12 Year Summary Report

I-80 Davis OGAC Pavement Noise Study

Traffic Noise Levels Associated With Aging Open Grade Asphalt Concrete Overlay

Prepared for:

California Department of Transportation
Division of Environmental Analysis
1120 N Street, Mail Stop 27
Sacramento, California 95814

Prepared by:

ILLINGWORTH & RODKIN, INC.
Acoustics • Air Quality

505 Petaluma Boulevard, South
Petaluma, California 94952

May 13, 2011

Table of Contents

EXECUTIVE SUMMARY – 1998 THROUGH 2010[a]

During June and July of 1998, an open grade asphalt concrete (OGAC) pavement overlay was applied to a 5.6-mile (9-kilometer) stretch of aged dense graded asphalt concrete (DGAC) along Interstate 80 to the east of Davis, California. Beginning in 1998, noise conditions have been monitored by Illingworth & Rodkin, Inc. as part of an ongoing study conducted by the California Department of Transportation (Caltrans) to evaluate the long-term effects of quieter highway pavement types on traffic noise. Noise evaluation of the OGAC pavement was conducted using the continuous flow traffic time integrated method (CTIM) of measuring traffic noise levels at locations adjacent to the roadway. The on-board sound intensity (OBSI) method of measuring tire-pavement noise close to the tire-pavement interface was also used beginning in 2002. Through 2008, measurements were conducted for more than 70 days over the past 10 years, resulting in a total of more than 275 hours of noise monitoring and generating an extensive data set. In 2009 and again in 2010, additional testing was conducted following up the original 10-year study. Results discussed in this report include; 1) a comparison of the acoustical performance of the OGAC pavement to the baseline DGAC and other pavement types, 2) a discussion of the acoustical attributes of the OGAC pavement, 3) a description of the effects of aging of the pavement on acoustical performance, 4) a description of seasonal trends in noise levels based on the data set, and 5) a description of the effect of wind conditions on the distant CTIM locations. A discussion comparing the CTIM and OBSI measurement techniques, as well as an analysis of the effectiveness of the OGAC pavement as a noise reduction technique as compared to an equivalent noise barrier and an assessment of the noise sensitivity of TNM to various model parameters is also included.

The OGAC pavement resulted in noise levels that were about 6 to 7 dBA below those measured for the baseline DGAC pavement at the CTIM reference positions, equivalent to the noise reduction achieved with an 8-foot high noise barrier. The OGAC has continued to maintain its acoustical characteristics and performance after a period of 10 years, with only a slight increase (~ 1½ dB) in noise levels over time. After 10 years, a more rapid increase in noise level occurred likely due to pavement raveling. Traffic noise levels for the OGAC overlay using the CTIM method increased by less than 3 dBA over the 12-year period and maintained similar spectra characteristics throughout the study. Changes in noise levels not attributable to pavement, such as those due to increased traffic volumes or changes metrological conditions, were found to result in variations of greater than 1 dBA at CTIM reference locations. Based on traffic noise modeling results for this investigation, changes in traffic along I-80 through the study area resulted in average noise increases due to traffic alone of about 1 dBA over the 12-year study period at the CTIM locations. Winter temperatures were found to result in noise levels that were, on average, 1.3 dBA higher than summer levels and wind conditions were found to affect noise levels by up to 2 dBA at only 65 feet from the edge of the near lane of the freeway and by 10 to 15 dBA or more at distances of 475 feet from the edge of the near lane of the freeway.

---

[a] Author's note: Sections 1 through 3 were original submitted as 10-year report and essentially remain unchanged. Results for year 11 and 12 were added in Section 4 as an update. The above summary and conclusions have been updated through year 12.

1 INTRODUCTION

Many studies have shown distinct differences in noise levels from traffic on different pavement surfaces[1,2,3]. With growing recognition that pavement selection can be an effective method for noise reduction, there has been increased interest on the part of highway agencies to consider the use of quieter pavements. In an effort to add quieter pavement selection as an option for noise abatement, the California Department of Transportation (Caltrans) is currently conducting several investigations into various aspects of this method of reducing noise, including noise measurement methodologies, acoustical performance longevity, pavement design parameters, and the use of pavement characteristics in traffic noise modeling software.

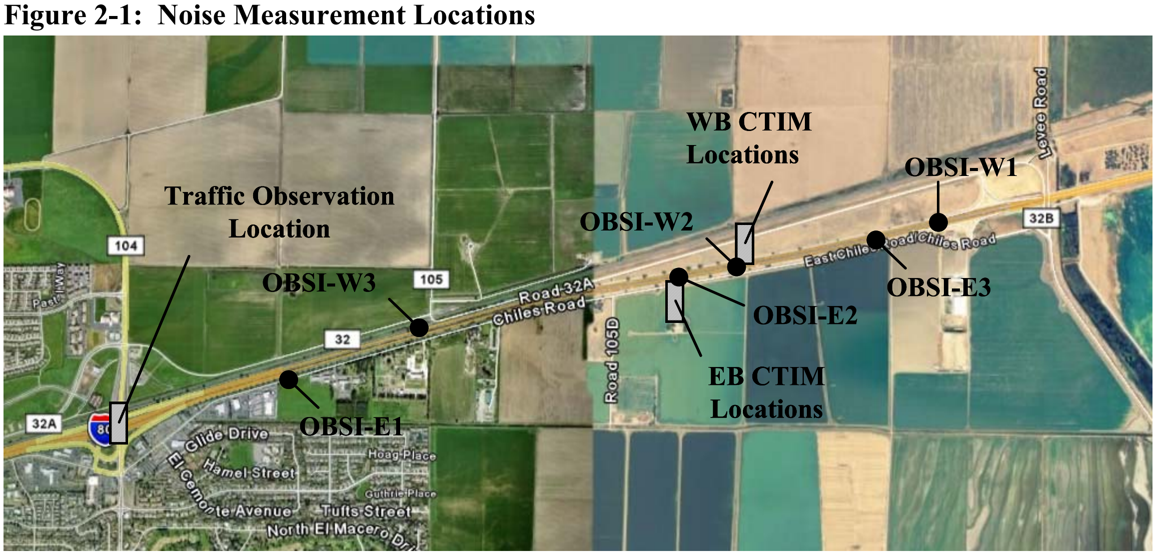
In order to evaluate the long-term performance of open-graded asphalt concrete (OGAC), Caltrans initiated a 10-year study to monitor the noise performance of a section of OGAC that was installed in 1998 on a high volume, multilane portion of Interstate 80 near Davis, California. This report presents noise data collected and results of the analysis through the first ten years of the study (1998 to 2008) with an update with measurements from 2009 and 2010 covering through year 12.

2 DESCRIPTION OF FIELD MEASUREMENTS AND DATA ANALYSIS METHODOLOGY

2.1 Description of Project Area

Measurements were conducted along Interstate 80 in Yolo County between Mace Boulevard and the Yolo Causeway (Yolo County Post Kilometer 9.3), just east of Davis, California. This section of Interstate 80 is a six lane divided freeway facility that lies adjacent to a floodplain, has no notable grade or cross slope, and is on a long tangent that passes through undeveloped agricultural fields. Urban development is occurring on the western end of the project area and is generating increasing traffic on the eastbound frontage road. A fairly dense 20-30 foot wide thicket of oleander vegetation separates the eastbound and westbound traffic lanes. Figure 2-1 shows the study area and measurement locations.

Figure 2-1: Noise Measurement Locations



2.2 Description of Pavement

Prior to the pavement rehabilitation project, the roadway bed consisted of 4.7 to 6.3-inch (120 to 160-mm) of dense graded asphalt concrete (DGAC) on top of a stabilized sub-grade. The pavement project consisted of the rehabilitation of the existing DGAC surfacing and the placement of a new AC overlay, made up of two different asphalt concrete layers. In some spots, the underlying base was removed and replaced. The new AC surfacing included the placement of 2.4-inch (60-mm) of dense-graded asphalt concrete (DGAC) leveling course in June and early July 1998 and the placement of a top layer made up of 1.0-inch (25-mm) of open-graded asphalt concrete (OGAC) in July 1998. A photograph of the OGAC pavement overlay is shown in Figure 2-2. Existing and project pavement overlay information were obtained from project plans[4]. Noise levels for the following pavement conditions were monitored for this study:

1. The original aged DGAC pavement - June of 1998, just prior to the pavement overlay,
2. The new DGAC leveling course - July of 1998
3. The OGAC overlay - August 1998, just after application, and
4. The OGAC overlay - three times per year (summer, winter, and spring) during the pavement aging process (1998 – 2008).

Asphalt material pavement types are described in Chapter 600 of the Highway Design Manual[5] and summarized as follows.

> **DGAC** consists of a mixture of bituminous material (paving asphalt) and a close graded aggregate ranging from coarse to very fine particles. DGAC is designated as Type A or Type B, depending on the specified aggregate quality and mix design criteria appropriate for the job conditions. Type A DGAC was used for this project.
>
> **OGAC** is a surface course used primarily over DGAC. The primary benefit of using OGAC is the reduction of wet pavement accidents by improving wet weather skid resistance, minimizing hydroplaning, reducing water splash and spray, and reducing nighttime wet pavement glare. Secondary benefits include better wet-night visibility of traffic stripes and markers, better wet weather (day and night) delineation between the traveled way and DGAC shoulders, and increased safety through reduced driver stress during rainstorms. OGAC surfacing is also known as an "open graded friction course".

The physical properties of the OGAC pavement at the I-80 Davis site has been measured and found to have an air void content of approximately 23%. With this level of void content, it would be classified as porous pavement. The maximum aggregate size has been measured to be ¾-in.

Figure 2-2: Photograph of OGAC Overlay

2.3 Test Methods

Noise evaluation of the pavement was conducted using two measurement approaches; the continuous flow traffic time integrated method (CTIM) of measuring traffic noise levels at locations adjacent to the roadway and the on-board sound intensity (OBSI) method of measuring tire-pavement noise close to the tire-pavement interface. A guidance document is currently being developed for CTIM as part of the FHWA Expert Task Group on Tire/Pavement Noise (ETG)[6] and a draft test procedure for the OBSI method is under development for the American Association of State Highway Agencies (AASHTO)[7]. Traffic volumes, travel speeds, and meteorological conditions were monitored simultaneous to CTIM measurements.

2.3.1 CTIM Measurements

The CTIM measurements followed the applicable procedures described in the FHWA document on highway noise measurements[8] and have been used as part of the foundation for the development of the ETG guidance document. Microphone locations differed from the FHWA procedure due to a need for site repeatability, site constraints, safety considerations, and to avoidance influencing freeway travel speeds. Traffic noise measurements were made at the following positions from the edge and elevation of the near travel lane of the freeway in both the eastbound and westbound directions:

1. Reference. Distance: 65-feet (20-meters), Height: 10-feet (3-meters)

2. Distant Low. Distance: 475-feet (145-meters), Height: 5-feet (1.5-meters)

3. Distant High. Distance: 475-feet (145-meters), Height: 15-feet (4.5-meters)

Reference locations were measured prior to the overlay (1998), just after, and 3 times per year (spring, summer, and winter) following the overlay application. Distant measurements were made during all summer monitoring periods, with additional monitoring in 1999, 2000, 2002, and 2003. Attended short-term measurements were made at the reference and distant locations during all measurement periods. CTIM measurements were made on mid-weekdays (Tuesdays, Wednesdays, and Thursdays) from about 9:00 am to 1:00 pm during free-flowing traffic conditions. Photographs of the measurement locations are shown in Figure 2-3.

Figure 2-3: Photographs of Wayside Measurement Locations

Overall A-weighted sound pressure levels were measured using Larson Davis Model 820 Sound Level Meters with ½ inch diameter G.R.A.S. Model 40DP random incidence microphones. L_{eq} and L_{50} noise levels were stored continuously in 5-minute intervals using the A-Weighting network (dBA) with a 'slow' response time (1 second exponential averaging). Simultaneous with the collection of continuous A-weighted data during each measurement day, 1/3rd octave band levels were sampled for at least two 5-minute periods at each location using a Larson Davis 2900 or 3000+ two-channel real time analyzer (RTA). The systems were calibrated at the beginning and end of each test session with a Larson Davis Model CAL200 Acoustic Calibrator. Measured CTIM noise level data are shown in Appendix A.

2.3.2 Onboard Sound Intensity Measurements

In 1998 when the study began, the OBSI measurement techniques had not been developed for use in a highway environment. At the time of the initial OBSI measurements, in September of 2002, the OBSI method was just beginning to be applied to the quantification of tire/pavement noise performance of pavements[9] in Caltrans projects. As such, some changes in the implementation of OBSI have occurred over time. However, the basic procedure has remained constant throughout the duration of this study and care was taken to ensure that changes to the procedure did not influence the results. Although this study predates the AASHTO draft standard, this study and other Caltrans-sponsored work were instrumental in the development of the procedure. As a result, the methods used in this study generally follow the procedures described in the current AASHTO draft standard.

Under the OBSI procedure, the sound intensity fixture and associated microphones were attached to and supported by the test vehicle alongside a test tire as indicated in Figure 2-4. Measurements were conducted on a 1997 Subaru Outback test vehicle with a single probe sound intensity fixture from September 2002 through December 2006. Beginning in April 2007, measurements were conducted on a 2004 Chevrolet Malibu with a dual probe fixture[10] to allow for the leading and trailing edge positions to be measured simultaneously. Each sound intensity probe consisted of two ½-inch G.R.A.S phased matched condenser microphones, installed on ½-inch G.R.A.S 26AK microphone preamplifiers, attached to a plastic probe holder at a spacing of 0.63 inches (16mm) in a side-by-side configuration, and fitted with a spherical windscreen. The probes were positioned 3 inches (75mm) above the pavement surface and 4 inches (100mm) from the face of the tire at locations opposite the leading and trailing contact patch of the tire. The probes(s) were oriented so that the sensitive axis was pointed toward the tire.

For the single probe measurement procedure, the microphone signals were input to a Larson Davis 2900 dual channel real-time analyzer and analyzed into ⅓ octave band levels in real time using a 5-second averaging time, corresponding to a distance of 440 feet at 60 mph. With the dual probe procedure, the microphone signals were acquired with the Bruel & Kjaer PULSE System in FFT narrow band and ⅓ octave band levels. Under both procedures, the microphones were calibrated using a Larson Davis Model CAL200 acoustic calibrator at the beginning and end of each measurement period. The acquired time signals of the microphones were viewed during data acquisition and, for the single probe the signals were also monitored audibly. Comparison testing conducted for the two systems on the Caltrans Pavement Research Test Section located on LA 138 in October 2006 found almost no bias between the two systems

Figure 2-4: OBSI Equipment Installed on the Test Vehicle

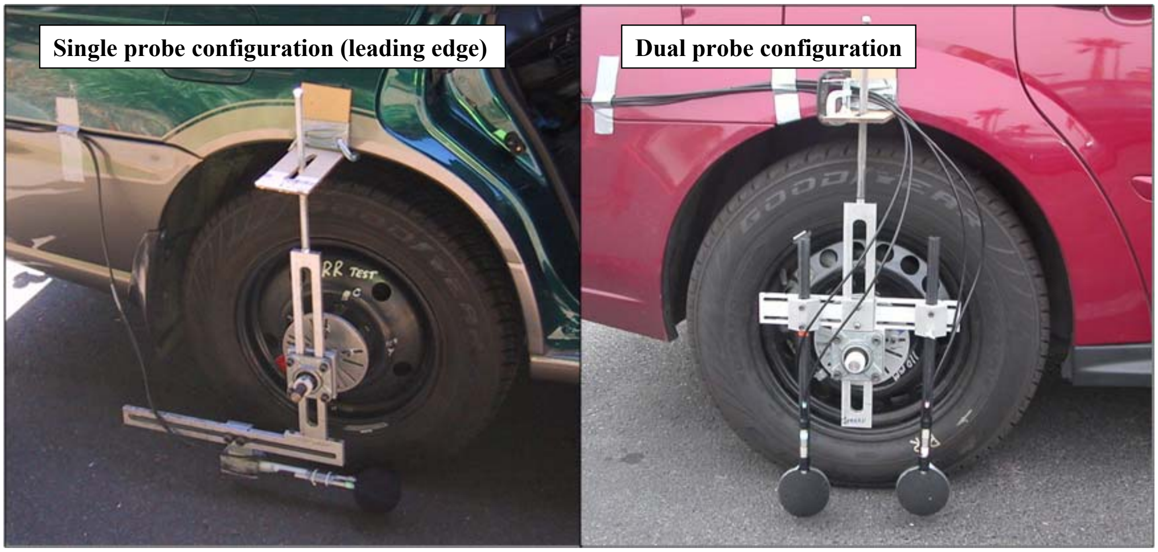


Figure 2-5: Goodyear Aquatred 3 Test Tire

and a relationship approaching 1-to-1. OBSI quality metrics of coherence between the two microphones comprising each probe and the difference between sound pressure and sound intensity level were monitored during data acquisition for the dual probe method and viewed during post processing under the single probe procedure. Data that did not meet the OBSI quality metrics was discarded.

Three (3) pavement measurement sections were selected for both the eastbound and westbound directions of travel between Mace Boulevard and the Yolo Causeway, for a total of six (6) sections. Measurement locations are indicated in Figure 2-1. Testing was conducted using a Goodyear Aquatred 3 test tire with a ‘cold’ tire inflation pressure of 30 psi and a load consisting of two people and the OBSI instrumentation. A photograph of the test tire is shown in Figure 2-5. Testing was conducted only in the outside through travel lane at a test speed of 60 mph (97 km/h) and test sections were selected to be nominally straight and free of dips or swells. Data from the leading and trailing edge positions were acquired separately and then averaged together during post-analysis. Three or more passes were made for each test section, which were averaged together during post analysis.

2.3.3 *Traffic Conditions*

Traffic conditions were monitored simultaneous to the CTIM measurements to facilitate the normalization of traffic noise levels at the CTIM positions. Vehicle volumes were counted manually in each travel direction of Interstate 80 for three vehicle types as defined by the U.S. national vehicle noise emissions database[11]; light-duty automobiles or trucks (2 axles, 4 tires, generally less than 9,900 lbs), medium trucks (2 axles, 6 tires, generally 9,900 to 26,400 lbs), and heavy trucks (3 or more axles, generally more than 26,400 lbs). Travel speeds were estimated based on spot measurements using a handheld STALKERatr radar gun.

Interstate 80 through the study area is a busy freeway with a considerably large amount of truck traffic. Caltrans[12] reports average annual daily traffic of 146,000 vehicles for 2006[b]. Trucks are reported to make up 7.6% of the volume on a daily basis. Truck volumes counted in this study were found to make up almost 10% of the volume. The higher measured truck percentage (compared to the Caltrans volumes) may have resulted because measurements were conducted during off-peak daytime travel periods. Free-flowing traffic speeds were relatively consistent throughout the study, with average auto speeds in the range of 67 to 71 mph (108 to 115 kph), and truck speeds in the range of 60 to 65 mph (95 to 105 kph). Slowed traffic conditions occurred very infrequently during the 9:00 am to 10:00 am hour and during occasional events on the freeway such as vehicle accidents or police pullovers. All data for slowed traffic or traffic congestion were discarded. Hourly average vehicle counts are shown in Appendix B.

2.3.4 *Meteorological Data*

Meteorological monitoring was conducted for June measurements. Air temperature and wind speed/direction were measured continuously in 5-minute intervals simultaneous to CTIM noise monitoring with a meteorological monitoring system manufactured by Met One Instruments. The system consists of a 10-meter tilt-style tower, equipped with wind sensors (speed and direction) at 10 meters, and temperature sensors (including an aspirated radiation shield) at both 2 and 10 meters above local grade. The data logger at the base of the tower provides power to the systems, processes signals from the sensors converting them to engineering units, and appropriately stores the data for retrieval by a portable computer. The monitoring system meets or exceeds the specifications established by the Environmental Protection Agency (EPA) for Prevention of Significant Deterioration (PSD) monitoring. Specific system components include:

- Universal 10-meter Tilt Tower and Base
- Met One Model 10B Wind Speed Sensor (at 10 meters)
- Met One Model 020B Wind Direction Sensor (at 10 meters)
- Met One Model 062 Air Temperature Difference Sensor (for 2 and 10 meters)
- Campbell Scientific CR10 Data logger
- Battery, Weatherproof Enclosure, and Cables for Data logger

Periodic measurements of dry and wet bulb temperature, which can be used to calculate relative humidity, were made manually using an Assman psychrometer. Ground level wind velocity was periodically

---

[b] West of the I-80 and US 50 junction, about 3 miles (5 kilometers) east of the study area.

measured at the attended noise measurement locations using Sims 3-cup digital anemometers. A summary of the measured meteorological conditions for each measurement period is included in Appendix C.

Measurement periods typically consisted of mostly clear skies (sun obscured by clouds less than 30% of each measurement period). Measurements were conducted during summer, winter, and spring to evaluate seasonal changes in pavement noise performance. Air temperatures were typically in the range of 70 to 85ºF (20 to 30ºC) during summer measurements, 45 to 55ºF (7 to 12ºC) in winter, and 60 to 70ºF (15 to 20ºC) during spring measurements. Summer and spring periods typically had a normal low-level temperature lapse of about –0.056ºF/ft (-0.10ºC/m) present. Because baseline measurements were conducted under summer conditions, summer measurements are emphasized in the report for comparison to baseline data.

Wind was typically present in the study area from spring through fall due to the flat and open topography of the area in the vicinity of the CTIM sites. Wind primarily blows across the roadway from southerly or northerly directions, resulting in a downwind or upwind condition at the measurement positions. Wind conditions are well documented to affect noise levels at distances greater than 100 feet from the roadway[13]. To assess the effects of wind on noise levels, data for the CTIM distant sites were categorized as *Upwind, Downwind*, or *Calm* using measured and observed meteorological conditions. Wind conditions are characterized by the magnitude of the cross-vector wind component with respect to the roadway; *Upwind* is less than 3.9-ft/s (+1.2-m/s), *Calm* is between –3.9-ft/s and +3.9-ft/s (–1.2-m/s and +1.2-m/s), and *Downwind* is greater than 3.9-ft/s (1.2-m/s). Care was taken to conduct measurements under similar seasonal meteorological conditions for each measurement year and measurements were avoided when winds exceeded 12 mph (5.5 m/s).

2.4 Data Analysis Methodology

2.4.1 Interference from Non-Highway Noise Events at CTIM Positions

To minimize noise contamination from noise sources other than the freeway at the CTIM measurement position, noise levels were measured continuously in 5-minute intervals. The noise measurement location was attended periodically during the measurement periods. Observers recorded noise levels associated with non-I-80 traffic events (e.g., aircraft, commuter rail, frontage road local truck traffic, etc.) to allow for editing of non-highway noise events from the data record. The following is a summary of the interference from non-highway noise events that occurred at each CTIM position and the methods used to minimize contamination of the data:

1. <u>Westbound Reference.</u> Mostly unaffected by noise sources other than freeway traffic. Intervals that were influenced by non-freeway noise sources, such as highway maintenance activities or freeway incidents, were removed from the data set.

2. <u>Eastbound Reference.</u> Periodically influenced by traffic using the adjacent frontage road (East Chiles Road). Traffic along this roadway was infrequent during the early years of this study, but increased gradually over time due to development further west. Increasing traffic on the frontage

road affected the eastbound reference noise levels slightly throughout the noise monitoring periods. Due to the noise contamination at the eastbound reference position, the data collected at the westbound reference position is considered more reliable for evaluating the noise level reductions from the OGAC overlay and findings in this study are primarily based on the westbound data set.

3. Westbound Distant. Periodically affected by traffic using the adjacent frontage road, as well as occasional aircraft and train passages. Westbound frontage road traffic was infrequent, with a high percentage of trucks that access the nearby landfill and vehicle speeds of about 45 mph (80 kph). Although infrequent, local traffic affected the measured L_{eq} substantially during almost all measurement intervals at the distant sites, causing the L_{eq} noise levels to be notably greater than the L_{50} levels. As a result, the L_{50} parameter was used for the analysis of noise attenuation between the westbound reference and distant locations. Periodically at the westbound distant sites, simultaneous freeway-only noise measurements were made by pausing the meter when other sources were significant (these types of measurements were made at each of the CTIM positions). These data were compared with corresponding continuous L_{50s} measured at the sites and found to be within one dBA agreement.

4. Eastbound Distant. Affected by infrequent farming activities and occasional aircraft or distant train passages. Tall corn or sunflowers during many of the summer measurement periods appeared to substantially affect the propagation of freeway traffic noise at the eastbound distant locations, especially the 5-ft (1.5-m) high microphone position. Data for any 5-minute interval that was substantially affected by non-freeway sources, such as infrequent farming activities and occasional aircraft or distant train passages, were discarded from the data set. Regular monitoring at the eastbound distant locations was discontinued in 2002 due to the difficulty in obtaining comparable data.

2.4.2 Traffic Noise Modeling for CTIM Positions

Federal Highway Noise Administration's Traffic Noise Model Version 2.5 (TNM) [14] was used to normalize traffic conditions for the purpose of evaluating noise level changes at the CTIM reference locations attributable to pavement. The model was not used to predict measured conditions. The TNM model is based upon the REMEL noise emission factors for automobiles, medium trucks and heavy trucks, with consideration given to vehicle volume, speed, roadway configuration, distance to receiver, and the acoustical characteristics of the site. The model was developed to predict hourly L_{eq} values for free-flowing traffic conditions. Inputs to the TNM model include the site geometry, traffic volumes, medium and heavy truck percentages, and vehicle speed. Traffic volumes, vehicle mix percentages, and traffic speeds were based on field observations and traffic volume counts conducted concurrent with the noise monitoring. Traffic conditions were converted to hourly data and input into TNM. Default (68ºF or 20ºC and 50% humidity) meteorological conditions, "average" pavement type were used in the model. A dense vegetation median was used to simulate the landscaped median (oleander bushes). "Field grass" ground type was used to describe the default ground for the majority of the study area. On the eastbound side, corn was present across much of the sound propagation path for the distant locations (about 330-ft or 100-m of the 475-ft or 145-m path) for about half of the summer measurement days. The cornfield was modeled as a tree zone. Model sensitivity testing found that the selection of different ground types had little effect on the results on the reference location model predictions and temperature and humidity had up to a 0.3-dBA effect on the results at the reference locations and up to 0.9 dBA at the distant locations[15]. Free-flowing traffic speeds were relatively consistent during the measurements. Slowed traffic conditions occurred very infrequently during the 9am to 10am hour and during occasional events on the freeway such as vehicle accidents or police pullovers. All data for slowed traffic or traffic congestion were discarded.

At the start of the study (1998), TNM 1.1 was used as the most up to date traffic model available from FHWA. Since 1998, several updates to TNM have been made available, including TNM 2.1 and TNM 2.5, which is currently (2008), the most up to date model available from FHWA. As the model was updated over time, modeling for 'new' measured data was conducted using more recent versions of the FHWA model. For consistency, the traffic conditions that had previously been modeled using older versions of the software were remodeled using TNM 2.1 in 2002 and again using TNM 2.5 in 2005. The results of this study are described based on TNM 2.5. Although small differences between the overall traffic noise levels occurred, the normalized results using TNM 2.5 were similar to findings from use of the previous versions of the model. An analysis of the effectiveness of the OGAC pavement as a noise reduction technique as compared to an equivalent noise barrier and an assessment of the noise sensitivity of TNM to various model parameters is included in Section 4.6.

2.4.3 Normalization of Traffic Noise Levels at CTIM Reference Positions

TNM was used to normalize CTIM traffic noise conditions and not to test or validate the model for the measured conditions. All monitoring periods were normalized to average traffic conditions existing on the first monitoring period (baseline) in June 1998. Normalization values were determined by calculating the difference in hourly modeled noise levels between each hourly monitoring period and the baseline, based on traffic conditions entered into TNM. The normalization values were then applied to measured noise levels for each monitoring period to allow for comparison of data. Modeled noise levels varied by about 2-dBA. An increase of about 1 dBA occurred over the 10-year study due to increases in traffic. No measurable changes in traffic could be detected over the study period. Unless otherwise noted, the overall CTIM noise levels are normalized for traffic conditions. The sampled traffic noise spectra were not normalized.

3 RESULTS OF FIELD MEASUREMENTS AND ANALYSIS

Noise evaluation of the OGAC pavement was conducted using the CTIM and OBSI measurement methods. Measurements were conducted for more than 70 days over the past 10 years, resulting in a total of more than 275 hours of noise monitoring and generating an extensive data set. Results discussed in this report include; 1) a comparison of the acoustical performance of the OGAC pavement to the baseline DGAC and other pavement types, 2) a discussion of the acoustical attributes of the OGAC pavement, 3) a description of the effects of aging of the pavement on acoustical performance, 4) a description of seasonal trends in noise levels based on the data set, and 5) a description of the effect of wind conditions on the CTIM locations. A discussion comparing the CTIM and OBSI measurement techniques, based on preliminary comparison testing, is included in Section 4.6, as well as an analysis of the effectiveness of the OGAC pavement as a noise reduction technique as compared to an equivalent noise barrier and an assessment of the noise sensitivity of TNM to various model parameters is also included.

3.1 Acoustical Performance of OGAC Overlay

This section compares the acoustical performance of the OGAC pavement to other pavements measured using the CTIM and OBSI measurement results. The CTIM reference location results for the OGAC pavement are compared to the noise levels measured at the same locations for the aged pre-overlay DGAC pavement and traffic noise levels modeled using TNM 2.5. Results at the distant CTIM locations are also discussed briefly. Following the CTIM discussion, OBSI levels are used to compare the Davis I-80 OGAC pavement to a database of other RAC, AC, and PCC pavements measured throughout the western United States.

3.1.1 CTIM Measurements

Measured noise levels at the westbound reference CTIM position during each summer monitoring period are shown in Figure 3-1 for the aged baseline DGAC and new/aged OGAC overlay conditions. Data shown are not normalized for traffic or meteorological conditions. The baseline measurements were taken on two days with different wind conditions (upwind/downwind) on each day resulting in the indicated scatter in those data. For the overlay data, scatter is inherent in the data resulting from traffic, meteorological, and other variables. Even with this scatter, the measured traffic noise levels for the OGAC pavement were substantially lower than the baseline DGAC and continue to be lower after 10 years. Review of the figure indicates a clearly measureable difference in noise levels associated with these two pavement types. Results for the eastbound position were similar.

The westbound reference CTIM noise levels for the OGAC overlay for the 1 month old and 10-year old conditions are shown in Figure 3-2, compared to the aged pre-overlay DGAC pavement and traffic noise levels modeled using TNM 2.5. As described earlier in this document, CTIM noise levels were normalized for traffic conditions. All pavements measured at the CTIM location (the old AC and new/aged OGAC) utilized the same test sites, eliminating the need to normalize the data for variables such as lane configuration, elevation, and ground type (although some ground type changes did occur even within this data set). Data could not be normalized for changes in meteorological conditions.

Figure 3-1: Measured Noise Levels at Westbound Reference CTIM Position

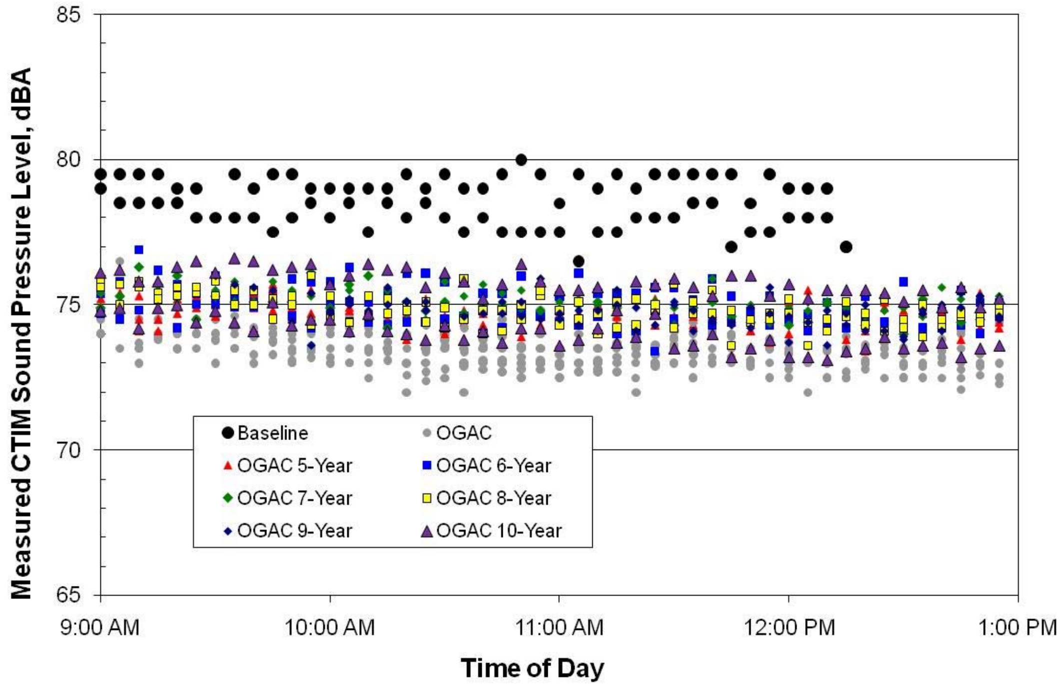
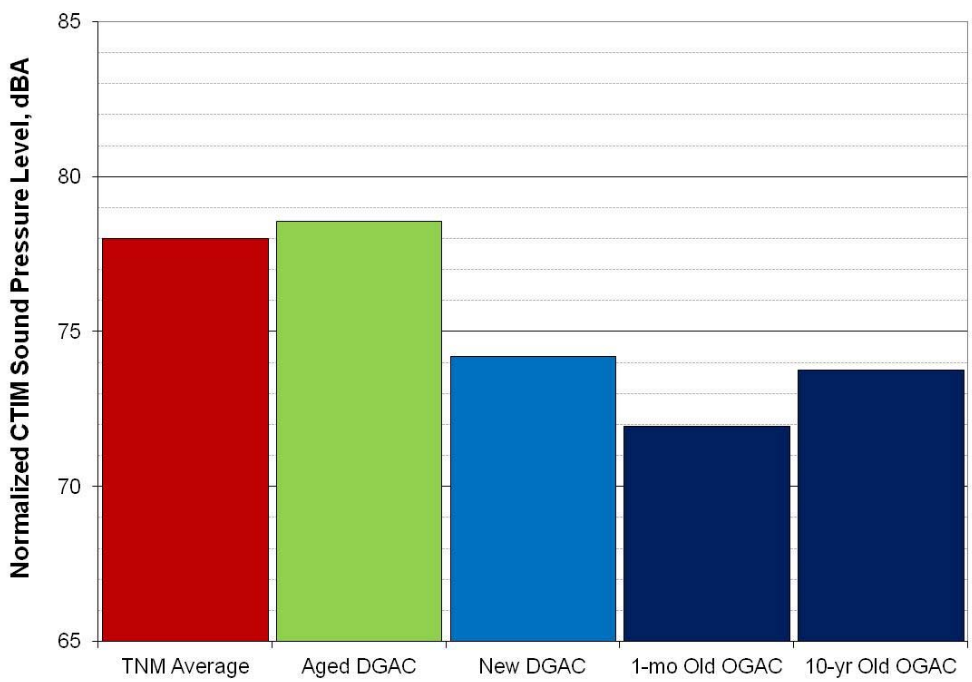


Figure 3-2: Normalized Sound Pressure Levels at CTIM Position for OGAC and Other Pavements



As indicated in the figure, reference CTIM noise levels for the aged DGAC baseline pavement were within 1 dBA of the TNM 2.5 modeling results and 4 to 7 dBA higher than the OGAC pavement traffic noise levels. The aged OGAC pavement increased by about 1 dBA over a period of 10 years from the new OGAC pavement condition, but continued to result in noise levels of about 5 dBA below the original aged DGAC pavement and 4 dBA below the TNM 2.5 Average pavement even after 10 years.

The eastbound CTIM position resulted in levels that were, on average, about 0.7 dBA higher than those measured at the westbound position. The higher noise levels at the eastbound CTIM location are likely attributable to interference from local frontage road traffic. As discussed previously, the L_{50} descriptor was used at the eastbound location in an effort to reduce the influence of the local frontage road traffic on the data. While this procedure did reduce the influence of the local frontage road traffic on the data, it is likely that some noise from this secondary source contributed to the measured noise levels at the eastbound reference location. Conversely, the L_{50} noise descriptor would not be expected to result in the same levels as the L_{eq}. For the westbound CTIM location, which was mostly unaffected by noise sources other than the freeway, the L_{50} noise levels were typically about 0.6 to 0.8 dBA lower than the L_{eq} levels.

Considerable variation in the acoustical data at the distant CTIM locations occurred, resulting primarily from wind conditions (see Section 4.5). To assess the effect of the OGAC overlay on traffic noise levels at the distant positions, measured noise levels for baseline aged DGAC were compared with noise levels associated with the OGAC under comparable wind conditions (see Figures 3-3 and 3-4). Noise levels were not normalized for traffic or meteorological conditions.

Under downwind conditions, when noise levels are highest, levels appear to be reduced by 3 to 5 dBA with the OGAC overlay. Upwind conditions produce an average reduction of about 3 to 4 dBA is indicated under upwind conditions with the OGAC overlay. Based on calm wind conditions, the OGAC overlay appears to generate noise levels that are about 10 dBA for the elevated position below those modeled using TNM 2.5. For the ground level position, the difference is greater, in the range of 13 to 15 dBA. The difference at both of these locations are likely attributable mostly to the accuracy of the model and modeling effort. These reductions are apparent, even after 10 years.

Figure 3-3: Measured Noise Levels at Westbound Distant Elevated CTIM Position

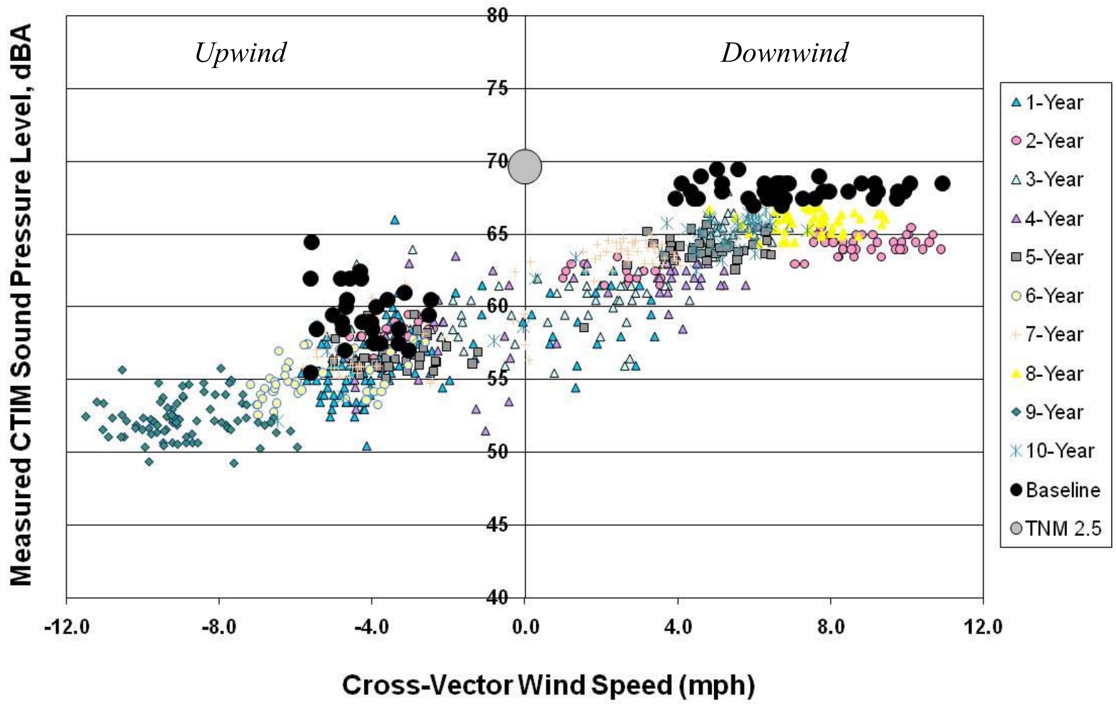
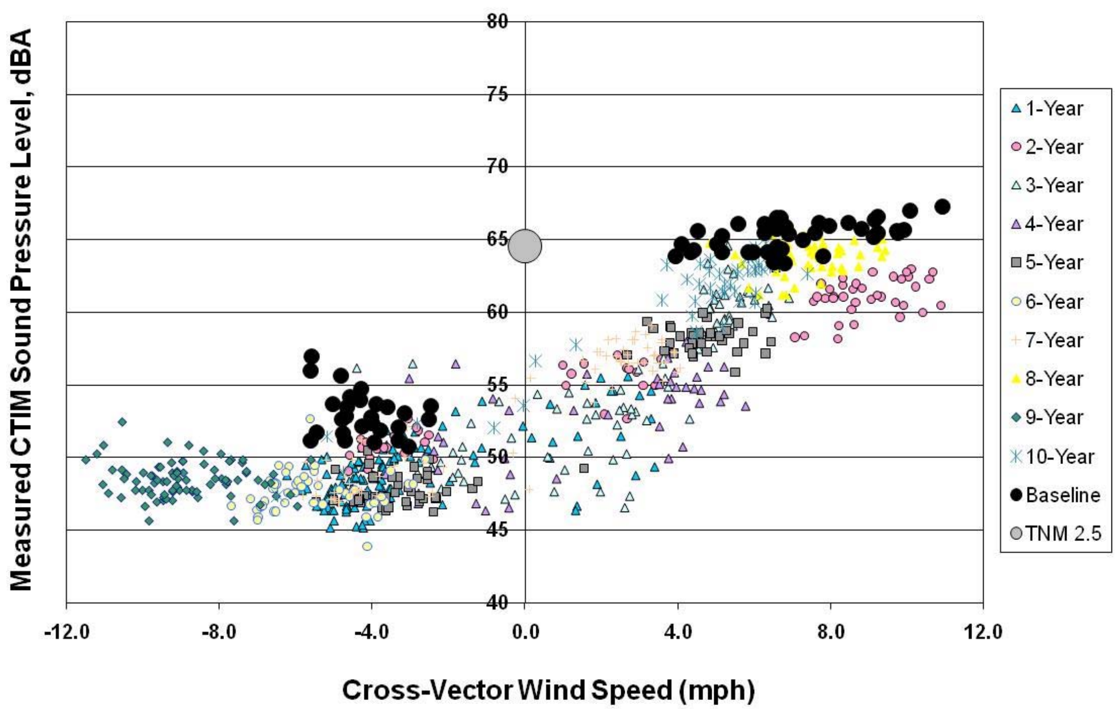


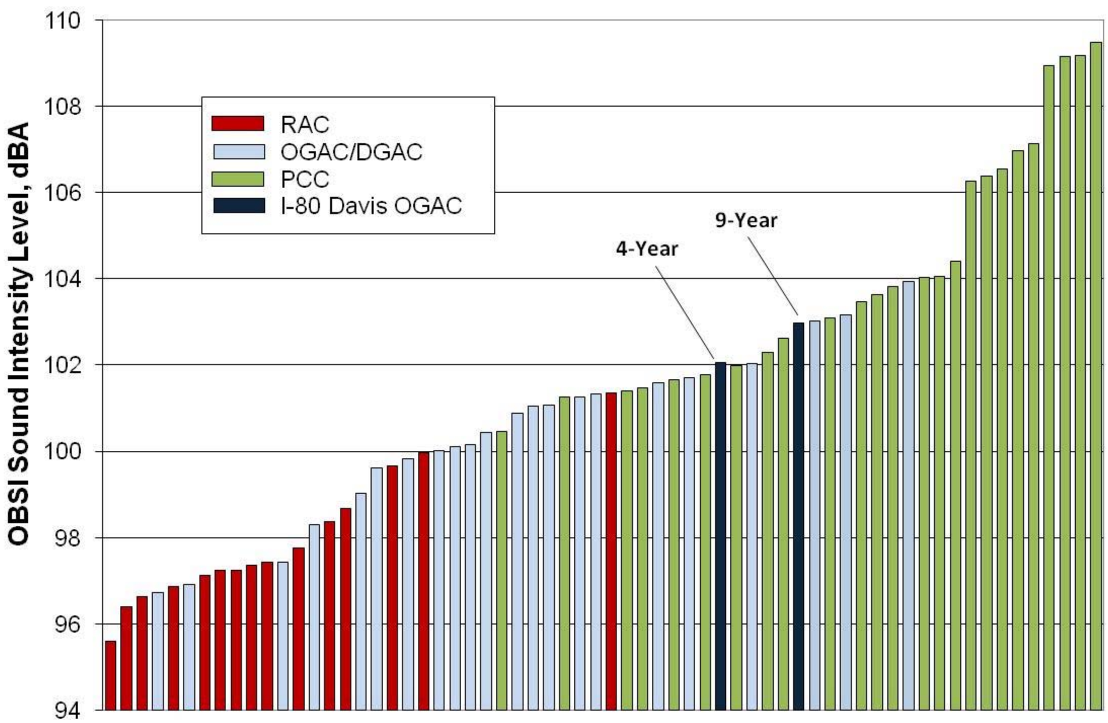
Figure 3-4: Measured Noise Levels at Westbound Distant Ground Level CTIM Position



3.1.2 Onboard Sound Intensity Measurements

Although OBSI measurements were not undertaken for this study until September 2002, and therefore, the baseline AC pavement was not measured, a large database of measured OBSI levels using the same methodology and test configuration discussed earlier in this report exists, which allows for the contextualization of the Davis I-80 pavement within a range of pavements measured using the OBSI method. Figure 3-5 shows the overall A-Weighted OBSI levels of the Davis I-80 OGAC overlay measured in September 2002 (4-year) and June 2007 (9-year), averaged over test sections in both the eastbound and westbound directions, as compared with other pavements in California, Arizona, and Nevada. OBSI measurements were not undertaken for this study until September 2002, and therefore the aged DGAC and new DGAC pavements were not measured. All OBSI shown were data measured by Illingworth & Rodkin, Inc. at 60 mph using the Aquatred 3 test tire under temperate, dry conditions, using the same methodology and test configuration discussed earlier in this paper. RAC, OGAC and DGAC, and PCC pavement types are indicated by color; the Davis I-80 data is indicated in dark blue.

Figure 3-5: Overall A-weighted OBSI levels for pavements in AZ, CA, and NV, 60 mph



As indicated in Figure 3-5 the overall OBSI levels for the Davis I-80 OGAC pavement were within the mid range of all pavements measured in Arizona, California, and Nevada and in the mid to upper range of OGAC pavements. The four year old pavement resulted in OBSI levels that were about 6 dBA greater than the new asphalt rubber friction course (ARFC) measured in the Arizona Quiet Pavement Pilot Program along SR 101[16] and about 8 dBA lower than the randomly transverse tined PCC pavement measured along I-215 in Nevada[17]. OBSI levels for the nine year old pavement were about 1 dBA higher than for the four year old pavement. The eastbound pavement resulted in OBSI levels that were, on average, 0.7 dBA higher than the westbound pavement. This is similar to the results for the wayside measurements, which also found that the eastbound reference noise levels were, on average, 0.7 dBA higher than the westbound reference levels. Although the eastbound and westbound sections were paved to the same specification, each was paved with a different batch of asphalt and installed on different days.

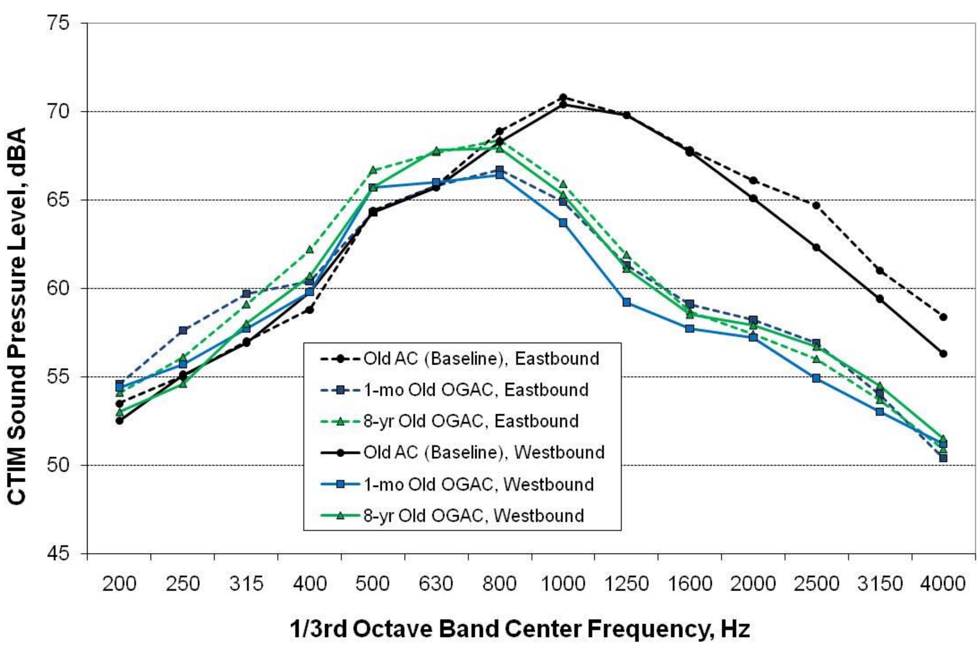
3.2 Spectral Attributes of OGAC Overlay

This section describes the acoustical attributes of the OGAC pavement as indicated for the CTIM and OBSI measurement results. A discussion comparing the two measurement techniques, based on a preliminary comparison analysis is included in Section 4.6.

3.2.1 CTIM Measurements

The ⅓ octave band spectra measured for the eastbound and westbound reference CTIM positions are shown in Figure 3-6 for the aged DGAC baseline pavement, the 1-month old OGAC, and the 8 year old OGAC measured during summer months. The data are not normalized for traffic or meteorological conditions; however, similar conditions existed for the compared data. Taking these variables into account, the eastbound and westbound results show consistent spectral shapes and trends. The ⅓ octave band spectra for the OGAC overlay are typical of porous pavements, which generally have reduced levels in the 1,600 to 2,500 Hz bands. Frequencies between 500 and 1,000 Hz, which are typically controlled by pavement roughness, varied or large aggregate size, and positive pavement texture, dominate the overall noise levels for this pavement. Observation of the pavement (see Figure 3-2) shows this to be a larger aggregate pavement with positive pavement texture.

Figure 3-6: ⅓ Octave band levels for Aged DGAC and OGAC Overlay at Westbound CTIM Reference Position



A comparison between the spectra for the OGAC and aged DGAC (baseline) pavement indicates that the noise reductions primarily occurred in the frequencies above 800 Hz. These were reduced by as much as 10 dB in some frequency bands as compared to the baseline pavement. This decrease is attributable to the increased porosity in the OGAC pavement as compared to the DGAC. Noise spectra for frequencies below 800 Hz were similar for both pavement types, with the OGAC resulting in slightly higher levels as compared to the baseline pavement. This is indicative of more surface texture for the OGAC pavement. The aged OGAC overlay exhibits a slight increase in noise levels as compared to the new OGAC, while maintaining the same noise spectra characteristics.

The ⅓ octave band spectra measured for the westbound distant CTIM positions during summer months are shown in Figures 3-7 and 3-8 for elevated position and in Figures 3-9 and 3-10 for the ground level position. As indicated in these figures and discussed further in Section 4.5, noise levels at the distant locations were typically 5 to 10 dB quieter under upwind conditions than downwind conditions. Even taking the meteorological variations into account, representative ⅓ octave band data collected at both westbound distant CTIM sites showed similar trends in noise levels to the OGAC overlay measured at the reference CTIM positions. Therefore, substantial decreases below the baseline DGAC pavement occurring in frequencies from 1000 Hz to 4000 Hz under both downwind and upwind conditions. In addition, although the overall noise level varied considerably at the distant CTIM locations due to differences in wind conditions, the noise spectra characteristics were maintained and the spectral shape at the distant locations was consistent with the spectral shape at the reference CTIM locations.

Figure 3-7: ⅓ Octave band levels for Aged DGAC and OGAC Overlay at Westbound CTIM Distant Elevated Position under Upwind Conditions

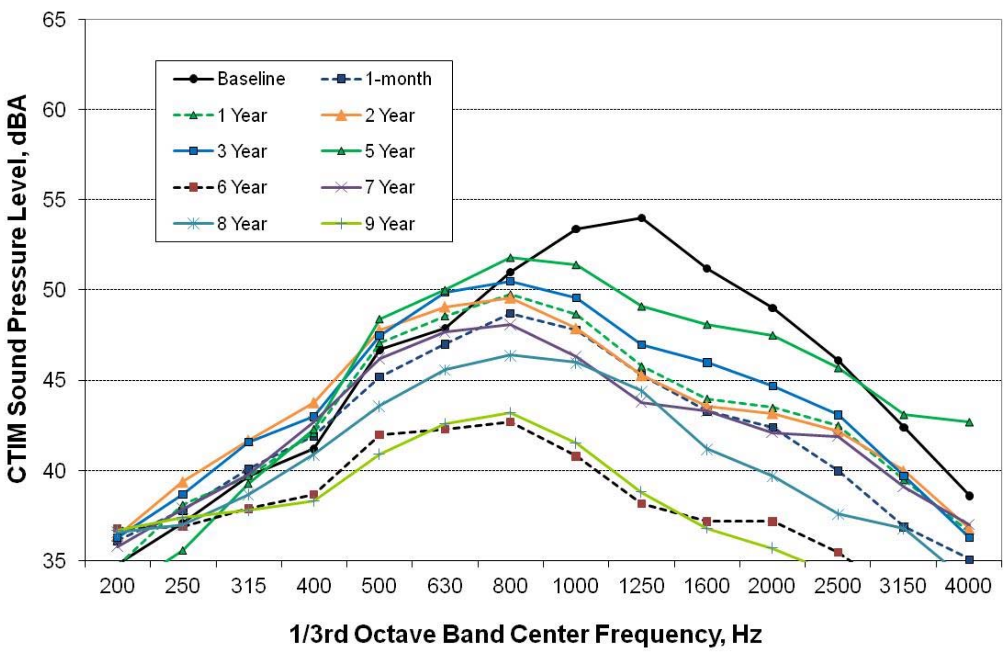


Figure 3-8: ⅓ Octave band levels for Aged DGAC and OGAC Overlay at Westbound CTIM Distant Elevated Position under Downwind Conditions

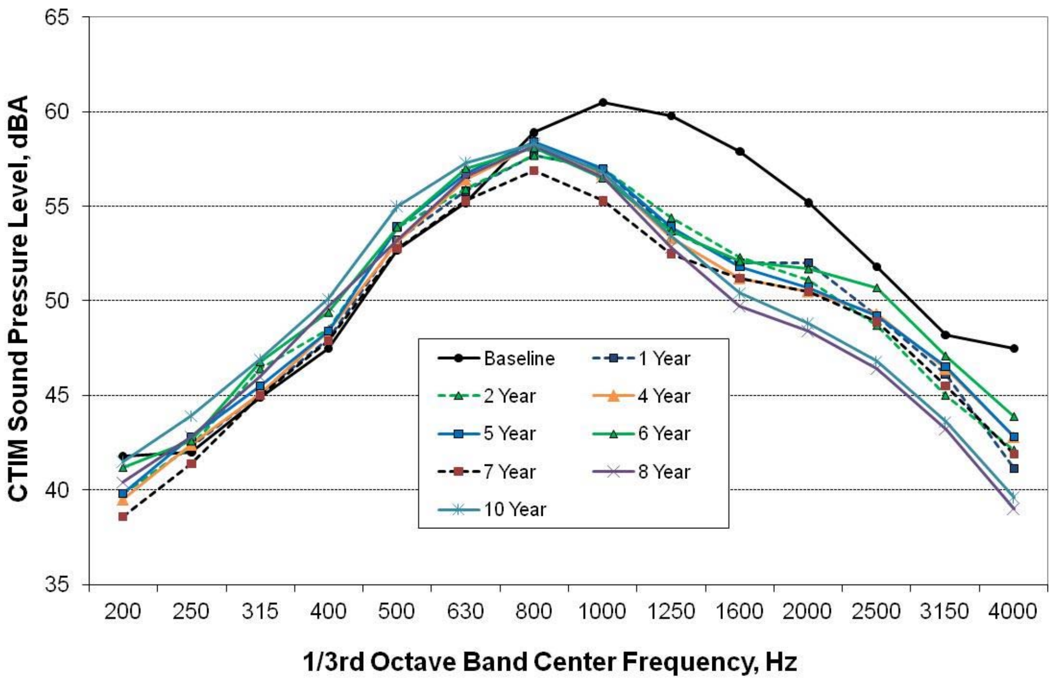


Figure 3-9: ⅓ Octave band levels for Aged DGAC and OGAC Overlay at Westbound CTIM Distant Ground Level Position under Upwind Conditions

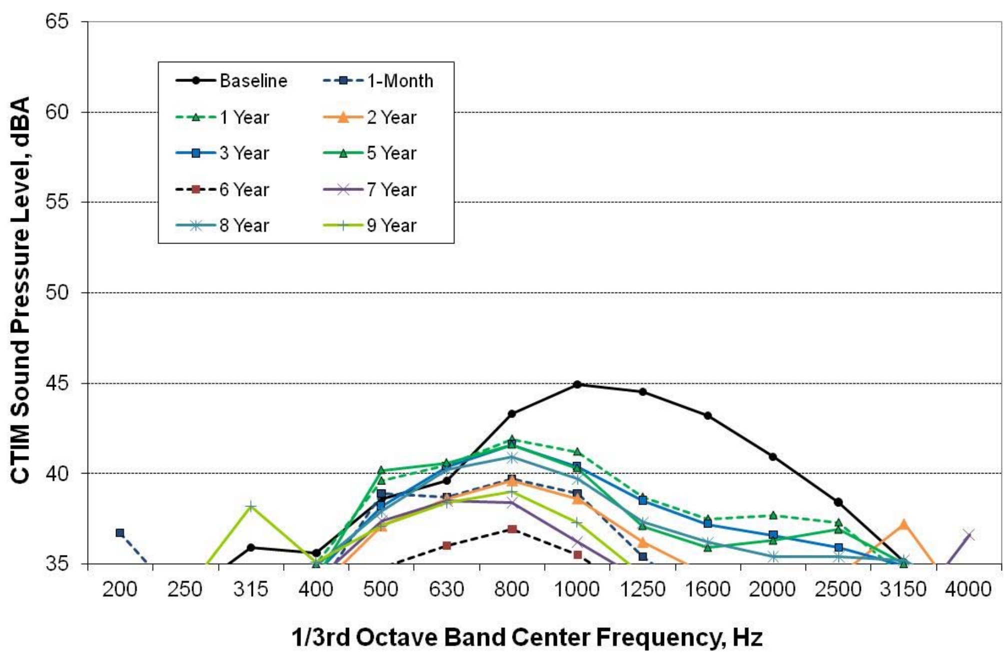
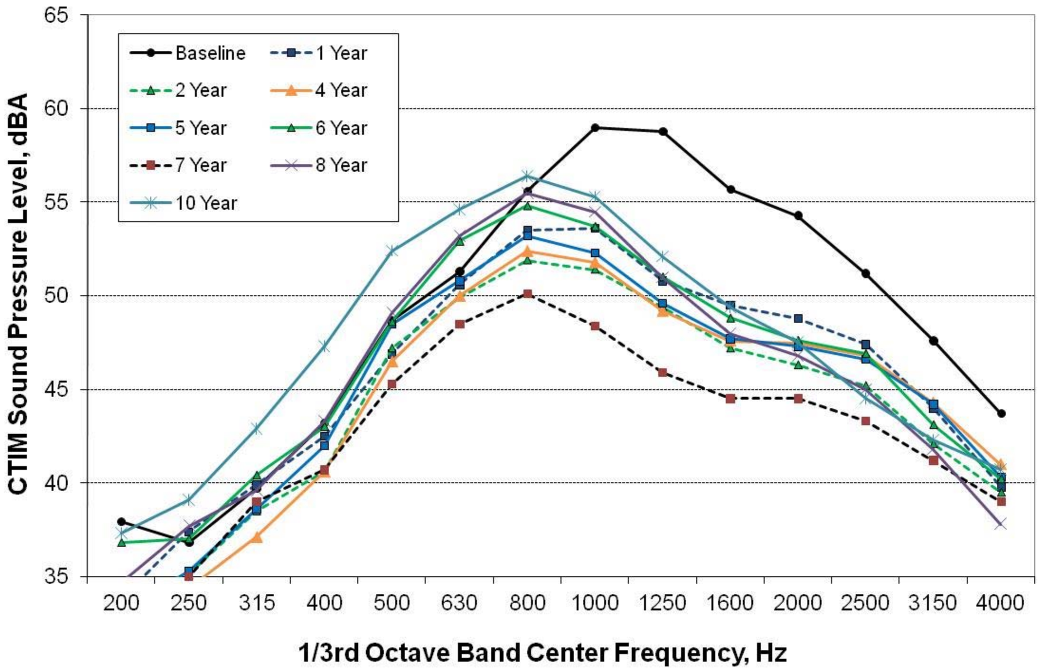


Figure 3-10: ⅓ Octave band levels for Aged DGAC and OGAC Overlay at Westbound CTIM Distant Ground Level Position under Downwind Conditions



3.2.2 Onboard Sound Intensity Measurements

Figure 3-11 plots the average OBSI spectra measured for the eastbound and westbound directions. Similar to the wayside results, the OBSI spectra indicate reduced levels in the 1,600 to 2,500 Hz bands with low frequency levels dominating the overall noise levels for the pavement. The eastbound and westbound directions resulted in similar spectral characteristics, although throughout the measurements, the westbound side resulted in OBSI levels that were, on average, about 0.7 dBA quieter than those measured on the eastbound side (with a standard deviation of about 0.4 dBA). This is similar to the wayside measurement results, which also found that the eastbound reference noise levels were, on average, 0.7 dBA higher than the westbound reference levels (see Section 3.1). As indicated in Figure 3-11, the quieter levels on the westbound side resulted from lower levels in the 800 to 1600 Hz bands; again similar to the wayside results (see the 1-month old OGAC data in Figure 3-6).

Figure 3-12 shows the spectra measured for each of the 6 sections (3 eastbound and 3 westbound) during the June 2006 measurements, which were indicative of the general variations between the established sections. The spectra between the six sections is relatively consistent, although levels diverged by up to 3.5 dBA in the frequencies between 800 to 1600 Hz bands and at 2500 Hz and above. The six sections resulted in very similar levels (within 1 dBA) at frequencies below 1000 Hz and in the 2000 Hz frequency band. All three of the westbound sections resulted in reduced levels in the 800 to 1600 Hz bands and raised levels at 2500 Hz and above, relative to the eastbound sections. For the westbound side, sections WB-1 and WB-2 were almost identical, while on the eastbound side, sections EB-2 and EB-3 resulted in

Figure 3-11: Average ⅓ Octave band OBSI levels for Eastbound and Westbound Travel Lanes

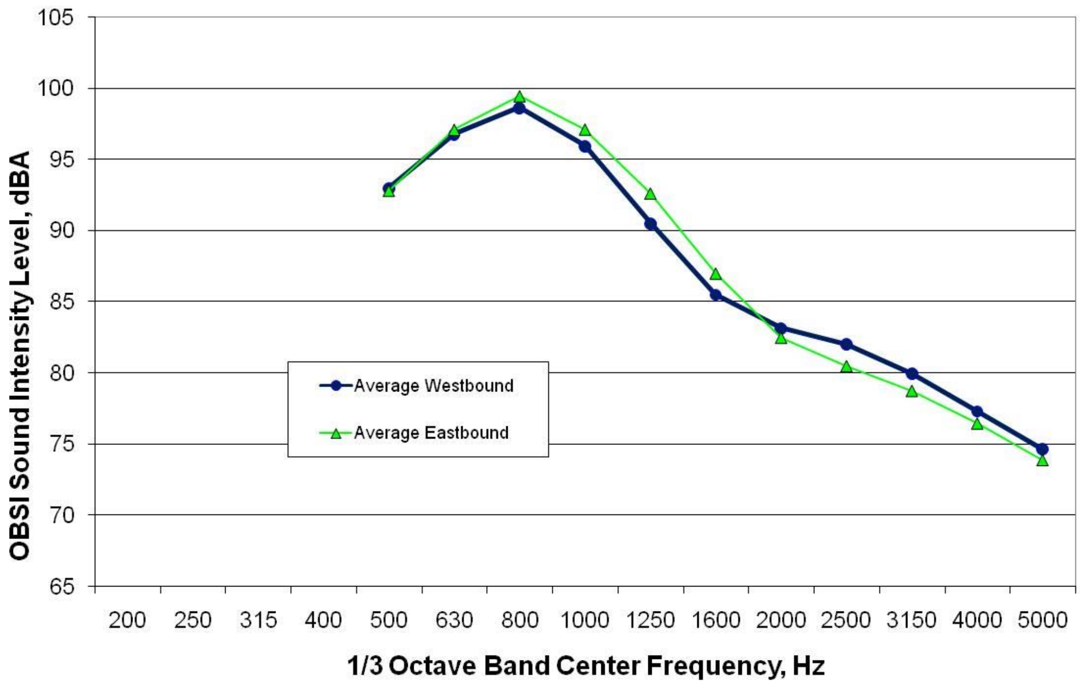
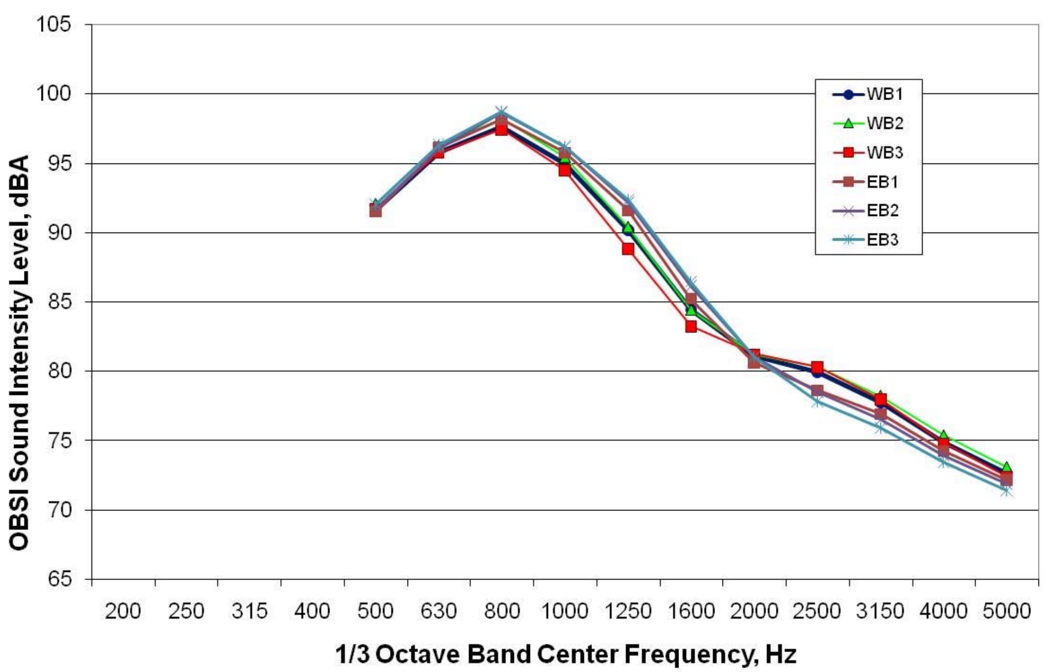


Figure 3-12: ⅓ Octave band OBSI levels for Each Test Section



similar levels. The remainder of this report will focus on the average OBSI levels for the eastbound and westbound directions only and will not include data for the individual test sites.

3.3 Aging of OGAC Pavement

One of the primary goals of this research was to monitor and evaluate the long term performance of a quieter highway pavement on reducing traffic noise. To assess the relationship between traffic noise level and pavement age, CTIM noise levels were monitored over a 10-year period beginning in 1998. OBSI measurements were conducted beginning in September 2002. June noise levels for the reference CTIM positions, normalized for traffic conditions and averaged for each measurement period, are shown in Figure 3-13. The OBSI levels for both the westbound and eastbound directions during each June measurement period are shown in Figure 3-14. Noise levels are not normalized for changes in meteorological conditions. The relationship between traffic noise and pavement age at the distant CTIM locations could not be meaningfully assessed due to the considerable variation in the acoustical data resulting primarily from wind conditions.

Figure 3-13: Normalized Reference CTIM Levels during Summer Monitoring Periods

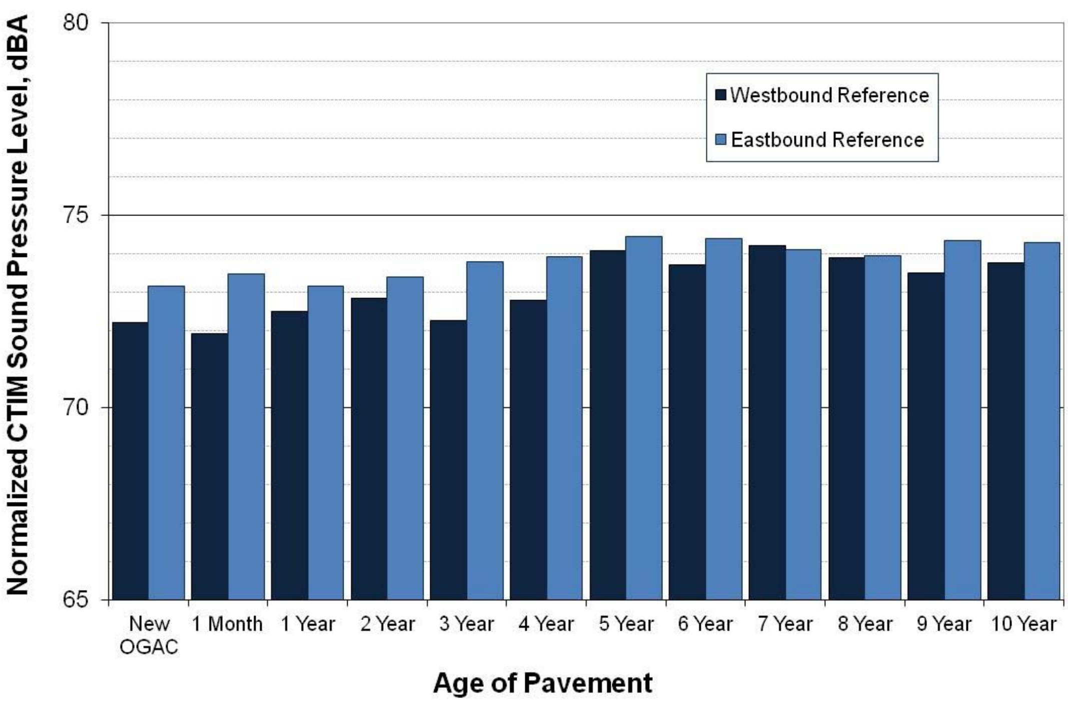
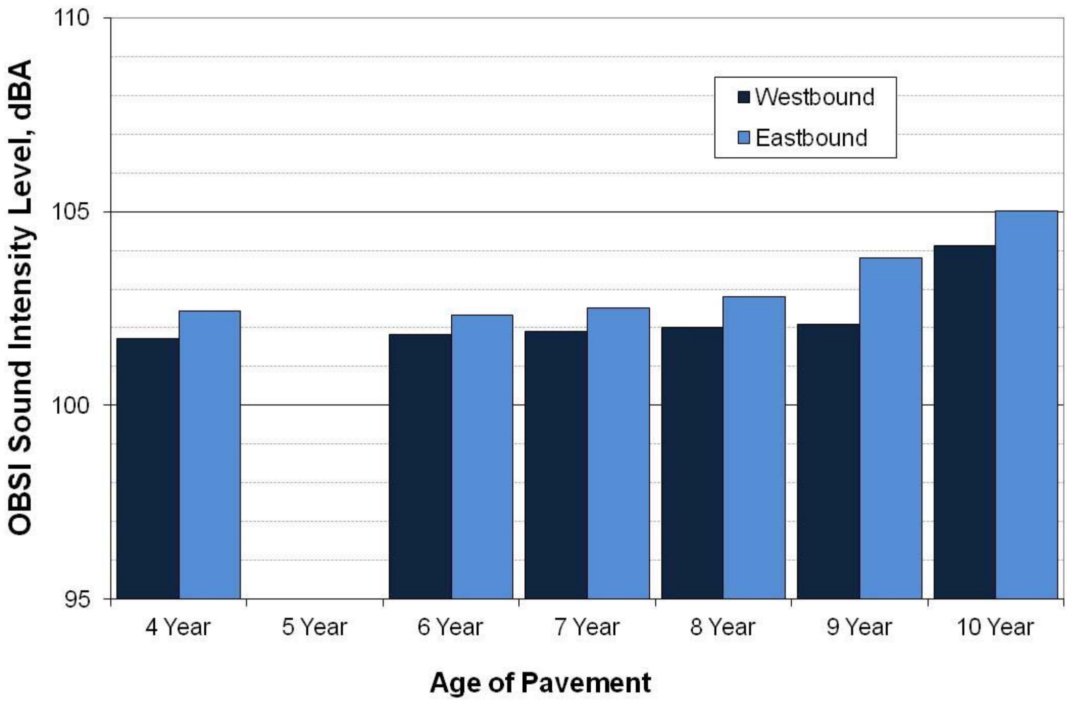


Figure 3-14: OBSI Levels during Summer Monitoring Periods



Based on the June data, the reference CTIM levels were found to increase at an average rate of about 0.2 and 0.1 dBA per year at the westbound and eastbound directions ($r^2 = 0.70$ and 0.71, respectively). The eastbound CTIM position resulted in levels that were about 0.7 dBA higher on average than those measured at the westbound position (as discussed in Section 4.1). The June OBSI levels were found to increase at an average rate of about 0.3 and 0.4 dBA per year for the westbound and eastbound directions, respectively ($r^2 = 0.51$ and 0.68). Not including the June 2008 OBSI data, which resulted in about a 2 dBA increase above the June 2007 data, the westbound OBSI summer data indicated a 0.1 dBA increase per year with an r^2 of 0.97. The westbound CTIM results over the same time period as the OBSI measurements, from 2002 to 2007, also showed an increase of 0.1 dBA per year. This abrupt increase in noise levels for the June 2008 measurements suggests physical unraveling of the pavement after 10 years possibly localized to outside travel lanes. Further testing would be needed to confirm this hypothesis.

The ⅓ octave band spectra for the OGAC overlay are plotted in Figure 3-15 for the westbound CTIM location against the aged DGAC pavement and in Figure 3-16 for the westbound OBSI, measured during the summer monitoring periods. Review of the spectra shows that although the levels are increasing somewhat over time, the spectral characteristics for the pavement have been maintained for both the CTIM and OBSI measurements. The spectral data are not normalized for traffic or meteorological conditions and slight shifts in the overall levels of the spectra are at least partially attributable to these variables.

Figure 3-15: ⅓ Octave band levels for Summer Monitoring Periods at Westbound CTIM Reference Position

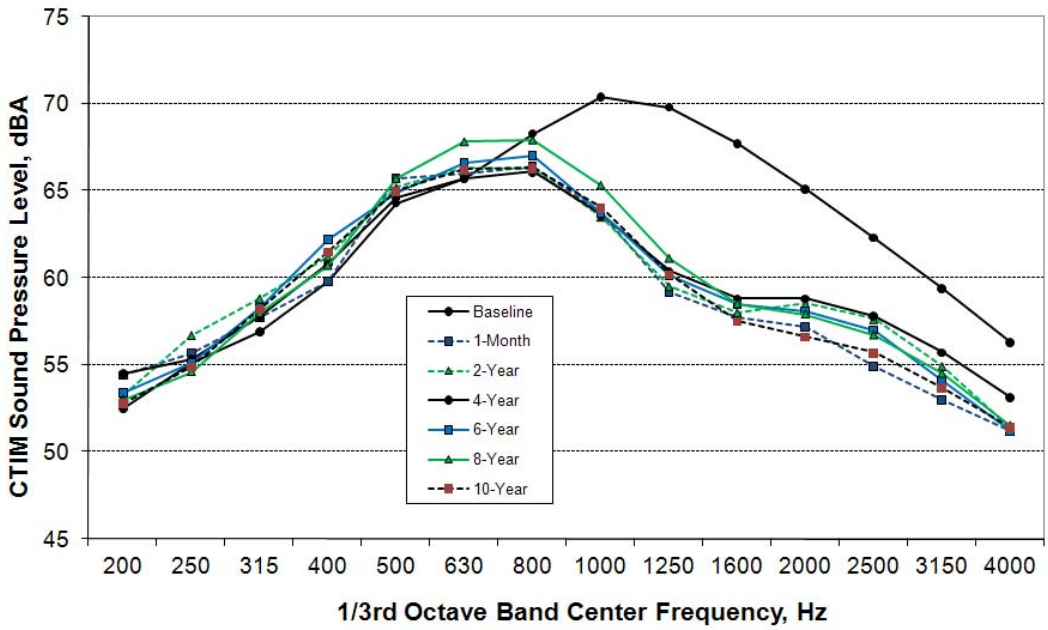
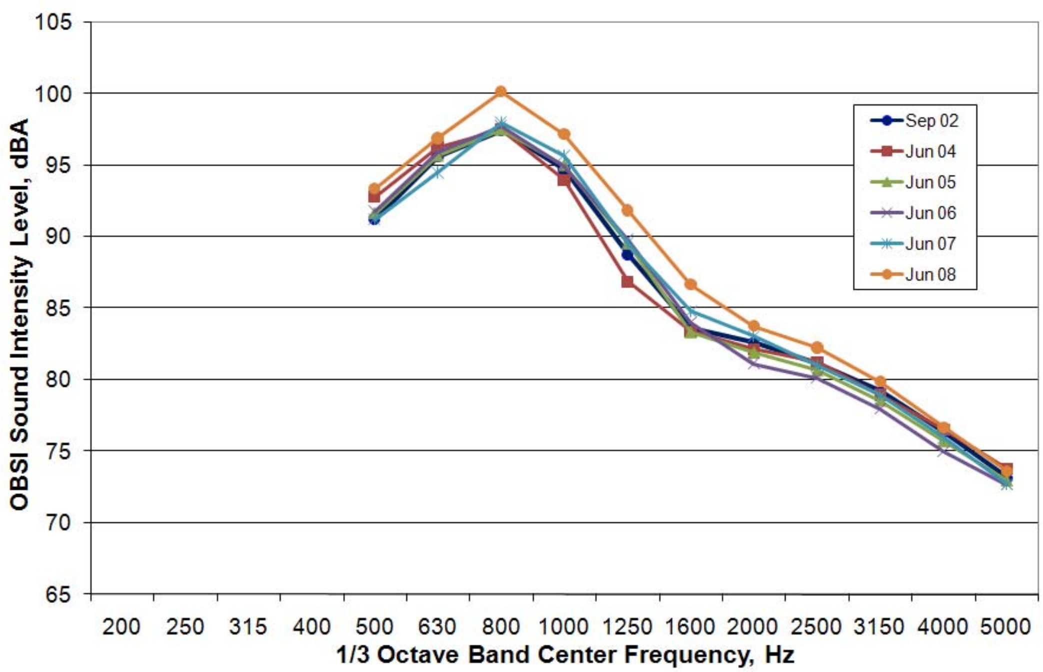


Figure 3-16: ⅓ Octave band OBSI levels during Summer Monitoring Periods, Westbound



3.4 Seasonal Trends

To assess seasonal trends, CTIM reference and OBSI measurements were conducted three times per year under spring, summer, and winter conditions. Figures 3-17 and 3-18 plot the overall A-weighted noise levels for the westbound CTIM reference and OBSI measurements, respectively, indicating seasonal measurements by color. Summer measurements are indicated in red, winter in blue, and spring in green. Noise levels are not normalized for changes in meteorological conditions or pavement age, although Figure 3-17 is normalized for traffic conditions. Even given the considerable scatter in the data, it is apparent that the levels varied seasonally, with the loudest noise levels associated with the coldest temperatures (winter). Based on the westbound data, CTIM noise levels were on average about 1.3 dBA louder during winter than during summer measurements. Spring conditions, which were more similar to summer, only had a 0.4 dBA difference. OBSI noise levels were, on average, about 1.7 dBA and 1.0 dBA louder during winter and spring measurements, respectively, than during summer measurements. OBSI variations are similar to, although somewhat greater than the variations indicated with the CTIM data. Figures 3-19 and 3-20 plot the westbound CTIM and OBSI data, respectively, for summer, spring and winter measurement periods. Although overall levels are higher during colder temperatures, the spectral shape is not affected substantially.

Figure 3-17: Seasonal Trends in Westbound CTIM Reference Levels

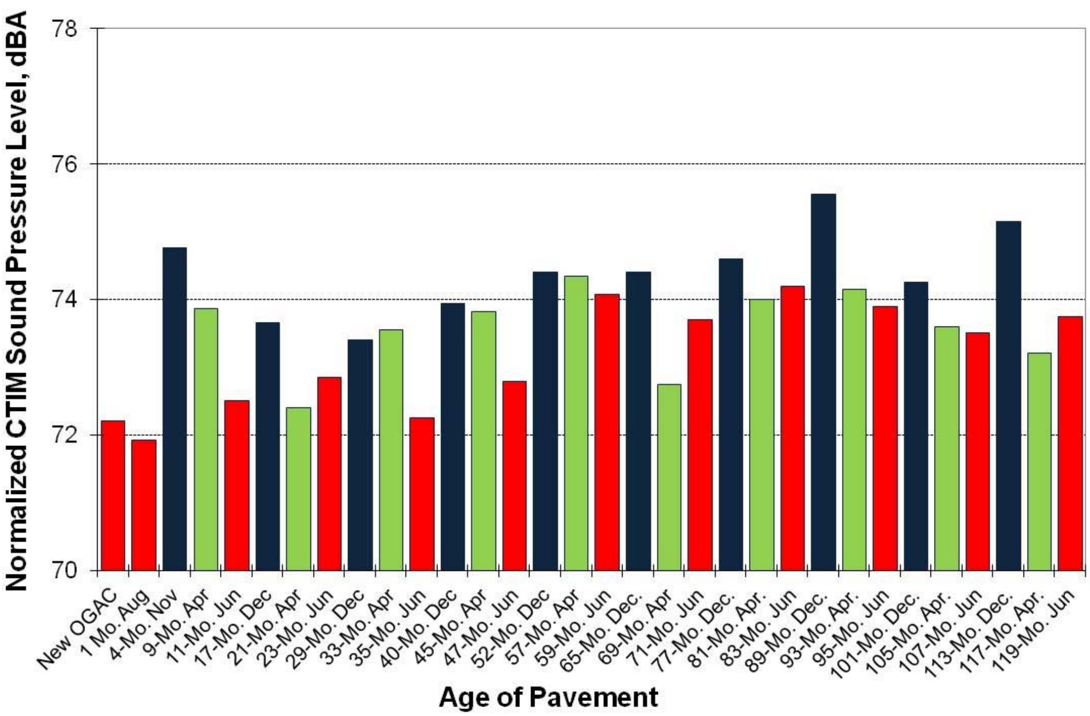


Figure 3-18: Seasonal Trends in Westbound OBSI Levels

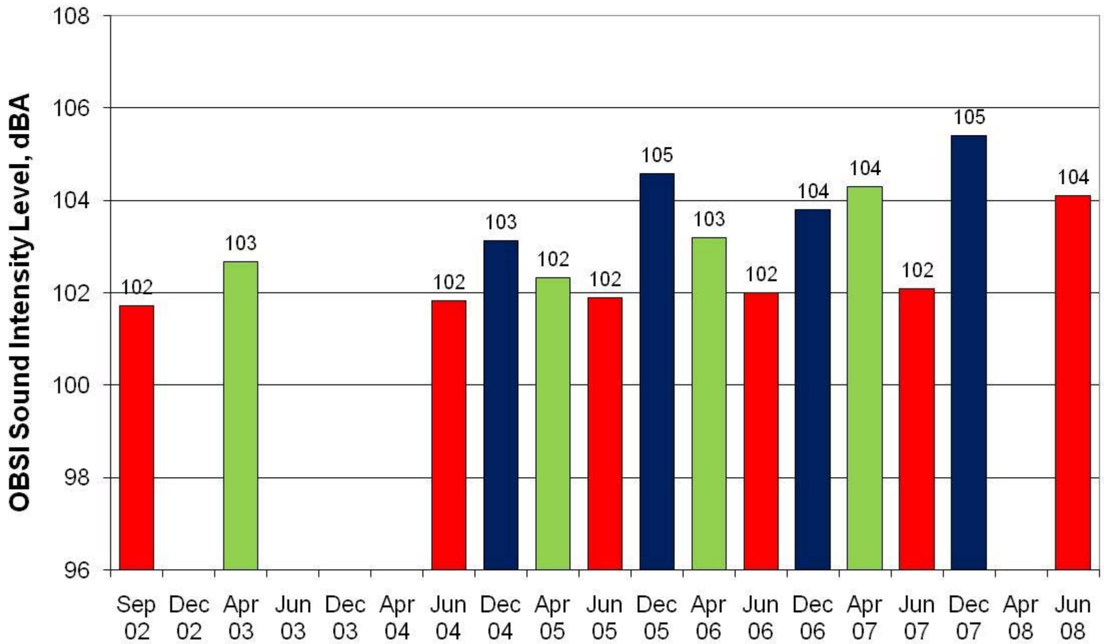


Figure 3-19: ⅓ Octave band levels for OGAC Overlay, 2006 Westbound CTIM Reference

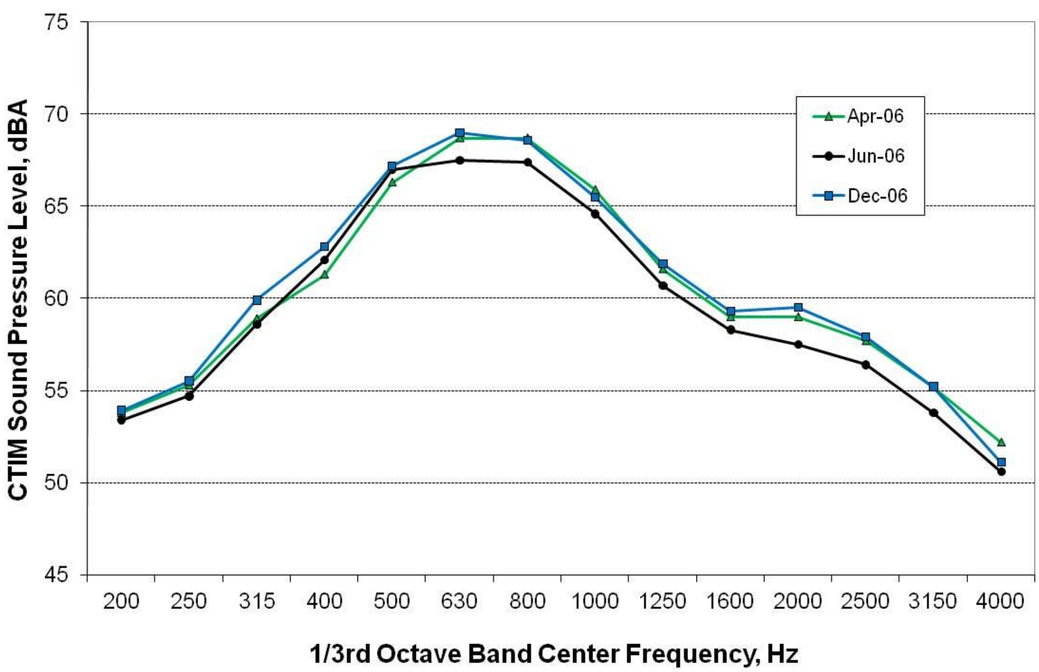
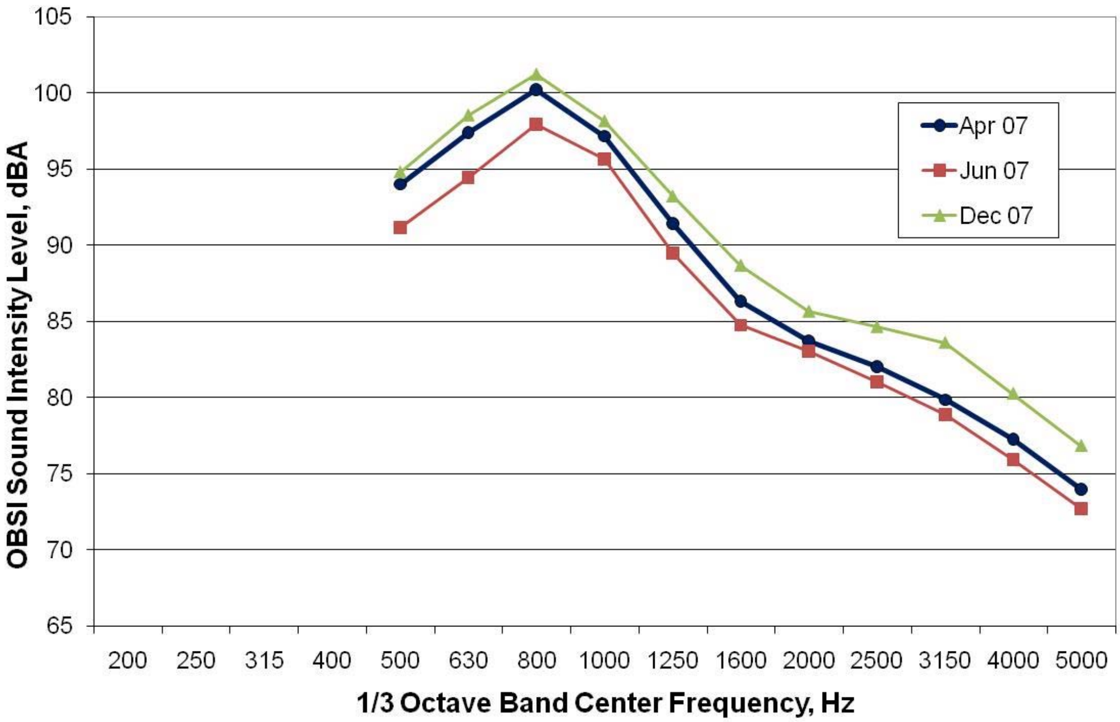


Figure 3-20: ⅓ Octave band levels for OGAC Overlay, 2007 Westbound OBSI

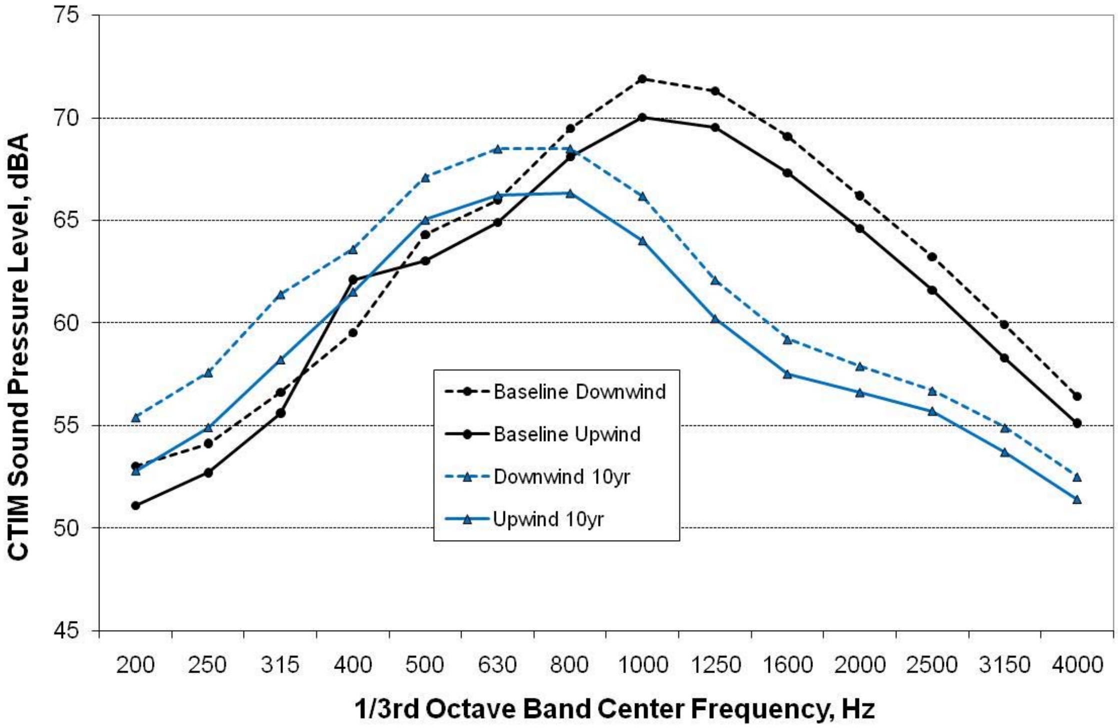


3.5 Effect of Wind Conditions on CTIM Noise Levels

As discussed in Section 3.3, wind flow was typically present in the study area from spring through fall due to the flat and open topography of the area in the vicinity of the CTIM sites. Wind primarily blows across the roadway from southerly or northerly directions, resulting in a downwind or upwind condition at the measurement positions.

Figure 3-21 shows the affect of wind on sound propagation at the westbound reference CTIM site (worst case shown). As indicated in the figure, noise levels at CTIM levels under downwind and upwind conditions fluctuated by up to about 2 dBA at the reference CTIM locations. Measured noise levels cannot be normalized for changes in meteorological conditions. As a result, some variation in noise levels would be attributable to these variations.

Figure 3-21: Effect of Wind on Noise Levels – CTIM Westbound Reference Position



Considerable fluctuation in measured traffic noise levels occurred at the distant CTIM sites due primarily to changes in meteorological conditions. Figures 3-22 and 3-23 show the affect of wind on sound propagation at the CTIM distant sites. The sound propagation is indicated with respect to the calculated delta or difference in noise levels between the reference and distant CTIM positions to minimize the influence of changes in traffic volumes on the distant CTIM data; a higher delta is representative of a lower sound level at the distant position. Considerable scatter is inherent in the data, especially for calm and upwind conditions, indicating that wind was not the only variable and/or that the measurement methodology used to describe wind is not adequate. Based on a linear interpolation, noise levels decreased by 0.9 dB /per mph at the elevated position (15-ft or 4.5-m above ground) and 0.75 dBA per mph at the ground level position (5-ft or 1.5-m above ground) over a crosswind vector range of -7.5 (upwind) to +9.5 mph (downwind). The effect of the magnitude of the crosswind vector over a range of -6 to +6 mph was typically 9 dB for the elevated position (15-ft or 4.5-m above ground) and 11 dB for the ground level position (5-ft or 1.5-m above ground). However, it should be noted that wind effects on traffic noise propagation do not appear to be linear (see Figures 3-22 and 3-23). At higher wind speeds, wind noise itself dominates the noise environment at the distant CTIM locations during upwind conditions. Because traffic noise levels are lower under upwind conditions than downwind conditions, wind-induced noise becomes dominant at lower wind speeds than under downwind conditions. TNM 2.5 under predicted the attenuation (which would result in an over-prediction of the traffic noise level) by about 6 dBA at the ground level position and by about 3 dBA at the elevated position under neutral wind conditions.

Figure 3-22: Effect of Wind on Noise Levels – CTIM Westbound Distant Elevated Position

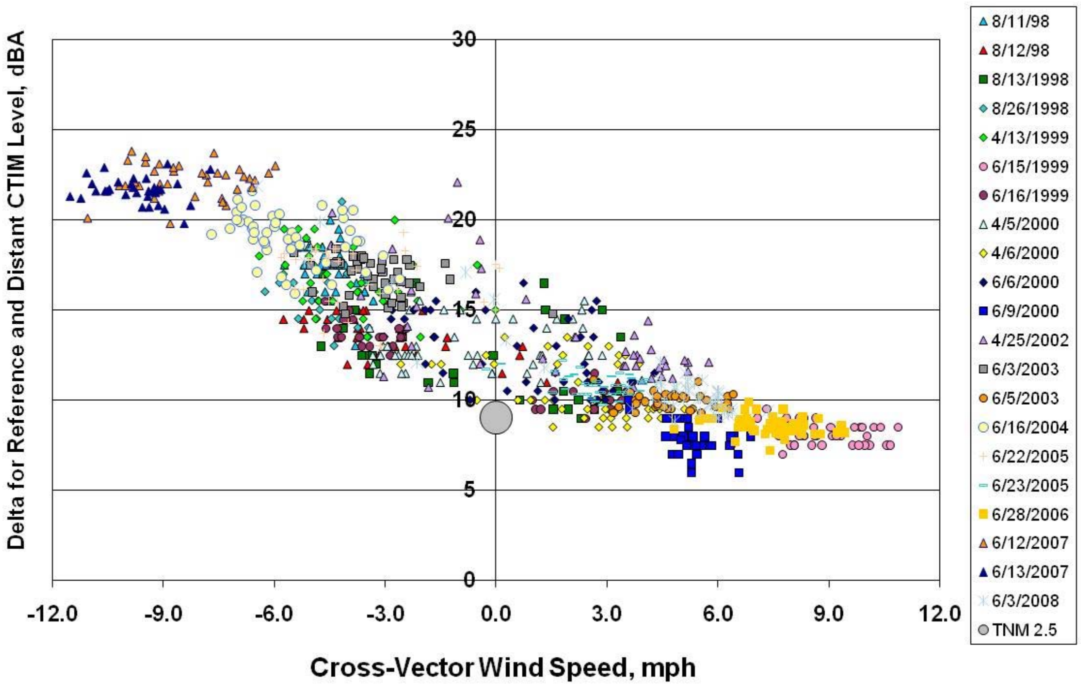
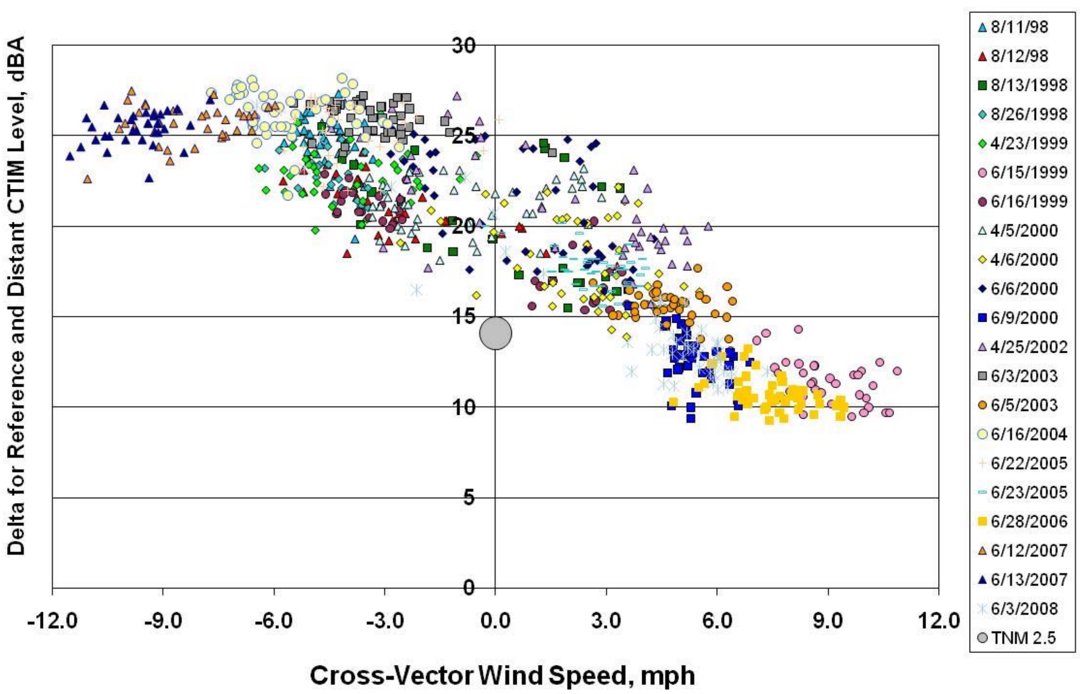


Figure 3-23: Effect of Wind on Noise Levels – CTIM Westbound Distant Ground Level Position



3.6 Additional Analysis of Measurement and Modeling Techniques

This section provides additional information and analysis on the measurement and modeling techniques used for this research investigation, including 1) a discussion comparing the CTIM and OBSI measurement techniques, based on preliminary comparison testing, 2) an analysis of the effectiveness of the OGAC pavement as a noise reduction technique as compared to an equivalent noise barrier, and 3) an assessment of the noise sensitivity of TNM to various modeling parameters.

3.6.1 Equivalent Noise Barrier Analysis

TNM 2.5 was used to determine the barrier height that would be required to obtain the same amount of noise reduction as that produced by the OGAC overlay. In this analysis, traffic data was input to the model with a *Field Grass* ground type and *Average* pavement type. The barrier was modeled for the CTIM positions on the westbound side of the roadway and with barrier modeled at the edge of the westbound shoulder. Results of the analysis are presented in Table 3-1 for barrier height increments of 2-ft (0.6-m) over the range from 6 to 16-ft (1.8 to 4.9 m).

Table 3-1: Analysis of Traffic Noise Reduction Produced by Roadside Sound Wall

Measurement Position	Measured Noise Reduction	Barrier Height (Ground type=Field Grass)					
		6-ft	8-ft	10-ft	12-ft	14-ft	16-ft
Reference	5 to 7	3	6	8	11	13	15
Distant Ground	4 to 5	2	2	3	6	7	8
Distant Elevated	4 to 5	4	5	6	6	11	12

Review of these results indicates that an 8-ft (2.4-m) high barrier would be required to achieve the same level of noise reduction performance at CTIM reference and distant elevated positions as that of the OGAC overlay. A 12-ft (3.7-m) high barrier would be required to achieve the same reduction at the CTIM distant ground level position.

3.6.2 Traffic Noise Modeling Sensitivity Test

Although the purpose for using the TNM model was to normalize CTIM measurement results for traffic conditions and not to accurately predict traffic noise levels at the microphone positions, the large differences between measured and modeled noise levels warrant some examination of the model input values. The model inputs included default (68ºF or 20ºC and 50% humidity) meteorological conditions and *Average* pavement type. A dense vegetation median, 8-ft (2.4-m) high was used to simulate the landscaped median (oleander bushes). Field grass ground type was used for the majority of the study area. Values for temperature or relative humidity were not varied for the model results.

TNM 2.5 under the predicted CTIM traffic noise levels by about 0 to 1.0 dBA at the reference measurement locations for existing DGAC pavement conditions and over predicted traffic noise levels by 3 to 6 dBA after placement of the OGAC during summer and spring monitoring periods. TNM 2.5

showed about a 1-dBA variation in the noise level resulting from the typical variations in traffic speeds encountered.

As part of the analysis conducted for the 7th year summary report in 2005[18], which included the update of modeled noise levels to TNM version 2.5, an investigation into the sensitivity of the model to variations in ground type and pavement type selections was made. Table 3-2 shows the difference at each westbound CTIM position between the different pavement and ground type conditions. The following discussion is based on modeling results using the average hourly traffic conditions for the June 2005 measurements. Intermediate represents an position measured during the June 2005 monitoring period, 130-ft (40-m) from the edge of the near travel lane, and 5-ft (1.5-m) above the ground.

Table 3-2: Analysis of TNM Modeling Conditions of Pavement Type and Ground Cover

Measurement Position (Measured Post-Overlay Level)	TNM 2.5 Model Results (dBA)					
	Average Pavement Type		OGAC Pavement Type		PCC Pavement Type	
	Field Grass (Standard)	Hard Soil	Field Grass	Hard Soil	Field Grass	Hard Soil
Reference (75 dBA)	78.7	79	76.9	77.4	80.8	81.1
Intermediate (68 dBA)	75.1	76.4	73.2	75.4	77.2	78.3
Distant Elevated (64 dBA)	69.9	70.1	67.5	69.1	71.1	71.9
Distant Ground (57 dBA)	65.2	69.3	60.8	69.1	64.0	70.6

Sensitivity to Ground Type - It is difficult to assess the measured drop off rate due to the meteorological influences at the distant positions, which are not accounted for in TNM 2.5. However, the measured average drop off rate is estimated to be 6 to 7 dBA per doubling of the distance from the roadway. TNM 2.5 indicates that noise levels drop off at a rate of about 5 to 6 dBA per doubling of the distance from the roadway using *Field Grass* and about 3 to 4 dBA per doubling of the distance from the roadway using *Hard Soil*. Changing the ground type to *Hard Soil* raised the modeled noise levels by 0.3 at the reference position, by 1 to 2 dBA at the distant elevated and intermediate positions, and by 7 dBA at the distant ground-level position. The predicted noise levels for distant ground-level positions is quite sensitive to the selected ground type.

Sensitivity to Pavement Type - Using *Average* pavement type, TNM 2.5 over-predicted the measured CTIM levels for the 2005 summer OGAC overlay conditions by about 4 dBA at the reference positions and by 6 to 8 dBA at the distant sites. A modeled pavement type of *OGAC* with *Field Grass* predicted noise levels of about 2 dBA below *Average* pavement conditions, but would still result in over-predictions of about 2 dBA at the reference position, about 7 dBA at the intermediate position, and by about 4 dBA at the distant positions.

4 ADDITIONAL MEASUREMENTS 2009 AND 2010

This section reports the results of additional CTIM and OBSI measurements that were conducted in June 2009 and October 2010. These results were not included in the first three chapters which was prepared previously and submitted to Caltrans in 2008.

4.1 Description of Measurements and Analysis

The CTIM measurements followed the procedures as described in Section 2. The most recent testing was conducted on June 10 and 11, 2009 (11-year) between the hours of 9:00am and 1:00pm and on October 13 and 14, 2010 (12-year) from 11:00am to 2:00pm. For the OBSI measurements, the test vehicle used during these test periods was a 2004 Chevrolet Malibu. During the June 2009 measurements, the Goodyear Aquatred 3 test tire (Aquatred), which was used during previous testing periods, and the Uniroyal Tiger Paw Standard Reference Test Tire (SRTT) were used for testing. Only the Aquatred was used in October 2010. The environmental conditions are summarized in Table 4-1 for the CTIM testing.

Table 4-1: Summary of Environmental Conditions Measured for Wayside Testing, June 2009 & October 2010

Test Date	Temperature Range	Relative Humidity	Barometric Pressure, hPa	Wind Speed, mph	Wind Direction
6/10/2009	64-72 ^{o}F (18-22 ^{o}C)	50-65%	1013-1014	3.5-8.1	S, W
6/11/2009	65-75 ^{o}F (18-24 ^{o}C)	50-68%	1013-1014	6.9-9.2	S, SSW
10/13/2010	75-87 ^{o}F (24-31 ^{o}C)	23-36%	1018-1019	4.6-5.8	N, NNW, VAR

As discussed in Section 3, at distances from the roadway greater than 100 feet (30.5 meters) noise levels are affected by wind conditions. In the test region, wind primarily blows from northerly and southerly directions, resulting in upwind and downwind conditions. The one-third octave band spectra for each distant microphone under both wind conditions have also been considered for these measurements.

Following the procedures described in Section 2, the Federal Highway Noise Administration's Traffic Noise Model, Version 2.5 (TNM) was used to normalize traffic conditions for the purpose of evaluating noise level changes with regards to the pavement at the CTIM reference locations. The model was used to normalize CTIM noise levels for traffic conditions, as opposed to predicting measured conditions. Normalization values in June 2009 and October 2010 were determined by calculating the difference in hourly modeled noise levels between each hourly monitoring period and the baseline data from 1998.

The OBSI testing was conducted on June 10, 2009 (11-year) between the hours of 11:00am and 3:00pm and on October 28, 2010 (12-year) from 11:00am to 2:00pm. The environmental conditions observed during testing with the Aquatred and SRTT tires are summarized in Table 4-2. Previous studies have been conducted to investigate the possible adjustment factors applied to sound intensity levels to account for temperature and barometric pressure effects; however, the average correction terms calculated for the June 2009 and October 2010 measurements are less than 1 dB, and therefore, are considered negligible.

Table 4-2: Summary of Environmental Conditions Measured for OBSI Testing, June 2009 & October 2010

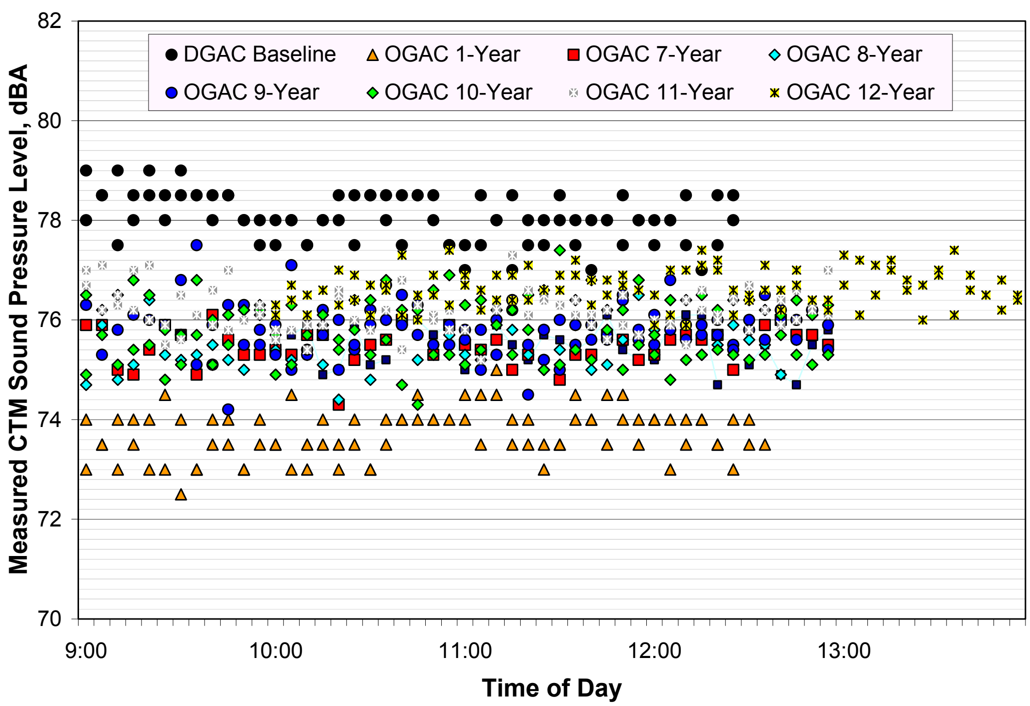
Test Date And Tire	Temperature Range	Relative Humidity	Barometric Pressure, hPa	Wind Speed, mph	Wind Direction
6/10/2009 Aquatred	73-75°F (23-24°C)	44-46%	1013	8.1-11.5	S, SSW
6/10/2009 SRTT	67-74 °F (19-23 °C)	50-56%	1014	5.8-11.5	S, SW
10/28/2010 Aquatred	63-65°F (24-31°C)	45-61%	1016-1017	4.6-5.8	NW, VAR

4.2 Results of Field Measurements and Analysis

4.2.1 CTIM Measurements

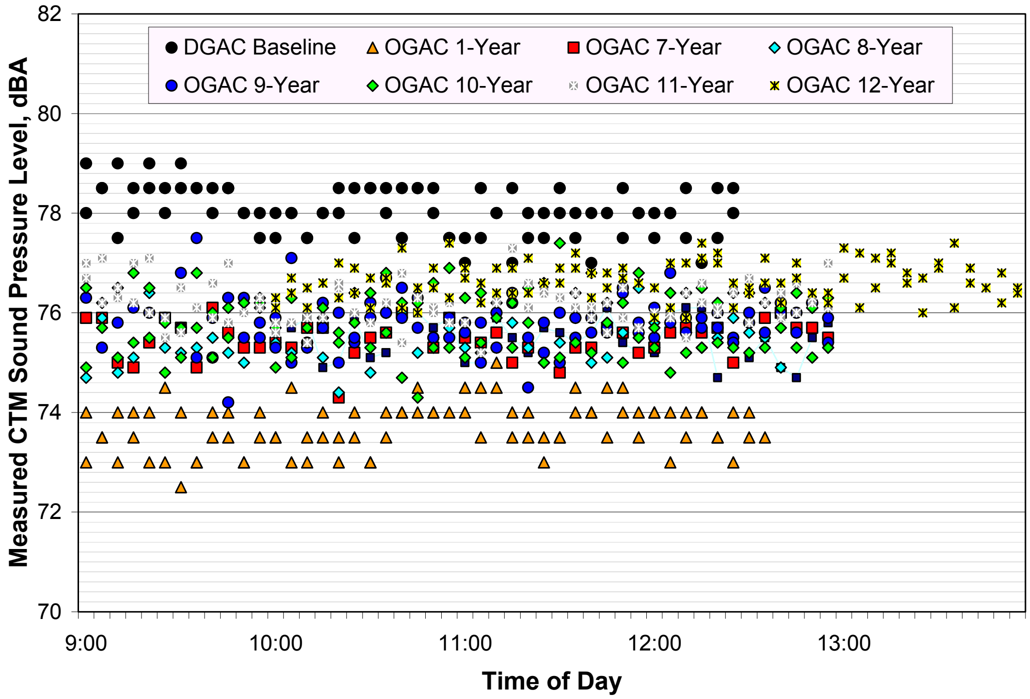
Measured 5-minute L_{eq} levels at the westbound reference (WBref) and eastbound reference (EBref) CTIM positions are shown in Figures 4-1 and 4-2, respectively. Each data set from the figures shows the

Figure 4-1: 5-Minute Leq Levels Measured Westbound Reference CTIM Position



summer measurements through June 2009 and includes measurements from October 2010. For the October 2010 data, the measurements were started later in the morning to better match the environmental conditions of the summer measurements. The data of Figures 4-1 and 4-2 are not normalized for either

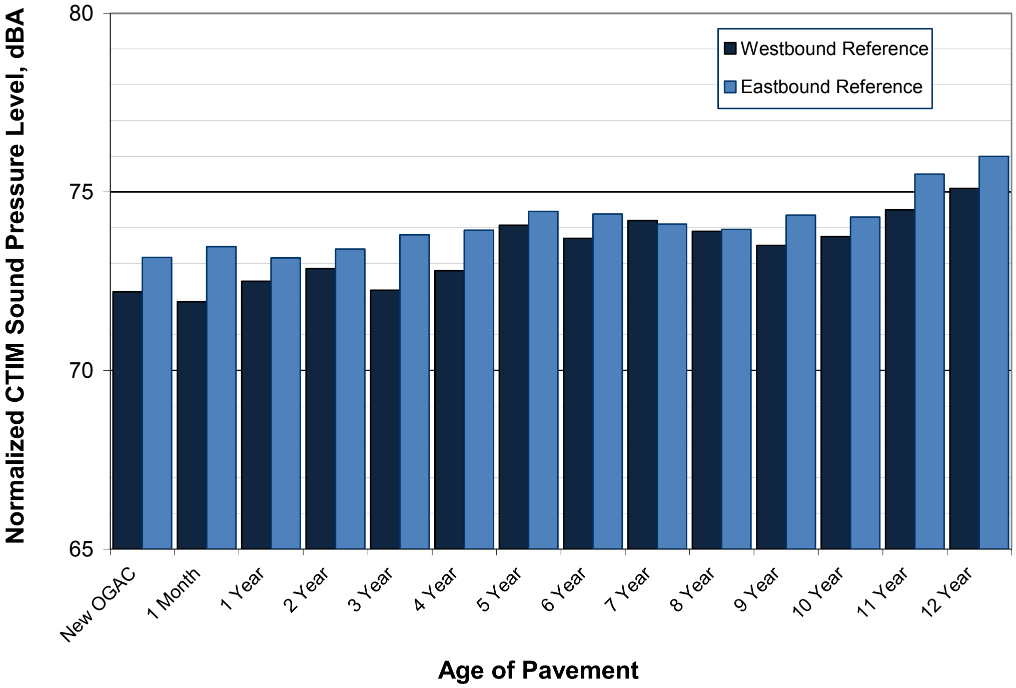
Figure 4-2: 5-Minute Leq Levels Measured at Eastbound Reference CTIM Position



traffic or meteorological conditions. Despite the scatter, which indicates the effects of varying wind conditions and traffic congestion, the measured traffic noise levels for the OGAC pavement are consistently lower than the baseline DGAC throughout the 12 years of study particularly for the westbound direction (Figure 4-1). In Figure 4-3, the average hourly L_{eq} levels normalized with the traffic data from the DGAC baseline measurements are shown for each testing period in 1998 through the 12-year measurements in October 2010 for the westbound and eastbound directions. These data correspond to the summer months with the exception of 2010 data that were acquired in October. Overall, the OGAC overlay pavement noise levels in the eastbound direction are consistently higher than the levels in the westbound direction by 0.8 dB on average. As mentioned in the previous Sections, the higher levels in the eastbound direction are likely due to local traffic on the frontage road. For this reason, L_{50} may be considered in the eastbound direction in an effort to reduce the frontage road influence. The average difference between the L_{eq} and L_{50} data is approximately 0.8 dBA. When averaged over the entire project duration, the hourly Leq TNM model results were approximately 78.8 and 78.6 dBA in the westbound and eastbound directions, respectively, with a standard deviation of about 0.4 dBA. This was expected since the traffic counts were fairly consistent for all testing periods.

The initial OGAC pavement overlay calculations in 1998 indicated a reduction of approximately 6 dB in the westbound direction and approximately 5 dB in the eastbound direction when compared to the older DGAC pavement (baseline) and normalized for traffic. For the first four years of the study, average reductions of approximately 6 and 4½ dB were calculated at the WBref and EBref positions, respectively. Starting in the fifth year however, calculated noise reductions were approximately 4.5 to 5 dB at WBref

Figure 4-3: Normalized Reference CTIM Levels during Summer Monitoring Periods



and 3.5 to 4 dB at EBref, which was maintained through the 10th year. In years 11 and 12, the average level reductions from the baseline were calculated to be 3.5 to 4 dB and 2 to 2.5 dB at WBref and EBref, respectively. Note that the 12-year measurements were taken in October instead of June, which may effect the comparison results. Figures 4-4 and 4-5 summarize the level reduction for each summer measurement and the October 2010 reductions.

Figures 4-6 and 4-7 show the one-third octave band spectra for the westbound and eastbound reference microphones, respectively, during the summer and October 2010 measurement periods. The data are not normalized for traffic or meteorological conditions. At frequency bands below 630 Hz, the aged baseline DGAC pavement produced in levels lower than the OGAC pavement by an average of 2 dB. At the higher frequencies, however, the baseline DGAC pavement yielded levels significantly higher, on average, than the OGAC pavements, consistent with other porous, OGAC pavements[19]. The greatest difference was between 1000 and 2000 Hz. In the westbound direction, the average level reduction for the OGAC pavements was approximately 8 dB, while in the eastbound the average reduction was about 7 dB. For the June 2009 (11-year) and October 2010 (12-year) measurements, WBref and EBref band levels were higher than in previous years, which is consistent with the hourly L_{eq} levels described above. The spectra in Figures 4-6 and 4-7 show a relatively consistent trend throughout the domain and result in a steady increase in band levels. For the eastbound direction, in the bands below 1600 Hz, the range in level is approximately 3 to 3.5 dB with the 1-year levels being the lowest. Above 1600 Hz, the 1-year levels are actually higher and are 2 to almost 3 dB greater than the 12-year results. The increase in the lower frequencies with time is expected and is likely due to the raveling of the pavement surface noted in

Figure 4-4: Calculated Noise Reductions from the 1998 Baseline DGAC Noise Levels at the Westbound Reference Position

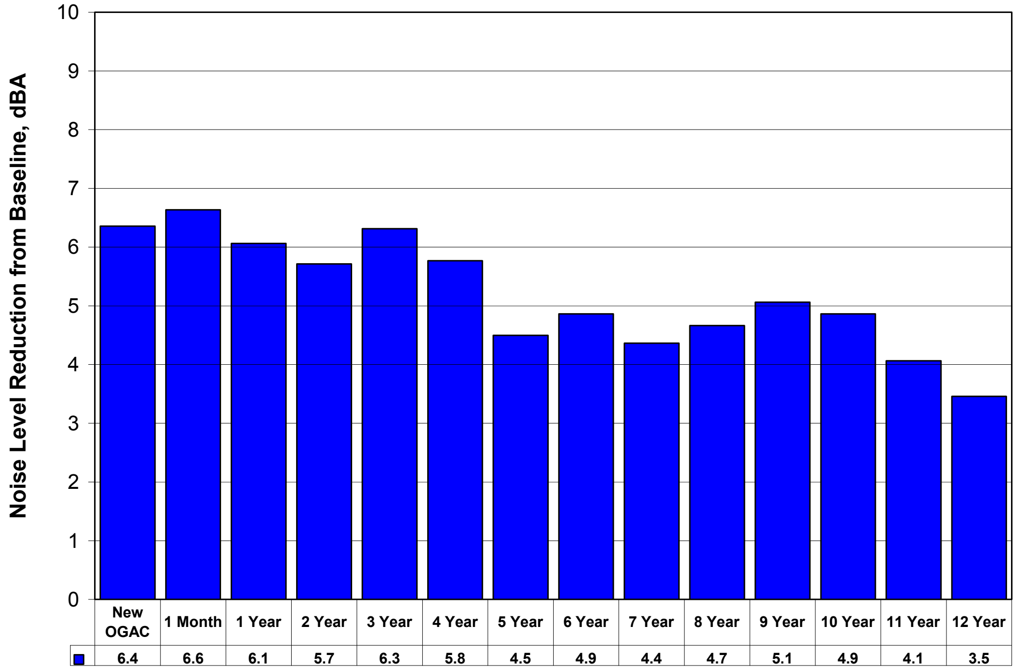


Figure 4-5: Calculated Noise Reductions from the 1998 Baseline DGAC Noise Levels at the Eastbound Reference Position

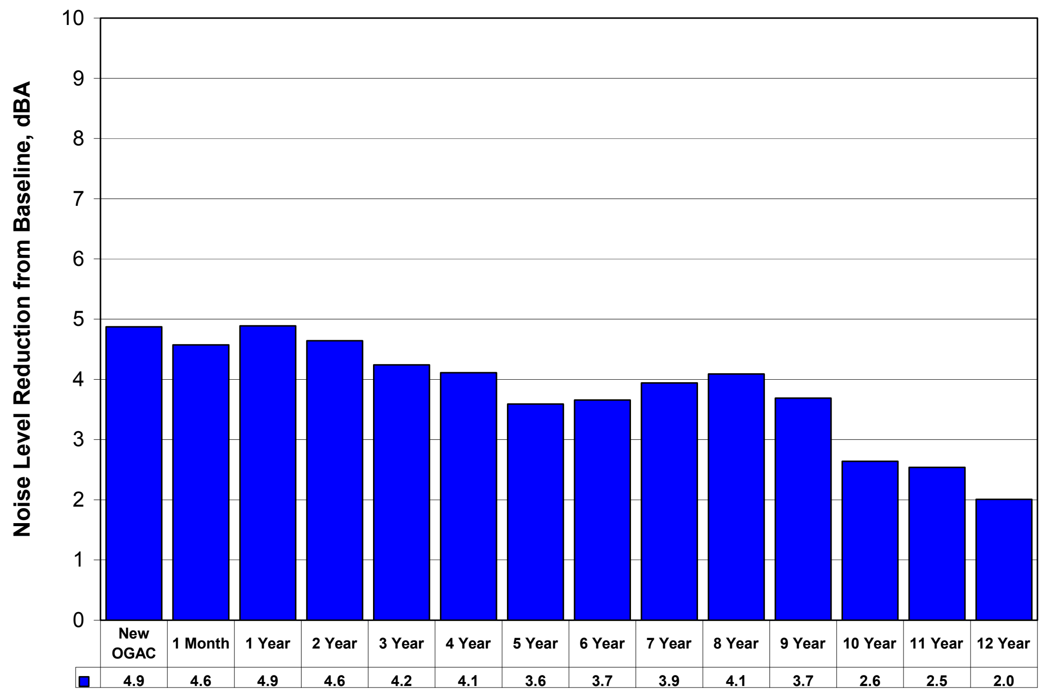


Figure 4-6: One-Third Octave Band Levels for the Yearly Summer Measurement Periods, as well as October 2010, at the Westbound Reference Microphone Location

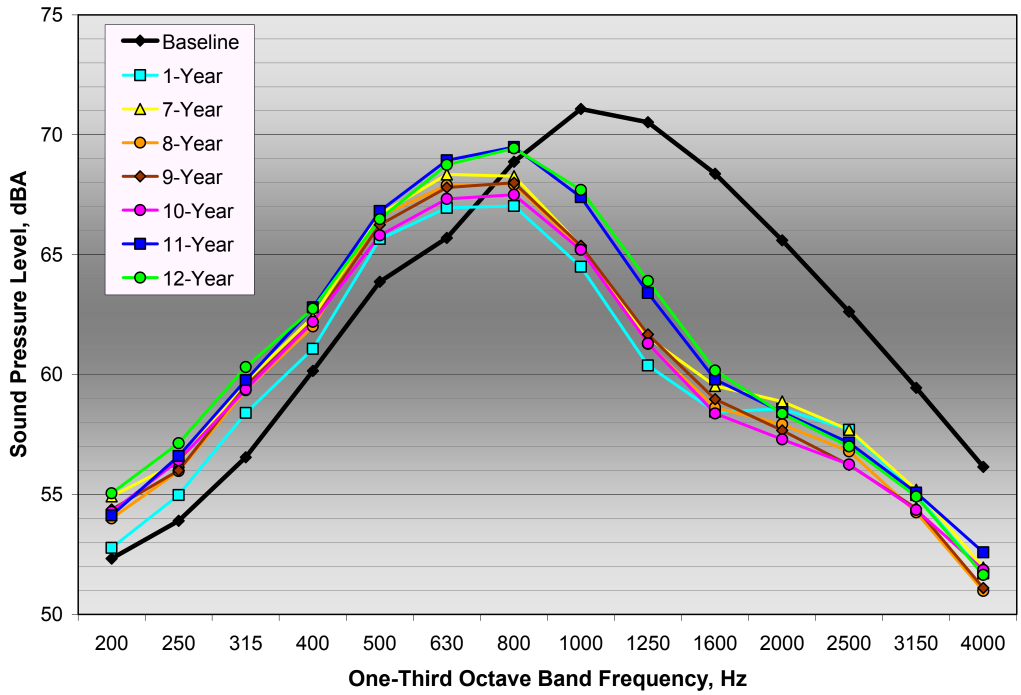
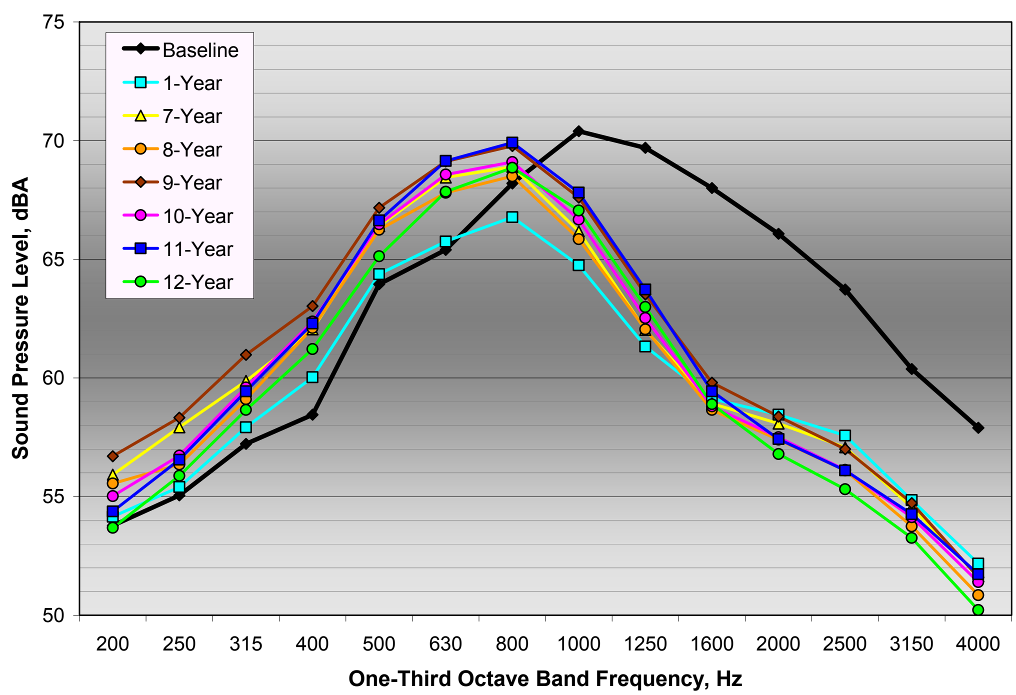


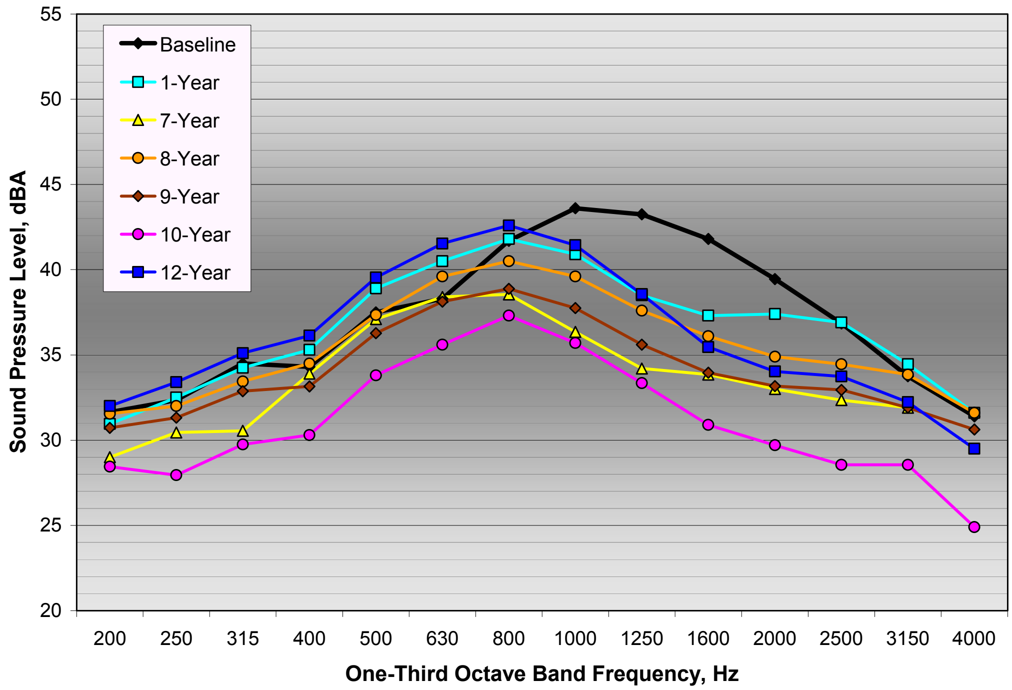
Figure 4-7: One-Third Octave Band Levels for the Yearly Summer Measurement Periods, as well as October 2010, at the Westbound Reference Microphone Location



other research which creates increased roughness and resultant higher levels[20]. Similar behaviors are seen in the eastbound direction results, although the differences are not as pronounced.

The spectra for the distant microphones were considered under upwind and downwind conditions. Figures 4-8 and 4-9 show the spectra for the ground level (5ft high) distant microphone in the westbound direction under upwind and downwind conditions, respectively (note the 10 dB shift in the Y-axis).

Figure 4-8: One-Third Octave Band Levels for the Yearly Summer Measurement Periods, as well as October 2010, at the Westbound Distant Ground Position Under Upwind Conditions



Unlike the spectra at the reference measurement locations, these spectra do not indicate consistent trends of increasing noise level with years since construction. As expected from Figure 3-4, the levels in the upwind condition are substantially lower (~15 dB) than in the downwind direction. Other than to note that the spectral differences between the baseline and OGAC are similar in shape to the reference position data, it is apparent that the use of these distant data are of little use in evaluating the term long performance of the OGAC due to the large amount of variation attributable to the wind conditions. The spectra results for the elevated distant microphone in the westbound direction under upwind and downwind conditions are shown in Figures 4-10 and 4-11, respectively (10 dB shift in Y-axis). For this microphone location, the noise levels for upwind and downwind conditions are not as different as in the ground level case, however they are typically 5 to 10 dB lower for upwind. At the elevated microphone location, the data collected at westbound distant CTIM site more closely follows those of the reference CTIM positions. Further, in the downwind case, the range of the OGAC levels is smaller and more comparable to the reference location. Note that the June 2009 (11-year) measurements were tested under downwind conditions only, while in October 2010 (12-year) only upwind conditions were observed.

Figure 4-9: One-Third Octave Band Levels for the Yearly Summer Measurement Periods, as well as October 2010, at the Westbound Distant Ground Position Under Downwind Conditions

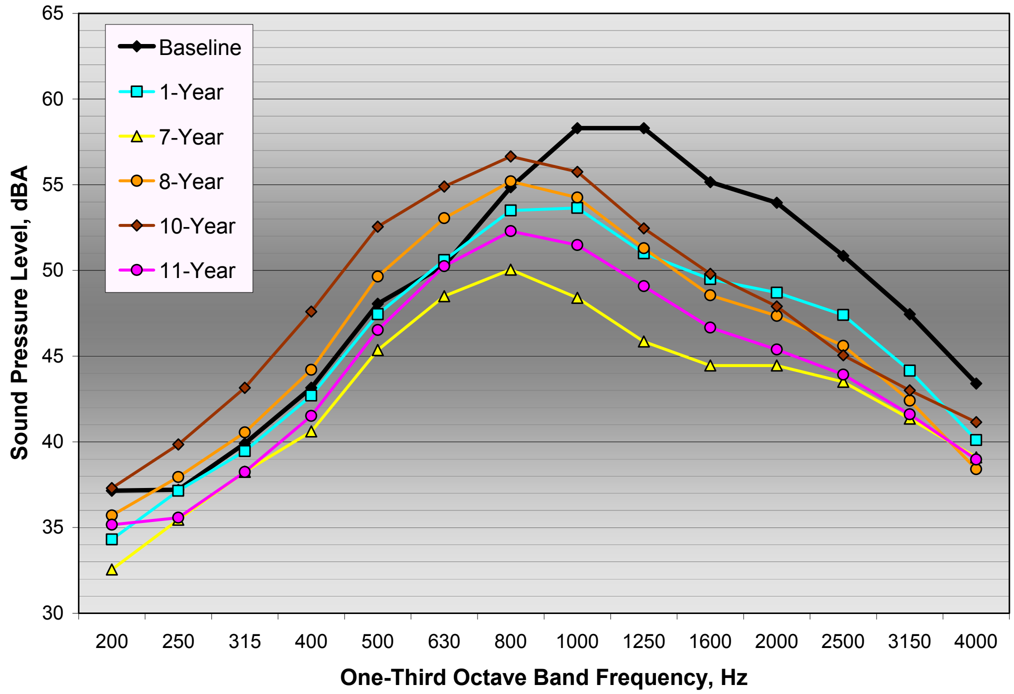


Figure 4-10: One-Third Octave Band Levels for the Yearly Summer Measurement Periods, as well as October 2010, at the Westbound Distant Elevated Position Under Upwind Conditions

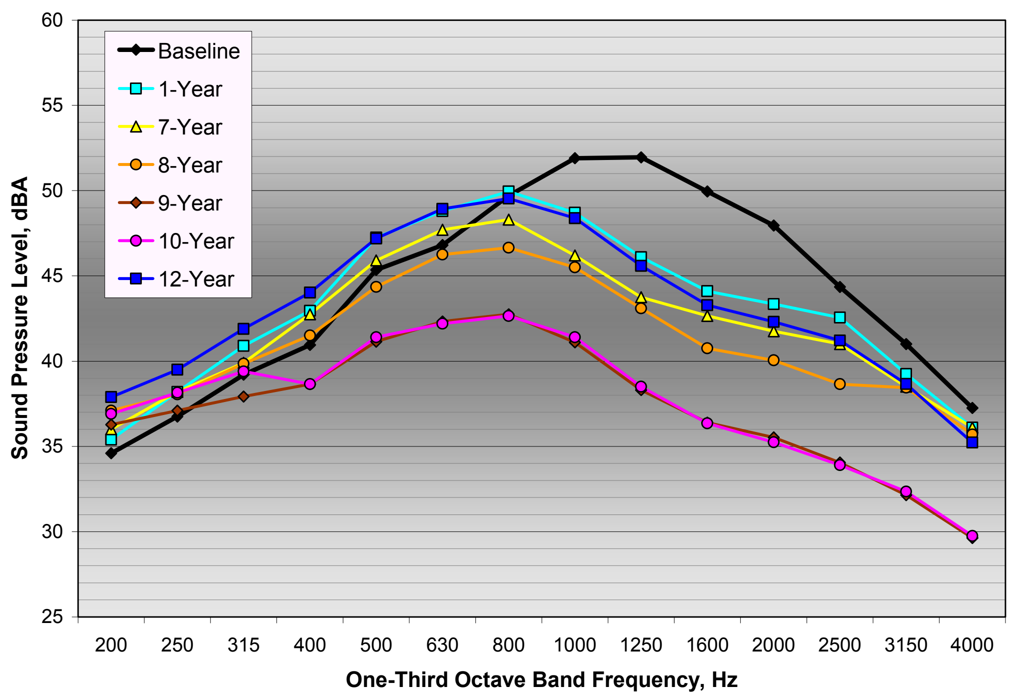
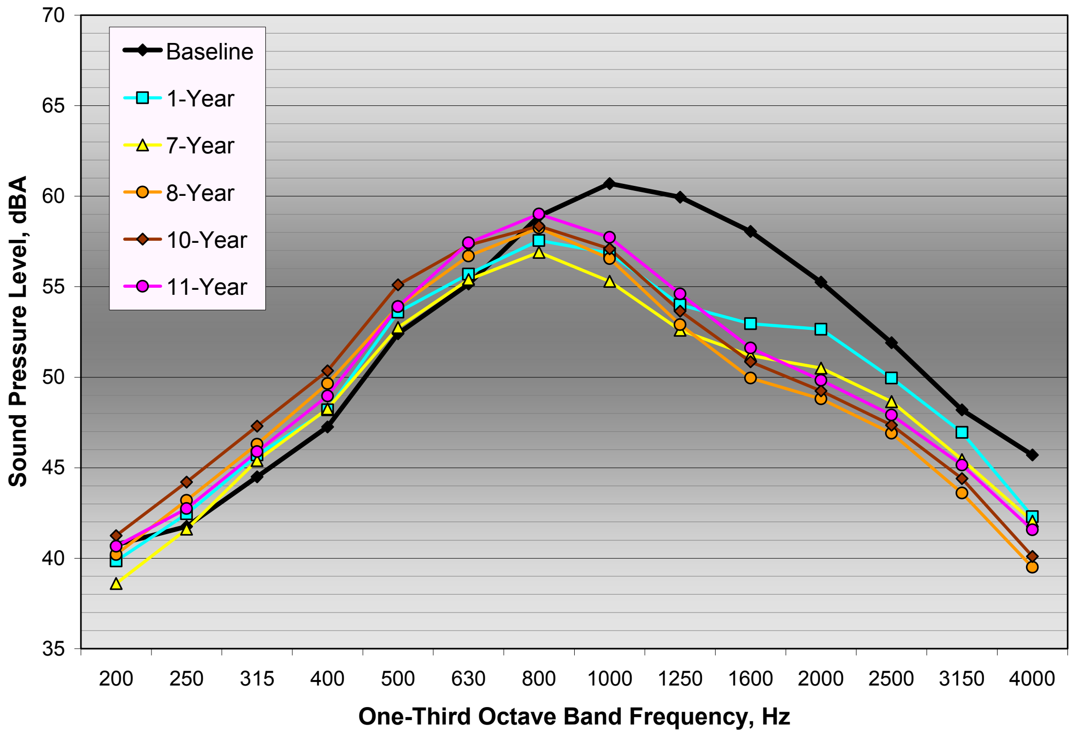


Figure 4-11: One-Third Octave Band Levels for the Yearly Summer Measurement Periods, as well as October 2010, at the Westbound Distant Elevated Position Under Downwind Conditions



4.2.2 OBSI Measurements

A-weighted OBSI tire/pavement noise levels collected in the outside lanes for both the eastbound and westbound directions of I-80 are shown in Figure 4-12 for the summer measurements and the October 2010 measurements. These reflect the averages of three segments in each direction as shown in Figure 2-1. The values for each individual segment are reported in Table 4-3. These data are not corrected for air density or tire noise temperature dependence due to the lack of accepted correction factors and are based on assumed values of 20ºC for air temperature and 101.325 kPa atmospheric pressure. In both eastbound and westbound directions, the measured OBSI levels in June 2008 increased about 2 dB following a generally upward trend begun in year 9 and 10. However, the results in October 2010 may be affected by the 10ºF temperature variation from the June measurements in the previous years. This could potentially add about 0.4 dB to the 2010 levels compared to 2009 based on recently reported findings[21,22] . Table 4-4 provides the numerical levels measured at each OBSI test summer/October test event as well as levels for the spring test in 2005 (not included in Figure 4-12). In comparing the eastbound pavement results with the westbound, the OBSI levels were higher in the eastbound direction by an average of 0.8 dB. This is similar to the results for the wayside measurements, which showed an average difference of 0.6 dB.

Figure 4-13 plots the average OBSI spectra measured for the eastbound and westbound directions in June 2009 and October 2010. The eastbound and westbound directions resulted in similar spectral

Figure 4-12: OBSI Levels during Summer Monitoring Periods and October 2010

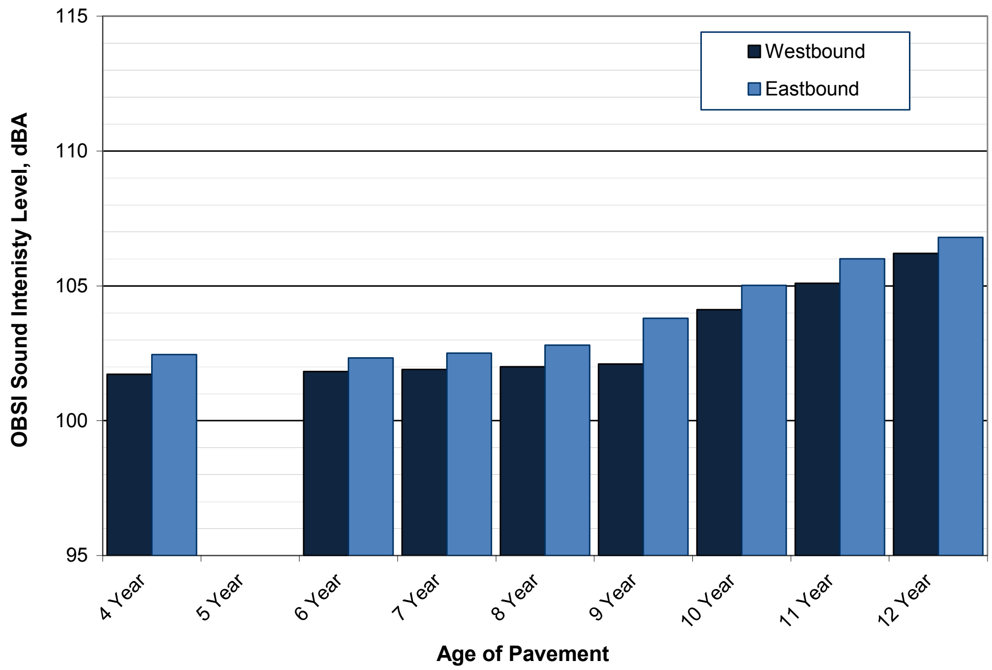
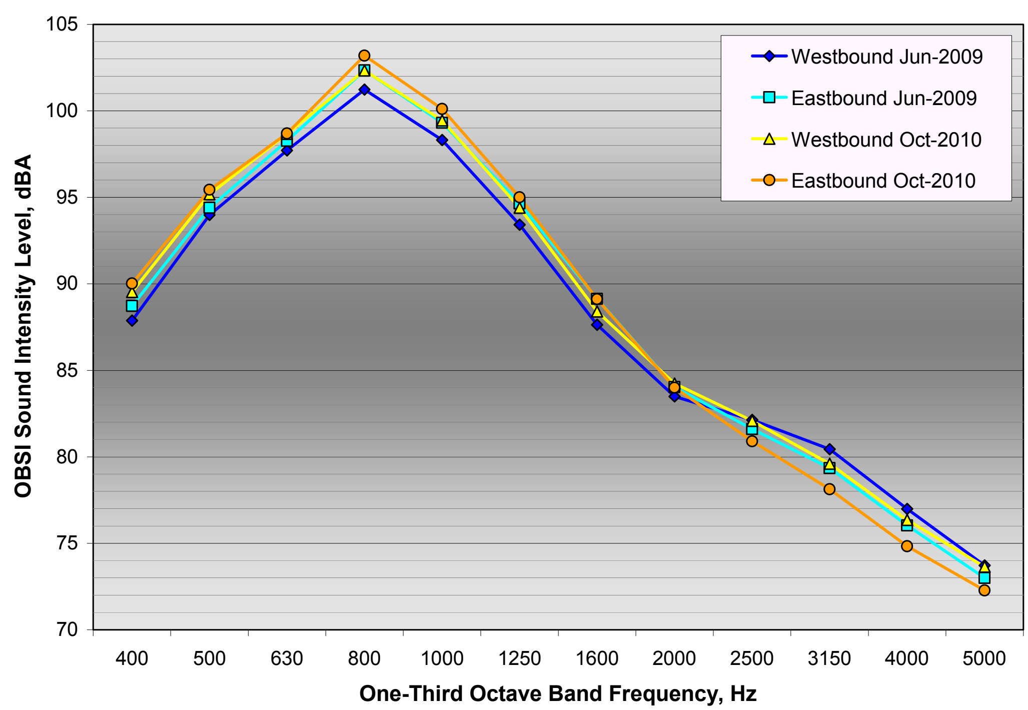
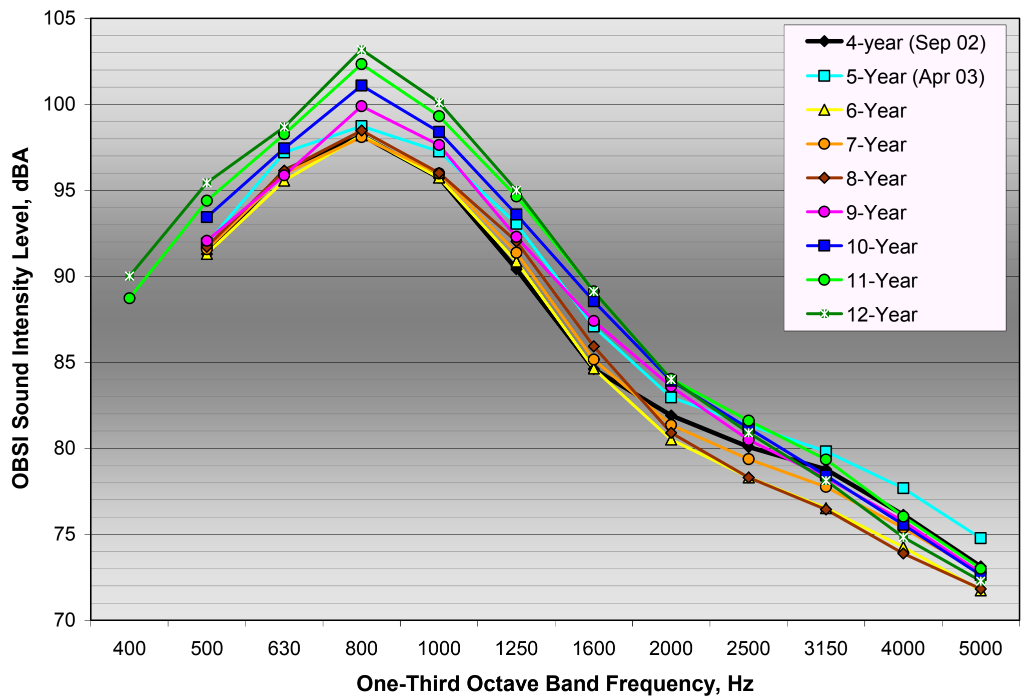


Figure 4-13: One-Third Octave Band OBSI Levels for Both Directions in June 2009 & October 2010



characteristics, although for frequency bands less than 2000 Hz, the westbound side resulted in OBSI levels that were an average 0.7 dB lower than in the eastbound side in June 2009 and 0.5 dB lower in October 2010. At frequencies above 2000 Hz, however, the westbound band levels are higher than the eastbound levels by 0.3 dB in June 2009 and 0.9 dB in October 2010. Figures 4-14 and 4-15 show the average OBSI spectra for each yearly measurement in the eastbound and westbound directions,

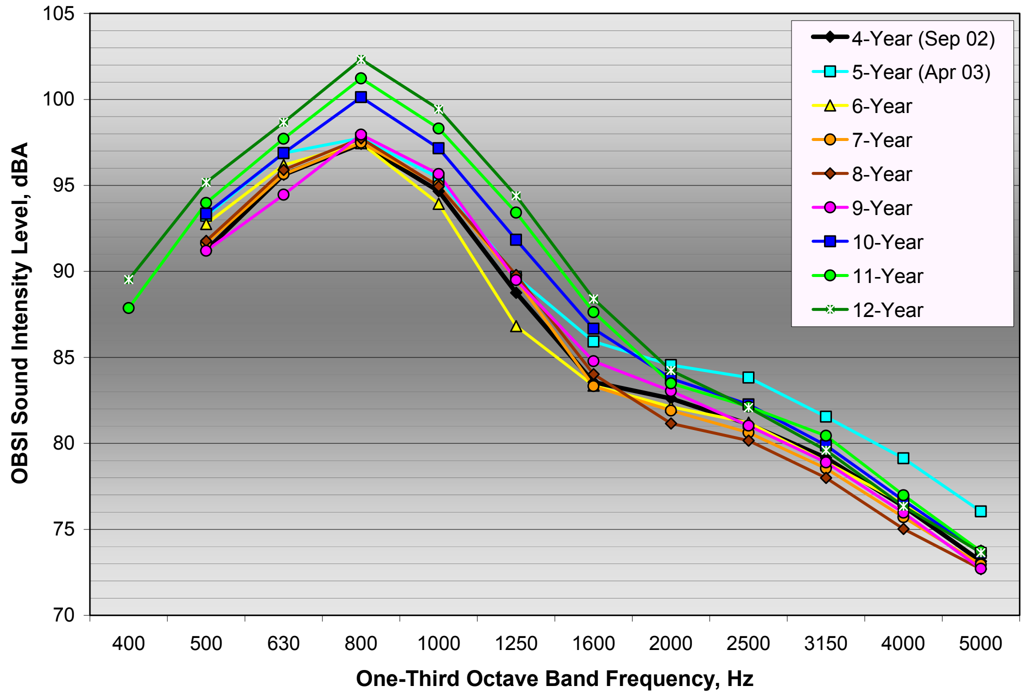
Figure 4-14: One-Third Octave Band OBSI Levels for the Yearly Measurement Periods in the Eastbound Direction



respectively. Similar to the findings of the OBSI overall levels, the most recent measurement periods (i.e., June 2008, June 2009, and October 2010) have trends throughout the spectra up to 1600 Hz in which the levels typically increase each year. Above 1600 Hz, there is some crossover of levels so that the most recent years do not necessarily produce the lowest level similar to the wayside trends noted for Figure 4-6 and 4-7. For the bands below 1600 Hz, the levels are consistently higher than in previous years: 1.5 to 3 dBA higher in June 2008; 2.5 to 4 dBA higher in June 2009; and 3 to 4.5 dBA higher in October 2010.

In June 2009 and October 2010, OBSI measurements were taken in all three travel lanes of travel in both the eastbound and westbound directions. Figure 4-16 shows the overall OBSI levels measured in each lane in 2009 and 2010. In both directions, the levels measured in the right travel lane, which is nearest the wayside shoulder and CTIM locations, resulted in the highest overall levels, and the left lane, which is the farthest from the CTIM locations, showed the lowest levels. The spectra for the eastbound lanes as measured in 2010 are shown in Figure 4-17. The increase in spectrum level from outside to inside lanes is strikingly similar to the effect of increasing age as shown in Fig 4-14. This implies that outside lane and the middle lane to a less degree experience a higher aging effect than does the inside lane. The same

Figure 4-15: One-Third Octave Band OBSI Levels for the Yearly Measurement Periods in the Westbound Direction



trends occur in the 2009 data and in the westbound lanes. Generally, heavy trucks operate predominately in the outside lane with some operation in the middle lane. The inside lane is almost exclusively light vehicles. This appears to provide an explanation for the increased levels in the middle and outside lanes[23]. The overall levels of Figure 4-16 also indicate that the OBSI levels measured in eastbound travel lanes are higher than in the westbound direction for each lane by an average of 0.6 dB in June 2009 and 0.4 dB in October 2010.

The ASTM P225/60R16 Radial Standard Reference Test Tire (SRTT) is the test tire specified in the recently developed American Association of State Highway Transportation Officials (AASHTO) Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method TP 76-11. For this reason, OBSI levels were measured with a SRTT in June 2009 in order that the levels for I-80 Davis OGAC pavement could be linked to newer data bases using this tire. This tire was tested between 11:25 am and 1:00 pm on June 10, 2009. Table 4-2 summarizes the environmental conditions observed during this time. The SRTT tire testing conditions were similar to the conditions for the Aquatred testing later that day. Testing for the SRTT was attempted in all six lanes, however heavy traffic conditions prevented obtaining results for the inside lane in the westbound direction. Figure 4-18 shows the overall OBSI level results for each lane using both test tires. Generally, the differences between the tires were small and not consistent with individual differences of at most 0.3 dB. In previous comparisons of the SRTT and Aquatred, the SRTT is typically about 1 dB lower in level[24,25]. However, it has also been found that as the pavement levels become higher, the differences

Figure 4-16: Overall A-Weighted OBSI Levels for Each Lane in June 2009 & October 2010

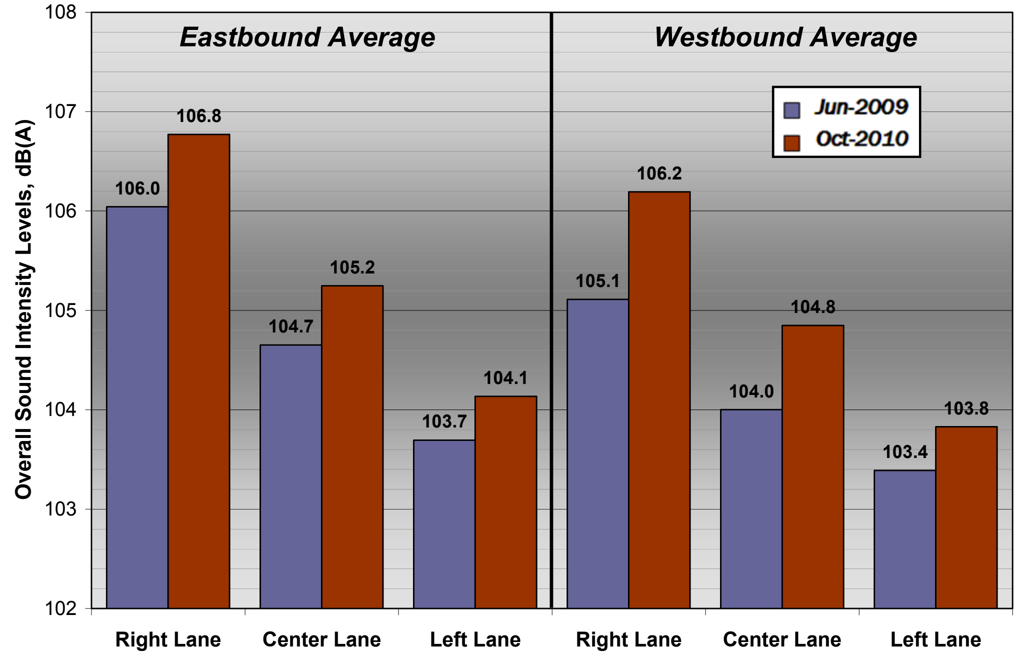


Figure 4-17: One-Third Octave Band OBSI Levels for Each Lane in the Eastbound Direction for October 2010

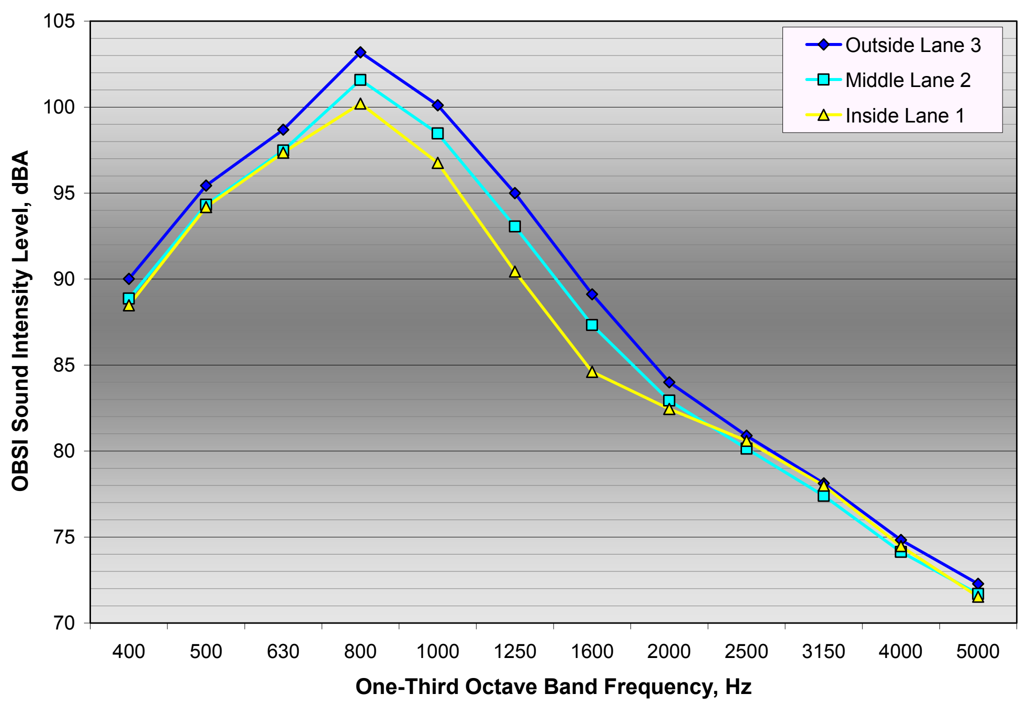
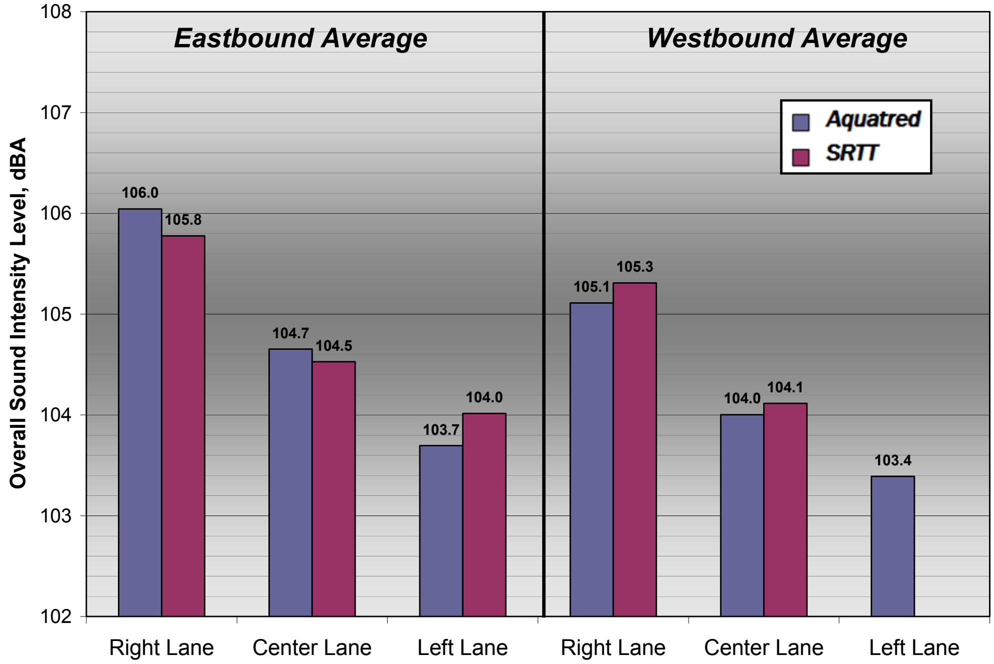


Figure 4-18: Overall A-Weighted OBSI Levels for Each Lane in June 2009, Goodyear Aquatred & Uniroyal SRTT Test Tires



between the two tires become less as the characteristics of the pavement tend to dominate over the differences in tire design. One-third octave band spectra are compared in Figure 4-19 for the Aquatred and SRTT tires in the eastbound direction as measured in the outside (right) lane and the inside (left) lane. The character of the spectra are generally similar, however, some consistent differences persist. For the both lanes of travel, the SRTT levels are lower than the Aquatred (2 to 3 dB) in the higher frequencies from 1000 to 2000 Hz. Below 800 Hz, the SRTT tire levels were slightly higher by typically about 1 dB. These trends were also seen the results for the center and the westbound direction of travel.

4.2.3 Acoustic Longevity

With 12 years of aging, the acoustic longevity to the OGAC can be assessed with greater certainty as the increases in noise level become greater in an absolute sense. In Figure 4-20, overall A-weighted sound pressure levels at the reference microphone locations are plotted for years since construction using the summer day and the October 2010 levels. Linear regressions on these data are shown producing a longevity factor of 0.20 dB/year for the westbound direction and 0.19 dB/year for the eastbound direction. The coefficients of determination (R^2) values for both regressions are fairly good with values of 0.77 and 0.76 for the westbound and eastbound directions, respectively. The scatter of individual data points is typically 0.6 dB or less about the regression line. Looking at both data sets, there appears to be several phases in the levels versus time. Between 0 and 5 years, the levels increase at fairly consistent rates. Between 5 and 10 years, the levels generally plateau and from 10 on to 12 years, they show a fairly rapid increase.

Figure 4-19: One-Third Octave Band OBSI Levels for Eastbound Lanes 1 & 3 in June 2009 for the Goodyear Aquatred & Uniroyal SRTT Test Tires

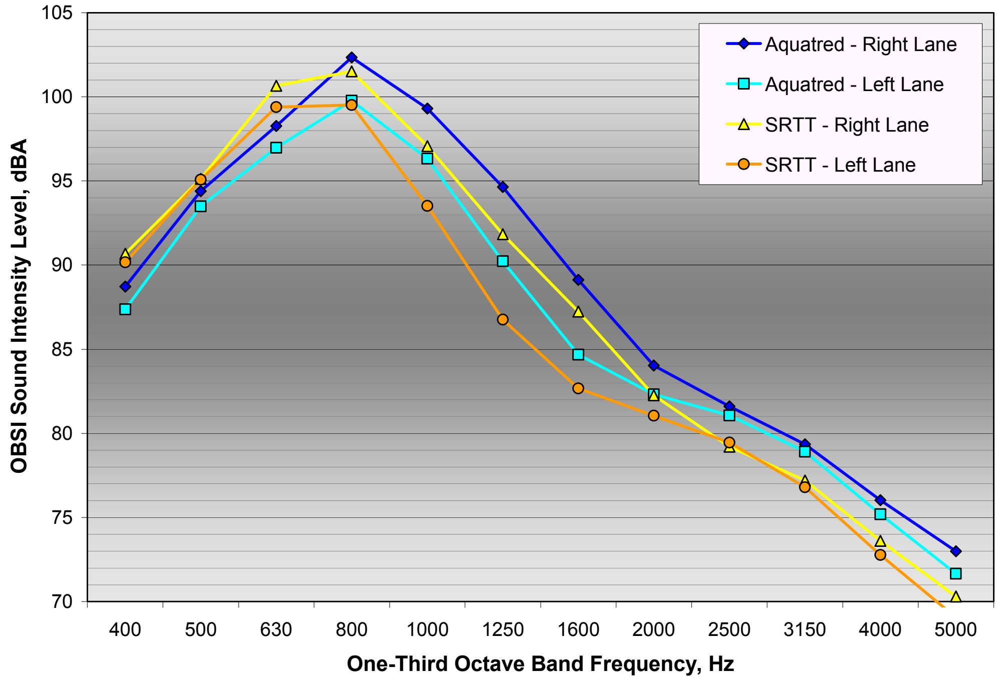
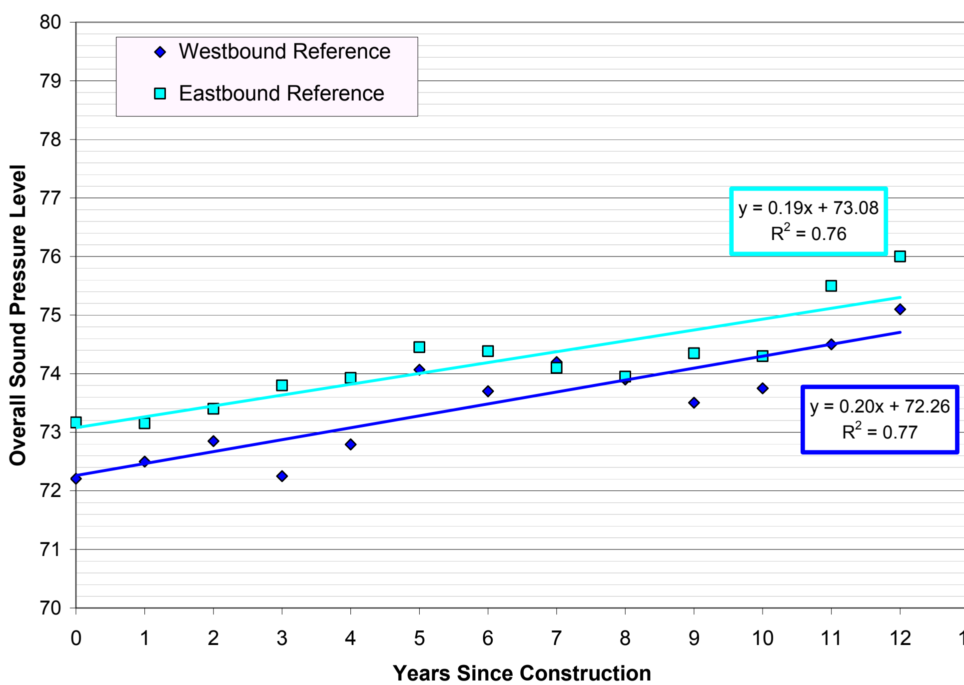


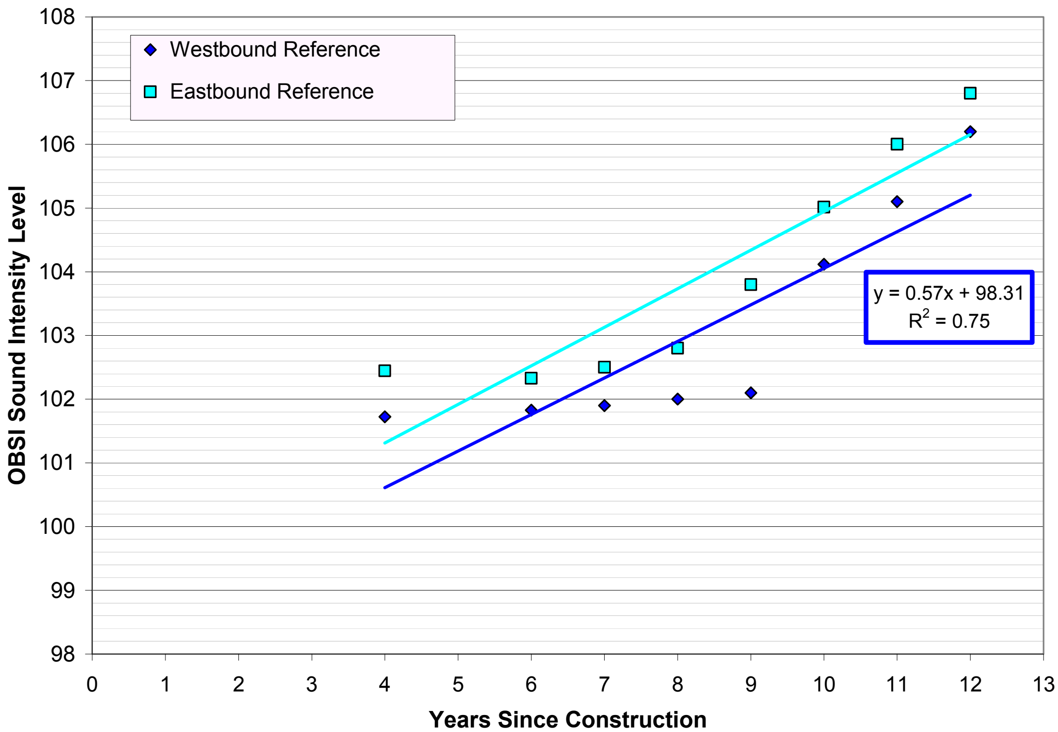
Figure 4-20: Overall CTIM Levels Versus Year of Construction for Reference Locations



Even though these trends are apparent, the use of the linear gradients seems appropriate knowing that there is uncertainty of 0.6 dB or less for any one year.

The overall A-weighted OBSI levels from year 4 to year 12 are plotted in Figure 4-21. The linear rates determined by data starting at year 4 are almost three times that of the wayside data. However, some of

Figure 4-21: Overall OBSI Levels Versus Year of Construction for Outside Lanes of Travel



the trends are similar to the wayside results. Between 4 and 8 to 9 years, the levels are fairly constant and then increase rapidly for year 10 and beyond. Although the R^2 values for these regressions are similar to the wayside data, the scatter about the regression line is greater with deviations for individual years of 1 dB or more occurring in some years. The rate defined by these data may also be somewhat exaggerated due to a number of issues. Without the initial performance, the slope of the regression is defined only by the later performance. The intercept for both directions is around 98½ dB. For a relatively coarse pavement with ¾ inch maximum aggregate size, this level is low compared to other similar pavement designs. Assuming the OBSI levels follow the same rate as the wayside results over the first three years, the OBSI year 0 levels would be around 101 dBA. In this case, the linear slopes would be closer to 0.36 dB/year. Further, the data of Figure 4-21 is only from the outside lane while the wayside levels receive some contribution from all three lanes (in each direction). From Figure 4-16, the inside lanes are about 2½ dB lower after 12 years. Assuming all lanes were nearly equal when new, the slopes for center and inside lanes would be correspondingly lower than the outside lane, possibly more in line with the wayside results. From these ambiguities, the one clear fact is that the OBSI levels in outside for the westbound direction increased by 4.5 dB over a period of 8 years and levels in the eastbound direction increased by 4.4 dB.

5 Conclusions

The OGAC pavement resulted in noise levels that were about 7 dBA below those measured for the baseline DGAC pavement, equivalent to the noise reduction achieved with an 8-foot high noise barrier, Over a period of 12 years, the sound pressure levels measured at reference locations 65 feet from the edge of the near lane of travel increased at linearized rate of about 0.2 dB/year with more rapid deterioration occurring in the last two years. Over this time period, the spectra characteristics in the critical frequencies below 2000 Hz remained nearly constant with an upward shift consistent with the overall levels. In the first four years of the study, the increases in level are similar to the findings for the Caltrans Thin Lift Study (LA 138)[26], which found wayside pavement noise increases of about 0.5 dBA for OGAC pavements over a period of 52 months.

Changes in noise level not attributable to pavement, such as those due to increased traffic volumes or changes metrological conditions, will result in changes in the overall noise environment. Based on traffic noise modeling results for this investigation, changes in traffic alone along I-80 through the study area resulted in an average traffic noise increase of about 1 dBA over the 12-year study period at the CTIM reference locations. Winter temperatures were found to result in noise levels that were, on average, 1.3 dBA higher than summer levels. Wind conditions were found to affect noise levels by up to 2 dBA at only 65 feet from the edge of the near lane of the freeway and more than 10 dBA at 475 feet from the edge of the near lane of the freeway. Findings of this study are limited to conditions on I-80, which included a relatively high percentage of trucks (about 2-3% medium-duty and 7% heavy-duty trucks), and high traffic speeds (~70 mph or ~110 kph). Effects, such as vehicle mix, vehicle speed, baseline pavement condition, and shielding effects, could affect the magnitude of noise level reductions attributable to OGAC overlays. This portion of I-80 does not normally experience snow and freezing conditions with moisture so that the results found this study may not be applicable to other environs. Further investigations conducted for a wide range of pavement types would be helpful in the establishment of pavement design parameters to allow highway agencies to utilize pavement selection as a tool for reducing traffic noise.

The rate of noise level increase with pavement aging was indicated to be greater for OBSI measurements than for the CTIM measurements. For the outside lane of travel, linearized increases were about 0.6 dB/year. For the inner lanes, the OBSI levels were 1½ to 2½ dB lower at the end of 12 years indicating that increase in OBSI level was likely less than that of the outside lane which experiences high volumes of heavy truck traffic possibly leading to increased pavement raveling over time. Further, the analysis period began at 4 years instead of at the beginning of the overlay which may also have exaggerated the apparent rate of OBSI increase with time. For comparison, the Caltrans Quieter Pavement Research asphalt test sections on the lower traffic volume LA 138 displayed rates of about 0.4 dB/year for OGAC pavement over a period of about 8 years[24].

For research studies such as this one, where the intent was to assess pavement under conditions that would simulate community noise exposure, the CTIM method is an appropriate choice. However, the results from these measurements are site and traffic specific and cannot generally be applied to other sites without some form of traffic noise modeling. Although OBSI measures exclusively tire-pavement noise and eliminates site and traffic variation variables, the data does not measure traffic noise as the community experiences. Prediction of noise levels at community locations requires the use of traffic noise modeling in which OBSI levels could be used to account for tire-pavement noise source levels. Prior research conducted for Caltrans and for the NCHRP 1-44 Project[27] found good correlation between OBSI measured with passenger car test tires and CPB/SPB levels for both light vehicles and heavy trucks. Further research into the effects of site-specific variables and pavement porosity on wayside (SPB/CPB or CTIM) measurements would enable the incorporation these effects into traffic prediction models to allow for the prediction of wayside noise levels from OBSI measurements.

6 PERSONNEL

The several authors have contributed to this report at different times and have participated in the measurements. These include Illingworth & Rodkin, Inc staff members: James Reyff, Dr. Paul Donavan, Carrie Janello, and Dana Lodico, P.E. (currently with Lodico Acoustics, LLC). Additional field support was provided by Mike Thill, Chris Peters, Phil Williams, and Jared McDaniel of Illingworth & Rodkin, Inc. Additional field staff was provided from Denise Duffy and Associates and in previous years by Haygood & Associates and Woodward Clyde. Technical and management oversight by Caltrans was provided by Bruce Rymer, P.E. and James Andrews, P.E.. This work was begun under task orders issued through the statewide "on-call" noise and vibration contract (Contract No. 43A0009) and was conducted under the recent contract managed by Illingworth & Rodkin, Inc. (Contract No. 43A0063).

7 REFERENCES

---

[1] Rymer, B., and Donavan, P., "Tire-pavement Noise Intensity Testing in Europe: The NITE Study and Its Relationship to Ongoing Caltrans Quiet Pavement Activities", Proceedings of the 80th Meeting of the Association of Asphalt Paving Technologists, Long Beach, California, March 7-9, 2005.

[2] Hendricks, Rudy, "California Vehicle Noise Emission Levels," Report No. FHWA/CA/TL-87/03. California Department of Transportation, Office of Transportation Laboratory, Sacramento, CA, January 1987.

[3] Fleming, G., Rapoza, A., and Lee, C., "Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model," Report No. FHWA-PD-96-008, U.S. Department of Transportation, Volpe National Transportation Systems Center, Acoustics Facility, Cambridge, MA, USA, 1995.

[4] Project Plans for Construction on State Highway in Yolo County in and near Davis from the Solano County Line to Yolo Causeway West, California Department of Transportation (Caltrans), Contract No. 03-444904, July 14, 1997.

[5] Highway Design Manual, California Department of Transportation, July 1, 2008.

[6] Guidance for Measuring the Influence of Road Surfaces on Traffic Noise Using a Continuous Flow Traffic Time Integrated Method (CTIM), Draft Guidance, Version 1, FHWA Expert Task Group on Tire/Pavement Noise, January 10, 2008.
[7] Standard Practice for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method, Draft National Standard, American Association of State Highway and Transportation Officials, Washington D.C., May 2008.
[8] Lee, C., and Fleming, G., *Measurement of Highway Related Noise,* U.S. Department of Transportation, Report No. DOT-VNTSC-FHWA-96-5, 1996.
[9] Donavan, P., and Rymer, B., "Assessment of Highway Pavements for Tire/Road Noise Generation", Proceedings of Society of Automotive Engineers Noise and Vibration Conference, Transverse City, MI, May 2003.
[10] Donavan, P., "Further Development of the Sound Intensity Method of Measuring Tire Noise Performance of In-Situ Pavements", prepared for California Department of Transportation, Division of Environmental Analysis, Sacramento, CA, prepared by Illingworth & Rodkin, Inc., Petaluma, CA, January 2006.
[11] Fleming, G., Rapoza, A., and Lee, C., *Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model,* Report No. FHWA-PD-96-098, U.S. Department of Transportation, Volpe National Transportation Systems Center, Acoustics Facility, Cambridge, MA, USA, 1995.
[12] Annual Average Daily Truck Traffic on the California State Highway System, Compiled by Traffic Data Branch, Division of Traffic Operations, State of California Department of Transportation, In Cooperation with the U.S. Department of Transportation, September 2008.
[13] Harris, C., "Handbook of Acoustical Measurements and Noise Control", Third Edition, Acoustical Society of America, Woodbury, NY, 1998.
[14] FHWA Traffic Noise Model® User's Guide", Final Report, U.S. Department of Transportation, January 1998, revised Final Report April 2004.
[15] Reyff, J., and Lodico, D., "I-80 Davis OGAC Pavement Noise Study, 7-Year Summary Report", prepared by Illingworth & Rodkin, Inc., prepared for California Department of Transportation, Sacramento, CA, November, 2005.
[16] Lodico, D., and Donavan, P., "Arizona DOT Quiet Pavement Pilot Projects Site 1 Measurements, Close Proximity (CPX) and On-Board Sound Intensity (OBSI), Routes 17, 51, 101, 202, and I-10", prepared for Arizona Department of Transportation, Phoenix, AZ, January 30, 2007.
[17] Lodico, D., and Donavan, P., "The Tire Noise Performance of Nevada Highway Pavements: On-Board Sound Intensity (OBSI) Measurements", prepared by Illingworth & Rodkin, Inc., prepared for the State of Nevada Department of Transportation, Carson City, NV, in cooperation with the California Department of Transportation, Sacramento, CA, June 16, 2008.
[18] Reyff, J., and Lodico, D., "I-80 Davis OGAC Pavement Noise Study, 7-Year Summary Report", prepared by Illingworth & Rodkin, Inc., prepared for California Department of Transportation, Sacramento, CA, November, 2005.
[19] Donavan, P., "Tire Noise Generation and Propagation over Non-Porous Asphalt Pavements", Compendium of Papers, TRB 90th Annual Meeting, Washington, D.C., January 2011.

[20] Lu, Q., E. Kohler, J. Harvey, and A. Ongel, "Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Three-Year Results", Research Report UCPRC-RR-2009-01, Prepared for the California Department of Transportation, January 2009.
[21] Rochat, J., "Pavement Effects in TNM and Temperature Corrections for Noise Measurements", Proceedings of the ADC40 Summer Meeting, Denver, CO, July 2010.
[22] Rasmussen, R., "Quiet Pavements a Mile High", Proceedings of the ADC40 Summer Meeting, Denver, CO, July 2010.
[23] Bendtsen, H., "California-Denmark Study on Acoustic Aging of Raod Pavements", Transportation Research Record, Journal of the Transportation Research Board, No. 2158, Environment 2010, pp 122-128.
[24] Donavan, P., "Eight Year Evaluation of the Noise Performance of the Caltrans Asphalt Research Pavements on LA 138", prepared by Illingworth & Rodkin, Inc., prepared for California Department of Transportation, Sacramento, CA, May, 2011.
[25] Donavan, P., and D. Lodico, "Tire/Pavement Noise of Test Track Surfaces Designed to Replicate California Highways", Proceedings of Inter-Noise 2009, Ottawa, Ontario, Canada, August 2009.
[26] Rochat, J., and Read, D., "Noise Benefits of asphalt pavements – Trends at ages up to 52 months", Noise Control Engineering J., February 11, 2008.
[27] Donavan, P., and D. Lodico, "Measuring Tire-Pavement Noise at the Source", NCHRP Report 630, Transportation Research Board, Washington, D.C., 2009