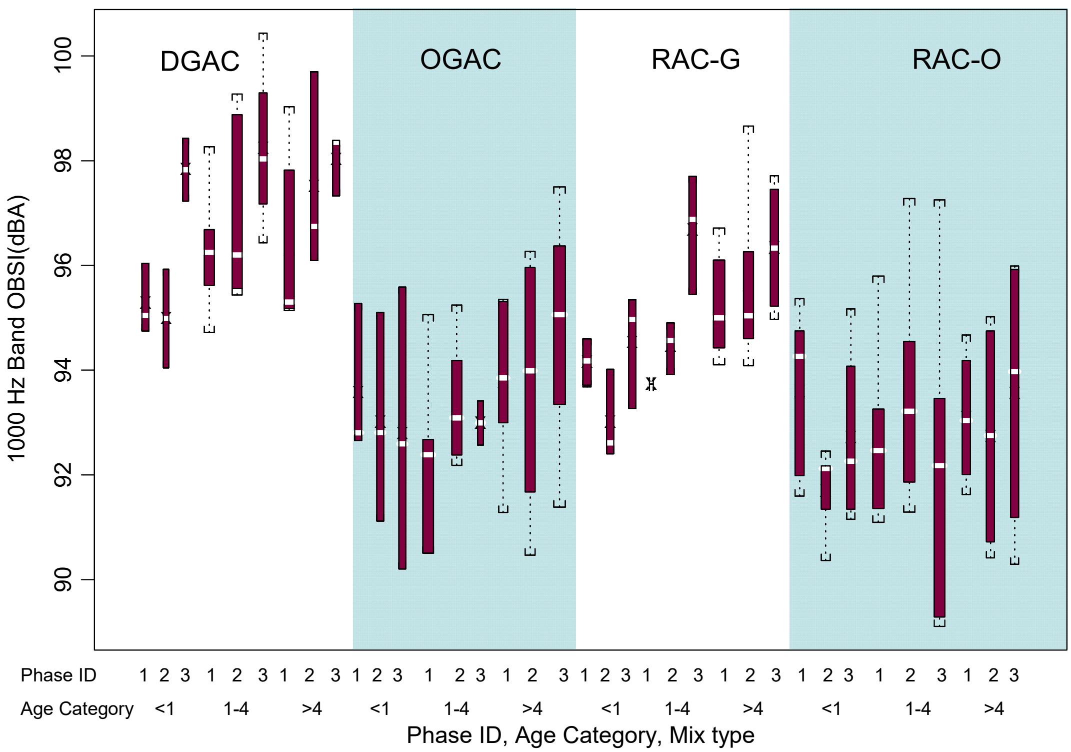

Figure 5.20: Sound intensity at 1,000 Hz for different initial age categories (Age Category) and for first, second, and third years of data collection (Phase ID).

Figure 5.21 shows the cumulative distribution function of 1,000-Hz noise reduction for both the OGAC and RAC-O types of open-graded mixes and 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 95.5 dB(A) for newly paved overlays, between 96 and 98 dB(A) for pavements with an age between three and nine years, and approximately 96.2 dB(A) for pavements older than nine years.

A negative value in Figure 5.21 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 quieter than the 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 7 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 a noise-reducing one, only 10 percent of OGAC and RAC-G pavements are noise-reducing, but about 70 percent of RAC-O pavements are noise reducing.

For pavements with an age between one and three years, OGAC and RAC-O pavements have similar noise-reducing properties (about 80 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 is better than RAC-G pavements. About 80 percent of RAC-O pavements, 90 percent of OGAC pavements, and 70 percent of RAC-G pavements are at least 3 dB(A) quieter than the average DGAC pavement.

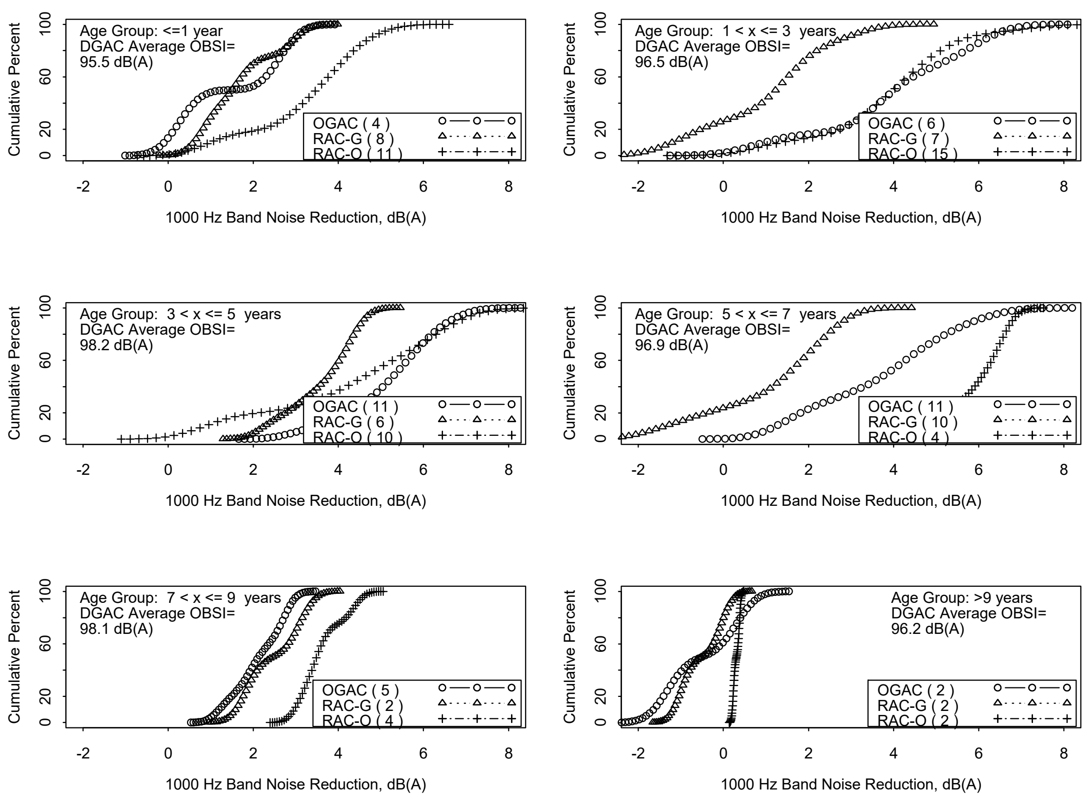

Figure 5.21: Cumulative distribution function of 1,000-Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups of pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.).

For pavements with an age between five and seven years, RAC-O, OGAC, and RAC-G pavements show significantly different noise-reducing properties, with RAC-O the best and RAC-G the worst. The corresponding plots for pavements with ages greater than seven 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 1,000-Hz band compared to DGAC mixes.

5.3.4.2 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 the important variables simultaneously.

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 single-variable regression model are given in Table 5.3. The P-values less than 0.05 are shown in bold.

Table 5.3: Regression Analysis of Single-Variable Models for 1,000-Hz Band Sound Intensity

Model Number	Variable Name	Coefficient	p-value	Constant Term	R^2
1	Age (year)	0.235	**<0.001**	93.316	0.090
2	Air-void Content (%)	-0.237	**<0.001**	97.105	0.313
3	Mix Type	-3.136	**<0.001**	96.724	0.422
4	Fineness Modulus	-2.849	**<0.001**	108.504	0.280
5	NMAS (mm)	0.229	**0.001**	91.391	0.063
6	C_u	0.087	**<0.001**	92.540	0.323
7	C_c	0.094	0.301	94.014	0.006
8	Rubber Inclusion	-1.193	**<0.001**	94.937	0.068
9	IRI (m/km)	0.845	**<0.001**	93.005	0.075
10	MPD (micron)	-0.002	**0.001**	96.335	0.068
11	BPN	0.004	0.832	94.090	0.000
12	Surface Thickness (mm)	0.015	0.137	93.750	0.013
13	Presence of Fatigue Cracking	1.262	**0.007**	94.160	0.041
14	Presence of Raveling	1.720	**<0.001**	93.915	0.109
15	Presence of Transverse Cracking	0.925	**0.012**	94.053	0.036
16	Presence of Bleeding	1.166	**0.012**	94.169	0.036
17	Presence of Rutting	2.056	**<0.001**	94.138	0.079
18	Permeability (cm/sec)	-22.112	**<0.001**	95.127	0.305
19	Average Annual Rainfall (mm)	0.000	0.631	94.219	0.001
20	Cumulative AADT in Coring Lane (×3.65e8)	8.273	**0.013**	93.973	0.035
21	Cumulative AADTT in Coring Lane (×3.65e8)	19.709	0.420	94.239	0.004
22	Cumulative ESALs in Coring Lane (×3.65e8)	0.024	0.631	94.284	0.001

The results in Table 5.3 show that the 1,000-Hz band sound intensity tends to be significantly affected by pavement age, air-void content, permeability, mix type, fineness modulus, NMAS, C_u, inclusion of rubber in the mix, surface roughness, MPD, the presence of surface distresses including fatigue/transverse cracking, rutting and bleeding, and the cumulative traffic volume. The signs of the estimated coefficients indicate that the 1,000-Hz band sound intensity increases with increasing pavement age, NMAS, C_u, surface roughness, cumulative traffic volume, and surface distresses, but decreases with increasing air-void content, permeability, fineness modulus, MPD, and the existence of rubber in the mix. This indicates that the 1,000-Hz band noise is caused through both the tire vibration and air-pumping mechanisms.

Based on the results in Table 5.3, 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, Equation 5.12, is:

$$\begin{aligned}&1000Hz\ Sound\ Intensity(dBA)=96.9251+0.1317\times Age(year)-3.3685\times ind(MixTypeOGAC)-1.5147\times ind(MixTypeRAC-G)\\&-4.2966\times ind(MixTypeRAC-O)-0.0277\times Thickness(mm)+0.00358\times NumberOfDays>30C\\&-0.0000549\times AADTTinCoringLane+0.8432\times ind(PresenceofRaveling)+0.5456\times ind(PresenceofRutting)\end{aligned} \quad \textbf{(5.12)}$$

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

	Value	Std. Error	t value	P-value
(Intercept)	96.9251	0.5983	161.9999	<0.0001
Age	0.1317	0.0512	2.5740	0.0110
PvmntTypeOGAC	-3.3685	0.3990	-8.4415	<0.0001
PvmntTypeRAC-G	-1.5147	0.3893	-3.8910	0.0001
PvmntTypeRAC-O	-4.2966	0.4131	-10.4013	<0.0001
Thickness	-0.0277	0.0081	-3.4371	0.0008
NoDaysTempGT30	0.00358	0.0025	1.4538	0.1481
AADTTCoringLane	-0.0000549	0.000091	-0.6010	0.5487
Raveling	0.8432	0.3041	2.7727	0.0063
Rutting	0.5456	0.4452	1.2255	0.2223

Residual standard error: 1.536 on 152 degrees of freedom; Multiple R-Squared: 0.57.

This regression model is similar to the multiple regression model for the overall sound intensity (Equation 5.2). At the 95 percent confidence level, age, mix type, surface layer thickness, and existence of raveling significantly affect the 1,000-Hz sound intensity. The 1,000-Hz sound intensity increases with pavement age and the existence of raveling distress, 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, 1.5, and 4.3 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. This conclusion is different from the direct observations from Figure 5.10. This is mostly due to the same reason discussed in Section 5.3.2.

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

For DGAC pavements

$$\begin{aligned}1000Hz\ Sound\ Intensity(dBA) = {}&97.7478 - 0.1753 \times AirVoid(\%) + 0.1245 \times Age(year) + 0.1422 \times FinenessModulus \\ &- 0.0238 \times Thickness(mm) - 0.00418 \times NumberOfDays > 30C + 0.000193 \times AADTTinCoringLane\end{aligned} \quad \textbf{(5.13)}$$

	Value	Std. Error	t value	P-value
(Intercept)	97.7478	5.1038	19.1518	0.0000
AirVoid	-0.1753	0.1652	-1.0613	0.2980
Age	0.1245	0.0876	1.4213	0.1667
FinenessModulus	0.1422	1.2181	0.1167	0.9079
Thickness	-0.0238	0.0177	-1.3434	0.1903
NoDaysTempGT30	-0.00418	0.00640	-0.6528	0.5194
AADTTCoringLane	0.000310	0.000193	1.6062	0.1199

Residual standard error: 1.571 on 27 degrees of freedom; Multiple R-Squared: 0.24.

For OGAC pavements

$$\begin{aligned}1000Hz\ Sound\ Intensity(dBA) = {}&98.6648 - 0.2553 \times AirVoid(\%) + 0.1454 \times Age(year) - 1.3200 \times FinenessModulus + 0.00404 \times MPD(micron) \\ &- 0.0441 \times Thickness(mm) + 0.00827 \times NumberOfDays > 30C + 0.000738 \times AADTTinCoringLane\end{aligned} \quad \textbf{(5.14)}$$

	Value	Std. Error	t value	P-value
(Intercept)	98.6648	3.8598	25.5621	0.0000
AirVoid	-0.2553	0.1142	-2.2352	0.0327
Age	0.1454	0.0772	1.8844	0.0689
FinenessModulus	-1.3200	0.9959	-1.3254	0.1947
MPD	0.00404	0.00104	3.8740	0.0005
Thickness	-0.0441	0.0189	-2.3393	0.0259
NoDaysTempGT30	0.00827	0.00442	1.8698	0.0710
AADTTCoringLane	0.000738	0.000192	3.8516	0.0006

Residual standard error: 1.072 on 31 degrees of freedom; Multiple R-Squared: 0.73.

For RAC-G pavements

$$1000Hz\ Sound\ Intensity(dBA) = 93.0266 - 0.1624 \times AirVoid(\%) + 0.2967 \times Age(year) + 0.0934 \times FinenessModulus + 0.00155 \times MPD(micron) - 0.0091 \times Thickness(mm) + 0.0104 \times NumberOfDays > 30C - 0.0000114 \times AADTTinCoringLane \quad \textbf{(5.15)}$$

	Value	Std. Error	t value	P-value
(Intercept)	93.0266	4.4230	21.0324	<0.0001
AirVoid	-0.1624	0.0769	-2.1121	0.0444
Age	0.2967	0.0621	4.7764	0.0001
FinenessModulus	0.0934	0.9076	0.1029	0.9188
MPD	0.00155	0.00060	2.5907	0.0155
Thickness	-0.00910	0.01266	-0.7187	0.4787
NoDaysTempGT30	0.0104	0.0035	2.9931	0.0060
AADTTCoringLane	-0.0000114	0.0001950	-0.0587	0.9537

Residual standard error: 0.9359 on 26 degrees of freedom; Multiple R-Squared: 0.67.

For RAC-O pavements

$$1000Hz\ Sound\ Intensity(dBA) = 105.8804 + 0.0582 \times AirVoid(\%) + 0.3415 \times Age(year) - 1.4389 \times FinenessModulus - 0.0021 \times MPD(micron) - 0.0554 \times NMAS(mm) - 0.1365 \times Thickness(mm) - 0.0052 \times NumberOfDays > 30C - 0.0001 \times AADTTinCoringLane \quad \textbf{(5.16)}$$

	Value	Std. Error	t value	P-value
(Intercept)	105.5077	6.7704	15.5838	<0.0001
AirVoid	0.0639	0.0774	0.8259	0.4140
Age	0.3424	0.0866	3.9554	0.0003
FinenessModulus	-1.5325	1.4869	-1.0307	0.3092
MPD	-0.00197	0.00099	-1.9865	0.0542
Thickness	-0.1392	0.0271	-5.1341	<0.0001
NoDaysTempGT30	-0.00485	0.00484	-1.0028	0.3223
AADTTCoringLane	-0.000130	0.000112	-1.1615	0.2527

Residual standard error: 1.2819 on 38 degrees of freedom; Multiple R-Squared: 0.60.

The results show that at a 95 percent confidence level, age is significant for RAC-G and RAC-O pavements. The estimated parameters indicate that the 1,000-Hz sound intensity increases with pavement age for all four mix types. Air-void content is a significant factor for OGAC and RAC-G pavements, and insignificant for DGAC and RAC-O pavements. Higher air-void content leads to a lower 1,000-Hz noise level for DGAC, OGAC, and RAC-G pavements. From the first two years of coring (2), it is known that the OGAC and RAC-O have similar distributions of air-void content so it is unclear why the sign of the air-void content is positive for RAC-O—although it can be seen that the p-value is very high, indicating considerable scatter in the data for this variable with respect to noise. 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 surface layer corresponds to a lower noise level at 1,000 Hz. Pavement surface roughness (MPD) is a significant factor for OGAC and RAC-G, and a higher MPD value corresponds to a higher noise level. For RAC-O pavements, MPD does not have a significant influence on noise level at the 95 percent confidence level.

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

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

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

5.3.5.1 Descriptive Analysis

Figure 5.13 shows the 2,000-Hz OBSI values observed in the three 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).

Comparing Figure 5.13 to Figure 5.10, it can be seen that the main difference between the increase trends of noise in the 1,000-Hz band and the 2,000-Hz band is that for newly paved overlays, the 1,000-Hz sound intensity increases slightly or even decreases with pavement age, while the 2,000-Hz sound intensity increases significantly with pavement age. Another difference is that for OGAC pavements older than five years the 1,000-Hz sound intensity increases significantly with pavement age, while the 2,000-Hz sound intensity barely increases with pavement age.

Figure 5.22 shows the box plots of 2,000-Hz OBSI in three 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.

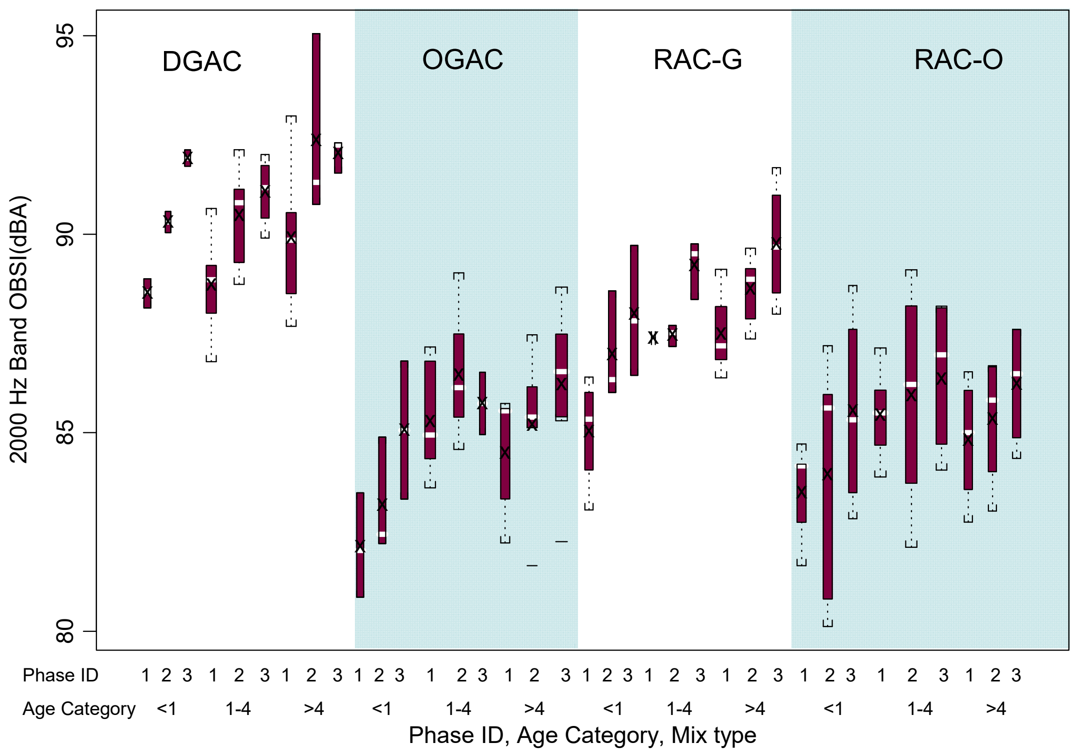

Figure 5.22: Sound intensity at 2,000 Hz for different initial age categories (Age Category) and for first, second, and third years of data collection (Phase ID).

Figure 5.23 shows the cumulative distribution function of 2,000-Hz noise reduction for both OGAC and RAC-O types of open-graded mixes and 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 and 92 dB(A) for pavements with ages between three and nine years, and approximately 90 dB(A) for pavements older than nine years.

A positive value in Figure 5.23 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 2,000-Hz band noiseWith 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 5 dB(A) for RAC-G pavements.

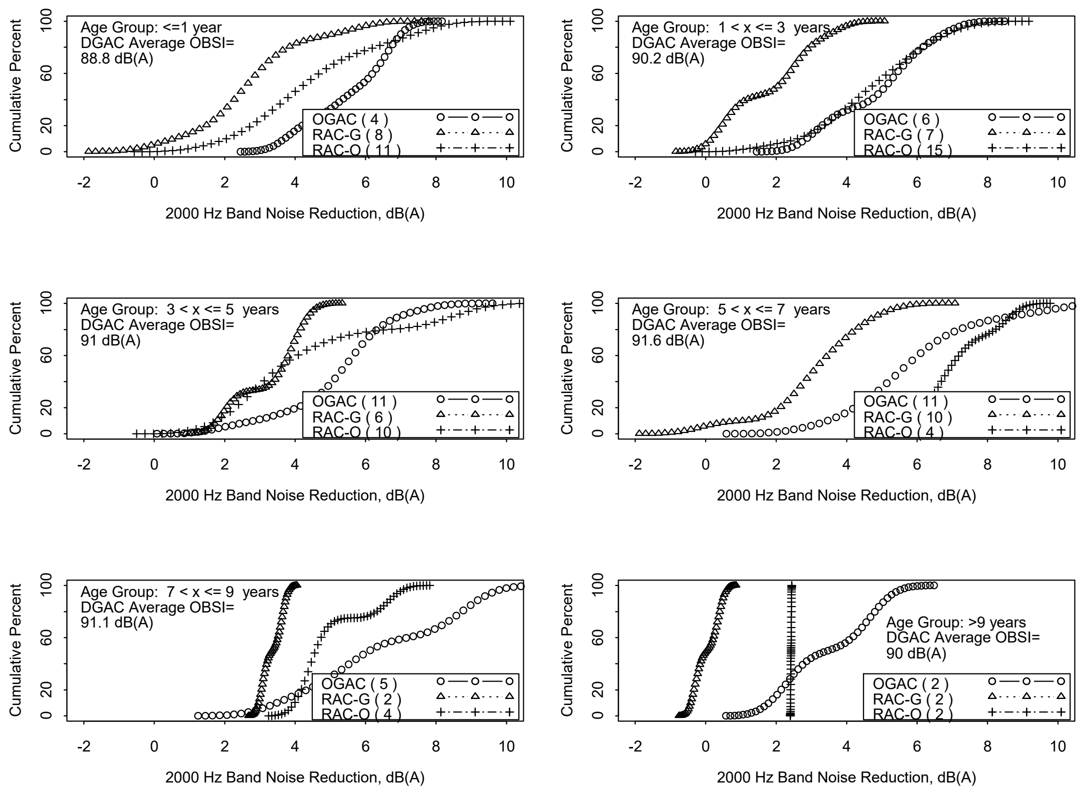

Figure 5.23: Cumulative distribution function of 2,000-Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups of pavement age.
(Notes: 1. positive value indicates a reduction in noise. 2. the numbers in parentheses in the legends represent the sample size of each mix type; the legend 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, about 90 percent of OGAC pavements, 70 percent of RAC-O pavements, and 30 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 seven years, the relative performances (in terms of reducing noise in 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 with older than seven 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.

5.3.5.2 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 important variables simultaneously.

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 single-variable regression model are given in Table 5.4. The P-values less than 0.05 are shown in bold.

Table 5.4: Regression Analysis of Single-Variable Models for 2,000-Hz Band Sound Intensity

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	0.243	**0.001**	85.801	0.065
2	Air-void Content (%)	-0.395	**<0.001**	91.469	0.585
3	Mix Type	-4.981	**<0.001**	90.214	0.523
4	Fineness Modulus	-4.213	**<0.001**	107.805	0.412
5	NMAS (mm)	0.323	**<0.001**	82.709	0.085
6	C_u	0.122	**<0.001**	84.324	0.432
7	C_c	-0.070	0.528	87.098	0.002
8	Rubber Inclusion	-1.032	**0.014**	87.376	0.034
9	IRI (m/km)	0.541	0.056	86.002	0.021
10	MPD (micron)	-0.004	**<0.001**	90.993	0.195
11	BPN	0.039	0.082	84.465	0.017
12	Surface Thickness (mm)	0.049	**<0.001**	84.946	0.093
13	Presence of Fatigue Cracking	1.485	**0.010**	86.651	0.039
14	Presence of Raveling	1.746	**<0.001**	86.436	0.076
15	Presence of Transverse Cracking	1.427	**0.001**	86.412	0.059
16	Presence of Bleeding	1.316	**0.020**	86.671	0.031
17	Presence of Rutting	1.649	**0.015**	86.711	0.035
18	Permeability (cm/sec)	-26.687	**<0.001**	87.812	0.300
19	Average Annual Rainfall (mm)	-0.001	**0.042**	87.425	0.024
20	Cumulative AADT in Coring Lane (×3.65e8)	7.126	0.081	86.544	0.017
21	Cumulative AADTT in Coring Lane (×3.65e8)	39.221	0.187	86.670	0.010
22	Cumulative ESALs in Coring Lane (×3.65e8)	0.071	0.235	86.711	0.008

The results in Table 5.4 show that the 2,000-Hz band sound intensity tends to be significantly affected by pavement age, air-void content, permeability, mix type, fineness modulus, NMAS, C_u, inclusion of rubber in the mix, MPD, the presence of surface distresses including fatigue/transverse cracking, rutting and bleeding, and average annual rainfall. Cumulative traffic volume is marginally significant (significant at a 90 percent confidence level). The signs of the estimated coefficients indicate that the 2,000-Hz band sound intensity increases with increasing pavement age, NMAS, C_u, and surface distresses, but decreases with increasing air-void content, permeability, fineness modulus and MPD, and the presence of rubber in the mix.

Based on the results in Table 5.4, 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 the independent variables, while mix property variables are excluded. The regression equation, Equation 4.17, is

$$\begin{aligned}&2000Hz\ Sound\ Intensity(dBA)=88.9632+0.2428\times Age(year)-5.1252\times ind(MixTypeOGAC)-2.3882\times ind(MixTypeRAC-G)\\&-4.7244\times ind(MixTypeRAC-O)+0.00077\times Thickness(mm)+0.00325\times NumberOfDays>30C\\&-0.0000051\times AADTTinCoringLane+0.2303\times ind(PresenceofRaveling)-0.2219\times ind(PresenceofRutting)\end{aligned} \quad \textbf{(5.17)}$$

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

	Value	Std. Error	t value	P-value
(Intercept)	88.9632	0.6861	129.6738	<0.0001
Age	0.2428	0.0587	4.1393	0.0001
PvmntTypeOGAC	-5.1252	0.4576	-11.2011	<0.0001
PvmntTypeRAC-G	-2.3882	0.4464	-5.3501	<0.0001
PvmntTypeRAC-O	-4.7244	0.4737	-9.9743	<0.0001
Thickness	0.000770	0.009235	0.0834	0.9336
NoDaysTempGT30	0.00325	0.002827	1.1482	0.2527
AADTTCoringLane	-0.00000510	0.000105	-0.0488	0.9611
Raveling	0.2303	0.3487	0.6605	0.5099
Rutting	-0.2219	0.5105	-0.4347	0.6644

Residual standard error: 1.7611 on 152 degrees of freedom; Multiple R-Squared: 0.60.

This regression model is similar to the multiple regression models for the overall sound intensity (Equation 4.2) and 1,000-Hz sound intensity (Equation 5.12), with the exception that surface layer thickness and raveling are not significant variables in this model. Raveling is not expected to be significant at 2,000 Hz and higher frequencies because it primarily affects the tire vibration mechanism, which does not influence these frequencies. At the 95 percent confidence level, age and mix type 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, 2.4, and 4.7 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, mix type variable is replaced with mix property variables and the model is estimated for each mix type separately. The regression equations, Equation 5.18 through Equation 5.21, are:

For DGAC pavements

$$2000Hz\ Sound\ Intensity(dBA) = 94.4195 - 0.5034 \times AirVoid(\%) + 0.2394 \times Age(year) - 0.1545 \times FinenessModulus - 0.0354 \times Thickness(mm) - 0.00422 \times NumberOfDays > 30C + 0.000398 \times AADTTinCoringLane \quad \textbf{(5.18)}$$

	Value	Std. Error	t value	P-value
(Intercept)	94.4195	4.2645	22.1407	0.0000
AirVoid	-0.5034	0.1380	-3.6479	0.0011
Age	0.2394	0.0732	3.2710	0.0029
FinenessModulus	-0.1545	1.0178	-0.1518	0.8805
Thickness	-0.0354	0.0148	-2.3939	0.0239
NoDaysTempGT30	-0.00422	0.00535	-0.7892	0.4368
AADTTCoringLane	0.000398	0.000161	2.4688	0.0202

Residual standard error: 1.3125 on 27 degrees of freedom; Multiple R-Squared: 0.54.

For OGAC pavements

$$2000Hz\ Sound\ Intensity(dBA) = 87.1217 - 0.3159 \times AirVoid(\%) + 0.1686 \times Age(year) + 0.6888 \times FinenessModulus + 0.000375 \times MPD(micron) - 0.0132 \times Thickness(mm) - 0.00715 \times NumberOfDays > 30C + 0.000925 \times AADTTinCoringLane \quad \textbf{(5.19)}$$

	Value	Std. Error	t value	P-value
(Intercept)	87.1217	4.5881	18.9888	0.0000
AirVoid	-0.3159	0.1358	-2.3269	0.0267
Age	0.1686	0.0917	1.8382	0.0756
FinenessModulus	0.6888	1.1838	0.5818	0.5649
MPD	0.000375	0.001240	0.3021	0.7646
Thickness	-0.0132	0.0224	-0.5900	0.5595
NoDaysTempGT30	-0.00715	0.00526	-1.3599	0.1837
AADTTCoringLane	0.000925	0.000228	-4.0616	0.0003

Residual standard error: 1.2740 on 31 degrees of freedom; Multiple R-Squared: 0.60.

For RAC-G pavements

$$2000Hz\ Sound\ Intensity(dBA) = 83.9463 - 0.3324 \times AirVoid(\%) + 0.3051 \times Age(year) + 0.8603 \times FinenessModulus + 0.001549 \times MPD(micron) - 0.0221 \times Thickness(mm) + 0.00121 \times NumberOfDays > 30C + 0.0007612 \times AADTTinCoringLane \quad \textbf{(5.20)}$$

	Value	Std. Error	t value	P-value
(Intercept)	83.9463	4.0365	20.7967	0.0000
AirVoid	-0.3324	0.0702	-4.7363	0.0001
Age	0.3051	0.0567	5.3823	0.0000
FinenessModulus	0.8603	0.8283	1.0386	0.3085
MPD	0.001549	0.000545	2.8440	0.0086
Thickness	-0.0221	0.0116	-1.9132	0.0668
NoDaysTempGT30	0.00121	0.00318	0.3805	0.7067
AADTTCoringLane	0.0007612	0.0001780	4.2771	0.0002

Residual standard error: 0.8541 on 26 degrees of freedom; Multiple R-Squared: 0.80.

For RAC-O pavements

$$2000Hz\ Sound\ Intensity(dBA) = 105.9474 - 0.1629 \times AirVoid(\%) + 0.3522 \times Age(year) - 3.5009 \times FinenessModulus - 0.00131 \times MPD(micron) - 0.00713 \times Thickness(mm) - 0.000395 \times NumberOfDays > 30C + 0.000248 \times AADTTinCoringLane \quad \textbf{(5.21)}$$

	Value	Std. Error	t value	P-value
(Intercept)	105.9474	7.4411	14.2382	0.0000
AirVoid	-0.1629	0.0850	-1.9151	0.0630
Age	0.3522	0.0951	3.7020	0.0007
FinenessModulus	-3.5009	1.6341	-2.1424	0.0386
MPD	-0.00131	0.00109	-1.1968	0.2388
Thickness	-0.00713	0.0298	-0.2392	0.8123
NoDaysTempGT30	-0.000395	0.00532	-0.0743	0.9412
AADTTCoringLane	0.000248	0.000123	2.0073	0.0500

Residual standard error: 1.4089 on 38 degrees of freedom; Multiple R-Squared: 0.57.

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 significant at a lower confidence level (90 percent) for RAC-O mixes. At the 95 percent confidence level, pavement age is a significant factor for DGAC, RAC-G and RAC-O pavements, and marginally significant for OGAC pavements. The surface layer thickness is significant for DGAC, marginally significant for OGAC, and insignificant for RAC-G and RAC-O pavements. Generally, thicker surface layer corresponds to lower 2,000-Hz sound intensity. Truck traffic volume is a significant factor that increases tire/pavement noise for all four mix types. Surface macrotexture (MPD) is significant for RAC-G pavements only, and higher MPD increases the 2,000-Hz noise on RAC-G pavements.

The aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise on all pavement types 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.

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

5.3.6.1 Descriptive Analysis

Figure 5.16 shows the 4,000-Hz OBSI values observed on each pavement section of the four mix types for the three survey years. The DGAC plot has one very high data point, which shows a 4,000-Hz sound intensity value of over 90 dB(A). This is believed to be a measurement error and will be deleted from the subsequent analysis. 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 5.24 shows the box plots of 4,000-Hz OBSI in three years for different mix types for three age categories. As the figure shows, 4,000-Hz band sound intensity generally increases with age for newly paved overlays of all mix types. For pavements older than four years, however, 4,000-Hz band sound intensity tends to decrease with time on the two open-graded mixes (OGAC and RAC-O), while it continues to increase with time on the dense- and gap-graded mixes.

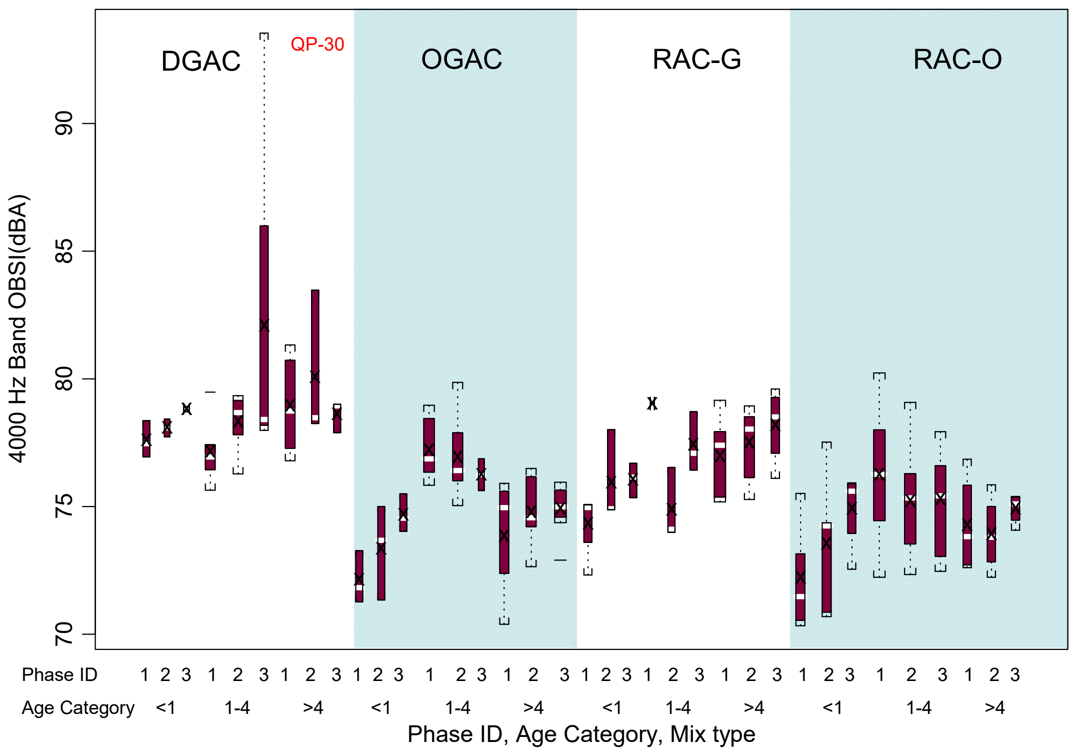

Figure 5.24: Sound intensity at 4,000 Hz for different initial age categories (Age Category) and for first, second, and third years of data collection (Phase ID).

Figure 5.25 shows the 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 77.3 dB(A) for newly paved overlays, between approximately 78 and 80 dB(A) for pavements with ages between three and nine years, and around 77.7 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 5.25 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 4,000-Hz band noise. With the exceptions of a few outliers, the noise reduction is generally between 0 and 7 dB(A) for open-graded pavements, and between –1 and 5 dB(A) for RAC-G pavements.

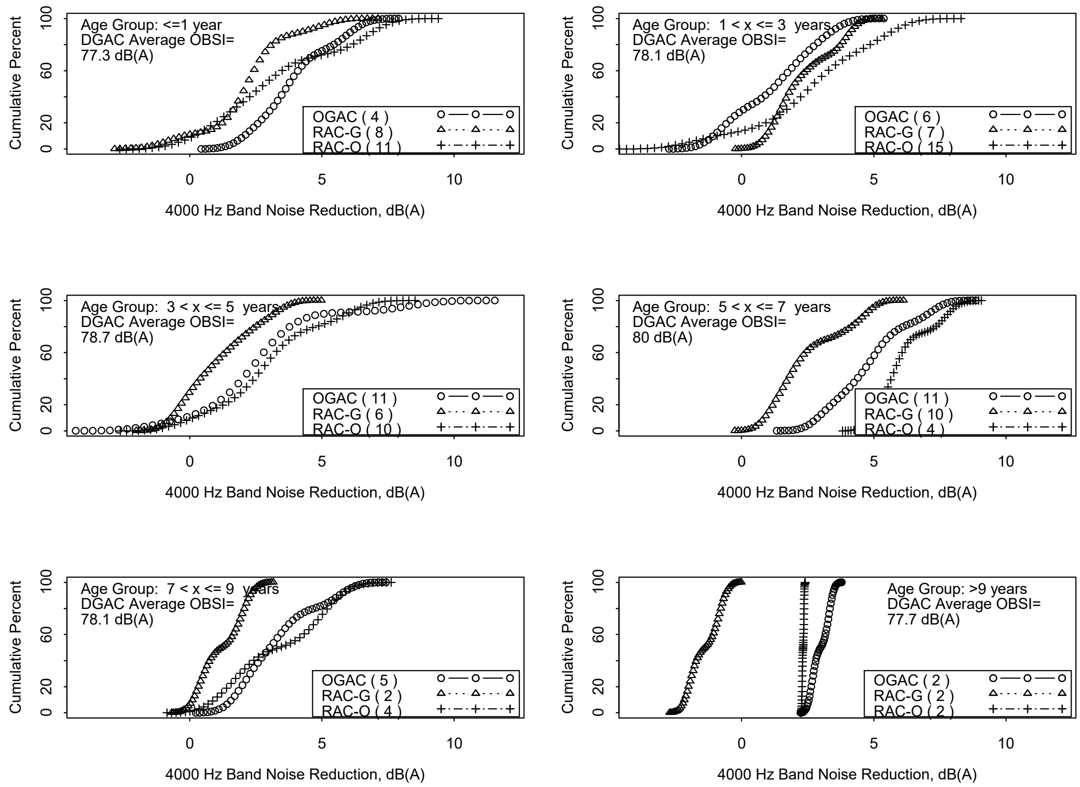

Figure 5.25: Cumulative distribution function of 4,000-Hz noise reduction of OGAC, RAC-O, and RAC-G mixes for different groups of pavement age.
(Notes: 1. Positive value indicates a reduction in noise. 2. The numbers in parentheses in the legends represent the sample size of each mix type; the legend within each plot shows the average noise level of DGAC mixes in each age group.)

For newly paved overlays (age less than or equal to three years), the three mix types, OGAC, RAC-G, and RAC-O, exhibit similar noise-reducing properties. Approximately 60 to 80 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 five 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 five years.

5.3.6.2 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 important variables simultaneously.

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 single-variable regression model are given in Table 5.5. The P-values less than 0.05 are shown in bold.

Table 5.5: Regression Analysis of Single-Variable Models for 4,000-Hz Band Sound Intensity

Model Number	Variable Name	Coefficient	P-value	Constant Term	R^2
1	Age (year)	0.194	**0.006**	75.243	0.043
2	Air-void Content (%)	-0.306	**<0.001**	79.654	0.366
3	Mix Type	-3.503	**<0.001**	78.669	0.307
4	Fineness Modulus	-3.687	**<0.001**	94.415	0.326
5	NMAS (mm)	0.134	0.105	74.366	0.015
6	C_u	0.088	**<0.001**	74.262	0.230
7	C_c	-0.133	0.222	76.537	0.009
8	Rubber Inclusion	-1.166	**0.004**	76.673	0.046
9	IRI (m/km)	0.119	0.670	75.894	0.001
10	MPD (micron)	-0.004	**<0.001**	80.272	0.206
11	BPN	0.031	0.162	74.197	0.011
12	Surface Thickness (mm)	0.046	**<0.001**	74.283	0.086
13	Presence of Fatigue Cracking	0.409	0.469	76.014	0.003
14	Presence of Raveling	0.874	0.064	75.852	0.020
15	Presence of Transverse Cracking	1.367	**0.002**	75.619	0.057
16	Presence of Bleeding	0.477	0.391	76.000	0.004
17	Presence of Rutting	0.531	0.424	76.022	0.004
18	Permeability (cm/sec)	-22.420	**<0.001**	76.887	0.221
19	Average Annual Rainfall (mm)	-0.001	**0.016**	76.746	0.033
20	Cumulative AADT in Coring Lane(×3.65e8)	9.473	**0.018**	75.671	0.032
21	Cumulative AADTT in Coring Lane(×3.65e8)	79.402	**0.006**	75.713	0.043
22	Cumulative ESALs in Coring Lane(×3.65e8)	0.161	**0.005**	75.761	0.044

The results in Table 5.5 show that the 4,000-Hz band sound intensity tends to be significantly affected by pavement age, air-void content, permeability, mix type, fineness modulus, C_u, inclusion of rubber in the mix, MPD, surface layer thickness, presence of transverse cracking, average annual rainfall, and cumulative traffic volume. The signs of the estimated coefficients indicate that the 4,000-Hz band sound intensity increases with pavement age, C_u, surface layer thickness, presence of transverse cracking, and cumulative traffic volume, but decreases with air-void content, permeability, fineness modulus, MPD, and presence of rubber in the mix. These results are similar to those obtained from the single-variable regression of the 2,000-Hz sound intensity.

Based on the results in Table 5.5, 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 the independent variables, while mix property variables are excluded. The regression equation, Equation 5.22, is

$$\begin{aligned}&4000Hz\ Sound\ Intensity(dBA)=76.1255+0.0926\times Age(year)-2.6027\times ind(MixTypeOGAC)-3.1598\times ind(MixTypeRAC-G)\\&-3.7747\times ind(MixTypeRAC-O)+0.0222\times Thickness(mm)+0.00548\times NumberOfDays>30C\\&+0.000389\times AADTTinCoringLane-0.4048\times ind(PresenceofRaveling)-0.0368\times Age\times ind(MixTypeOGAC)\\&+0.4075\times Age\times ind(MixTypeRAC-G)+0.1128\times Age\times ind(MixTypeRAC-O)\end{aligned} \quad \textbf{(5.22)}$$

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

	Value	Std. Error	t value	P-value
(Intercept)	76.1255	0.7058	107.8560	<0.0001
Age	0.0926	0.0817	1.1338	0.2587
PvmntTypeOGAC	-2.6027	0.8166	-3.1871	0.0017
PvmntTypeRAC-G	-3.1598	0.6890	-4.5860	<0.0001
PvmntTypeRAC-O	-3.7747	0.7040	-5.3614	<0.0001
Thickness	0.0222	0.0089	2.4861	0.0140
NoDaysTempGT30	0.00548	0.00277	1.9802	0.0495
AADTTCoringLane	0.000389	0.000104	3.7292	0.0003
Raveling	-0.4048	0.3484	-1.1620	0.2471
Age*PvmntTypeOGAC	-0.0368	0.1392	-0.2647	0.7916
Age*PvmntTypeRAC-G	0.4075	0.1289	3.1610	0.0019
Age*PvmntTypeRAC-O	0.1128	0.1283	0.8791	0.3807

Residual standard error: 1.6940 on 150 degrees of freedom; Multiple R-Squared: 0.49.

This regression model is similar to the multiple regression models for the 2,000-Hz sound intensity (Equation 5.17), with the exception that truck traffic volume and surface layer thickness are significant variables in this model, and pavement 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 2.6, 3.2, and 3.8 dB(A), respectively. The 4,000-Hz sound intensity also increases with truck traffic volume and surface layer thickness.

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

For DGAC pavements

$$4000Hz\ Sound\ Intensity(dBA) = 83.1807 - 0.3059 \times AirVoid(\%) + 0.1330 \times Age(year) - 0.8407 \times FinenessModulus$$
$$-0.0157 \times Thickness(mm) + 0.000625 \times NumberOfDays > 30C + 0.000572 \times AADTTinCoringLane \quad \textbf{(5.23)}$$

	Value	Std. Error	t value	P-value
(Intercept)	83.1807	3.2692	25.4439	<0.0001
AirVoid	-0.3059	0.1058	-2.8917	0.0075
Age	0.1330	0.0561	2.3705	0.0252
FinenessModulus	-0.8407	0.7802	-1.0775	0.2908
Thickness	-0.0157	0.0113	-1.3817	0.1784
NoDaysTempGT30	0.000625	0.004101	0.1524	0.8800
AADTTCoringLane	0.000572	0.000124	4.6299	0.0001

Residual standard error: 1.0062 on 27 degrees of freedom; Multiple R-Squared: 0.64.

For OGAC pavements

$$4000Hz\ Sound\ Intensity(dBA) = 88.2506 - 0.0827 \times AirVoid(\%) + 0.0689 \times Age(year) - 1.9161 \times FinenessModulus - 0.00225 \times MPD(micron)$$
$$+0.0515 \times Thickness(mm) - 0.0109 \times NumberOfDays > 30C + 0.0000462 \times AADTTinCoringLane \quad \textbf{(5.24)}$$

	Value	Std. Error	t value	P-value
(Intercept)	88.2506	4.3114	20.4690	0.0000
AirVoid	-0.0827	0.1276	-0.6479	0.5218
Age	0.0689	0.0862	0.7988	0.4305
FinenessModulus	-1.9161	1.1125	-1.7224	0.0950
MPD	-0.00225	0.00117	-1.9350	0.0622
Thickness	0.0515	0.0211	2.4466	0.0203
NoDaysTempGT30	-0.0109	0.0049	-2.1958	0.0357
AADTTCoringLane	0.0000462	0.0002140	0.2161	0.8303

Residual standard error: 1.1972 on 31 degrees of freedom; Multiple R-Squared: 0.69.

For RAC-G pavements

$$4000Hz\ Sound\ Intensity(dBA) = 70.4709 - 0.2148 \times AirVoid(\%) + 0.3560 \times Age(year) + 1.4312 \times FinenessModulus$$
$$-0.0000058 \times MPD(micron) - 0.0110 \times Thickness(mm) - 0.01280 \times NumberOfDays > 30C + 0.000940 \times AADTTinCoringLane \quad \textbf{(5.25)}$$

	Value	Std. Error	t value	P-value
(Intercept)	70.4709	5.3456	13.1831	<0.0001
AirVoid	-0.2148	0.0929	-2.3107	0.0290
Age	0.3560	0.0751	4.7419	0.0001
FinenessModulus	1.4312	1.0969	1.3048	0.2034
MPD	-0.00000580	0.00072140	-0.0080	0.9936
Thickness	-0.0110	0.0153	-0.7186	0.4788
NoDaysTempGT30	-0.01280	0.00422	-3.0363	0.0054
AADTTCoringLane	0.000940	0.000236	3.9871	0.0005

Residual standard error: 1.1311 on 26 degrees of freedom; Multiple R-Squared: 0.69.

For RAC-O pavements

$$4000Hz\ Sound\ Intensity(dBA) = 89.6892 - 0.1659 \times AirVoid(\%) + 0.3213 \times Age(year) - 2.3077 \times FinenessModulus - 0.00364 \times MPD(micron) + 0.0201 \times Thickness(mm) - 0.00706 \times NumberOfDays > 30C + 0.000681 \times AADTTinCoringLane \quad \textbf{(5.26)}$$

	Value	Std. Error	t value	P-value
(Intercept)	89.6892	7.2131	12.4341	0.0000
AirVoid	-0.1659	0.0824	-2.0121	0.0513
Age	0.3213	0.0922	3.4832	0.0013
FinenessModulus	-2.3077	1.5841	-1.4568	0.1534
MPD	-0.00364	0.00106	-3.4369	0.0014
Thickness	0.0201	0.0289	0.6969	0.4901
NoDaysTempGT30	0.00706	0.00516	1.3683	0.1793
AADTTCoringLane	0.000681	0.000120	5.6960	0.0000

Residual standard error: 1.3658 on 38 degrees of freedom; Multiple R-Squared: 0.67.

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

The aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise on all pavement types.

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

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 A.4: Boxplots and Cumulative Distribution of Noise Reduction for Sound Intensity at Other Frequency Bands.

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 is about 101.3 dB(A) for newly paved overlays, 102.4 dB(A) for pavements between one and three years old, and between 103 and 104 dB(A) for pavements older than three years. 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 2.5, 1.6, and 3.1 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 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 most pavements, and higher permeability leads to a lower noise level. For DGAC, RAC-G, and RAC-O pavements, the aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise. For OGAC pavements, however, a coarser gradation seems to significantly reduce tire/pavement noise. Pavement surface macrotexture (MPD) is a significant factor for OGAC 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, RAC-G, and RAC-O pavements are generally higher than the values measured on DGAC 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, the sound intensities at the frequencies higher than 1,000 Hz increase with age in the first three 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 changes slightly with age in the first three years, while the sound intensity in the frequency band between 1,000 Hz and 2500 Hz increases significantly with age.
3. For pavements with an initial age between 1 and 4 years, sound intensity increases with age for frequencies lower than 2,500 Hz, and decreases slightly with age for frequencies higher than 2,500 Hz on OGAC and RAC-O pavements, while it generally increases with age for all frequency levels on DGAC and RAC-G pavements.
4. For the oldest pavements (initial age >4 years), the increase of sound intensity with age mainly occurs at frequencies lower than 2,500 Hz on OGAC, RAC-G, and RAC-O pavements; while for the oldest DGAC pavements, the increase of sound intensity with age mainly occurs at frequencies between 800 Hz and 2,500 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 nonrubberized pavements (DGAC and OGAC).
2. Multiple regression analysis on all mixes shows that mix type, surface layer thickness, number of high temperature days, truck traffic in the coring lane, and existence of raveling significantly affect the 500-Hz band sound intensity. The 500-Hz band noise increases with pavement age, truck traffic volume, and the existence of raveling distress, but decreases with the surface layer thickness and the 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) is lower than the values measured on dense-graded pavements (DGAC). After the pavements were exposed to traffic, the change trends of 1,000-Hz sound intensity with pavement age are very similar to those of overall sound intensity. For pavements between one and seven years old, OGAC and RAC-O pavements have similar noise-reducing properties in terms of 1,000-Hz and 2,000-Hz sound intensities, while RAC-G pavements begin to lose their noise reducing properties for that age group.
2. Multiple regression analysis on individual mix type shows that air-void content is a significant factor for OGAC and RAC-G pavements, and insignificant for DGAC and RAC-O pavements. Higher air-void content leads to a lower 1,000-Hz noise level for DGAC, OGAC, and RAC-G pavements. For 1,000-Hz sound intensity, pavement surface roughness (MPD) is a significant factor for OGAC and RAC-G, and a higher MPD value corresponds to a higher 1,000-Hz noise level. 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 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). The 2,000-Hz sound intensity increases 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 marginally significant for RAC-O pavements. For 2,000-Hz sound intensity, MPD is significant for RAC-G pavements only, and higher MPD increases the 2,000-Hz noise on 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 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 with between three and five 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 five 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, marginally significant for RAC-O pavements, and insignificant for OGAC pavements. For all mixes, higher traffic volume and larger air-void content lead to 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.. Pavement surface macrotexture (MPD) is only significant on RAC-O pavements, and higher MPD values lead to a lower 4,000-Hz noise level.

6. ENVIRONMENTAL SECTIONS RESULTS AND ANALYSIS

Twenty-three environmental test sections (labeled as "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 both new asphalt mixes, such as Type G-MB, Type D-MB, RUMAC-GG, and EU gap-graded mixes, and commonly used mixes as controls, such as OGAC, RAC-O, DGAC, and RAC-G. For more information, see Appendix A.1: List of Test Sections Included in the Study. Detailed descriptions of the mixes are included in the two-year noise study report (2).

All the environmental test sections were tested during the three-year survey. This chapter presents an analysis of the performance trends of the different mixes at each site.

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. Except for the DGAC control surface, all the sections were placed with both 45- 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 different mixes over three 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 6.1 shows the three-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. All sections show an increase in macrotexture values with age, except 45-mm Type G-MB mix. This increase is probably due to an increase in distresses, mostly raveling, under traffic.

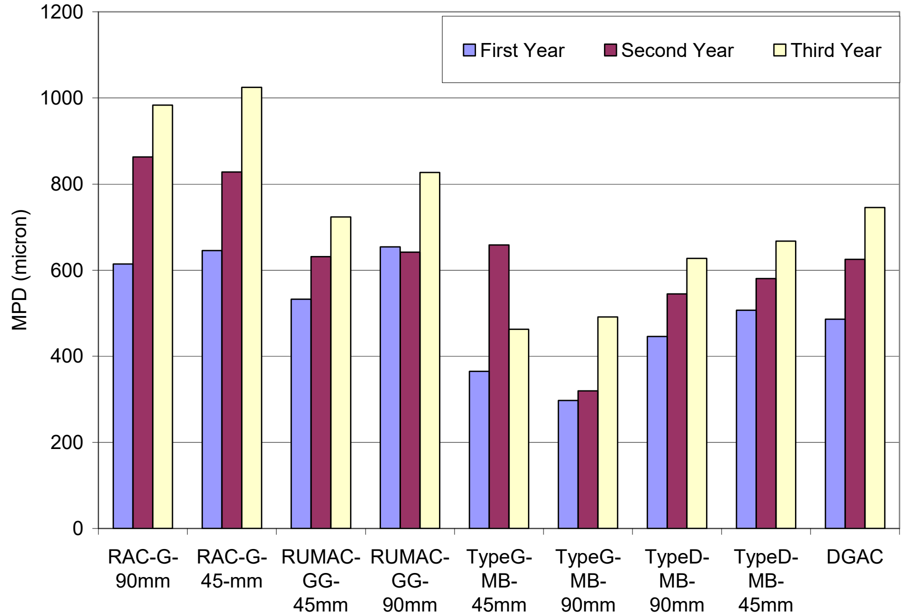

Figure 6.1: Three-year MPD values for Fresno 33 sections.

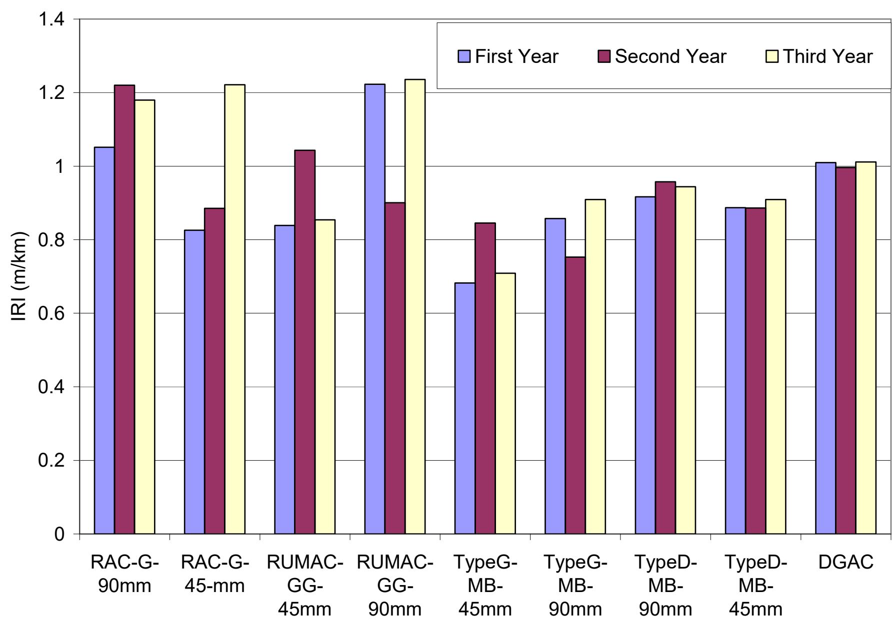

Figure 6.2: Three-year IRI values for Fresno 33 sections.

Figure 6.2 shows the three-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. IRI generally did not change significantly with age in the three survey years for all sections except 45-mm RAC-G mix, which showed a marked increase from the second to the third year.

Figure 6.3 shows the three-year overall sound intensity levels for the Fresno 33 sections. The figure shows that the noise level increased significantly on the RAC-G, RUMAC-G, and Type D-MB sections. The DGAC section has the lowest noise level in the third survey year. The three-year noise spectra, as shown in Appendix A.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.

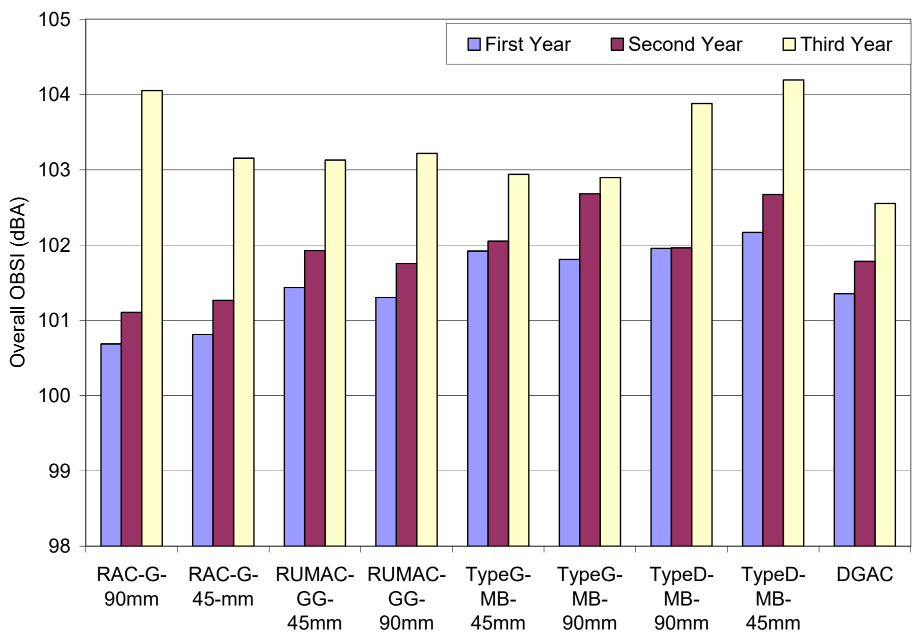

Figure 6.3: Three-year Overall OBSI values for Fresno 33 sections.

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

The three-year condition survey data, as shown in Appendix A.7, shows that after serving for two years, all the mixes except the DGAC mix show bleeding. The bleeding did not become worse in the third 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.

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. In the third survey year, however, 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.

Increasing thickness did not reduce fatigue cracking on the RAC-G mix, but may reduce the amount of transverse cracking. Increasing thickness may help reduce the cracking for RUMAC-GG and Type D-MB. The 90-mm RUMAC-GG mix is more resistant to cracking compared to the 90-mm Type G-MB.

6.2 Sacramento 5 and San Mateo 280 Sections

The Sacramento 5 and San Mateo 280 sites consist of thin RAC-O overlays of 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 three 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 section?

It has been known from the first two years of data 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 (2).

Figure 6.4 shows the three-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 considered "fair" for Interstates by FHWA (less than 1.88 m/km [119 in./mi]) (3). Analysis of the first two-year data showed that both the Sacramento 5 and San Mateo 280 sites have higher IRI values than the majority of the QP sections, probably due to the cracked PCC underneath, which has a high IRI value (2). Figure 6.4 shows that IRI increased with pavement age on all three sections.

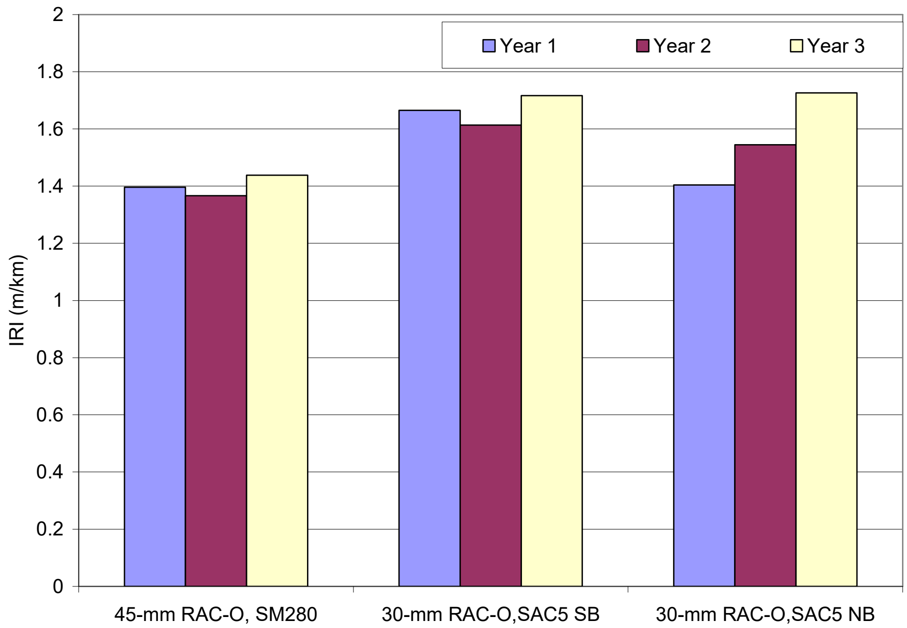

Figure 6.4: Three-year IRI values for Sacramento 5 and San Mateo 280 sections.

Figure 6.5 shows the three-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. The San Mateo 280 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 6.6 shows the three-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, which is likely due to the higher MPD values and more reflective cracking (which will be discussed below) in the northbound section. There is a continuous reduction in the noise levels of the San Mateo 280 section. The reason is unknown. It may be due to an increase of permeability that resulted from the cleaning effect of high traffic volume and high rainfall level.

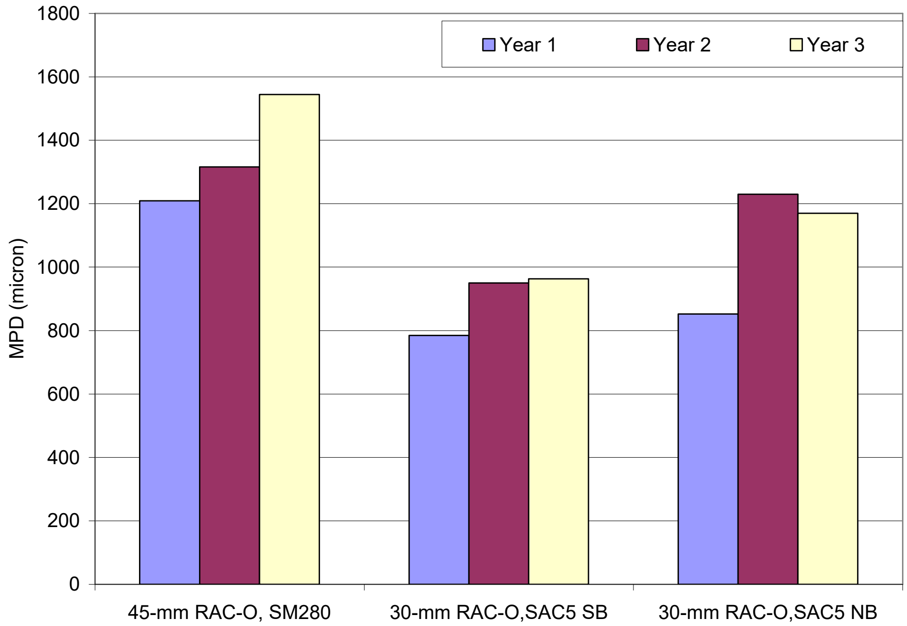

Figure 6.5 Three-year MPD values for Sacramento 5 and San Mateo 280 sections.

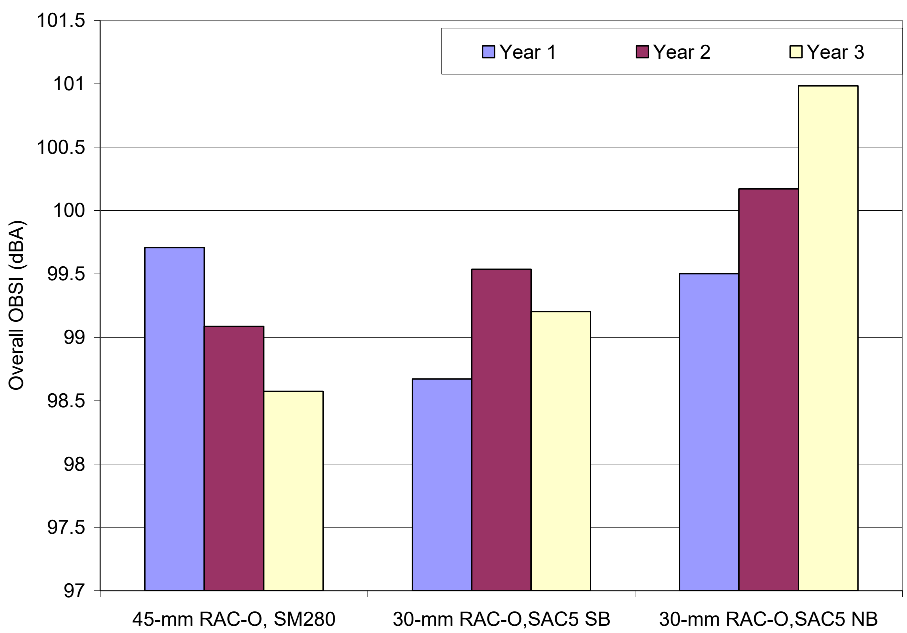

Figure 6.6: Three-year overall OBSI values for Sacramento 5 and San Mateo 280 sections.

According to the condition survey (Appendix A.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 both the number and 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 in the second and third years (0.1 m^2 in the second year and 0.25 m^2 in the third year). There was no reflective cracking on this section.

In summary, the northbound direction of the Sacramento 5 site has higher noise levels and more distresses than the southbound direction. 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 technical memorandum was prepared in September 2008 comparing OBSI measurements from the UCPRC and Illingworth & Rodkin test vehicles, and examining in detail possible explanations for the difference in OBSI noise levels between the north- and southbound directions of the Sacramento 5 sections. It is included in this report as Appendix A.8.

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 three 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 has been 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 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 (2).

Figure 6.7 shows the three-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 provide "good" ride according to the FHWA criteria for non-Interstate highways of less than 1.50 m/km (95 in./mi) (2). IRI changed slightly with age on all sections except for the 75-mm OGAC westbound section.

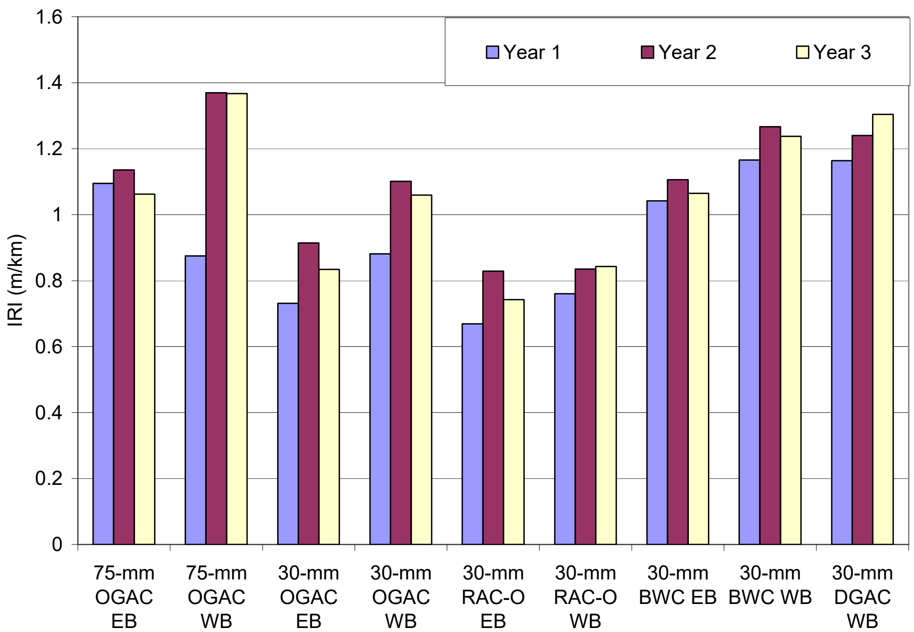

Figure 6.7: Three-year IRI values for the LA 138 sections.

The third-year MPD was not measured on 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.

Figure 6.8 shows the three-year overall sound intensity levels for the LA 138 sections. There are errors in the 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 (2).

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 is much less from the second survey year to the third.

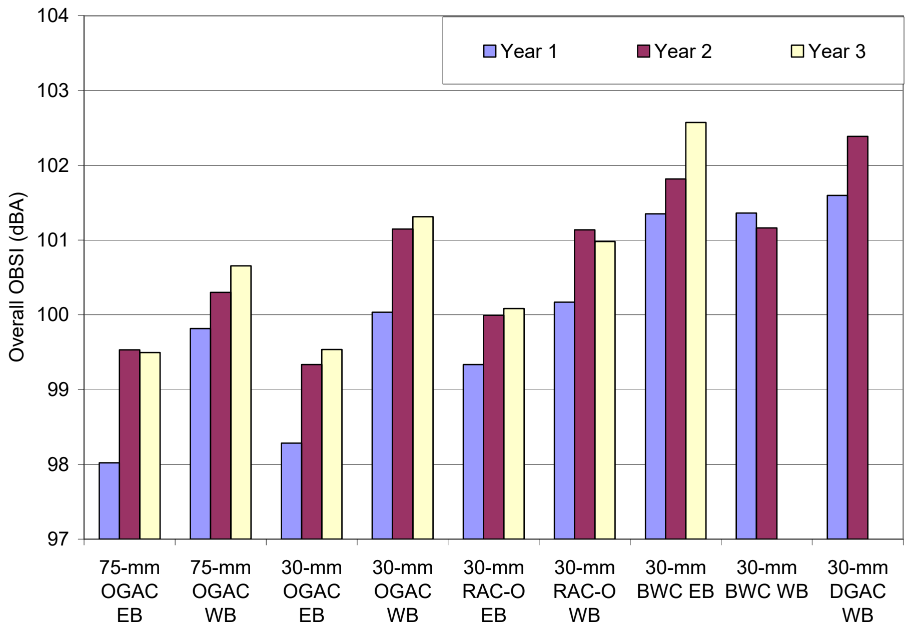

Figure 6.8: Three-year overall OBSI values for LA 138 sections.

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 three-year distress data for each eastbound section are given in Appendix A.7.

Transverse cracking appeared to be the major distress on all the eastbound sections. The westbound DGAC section also showed a small area of fatigue cracking in addition to transverse cracking. The number and length of the cracks increased from the first survey year to the second survey year for all sections. Transverse cracking developed between the second survey year and the third 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. It appears that distress progression is less significant on the RAC-O section.

In summary, increased thickness was not found to increase durability or provide any noise reduction as measured by the OBSI method. Open-graded mixes have the lowest noise levels among all mix types in the three 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.

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 has been known from the first two years of data that EU-GG retains its permeability longer than Caltrans RAC-G mixes (1). Figure 6.9 shows the three-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 2.4), and that it has not changed significantly with pavement age over the three survey years.

Figure 6.10 shows the three-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 3.3), and it increased slightly from the second to the third survey year. The sound intensity on this section was not measured in the third year. Based on the first two years of data, the EU-GG mix has noise levels close to those of the RAC-G mixes (2). The condition survey revealed no distresses in the first year, bleeding in the second year (of an area of 150 m^2), and minor raveling and transverse cracking in the third year. A malfunction of the OBSI apparatus resulted in no noise measurements for the third year. Fourth year measurements will be collected next 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.

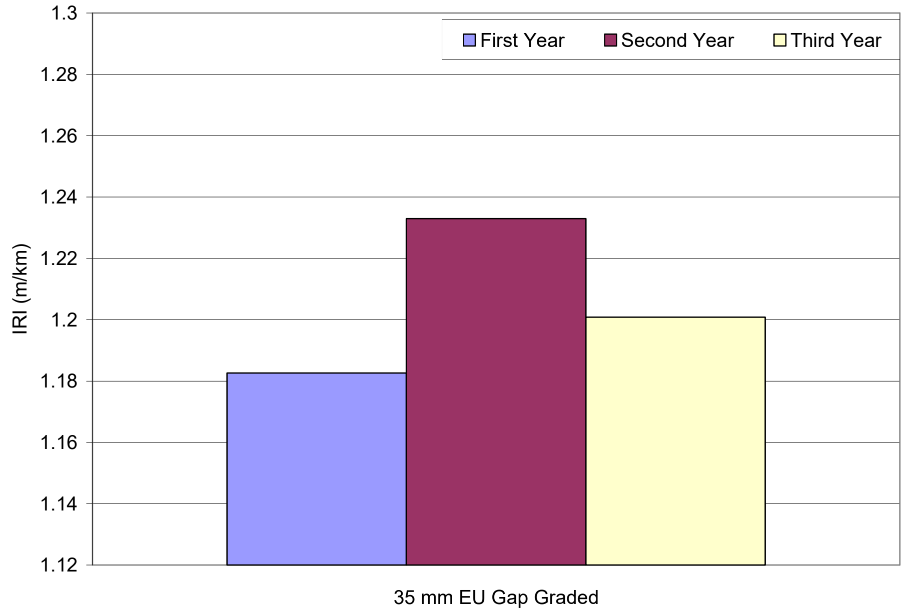

Figure 6.9: Three-year IRI values for LA 19 section.

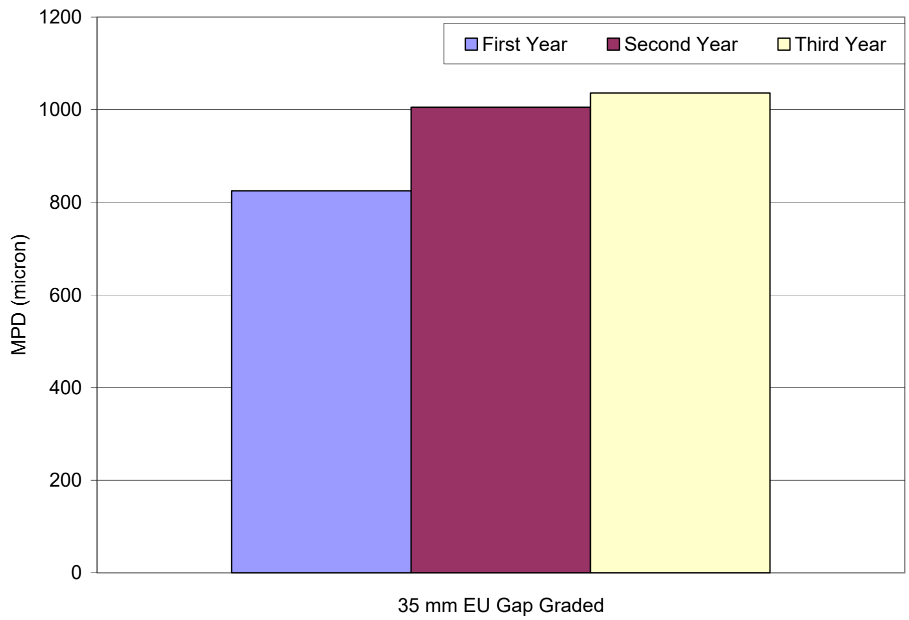

Figure 6.10: Three-year MPD values for LA 19 section.

6.5 Yolo 80 Section

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 (2).

Figure 6.11 shows the three-year IRI values for the Yolo 80 section. The figure shows that the IRI values increased slightly in the third survey year, but that overall the section has good ride quality over the three survey years. Figure 6.12 shows the three-year MPD values for the Yolo 80 section. The figure shows that the MPD values of 1,000, 1,350, and 1,375 microns in the first, second, and third 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 6.13 shows the three-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 dB(A) in the third survey year, which is higher than other open-graded mixes tested (see Figure 5.2). The noise spectra of this section (Appendix A.5) 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 6.11) and reduction of permeability. However, permeability was not measured in the third survey year.

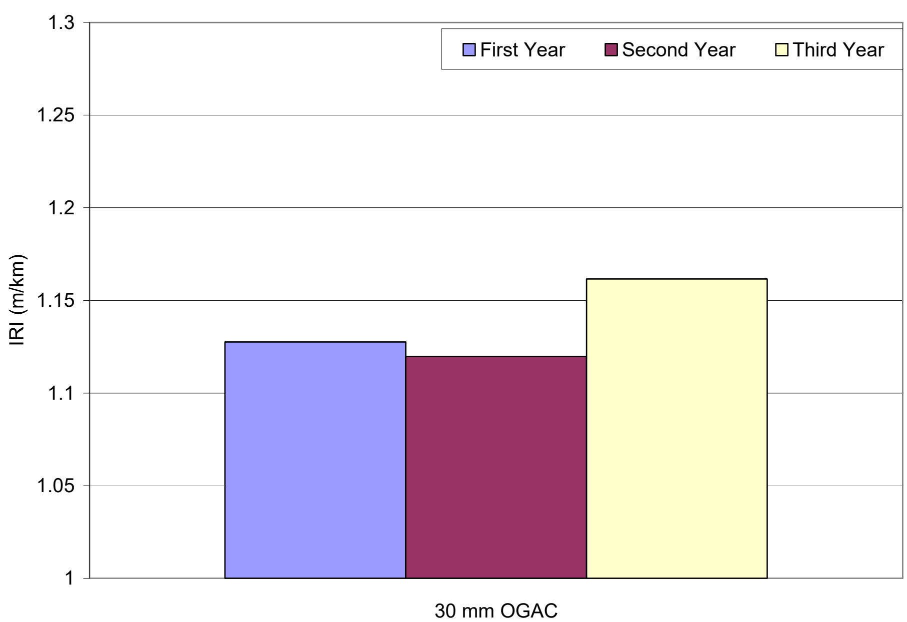

Figure 6.11: Three-year IRI values for the Yolo 80 section.

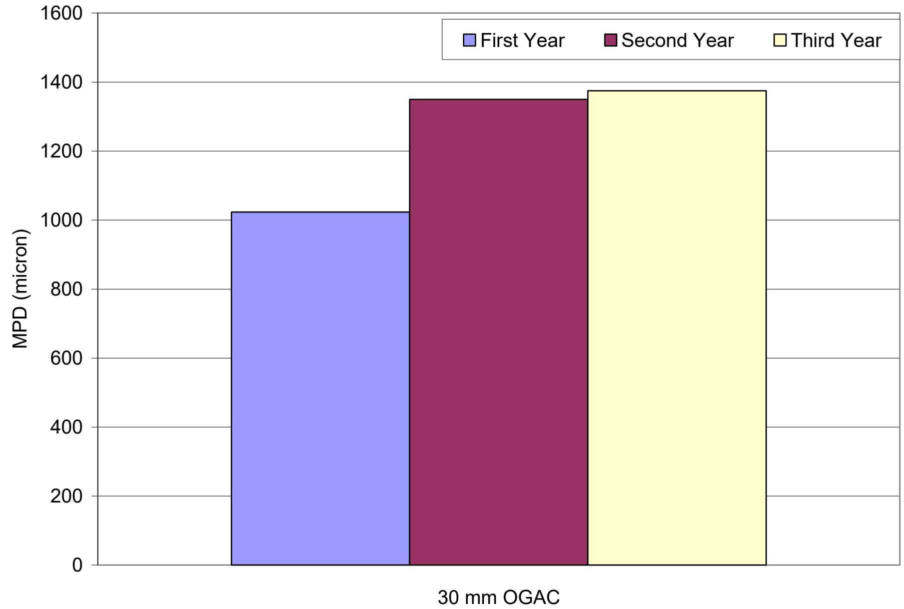

Figure 6.12: Three-year MPD values for the Yolo 80 section.

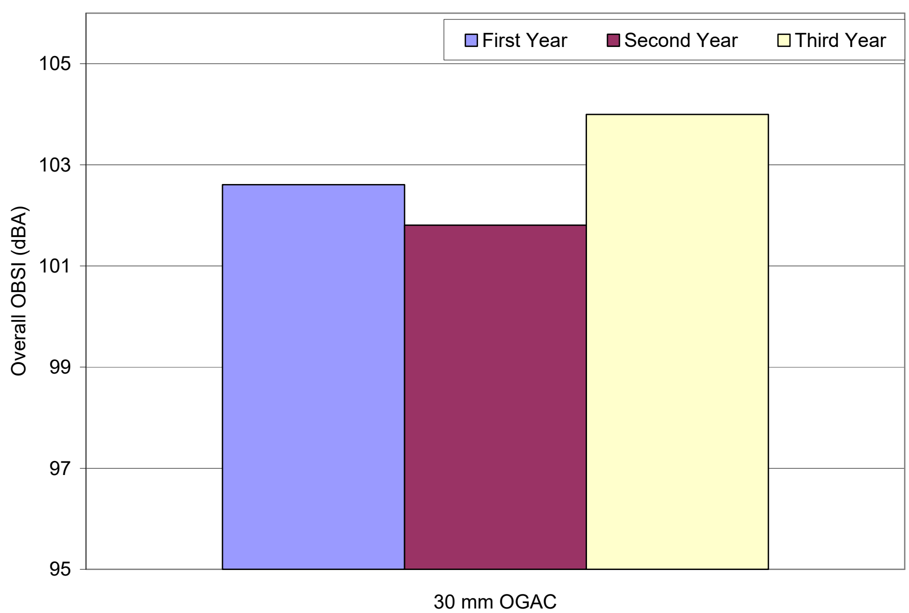

Figure 6.13: Three-year OBSI values for the Yolo 80 section.

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

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

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 have higher MPD and IRI values than Type G-MB, Type D-MB, and DGAC mixes. Tire/pavement noise increased significantly in the third survey year on the RAC-G, RUMAC-G, and Type D-MB sections. Type G-MB is 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 are prone to bleeding.
- Increasing thickness does not reduce fatigue cracking but may reduce the transverse cracking on the RAC-G mix. Increasing thickness may help reduce cracking of RUMAC-GG and Type D-MB. There appears to be no noise reduction benefit from increasing the thickness of the RAC-G, RUMAC-GG, Type G-MB, and Type D-MB mixes.
- 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 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 three 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 nonrubberized 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 nine 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. RESULTS AND ANALYSIS FOR NEW SURFACES MEASURED FOR THE FIRST TIME IN SURVEY YEAR 3

As part of the PPRC SPE 4.19 work plan testing was performed on additional sections with surface types that were not included in the first two years of data collection. These sections were tested as part of the following special studies:

- SemMaterial™ Bituminous Wearing Course (BWC) sections
- Skidabrader™ retexturing sections, before and after
- Mesa rodeo test sections
- Arizona highway I-10 sections
- California Highway Patrol sections (profilometer only)

7.1 SemMaterial BWC Sections

To provide additional data regarding BWC, a set of eight sections at five different locations were tested by the UCPRC car in July 2007. These sections were identified by industry as being "more representative" of BWC than the BWC placed on the LA-138 section discussed in Section 6.3 of this report, which showed no noise advantages compared to DGAC.

The testing speed was 60 mph (97 km/h), except in section BWC-01 where the speed was 35 mph (56 km/h). Table 7.1 presents the locations of the eight pavement sections.

Table 7.1: BWC Section Locations

Section ID	Direction	Location	Section Name
BWC-01	–	04NAP-AmCanyon-W	American Canyon Rd
BWC-02	N	06KER99N5.4	Kern 99
	S	06KER99S5.4	
BWC-03	–	10SJO5N4.5	I-5
BWC-04	N	01MEN101N78.5	Laytonville
	S	01MEN101S78.5	
BWC-05	E	05MON156E2.0	Castroville
	W	05MON156W2.0	

No traffic closures were used for the sections, nor were there coring, permeability testing, or friction testing. The physical properties of some of these sections were obtained from the product manufacturer, SemMaterials, and are presented in Table 7.2.

Table 7.2: Physical Properties of BWC Sections from SemMaterial and UCPRC OBSI Measurements

Section ID		NMAS	Construction Year	OBSI	Type	Comment
BWC-01		9.5 mm	2007	99.5	BWC-G	Gap graded bonded wearing course
BWC-02	N		2006	99.9	BWC-G PM	BWC gap graded polymer modified
	S			98.8	RBWC-O	RBWC Type O Rubber Mix
BWC-03			2005	100.0	RBWC-O	5/8 inch thick. First Rubber bonded wearing Course Rubber project in CA (built in 2005)
BWC-04	N		2006	98.4	BWC-O PM	Open Graded Mix over Open Graded Mix
	S			99.4		
BWC-05	E	9.5 mm	2005	98.0	BWC-G PM	
	W	9.5 mm	2005	98.4		

7.1.1 Sound Intensity Measurements

The overall sound intensity levels in each test section are presented in Figure 7.1. Results from section BWC-01 were converted from 35 mph to 60 mph (48 and 97 km/hr) using equations developed by the UCPRC. Figure 7.2 shows the spectral content for those sections tested at 60 mph.

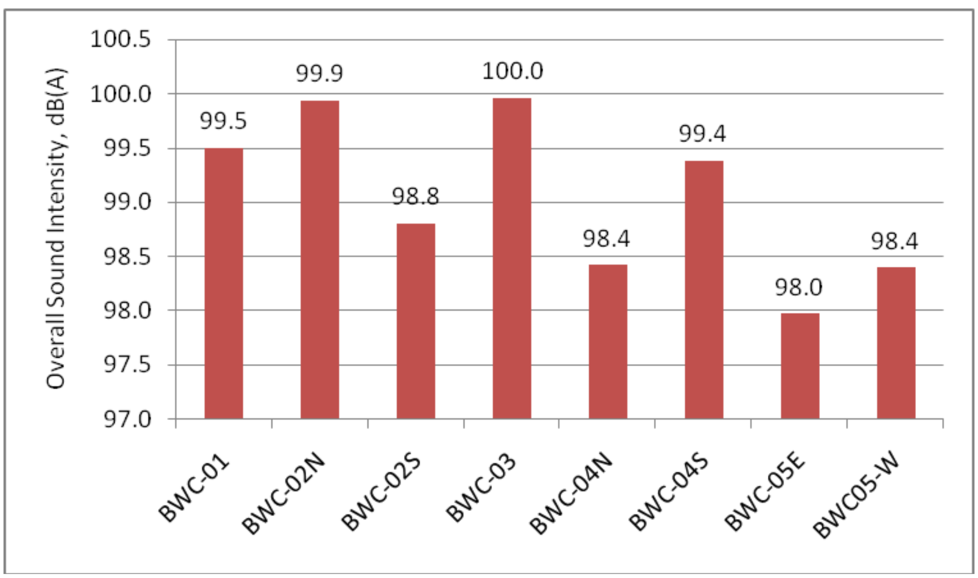

Figure 7.1: Overall sound intensity levels.

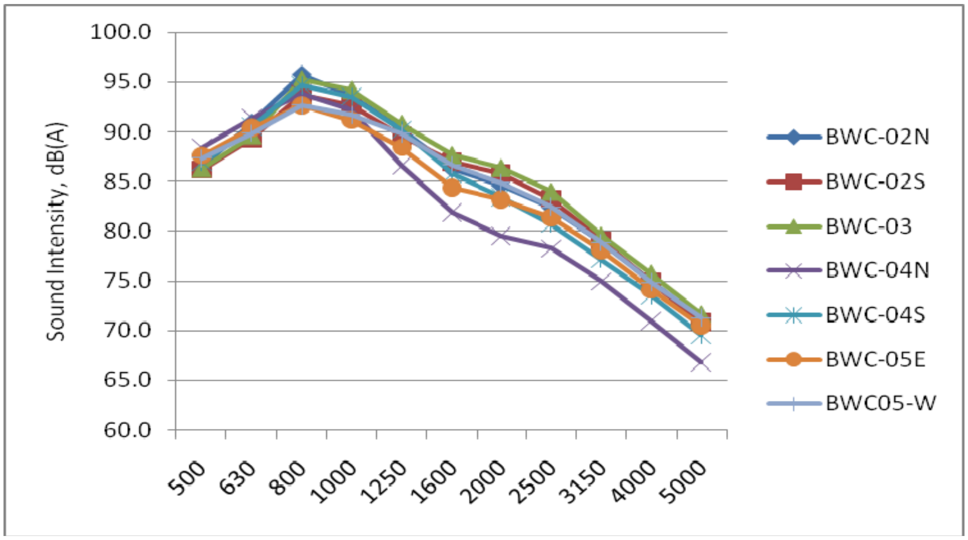

Figure 7.2: Spectral sound intensity levels.

Figure 7.3 compares the OBSI levels of these eight BWC sections with the QP and ES pavement sections measured in the first and second years of data collection. The OBSI levels for the other sections were calculated as the average of first and second year levels. Sections shown with red bars are the BWC section, those shown with yellow bars are the ES sections, and those shown in blue are the QP sections. An important observation is that BWC sections ES-07 and ES-08, from the set of sections in LA-138, present sound intensity levels approximately 2.5 dB(A) higher than the average of the eight BWC sections included in this special study.

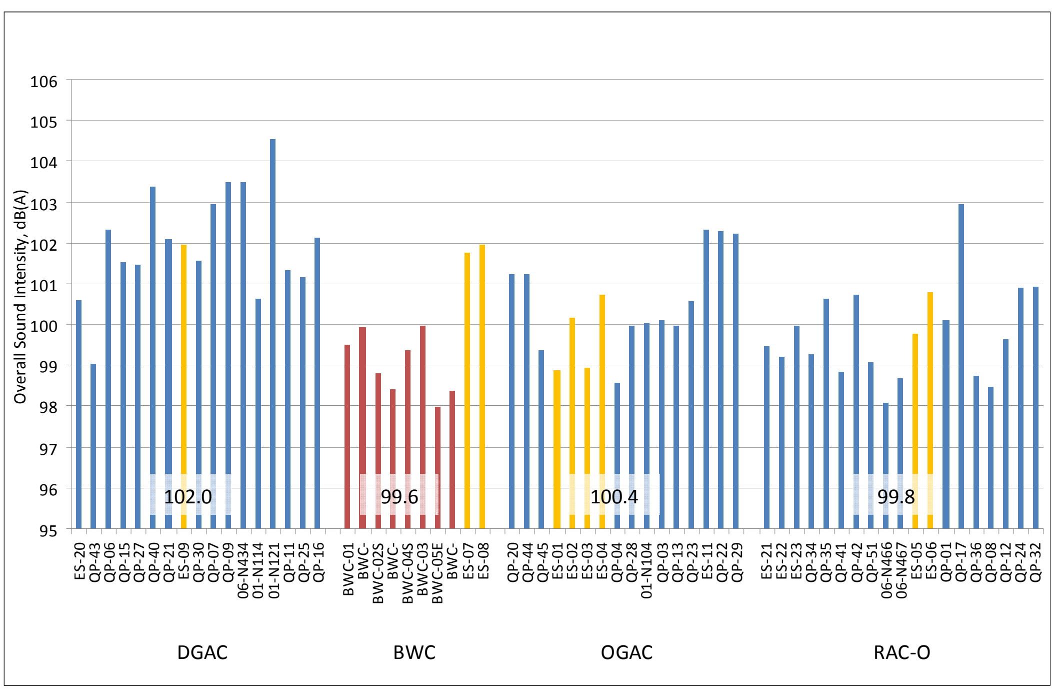

Figure 7.3: Sound intensity levels of BWC compared to other pavement types.

7.1.2 International Roughness Index and Mean Profile Depth

In addition to the OBSI measurements, the International Roughness Index (IRI) was obtained from elevation profiles measured on both wheelpaths. The results for each section are shown in Figure 7.4. The right wheelpath was often much rougher than the left wheelpath in the sections on city streets, as can be seen in the figure. The two wheelpaths had similar IRI on the high-speed sections.

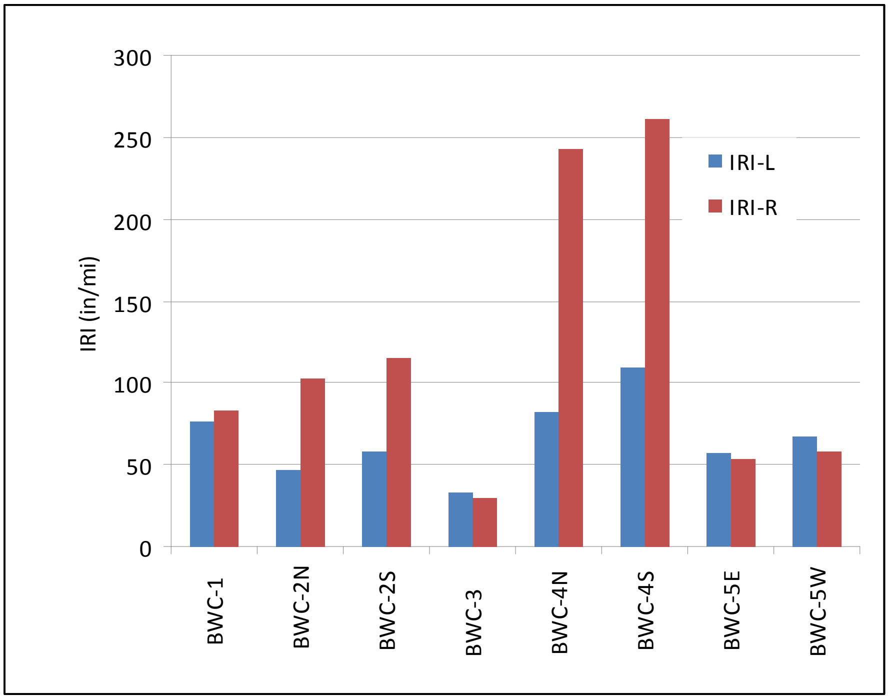

Figure 7.4: Left and right wheelpath IRI levels for each section.

Similarly, the pavement surface texture in terms of the Mean Profile Depth (MPD) was evaluated and the results are shown in Figure 7.5.

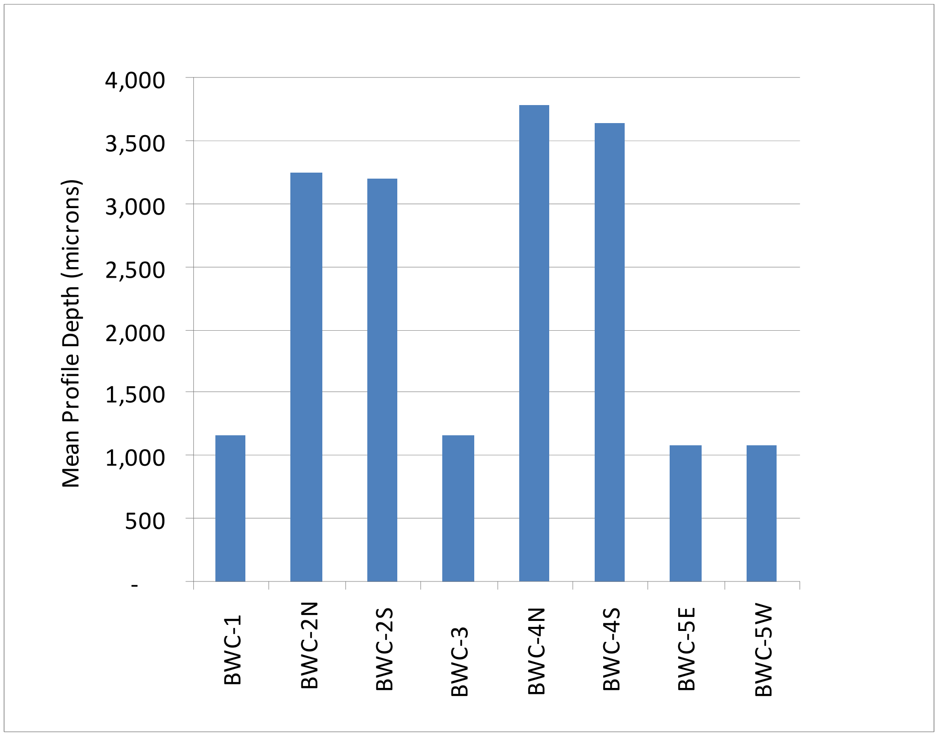

Figure 7.5: Mean Profile Depth.

7.2 Skidabrader Retexturing Sections, Before and After

Four sets of pavement sections were tested for noise both before (July 9, 2008) and after (July 15, 2008) retexturing using the Skidabrader process. The test sections are on Interstate 505 (I-505) near State Route 16 (SR-16) in Yolo County.

7.2.1 Before Skidabrader Treatment

Four pavement surface types were evaluated: burlap drag PCC (BD), open-graded AC (OG), dense-graded AC (DG), and longitudinally tined PCC (LT). Each pavement section was one mile long, and the last 440 ft (five seconds of testing) was measured at the end of each quarter mile using the UCPRC instrumented noise testing car. The testing was repeated three times. The test tire was a Standard Reference Test Tire (SRTT), in this case tire number UCPRC SRTT#1, and the testing speed was 60 mph. Figure 7.6 shows the schematic location of the four pavement sections and the postmiles. The DG section is on the shoulder next to the OG section.

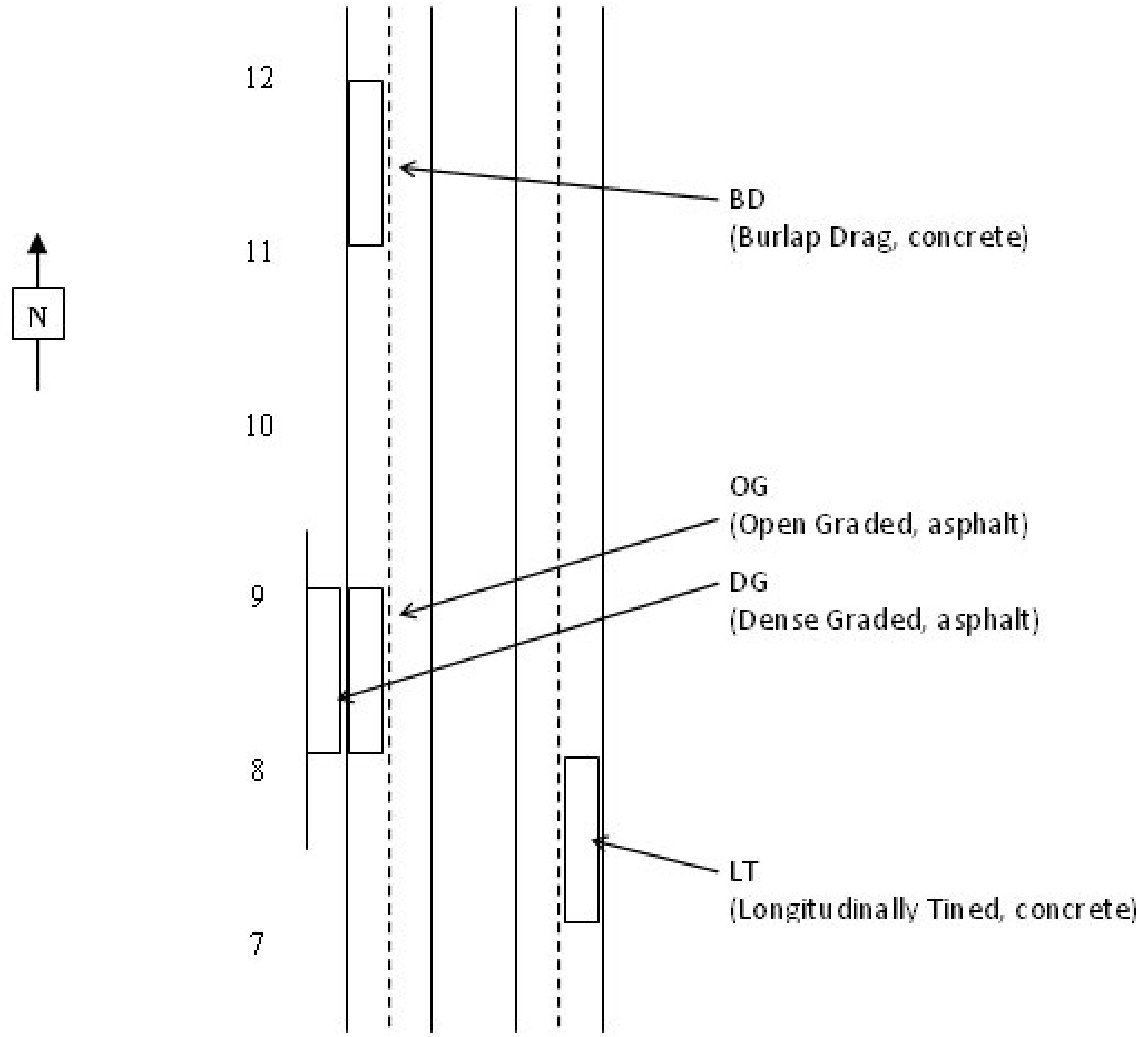

Figure 7.6: Schematic location of pavement sections (post-miles shown on left side).

Figure 7.7 shows the overall OBSI levels for each segment, including the range over the three runs. A larger range of variability was observed on the open-graded pavement, due to transverse variations in the lane, where the noise levels in the wheelpath and outside the wheelpath are different. Figure 7.8 compares the spectral content using the first segment of each section. The BD and OG pavements had similar average overall OBSI levels, at 104.4 and 104.6 dB(A) respectively, but very distinct spectral contents. The quietest pavement was the DG, at 99.7 dB(A). The LT pavement had a noise level of 103.5 dB(A). The spectra content for the two PCC pavements were similar. Figure 7.9 through Figure 7.12 show the spectra on the four quarter-mile segments of each section.

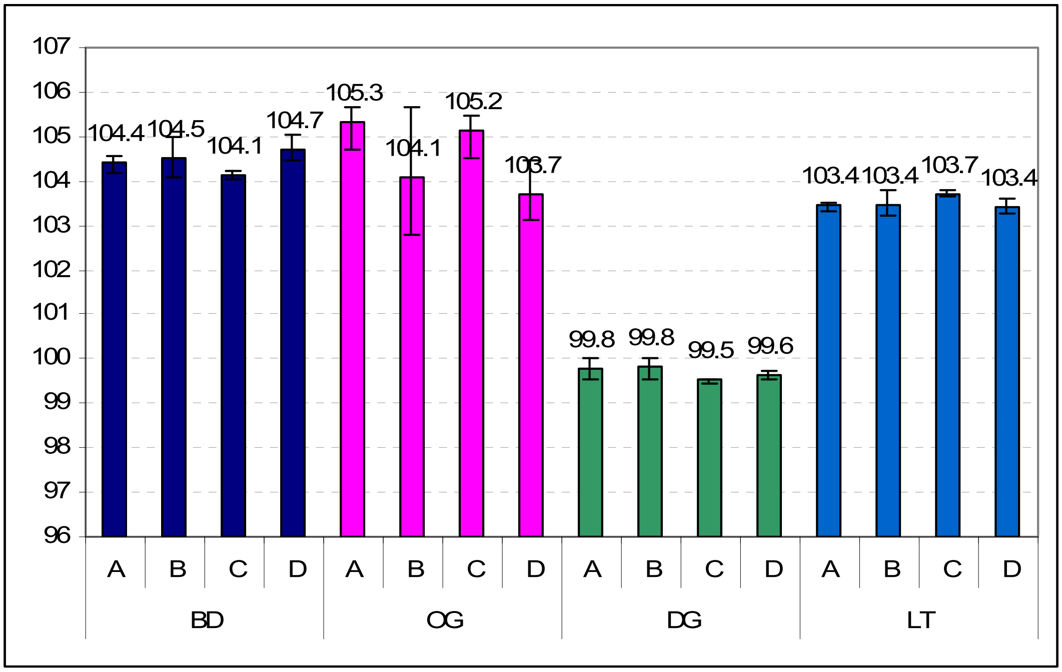

Figure 7.7: Overall OBSI levels in each section for each pavement type.

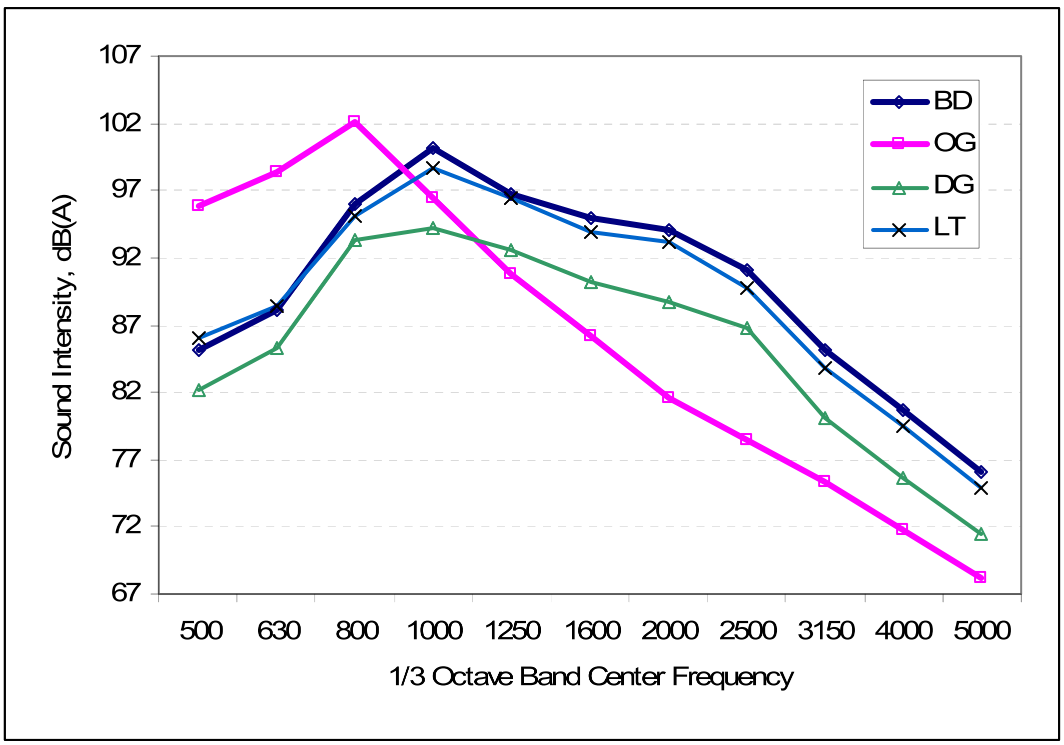

Figure 7.8: Comparison of OBSI one-third band spectra across pavement types.

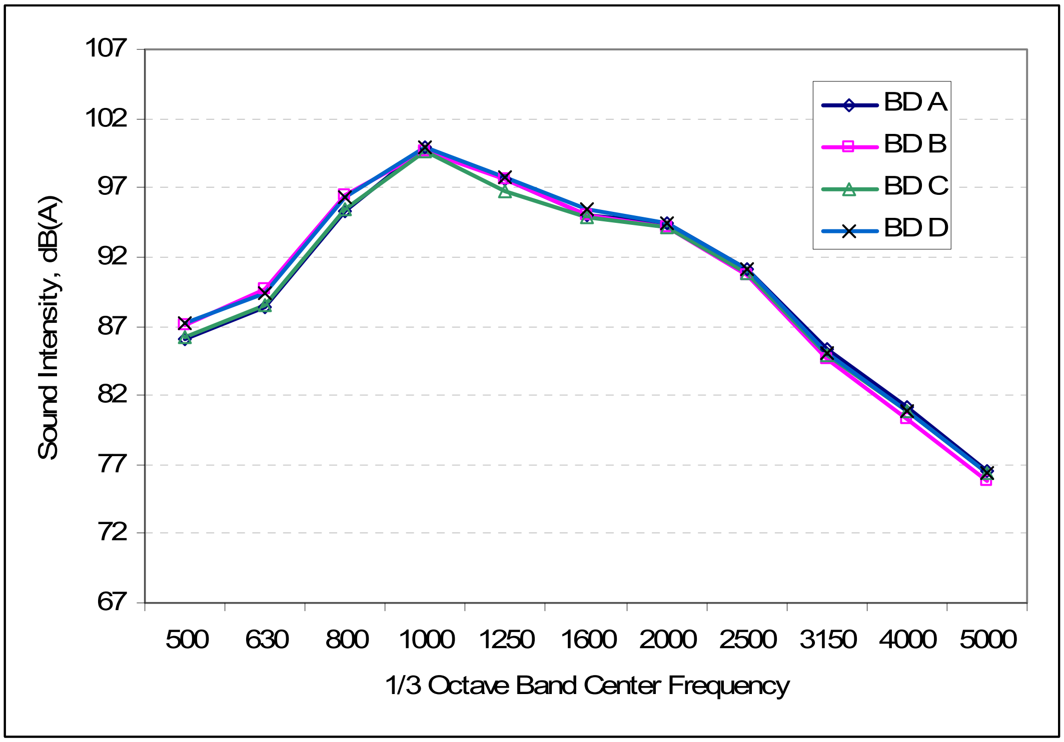

Figure 7.9: OBSI for one-third band spectra for burlap drag PCC pavement (BD) segments.

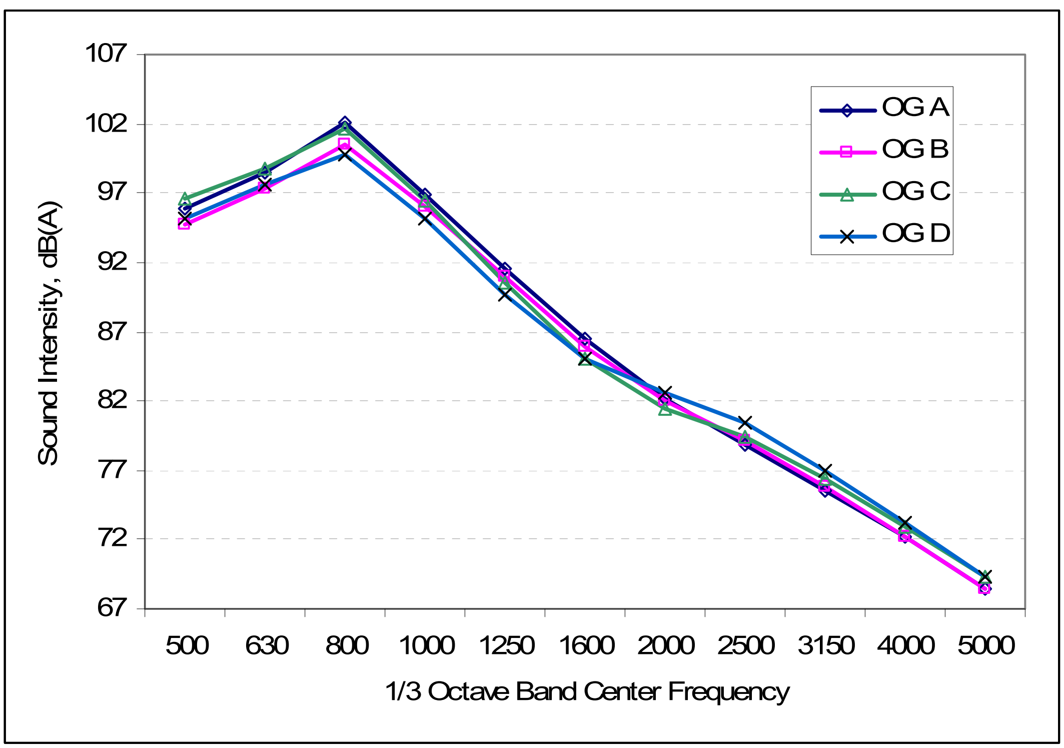

Figure 7.10: OBSI for one-third band spectra for open-graded asphalt pavement (OG) segments.

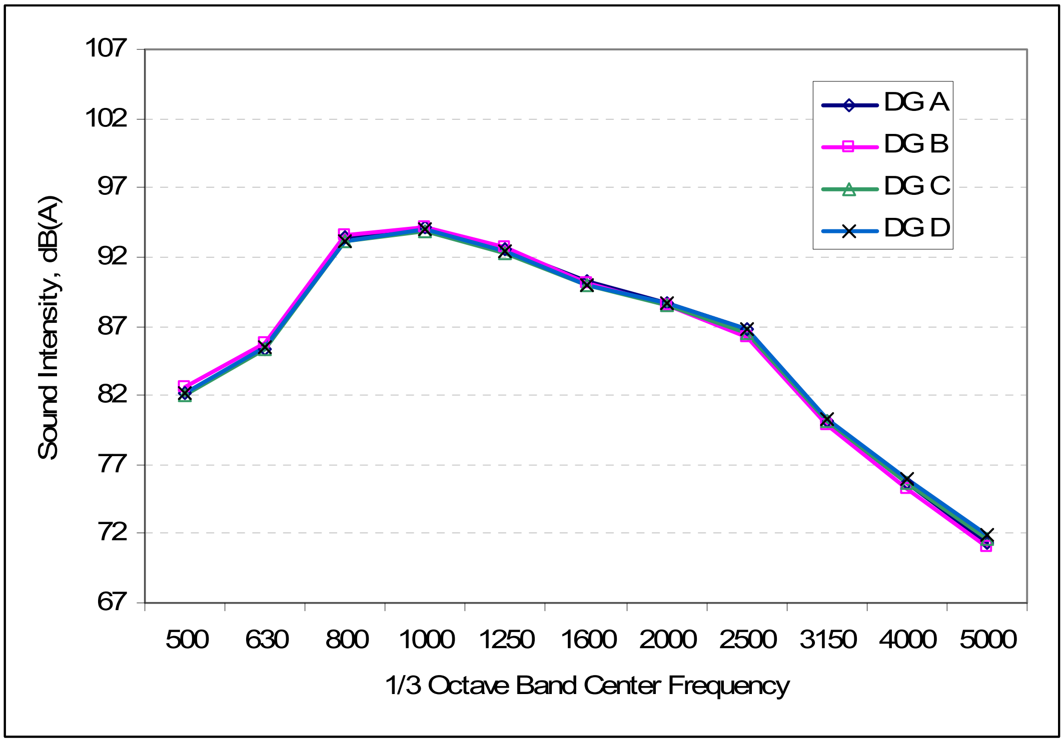

Figure 7.11: OBSI for one-third band spectra for dense-graded asphalt pavement (DG) segments.

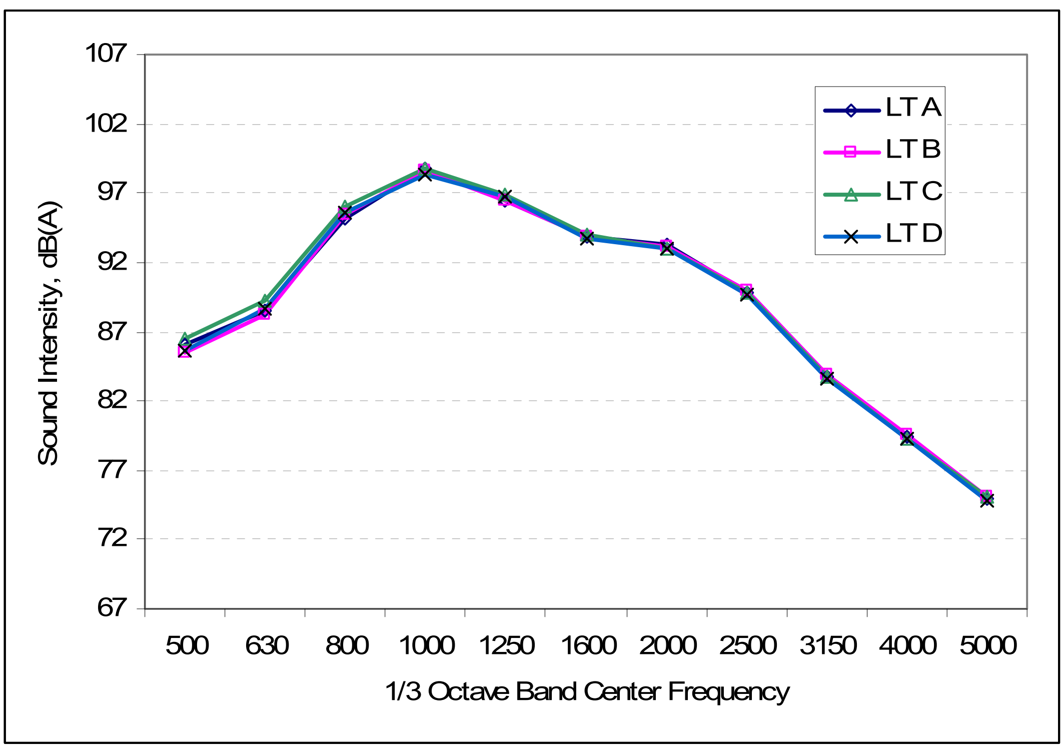

Figure 7.12: OBSI for one-third band spectra for longitudinally tined PCC pavement (LT) segments.

7.2.2 *After Skidabrader Treatment*

The test sections tested before Skidabrader texturing were tested again several days afterward. On the DG section a fifth quarter-mile long segment was evaluated on texture identified as 100 feet per minute ("100/min") and 130 feet per minute ("130/min").

Figure 7.13 shows the overall OBSI one-third octave band spectra results after the retexturing with Skidabrader. The overall OBSI levels are computed from the noise levels measured in one-third octave bands from 500 Hz to 5,000 Hz. The vertical lines in the charts represent variability (range) for three repeat runs. Table 7.3 presents a comparison of results before and after retexturing. Figure 7.14 through Figure 7.17 show the spectral content before and after retexturing.

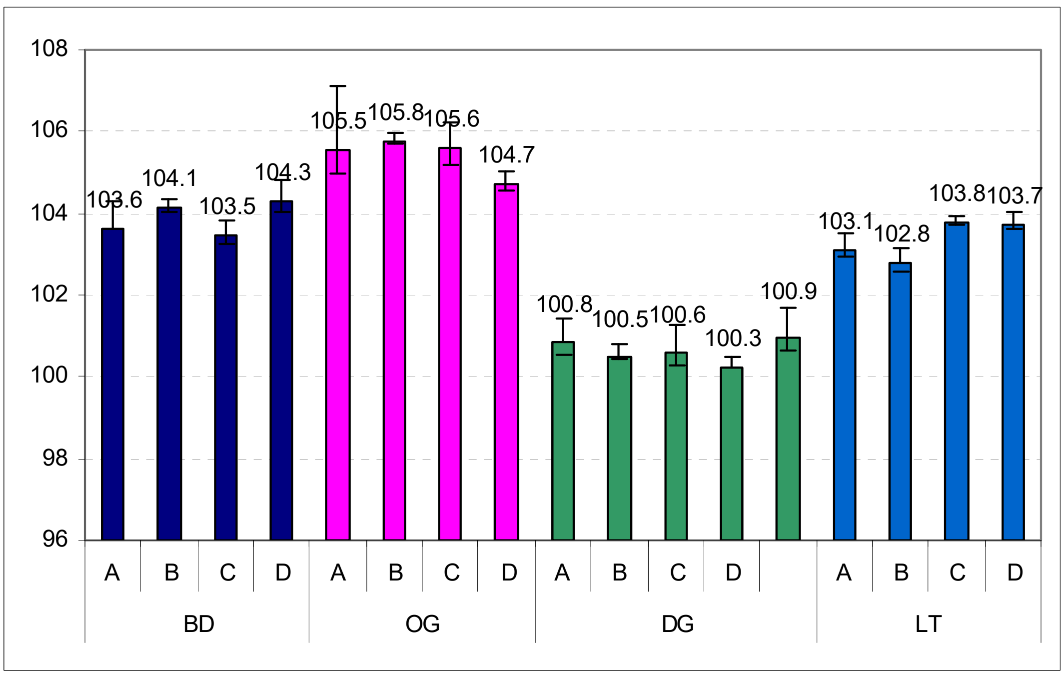

Figure 7.13: Overall OBSI levels after Skidabrader.

Table 7.3: Comparison of OBSI Levels Before and After Skidabrader

Pavement Type	Segment	Overall OBSI per Segment			Overall OBSI per Pavement Type		
		Before	After	Difference	Before	After	Difference
BD	A	104.4	103.6	-0.8	104.4	103.9	-0.5
	B	104.4	104.1	-0.3			
	C	104.1	103.5	-0.6			
	D	104.6	104.3	-0.3			
OG	A	105.3	105.5	0.3	104.1	105.4	1.3
	B	104.1	105.8	1.7			
	C	104.4	105.6	1.2			
	D	102.7	104.7	2.0			
DG	A	100.0	100.8	0.9	99.8	100.6	0.8
	B	99.9	100.5	0.5			
	C	99.6	100.6	1.0			
	D	99.8	100.3	0.5			
	E*	99.8*	100.9	1.1*			
LT	A	103.5	103.1	-0.4	103.5	103.4	-0.1
	B	103.4	102.8	-0.6			
	C	103.6	103.8	0.2			
	D	103.3	103.7	0.4			
						Average difference	0.4

* Note: Segment E on pavement DG was not tested before retexturing, however the average OBSI from the other segments was used in the calculation.

Changes between -0.3 and -0.8 dB(A) were measured on the burlap drag concrete, while changes of -0.6 to +0.4 dB(A) were measured on the longitudinally tined concrete. The first segment of the burlap drag section includes the bridge, but the results were not separated between pavement and bridge. Segments A and B on the longitudinally tined concrete saw a reduction (change of -0.4 and -0.6 dB(A)), while segments C and D saw an increase in noise (change of +0.2 and +0.4dB(A)).

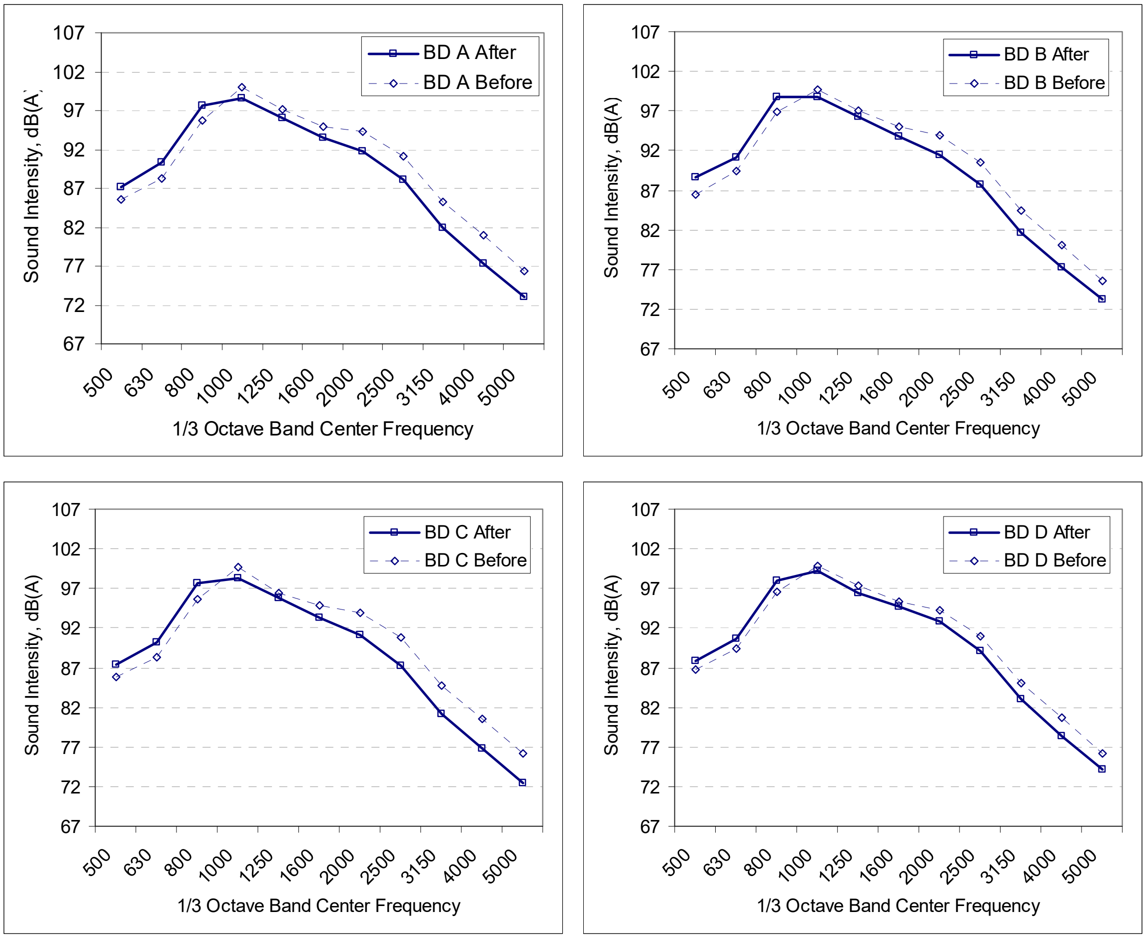

Figure 7.14: OBSI spectra for before and after Skidabrader for burlap drag PCC pavement (BD) segments.

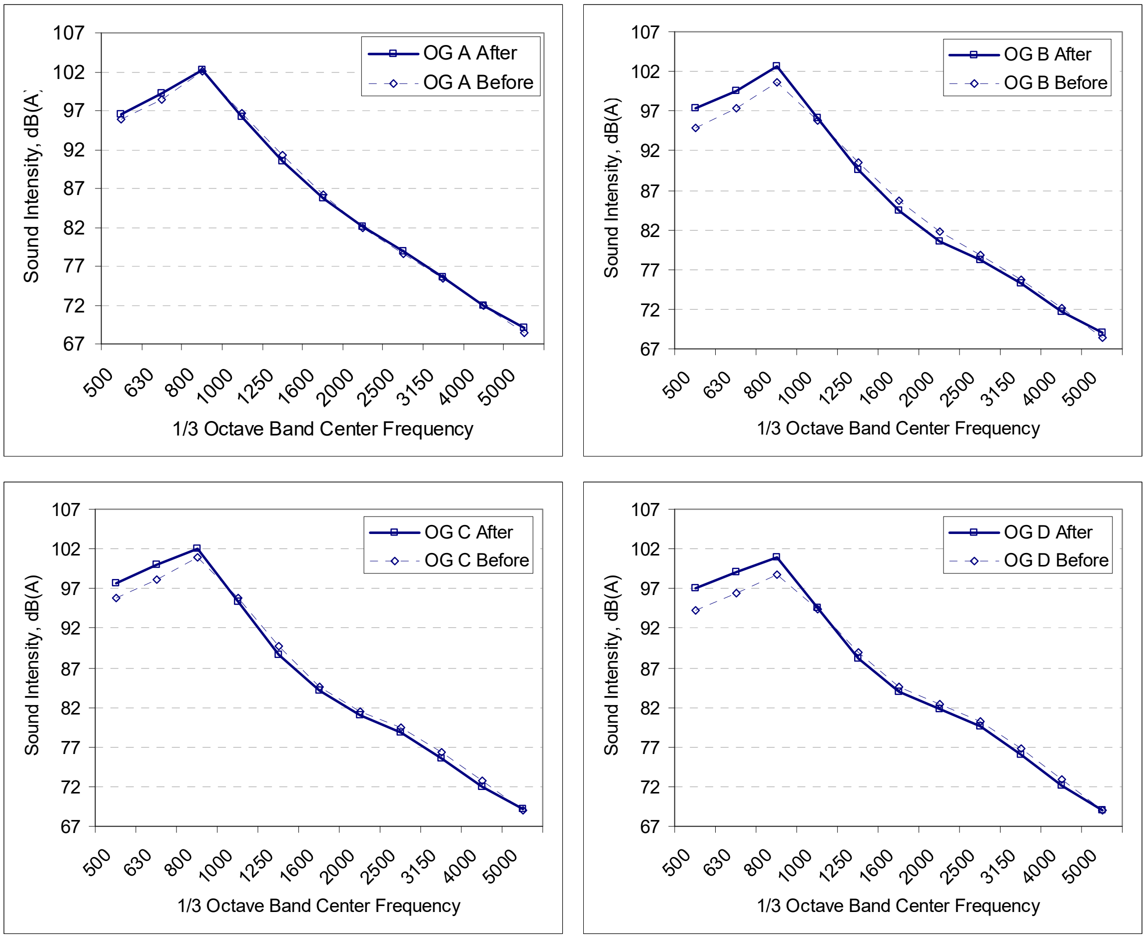

Figure 7.15: OBSI spectra for before and after Skidabrader for open-graded AC pavement (OG) segments.

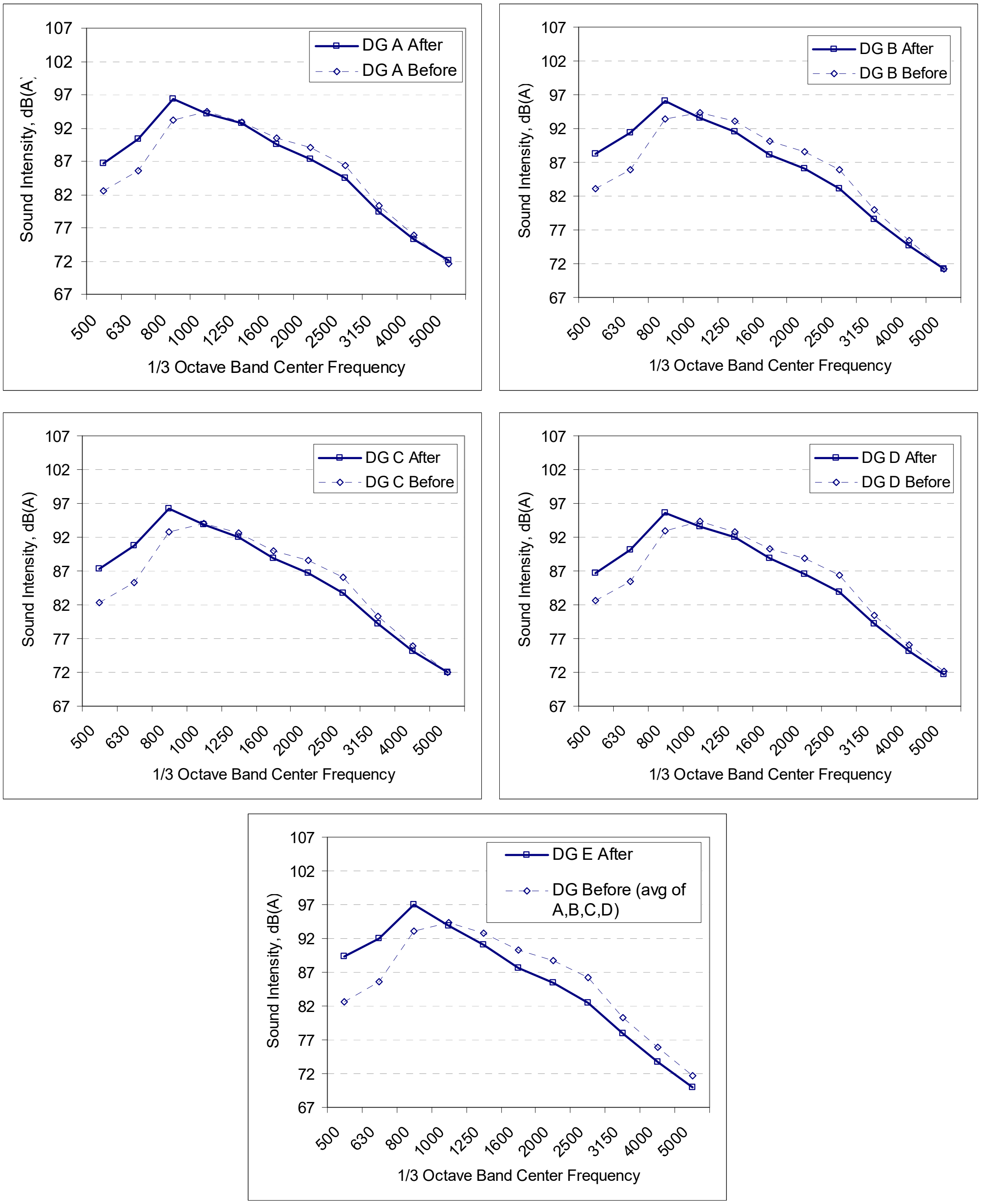

Figure 7.16: OBSI spectra for before and after Skidabrader for dense-graded AC pavement (DG) segments.

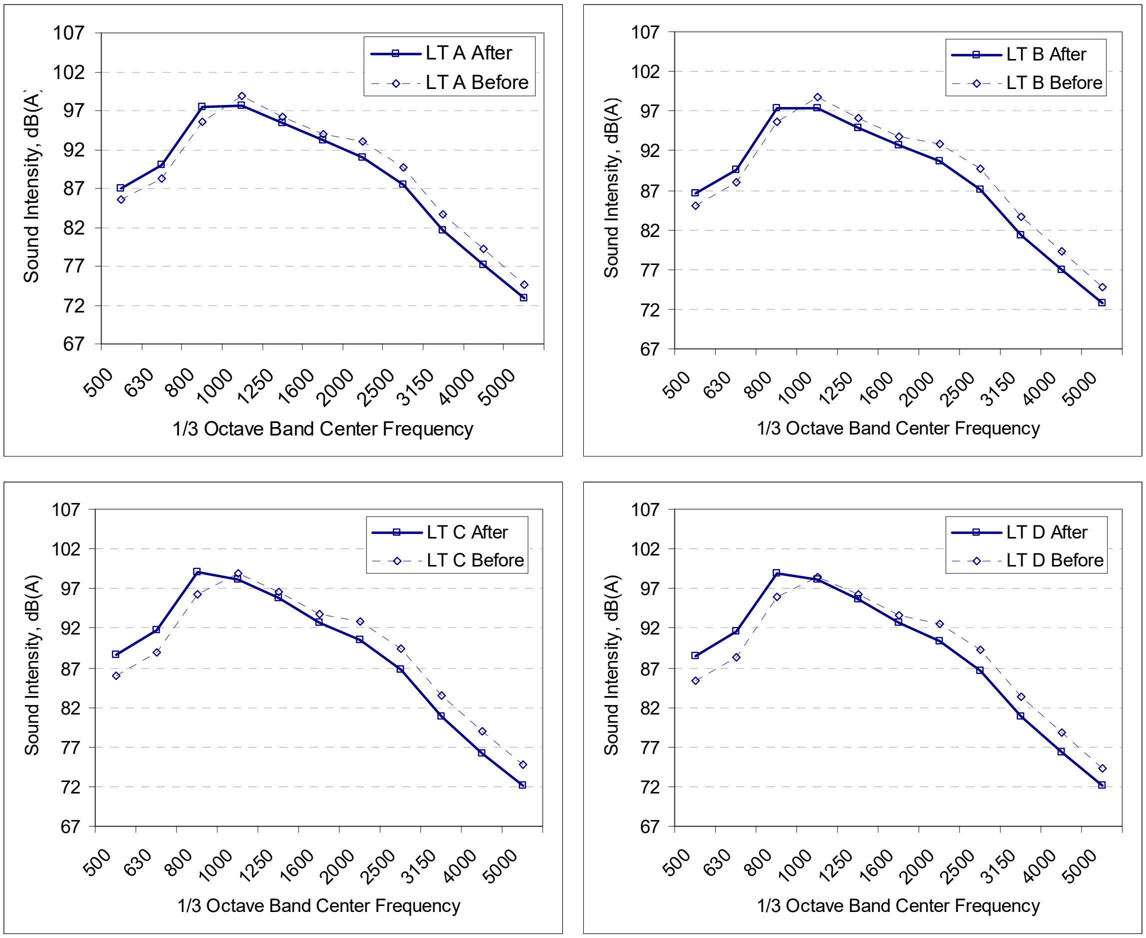

Figure 7.17: OBSI spectra for before and after Skidabrader for longitudinally tined PCC pavement (LT) segments.

7.3 Other Testing

7.3.1 Mesa Rodeo Test Sections

A total of eight sections, some of them measured more than once, were tested in this rodeo, which took place in Mesa, Arizona on March 27 and 28, 2008. The UCPRC noise car participated with noise cars from the TransTech Group, Illingworth & Rodkin, and the American Concrete Pavement Association. With funding from the Caltrans Division of Environmental Analysis, a report was prepared by Illingworth & Rodkin comparing the OBSI measurements from the four noise cars. UCPRC travel was paid by the Noise Research Pooled Fund Study.

7.3.2 Arizona I-10

A number of pavement test sections, primarily concrete pavement surfaced with thin asphalt rubber overlays, were tested for OBSI with the UCPRC noise car in the vicinity of Phoenix, Arizona on March 27, 2008. The 30 sections were tested were subjected to only one pass with the noise car because of time constraints. The data were reported to Bill Farnbach and Bruce Rymer of Caltrains, and shared with the Rubber Pavements Association with their authorization.

7.3.3 California Highway Patrol Sections (Profilometer Only)

A pavement section was tested at the California Highway Patrol Academy in West Sacramento on February 8, 2008. The objective was to check the repeatability of profilometers. The data were reported to James Lee of Caltrans.

7.4 Summary of the New Surface Testing

The following observations were made regarding the testing on the new surfaces:

7.4.1 Testing on BWC Sections

- The additional BWC sections tested are 2 to 4 dB(A) quieter than the BWC sections that are part of the LA 138 experiment. These additional BWC sections have noise levels similar to those of the open-graded QP and ES sections.
- The additional BWC sections have IRI values that are generally good to fair, based on FHWA criteria, except for the right wheelpaths of urban sections, which had high IRI values.
- The MPD values of the BWC sections are either at the lower range of values for open-graded mixes, or considerably higher than values for open-graded mixes, depending on the test section.

7.4.2 Testing on Skidabrader Sections

- The results from these test sections indicate that retexturing with the Skidabrader process increased the OBSI on the dense-graded and open-graded asphalt pavements.
- The increase mostly comes from higher levels of low-frequency noise, and in the case of dense-graded it is accompanied by a reduced high-frequency noise.
- For the asphalt sections, the noise in the open-graded pavement increased 1.3 dB(A) on average [from +0.3 to 2.0 dB(A)], while the dense-graded pavement increased 0.8 dB(A) on average [from 0.5 dB(A) to 1.1 dB(A)]. In the dense-graded pavement, the segment with a texture labeled as “130 feet per minute” increased the noise by 1.1 dB(A), while the other four segments with texture called “100 feet per minute” ranged between +0.5 and +1.0 dB(A).
- On burlap drag and longitudinally tined concrete pavements, small to moderate reductions in overall tire/pavement noise were caused by retexturing, including lower levels of high-frequency noise, but higher levels of low-frequency noise.
- Noise reductions of between -0.3 and -0.8 dB(A) were measured on the burlap drag concrete, while changes of -0.6 to +0.4 dB(A) were measured on the longitudinally tined concrete.

Segments A and B on the longitudinally tined concrete saw a noise reduction of -0.4 to -0.6 dB(A), while segments C and D saw an increase in noise of change of +0.2 to +0.4dB(A).

7.4.3 Testing on Other Sections

- No conclusions could be drawn from the testing on the Arizona I-10 sections because there were too many sections with different materials, and it was not clear if labeling of the sections in the plans was the same as in the field. Results from the CHP site were not analyzed by the UCPRC. Results from the Mesa Rodeo are included in the Illingworth and Rodkin report.

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

One of the objectives of this multiyear monitoring study is to estimate how long open-graded mixes last in terms of the performance variables permeability, friction, roughness, durability, and noise level. The new performance regression models developed as part of this study from the pooled three years of data collected, presented in Chapters 2 through 5, were used to estimate the lifetime of the different mixes with respect to the following performance criteria: roughness (IRI), noise (OBSI), and durability (bleeding, raveling, transverse/reflective cracking). These new models have improved prediction capability compared to the models from the first two years of data collection because of the additional observations. This chapter estimates the time to failure for different mixes under different climate and traffic conditions using the respective regression models.

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 estimation 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 neither permeability nor friction were measured in the third survey year, the performance models for them are have not been updated.

8.1 Prediction of IRI

In Chapter 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 2.1) is easier to use because it does not need the mix characteristic inputs such as MPD and permeability.

Equation 2.1 shows that the average annual rainfall and the number of days with temperature higher than 30°C are statistically significant in affecting IRI, while truck traffic and annual freeze-thaw cycles are statistically marginally 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, some typical values of the independent variables are 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 (6)—the two TI values correspond to 204 and 2,291 AADTT in the coring lane, and ten-year ESALs of 1.0 million and 11.2 million, respectively.

Values for the environmental factors are selected to represent different climate conditions, as shown in Table 8.1. 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 (7). Once the fourth year of data is collected (PPRC SPE 4.27), predictions will be made for all nine California climate regions defined for mechanistic-empirical design and PG asphalt binder selection.

Table 8.1: 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, is selected as the threshold value for a pavement to reach failure. Table 8.2 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 nonrubberized mixes, and that open-graded mixes retain acceptable riding smoothness longer than dense- or gap-graded mixes. The 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 8.2, where all predicted lifetimes are greater than 10 years. This conclusion is consistent with observations from the sections investigated, as discussed in Section 2.1. The longest life predicted by the model is 21 years for RAC-O for TI=9, Low Rainfall/High Temperature (South Coast).

Table 8.2: 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	>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: 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 Appendix A.10.

8.2 Prediction of Tire/Pavement Noise

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

Equation 5.2 shows that the overall OBSI is statistically significantly affected by pavement age, mix type, surface layer thickness, and the presence of raveling distress. Environmental and traffic variables seem to have no significant effect. However, the raveling model (Equation 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 5.2 includes the mix type, surface layer thickness, the presence of raveling and rutting in the independent variable list. To apply this model, the surface layer thickness is assumed as 60 mm, 30 mm, 40 mm, and 30 mm for DGAC, OGAC, RAC-G, and RAC-O mix, 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 4.3.

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 102.4 dB(A).

The estimated ages for open- and gap-graded mixes are shown in Table 8.3 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 no significant 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. This effect, however, 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 4.3) used here does not fit the raveling data well (the coefficient of determination, R^2, is only 0.31) because of the limited amount of raveling data and the large variability in the data.

To exclude the use of pavement distresses as the independent variable for tire/pavement noise prediction, the second model (Equation 5.3 through Equation 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, NMAS, 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 as used in the first model, and the same values of traffic and environmental variables as used in Section 8.1 are used here. Both permeability and MPD change with pavement age. They are estimated from regression models developed previously (Equation 8 in the report on the first two years of this study (2) for permeability, and Equation 3.1 for MPD). The estimated ages for open- and gap-graded mixes are shown in Table 8.4.

Table 8.3: 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	–	6	3	>10
	Moderate Rainfall/ Low Temperature	–	6	3	>10
	High Rainfall/ Moderate Temperature	–	6	3	>10
	Moderate Rainfall/ Moderate Temperature	–	6	3	>10
Low Traffic (TI=9)	Low Rainfall/ High Temperature	–	7	4	>10
	Moderate Rainfall/ Low Temperature	–	7	4	>10
	High Rainfall/ Moderate Temperature	–	7	4	>10
	Moderate Rainfall/ Moderate Temperature	–	7	4	>10

Note: 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.

Table 8.4: 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	7	>>10
	Moderate Rainfall/ Low Temperature	–	>10	10	>>10
	High Rainfall /Moderate Temperature	–	>10	9	>>10
	Moderate Rainfall/ Moderate Temperature	–	>10	9	>>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: 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.

It can be seen from Table 8.4 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 various mixes (OGAC, RAC-G, and RAC-O) , but not significantly different for various traffic and environmental conditions. The relative rank of the three mixes remains the same as in the first model and is consistent with the observations in Chapter 5, that is, RAC-O mixes remain quieter, with respect to the tire/pavement noise of DGAC mixes, longer than OGAC mixes, and OGAC mixes remain quieter than DGAC mixes longer than do RAC-G mixes. The lifetime of RAC-O is over 14 years under various traffic and climate conditions. This conclusion has to be interpreted carefully because it is extrapolated from RAC-O pavement sections that are less than 10 years old. In the data set, only two RAC-O sections are between eight and ten years old, and all the other RAC-O sections are less than seven years old. The estimated parameters of the regression model, therefore, were heavily weighted on the young RAC-O sections.

It must be emphasized that the pavement life for open- and gap-graded mixes in terms of noise reduction in this section is defined as the time for the OBSI to reach the level of a typical DGAC pavement with an age of one to three years. The values in Table 8.3 and Table 8.4 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 3 dB(A)] that can be detected by human ears.

8.3 Prediction of Pavement Distresses

In Chapter 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 do not fit the data well. The coefficient of determination, R^2, is generally smaller than 0.50. This section will use these models to give an indication of how soon bleeding, raveling, and transverse/reflective cracking will occur on various asphalt surface mixes.

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

Equation 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 DGAC, OGAC, RAC-G, and RAC-O mix, respectively. Environmental and traffic variables use the same values as in Section 8.1.

Table 8.5 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. Among the four climate combinations, bleeding occurs earlier in regions with higher temperatures (inland areas).

Table 8.5: 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	>10	10	5	10
	Moderate Rainfall/ Low Temperature	>10	>10	6	>10
	High Rainfall/ Moderate Temperature	>10	10	5	>10
	Moderate Rainfall/ Moderate Temperature	10	9	4	9
Low Traffic (TI=9)	Low Rainfall/ High Temperature	>>10	>10	8	>10
	Moderate Rainfall/ Low Temperature	>>10	>>10	9	>>10
	High Rainfall/ Moderate Temperature	>>10	>10	8	>10
	Moderate Rainfall/ Moderate Temperature	>10	>10	7	>10

Note: 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.

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

Table 8.6 shows the estimated ages to occurrence of raveling for different mixes. Here the occurrence of raveling is defined as five percent of 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.

Table 8.6: 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	>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: 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.

Equation 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 is assumed as 60 mm, 30 mm, 40 mm, and 30 mm for DGAC, OGAC, RAC-G, and RAC-O mix, respectively. Environmental and traffic variables use the same values as in Section 8.1. It is 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 8.7 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 8.7 also shows that transverse/reflective cracking occurs earlier in rubberized mixes than in nonrubberized mixes. As discussed in Section 4.3.1, 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 8.7: Predicted Age 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	4	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	10	6	7
	Moderate Rainfall/ Low Temperature	4	5	2	3
	High Rainfall/ Moderate Temperature	6	8	4	5
	Moderate Rainfall/ Moderate Temperature	5	7	4	5

Note: 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.

8.4 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-rubberzied 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. This reinforces what was seen in the two-year noise study (2): that permeability and friction do not control the mix performance life either. For RAC-G mixes, the controlling performance indices include noise and the occurrence of bleeding and transverse/reflective cracking. For RAC-G mixes, the controlling performance index is the occurrence of transverse/reflective cracking.

9 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, more durable pavement surfaces.

This study compares three 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 three-years of data were analyzed in this report with the following objectives:

1. Evaluate the durability and effectiveness of the OGAC, RAC-O, and RAC-G asphalt mix types in reducing noise, as measured with On-board Sound Intensity (OBSI).
2. Evaluate the pavement characteristics that affect tire/pavement noise.
3. Evaluate the changes in the following pavement performance parameters over time and 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

This report presents interim results that will be finalized after collection and analysis of the fourth-year data (which will be pooled with data from the first three years). The fourth-year data will be collected in the year 2009.

9.1 Performance of Open-Graded Mixes

Newly paved OGAC and RAC-O open-graded mixes had lower noise than the average level of DGAC mixes by 2.5 dB(A) and 3.1 dB(A), respectively. For comparison, the average tire/pavement noise level on DGAC pavements is approximately 101.3 dB(A) for newly paved overlays, 102.4 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 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 DGAC longer than is OGAC.

For newly paved overlays, open-graded mixes have higher low-frequency noise and lower high-frequency noise than DGAC mixes. In the first three years after the open-graded mixes are exposed to traffic, high-frequency noise increases with age due to the reduction of air-void content under traffic, while low-frequency noise decreases with age, likely due to the reduction of surface roughness caused by further compaction under traffic. These opposing changes leave the overall sound intensity nearly unchanged. For open-graded pavements older than three years, noise in the frequencies between 500 and 2,500 Hz increases with age, while noise in the frequencies over 2500 Hz changes slightly or even diminishes with age.

Among the two open-graded mixes, MPD has lower initial values and increases 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 increases noise on OGAC pavements, but does not significantly affect noise on RAC-O pavements.

Based on the condition survey for pavements less than ten 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 the 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 no major difference in pavement distresses between OGAC and RAC-O mixes.

9.2 Performance of RAC-G Mixes

The newly paved RAC-G mixes are quieter than an average DGAC mix by about 1.6 dB(A). Within a few years after the pavements are exposed to traffic, the tire/pavement noise on RAC-G mixes approaches the average noise level of DGAC pavements of similar ages. Among newly paved overlays, RAC-G mixes have higher low frequency noise and lower high frequency noise than DGAC mixes. In the first three years after the pavements are exposed to traffic, high frequency noise increases with age due to the reduction of air-void content under traffic, while low frequency noise is nearly unchanged with age. For RAC-G pavements older than three years, noise of all frequencies increases with age.

The IRI value on newly paved RAC-G mixes is lower than that on DGAC mixes and it does not increase with age, unlike the IRI on DGAC pavements, which increases with age. RAC-G mixes have a permeability level as high as that of open-graded mixes in the first three years after construction, but under traffic the permeability decreases 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 ten 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 nonrubberized 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. No other significant difference was observed between RAC-G and DGAC mixes in terms of pavement distresses.

9.3 Variables Affecting Tire/Pavement Noise

The findings from this third year of the study regarding variables affecting tire/pavement noise are generally consistent with the findings from analysis of the two-year data (2). 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 DGAC, RAC-G, and RAC-O pavements, the aggregate gradation variable (fineness modulus) does not seem to significantly affect tire/pavement noise. For OGAC pavements, however, a coarser gradation seems to significantly reduce 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.

At frequencies below 1,000 Hz, the aggregate gradation variable (fineness modulus) does not significantly affect the noise level for all pavements.

At frequencies above 1,000 Hz, higher macrotexture (MPD) values seem to significantly reduce the noise level on RAC-O mixes. On the other hand, higher macrotexture values increase the noise level on gap-graded mixes.

9.4 Performance of Experimental Mixes

The bituminous wearing course (BWC) mix placed on the LA 138 sections has 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 tested for the first time in the third year are similar to or lower 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:

- RUMAC-GG performed similarly to RAC-G in terms of tire/pavement noise and ride quality when placed in a thin (45 mm) or a thick (90 mm) lifts. However, RUMAC-GG was more crack resistant than RAC-G when placed in a thick lift (90 mm).
- Although the Type G-MB mix has higher noise levels than the RAC-G mix soon after construction, the increase in noise with age is less significant on the Type G-MB mix than on the RAC-G mix and the Type D-MB mix.
- The Type G-MB mix is more susceptible to bleeding than other mixes.
- The Type D-MB mix is more resistant to cracking than the DGAC mix but it is also more susceptible to bleeding.
- The Type D-MB mix has a noise level similar to the DGAC mix soon after construction, but its noise level increases 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) had noise levels as high as those of the DGAC mix.

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

Old concrete surfaces with burlap drag and longitudinally tined surface textures that were then retextured with Skidabrader technology showed slight decreases in noise of -0.5 and -0.1 dB(A), respectively. The results showed increases in noise on OGAC and DGAC surfaces that were similarly retextured of 1.3 and 0.8 dB(A), respectively.

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APPENDICES

A.1: List of Test Sections Included in the Study

A.1.1: List of Quiet Pavement (QP) Sections

Mix Type	Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	AADT on the Coring Lane	Rainfall Since Construction (mm)
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	1,002
			Low	NA		–	–	–
		Low	High	03-Yol-80-0.0/0.4	QP-45	<1	20,833	867
			Low	05-SCR-152-7.6/8.0	QP-20	<1	3,050	1,214
	1 to 4 years old	High	High	04-Mrn-101-0.0/2.5	QP-28	4	13,625	758
			Low	04-Son-121-3.4/7.3	QP-4	4	8,230	760
		Low	High	04-SCl-237-R3.8/7.10	QP-23	5	15,639	407
			Low	08-SBd-38-S0.0/R5.0	QP-13	5	4,733	253
	5 to 8 years old	High	High	04-Mrn-37-12.1/14.4	QP-3	5	8,482	436
			Low	01-MEN-1-0.1/15.2	01-N103 01-N104 01-N105	5	1,450	968
		Low	High	04-SCl-237-R1.0/2.3	QP-22	8	15,148	414
			Low	03-Sac-16-6.9/20.7	QP-29	8	6,367	483

Mix Type	Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	AADT on the Coring Lane	Rainfall Since Construction (mm)
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	834
			Low	01-MEN-20-R37.9/43.0	QP-41	<1	5,200	2,099
				01-LAK-29-R37.3/R37.6	QP-42	<1	5,850	1,093
		Low	High	06-TUL-99-42.0/47.0	QP-35	<1	10,400	402
			Low	06-TUL-63-19.8/R30.1	QP-34	<1	3,325	442
	1to 4 years old	High	High	03-Sac-50-16.10/17.30	QP-8	5	17,694	523
			Low	10-Ama-49-14.7/17.6	QP-17	3	4,060	876
		Low	High	07-LA-710-6.8/9.7	QP-1	3	19,208	417
				04-CC-680-23.9/24.9	QP-36	3	17,107	507
			Low	06-Tul-65-21/29	06-N466 06-N467 06-N468	3	4,919	293
	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	886
		Low	High	04-SCl-85-1.9/4.7	QP-24	8	16,986	496
			Low	08-SBD-58-R0.0/5.3	QP-12	5	6,497	183

Mix Type	Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	AADT on the Coring Lane	Rainfall Since Construction (mm)
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	2,105
		Low	High	04-SCl-280-R0.0/R2.7	QP-26	<1	25,667	582
			Low	06-TUL-63-19.8/R30.1	QP-33	<1	4,800	442
	1 to 4 years old	High	High	04-Mrn-101-18.9/23.1	QP-2	4	2,100	535
			Low	04-Son-1-0.0/8.4	QP-31	5	2,250	956
		Low	High	08-Riv-15-33.8/38.4	QP-14	5	19,528	252
			Low	05-SLO-46-R10.8/R22.0	QP-19	4.5	3,233	405
	5 to 8 years old	High	High	04-Mrn-101-2.5/8.5	QP-5	9	20,925	270
			Low	10-Cal-4-0/18.8	QP-18	6	2,211	880
		Low	High	11-SD-8-0.8/1.9	QP-46	6	26,607	321
			Low	07-Ven-34-4.3/6.3	QP-10	5	8,007	395

Mix Type	Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	AADT on the Coring Lane	Rainfall Since Construction (mm)
Dense-Graded Asphalt Concrete (DGAC)	Less than 1 year old	High	High	03-Pla-80-14.3/33.3	QP-27	<1	8,333	298
			Low	01-MEN-20-R37.9/43.0	QP-40	<1	5,200	2,105
		Low	High	06-FRE-99-10.7/15.9	QP-6	<1	15,500	493
			Low	07-LA-138-60.2/61.6	QP-15	<1	7,750	247
	1 to 4 years old	High	High	03-ED-50-17.3/18.3	QP-21	3	12,969	1,431
			Low	03-ED-50-18.5/20.3	QP-30	4	6,385	1,137
		Low	High	06-KER-99 29.5/31.0	QP-7	5	10,417	158
			Low	04-SOL-113-0.1/18.0	QP-43	1	2,750	513
	5 to 8 years old	High	High	04-SM-280-9.6/10.8	QP-9	5	10,986	531
			Low	01-Men-1-20.8/38.7	01-N114	7	813	954
					01-N121	7	581	954
		Low	High	04-Ala-92-6.6/8.8	QP-16	14	6,744	437
			Low	06-KER-65-R0.0/2.9	06-N434	6	3,107	144
					06-N436	6	4,950	144
				07-LA-60 R25.4/R30.5	QP-11	7	29,818	371
				04-CC-680-23.9/24.9	QP-25	8	18,071	308

Mix Type		Age	Rainfall Category	Traffic Volume (AADT)	DIST/CTY/RTE/PM	Site ID	Age at First Year of Collection	AADT on the Coring Lane	Rainfall Since Construction (mm)
F-mixes	RAC Binder	Less than 1 year old	High	Low	01-Men-101-37.4/38.8	QP-52	1	4,000	1,679
		1 to 4 years old	High	Low	01-Men-101-50.8/ 51.5	QP-47	3	5,081	1,426
					01-HUM-101-111.1/111.5	QP-50	4	2,130	1,183
	Conventional Binder	5 to 8 years old	High	Low	01-Men-20-21.19/21.69	QP-48	8	1,289	1,187
					01-Men-20-22.18 /22.68	QP-49	8	1,289	1,187

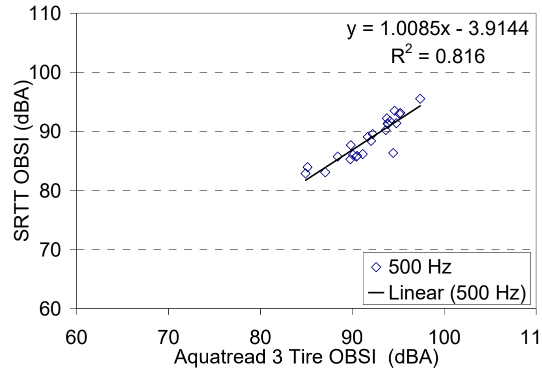
A.1.2 List of Caltrans Environmental Noise Monitoring Site (ES) Sections

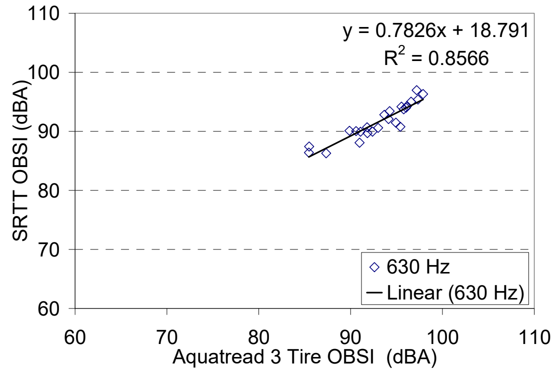
Site Name	Site Location	Mix Types, Design Thicknesses	Construction Date
Los Angeles 138 (LA 138)	07-LA-138/PM 16.0-21.0	OGAC, 75 mm OGAC, 30 mm RAC-O, 30 mm BWC, 30 mm DGAC, 30 mm	Spring 2002
Los Angeles 19 (LA 19)	07-LA-19/ PM 3.4	European gap-graded, 30 mm	May 2005
Yolo 80	03-Yolo-80/PM 2.9-5.8	OGAC, 20 mm	Summer 1998
Fresno 33 (Fre 33)	06-Fre-33/PM 70.9-75.08	RAC-G, 45 mm RAC-G, 90 mm RUMAC-GG, 45 mm RUMAC-GG, 90 mm Type G-MB, 45 mm Type G-MB, 90 mm Type D-MB, 45 mm Type D-MB, 90 mm DGAC, 90 mm	Summer 2004
San Mateo 280 (SM 280)	04-SM-280/PM R0.0-R5.6	RAC-O, 45 mm	Fall 2002
Sacramento 5 (Sac 5)	03-Sac-5/PM 17.2-17.9 North and Southbound directions	RAC-O, 30 mm	Summer 2004

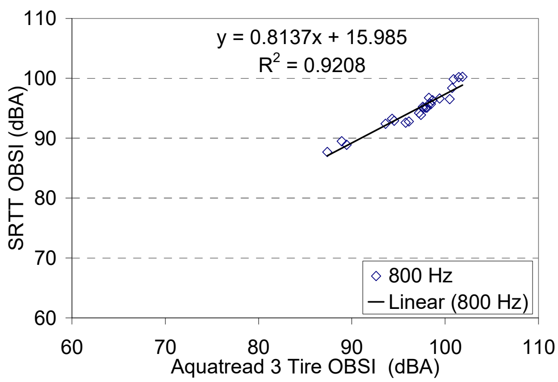
OGAC: Open-graded asphalt concrete
RAC-O: Rubberized open-graded asphalt concrete
BWC: Bonded wearing course
RAC-G: Rubberized gap-graded asphalt concrete (wet process)
RUMAC-GG: Rubber-modified asphalt concrete (dry process, a local-government specification)
Type D-MB: Dense-graded rubberized asphalt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

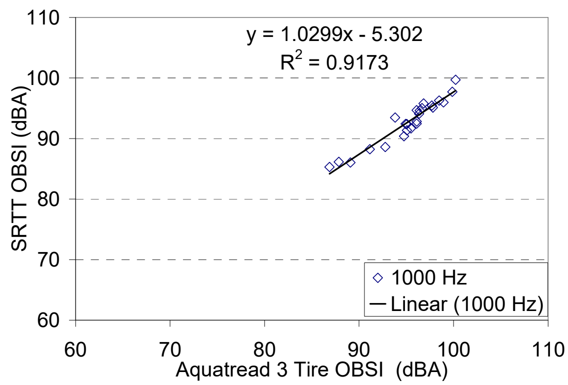
A.2: Correlation Between Aquatred 3 Tire OBSI and SRTT OBSI

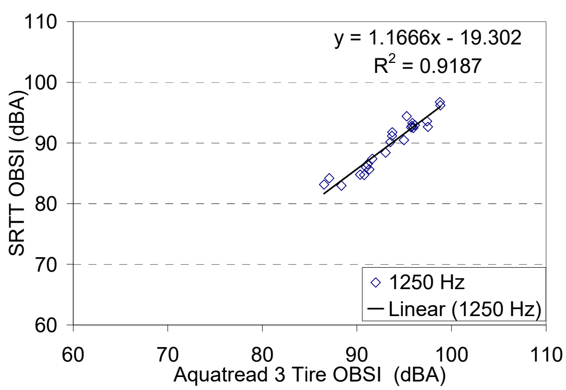
A.2.1 Plots of Aquatred 3 Tire OBSI versus SRTT OBSI

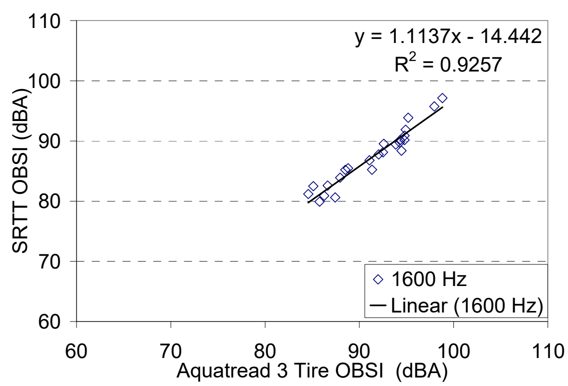


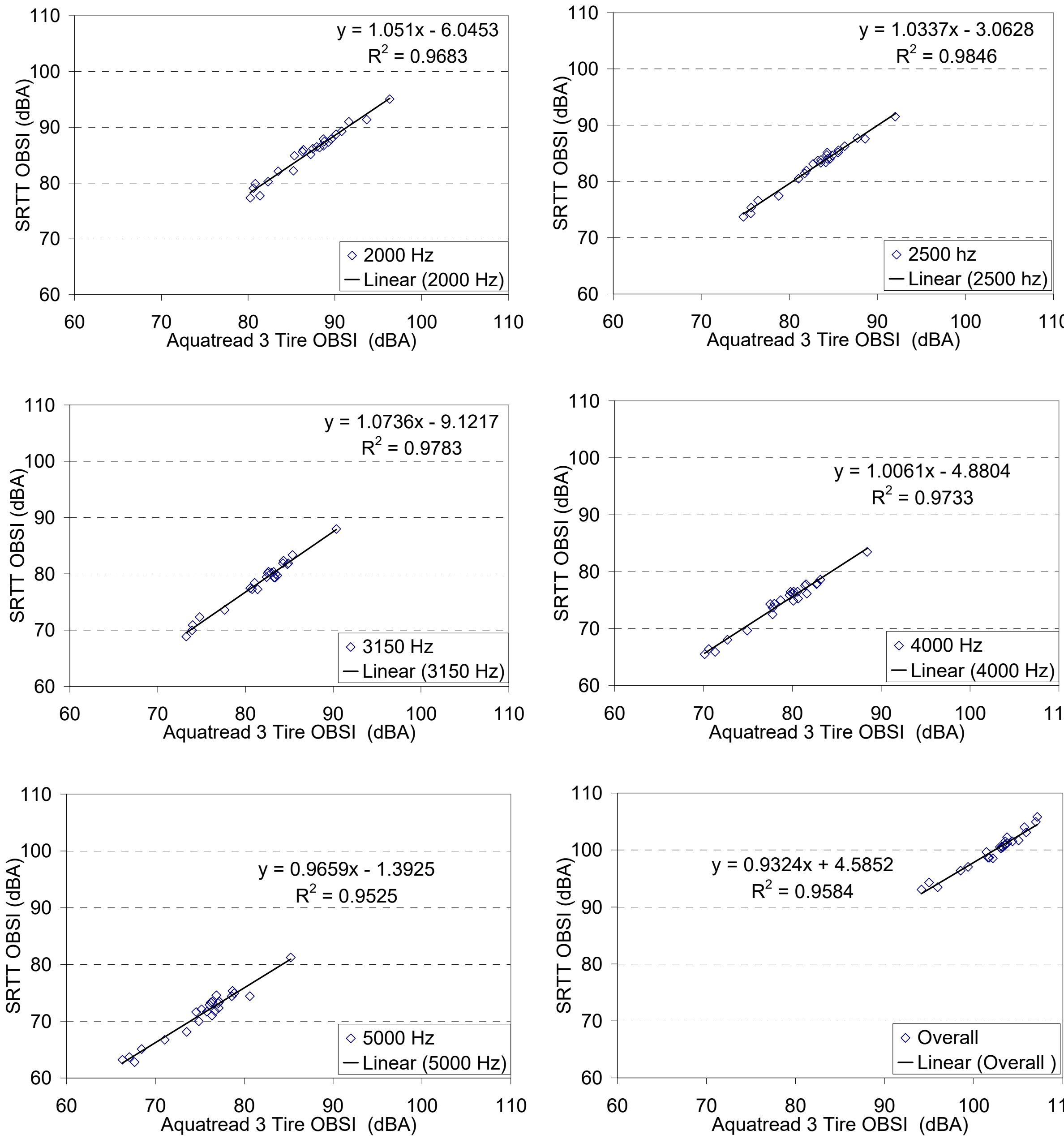











y = 1.051x - 6.0453
R2 = 0.9683
2000 Hz
Linear (2000 Hz)
SRTT OBSI (dBA)
Aquatread 3 Tire OBSI (dBA)
y = 1.0337x - 3.0628
R2 = 0.9846
2500 hz
Linear (2500 hz)
y = 1.0736x - 9.1217
R2 = 0.9783
3150 Hz
Linear (3150 Hz)
y = 1.0061x - 4.8804
R2 = 0.9733
4000 Hz
Linear (4000 Hz)
y = 0.9659x - 1.3925
R2 = 0.9525
5000 Hz
Linear (5000 Hz)
y = 0.9324x + 4.5852
R2 = 0.9584
Overall
Linear (Overall)

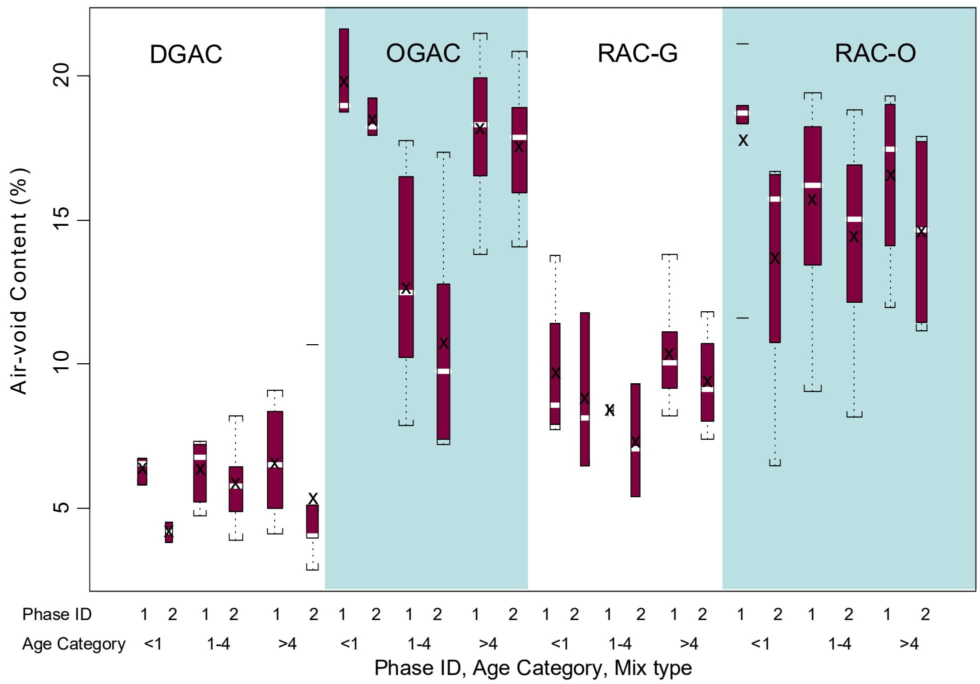
A.2.2 Simple Linear Regression Results

One-Third Octave Band	Slope*	Intercept	R^2
500	1.0085	-3.9144	0.8160
630	0.7826	18.7910	0.8566
800	0.8137	15.9850	0.9208
1,000	1.0299	-5.3020	0.9173
1,250	1.1666	-19.302	0.9187
1,600	1.1137	-14.442	0.9257
2,000	1.0510	-6.0453	0.9683
2,500	1.0337	-3.0628	0.9846
3,150	1.0736	-9.1217	0.9783
4,000	1.0061	-4.8804	0.9733
5,000	0.9659	-1.3925	0.9525
Overall	0.9324	4.5852	0.9584

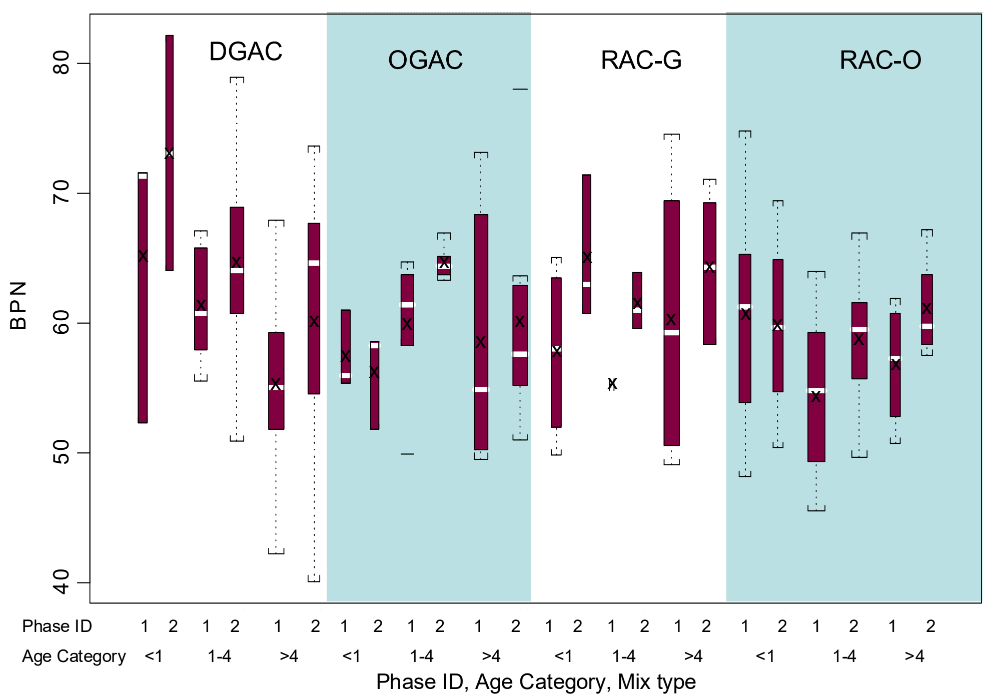
* OBSI(SRTT) = OBSI(Aquatred) × Slope + Intercept

A.3: Box Plots of Air-Void Content, Permeability, and BPN

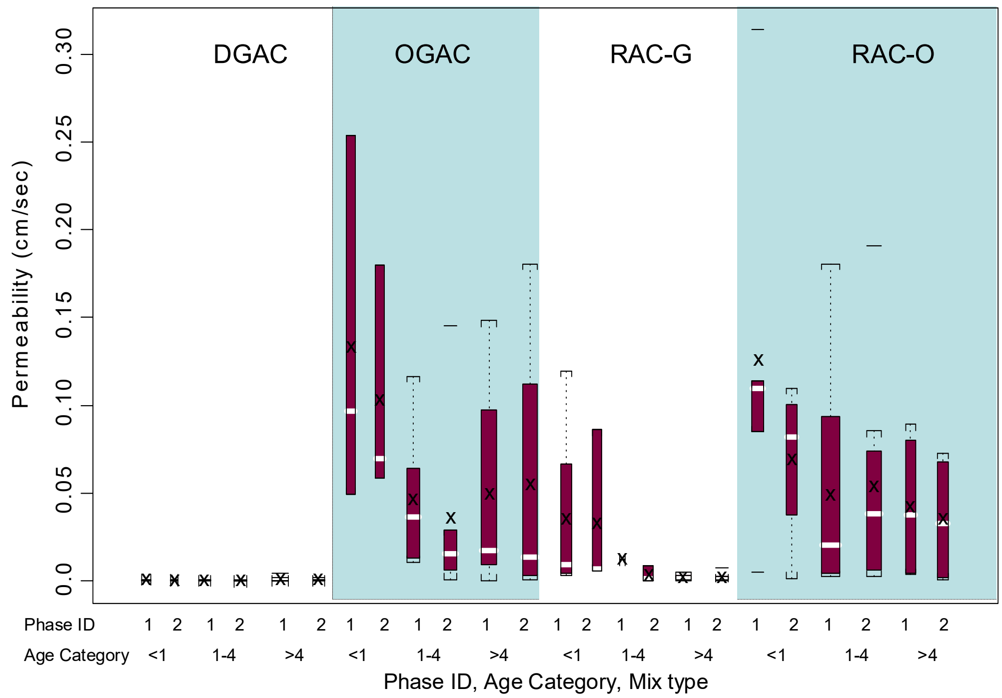
A.3.1 Box Plots of Air-Void Content



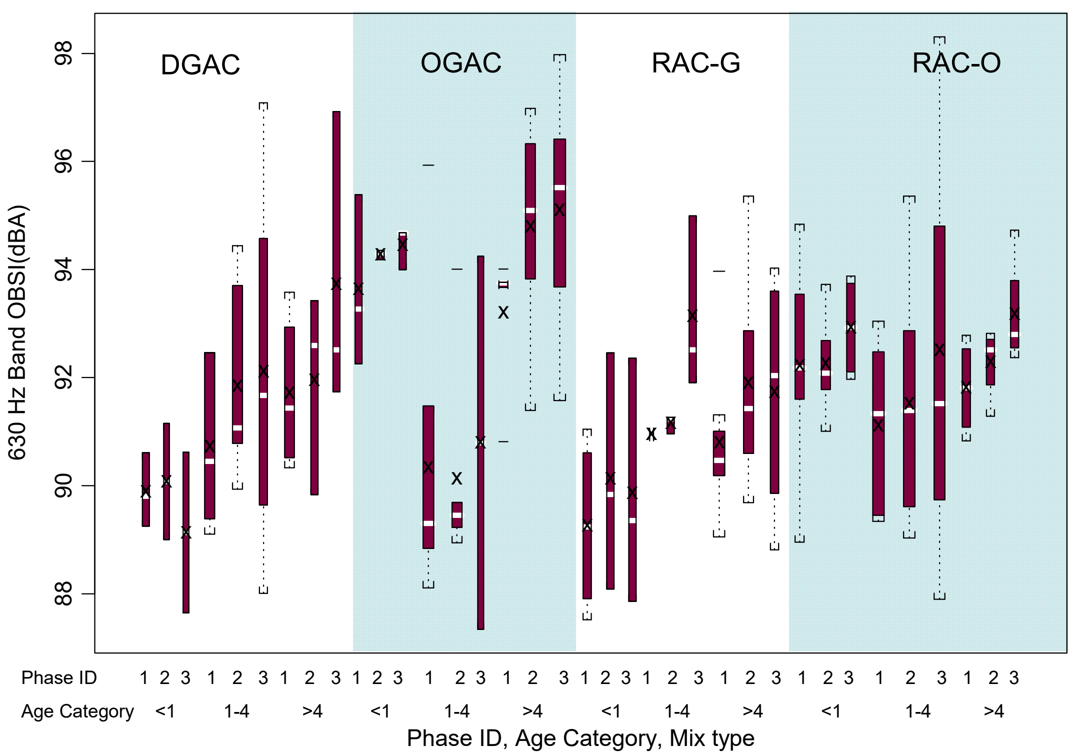
A.3.2 Box Plots of BPN

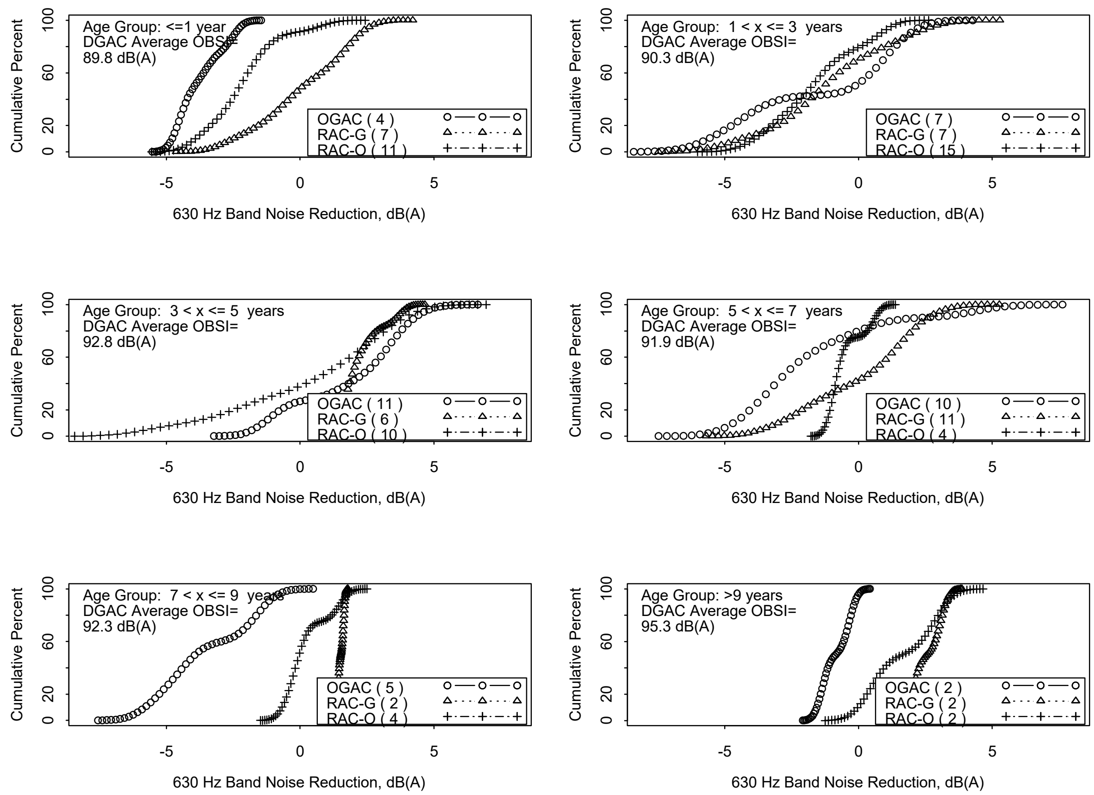


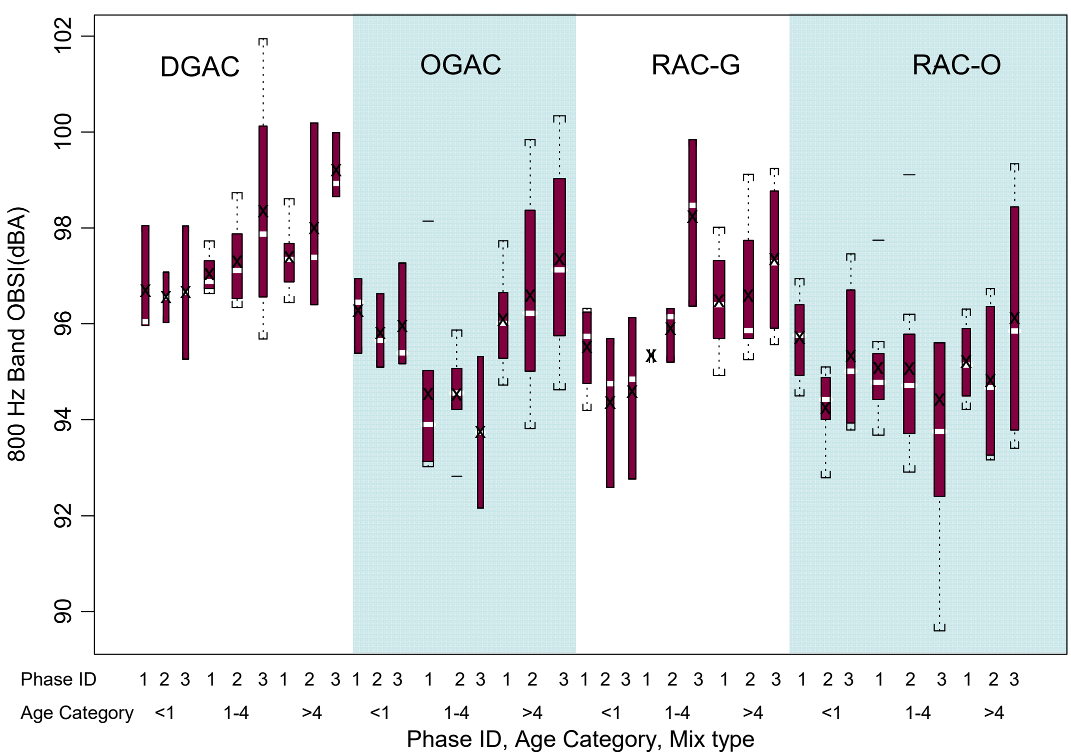
A.3.3 Box Plots of Permeability

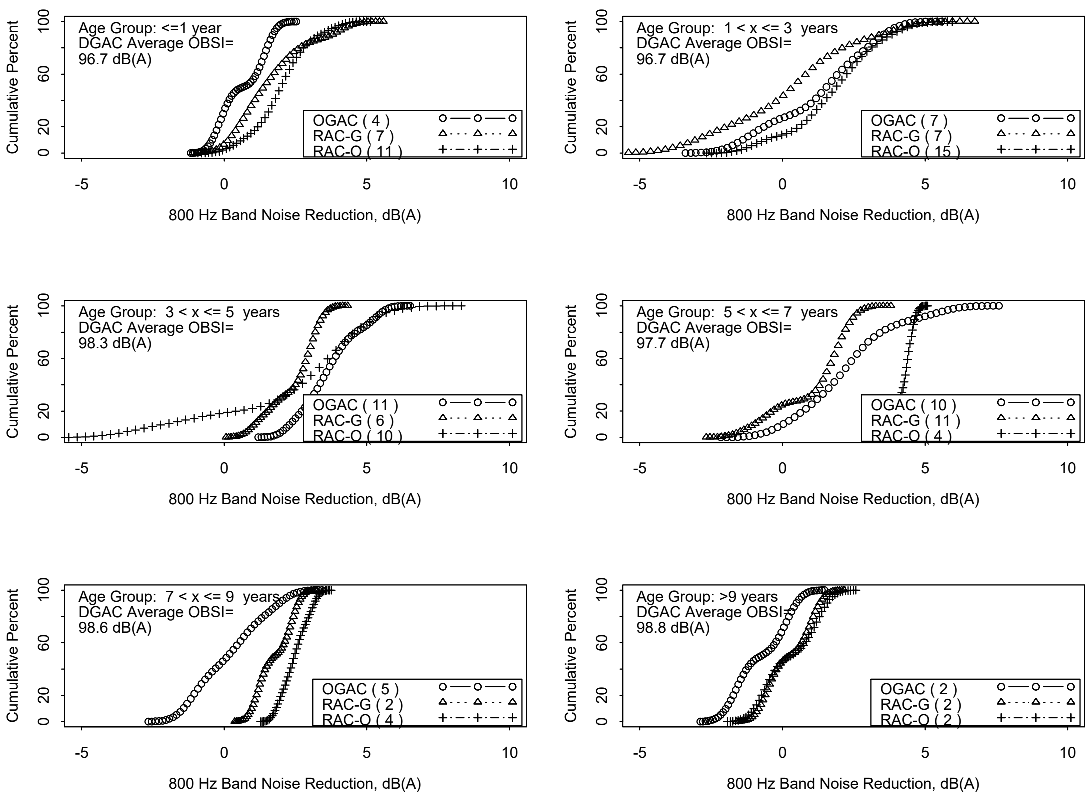


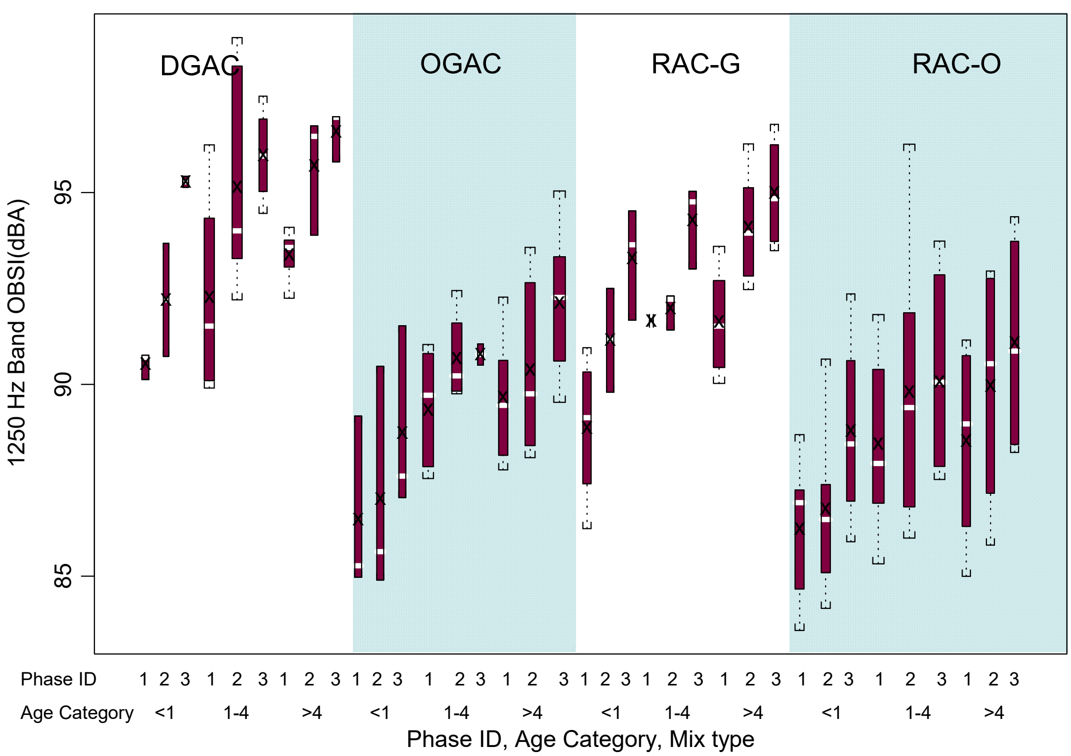
A.4: Boxplots and Cumulative Distribution of Noise Reduction for Sound Intensity at Other Frequency Bands

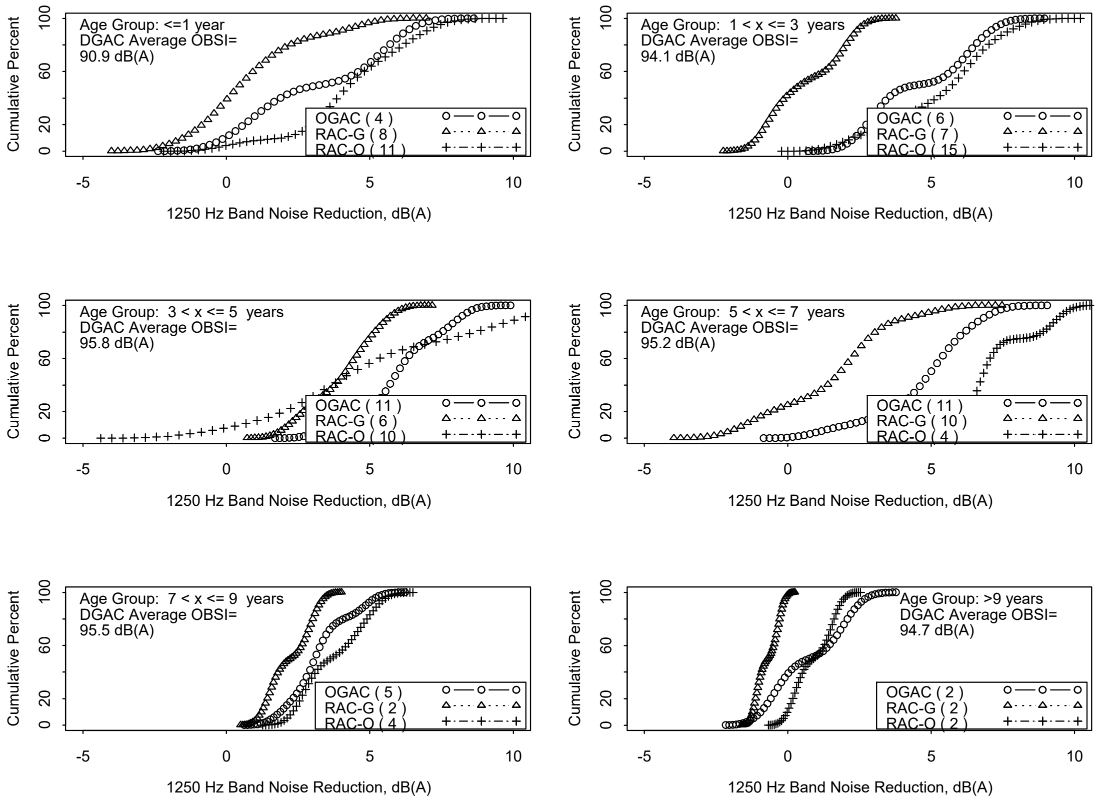


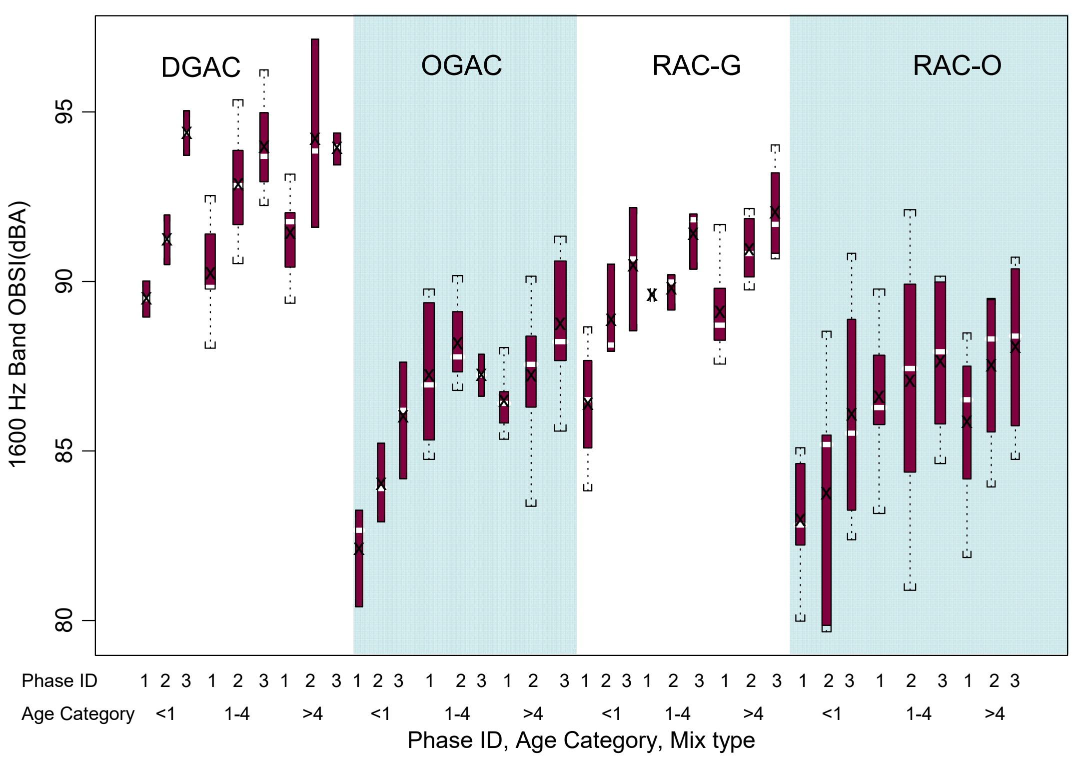

Age Group: <=1 year
DGAC Average OBSI=
89.8 dB(A)
OGAC (4)
RAC-G (7)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
90.3 dB(A)
OGAC (7)
RAC-G (7)
RAC-O (15)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
92.8 dB(A)
OGAC (11)
RAC-G (6)
RAC-O (10)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
91.9 dB(A)
OGAC (10)
RAC-G (11)
RAC-O (4)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
92.3 dB(A)
OGAC (5)
RAC-G (2)
RAC-O (4)
Age Group: >9 years
DGAC Average OBSI=
95.3 dB(A)
OGAC (2)
RAC-G (2)
RAC-O (2)
Cumulative Percent
630 Hz Band Noise Reduction, dB(A)

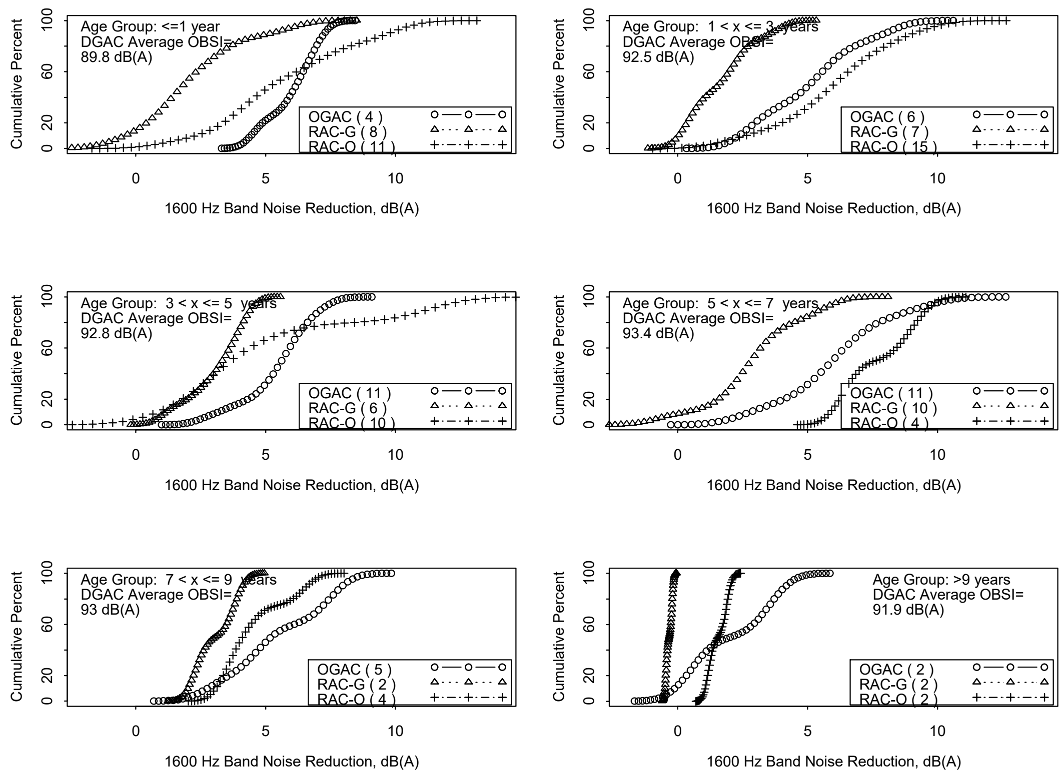

DGAC
OGAC
RAC-G
RAC-O
800 Hz Band OBSI(dBA)
Phase ID
Age Category
<1
1-4
>4
Phase ID, Age Category, Mix type

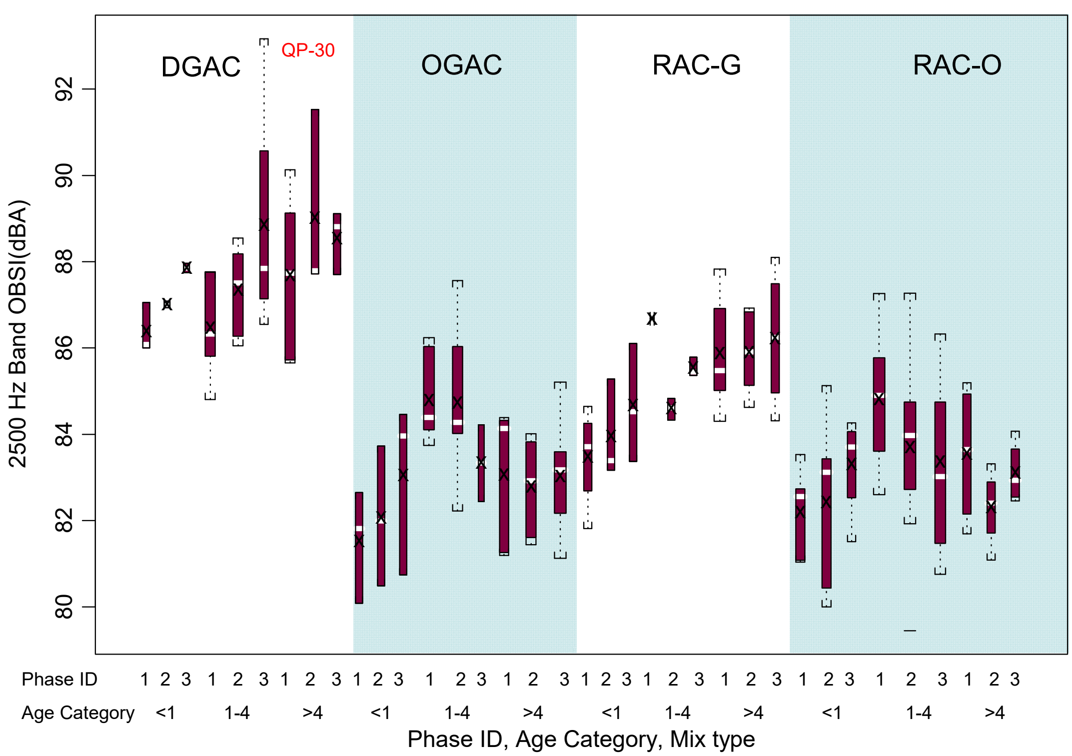

Age Group: <=1 year
DGAC Average OBSI=
96.7 dB(A)
OGAC (4)
RAC-G (7)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
96.7 dB(A)
OGAC (7)
RAC-G (7)
RAC-O (15)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
98.3 dB(A)
OGAC (11)
RAC-G (6)
RAC-O (10)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
97.7 dB(A)
OGAC (10)
RAC-G (11)
RAC-O (4)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
98.6 dB(A)
OGAC (5)
RAC-G (2)
RAC-O (4)
Age Group: >9 years
DGAC Average OBSI=
98.8 dB(A)
OGAC (2)
RAC-G (2)
RAC-O (2)
Cumulative Percent
800 Hz Band Noise Reduction, dB(A)

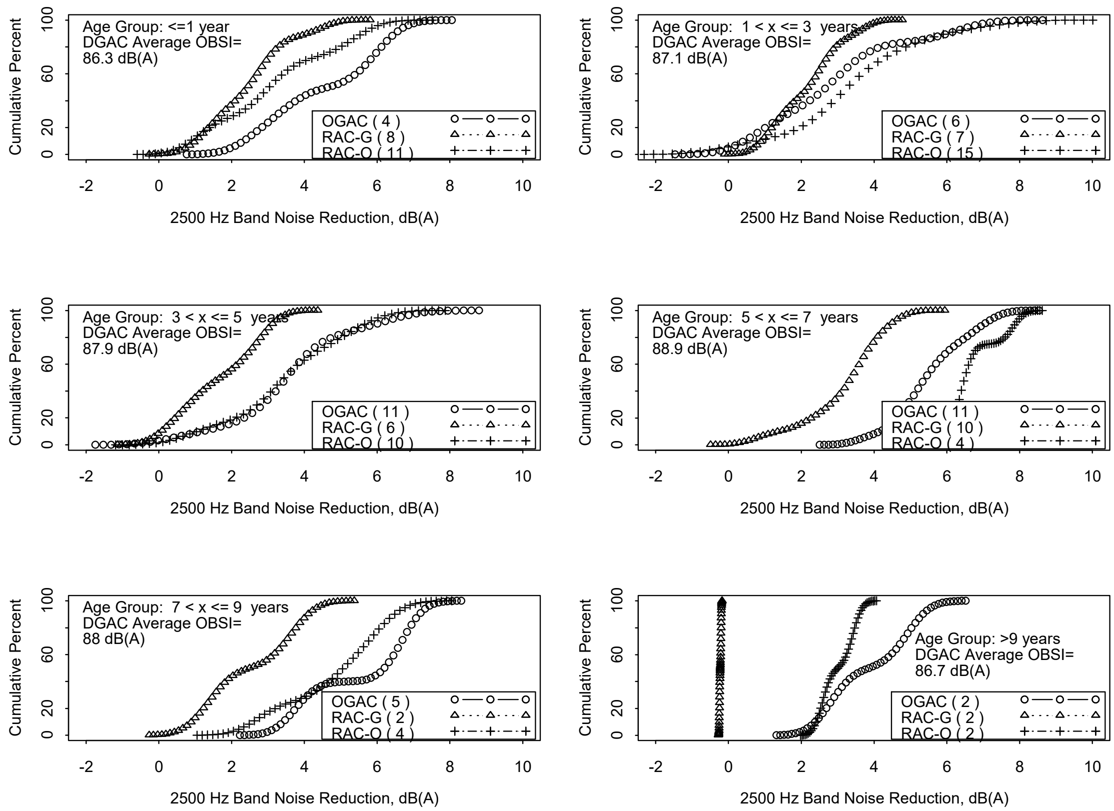

DGAC
OGAC
RAC-G
RAC-O
1250 Hz Band OBSI(dBA)
Phase ID
Age Category
<1
1-4
>4
Phase ID, Age Category, Mix type

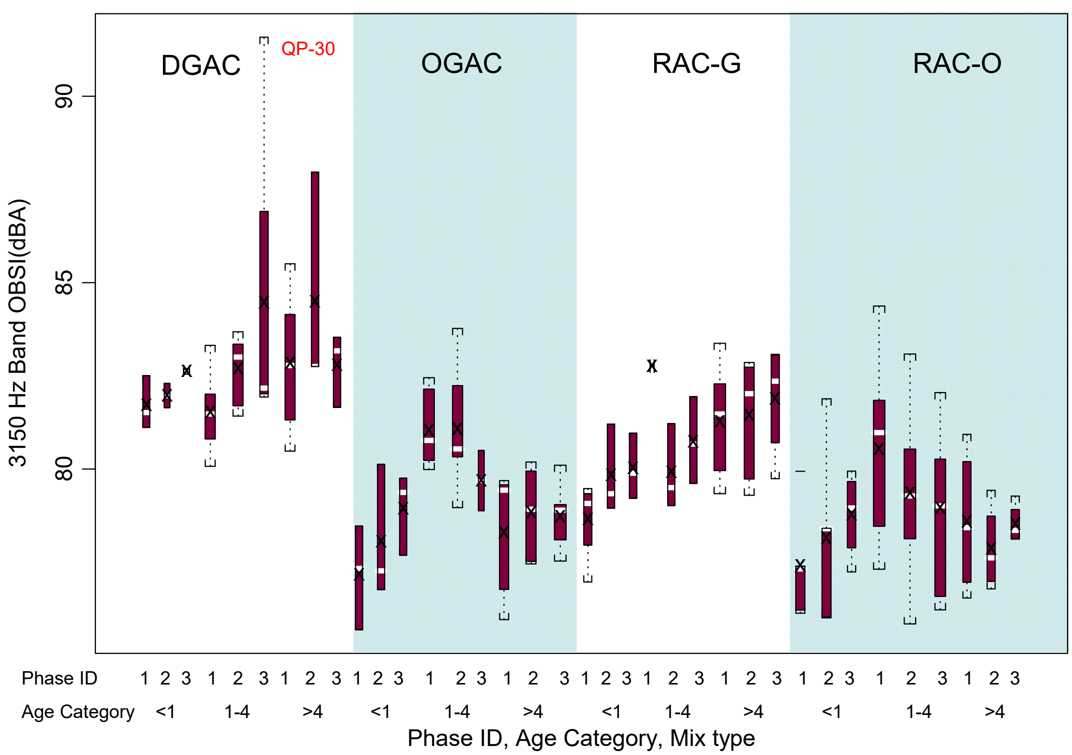

Age Group: <=1 year
DGAC Average OBSI=
90.9 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
94.1 dB(A)
OGAC (6)
RAC-G (7)
RAC-O (15)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
95.8 dB(A)
OGAC (11)
RAC-G (6)
RAC-O (10)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
95.2 dB(A)
OGAC (11)
RAC-G (10)
RAC-O (4)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
95.5 dB(A)
OGAC (5)
RAC-G (2)
RAC-O (4)
Age Group: >9 years
DGAC Average OBSI=
94.7 dB(A)
OGAC (2)
RAC-G (2)
RAC-O (2)
Cumulative Percent
1250 Hz Band Noise Reduction, dB(A)

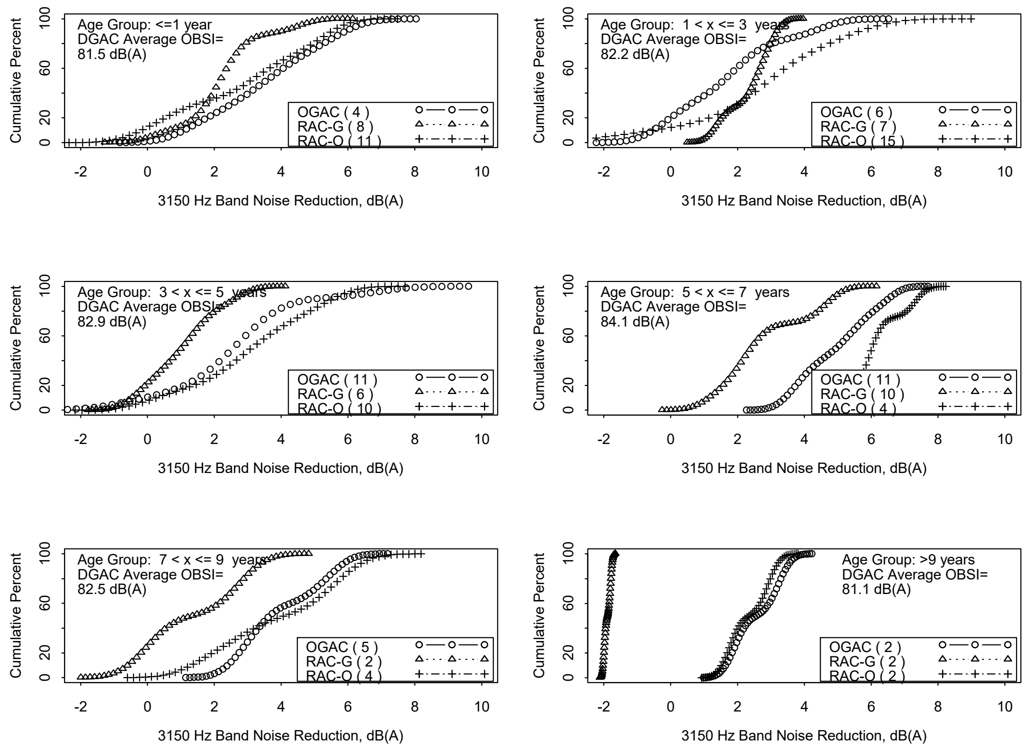

DGAC
OGAC
RAC-G
RAC-O
1600 Hz Band OBSI(dBA)
Phase ID
Age Category
<1
1-4
>4
Phase ID, Age Category, Mix type

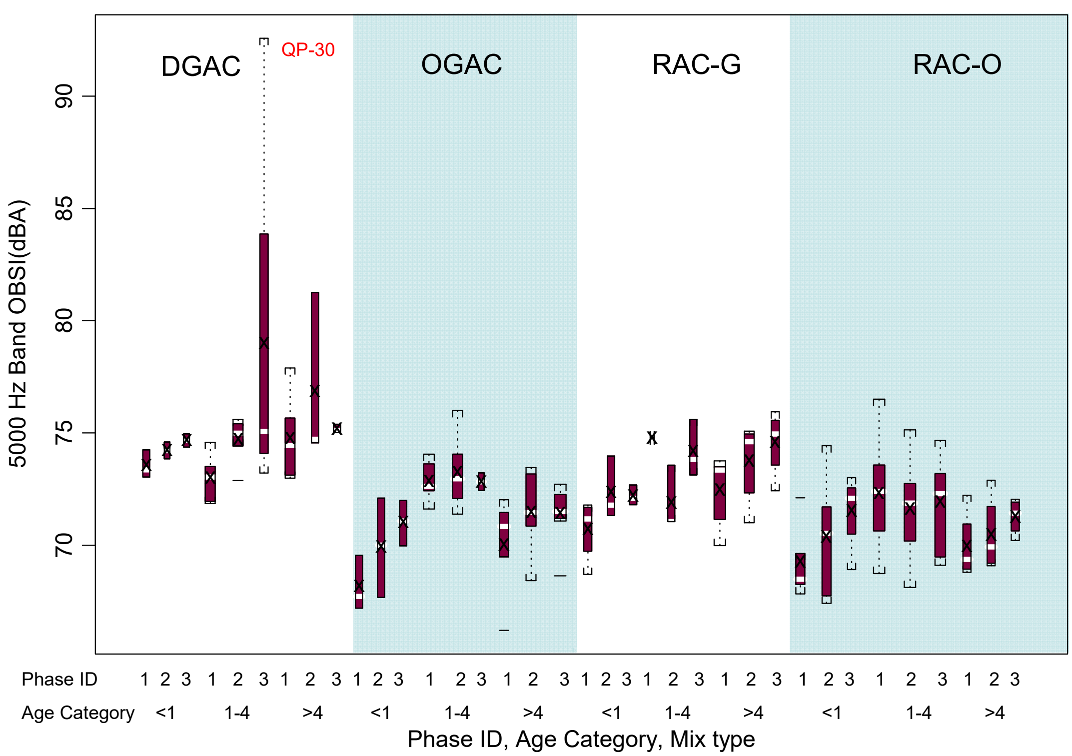

Age Group: <=1 year
DGAC Average OBSI=
89.8 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
92.5 dB(A)
OGAC (6)
RAC-G (7)
RAC-O (15)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
92.8 dB(A)
OGAC (11)
RAC-G (6)
RAC-O (10)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
93.4 dB(A)
OGAC (11)
RAC-G (10)
RAC-O (4)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
93 dB(A)
OGAC (5)
RAC-G (2)
RAC-O (4)
Age Group: >9 years
DGAC Average OBSI=
91.9 dB(A)
OGAC (2)
RAC-G (2)
RAC-O (2)
Cumulative Percent
1600 Hz Band Noise Reduction, dB(A)

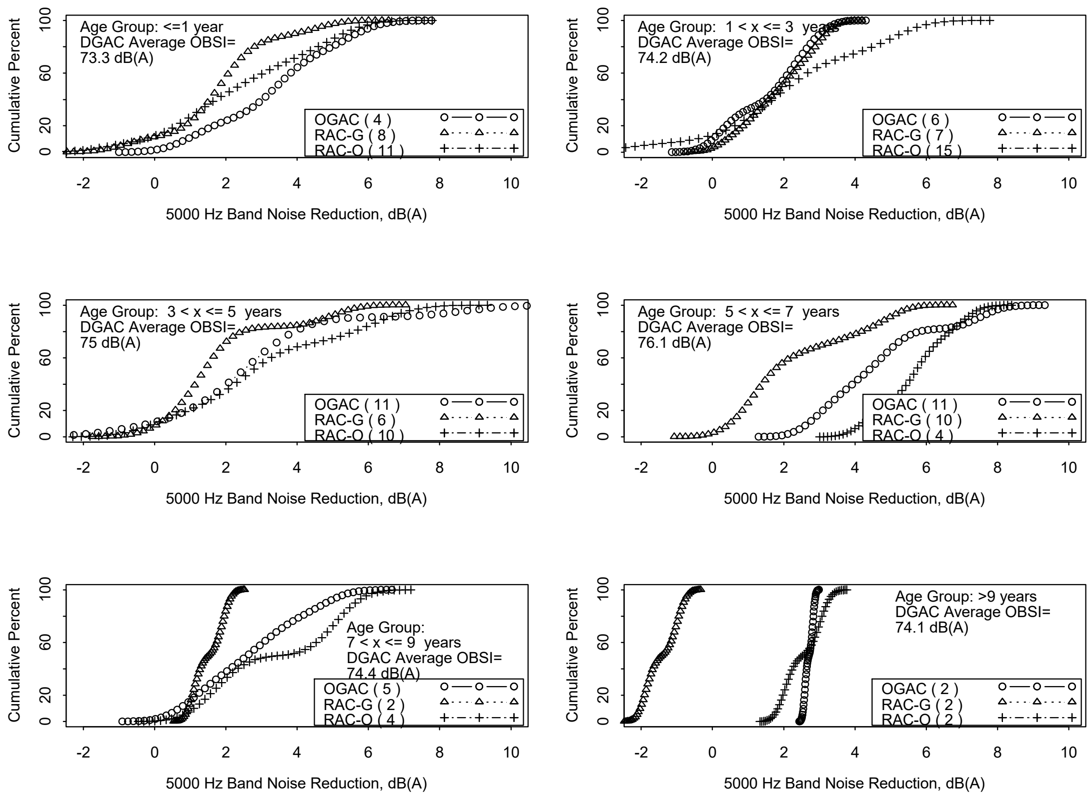

DGAC
QP-30
OGAC
RAC-G
RAC-O
2500 Hz Band OBSI(dBA)
Phase ID
Age Category
<1
1-4
>4
Phase ID, Age Category, Mix type


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=
87.1 dB(A)
OGAC (6)
RAC-G (7)
RAC-O (15)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
87.9 dB(A)
OGAC (11)
RAC-G (6)
RAC-O (10)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
88.9 dB(A)
OGAC (11)
RAC-G (10)
RAC-O (4)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
88 dB(A)
OGAC (5)
RAC-G (2)
RAC-O (4)
Age Group: >9 years
DGAC Average OBSI=
86.7 dB(A)
OGAC (2)
RAC-G (2)
RAC-O (2)
Cumulative Percent
2500 Hz Band Noise Reduction, dB(A)

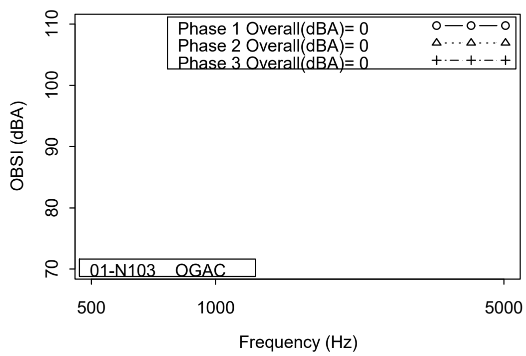

DGAC
QP-30
OGAC
RAC-G
RAC-O
3150 Hz Band OBSI(dBA)
Phase ID
Age Category
<1
1-4
>4
Phase ID, Age Category, Mix type

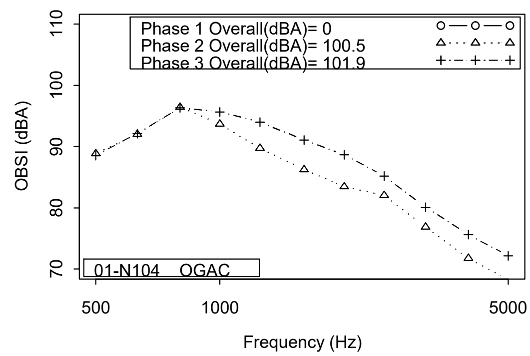

Age Group: <=1 year
DGAC Average OBSI=
81.5 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
82.2 dB(A)
OGAC (6)
RAC-G (7)
RAC-O (15)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
82.9 dB(A)
OGAC (11)
RAC-G (6)
RAC-O (10)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
84.1 dB(A)
OGAC (11)
RAC-G (10)
RAC-O (4)
Age Group: 7 < x <= 9 years
DGAC Average OBSI=
82.5 dB(A)
OGAC (5)
RAC-G (2)
RAC-O (4)
Age Group: >9 years
DGAC Average OBSI=
81.1 dB(A)
OGAC (2)
RAC-G (2)
RAC-O (2)
Cumulative Percent
3150 Hz Band Noise Reduction, dB(A)

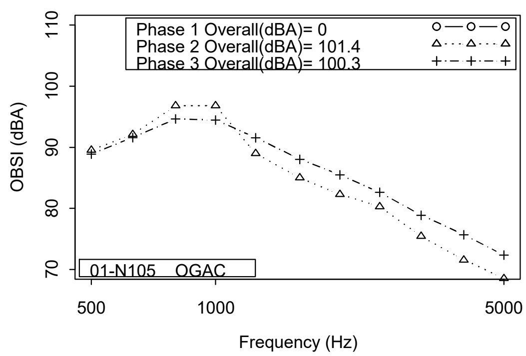

DGAC
QP-30
OGAC
RAC-G
RAC-O
5000 Hz Band OBSI(dBA)
Phase ID
Age Category
<1
1-4
>4
Phase ID, Age Category, Mix type

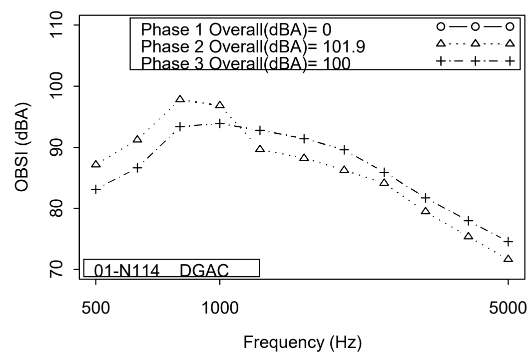

Age Group: <=1 year
DGAC Average OBSI=
73.3 dB(A)
OGAC (4)
RAC-G (8)
RAC-O (11)
Age Group: 1 < x <= 3 years
DGAC Average OBSI=
74.2 dB(A)
OGAC (6)
RAC-G (7)
RAC-O (15)
Age Group: 3 < x <= 5 years
DGAC Average OBSI=
75 dB(A)
OGAC (11)
RAC-G (6)
RAC-O (10)
Age Group: 5 < x <= 7 years
DGAC Average OBSI=
76.1 dB(A)
OGAC (11)
RAC-G (10)
RAC-O (4)
Age Group:
7 < x <= 9 years
DGAC Average OBSI=
74.4 dB(A)
OGAC (5)
RAC-G (2)
RAC-O (4)
Age Group: >9 years
DGAC Average OBSI=
74.1 dB(A)
OGAC (2)
RAC-G (2)
RAC-O (2)
Cumulative Percent
5000 Hz Band Noise Reduction, dB(A)

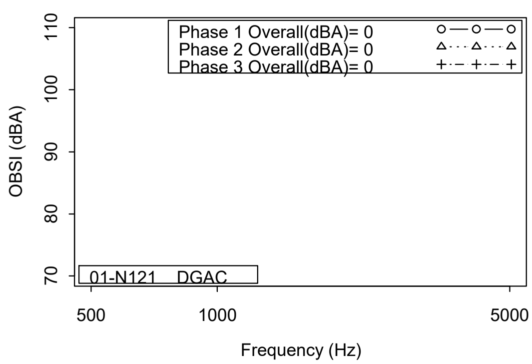
A.5: Sound Intensity Spectra Measured in Three Years for Each Pavement Section

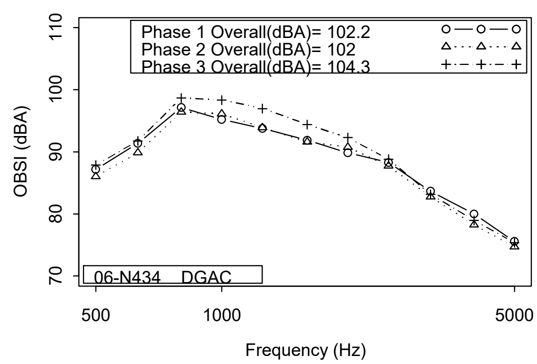

Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
01-N103 OGAC
OBSI (dBA)
Frequency (Hz)

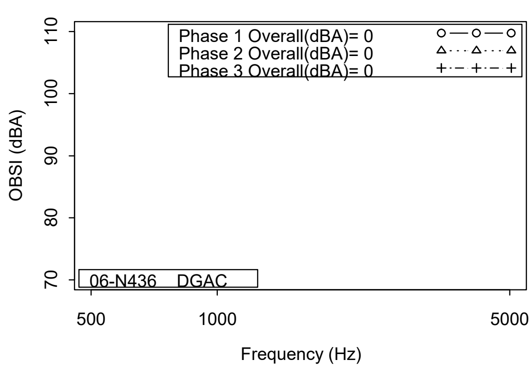

Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 101.9
01-N104 OGAC
OBSI (dBA)
Frequency (Hz)

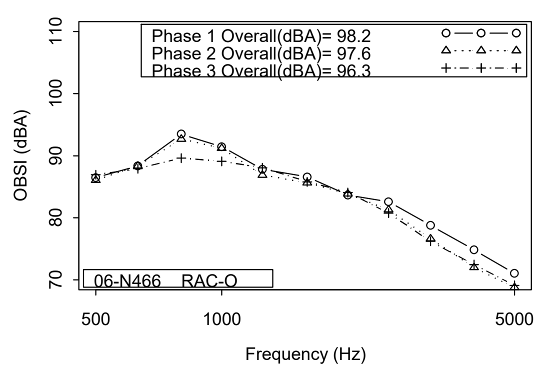

Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 101.4
Phase 3 Overall(dBA)= 100.3
01-N105 OGAC
OBSI (dBA)
Frequency (Hz)

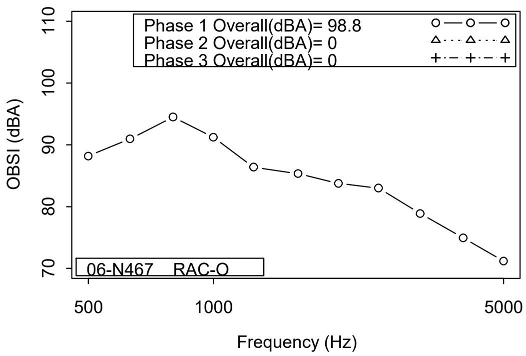

Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 101.9
Phase 3 Overall(dBA)= 100
01-N114 DGAC
OBSI (dBA)
Frequency (Hz)

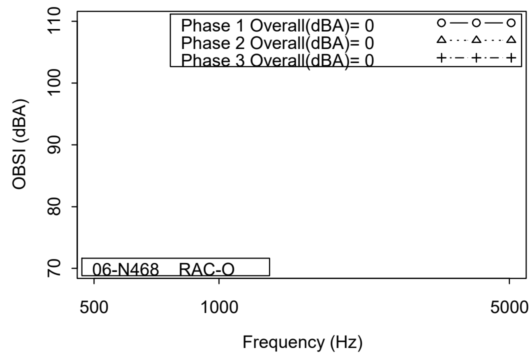

Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
01-N121 DGAC
OBSI (dBA)
Frequency (Hz)

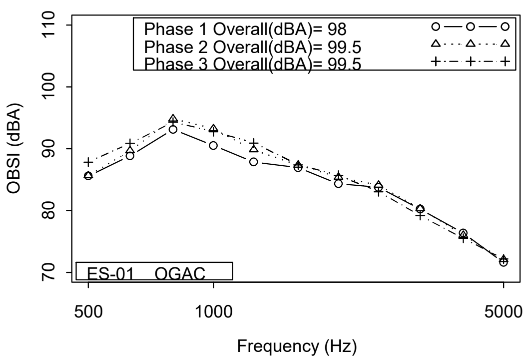

Phase 1 Overall(dBA)= 102.2
Phase 2 Overall(dBA)= 102
Phase 3 Overall(dBA)= 104.3
06-N434 DGAC
OBSI (dBA)
Frequency (Hz)

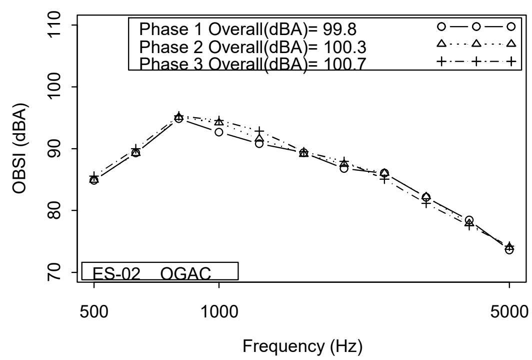

Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
06-N436 DGAC
OBSI (dBA)
Frequency (Hz)

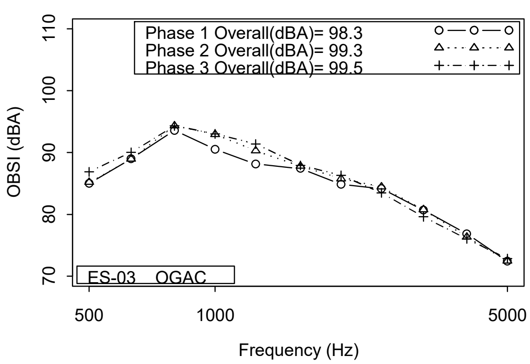

Phase 1 Overall(dBA)= 98.2
Phase 2 Overall(dBA)= 97.6
Phase 3 Overall(dBA)= 96.3
06-N466 RAC-O
OBSI (dBA)
Frequency (Hz)

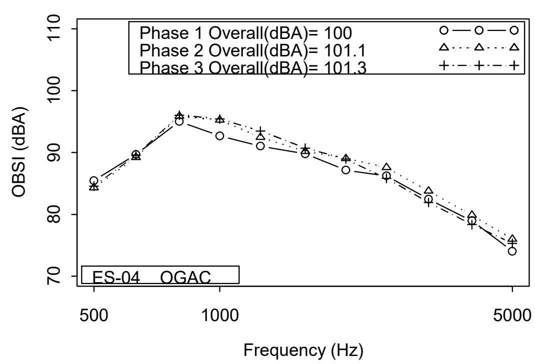

Phase 1 Overall(dBA)= 98.8
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
06-N467 RAC-O
OBSI (dBA)
Frequency (Hz)

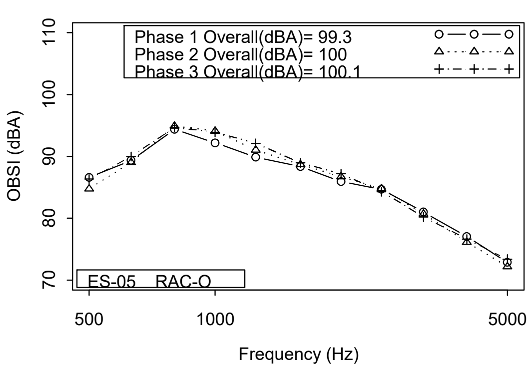

Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
06-N468 RAC-O
OBSI (dBA)
Frequency (Hz)

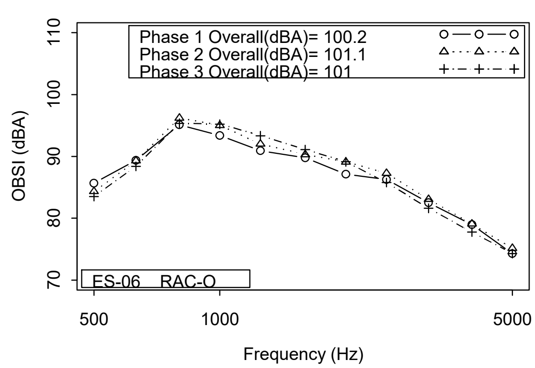

Phase 1 Overall(dBA)= 98
Phase 2 Overall(dBA)= 99.5
Phase 3 Overall(dBA)= 99.5
ES-01 OGAC
OBSI (dBA)
Frequency (Hz)

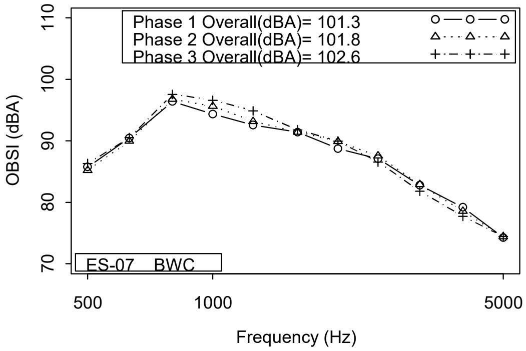

Phase 1 Overall(dBA)= 99.8
Phase 2 Overall(dBA)= 100.3
Phase 3 Overall(dBA)= 100.7
ES-02 OGAC
OBSI (dBA)
Frequency (Hz)

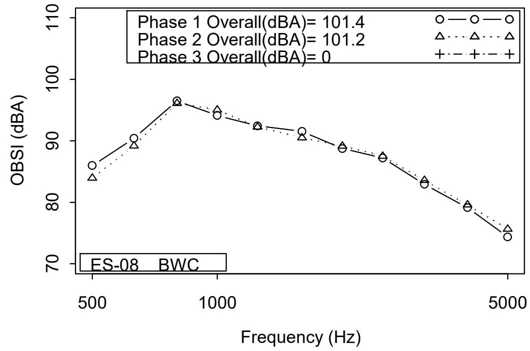

Phase 1 Overall(dBA)= 98.3
Phase 2 Overall(dBA)= 99.3
Phase 3 Overall(dBA)= 99.5
ES-03 OGAC
OBSI (dBA)
Frequency (Hz)

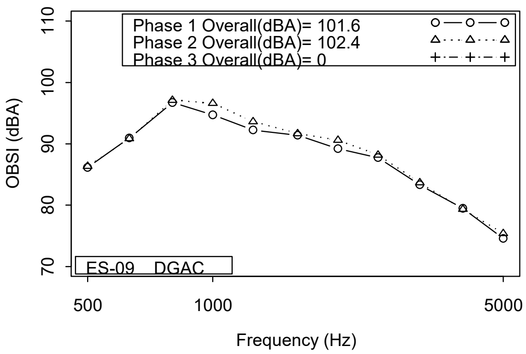

Phase 1 Overall(dBA)= 100
Phase 2 Overall(dBA)= 101.1
Phase 3 Overall(dBA)= 101.3
ES-04 OGAC
OBSI (dBA)
Frequency (Hz)

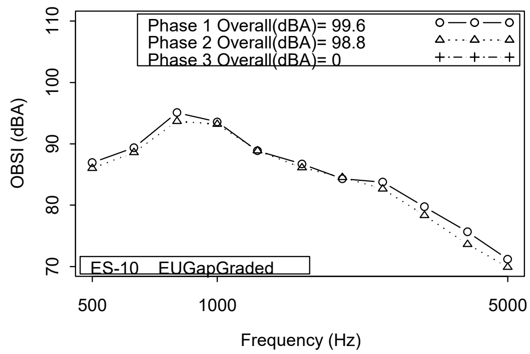

Phase 1 Overall(dBA)= 99.3
Phase 2 Overall(dBA)= 100
Phase 3 Overall(dBA)= 100.1
ES-05 RAC-O
OBSI (dBA)
Frequency (Hz)

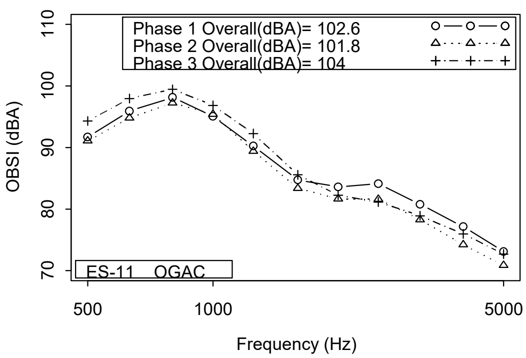

Phase 1 Overall(dBA)= 100.2
Phase 2 Overall(dBA)= 101.1
Phase 3 Overall(dBA)= 101
ES-06 RAC-O
OBSI (dBA)
Frequency (Hz)

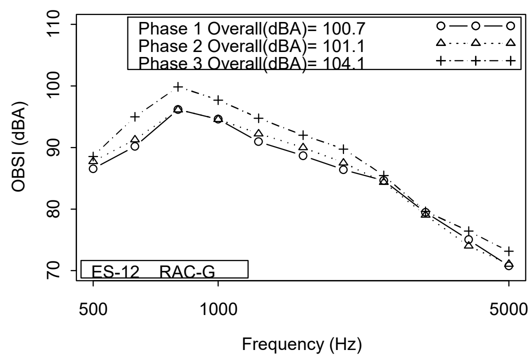

Phase 1 Overall(dBA)= 101.3
Phase 2 Overall(dBA)= 101.8
Phase 3 Overall(dBA)= 102.6
ES-07 BWC
OBSI (dBA)
Frequency (Hz)

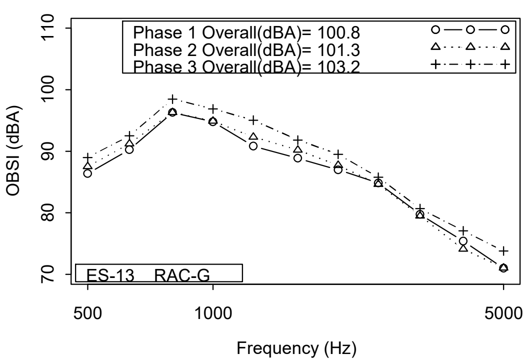

Phase 1 Overall(dBA)= 101.4
Phase 2 Overall(dBA)= 101.2
Phase 3 Overall(dBA)= 0
ES-08 BWC
OBSI (dBA)
Frequency (Hz)

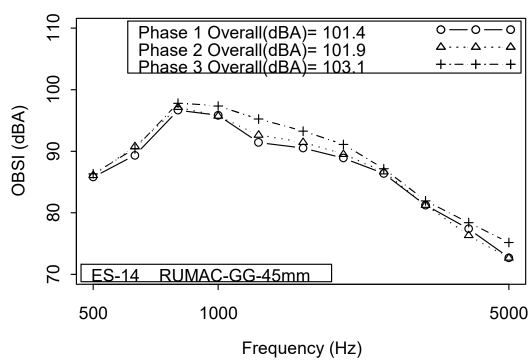

Phase 1 Overall(dBA)= 101.6
Phase 2 Overall(dBA)= 102.4
Phase 3 Overall(dBA)= 0
ES-09 DGAC
OBSI (dBA)
Frequency (Hz)

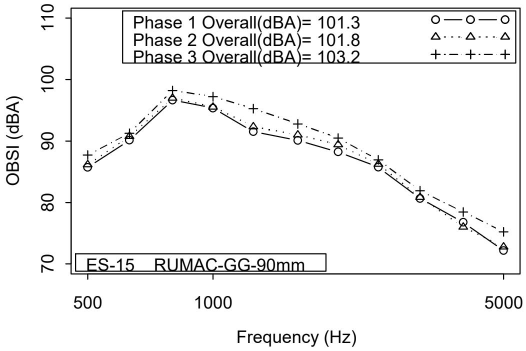

Phase 1 Overall(dBA)= 99.6
Phase 2 Overall(dBA)= 98.8
Phase 3 Overall(dBA)= 0
ES-10 EUGapGraded
OBSI (dBA)
Frequency (Hz)

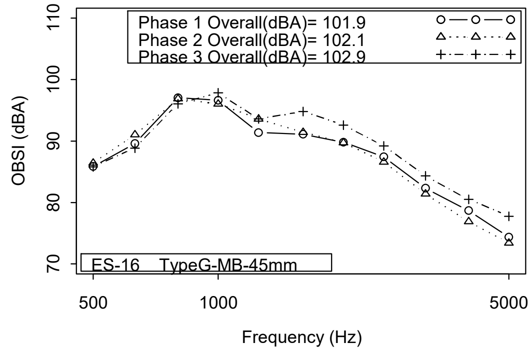

Phase 1 Overall(dBA)= 102.6
Phase 2 Overall(dBA)= 101.8
Phase 3 Overall(dBA)= 104
ES-11 OGAC
OBSI (dBA)
Frequency (Hz)

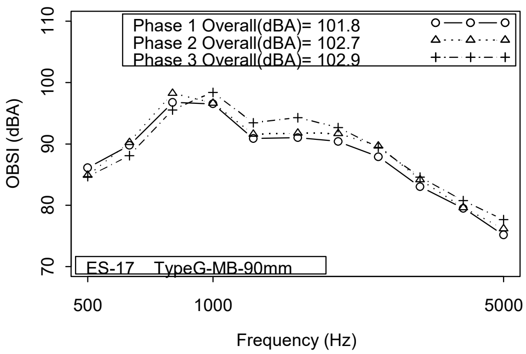

Phase 1 Overall(dBA)= 100.7
Phase 2 Overall(dBA)= 101.1
Phase 3 Overall(dBA)= 104.1
ES-12 RAC-G
OBSI (dBA)
Frequency (Hz)

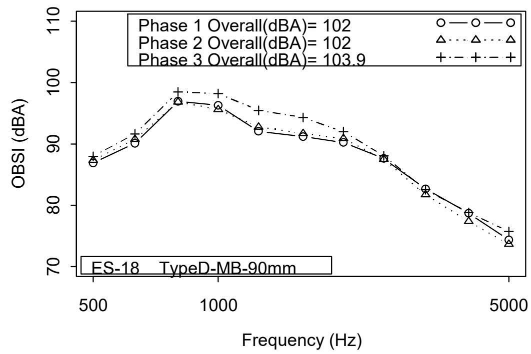

Phase 1 Overall(dBA)= 100.8
Phase 2 Overall(dBA)= 101.3
Phase 3 Overall(dBA)= 103.2
ES-13 RAC-G
OBSI (dBA)
Frequency (Hz)

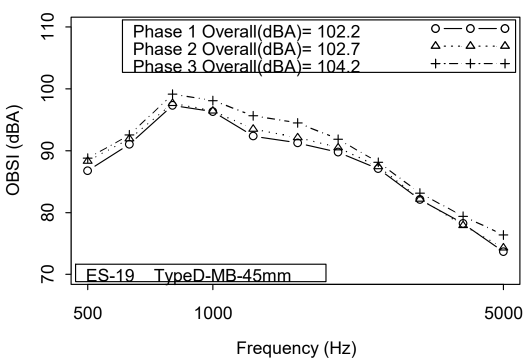

Phase 1 Overall(dBA)= 101.4
Phase 2 Overall(dBA)= 101.9
Phase 3 Overall(dBA)= 103.1
ES-14 RUMAC-GG-45mm
OBSI (dBA)
Frequency (Hz)

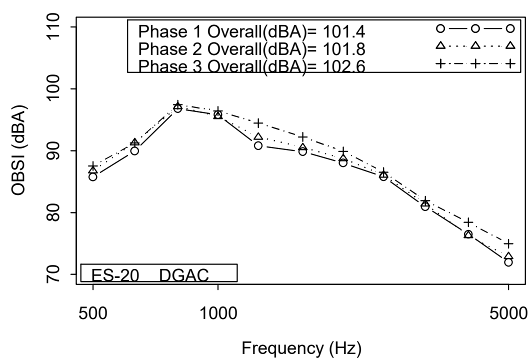

Phase 1 Overall(dBA)= 101.3
Phase 2 Overall(dBA)= 101.8
Phase 3 Overall(dBA)= 103.2
ES-15 RUMAC-GG-90mm
OBSI (dBA)
Frequency (Hz)

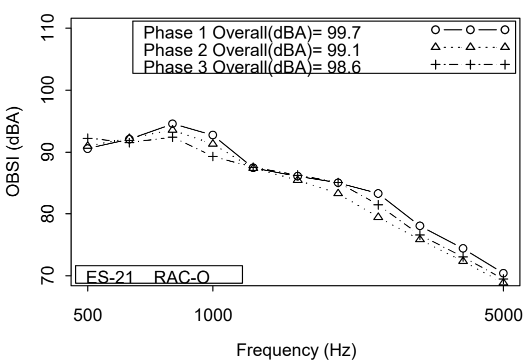

Phase 1 Overall(dBA)= 101.9
Phase 2 Overall(dBA)= 102.1
Phase 3 Overall(dBA)= 102.9
ES-16 TypeG-MB-45mm
OBSI (dBA)
Frequency (Hz)

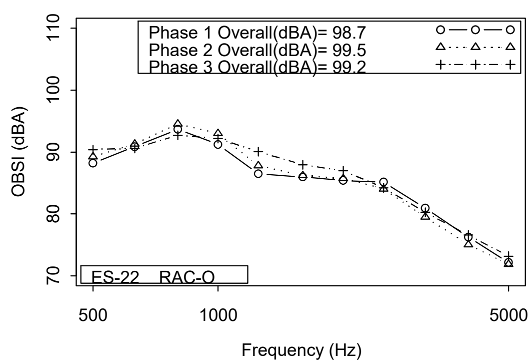

Phase 1 Overall(dBA)= 101.8
Phase 2 Overall(dBA)= 102.7
Phase 3 Overall(dBA)= 102.9
ES-17 TypeG-MB-90mm
OBSI (dBA)
Frequency (Hz)

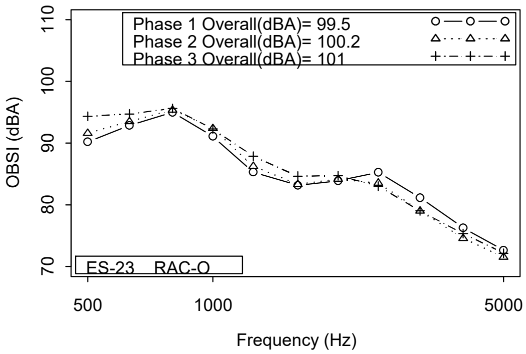

Phase 1 Overall(dBA)= 102
Phase 2 Overall(dBA)= 102
Phase 3 Overall(dBA)= 103.9
ES-18 TypeD-MB-90mm
OBSI (dBA)
Frequency (Hz)

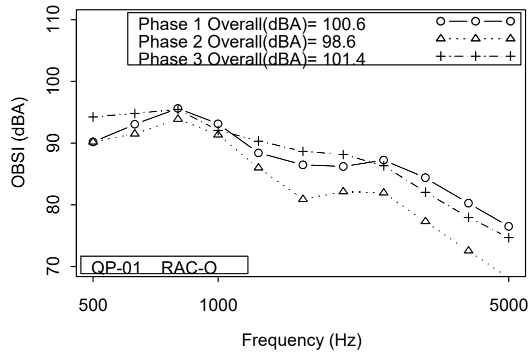

Phase 1 Overall(dBA)= 102.2
Phase 2 Overall(dBA)= 102.7
Phase 3 Overall(dBA)= 104.2
ES-19 TypeD-MB-45mm
OBSI (dBA)
Frequency (Hz)

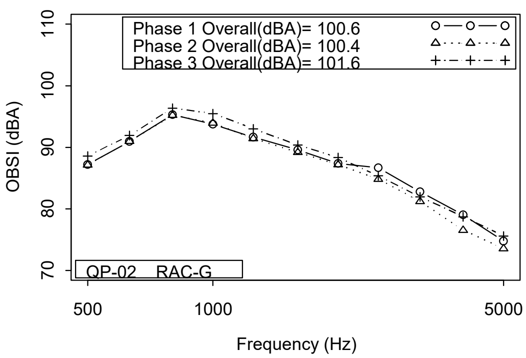

Phase 1 Overall(dBA)= 101.4
Phase 2 Overall(dBA)= 101.8
Phase 3 Overall(dBA)= 102.6
ES-20 DGAC
OBSI (dBA)
Frequency (Hz)

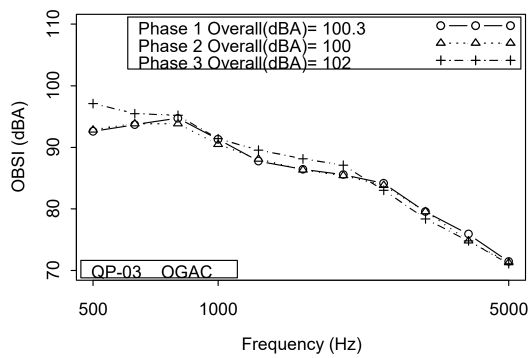

Phase 1 Overall(dBA)= 99.7
Phase 2 Overall(dBA)= 99.1
Phase 3 Overall(dBA)= 98.6
ES-21 RAC-O
OBSI (dBA)
Frequency (Hz)

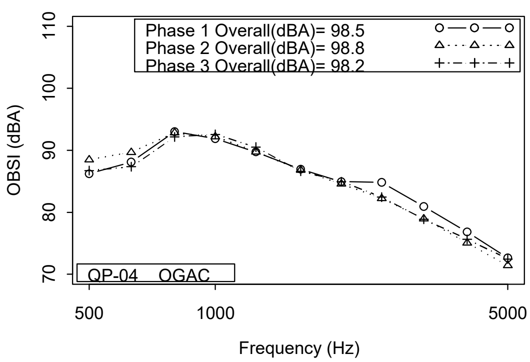

Phase 1 Overall(dBA)= 98.7
Phase 2 Overall(dBA)= 99.5
Phase 3 Overall(dBA)= 99.2
ES-22 RAC-O
OBSI (dBA)
Frequency (Hz)

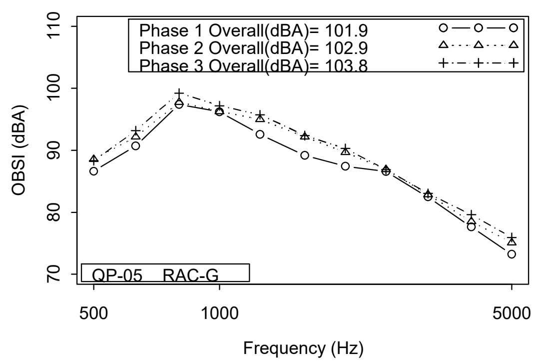

Phase 1 Overall(dBA)= 99.5
Phase 2 Overall(dBA)= 100.2
Phase 3 Overall(dBA)= 101
ES-23 RAC-O
OBSI (dBA)
Frequency (Hz)

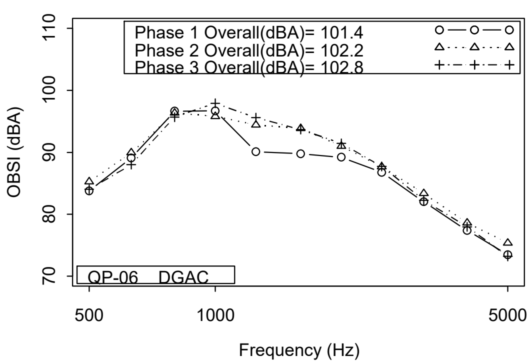

Phase 1 Overall(dBA)= 100.6
Phase 2 Overall(dBA)= 98.6
Phase 3 Overall(dBA)= 101.4
QP-01 RAC-O
OBSI (dBA)
Frequency (Hz)

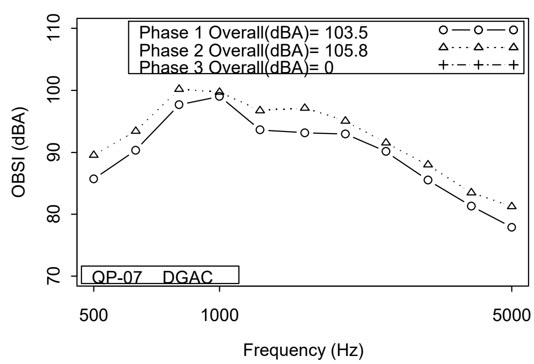

Phase 1 Overall(dBA)= 100.6
Phase 2 Overall(dBA)= 100.4
Phase 3 Overall(dBA)= 101.6
QP-02 RAC-G
OBSI (dBA)
Frequency (Hz)

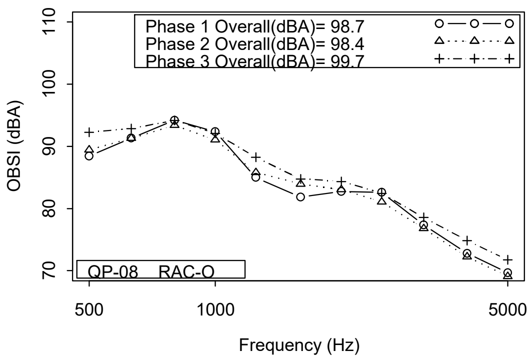

Phase 1 Overall(dBA)= 100.3
Phase 2 Overall(dBA)= 100
Phase 3 Overall(dBA)= 102
QP-03 OGAC
OBSI (dBA)
Frequency (Hz)

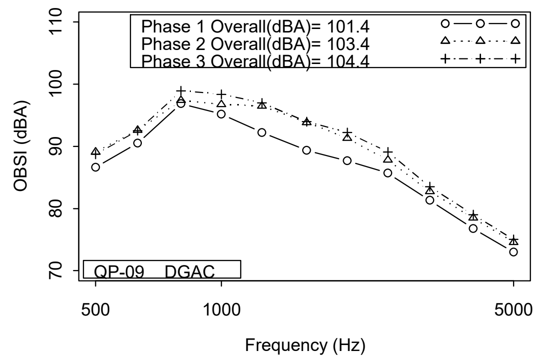

Phase 1 Overall(dBA)= 98.5
Phase 2 Overall(dBA)= 98.8
Phase 3 Overall(dBA)= 98.2
QP-04 OGAC
OBSI (dBA)
Frequency (Hz)

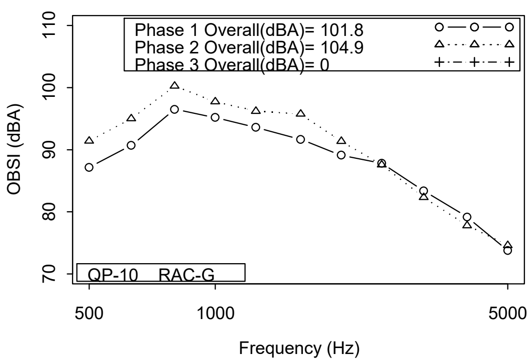

Phase 1 Overall(dBA)= 101.9
Phase 2 Overall(dBA)= 102.9
Phase 3 Overall(dBA)= 103.8
QP-05 RAC-G
OBSI (dBA)
Frequency (Hz)

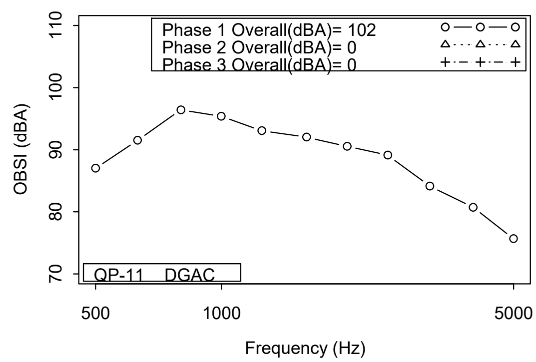

Phase 1 Overall(dBA)= 101.4
Phase 2 Overall(dBA)= 102.2
Phase 3 Overall(dBA)= 102.8
QP-06 DGAC
OBSI (dBA)
Frequency (Hz)

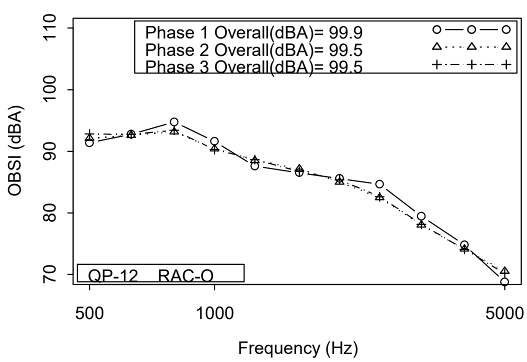

Phase 1 Overall(dBA)= 103.5
Phase 2 Overall(dBA)= 105.8
Phase 3 Overall(dBA)= 0
QP-07 DGAC
OBSI (dBA)
Frequency (Hz)

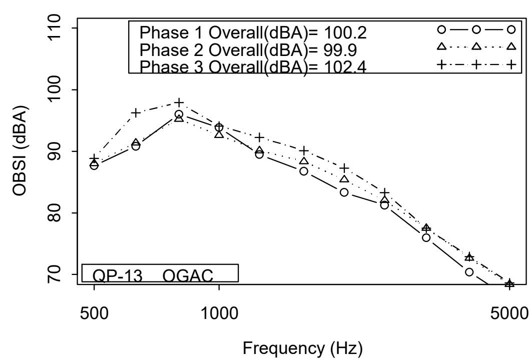

Phase 1 Overall(dBA)= 98.7
Phase 2 Overall(dBA)= 98.4
Phase 3 Overall(dBA)= 99.7
QP-08 RAC-O
OBSI (dBA)
Frequency (Hz)

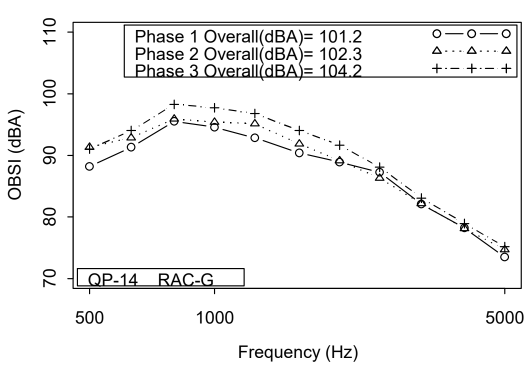

Phase 1 Overall(dBA)= 101.4
Phase 2 Overall(dBA)= 103.4
Phase 3 Overall(dBA)= 104.4
QP-09 DGAC
OBSI (dBA)
Frequency (Hz)

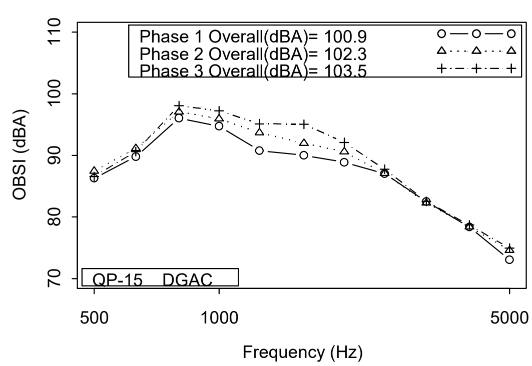

Phase 1 Overall(dBA)= 101.8
Phase 2 Overall(dBA)= 104.9
Phase 3 Overall(dBA)= 0
QP-10 RAC-G
OBSI (dBA)
Frequency (Hz)

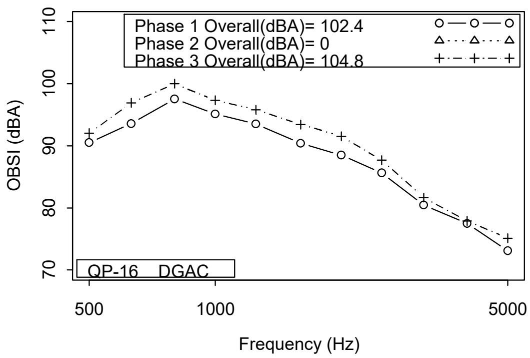

Phase 1 Overall(dBA)= 102
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
QP-11 DGAC
OBSI (dBA)
Frequency (Hz)

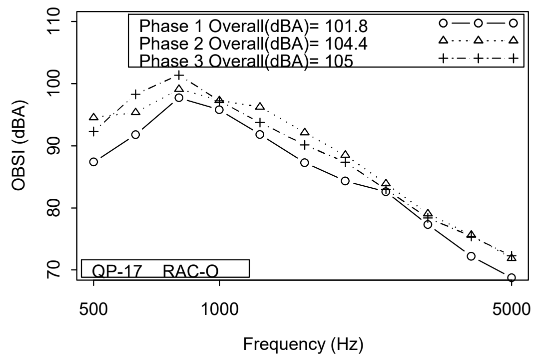

Phase 1 Overall(dBA)= 99.9
Phase 2 Overall(dBA)= 99.5
Phase 3 Overall(dBA)= 99.5
QP-12 RAC-O
OBSI (dBA)
Frequency (Hz)

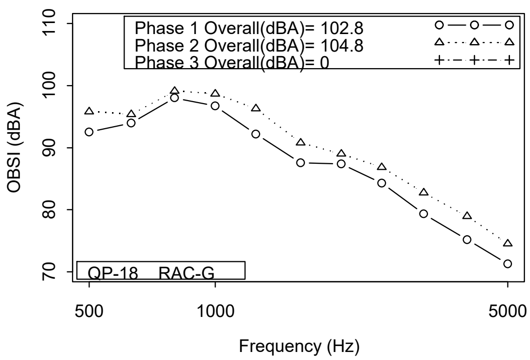

Phase 1 Overall(dBA)= 100.2
Phase 2 Overall(dBA)= 99.9
Phase 3 Overall(dBA)= 102.4
QP-13 OGAC
OBSI (dBA)
Frequency (Hz)

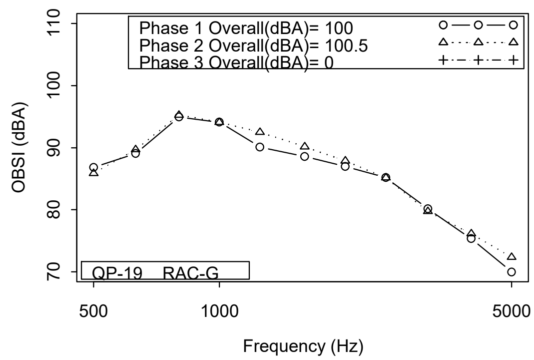

Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 102.3
Phase 3 Overall(dBA)= 104.2
QP-14 RAC-G
OBSI (dBA)
Frequency (Hz)

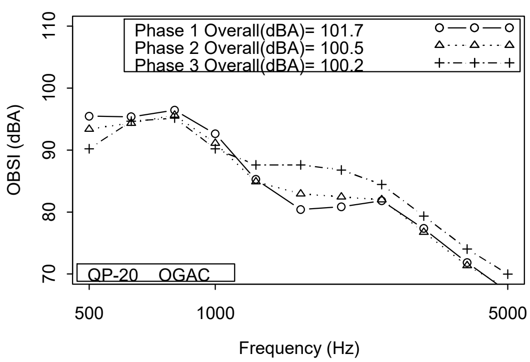

Phase 1 Overall(dBA)= 100.9
Phase 2 Overall(dBA)= 102.3
Phase 3 Overall(dBA)= 103.5
QP-15 DGAC
OBSI (dBA)
Frequency (Hz)

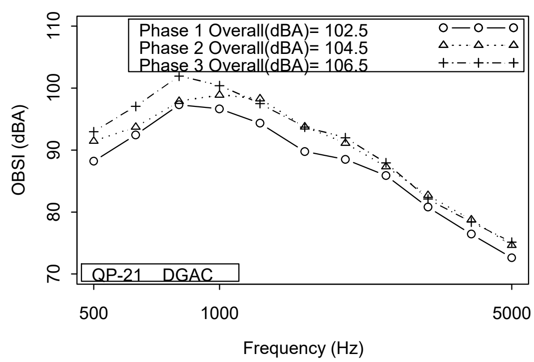

Phase 1 Overall(dBA)= 102.4
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 104.8
OBSI (dBA)
Frequency (Hz)
QP-16 DGAC

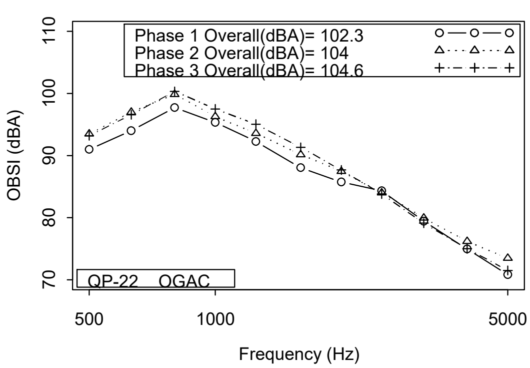

Phase 1 Overall(dBA)= 101.8
Phase 2 Overall(dBA)= 104.4
Phase 3 Overall(dBA)= 105
OBSI (dBA)
Frequency (Hz)
QP-17 RAC-O

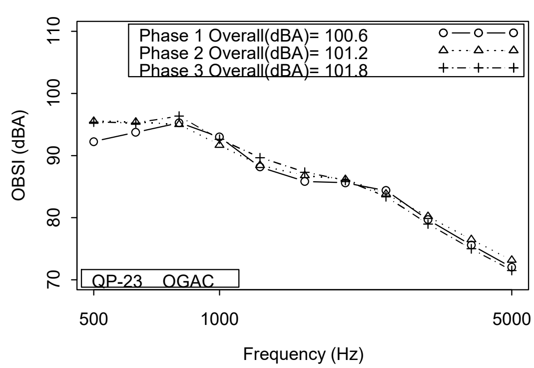

Phase 1 Overall(dBA)= 102.8
Phase 2 Overall(dBA)= 104.8
Phase 3 Overall(dBA)= 0
OBSI (dBA)
Frequency (Hz)
QP-18 RAC-G

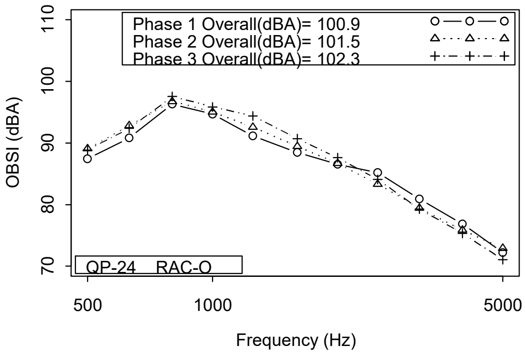

Phase 1 Overall(dBA)= 100
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 0
OBSI (dBA)
Frequency (Hz)
QP-19 RAC-G

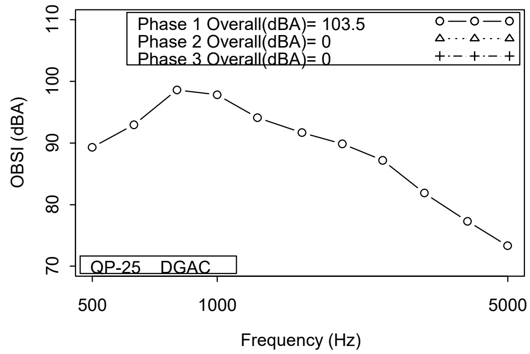

Phase 1 Overall(dBA)= 101.7
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 100.2
OBSI (dBA)
Frequency (Hz)
QP-20 OGAC

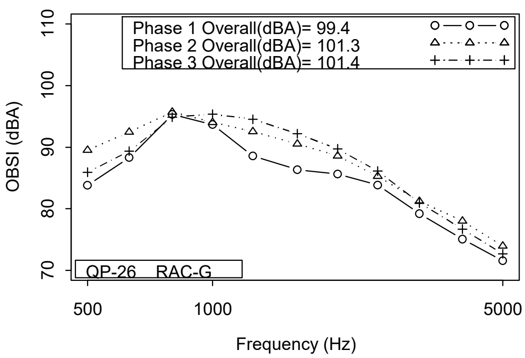

Phase 1 Overall(dBA)= 102.5
Phase 2 Overall(dBA)= 104.5
Phase 3 Overall(dBA)= 106.5
OBSI (dBA)
Frequency (Hz)
QP-21 DGAC

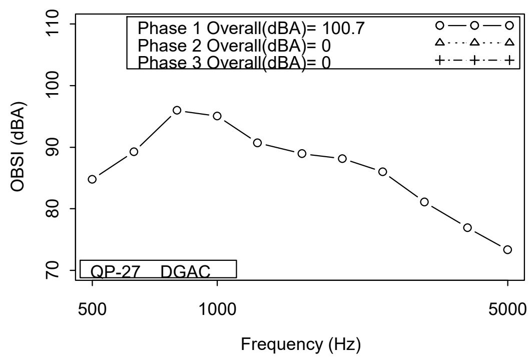

Phase 1 Overall(dBA)= 102.3
Phase 2 Overall(dBA)= 104
Phase 3 Overall(dBA)= 104.6
OBSI (dBA)
Frequency (Hz)
QP-22 OGAC

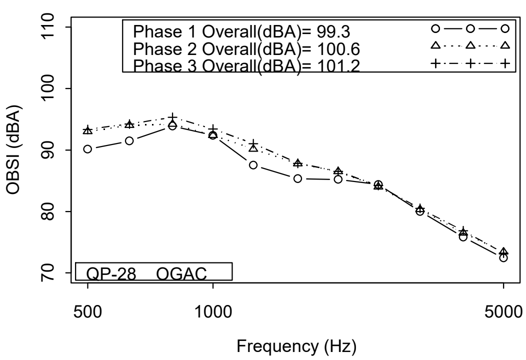

Phase 1 Overall(dBA)= 100.6
Phase 2 Overall(dBA)= 101.2
Phase 3 Overall(dBA)= 101.8
OBSI (dBA)
Frequency (Hz)
QP-23 OGAC

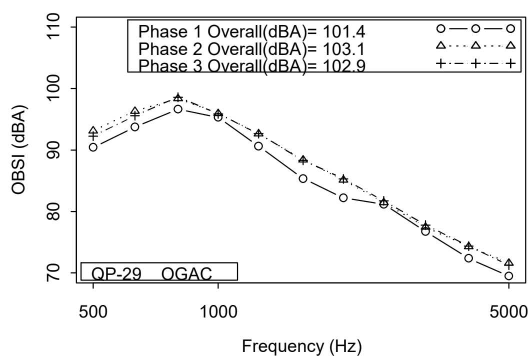

Phase 1 Overall(dBA)= 100.9
Phase 2 Overall(dBA)= 101.5
Phase 3 Overall(dBA)= 102.3
QP-24 RAC-O
OBSI (dBA)
Frequency (Hz)

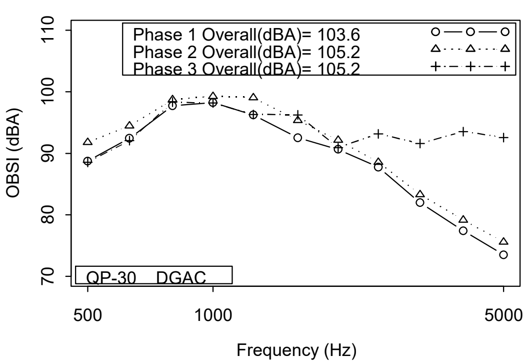

Phase 1 Overall(dBA)= 103.5
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
QP-25 DGAC
OBSI (dBA)
Frequency (Hz)

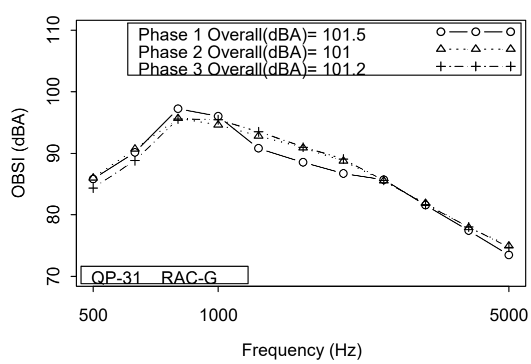

Phase 1 Overall(dBA)= 99.4
Phase 2 Overall(dBA)= 101.3
Phase 3 Overall(dBA)= 101.4
QP-26 RAC-G
OBSI (dBA)
Frequency (Hz)

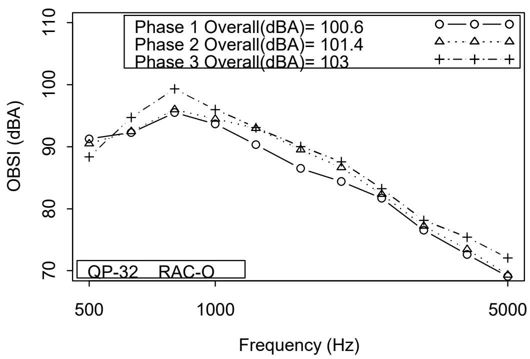

Phase 1 Overall(dBA)= 100.7
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
QP-27 DGAC
OBSI (dBA)
Frequency (Hz)

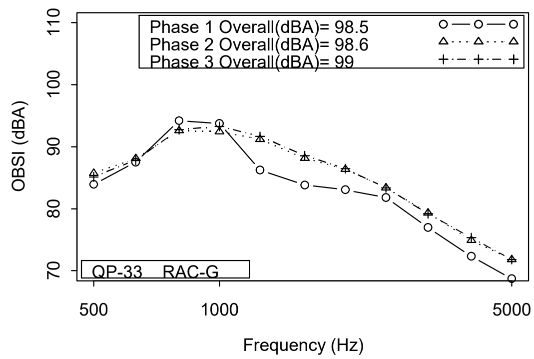

Phase 1 Overall(dBA)= 99.3
Phase 2 Overall(dBA)= 100.6
Phase 3 Overall(dBA)= 101.2
QP-28 OGAC
OBSI (dBA)
Frequency (Hz)

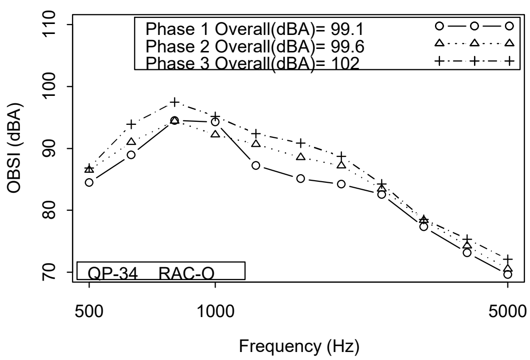

Phase 1 Overall(dBA)= 101.4
Phase 2 Overall(dBA)= 103.1
Phase 3 Overall(dBA)= 102.9
QP-29 OGAC
OBSI (dBA)
Frequency (Hz)

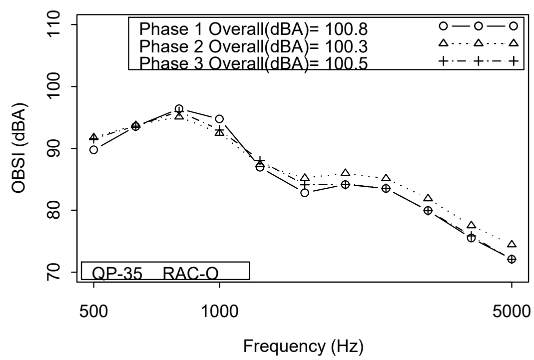

Phase 1 Overall(dBA)= 103.6
Phase 2 Overall(dBA)= 105.2
Phase 3 Overall(dBA)= 105.2
QP-30 DGAC
OBSI (dBA)
Frequency (Hz)

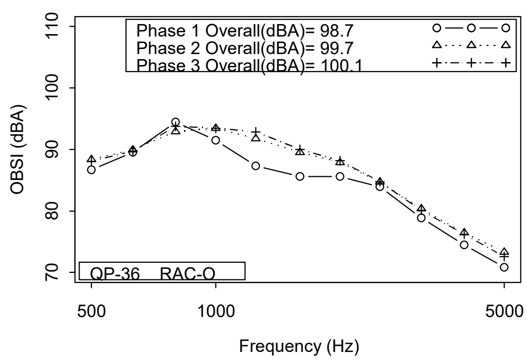

Phase 1 Overall(dBA)= 101.5
Phase 2 Overall(dBA)= 101
Phase 3 Overall(dBA)= 101.2
QP-31 RAC-G
OBSI (dBA)
Frequency (Hz)

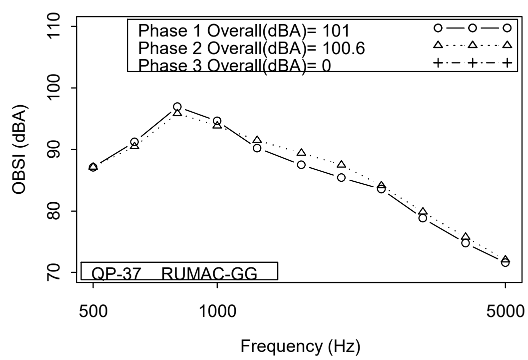

Phase 1 Overall(dBA)= 100.6
Phase 2 Overall(dBA)= 101.4
Phase 3 Overall(dBA)= 103
QP-32 RAC-O
OBSI (dBA)
Frequency (Hz)

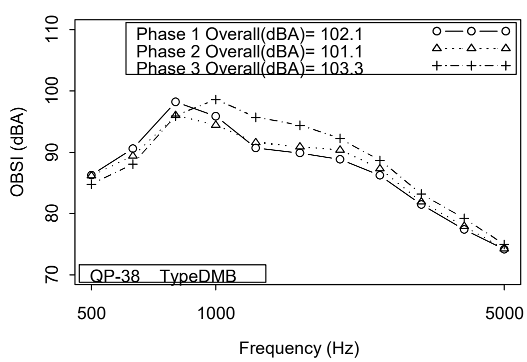

Phase 1 Overall(dBA)= 98.5
Phase 2 Overall(dBA)= 98.6
Phase 3 Overall(dBA)= 99
QP-33 RAC-G
OBSI (dBA)
Frequency (Hz)

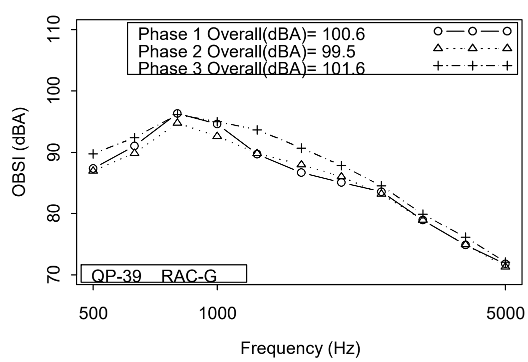

Phase 1 Overall(dBA)= 99.1
Phase 2 Overall(dBA)= 99.6
Phase 3 Overall(dBA)= 102
QP-34 RAC-O
OBSI (dBA)
Frequency (Hz)

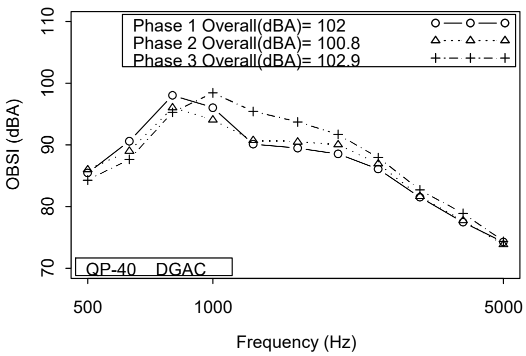

Phase 1 Overall(dBA)= 100.8
Phase 2 Overall(dBA)= 100.3
Phase 3 Overall(dBA)= 100.5
QP-35 RAC-O
OBSI (dBA)
Frequency (Hz)

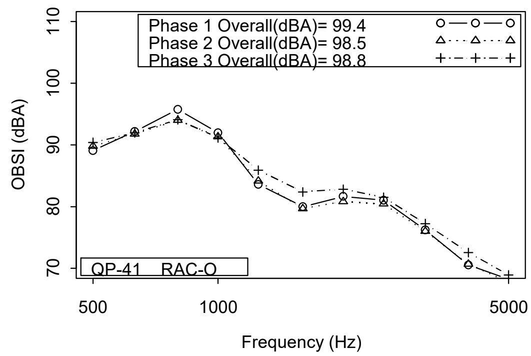

Phase 1 Overall(dBA)= 98.7
Phase 2 Overall(dBA)= 99.7
Phase 3 Overall(dBA)= 100.1
QP-36 RAC-O
OBSI (dBA)
Frequency (Hz)

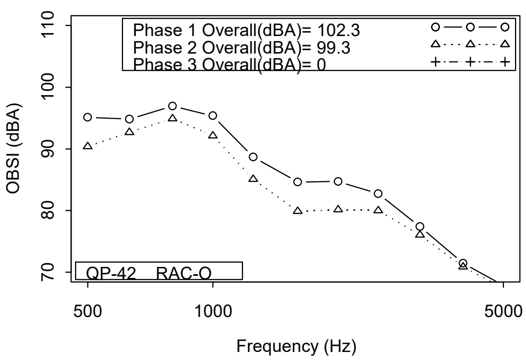

Phase 1 Overall(dBA)= 101
Phase 2 Overall(dBA)= 100.6
Phase 3 Overall(dBA)= 0
QP-37 RUMAC-GG
OBSI (dBA)
Frequency (Hz)

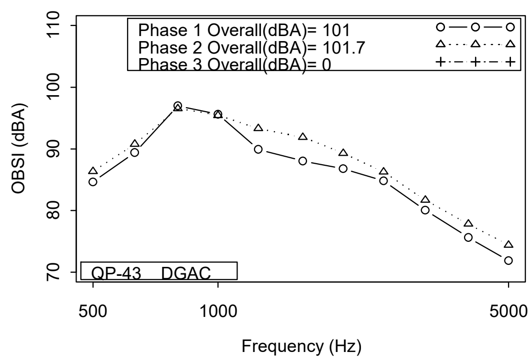

Phase 1 Overall(dBA)= 102.1
Phase 2 Overall(dBA)= 101.1
Phase 3 Overall(dBA)= 103.3
QP-38 TypeDMB
OBSI (dBA)
Frequency (Hz)

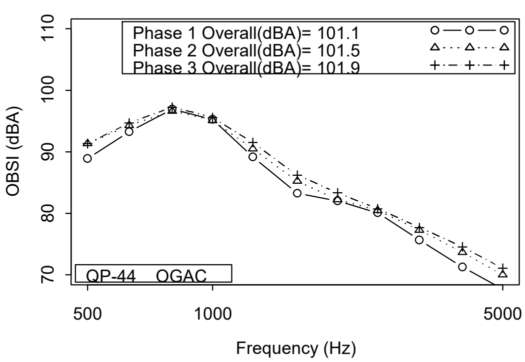

Phase 1 Overall(dBA)= 100.6
Phase 2 Overall(dBA)= 99.5
Phase 3 Overall(dBA)= 101.6
QP-39 RAC-G
OBSI (dBA)
Frequency (Hz)

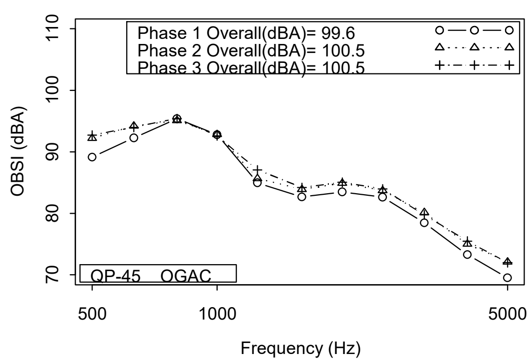

Phase 1 Overall(dBA)= 102
Phase 2 Overall(dBA)= 100.8
Phase 3 Overall(dBA)= 102.9
QP-40 DGAC
OBSI (dBA)
Frequency (Hz)

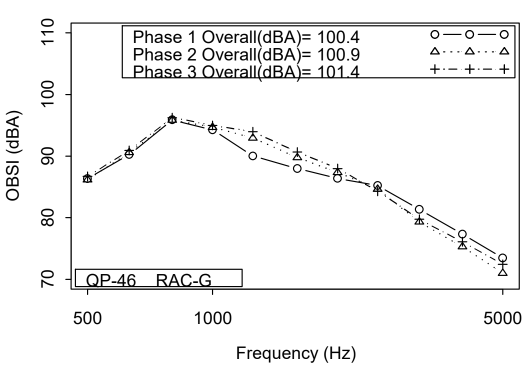

Phase 1 Overall(dBA)= 99.4
Phase 2 Overall(dBA)= 98.5
Phase 3 Overall(dBA)= 98.8
QP-41 RAC-O
OBSI (dBA)
Frequency (Hz)

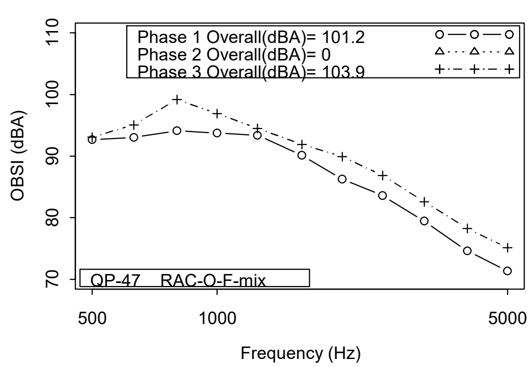

Phase 1 Overall(dBA)= 102.3
Phase 2 Overall(dBA)= 99.3
Phase 3 Overall(dBA)= 0
QP-42 RAC-O
OBSI (dBA)
Frequency (Hz)

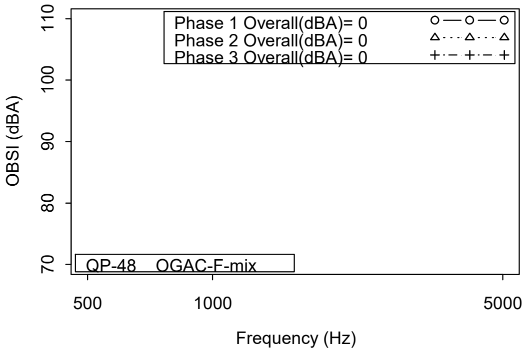

Phase 1 Overall(dBA)= 101
Phase 2 Overall(dBA)= 101.7
Phase 3 Overall(dBA)= 0
QP-43 DGAC
OBSI (dBA)
Frequency (Hz)

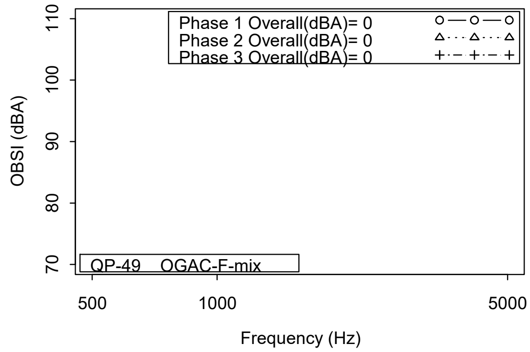

Phase 1 Overall(dBA)= 101.1
Phase 2 Overall(dBA)= 101.5
Phase 3 Overall(dBA)= 101.9
QP-44 OGAC
OBSI (dBA)
Frequency (Hz)

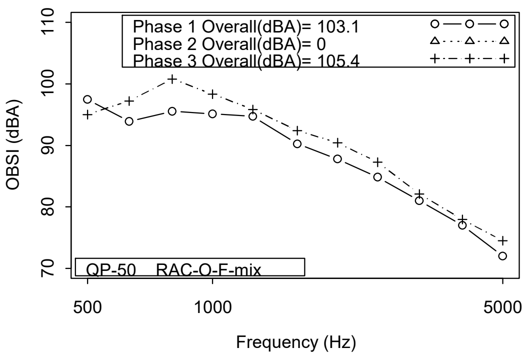

Phase 1 Overall(dBA)= 99.6
Phase 2 Overall(dBA)= 100.5
Phase 3 Overall(dBA)= 100.5
QP-45 OGAC
OBSI (dBA)
Frequency (Hz)

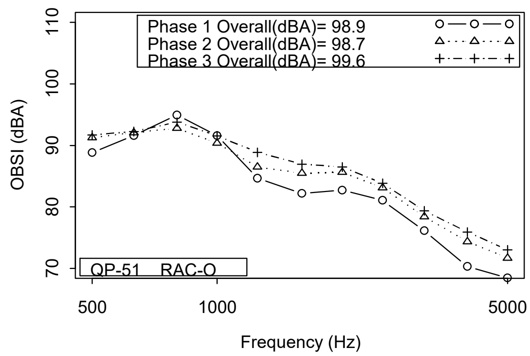

Phase 1 Overall(dBA)= 100.4
Phase 2 Overall(dBA)= 100.9
Phase 3 Overall(dBA)= 101.4
QP-46 RAC-G
OBSI (dBA)
Frequency (Hz)

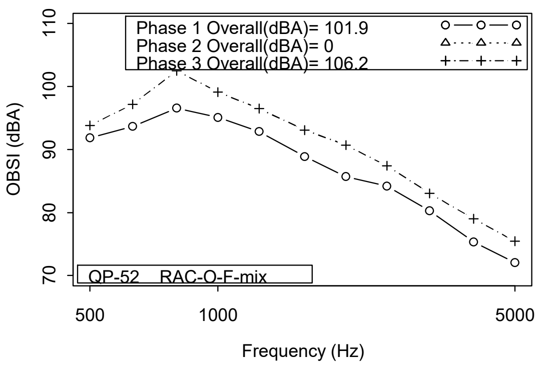

Phase 1 Overall(dBA)= 101.2
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 103.9
QP-47 RAC-O-F-mix
OBSI (dBA)
Frequency (Hz)


Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
QP-48 OGAC-F-mix
OBSI (dBA)
70
80
90
100
110
500
1000
5000
Frequency (Hz)


Phase 1 Overall(dBA)= 0
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 0
QP-49 OGAC-F-mix
OBSI (dBA)
70
80
90
100
110
500
1000
5000
Frequency (Hz)

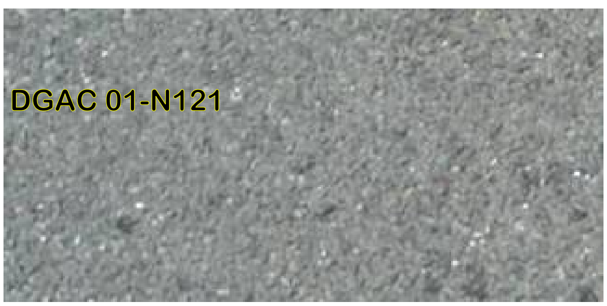

Phase 1 Overall(dBA)= 103.1
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 105.4
QP-50 RAC-O-F-mix
OBSI (dBA)
70
80
90
100
110
500
1000
5000
Frequency (Hz)


Phase 1 Overall(dBA)= 98.9
Phase 2 Overall(dBA)= 98.7
Phase 3 Overall(dBA)= 99.6
QP-51 RAC-O
OBSI (dBA)
70
80
90
100
110
500
1000
5000
Frequency (Hz)


Phase 1 Overall(dBA)= 101.9
Phase 2 Overall(dBA)= 0
Phase 3 Overall(dBA)= 106.2
QP-52 RAC-O-F-mix
OBSI (dBA)
70
80
90
100
110
500
1000
5000
Frequency (Hz)

A.6: Close-up Photos of Pavements Included in This Study

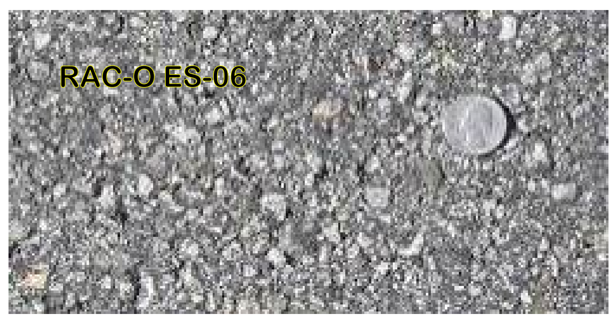
(Note: The diameter of the U.S. quarter coin is 24 mm.)



DGAC 06-N436

NA

RAC-O 06-N467	RAC-O 06-N468
NA	NA




BWC ES-07


BWC ES-08


DGAC ES-09


EU Gap Graded ES-10


OGAC ES-11


RAC-G ES-12


RAC-G ES-13


RUMAC-GG-45mm ES-14


RUMAC-GG-90 mm ES-15


MB-G-45-mm ES-16


MB-G-90-mm ES-17


MB-D-90-mm ES-18


MB-D-45-mm ES-19


DGAC ES-20


RAC-O ES-21


RAC-O ES-22


RAC-O ES-23


RAC-O QP-1


RAC-G QP-2


OGAC QP-3


OGAC QP-4


RAC-G QP-5


DGAC QP-6


DGAC QP-7


RAC-O QP-8


DGAC QP-9


RAC-G QP-10


DGAC QP-11


RAC-O QP-12


OGAC QP-13


RAC-G QP-14


DGAC QP-15


DGAC QP-16


RAC-O QP-17


RAC-G QP-18


RAC-G QP-19


OGAC QP-20


DGAC QP-21


OGAC QP-22


OGAC QP-23


RAC-O QP-24


DGAC QP-25


RAC-G QP-26


DGAC QP-27


OGAC QP-28


OGAC QP-29


DGAC QP-30


RAC-G QP-31


RAC-O QP-32


RAC-G QP-33


RAC-O QP-34


RAC-O QP-35


RAC-O QP-36


RUMAC-GG QP-37


MB-D QP-38


RAC-G QP-39


DGAC QP-40


RAC-O QP-41


RAC-O QP42


DGAC QP-43


OGAC QP-44


OGAC QP-45


RAC-G QP-46


RAC-O-F mix QP-47


OGAC-F-mix QP-48


OGAC-F-mix QP-49


RAC-O-F-mix QP-50


RAC-O QP-51


RAC-O-F-mix QP-52

A.7: Condition Survey of Environmental Noise Monitoring Site Sections for Three Years

Site Name	Mix Types	First-Year	Second-Year	Third-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 low-severity transverse crack with a length of 3.6 m
	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 low-severity transverse crack with a length of 1.6 m
	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
	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
	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
Los Angeles 19 (LA 19)	European Gap-Graded mix, 30 mm (ES-10)	No distresses	150 m^2 bleeding	150 m^2 medium bleeding; 1 m^2 raveling; 1 low-severity transverse crack with a length of 1 m
Yolo 80	OGAC, 20 mm (ES-11)	60 m^2 raveling	300 m^2 raveling; 300 m^2 bleeding	300 m^2 medium raveling; 300 m^2 medium bleeding; 3-m low-severity fatigue crack; 1 low-severity pothole of 0.2 m^2;
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 medium bleeding; 21 low severity patching with area of 4.7 m^2
	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

Site Name	Mix Types	First-Year	Second-Year	Third-Year
	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
	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 low severity fatigue cracking; 3-m low severity longitudinal cracking; 10 low-severity transverse cracks with a length of 18 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
	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
	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 medium bleeding; 1 low-severity transverse crack with a length of 2 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
	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
San Mateo 280 (SM 280)	RAC-O, 45 mm (ES-21)	No distresses	0.1 m^2 raveling	0.25 m^2 medium raveling
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
	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

A.8 Technical Memorandum for Sacramento I-5 sections

TM 4.19-007

Noise testing Hwy 5 Florin

From: **Erwin Kohler, Dynatest Consulting, Inc.**
To: **John Harvey, UCPRC**
Date: **September 10, 2008**

Introduction

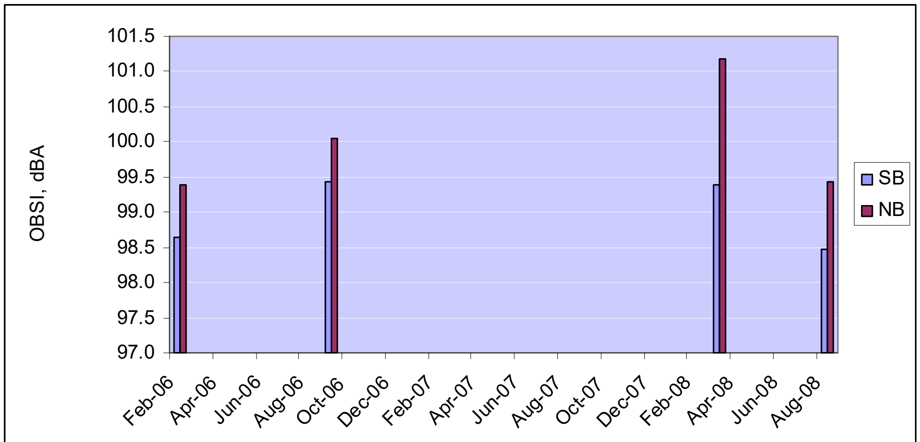
The On-board Sound Intensity (OBSI) method was used to test a RAC-O overlay constructed in 2004 on jointed plain concrete pavement on Interstate 5 in Sacramento, north of Florin Road. One of these monitoring sections is in the southbound direction and the other in the northbound direction. The length of the monitoring sections is 440 ft. Both sections are on the outermost lane, and both are near the south end of the overlay project near the Florin Road overcrossing.

The two monitoring sections on I-5 at Florin Road were measured for OBSI on four occasions, as shown in Figure A.1. The sections were originally investigated as part of UCPRC Project 4.16, with the southbound section identified as Environmental Section 22 (ES-22) in that experiment (refer to Appendix A.7 for further details) and the northbound section identified as ES-23. The first two of the OBSI measurements were performed as part of Project 4.16 in 2006. As part of the 4.16 project, both sections were also cored and subjected to various field measurements, such as friction and permeability. The cores were tested in the laboratory for air-void content and aggregate gradation. A third set of measurements was made in March 2008 as part of Project 4.19.

In August 2008, a fourth set of measurements was taken on every lane as part of Project 4.19, first at the postmile of the monitoring test sections, and then along the entire overlaid length of pavement, which is 0.7 mi long.

OBSI at the Monitoring Sections

The OBSI measurements taken during the first two rounds of testing were obtained with an Aquatred 3 tire, but have been converted to a Standard Reference Test Tire (SRTT) tire, using frequency-by-frequency linear formulas developed by the UCPRC for their specific Aquatred 3 tire. The spectral data has been adjusted with an air density correction that uses as inputs the air temperature, relative humidity, and atmospheric pressure at the time of testing. The data from the the first three sets of measurements and from the fourth site visit on August 18, 2008 is shown in Figure A.1. The trends in the figure reveal three interesting facts: (1) The noise levels for the northbound direction are higher than those for the southbound direction, (2) The August 2008 results are low, and (3) the OBSI level continually increased for the first three measurements on the northbound section, until the low noise levels measured at the fourth visit in August 2008.



	Feb-06	Sep-06	Mar-08	Aug-08
SB	98.6	99.4	99.4	98.5
NB	99.4	100.0	101.2	99.4

Figure A.1.: UCPRC overall OBSI levels on monitoring section of I-5, southbound (SB) and northbound (NB).

Figure A.2 shows OBSI levels measured by UCPRC and by Illingworth and Rodkin Inc (I&R)[1]. The UCPRC results are from the monitoring sections in the outside lanes, while the I&R results are averages from five segments in the southbound direction and four segments in the northbound direction, all in the outside lanes. The results in August 2008 are lower than some of the previous measurements. This is true for both directions, and applies to both the UCPRC and the I&R data.

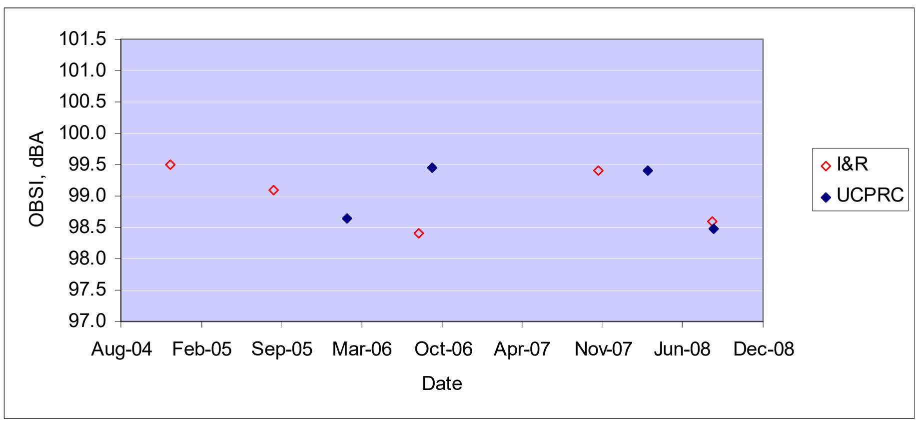


Figure A.2: Overall OBSI spectra levels by I&R and UCPRC on southbound I-5.

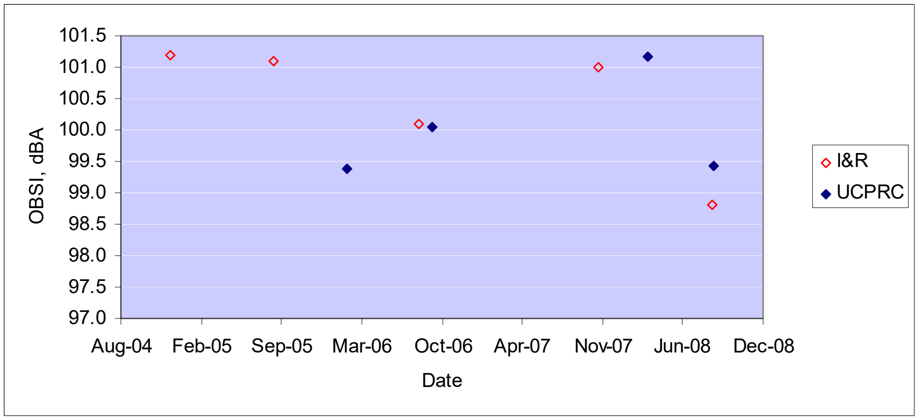


Figure A.3: Overall OBSI spectra levels by I&R and UCPRC on northbound I-5.

Figure A.4 compares the UCPRC spectral data between the southbound (SB) and northbound (NB) sections. Low-frequency noise is responsible for the higher overall OBSI level in the northbound direction. Figure A.5 and Figure A.6 present the spectral data for the two sections on the four occasions they were tested by the UCPRC.

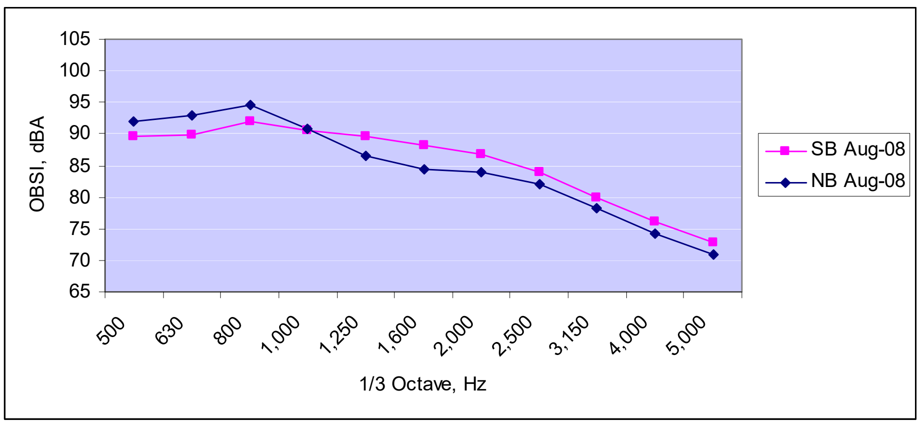


Figure A.4: Comparison of UCPRC OBSI spectra levels on the SB and NB sections in August 2008 (SRTT).

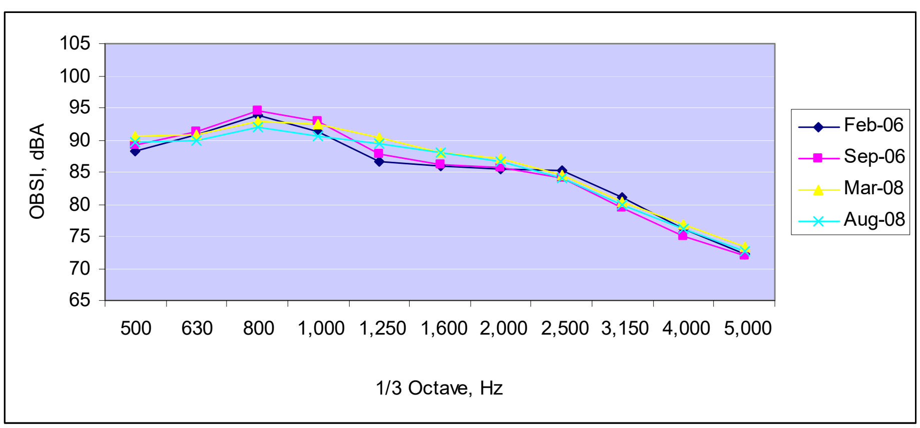


Figure A.5: UCPRC OBSI spectra levels on the monitoring section on I-5 southbound (SRTT) for four site visits.

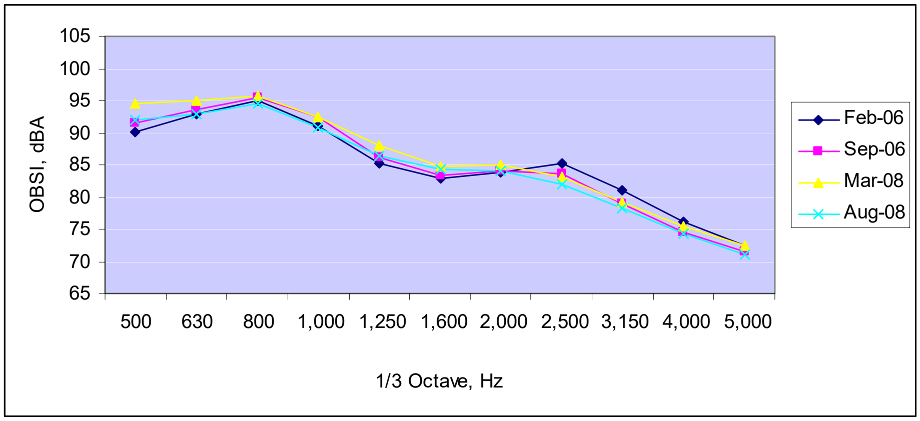


Figure A.6: UCPRC OBSI spectra levels on the monitoring section on I-5 northbound (SRTT).

For completeness, the pavement and air temperature data at time of the UCPRC OBSI measurements is presented in Table A.1, along with other atmospheric conditions.

Table A.1: Temperature, pressure, and relative humidity at times of UCPRC testing

	2/16/2006	9/14/2006	3/5/2008	8/18/2008
Pavement temperature (°F)	73.3	101.7	82.0	88.2
Air temperature (°F)	56.3	80.0	72.8	71.5
Barometric pressure (inches Hg)	na	na	30.1	29.9
Relative humidity (%)	na	na	23.1	56.3
Time of day	9:44 AM	3:16 PM	3:02 PM	10:15 AM

Additional Information from Monitoring Sections

The UCPRC report on the first and second years of monitoring of flexible sections [2], and the UCPRC Environmental Sections (ES) report [3] both contain additional data about the I-5 overlay pavements. Detailed discussion of air-void content, permeability, roughness, macrotexture, surface distresses, and friction between the SB and NB lanes can be found in reference [2]. A summary of only the most relevant information is included here, with the intent of understanding the different OBSI measurements.

Figure A.7 shows that the air-void content in the NB direction is higher than in the SB direction, and coincides with the higher permeability measured in the NB direction. Permeability measured in situ decreased from February to September 2006. For the SB direction, permeability changed from 0.48 to 0.39 mm/sec, while for the NB direction it changed from 0.94 to 0.63 mm/sec (these are average of center of the lane and wheelpath). Reduced permeability could be associated with reduced sound absorption. These differences in air-void content and permeability between SB and NB are consistent with the sound absorption measured from cores at the center of the lane and at the right wheelpath, which are shown in Figure A.8 and Figure A.9. The wheelpath sound absorption over the range of frequencies tested in the impedance tube is 28 percent in the NB section compared to 14 percent in the SB direction. It must be noted that the peak absorptions occur at different frequencies [4]. The aggregate gradations reported in reference [3] are repeated in Table A.2, and indicate no noticeable difference in aggregate size.

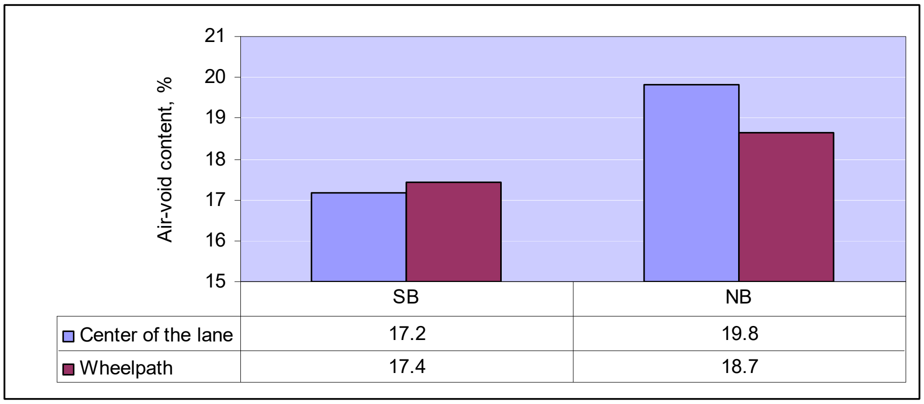


Figure A.7: Air-void content in SB and NB directions from cores taken in February 2006.

Table A.2: Aggregate Gradation (percent passing each sieve by mass) for SB and NB Sections

Gradation	SB	NB
25.00 mm (1 in.)	-	-
19.00 mm (3/4 in.)	100	100
12.50 mm (1/2 in.)	99	97
9.50 mm (3/8 mm)	89	87
4.75 mm (No.4)	35	34
2.36 mm (No. 8)	17	17
2.00 mm (No. 10)	—	—
1.18 mm (No. 16)	11	12
425 µm (No. 40)	—	—
75 µm(No. 200)	4.2	3.9

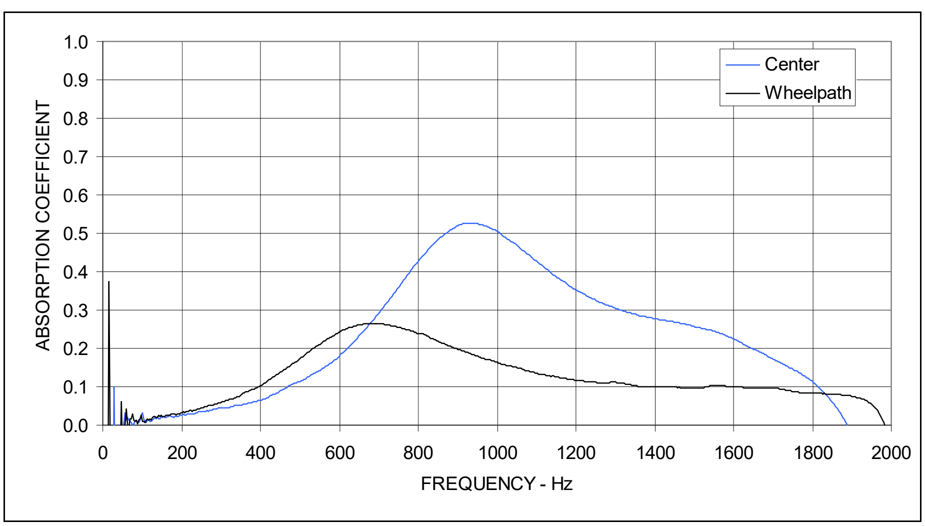


Figure A.8: Sound absorption measured on cores from SB section.

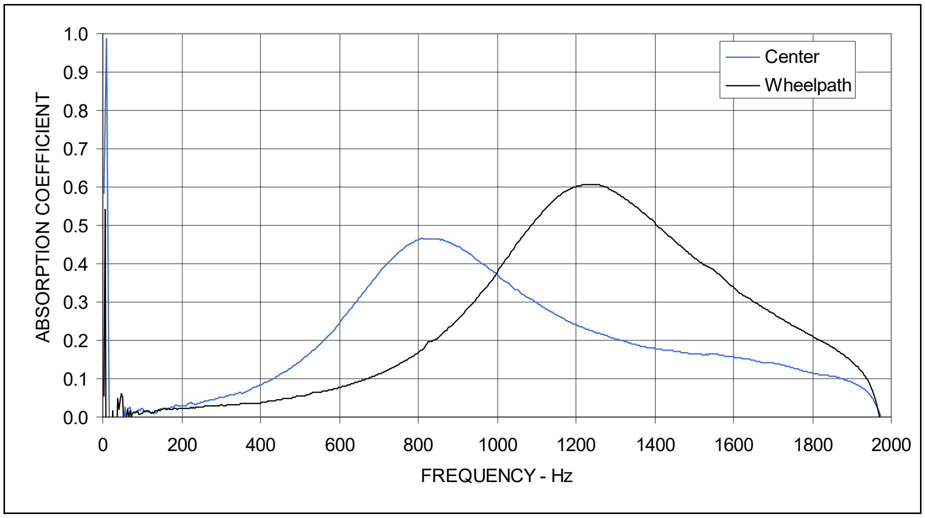


Figure A.9: Sound absorption measured on cores from NB section.

Pavement macrotexture and surface elevation profiles were also measured each time OBSI was collected with the UCPRC vehicle. A history of macrotexture in both directions is presented in Figure A.10, where it can be seen that Mean Profile Depth (MPD) is increasing with time for both directions. This is an indication of loss of binder and fine aggregate between larger particles on the surface, creating the surface distress known as raveling. Figure A.11 shows that the roughness was slightly higher in March 2008 than it August 2008, but it has in general remained very good.

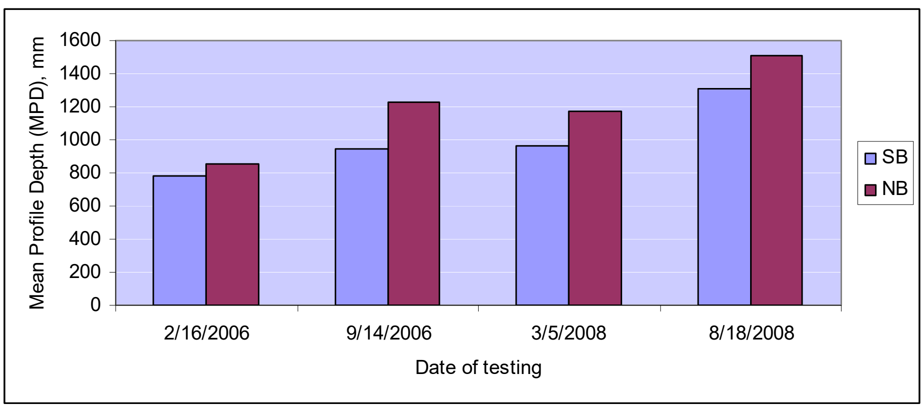


Figure A.10: Changes in macrotexture over time in terms of MPD.

Figure A.11: Changes in ride quality over time in terms of IRI.

Figure A.12 presents a typical longitudinal profile along the 440 feet of the monitoring section on the NB direction. The plots contain the four sets of data. The lines extending below the curves correspond to points where the laser dot goes into a crack. A detailed view of the first 100 feet of pavement in the northbound section (ES-23) is shown in Figure A.13, and it can be seen that cracks have reflected at spacings of 12, 13, 18, and 19 feet, which is the joint spacing on the underlying concrete slabs. This shows that the overlay has developed cracks that are reflected from the underlying pavement. Detailed observations from the profilometer data, confirmed by visual inspection, showed that transverse cracks on the surface are as wide as 5 inches. The width of the cracks is increasing due to spalling, as shown in an example of a reflective crack in Figure A.14. Cracks and joints are known to be responsible for “slap” noise. More photographs of early cracking (in 2005) can be found in Reference [5].

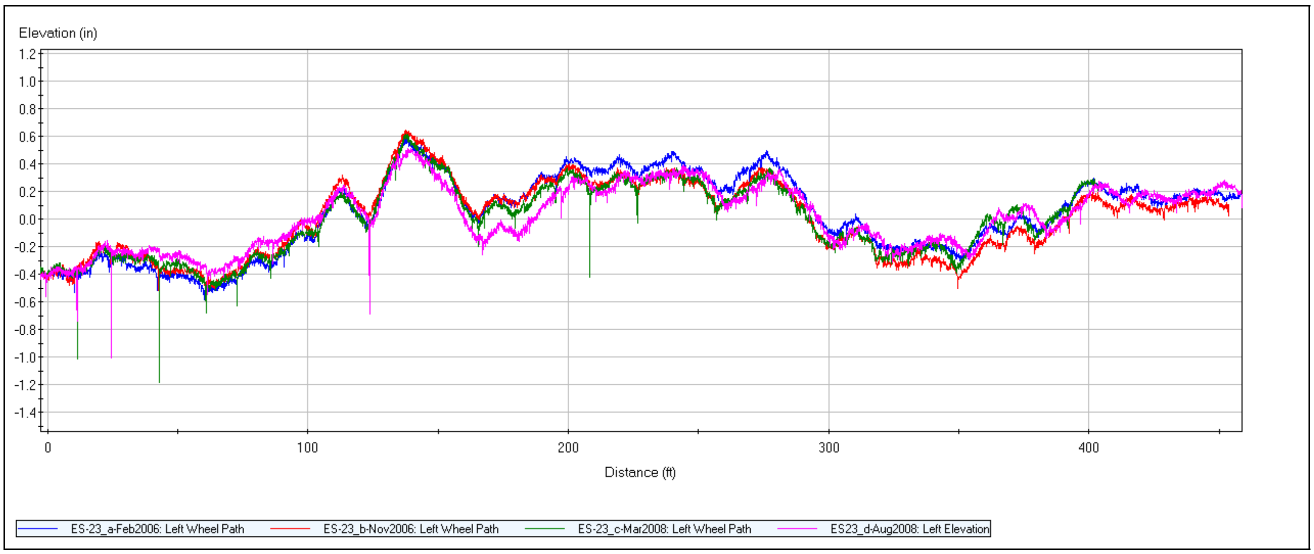


Figure A.12: Pavement profile at 1-inch intervals, NB direction.

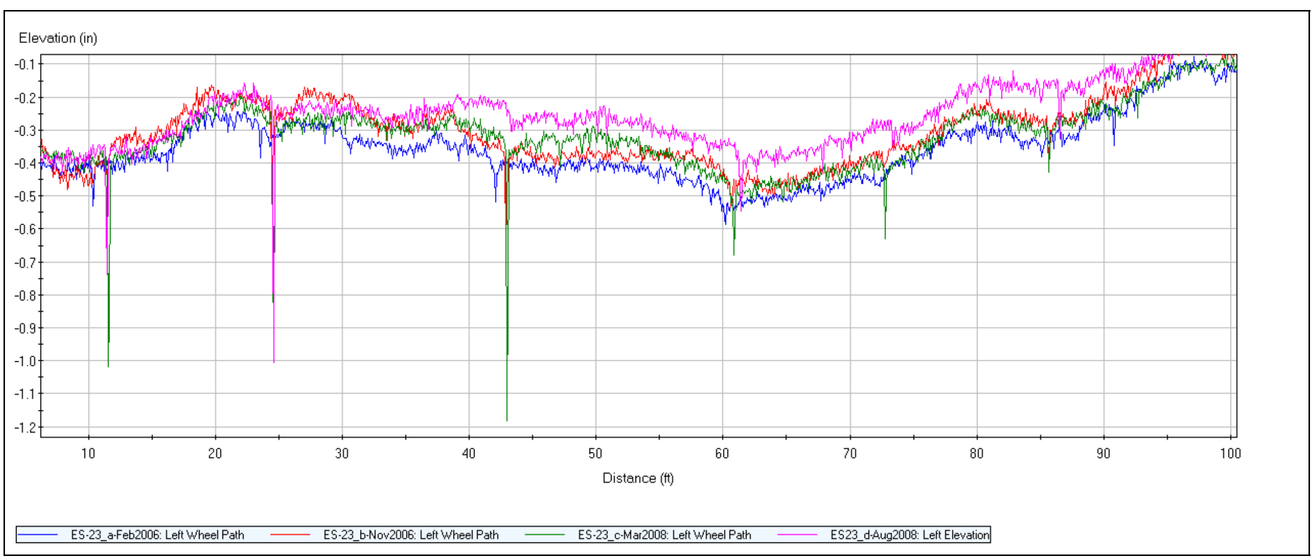


Figure A.13: Detail of first 100 ft of pavement elevation profile on NB direction indicating wide cracks.

Figure A.14: Wide reflective cracks in the monitoring section in the NB direction.

OBSI on Whole Length of Overlaid Pavement
Given the variability observed between southbound and northbound directions, it was considered appropriate to determine variability along the entire length of the overlay project, consisting of 0.7 miles total length in each direction. Although standard OBSI is measured over 5.0 seconds, a nonstandard OBSI with a 2.5-second test reporting interval was used to test every lane. The results are shown in Figure A.15 and Figure A.16 for the southbound and northbound lanes, respectively. An overall comparison across lanes is shown in Figure A.17, where the SB direction noise levels are 98.2 dBA and the NB direction levels are 100.4 dbA. These results were obtained by taking the arithmetic average of intensity at each frequency for the whole length of each lane, and then using these averages to calculate the OBSI of each lane. The OBSI for each lane was then averaged to obtain the values reported at the top of Figure A.17.

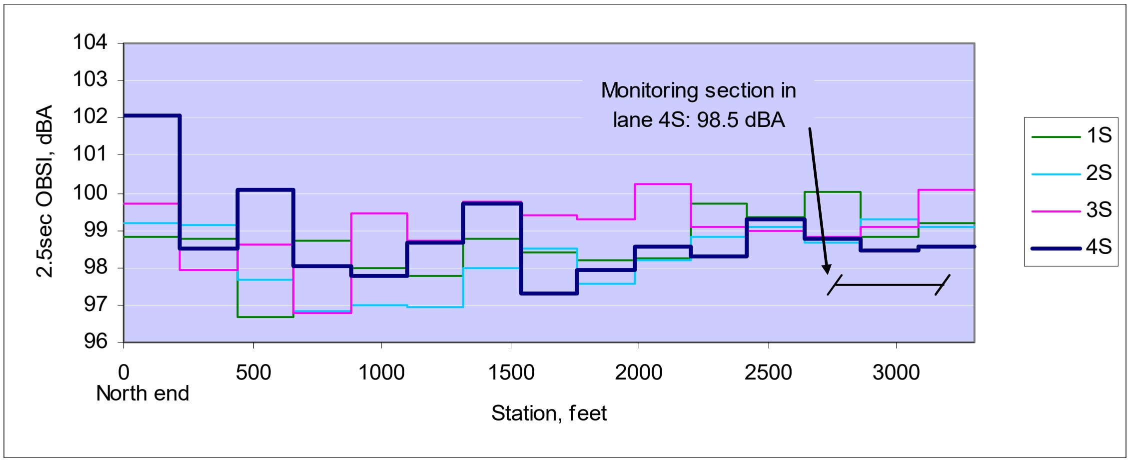


Figure A.15: Overall 2.5-sec OBSI levels for whole length of southbound lanes (Note: 1S is the first [inner] southbound lane, 2S is the second southbound lane, etc).

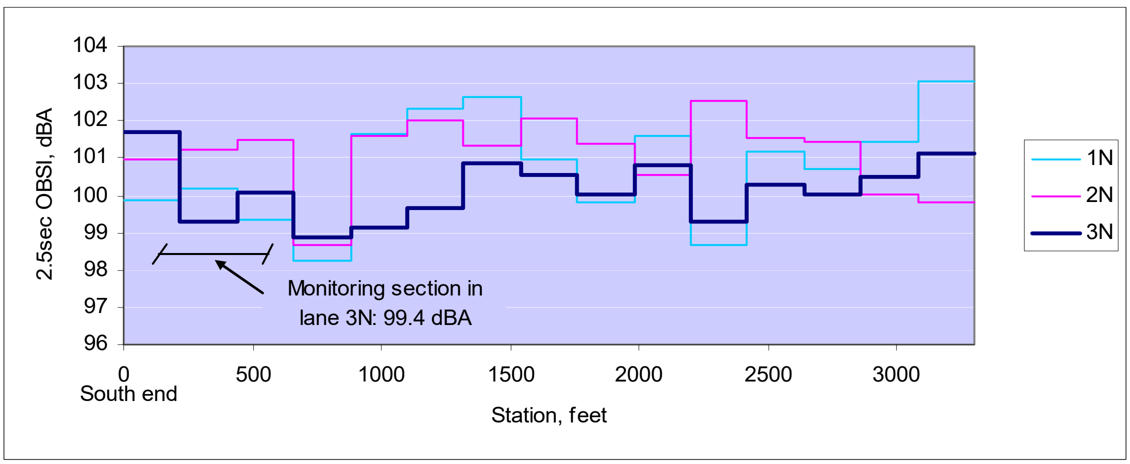


Figure A.16: Overall 2.5-sec OBSI levels for whole length of northbound lanes (Note: 1N is the first [inner] northbound lane, 2N is the second northbound lane, etc).

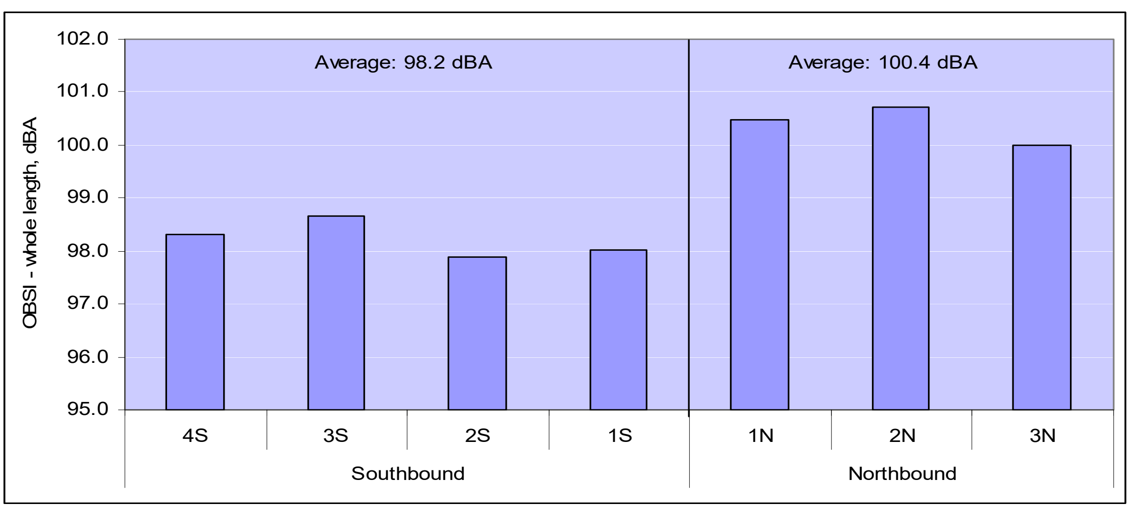


Figure A.17: OBSI levels for each lane taking whole project length results.

Images that show the view from the car during testing are presented in Figure A.18. The pictures of the outside lanes (4S and 3N) in Figure A.18 show markings on the shoulder that represent the starting point for the monitoring sections. Figure A.19 shows the location of the monitoring sections relative to the overlay project.

Figure A.18: Images of the pavement in every lane as seen from testing car, August 2008.

Figure A.19: Depiction of southbound lanes tested over the whole length and the approximate location of monitoring sections (red lines) in the northbound and southbound outer lanes.

Discussion of Results

Changes in Noise Levels over Time

The UCPRC noise data for February 2006, September 2006, and March 2008 showed an increase in noise level for the NB monitoring section. This was not the case for the SB direction, where the March 2008 level was very similar to the Sept 2006 results. The latest OBSI results obtained in August 2008 are surprisingly low as shown in Figure A.1, but are consistent for the SB and NB directions. Similarly low readings in August 2008 were reported by I&R. An unexplained seasonal effect can be claimed as the reason for these lower OBSI levels, as pavement temperature does not seem to have played a role. The transverse joints from the underlying concrete are increasingly appearing as reflective cracks in the RAC-O overlay. One hypothesis is that the decrease in noise measurements between March 2008 and August 2008 is due to closing of the joints during the hot temperatures in August as compared to the cold temperatures in March, and smoothing of the sharp edges of the spalled reflective cracks under traffic during the hot summer months prior to the August measurements.

Northbound versus Southbound Difference

There is a clear difference of at least 1.3 dBA between the OBSI levels of the two directions. The SB OBSI results range from 98.4 to 99.5 dBA, while the NB results range from 98.8 to 101.2 dBA (Figures A.2 and A.3). This difference originates in greater low-frequency noise in the NB direction (Figure A.4), which has higher levels of macrotexture. A difference in aggregate size is in general the main reason for different surface macrotexture, but in this case the gradations revealed almost identical distribution of aggregate sizes (Table A.2). The air-void content in the SB direction is lower than in the NB direction (Figure A.7) although the two directions have similar aggregate maximum size and gradation. This suggest that the difference in air-void content may be due to the amount of binder and the compaction effort. A lower amount of binder in the mix for the NB direction fits as an explanation for the greater air-void content, greater macrotexture, and greater sound absorption, and it is considered the most plausible explanation for the difference in tire/pavement noise level. This follows the observation in Reference 2 that increased air-void content above about 15 percent air-voids does not necessarily result in lower tire/pavement noise if it is accompanied by greater macrotexture.

Despite considerable variability within each lane along the 0.7 miles of pavements (Figures A.15 and A.16), air-void content differences (possibly due to different compaction effort, different compaction temperatures, or different binder contents) from SB to NB do not seem to account for the difference in noise levels between the two directions by themselves. Experience shows that compaction at colder temperatures results in higher air-voids, and greater susceptibility to raveling, all other factors being equal. Also, if the compaction effort during construction was the reason for the noise difference, smoothness (ride quality) would probably be different by now. Variability of OBSI levels within each lane is probably best explained by differences in the raveling rate as measured by MPD, which is controlled by a difference in compaction temperature, compaction effort, and/or binder content.

References

1. Donavan, P. (2008) "OBSI Measurements from the Sac 5 RAC(O) Project." Memo to Bruce Rymer, September 3rd, 2008
2. 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". Report UCPRC-RR-2007-03.
3. Ongel, A. and Kohler, E. (2006); " Surface Condition and Road-Tire Noise on Caltrans Experimental Noise-Reducing Pavement Sections". Report UCPRC-RR-2006-10.
4. Ongel, A.; E. Kohler and J. Nelson (2007) "Acoustical Absorption of Open-Graded, Gap-Graded, and Dense-Graded Asphalt Pavements" Report UCPRC-RR-2007-13.
5. Ongel, A.; N. Santero, and J. Harvey (2005) "Report of Field Site Visit District 3, Sacramento Interstate 5, PM 17.2-17.9 RAC-O Overlay" Technical memorandum UCPRC-TM-2005-07.

A.9 Photos of Skidabrader Sections

Figure B.1. View of segments A, B, C, and D on BD pavement.

Figure B.2. View of segments A, B, C, and D on OG pavement

Figure B.3. View of segments A, B, C, and D on DG pavement

Figure B.4. View of segments A, B, C, and D on LT pavement.

A.10: Actual Values Predicted by Regression Models for Chapter 8

Table A.10.1: 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	14	17
	High Rainfall/ Moderate Temperature	11	14	13	16
	Moderate Rainfall/ Moderate Temperature	12	15	14	17
Low Traffic (TI=9)	Low Rainfall/ High Temperature	16	19	18	21
	Moderate Rainfall/ Low Temperature	13	16	15	18
	High Rainfall/ Moderate Temperature	12	15	14	17
	Moderate Rainfall/ Moderate Temperature	13	16	15	18

Table A.10.2: 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	-	6	3	12
	Moderate Rainfall/ Low Temperature	-	6	3	12
	High Rainfall/ Moderate Temperature	-	6	3	12
	Moderate Rainfall/ Moderate Temperature	-	6	3	12
Low Traffic (TI=9)	Low Rainfall/ High Temperature	-	7	4	14
	Moderate Rainfall/ Low Temperature	-	7	4	13
	High Rainfall/ Moderate Temperature	-	7	4	13
	Moderate Rainfall/ Moderate Temperature	-	7	4	13

Table A.10.3: 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	7	15
	Moderate Rainfall/ Low Temperature	-	11	10	15
	High Rainfall/ Moderate Temperature	-	11	9	15
	Moderate Rainfall/ Moderate Temperature	-	11	9	15
Low Traffic (TI=9)	Low Rainfall/ High Temperature	-	11	6	15
	Moderate Rainfall/ Low Temperature	-	11	10	15
	High Rainfall/ Moderate Temperature	-	11	8	15
	Moderate Rainfall/ Moderate Temperature	-	11	8	15

Table A.10.4: 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	11	10	5	10
	Moderate Rainfall/ Low Temperature	12	11	6	11
	High Rainfall/ Moderate Temperature	11	10	5	11
	Moderate Rainfall/ Moderate Temperature	10	9	4	9
Low Traffic (TI=9)	Low Rainfall/ High Temperature	16	15	8	15
	Moderate Rainfall/ Low Temperature	18	16	9	17
	High Rainfall/ Moderate Temperature	16	15	8	15
	Moderate Rainfall/ Moderate Temperature	15	13	7	14

Table A.10.5: 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	13	14	12	13
	Moderate Rainfall/ Low Temperature	14	15	14	15
	High Rainfall/ Moderate Temperature	12	13	12	13
	Moderate Rainfall/ Moderate Temperature	13	15	13	14
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