Traffic noise has become a growing public concern and the California Department of Transportation (Caltrans) has responded by initiating a number of studies to examine the impact various standard pavements have on traffic noise levels. Four very different acoustical studies and preliminary results are presented. Through these studies, Caltrans developed a quick, accurate, inexpensive, and portable method of equitably measuring and comparing tire/pavement noise levels. The measurement method utilizes sound intensity (SI) and was first used by General Motors in a test track environment for tire development. Caltrans adopted this technology as an alternative to the two existing sound pressure methods currently used in Europe - Statistical Passby (SPB) and Close Proximity (CPX). Using sound intensity, Caltrans and the Arizona Department of Transportation developed a database of pavement acoustic characteristics. The European community has been experimenting with quiet pavements for many years, and in May 2004, the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) jointly sponsored an international scanning tour to examine European quiet pavement technology. In September 2004, Caltrans, General Motors, and the FHWA sponsored a follow-up study that used the sound intensity technology to measure and compare some of the European quiet pavements seen on the scanning tour to the California and Arizona quiet pavements. The Noise Intensity Testing in Europe (NITE) study is the first definitive comparison of quiet pavements on multiple continents. Among the many findings of the NITE study, the principle conclusion is that several of the quietest ‘off-the-shelf’ open-graded asphalt pavements in California and Arizona...
compare very favorably to the optimized quiet pavements of Europe.

Key Words: quiet pavement, traffic noise, tire/pavement noise, NITE Study, sound intensity, Statistical Passby, SPB, Close Proximity, CPX

Introduction

Within the United States, the current method of mitigating traffic noise impacts of transportation projects is the construction of sound walls to intercept the transmission between the traffic noise source and the receiver. Sound walls have geometric limitations; they have to interrupt the line-of-sight between the source and the receiver and they effectively attenuate noise levels only 200 to 250 feet directly behind the wall. The State of California constructs sound walls only when a “readily noticeable” reduction of 5 dBA can be achieved. At more than $1.3 million per mile, sound walls are the only noise mitigation solution recognized by the Federal Highway Administration (FHWA)—the principle-funding source for many road construction projects. The principle singular solution of sound walls leaves very little room for context sensitive design and flexibility, and their shortcomings become especially apparent when the walls block scenic views, negatively impact future road widening projects, add additional dead weight to bridge structures, or simply fail to effectively shield receivers from traffic noise. For these reasons, several years ago, Caltrans became interested in the use of “quiet pavements” as an alternative approach to turning down the volume of the irritating noise at the source rather than try to intercept, interrupt, or contain the objectionable sound.

One of the issues of use of asphalt based quiet pavements has been its longevity in abating traffic noise. To develop an understanding of this issue, Caltrans has embarked on several projects investigating the long-term performance of potentially quiet, thin lift asphalt overlays. The first of these was on a portion of the heavily trafficked Interstate I-80 near Davis, California (1). This project is in its sixth year of investigation. In 2000, Caltrans constructed five, specifically constructed sections of different asphalt overlays including one section of dense graded asphalt to
be used for reference (2, 3). These sections have since been monitored for tire/pavement noise using a number of different techniques. As with the I-80 site, these will also be monitored over time to determine their continuing effectiveness. In addition to these test cases, Caltrans has also been monitoring the tire/pavement noise performance of pavement projects throughout the state to gain a more thorough understanding quiet of pavement applications.

In addition to quiet pavement investigations, Caltrans has been developing a new method for determining the in situ performance of pavements using techniques which ride on-board a test vehicle. In 2002, Caltrans developed the application of tire/pavement noise sound intensity measurement to evaluating the performance of highway pavements (4). Once validated, this technique has been used to develop a state-wide pavement noise data base, to evaluate the performance pavement rehabilitation projects, and to investigate pavement noise issue in situations such as bridge decks where conventional measurements along the roadside are not feasible. With the advent of this new, portable technology, it has also been possible to measure the performance of so-called quiet pavements in Europe in a consistent manner that could be compared directly to data from California and Arizona. Under the Noise Intensity Testing in Europe (NITE) project, this goal of obtaining comparable data between the continents was achieved in 2004.

Measurement Methods

Caltrans uses a variety of methods to evaluate the noise performance of pavements. For evaluating the effect of pavement changes on traffic noise, time averaged, Leq, measurements taken from the shoulder next the traffic flow (wayside) are preferred. Other methods such as statistical and controlled passby measurement of individual cars and trucks are used if absolutely necessary, however, the results have to be combined in some manner to obtain an approximation of time averaged traffic noise. For evaluating the effect of pavement changes on tire/pavement noise, noise source level measurements are preferred, or more explicitly, the sound intensity (SI) method.
Wayside Measurement

Wayside measurement can be divided into categories by two methods. The first involves vehicle flow: either by a time average of multiple vehicles or by measuring the maximum noise level of single vehicles. The second classification method is by the intent of the measurement: determination of the effect on traffic noise of a parameter change (e.g., pavement), or determination of the effect on tire/pavement noise of a parameter change using a certain traffic flow. In principle, time average measurements of traffic flows are the clearest method of determining how a parameter change affects noise in the “community”. However, it does have pitfalls in that it is subject to uncertainty due to environmental conditions and extraneous noises, differences in traffic volume, mix, and speed for the before and after conditions, and site-to-site variation if pavements at different locations are to be compared. These sources of uncertainty can be minimized by limiting before and after measurements to certain conditions and/or using traffic noise models to adjust the noise data to account for traffic and site conditions. Because of these uncertainties and the contribution of other vehicle noise sources, time average measurements do not yield very precise measures of the effect of a pavement change on tire/pavement noise.

More removed from a direct measure of noise in the community is the statistical passby method as implemented by either the ISO 11819-1 Statistical Passby (SPB) (5) standard or the FHWA procedures (6) for measuring highway-related noise. Under these procedures, the maximum passby levels of individual, isolated vehicles are measured for selected vehicles in a light traffic flow. Because of the relatively low level of a single vehicle passby, these measurements are at distances of 15 m or less and levels for community exposure beyond a distance of more than 30 m must be modeled or approximated in some manner. Measurement at locations of 7.5 to 15 m away from the vehicle are typically not highly affected by varying environmental conditions. They are also not dependent on traffic volume or mix because each vehicle is measured independently. Within each vehicle category, the spread in noise level can be considerable due to vehicle-to-vehicle variation and vehicle speed (Figure 1) (2). As a result, the averaging of large number of vehicles is required to gain confidence in the results. Once average levels are assigned to each
Figure 1: Results of statistical passby test on LA 138 for passenger car and light trucks

vehicle category, the results can be considered for each category, or the results can be recombined in some manner to estimate the effects of a parameter change on the noise of a traffic mix. Although the statistical passby methods offer some improvement over time-average measurements for vehicle categories, they do not yield very precise measures of the effect of a pavement change on tire/pavement noise.

The third wayside measurement technique, controlled vehicle passby, offers the highest level of precision of the wayside techniques for evaluating tire/pavement noise changes. Although the mechanics of this procedure are similar to the SPB method, maximum passby levels of one or more individual vehicles are measured at a known speed and operating condition. The vehicle and operating condition can be selected to maximize the strength of tire/pavement noise source relative to powertrain and exhaust noise. However, the measured noise level is related to the test vehicle and tires and not necessarily representative of vehicles.
within a category. For this reason, controlled vehicle passby methods tend to be used for relative comparison of tire/pavement noise. However, it is generally reported that relative changes due to pavement are not strongly influenced by tire design for passenger cars and light trucks. Like the SPB methods, controlled passby measurements are limited to situations where traffic volume is low enough that the noise from individual vehicles can be acoustically, and hence physically, separated from other vehicles in the traffic flow.

All three of the above wayside measurement techniques have been employed by Caltrans for evaluating noise due to pavement changes. In many cases, the situation and site dictates the type of wayside measurement. Cost is also a factor as both the time-average and SPB methods can be labor and time intensive. In some situations, applying any of the methods in a standard manner is difficult or impossible. However, wayside techniques, and in particular, time-average measurements remain as the only empirical method of assessing the effects of parameter changes such as pavement on traffic noise in the community.

**Sound Intensity Measurement**

After examining the available wayside techniques, Caltrans decided that it was necessary to consider tire/pavement noise source level or “near field” methods. This was done to increase the precision of tire/pavement noise measurement so that incremental and directional improvements in noise could be identified and to make the measurement of many pavements practical. At the time, the only near source level measurement technique in use for highways was the Close Proximity (CPX) method as defined in a draft ISO Standard, ISO/CD 11819-2 (7). However, this method involved the construction or purchase and maintenance of a specifically designed trailer and produced an expected accuracy of only within 2 dB. Further, the standard could not be implemented in the US as the specified tires were not available. As a result, Caltrans decided to pursue development of a new approach, the sound intensity (SI) method, which had been originally developed as a source level measurement technique for tire noise research work on test tracks (8,9).

In applying the SI method, two locations of the intensity probe are used, one opposite the leading edge and one opposite the
trailing edge of the tire contact patch. The probe positions are 75 mm above the ground and 100 mm out from the tire sidewall. The probe is supported by a fixture mounted to the wheel studs of the test tire/wheel. The probe consists of two 12.5 mm diameter, phase matched condenser microphones spaced 16 mm apart and fitted with nose cones. Signals from these microphones are input to a two-channel, real-time analyzer for immediate SI measurement in true 1/3 octave bands. Since measurements are made separately at the leading and trailing edges of the contact patch, a minimum of two passes are required over the test pavement. These are averaged on an energy basis to determine the reported sound intensity for a given tire or pavement. The effective frequency range of the measurements is from the 1/3 octave band centered at 500 hertz to the 5000 hertz band. A photograph of the SI fixture and probe installed on the right rear wheel of a test vehicle is provided in Figure 2 with a custom shape windscreen placed over the microphones.

Figure 2: Sound Intensity (SI) probe mounted on right rear wheel of Opel Vector test car used in the NITE project

To apply the SI method to evaluating highway pavements, several issues were of concern. These included the selection of a
test speed, the survivability of the probe and fixture in an uncontrolled highway environment, development of a pavement/noise sampling strategy, selection of test tires, and correlation to passby measures. For purposes of rapid data collection, researchers desired to use primarily one test speed as well as one single test tire. Because the measurements were to be made in existing traffic, the test speed choice was important for maintaining safe vehicle-spacing, consistent data collections, and avoid influencing existing traffic flow. As a result, a test speed of 97 km/h (60 mph) was selected. This has since proven to be a very viable test speed on California and Arizona highways. For sampling tire/pavement noise, a 5-second linear average of the data is typically used. If pavement features cover a shorter distance than the 134 m at 97 km/h, a shorter averaging is used with more repeat runs. For longer pavement sections, multiple 5-second samples are acquired and averaged at a later time, as appropriate. Typically, two passes over the test pavement are made for each microphone location. These passes are generally within a few tenths of a decibel of each other. For the primary test tire, a Goodyear Aquatred 3 P205/70R15 was selected. Similar to results reported in the literature, engineers found that this tire rank orders pavements consistently, compared with other passenger car tire designs (3) making the choice of a tire somewhat arbitrary.

As part of the development of the SI method, attention has been given to correlating SI levels to controlled passenger car passby tests with the same tires. To date, this has been done for 3 different tire sets, at 3 different speeds and on 12 different pavements, both AC and PCC. Comparisons of the overall A-weighted (approximates the frequency response of the human ear) SI and passby levels are given in Figure 3 for microphone positions both 7.5 m and 15 m from the centerline of vehicle travel. Considering the whole data set, the average difference from a best fit, 1-to-1 relationship is 0.6 dB for the 7.5 m data, and 0.7 dB for the 15 m data. In later project applications, changes in SI levels have been found to track very well with changes measured by both SPB and time averaged measurements.
Data Base of Pavement Noise Performance

After the demonstration of SI method, it was used to determine the range of noise performance of different pavements in use in California. Since its inception, the data base has grown to over 100 different pavements and bridge decks and includes data from both California and Arizona. The overall, A-weighted sound intensity levels of a representative cross section of these different pavements are given in Figure 4. These data, collected at a test speed of 97 km/h (60 mph) and excluding the typically higher level bridge decks, still display a range of over 13 dB. Within this data set, generic pavement groupings include “PCC” for Portland Cement Concrete, “DGA” or “DGAC” for Dense Graded Asphalt Concrete, and “OG/RAC” for Open Graded/Rubber Asphalt Concrete. The data of Figure 4 are useful in several ways. First, the pavements with the lowest 1/3 of sound intensity are either open-graded and/or rubberized asphalt. The middle 1/3 are mostly dense-graded asphalt with some overlap of OGAC and the quieter
of the PCC surfaces. The upper 1/3 is dominated by PCC except for a “chip seal” surface that contained very large, angular aggregate that generated high levels of lower frequency noise. With some idea of type and condition of existing pavement on highway, these data can be used to roughly estimate what improvement might be expected by modifying an existing surface. Once a project is better defined, SI measurements can be of the actual existing surface to more accurately determine the expected improvement.

**I-80 Davis OGAC Long-Term Study**

In 1998, Caltrans began a long-term study of the effect of an OGAC pavement overlay applied to a 9-kilometer stretch of I-80 just east of Davis, California. Prior to the pavement rehabilitation project, the roadway bed consisted of 120 to 160 mm of aged DGAC. In some spots, the underlying base was removed and replaced. The new AC surfacing began with the placement of 60 mm of DGAC as a leveling course in June and early July 1998. This was subsequently covered with 25 mm of OGAC in July 1998. Since that time, the noise performance of the overlay has...
been monitored using time-averaged wayside measurements made in late fall/early winter, spring, and June of each year. Five minute Leq measurements are routinely made at a reference position located 20 meters from the edge of the nearest travel way. Traffic counts and speed measurements are also measured corresponding to the noise measurements. Distant noise measurements at about 145 meters from the edge of the nearest travel lane have also been made on a yearly basis accompanied with measurements of wind speed, wind direction, and temperature.

The results of the noise measurements at the reference position are shown in Figure 5 along with the corresponding predictions from the FHWA Traffic Noise Model (TNM version 2.1). In addition to the overlay results, the noise levels for the old DGAC are shown as a baseline for assessing noise reduction. It is seen that initially the OGAC provided about a 6 dB reduction compared to the old DGAC and the results of TNM. Over time, both the measured traffic noise and the TNM results have crept up, however, the improvement relative to the modeled results still maintain at 5 dB or slightly more. Even at the relative close measurement distance, the measured levels show some variation that is not related to traffic conditions. As indicated in the plot, upwind versus downwind can be a factor of as much as 2 dB (month 57) even though wind is below the recommended maximum of FHWA procedures. There is also some indication of differences that appear to be related to the time of the year. In the winter and spring months, the levels tend to be higher, while lower in the summer and fall. This effect is on the order of 1 dB.

Tire/pavement noise source levels have also been found to show this cycle from the limited sound intensity measurements that have been made to compliment the wayside data (Figure 6). A more complete presentation of the I-80 Davis study is reported in Reference No. 1.
Figure 5: Wayside time average Leq levels measured 20 m from the edge of the near travel lane of I-80 before and after the OGAC overlay with corresponding results from TNM ver. 2.1

Figure 6: Overall A-weighted sound intensity levels measured on the I-80 OGAC overlay at different times of the year corresponding to times of wayside measurements
In 2002, Caltrans constructed 5 sections of different types of AC pavement on a portion of State Route 138 in a remote area in northern Los Angeles County. These sections consisted of a dense graded asphalt concrete which was to serve as a reference section over time, an open-graded asphalt concrete 75 mm in thickness, another OGAC section 30 mm in thickness, an open-graded rubberized asphalt concrete surface (RAC(O)), and a bonded wearing course (BWC) surface. In the initial measurements, all test sections displayed lower levels than the reference DGAC for both passby measurements of the controlled test car and sound intensity (Figure 7). The thicker OGAC pavement is consistently quieter. However, the RAC(O) surface is almost as quiet at the OGAC. The thinner OGAC is slightly noisier than these two surfaces. These results were confirmed by independent SPB measurements for light vehicles completed by the US DOT Volpe Center (2). Since October 2002, the LA 138 surfaces have been measured with sound intensity in the fall and spring of each year, and once in the summer (Figure 8). Over this time period, the noise level has increased slightly with time for some sections, especially for the reference DGAC and 30 mm OGAC. In all cases except the DGAC, the levels for the spring measurements are higher than the fall or summer. At this point in the long-term research project, it is too soon to draw conclusions regarding these observations, however, they are similar to the trends of the I-80 Davis study. Despite these effects, with the exception of March 2003 when the DGAC reference section produced lower noise levels, the relative differences between the different test pavements has remained constant with the thicker OGAC being more than 4 dB quieter than the DGAC.
Figure 7: Sound intensity and passby levels measured on the LA 138 test sections in Oct ’02 as normalized to the reference DGAC section.

Figure 8: Overall sound intensity level for LA 138 pavement research test sections measured over an 18-month period.
Between June and November of 2002, Caltrans completed a pavement rehabilitation project on a portion of Interstate I-280 in San Mateo County, California. The existing pavement was older PCC with some slab faulting. The faulting was repaired as required and new surface treatments applied. All of the PCC lanes were ground using a “regular” diamond grinding process with a vertical/horizontal variation specified at 19 mm/0.1 km. Afterwards, one section was ground a second time to achieve a higher-grade grind finish with a variation specified at 8 mm/0.1 km. Additional sections received an open graded, rubberized asphalt concrete RAC(O) overlay. As a result, in the post-project state, three new surfaces existed on this segment of I-280 in both the north and south bound directions. In order to capture the change in pavement/tire noise with these new surfaces, pre- and post-project SI measurements were conducted. Based on previous SI data and other wayside data (4), it was anticipated that the RAC(O) overlay would provide significant attenuation of tire/pavement noise.

A total of six sections of roadway were measured in the pre-project existing state. These corresponded to the location where each of the three new surfaces were to be applied as measured in the south and north bound directions. On the southbound sections, the pavement appeared to be consistent although periodic transverse joints produced slapping sounds audible inside the test vehicle and on the digital audio tape (DAT) recordings. In the northbound direction, some grinding had already taken place leaving only existing data for one section. After the surface treatments were applied, the measurements were repeated and the resultant overall A-weighted levels are shown in Figure 9.

These data indicate several things. First, in all cases where direct comparison is available, all of the surfaces produced improvement. The reductions with the RAC(O) were greater than either of the grindings applied to the PCC. One interesting aspect of the pre-project data is the 2 dB range in level. As a result, it was difficult to determine what the typical reduction was for each surface treatment other than to state a range. With the on-board measurements, however, it was possible to average over the sections in a manner consistent with the project as well as to
evaluate localized performance. This level of detail would typically not be contemplated using passby or wayside methods. For this project, after all the data were considered, it was concluded that the RAC(O) produced a project average of 6.2 dB reduction, the regular grind, a 1.0 dB reduction, and the texture grind, a 0.9 dB reduction. One interesting side note to this testing was that the highway shoulders were non-rubber OGAC. Direct SI comparison between the OGAC shoulder and the RAC(O) travel lane yielded virtually the same acoustic results.

Figure 9: Pre- and post-project overall sound intensity levels for I-280 pavement rehabilitation with the indicated reduction for each section.


I-5 Bridge Decks

Tire/pavement noise from bridge deck surfaces is increasingly an issue for environmental impact communities. In California, bridge decks and viaducts typically have surfaces of rough-textured, transversely tined PCC for safety wet/ice reasons. Some recently constructed surfaces have generated noise complaints from neighbors as well as concern by highway engineers. On-board techniques are ideally suited for evaluating the noise produced by bridge decks and with the data base already developed, a comparison of tire/pavement noise levels to other on-grade surfaces is readily made.

One application involved a newly resurfaced bridge deck in Northern California on Interstate I-5 near Redding. In this case, the new bridge surface in the northbound direction was generating complaints relative to the old surface and the existing southbound surface. SI measurements were made on both the north and southbound deck surfaces as well as the AC approaches to each. The result of this testing is given in Figure 10 on an overall A-weighted basis. The levels are louder than any of the on-grade surfaces measured in California by 3 to 7 dB. The northbound deck is indeed louder (4 dB) than the southbound deck and is expected to be similarly louder than the surface it replaced. Possibly contributing to the perceived noise of the northbound deck is the 11 dB increase in noise in the transition from the AC approach to the textured PCC deck surface itself (Figure 10). Using the data base of Figure 4 and results of PCC texture study completed on Route 58 bypassing Mojave, California, it was determined that grinding the surface could result in sound intensity levels of 103 dB or less (4). Based on this information, it was decided to grind the northbound bridge deck. The change in sound intensity level with re-surfacing is shown in Figure 11 along with comparable other ground PCC surfaces. These data indicate that a reduction of about 10 dB was achieved producing a noticeable improvement for the affected residences.
Figure 10: Overall sound intensity levels for I-5 bridge deck surfaces and approaches

Figure 11: Reduction in overall sound intensity levels for I-5 bridge deck with grinding of the northbound span.
Noise Intensity Testing in Europe – the NITE Project

With the development of a consist tire/pavement noise data base in California and Arizona, there was considerable interest in applying this same measurement approach to pavements in Europe. In May of 2004, a delegation from the US undertook a “Scanning” tour of European countries to discover and document the state of the practice in European technology for quiet pavement systems. The Europeans have been experimenting with quiet pavement design much longer than the US. Although this tour was successful in its qualitative assessment, because of measurement method and test tire differences between researchers in Europe and the US, there was no common scale to compare the performance of European pavements to those in the US. To fill this void, Caltrans initiated a project to perform sound intensity measurements in Europe that could be compared directly to those in the California/Arizona (CA/AZ) data base. This became the Noise Intensity Testing in Europe or “NITE” Project. General Motors supplied logistical support and the FHWA made a financial contribution to the project.

Project Definition & Preliminary Work

In principle, sound intensity measurements of European roadways could readily be accomplished, as the sound intensity fixture and measurement equipment are quite portable. However, to definitively tie the European data to the CA/AZ database, the same tire design as used in the US was required for the European testing. As the US test tire was not available in Europe, tires were shipped from the US. It was also necessary to identify a test vehicle that could accommodate the P205/15R tire size used in the CA/AZ data. With the assistance of General Motors, it was determined that the 2004 Chevrolet Malibu and 2004 Opel Vectra had common wheel designs and could accommodate the P205/15R tire size. This allowed direct comparison testing between the CA/AZ test tire and the test tire to be used in Europe prior to shipping the new test tires. To accomplish this, “back-to-back” sound intensity measurements were made on 3 different pavements for the CA/AZ tire as mounted on the normal 1998 Subaru Legacy Outback test vehicle and the tire for the European testing as mounted on a Chevrolet Malibu. Consistent with other testing of
this tire design mounted on other vehicles and test trailers, the
difference in tire/pavement noise between the two test tire/vehicles
was found to be 0.8 dB or less for the 3 different surfaces.

For testing in Europe, an Opel Vectra was provided by
General Motors. Prior to the pavement testing, sound intensity and
passby tests were conducted at the Opel Proving Ground on their
ISO 10844 test track surface used for vehicle passby noise
development. For constant-speed-cruise-conditions, the
relationship between sound intensity and passby levels was
identical to that demonstrated in the CA/AZ testing.

After the verification testing at the Opel Proving Ground,
sound intensity measurements were conducted in four different
countries on a total of 66 different pavements. As the primary
interest of the project was for higher speed pavement performance,
the majority of the testing was performed at 97 km/h. However, 33
pavements were also tested at 56 km/h. The test pavements were
located in Germany, the Netherlands, France, and Belgium. The
specific test sites were selected to capture the performance of
pavements considered to be “quiet” as well as to document the
range of performance displayed by typical pavements in Europe.
The selection of the sites was accomplished with input from
researchers in the individual countries as well as from members of
the Scan tour. The measurement period was three weeks in
duration and was completed in October of 2004.

Results of Testing
The range in tire/pavement noise sound intensity levels of
these European pavements is shown in Figure 12 for 97 km/h. For
the European pavements, additional generic groupings were added
to include pavement types pavements not commonly found in
California or Arizona. These are “PA” for Porous Asphalt,
“DLPA” for Double Layer Porous Asphalt, and “SMA” for Stone
Mastic (or Matrix) Asphalt. In CA/AZ, the term “open graded” is
somewhat casually used to refer AC surfaces that may have some
degree of porosity. However, these can have lower void ratios, on
the order of 5 to 8 percent. In Europe, porous pavements typically
imply void ratios on the order of 15 to 20 percent. To distinguish
this, the “PA” nomenclature is used in Figure 12. The DLPA
nomenclature refers to two layers of porous AC typically with
differing aggregate size ranges to achieve different amounts of
permeability. An example of this type of pavement is shown in Figure 13. Typically, the top layer is constructed of smaller aggregate to reduce noise while the lower layer uses larger aggregate to improve drainage. Different top layer aggregate sizes are used to optimize noise performance. SMA pavements are not common in California. These pavements typically feature a large amount of stone-to-stone contact, viscous binder, and low air voids. A SMA pavement is shown in Figure 14. It should be noted that in Europe, pavements termed dense-graded AC appeared to be quite different than those in California (Figure 15). Comparing Figures 4 and 12, it is seen that the overall ranges in noise levels for the CA/AZ pavements and European pavements are nearly identical at about 13 dB. In terms of absolute level, the quietest European pavements are slightly lower (~2 dB) than the quietest from the CA/AZ database.

Figure 12: Range of overall A-weighted sound intensity levels at 97 km/h as measured in Europe for the NITE project
Figure 13: Double layer porous AC construction in the Netherlands with 6 to 8 mm aggregate on top layer

Figure 14: Example of SMA pavement in Belgium
Figure 15: Comparison of dense-graded asphalt concrete from the Netherlands (left) and California (right).

As with the CA/AZ data, the 97 km/h NITE results exhibit considerable overlap between pavement categories (Figure 12). The exception to this is the DLPA category, which, as a group, defined the quieter end of the data set. It is also noteworthy that one of the PCC pavements produced levels comparable to the DLPA surfaces. This was a porous PCC pavement with a diamond-ground surface.

Results for the 56 km/h NITE data are shown in Figure 16. The range of these data is smaller than that in the 97 km/h data, however, the noisier transversely tined PCC surfaces were not included in this data set. Relative to limited 56 km/h data obtained in California, the range of 10 dB is similar. Further, the levels for the quietest and loudest pavements in both data sets are virtually identical. Similarly, at 97 km/h, the ground porous PCC pavement was almost as quiet as the quietest AC pavements. A second, unground porous PCC, is also included in this data set (not in the 97 km/h data set), and it also performed well being only about 1 dB higher than the ground section.

The NITE data can be used to examine tire/pavement noise within some of the general pavement categories. In Figure 17, the range of level for the SMA surfaces is plotted along with the available information on aggregate size. Although the rank ordering is not perfect, the general trend is that the smaller aggregate sizes produce lower noise levels. This trend is not unexpected based on other pavement noise studies. Data for the DGAC surfaces is given in Figure 18. In this case, the documentation is not as complete, but the same trend of aggregate
Figure 16: Range of overall A-weighted sound intensity levels at 56 km/h as measured in Europe for the NITE project.

Figure 17: Range of performance for European SMA pavements of varying aggregate size.
Figure 18: Range of performance for European DGA pavements of varying aggregate size
size versus noise is suggested. In comparison to Figure 17, the DGAC displays almost the identical range and magnitude in tire/pavement noise levels. Results for the single layer porous AC surfaces (Figure 19) display a slightly wider range than the DGAC or SMA and do not show quite as much relation to aggregate size. It has also reported that porous AC surfaces can lose their porosity through clogging over time, which may account for a portion of the range of noise performance indicated. In contrast to the single layer PA, the double layer PA surfaces display remarkably little range in SI levels (Figure 20), and all surfaces performed relatively well. The consistency of these results may be due to the fact that all these surfaces were within a few years old or were on test tracks instead of in-use roadways.

Figure 19: Range of performance for European Porous AC pavements of varying aggregate size
Comparisons between the NITE and CA/AZ Results

One of main purposes of the NITE project was to determine if the pavement technology in Europe produced quieter pavements. Large relative reductions for quiet pavements relative to some baseline pavements have been reported in the literature from Europe. Comparing Figures 4 and 12, the range and level of tire/pavement noise appears to be quite similar. This issue can be examined more closely by comparing the range of commonly occurring pavements to quiet pavements. As the lowest levels were measured in the Netherlands, these data were chosen for these comparisons. In Figure 21, several DGAC and PCC pavements, which were found on existing motorways, are plotted with two different DLPA pavements. The typical improvement in level with the DLPA is about 10 dB. In Arizona, although there is a limited amount of longitudinal and random transverse tined PCC, the bulk of the PCC is uniform transverse tined. Relative to Arizona Asphalt Rubber Friction Courses (ARFC) overlays that have been recently applied in the Arizona Quiet Pavement Pilot Project, reductions on the order of 9 dB are typical (Figure 22). In California, however, the range of possible improvement is smaller primarily due to the absence of the use of transverse tining for on-
grade PCC surfaces (Figure 23). As a result, the typical higher levels are about 3 dB lower than Arizona or the Netherlands and the range of possible improvement is on the order of 6 dB. These data emphasize that the benefits of a quiet pavement will be a function of both the performance of the quiet pavement and the pavement that it replaces. It also emphasizes that care must be taken in assuming that the reductions found in one state or country will realized in another.

It is also instructive to compare the quieter pavements measured in Europe, California, and Arizona (Figure 24). In Europe, the quieter pavements are “drainage” pavements, intentionally constructed to be water (and air) permeable. As a result, they should provide sound absorption characteristics, which would decrease tire noise generation and propagation. For the CA/AZ surfaces, high permeability is not necessarily achieved with the open-graded designs. Further, there has been no indication of improved sound absorption of these surfaces relative to others. However, two of three CA/AZ pavements contain rubber, which is not found in European pavements. At this time, the role of the rubber content on noise performance is not understood. Another difference is that European porous pavements tend to be thicker, by 40 to 120 mm. For the CA/AZ rubberized pavements (AZ ARFC & LA 138 RAC(O)), the overlays are thinner (25 to 30 mm total thickness), but can achieve virtually the same acoustical performance of the thicker permeable European surfaces. From the LA 138 results (Figure 7), nearly doubling the thickness of the OGAC layer only produced a ½ dB or less improvement in noise performance. A final difference between the European pavements and the CA/AZ pavements is aggregate size. The European pavements have maximum aggregate sizes of 6 to 8 mm. The CA/AZ pavements range from 9.5 mm to 12.5 mm. The relationships between permeability, porosity, pavement thickness, aggregate size, and rubber content are clearly an area for further work.
Figure 21: Typical noisier pavements in the Netherlands compared to typical quiet pavements

Figure 22: Typical noisier pavements in the Arizona compared to typical quiet pavements
Figure 23: Typical noisier pavements in the California compared to typical quiet pavements

Table:

<table>
<thead>
<tr>
<th>Pavement</th>
<th>Sound Intensity Level, dBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR 84 Chip Seal</td>
<td>~6 dB</td>
</tr>
<tr>
<td>I-280 Older PCC</td>
<td></td>
</tr>
<tr>
<td>I-80 Older PCC</td>
<td></td>
</tr>
<tr>
<td>SR 14 Older PCC</td>
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<tr>
<td>SR 85 Long Tine PCC</td>
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</tr>
<tr>
<td>I-80 DGA</td>
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</tr>
<tr>
<td>I-40 DGA</td>
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</tr>
<tr>
<td>LA 138 OGAC</td>
<td></td>
</tr>
<tr>
<td>I-280 RAC(O)</td>
<td></td>
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<tr>
<td>LA 138 RAC(O)</td>
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</tbody>
</table>

Figure 24: Quietest pavements in Europe and California/Arizona
Summary

Although not a replacement for wayside traffic noise measurements, the sound intensity method has proven to be a very useful tool in evaluating the influence of pavement on tire/pavement noise generation. With its ease of deployment, portability, and time efficiency, sizable, consistent databases have been readily developed for California, Arizona, and four countries in Europe. Within Caltrans, it is quickly becoming the preferred, scientific tool for evaluating pavements and guiding quiet pavement applications with wayside measurements to follow where practical.

From the Caltrans studies performed in California and Arizona, the following observations have been made:

1. Pavement type can reduce tire/pavement noise up to 8 or 10 dB depending on the existing and final pavement.
2. A significant range in tire/pavement noise performance is in each of the generic groupings of pavement (PCC, DGAC, and OGAC/RAC).
3. Surface roughness/texture controls the lower tire/pavement noise frequencies (below ~1000 hertz).
4. As a group, open-graded and/or rubberized asphalt concrete show the best tire/pavement noise performance.
5. Grinding of PCC surfaces can be effective in reducing tire/pavement noise by reducing texture effect (such as transverse tining) and by reducing joint slap.

The first 3 of these were confirmed in the NITE testing. Since ground PCC and rubberized AC surfaces were not studied in the NITE project, these were neither confirmed nor discounted. From the NITE testing, the following observations were made:

1. Highly porous 2-layer AC constructions can provide only slightly better tire/pavement noise performance than the quiet pavements currently in use in California and Arizona.
2. Porous PCC can produce tire/pavement noise performance similar to that of other quiet pavements.
3. Exposed aggregate PCC surfaces were not found to be particularly quiet relative to longitudinal texture.
4. The range in tire/pavement noise performance of SMA pavements is similar to that of DGAC, and both are at least loosely related to aggregate size.

References

