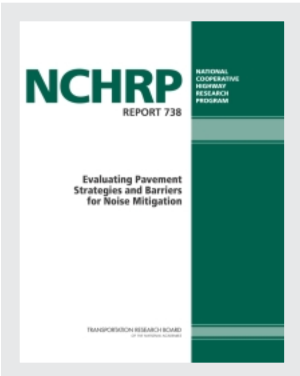

Evaluating Pavement Strategies and Barriers for Noise Mitigation

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 738

Evaluating Pavement Strategies and Barriers for Noise Mitigation

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Information on agency highway noise policies, practices, and project case studies was provided by Bruce Rymer and James Andrews of the Division of Environmental Analysis, California Department of Transportation; Gregory Smith and Joseph Rauseo of the Human Environment Unit, North Carolina Department of Transportation; Fred Garcia of the Environmental Planning Section, Arizona Department of Transportation; and Ryan McNeill of the Massachusetts Highway Department.

FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research Board

This report presents a methodology for evaluating feasibility, reasonableness, effectiveness, acoustic longevity, and economic features of pavement strategies and barriers for noise mitigation. The methodology uses life-cycle cost analysis (LCCA) to examine the economic features of mitigation alternatives, the FHWA Traffic Noise Model (TNM®) to integrate the noise reduction performance of pavements and barriers, and on-board sound intensity (OBSI) measurements as an input to the prediction model. This approach provides a rational basis for evaluating alternatives for noise mitigation. The material contained in the report will be of immediate interest to state engineers and others concerned with pavement design and construction and the noise impact on nearby communities.

Noise barriers have been used for many years as a noise mitigation measure. These barriers are costly to build but they require minimal maintenance and maintain their noise reduction features for a substantially long period. Title 23, Part 772, of the *Code of Federal Regulations* requires that noise analysis be performed for specific types of projects when potentially impacted receptors are present. Noise barriers are considered when noise impacts are identified and when a noise abatement measure is constructible, provides a meaningful noise reduction, is cost reasonable to build, and is desired by the public. This regulation identifies several noise mitigation measures but excludes pavements as a noise abatement measure. Recent advances in quiet pavement technology have shown the potential for using such abatement technology as an alternative to noise barriers. However, issues such as cost, maintenance requirements, and the ability to maintain noise reduction features over time need to be addressed when considering quiet pavement technology. Research was needed to develop a methodology for evaluating the feasibility, reasonableness, effectiveness, and longevity of acoustic and economic features of pavement strategies and barriers used for noise mitigation. Such a methodology will demonstrate the potential of quiet pavement technology as a noise abatement measure and thus assist with the selection of the reduction measure or combination of measures that will provide the desired acoustic characteristics while yielding cost savings.

Under NCHRP Project 10-76, “Methodologies for Evaluating Pavement Strategies and Barriers for Noise Mitigation,” Illingworth & Rodkin of Petaluma, California, worked with the objective of developing a methodology for evaluating the feasibility, reasonableness, effectiveness, acoustic longevity, and economic features of pavement strategies and barriers used for noise mitigation. To accomplish this objective, the researchers first reviewed the practices and processes for evaluating pavement strategies and barriers proposed for noise abatement. The researchers then evaluated potential methodologies and developed considerations for feasibility, reasonableness, effectiveness, acoustic longevity, and economic features of pavement and barriers, and identified those issues that need to be considered in a rational methodology. This evaluation considered the relationship between OBSI and wayside measurements and TNM predictions; the noise reduction provided by both barriers and quieter pavement as a function of distance as well as the additional noise reduction provided by porous, sound-absorbing pavements; the variety of possible strategies including quieter pavement alone, barriers alone, and combined barriers and quieter pavement; the longevity of acoustic properties; and LCCA.

Based on the results of the evaluation, a methodology that considers acoustic and economic features of both pavements and barriers was developed. The methodology uses OBSI data to quantify the noise levels of existing and future pavement projects and to assess the pavement acoustic performance over time, a modified version of TNM to determine current and future noise levels to analyze feasibility and reasonableness, and LCCA to evaluate the initial cost of abatement and cost of maintaining that performance over the life of the project. The methodology also incorporates a measure of the effectiveness of the resulting predicted level of traffic noise. The developed methodology was then applied to several example cases that considered a variety of highway situations and scenarios involving quieter pavement only, barriers only, and combined pavement and barrier. These scenarios were evaluated for feasibility, reasonableness, effectiveness, and economic features with consideration of pavement acoustic longevity. Finally, the methodology was then refined based on the findings of these case studies.

The appendices contained in the research agency's final report provide elaborations and detail on several aspects of the research. These appendices are not published herein but are available on the TRB website (http://www.trb.org/Main/Blurbs/169200.aspx).

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

SUMMARY

Evaluating Pavement Strategies and Barriers for Noise Mitigation

Background

Over the past decade, consideration of quieter pavement as an alternative to barriers for highway noise mitigation has been advanced by highway agencies and the public. As an abatement measure, barriers have a higher initial cost than quieter pavements but have lower ongoing costs due to minimal maintenance requirements. Additionally, the noise reduction benefit provided by barriers does not change over time. In contrast, the noise reduction provided by quieter pavements typically diminishes with time. Although the initial cost of quieter pavement can be lower than barriers, the ongoing cost needed to maintain the desired noise reduction performance can be greater.

Title 23, Part 772, of the *Code of Federal Regulations* (23 CFR 772) requires that noise analysis be performed for specific types of projects when potentially impacted receptors are present. Although this regulation identifies several noise mitigation measures, it does not include pavements as a noise abatement measure. Developing a rational methodology for evaluating the acoustic and economic features of pavement strategies and barriers will help demonstrate the potential of quiet pavement technology as a noise abatement measure.

Overview of the Project

This research focused on developing a methodology to account for the acoustic performance and life-cycle costs of both types of mitigation measurements when used separately or in combination to allow a systematic and fair comparison of abatement alternatives. This methodology provides a means of evaluating pavement strategies and barriers together for feasibility, reasonableness, effectiveness, acoustic longevity, and economic features. It incorporates the use of (1) on-board sound intensity (OBSI) data to account for the effect of pavement performance on tire noise source levels; (2) the Federal Highway Administration Traffic Noise Model (FHWA TNM®) with a modification to adjust for tire–pavement noise based on OBSI data; and (3) life-cycle cost analysis (LCCA) to compare the costs of barriers, quieter pavement, and combinations of pavements and barriers.

The LCCA provided a means for evaluating the economic features of barriers and pavement strategies. The modified version of the FHWA TNM allowed for the modification of the ground-level vehicle noise source strength to account for differences in tire–pavement noise levels using OBSI levels. In this manner, TNM can be used to predict the traffic noise levels for different barrier designs, different pavements, and any combinations of these. OBSI can also be used to establish rates at which pavement noise performance degrades over time for purposes of predicting future levels and/or for monitoring the performance of pavement over its life cycle.

In addition to accounting for economic features and acoustic longevity, the methodology provides a means for evaluating feasibility and reasonableness on the basis of overall noise reduction attributable to insertion of the barrier, use of the pavement, or a combination of the two instead of insertion loss only as is done currently. In addition to feasibility and reasonableness, a third evaluation parameter, *effectiveness*, has been included to go beyond the relative measures of insertion loss and noise reduction to consider the absolute level performance of the noise abatement. This parameter is needed because the relative metrics of barrier insertion loss and tire–pavement noise reduction when considered separately do not necessarily identify the quietest noise abatement alternative. For example, the most *effective* low traffic noise levels may not be achieved by combining good barrier insertion loss with noisier pavement or by combining a short (or no) barrier with a moderately quieter pavement.

The proposed methodology was applied to several typical highway project case studies. These cases demonstrated that the methodology is appropriate for evaluating pavement strategies and barriers in order to identify alternatives that meet cost- and acoustic-effectiveness criteria similar to that used currently by highway agencies.

CHAPTER 1

Background and Research Approach

Background

In the past decade, considerable interest in quieter pavement technology has been shown by state and local transportation agencies, the Federal Highway Administration (FHWA), and the general public. This interest has been advanced by a number of research and pilot projects that have demonstrated traffic noise reductions over existing pavements by the application of quieter pavement overlays and surface texture modifications. These reductions have been documented both with objective noise measurements and the reaction of the public to the quieter pavements. In addition, the understanding of quieter pavements in the United States has increased dramatically in this time period particularly by the advent of the on-board sound intensity (OBSI) method of quantifying the tire noise performance of these pavements at the source (*1, 2, 3, 4*). With this knowledge and interest, the potential for quieter pavements to be used as alternatives or supplements to traditional barriers for traffic noise abatement has been considered.

On the surface, a comparison of barriers and quieter pavement appears to be straightforward. Initially, barriers typically cost more to build than using quieter pavement and the reduction in traffic noise at receptor locations can be comparable depending on the existing noisier pavement and the height of the barrier (*5*). Over time, however, the noise performance of quieter pavements degrades resulting in less noise reduction and higher traffic noise levels. To maintain the noise performance of the quieter pavement, the pavement will need to be replaced or treated, possibly at a faster rate than typically required for rehabilitation. As a result, there may be higher long-term recurring costs associated with using quieter pavement for noise reduction than would be incurred for a noise barrier. For barriers, the amount of noise reduction defined by the insertion loss of the barrier is generally invariant with time and requires little, if any, additional cost to maintain its performance over time. Because of the difference in the performance-maintenance requirements of these two approaches, methodologies need to be developed for comparing these two noise abatement or reduction options beyond the initial costs.

Other issues add to the complexity of comparing barriers and quieter pavement. Maintaining reduced noise levels with quieter pavement will require periodic acoustic rehabilitation of the pavement to achieve a specific range of traffic noise levels at the receptors, assuming constant traffic volumes and conditions. For barriers, although the amount of noise reduction remains unchanged if the traffic mix does not change, the traffic noise levels will still increase by an unspecified amount as the pavement ages. Also, for many highway projects, barriers are often a local solution not extending the entire length of the project. However, the same pavement type is generally constructed throughout the project and local solutions may not be practical. Further, in some cases, barriers may not provide sufficient insertion loss to be considered, may not be physically possible, may not provide noise reduction to a sufficient number of the receptors to be viable, or may not be desired by the community. In these situations, quieter pavement may provide some amount of noise reduction.

FHWA Policy

In 1997, Title 23, Part 772, of the *Code of Federal Regulations* (23 CFR 772) required that for Federal-Aid highway projects, noise analysis must be performed for specific types of projects when potentially impacted receptors are present. This regulation identified five noise abatement options and required that the selected abatement be both feasible and reasonable. In 2010, 23 CFR 772 was updated and published on July 13 for implementation by state agencies 1 year later (*6*). The updated version of 23 CFR 772 incorporates some of the information and definitions that were included in the original 1995 "Highway Traffic Noise Analysis and Abatement Policy and Guidance" (*7*). To support the update of 23 CFR 772, the document "Highway Traffic Noise: Analysis and Abatement Guidance" was initially released in June 2010 and revised in January 2011 (*8*). The revised policy includes changes that affect abatement measures and analysis, but the basic approach remains. The five approved methods of noise abatement remain the same and exclude the use of pavement as an abatement option. In practice, barriers will likely remain the primary method of abating traffic noise (*9*). However, the use of pavement types other than FHWA Traffic Noise Model (FHWA TNM®) Average Pavement can now be considered in the analysis, upon documentation and approval by FHWA through the Quieter Pavement Pilot Program process.

In regard to evaluating noise abatement options, the concept of feasibility remains essentially the same as in the earlier 23 CFR 772; however, some changes were incorporated in the new policy. Barriers or other methods are not feasible if they do not reduce predicted noise levels by 5 dB or more for some number of impacted receptors where the number is now defined by the highway agency noise policy (*6*). Feasibility also continues to include the physical ability to be built from an engineering perspective.

Reasonableness of noise abatement continues to consider the cost of abatement relative to the number of benefited receptors and the view of affected residents as well as other circumstances. However, newly added to reasonableness criteria is the noise reduction design goal. This provision mandates that agencies establish the noise reduction design goal between 7 and 10 dB for the minimum amount of noise reduction produced by the abatement. The abatement must meet or exceed this goal for some number of benefited receptors in order to be considered reasonable. Although the noise reduction design goal does not replace the acoustic feasibility criterion of 5 dB with 7 to 10 dB, it can have this effect in some cases when the barrier is feasible but does not achieve at least 7 to 10 dB for some benefited receptors.

Another change in 23 CFR 772 was the requirement that highway agencies define the threshold of noise reduction, which determines a benefited receptor, as a reduction of not less than 5 dB. Previously, the threshold varied by state over a range of 3 to 6 dB with one state using 6 dB for the first row of receptors and 4 dB for the second.

Other Considerations

The tire noise performance of the pavement used in TNM corresponds to an average of the performance of pavements that was determined from statistical pass-by (SPB) measurements documented in the FHWA Reference Energy Mean Emission Levels (REMEL) database (*10*). For the purposes of this research project, pavements were grouped into three categories: portland cement concrete (PCC), dense-graded asphalt concrete (DGAC), and open-graded asphalt concrete (OGAC). Averages of SPB data for PCC and DGAC pavements were formed for different vehicle categories. This "Average Pavement" type is used in TNM traffic noise predictions as required by 23 CFR 772.

During the course of this research, the FHWA, through the Volpe National Transportation Systems Center, was conducting a study to identify potential methods of incorporating pavement-specific tire noise performance into TNM (*11*). These methods included adjustment of the tire source levels based on OBSI data combined with accounting for pavement sound absorption, expanding the REMEL database to include pavement types to be used in TNM, or applying post-calculation corrections to the model results. The first report on FHWA's study demonstrated and concluded that "using OBSI data is a valid option for incorporating a broad range of pavement effects in the FHWA TNM" (*12*). This approach is very attractive for application in methodologies for evaluating pavement strategies and barriers in noise abatement for several reasons. First, it allows a state highway agency (SHA) to input the actual tire noise source levels for the pavements it is considering in a project rather than a nationwide average that may or may not be appropriate to the state. Second, it allows the prediction of changes in traffic noise levels if the tire noise performance of the quieter pavement changes over time. Third, it properly spatially locates the region where noise source strength changes, allowing more accurate propagation modeling. For these reasons, the use of OBSI in TNM became a significant element of the methodology developed in this research.

Also during the course of this research, the standardization of OBSI for measurement of the tire noise performance of pavements progressed sufficiently to be considered as a method that could be used by any SHA. In 2011, the American Association of State Highway and Transportation Officials (AASHTO) TP 76 OBSI procedure (*4*) completed its 11th round of revision as a provisional standard and further substantive changes are not expected. Also NCHRP Project 1-44(1), "Measuring Tire–Pavement Noise at the Source: Precision and Bias Statement," was completed and the final report is now available (*13*). The results of NCHRP 1-44(1) further quantified the uncertainty produced by measurement variables, recommended more controls, and established expected precision and bias values.

Research Objective

The objective of this research was to develop a methodology for evaluating the feasibility, reasonableness, effectiveness, and longevity of acoustic and economic features of pavement strategies and barriers used for noise mitigation of highway traffic noise. The approach used to accomplish this objective is described in this chapter.

The need for this research was driven by (1) the complexity of evaluating both barriers and quieter pavement on an "equal playing field" for use by state and local agencies and (2) the need to develop a methodology that can be used in making such evaluations independent of policies.

Research Approach

The intent of the research was explicitly not to develop or propose changes to federal policy but to develop a methodology that can be adapted into FHWA policy in a manner that the agency could define at a later time if desired. Therefore, the basic framework of 23 CFR 772 was considered in this research, particularly in regard to feasibility and reasonableness. Also, the case studies used to illustrate application of the proposed methodology considered state agency policies developed to meet the older version of 23 CFR 772.

To accomplish the project objective, the research included the following four tasks:

1. **Collect and review information.** Information regarding existing methodologies for evaluating the feasibility, reasonableness, effectiveness, and longevity of acoustic and economic features of both pavement and barriers was gathered and reviewed. Initially, this information was divided into several specific topics including pavement acoustic longevity, barriers, cost–benefit, life-cycle cost analysis (LCCA), noise policies, and the FHWA TNM implementation. As it became apparent that sound absorption by the pavement could also influence the predicted noise level, the category of effective flow resistivity was added. In this task, over 130 sources of information were identified and more than 60 of these were further reviewed and referenced.
2. **Identify and evaluate methodologies and issues.** The information collected and reviewed in Task 1 was evaluated and summarized and specific issues were identified as considerations for defining and potentially implementing the methodologies. Each aspect of the identified methodologies was examined in detail. For *feasibility,* technical acoustic issues considered the relationship between OBSI and wayside measurements and TNM predictions, the noise reduction provided by both barriers and quieter pavement as a function of distance, and the additional noise reduction provided by porous, sound-absorbing pavements. For *reasonableness,* different strategies were evaluated including quieter pavement alone, barriers alone, and combined barriers and quieter pavement. Aspects of *effectiveness* were explored to develop a definition of this term in regard to traffic noise, particularly in comparison to *feasibility.* For *longevity,* the limited available studies were reviewed and issues regarding collecting longevity data identified. For economic comparisons, cost–benefit analysis was considered but LCCA was regarded as a more fair method for comparing the costs of pavement and barrier solutions. This work provided an overall approach for developing the methodology in Task 3.
3. **Develop the methodology.** The analysis performed in Task 2 was used to develop the initial proposed methodology. The methodology included the use of OBSI data to quantify the noise levels of existing and future pavement projects and to assess the pavement acoustic performance over time. These data were used in the modified version of TNM to determine current and future noise levels for comparison to noise levels abated by barriers. These TNM results were then used to analyze feasibility and reasonableness in a manner similar to 23 CFR 772. A dimension of *effectiveness* was introduced based on the resulting predicted level of traffic noise. Economic features were evaluated using an LCCA that takes into account the initial cost of abatement and the cost of maintaining that performance over the life of the project.
4. **Demonstrate applications of the methodology.** The proposed methodology was applied to several example cases. One case involved a simple, flat highway geometry to illustrate use of the methodology in an idealized case. Other case studies considered actual highway projects from several states and scenarios involving quieter pavement only, barriers only, and combined pavement and barrier. These scenarios were evaluated for feasibility, reasonableness, effectiveness, acoustic longevity, and economic features. The methodology was refined based on the findings of these case studies.

Report Organization

The report consists of six chapters and a list of references. Chapter 1 describes the background and research approach. Chapter 2 reviews how the existing process for highway traffic noise analysis is proposed to be modified with the inclusion of OBSI measurements and the use of LCCA. Chapter 3 addresses the evaluation parameters of highway traffic noise analysis, including feasibility, reasonableness, and effectiveness. Chapter 4 develops a scenario of new highway construction and presents how the proposed analysis and evaluation parameters would be applied to three examples based on this scenario. Chapter 5 applies the analysis and evaluation methodology to actual highway projects in three states and presents the findings. A summary and suggestions for further research are presented in Chapter 6.

Eight appendices to the report are available on the TRB website (http://www.trb.org/Main/Blurbs/169200.aspx). Appendix A explores the effect of porous, sound-absorptive pavement on traffic noise and its prediction. Appendix B provides an overview of pavement LCCA as implemented by FHWA and Appendix C illustrates the application of LCCA to a hypothetical situation involving a new highway project. Appendix D discusses feasibility, reasonableness, the new evaluation parameter of effectiveness, and the results of the supporting literature search. Appendix E provides information on the acoustic longevity performance of different pavements and Appendix F summarizes findings on the economic features and cost–benefit analysis. Appendices G and H provide detailed information on the LCCA performed for two highway widening projects.

CHAPTER 2

New Elements for the Highway Traffic Noise Analysis Process

Overview of New Elements

In the early stages of this research, concepts for the analysis of the features of pavement strategies and barriers used for noise mitigation were developed. One of the primary elements of the analysis process was the use of OBSI measurements to provide quantification of pavement performance as it relates to traffic noise initially and over the life of the pavement. Although other methods for quantifying the effect of pavement on traffic noise were considered, OBSI was preferred due to cost, ease of use, its ability to economically monitor the noise performance of pavement at many locations, and its evolution into an AASHTO standard method of test as well as the demonstrated potential for incorporating OBSI data into TNM 2.5 (*11*).

The use of an OBSI-defined ground-level source strength (GLSS) TNM was another key element in the methodology. TNM provides the means for predicting barrier performance and when combined with the ability to modify vehicle GLSS using OBSI data, it produces a method to evaluate the noise reduction potential of either barriers, quieter pavement, or both in a consistent manner. TNM also is required by 23 CFR 772, is widely used in the United States for traffic noise prediction, and is known to SHAs and those who assist them in highway noise studies. There is also an existing infrastructure to provide training on the use of TNM.

The final key element is the application of LCCA as a means for economic analysis of alternatives that include quieter pavement, barriers, or a combination of the two. The approaches used for evaluating/selecting pavement design alternatives (*14, 15*) can be used for this analysis. By including barrier life-cycle costs and the cost of maintaining the performance of a quieter pavement over a life cycle, the analysis can be extended to consider these noise reduction alternatives.

The application of OBSI, a GLSS-modified TNM, and LCCA is envisioned to integrate into the existing highway traffic noise analysis process as shown in Figure 1. The existing four relevant steps of this analysis process, specified in Appendix A of "Highway Traffic Noise: Analysis and Abatement Guidance" (*8*), are shown in Figure 1 (on the left). The inputs to this process are shown in shaded parallelograms; the revised inputs in white parallelograms. For determining existing levels, the revised inputs include the measurement of the OBSI levels of the existing pavement and modeling the existing conditions with the GLSS-modified TNM. Using the actual noise performance of the existing pavement should also aid in validation of the model. For predicting the future levels, the GLSS-modified TNM is also used with the appropriate OBSI levels for the proposed pavement of the project. To consider acoustic longevity of the pavement, performance levels corresponding to those of the aged pavement could be used together with those for the new pavement. If the predicted levels at a chosen life of the pavement exceed the Noise Abatement Criteria (NAC), other noise abatement alternatives need to be developed and assessed. This revised process permits the consideration of barriers, pavement, and combinations of barriers and quieter pavement for noise abatement. For those alternatives that are feasible, LCCA is performed to consider the initial costs as well as the costs required to maintain the acoustic performance of the abatement over the project life. The results of the LCCA are then evaluated for reasonableness. Finally, the effectiveness of the alternatives is assessed to determine the most effective alternative that meets the feasibility and reasonableness criteria.

The key elements supporting the process outlined in Figure 1 (i.e., OBSI, TNM, and LCCA) are discussed in this chapter. The evaluation parameters of feasibility, reasonableness, effectiveness, acoustic longevity, and economic features are further developed in Chapter 3.

On-Board Sound Intensity

Use of OBSI Measurements

In order to consider quieter pavements as an alternative to barriers, it is necessary to employ a method for quantifying the initial performance of various pavement options, predicting the future noise levels, and monitoring the performance of the

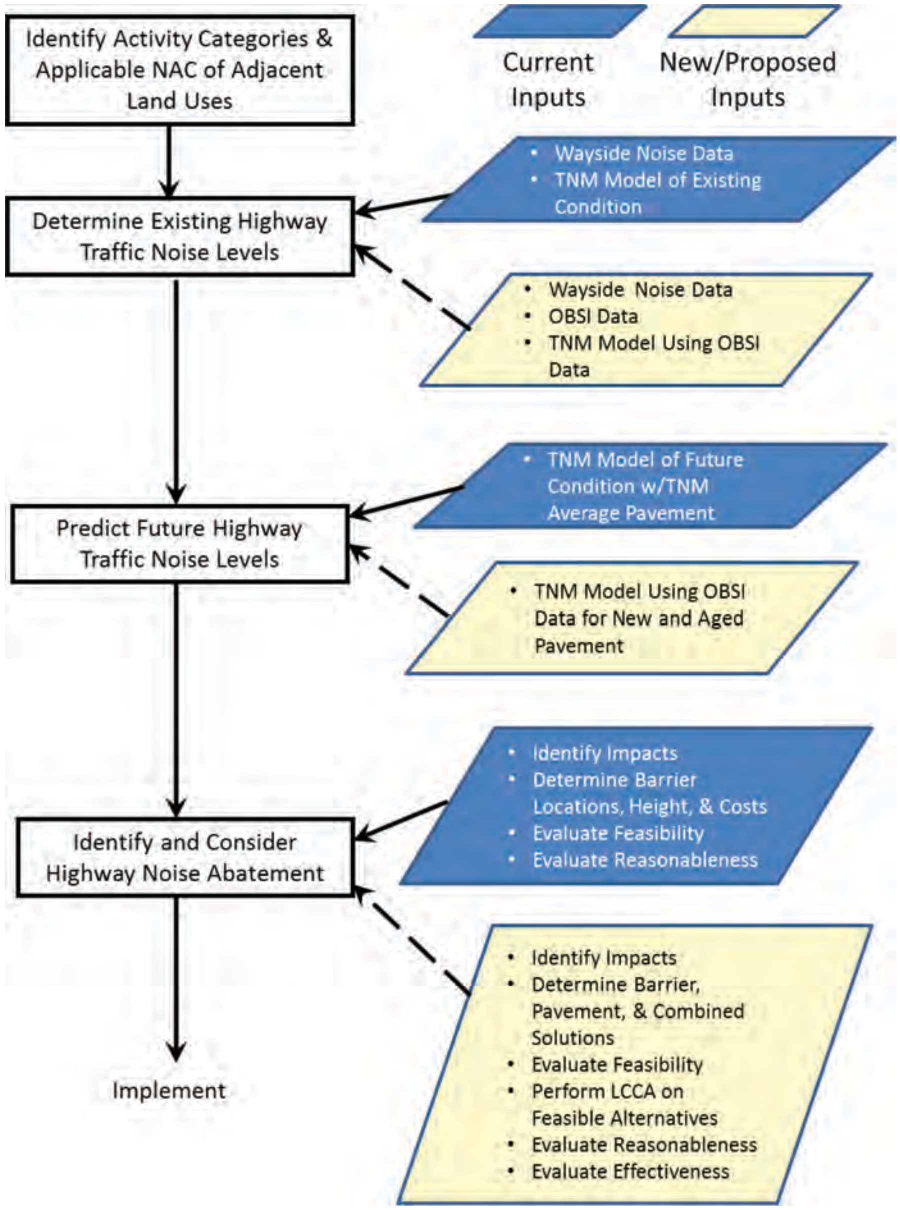


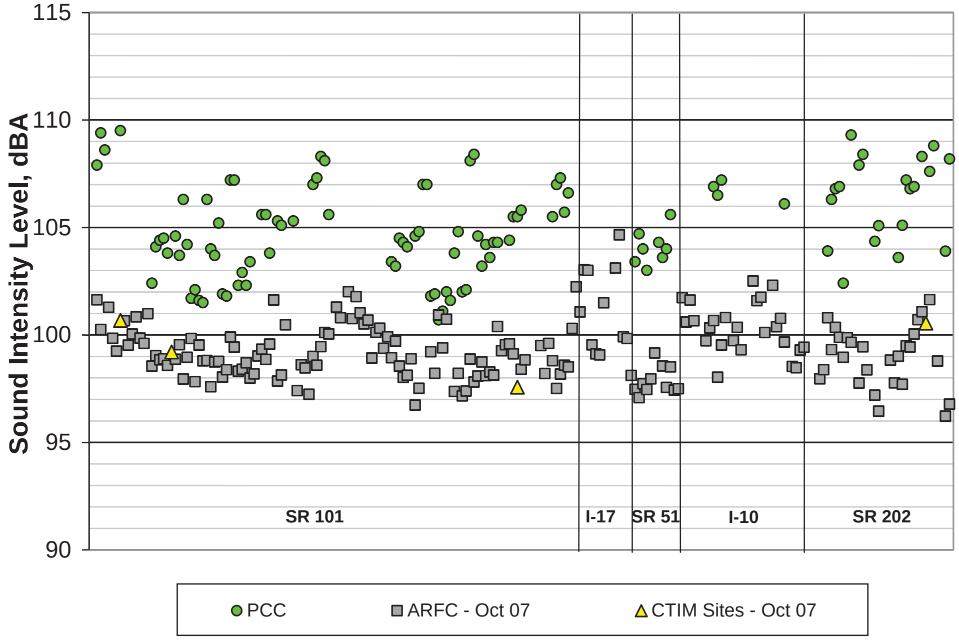
Figure 1. Highway noise abatement process—current and revised.

pavement over time. Three AASHTO standard methods of test are currently available for evaluating the noise performance of the pavements: the Continuous-Flow Traffic Time-Integrated Method (CTIM) TP 99 (*16*), the Statistical Isolated Pass-By (SIP) Method TP 98 (*17*), and the OBSI Method TP 76 (*4*).

CTIM is intended to monitor changes in traffic noise levels at the same site over time, that is, quantify the initial noise reduction provided by a quieter pavement and then monitor noise levels as the pavement ages. However, this method is not intended for predictive purposes or comparing the performance of pavements from one site to another.

The SIP method is intended to quantify pavement performance from site to site as well as over time and is therefore more suited to the purpose of this research. In principle, SIP measurements at various sites could be used to statistically quantify the performance of different pavement types for each vehicle category, essentially developing pavement-specific REMEL that could be used in TNM to predict traffic noise levels as part of a highway noise assessment. Sites of the same pavement design, but of different ages, could also be measured to estimate acoustic longevity for input into the LCCA. However, this approach yields localized results and requires data from a large sample of the sites.

When combined with TNM, OBSI provides an efficient and precise method for quantifying both predicted and ongoing traffic noise levels of a quieter pavement. An example of OBSI results, from the Arizona Department of Transportation (ADOT) Quiet Pavement Pilot Program (QPPP), is shown



Source: Data from Donavan et al. (*18*).

Figure 2. OBSI levels from the ADOT QPPP.

in Figure 2 for a transversely tined PCC pavement prior to and after the application of an asphalt rubber friction course (ARFC) (*18*).

In the QPPP, OBSI was measured at 115 mileposts in both directions of travel throughout the project area within the greater Phoenix area, in less than 4 hours. These data showed considerable variation in the pre-overlay levels likely due to differences in tine spacing (random versus uniform) and tine depth, both of which are known to produce significant noise level variation (*19*). For the ARFC overlay, the variation was typically 2 to 5 dB versus 5 to 8 dB for the PCC pavement.

Also shown in Figure 2 are the CTIM data for four sites. For these locations, the levels ranged from 97.6 to 100.7 dBA compared to the average of 99.3 dBA for the ARFC data. This almost 3 dB difference could be a factor in the decision to build a barrier or to require pavement rehabilitation to maintain acoustic performance.

While variation shown in Figure 2 may be somewhat extreme, variations of 2 to 4 dB have been reported for both pre- and post-project measurements in adjacent segments of a similar pavement when averaged over the standardized 440 ft at 60 mph (*20, 21, 22*). Also, variations in the OBSI level of 2 to 3 dB between inside and outside lanes for the same segment of roadway have also been documented for the California Department of Transportation (Caltrans) I-80 Davis OGAC Pavement Noise Study after 10 years of service (*23*). In this case, the higher levels were found in the outer lanes, which receive the highest volume of heavy truck traffic, in both directions of travel. In this situation, wayside monitoring of the pavement performance would detect the increase in traffic noise level with pavement aging to suggest that all lanes would need to be rehabilitated although rehabilitation of only the outside lanes would be necessary.

The variation indicated in Figure 2 for the pre-overlay pavement presents a concern in the highway noise assessment. If the pre-project wayside levels are measured and used to reconcile the difference between measured level and those predicted by TNM, judgments concerning the number of impacted receptors could be biased based on specific local pavement conditions. This possibility is also illustrated by the OBSI levels measured along a 24 mi corridor of California State Route 85 in Santa Clara County (SCL 85)—a Caltrans-proposed express lane project. The data, shown in Figure 3 for the northbound outer lanes, display three distinct pavement areas centered about 98, 103.5, and 107 dBA for the hot-mix asphalt (HMA) section with a new overlay, the ground PCC section, and the old longitudinally tined section, respectively. SIP measurements could not be made because of traffic density, and CTIM data could not be used to quantify the performance of the pavement from location to location. In the absence of the OBSI data, TNM could not be properly calibrated to match the actual conditions along this project.

Comparison of REMEL and OBSI Levels

Research performed under NCHRP Project 1-44 has shown that light vehicle pass-by levels could be predicted from OBSI data within a standard deviation of 0.8 dB when site-to-site

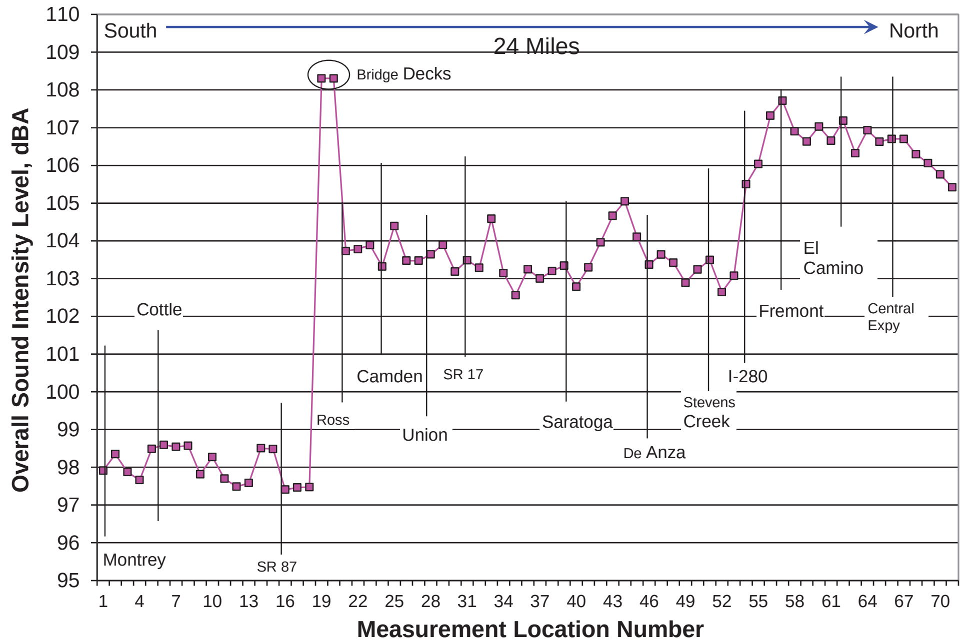
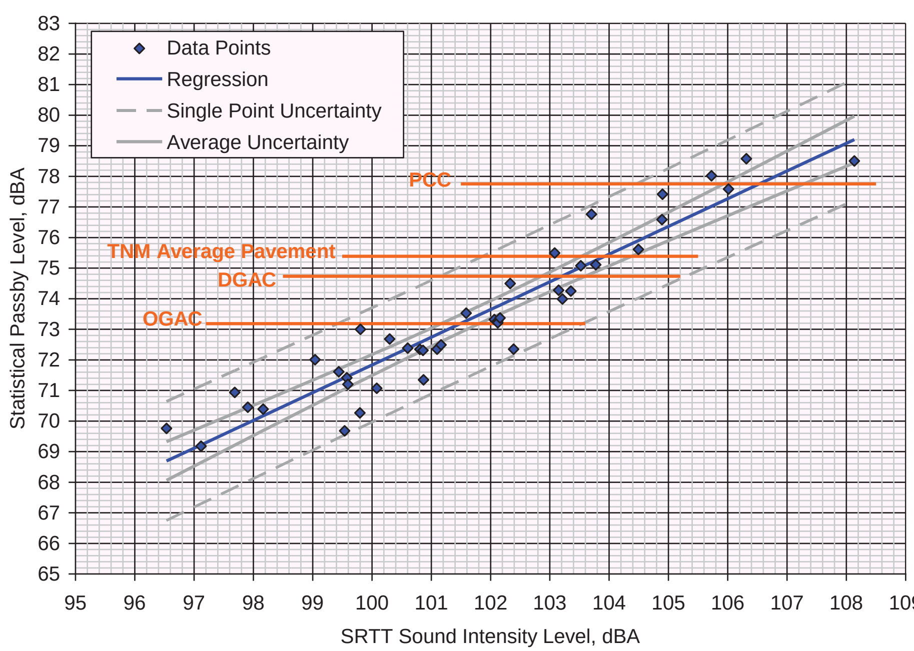


Figure 3. Overall OBSI levels measured on SCL 85.

variations are normalized by comparing the results of controlled pass-by levels to the OBSI levels (*3*). These SIP and OBSI data are shown in Figure 4 for pavements at 12 different sites as measured at a distance of 50 ft for a speed range typically of 50 to 70 mph. Also shown is the linear regression of the data points and the average and single-point uncertainties. The REMEL statistical light vehicles pass-by levels at 60 mph are also shown for each pavement type including TNM Average Pavement. By projecting the intersection of REMEL data with the regression line on to the *x*-axis, an estimate of the OBSI level for each pavement type can be obtained. For TNM Average Pavement, the corresponding OBSI level is 104.0 dBA with an average uncertainty of ±0.4 dB. For PCC, DGAC, and OGAC, the corresponding OBSI levels are 106.6 ± 0.6 dB, 103.2 ± 0.3 dB, and 101.4 ± 0.3 dB, respectively. Based on these data, the predicted traffic noise levels for light



Source: Data from Donavan and Lodico (*3*).

Figure 4. Overall A-weighted light vehicle SIP levels versus OBSI.

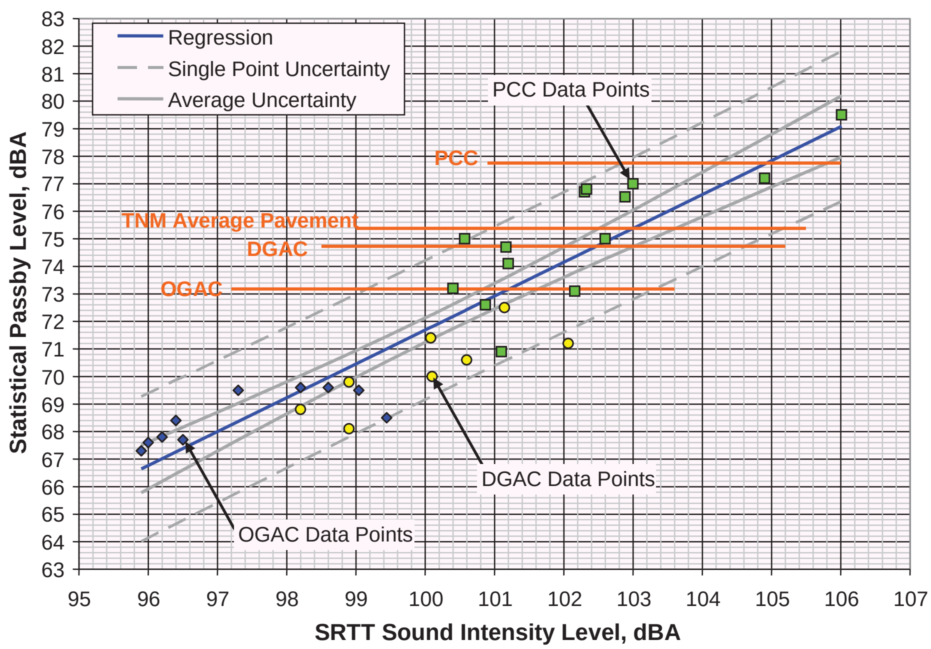
vehicles for pavements with OBSI levels between 96 and 97 dBA would average about 7 dB lower than TNM Average Pavement but about 3 dB higher than TNM Average Pavement for pavements with the OBSI levels around 107 dBA. Thus, the total difference in traffic noise levels for these two cases would be about 10 dB.

A wider range of pavements and sites can be examined by combining the results from several studies. In these cases, corresponding OBSI data were obtained using ASTM International Standard Reference Test Tire (SRTT) at or close to the same time as the SPB measurements. In a few cases, OBSI levels were estimated for older Goodyear Aquatred 3 data using defined relationships (*24*). The data presented in Figure 5 are for 12 sites from NCHRP Project 1-44 (*3*), 7 sites from a REMEL-like study of PCC textures (*25*), and 5 asphalt concrete (AC) pavements from Caltrans Quieter Pavement Research projects conducted on LA 138 (*26, 27*). To obtain data for a selected vehicle speed of 60 mph, a logarithmic regression was fit to the pass-by level versus vehicle speed data for each site and data set. The level of this regression line at 60 mph was taken as the pass-by level to correspond to the OBSI data measured at 60 mph. This process produced a total of 32 data points for a vehicle speed of 60 mph as shown in Figure 5.

Compared to the results of Figure 4, there is greater uncertainty in this additional data set, likely because these data could not be normalized for site variation. As a result, the average uncertainty in the regression ranges from 0.3 dB to 0.8 dB for the higher OBSI levels. The slope of the regression line at 1.2 dB pass-by/OBSI is also greater than that for the multi-speed data of Figure 4 which is 0.9 dB pass-by/OBSI. As a result, the projected OBSI levels corresponding to the REMEL pavements are lower: 105.0 dBA ± 0.8 dB for PCC, 103.0 dBA ± 0.5 dB for TNM Average, 102.5 dBA ± 0.5 dB for DGAC, and 101.2 dBA ± 0.4 dB for OGAC. With the steeper slope of the regression of these data, the quieter pavements around 96 dBA would be expected to yield traffic noise level predictions on average about 8 dB lower than TNM Average and about 3.5 dB higher than average for the loudest pavement for a total range of about 11.5 dB.

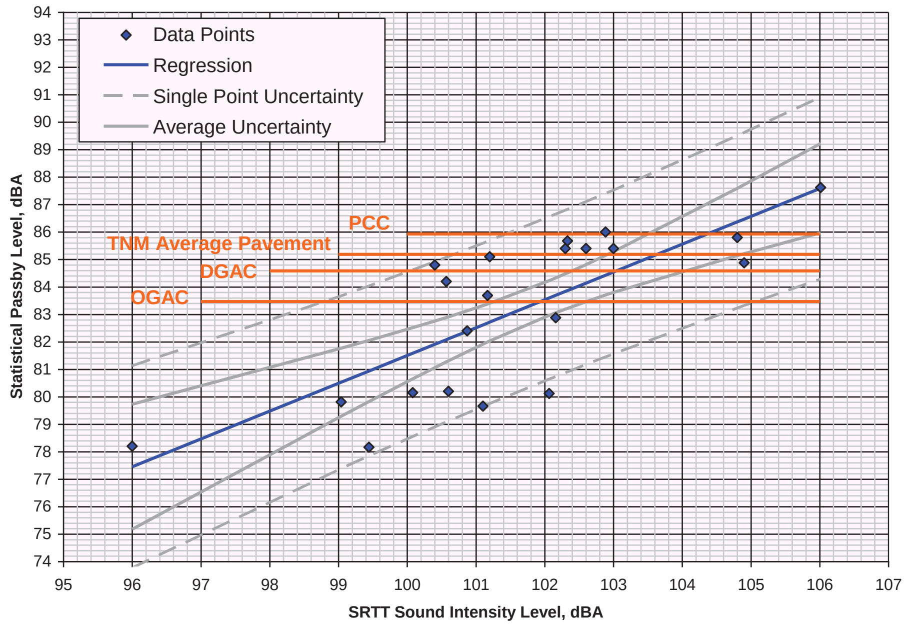
As shown in Figure 5, pavement types represented by the data points follow the same order of the REMEL pavement-type averages. The OBSI data are lower than those of the REMEL data pavement-type averages, probably because they were obtained from new pavements. Considering the range of OBSI levels reported for pavements of different ages, the indicated OBSI levels for all three REMEL pavement types appear to be reasonable although possibly slightly higher than would be expected (*2, 22, 28, 29, 30*).

The results of a comparison of heavy truck statistical pass-by levels and OBSI levels are presented in Figure 6. The scatter of these limited data is greater than for the light vehicles (Figure 5) with about double the average uncertainty range (0.7 to 1.2 dB). The slope of the regression line in this case is 1.0 dB pass-by/OBSI indicating that the reduction in tire–pavement noise levels translates directly to reduction in truck pass-by noise at 60 mph, similar to the findings of NCHRP Project 1-44 (*3*). However, the truck regression line slope is lower than that for light vehicles suggesting that truck pass-by



Source: Data from Donavan and Lodico (*3*), Donavan (*22, 24*), and Illingworth & Rodkin, Inc. (*23*).

Figure 5. Overall A-weighted light vehicle SIP levels versus OBSI.



Source: Data from Donavan and Lodico (*3*).

Figure 6. Overall A-weighted heavy truck SIP levels versus OBSI.

noise at this speed may be slightly less influenced by pavement changes than light vehicles. For these results, the REMEL values for TNM Average Pavement corresponds to an OBSI level of 103.6 dBA ± 0.9 dB, which is in the same range as that for light vehicles. Using the linear regression line for the heavy trucks, the pass-by levels for quieter pavements with OBSI levels around 96 dBA would be on average about 7.5 dB lower than TNM Average Pavement but about 2.5 dB higher than TNM Average for noisier pavements with OBSI levels around 106 dBA. This yields a total range of about 10 dB between the quieter and noisier pavements and indicates slightly lower sensitivity to pavement changes for heavy trucks than for light vehicles as presented in Figure 5.

Implementation of On-Board Sound Intensity in TNM

The approach for implementing OBSI in TNM was developed as part of the FHWA TNM Pavement Effects Implementation (PEI) Study (*11*). This study examined measured CTIM sound levels from three ADOT QPPP sites with different pavement surfaces (ARFC, longitudinally tined PCC, and transversely tined PCC) and the OBSI averages based on the Goodyear Aquatred 3 test tire. Starting with the existing spectrum levels for DGAC Average Pavement within TNM, the ground-level (tire noise) source strength was adjusted by comparing average DGAC OBSI levels to those for each of the three specific pavements. This produced scaled spectra for each pavement type, which were used to compute pavement-specific TNM values for comparison to TNM Average Pavement results and the measured CTIM data. The predicted levels using TNM Average Pavement exceeded the measured levels for the ARFC site by 5.0 dB. However, the measured levels for the PCC pavements exceeded the predicted levels by 1.1 and 3.5 dB for the longitudinally and transversely tined surfaces, respectively. By adjusting the TNM predictions with the pavement-specific source levels, the predicted levels for the PCC pavement became 0.3 dB lower than the measured levels and the predicted levels for the ARFC exceeded the measured levels by 1.8 dB (instead of 5.0 dB). Thus, the total error when considering the ARFC and transversely tined PCC pavements is 8.5 dB using TNM Average Pavement but only 2.1 dB for the TNM/OBSI-adjusted results. When considering the ARFC and longitudinally tined PCC pavements, the error is reduced from 6.1 dB to 2.1 dB.

The difference in the measured levels cited for the QPPP sites can also be compared to differences in the levels estimated by using the specific pavement-type averages in TNM as determined in the REMEL study. Using these levels is another approach for accounting for generic pavement types in TNM calculations. For this comparison, TNM OGAC is assumed to represent the ARFC, while TNM PCC represents the two PCC pavements. At 65 mph, the overall A-weighted difference between TNM Average Pavement for light vehicles and OGAC is 2.2 dB compared to 3.2 dB obtained with the OBSI implementation in TNM. For TNM PCC, the difference to TNM Average Pavement is 2.4, while the OBSI-adjusted differences were 0.8 and 3.2 dB for the longitudinally and transversely tined PCC pavements, respectively. For this example, using OBSI-adjusted TNM levels provides better fidelity than simply using the TNM averages for different

Table 1. Overall OBSI levels for the SRTT (hypothetical case).

Pavement Description	Pavement Age			
	New	7 Years	8 Years	20 Years
RAC(O) from LA 138	96.0	99.3	99.7	
DGAC from LA 138	99.8	101.9	102.2	
OGAC 75 mm from LA 138	95.6	99.3	99.8	
OGAC 30 mm from LA 139	96.3	100.0	100.6	
ARFC from ADOT QPPP	94.4	99.4	100.0	
Long. Tined PC from Mojave	102.4			105.1
Ground PCC from Mojave	99.6			
Random Trans. Tined PCC from Ohio			108.6	
Semi-Uniform Trans. Tined from NC			105.2	
Ground PCC from NC			101.6	
S9.5 HMA from NC	98.7			

pavements because the lower levels of the ARFC are more closely represented and distinction between the two PCC textures is captured. For medium and heavy trucks, the TNM pavement-type averages provide even smaller distinctions between pavement types than for light vehicles (*10*).

The relationship between the SIP levels of the REMEL database and OBSI levels is not known. However, the relationships between OBSI levels and TNM results based on OBSI adjustment of the GLSS were examined for a mixed traffic flow condition on simple six-lane highway geometry (described in Chapter 3). OBSI one-third octave band spectra from 400 to 5,000 Hz corresponding to various pavements were used to modify the GLSS, and the traffic noise levels were calculated with the modified version of TNM based on SRTT OBSI levels. The overall A-weighted OBSI levels for the different pavements are given in Table 1, and the results of the analysis are shown in Figure 7 for a distance of 50 ft from the center of the nearest travel lane. The slope of the regression line of 0.81 indicates a lower sensitivity of the TNM-calculated levels to the OBSI input than the approximate one-to-one relationship of SIP levels to OBSI levels seen in Figures 4, 5, and 6. A similar result was obtained for TNM levels at 100 ft as shown in Figure 8 (the slope is 0.79).

The OBSI level corresponding to TNM Average Pavement can be estimated from the data in Figures 7 and 8. These figures also show the calculated TNM level for Average Pavement. The regression line for the 50 ft distance (Figure 7) shows a predicted TNM level of 77.1 dBA corresponding to

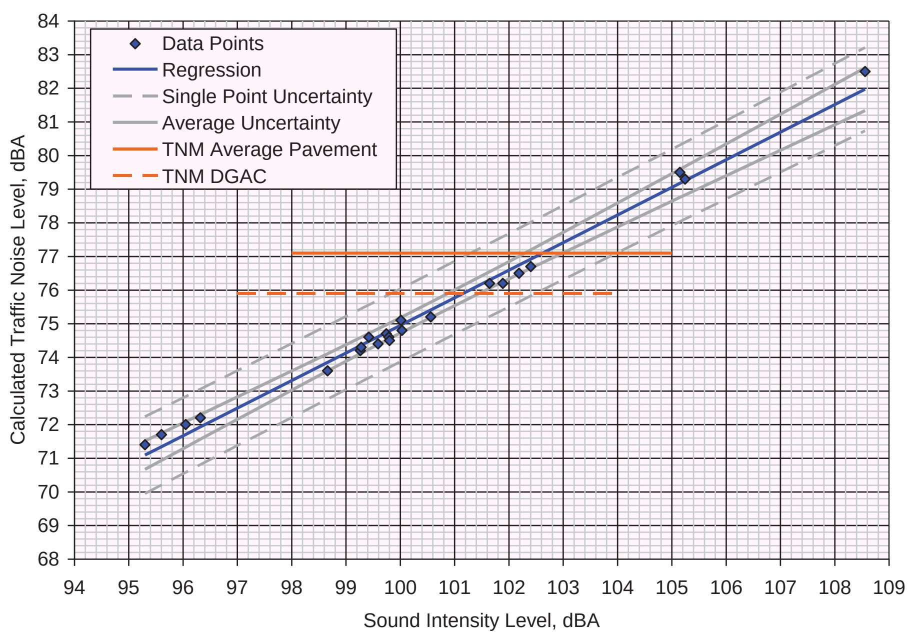


Figure 7. TNM-predicted traffic noise levels at 50 ft from center of near lane versus SRTT OBSI levels.

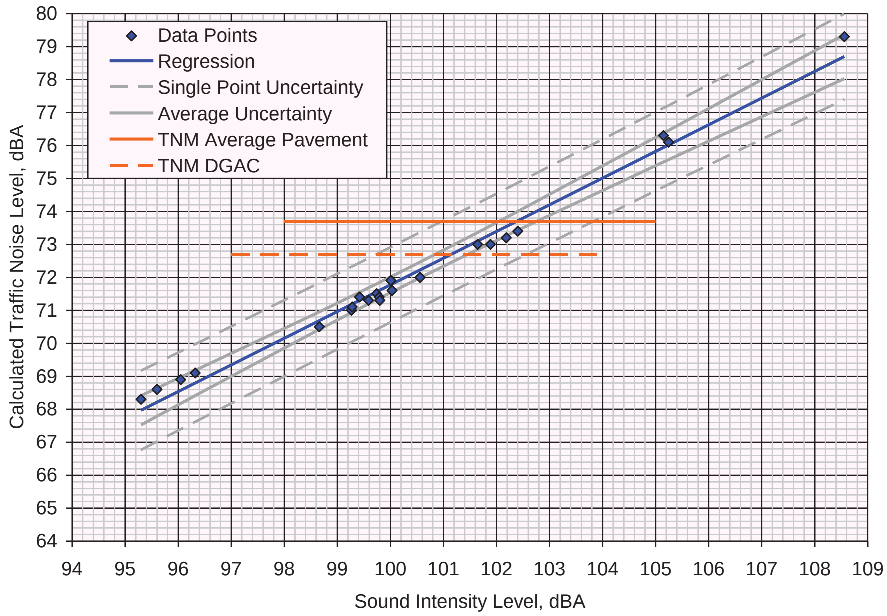


Figure 8. TNM-predicted traffic noise levels at 100 ft from center of near lane versus SRTT OBSI levels.

an OBSI level of 102.7 dBA. For the 100 ft receptor distance (Figure 8), the corresponding OBSI level is 102.4 dBA. These OBSI levels are about 0.5 to 1 dBA lower than those estimated from the statistical pass-by data (Figures 4 and 5).

A plausible reason for the difference in the slope of wayside versus OBSI levels for the SIP and TNM predictions is the vehicle source distributions used in TNM. For light vehicles, the source strength is approximated by placing a portion of the source strength 5 ft above the pavement and the rest at the pavement surface. The energy placed in the upper source position comprises 37.3% of the total source strength of frequencies below 800 Hz, 2.4% of the frequencies above 2,000 Hz, and a transition between these two frequencies (*10*). As a result, only a portion of the model noise emission of the vehicle is changed when the GLSS is modified using the OBSI data. For medium trucks, the source strength in the upper position comprises 56% of the total source strength of frequencies below 800 Hz and 6.7% of frequencies above 1,600 Hz (*10*). Changing the GLSS will have less effect on the modeled emission for this vehicle type than on that of light vehicles. For heavy trucks, the two sources are assumed to be at the pavement surface and 12 ft above the surface. The model includes a complicated split for heavy trucks (*31*). For typical heavy truck spectra, about 57% of the lower frequency and 46% of the higher frequency source strength are located at the upper position (*32*). Given these source splits, a one-to-one relationship between GLSS-modified TNM-predicted levels and OBSI level cannot occur as only 43% and 54% of the lower and higher frequencies, respectively, of the total source strength are assumed to be at ground level.

To document the effect of source height splits, TNM values with the GLSS adjustments were computed for different vehicle types and compared to the input OBSI levels. For this purpose, the traffic flows used to generate the results of Figures 7 and 8 were recalculated for 100% of each vehicle type; the results of this analysis are shown in Figure 9 for a non-barrier case. The slopes of the regression lines decrease with increased source height distributions, ranging from 0.87 for all light vehicle traffic to 0.75 for all heavy truck traffic. The slope for the traffic mix (94% light vehicles, 3% medium trucks, and 3% heavy trucks) is slightly greater than all light vehicles. Figure 9 also shows the TNM-calculated levels for each vehicle type for Average Pavement from which the projected OBSI levels can be determined. The levels are 102.0 dBA for heavy trucks and 102.7 dBA for light vehicles, indicating that the use of SRTT OBSI data is representative of all of these vehicle types.

FHWA Traffic Noise Model

A critical component of developing a methodology to evaluate quieter pavement strategies and barriers for traffic noise mitigation is the ability to predict the performance of the different alternatives within a single framework. The FHWA TNM was chosen in this research as the most appropriate tool for several reasons: TNM is the required means of predicting traffic noise levels within the current FHWA traffic noise policy (*6*); it is in widespread use by state and local agencies and by other practitioners involved with predicting traffic noise; and training is currently available for its use. In

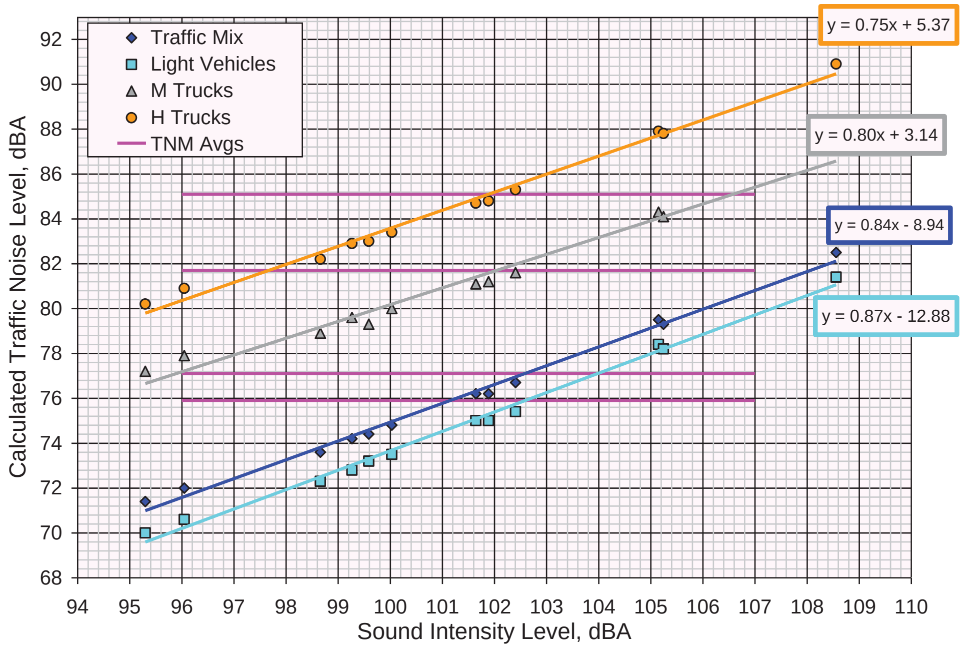


Figure 9. TNM-predicted traffic and vehicle-type noise levels at 50 ft from center of near lane versus SRTT OBSI.

addition, there are a variety of methods by which pavement noise performance can be included in the predicted levels. Within TNM, averages for the three different pavement types developed in the REMEL database are incorporated in the PCC, DGAC, and OGAC Average Pavements. Although these pavements are currently not approved for use in the FHWA traffic noise assessments, they could be implemented with the shortcomings discussed previously. Also, with a further extension of the database, REMEL values for some pavement types such as transversely tined PCC pavement could possibly be included. In addition, an agency can develop specific REMEL for a pavement within its jurisdiction for use in TNM (with FHWA approval). There is the possibility of incorporating specific pavement performance through OBSI data. For the reasons discussed in the previous section, the OBSI approach was incorporated in the methodology developed in this project.

The use of OBSI results in TNM is considered the most promising approach to implementing pavement performance in highway noise studies. The TNM predictions (Figures 7 through 9) are less sensitive to changes in OBSI level than the pass-by levels (Figures 4 through 6). Although some actual CTIM and OBSI field results have shown relationships closer to one-to-one (*17, 33*), use of the OBSI-modified GLSS in TNM provides a somewhat conservative approach to accounting for pavement that will not overestimate the effects of quieter pavement. Also, the OBSI GLSS-modified TNM approach accounts for some of the effects of porous pavement in predicting traffic noise levels. Porous pavements affect both the strength of tire noise sources and the propagation of tire noise over the sound-absorbing pavement (*16*). OBSI measurements account for the effects on source strength but not the noise reduction due to the additional attenuation of sound propagating over the pavement to the side of the roadway. The effect of porous pavements on propagation could reduce wayside levels by as much as 2 dB (*34*). This effect can be accounted for in TNM by assigning an effective flow resistivity (EFR) that accounts for the sound-absorbing properties of the pavement. The method of defining the proper EFR values for single finite porous layers is part of FHWA-sponsored research (*11*). In the absence of this definition, the OBSI method could still be applied, but noise reduction for a porous pavement may be conservative. An evaluation of the potential influence of sound propagation over porous pavement is presented in Appendix A.

Life-Cycle Cost Analysis

Application of Life-Cycle Cost Analysis

A critical component of developing a methodology for evaluating quieter pavement strategies and barriers is a framework for comparing costs of the two types of mitigation methods on an equivalent basis that recognizes the different nature of the two abatement methods. The cost of barriers can be considered part of the overall initial cost of the project. They are expected to provide a fixed amount of noise reduction throughout the project life. However, the baseline noise level for a "quieter pavement" is not defined. To maintain its absolute performance, the pavement will most likely need to be rehabilitated on a shorter cycle than would normally be required for a pavement that is not intended to provide noise mitigation. As a result, the recurring cost of more frequent rehabilitation may outweigh the initial cost savings of the quieter pavement. LCCA provides an approach for comparing these alternatives (Appendix B provides a summary discussion of LCCA).

LCCA considers the cost of different pavement alternatives over the life of the highway project. The length of "life" or analysis period varies by state from 28 to 50 years. However, the FHWA recommends that the life be long enough to cover at least one cycle of rehabilitation for each pavement considered. The costs of each rehabilitation event during the analysis period are added together along with any other periodic maintenance costs. These costs are added to the initial construction costs (all in equivalent dollars) to estimate the total lifetime cost. In this manner, the pavement design alternatives can be compared on an equal basis. The rehabilitation cycle is defined as the time period in which the pavement will deteriorate to the agency's minimum acceptable condition. User costs such as time lost due to delays and vehicle damage can also be included (although they are often omitted). Current LCCA practice for pavements consider noise abatement as an external cost to the analysis and hence not included in the analysis (*35*). That is, the initial cost of barriers is not included as it would be the same cost regardless of the pavement-type selection.

With some additional considerations, LCCA can be used to analyze pavement and barrier strategies for noise abatement. For quieter pavement options, the rehabilitation cycle would need to account for acoustic longevity. Depending on the pavement, the cycle may need to be shortened to ensure that an acceptable level of noise reduction performance is maintained throughout the life of the pavement. This would ensure that the FHWA criterion of maintaining the noise abatement "in perpetuity" is met (*36*). The initial costs for including barriers in the project would also have to be determined and added to the appropriate pavement choice. Barrier maintenance costs such as repairs and graffiti removal would also need to be included in the analysis. If acceptable levels for a quieter pavement are established, then the cost of periodic monitoring of the pavement's acoustic performance using OBSI might also be included in the analysis.

Although implementing noise abatement options in the LCCA appears to be relatively straightforward, several issues need to be considered. Recognizing that the results of the LCCA are only as good as the input data, sufficient data are needed to be certain of the assumed level of noise reduction achieved with a specific pavement design and construction. Also the acoustic longevity of the specific design also needs to be determined for use in defining the rehabilitation cycle; the acoustic performance of the anticipated rehabilitation needs to be defined; and the maintenance costs of the barriers need to be determined. If combinations of quieter pavement and different barrier heights are evaluated, barrier costs need to be determined on a per-square-foot basis in order to optimize the overall noise abatement system as a function of barrier height. These issues indicate the need for gathering adequate data for use as inputs to the LCCA.

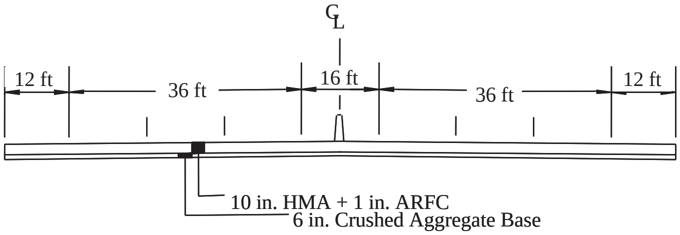
Example of LCCA Application

To illustrate the application of the LCCA to evaluate the economic features of pavement and barrier strategies for highway noise abatements, several abatement alternatives were evaluated for a hypothetical Type 1 highway project. The assumed project is a new six-lane highway (three lanes in each direction) in an area of sensitive noise receptors. Two different alternatives were considered: a PCC pavement and an HMA pavement with a 12 ft barrier. Example inputs that are not specific to any one actual project were selected based on information available in the literature. Therefore, the results of this analysis may not reflect assessments made using data generated by highway agencies (details of the analysis are provided in Appendix C). This example does not discuss noise impacts; these are discussed in examples provided in Chapter 4.

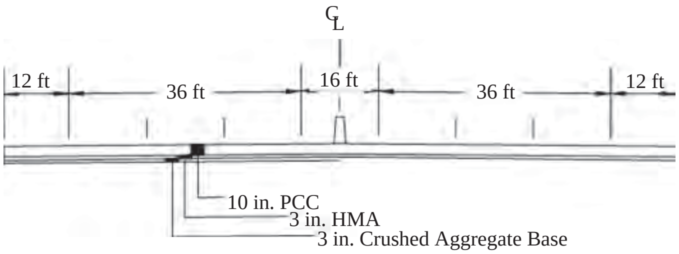
Project Scenario

The project scenario includes a new highway facility 1 mi in length with six 12 ft wide lanes (three lanes in each direction), a 12 ft wide outside shoulder, and an 8 ft wide inside shoulder. Two alternatives, shown in Figure 10, were considered:

- New HMA pavement with a 1 in. ARFC overlay. Assumed future rehabilitation includes a 2 in. HMA dense-graded mill and overlay every 18 years and a 1 in. ARFC overlay placed every 7 years to maintain acoustical qualities. The acoustic longevity of the ARFC is based on an assumed initial OBSI level of 95.3 dBA, which is assumed to degrade to 99.4 dB after 7 years when acoustic rehabilitation is assumed to be needed based on a 3 dB degradation in noise level as predicted in TNM [a barely noticeable change (*7*)].
- New PCC pavement with an initial longitudinally tined surface. Assumed future rehabilitation includes diamond grinding on a 20-year cycle. This alternative assumes an initial OBSI level of 102.4 dBA, which degrades to 105.1 dBA after 20 years and will be restored to 99.6 dBA by diamond grinding. This alternative includes the use of a 12 ft high concrete noise wall to provide the noise abatement.



10a: HMA pavement



10b: PCC pavement

Figure 10. Pavement cross sections for six-lane highway scenario.

The assumed traffic flow includes a daytime hourly average in traffic volume of 8,000 vehicles with 3% medium trucks and 3% heavy trucks all traveling at a speed of 65 mph. The pavement sections were assumed to be appropriate for a 50-year service that was also used as the analysis period for this case. The initial construction cost for the pavement alternatives was estimated using information available from state departments of transportation (DOTs) [e.g., the Washington State DOT (WSDOT) (*37, 38*)]; the resulting construction costs are shown in Table 2.

To estimate the initial barrier construction cost, the average cost from the FHWA summary of $27/ft^2 was used for the analysis (*39*). Since the inventory does not show an overall trend for an annual cost increase, no cost escalation was assumed from 2007 to 2011. Although a variety of sources were used in an attempt to determine barrier maintenance costs, little information was found related to the actual maintenance-related costs. A 1999 report prepared for the Illinois Department of Transportation (IDOT) (*40*) documented extensive surveys, considerations, evaluations, and LCCA calculations conducted for a variety of barriers in Illinois. Table 3 provides a summary of the costs associated with concrete barriers and application frequency based on the FHWA and IDOT information. The following assumptions were also used to develop these costs:

Table 3. Summary of concrete barrier cost and performance life.

Treatment	Total Project Cost	Life (years)
Initial construction	$3,421,000	50
Surface maintenance	$253,000	15
Graffiti removal[1]	$2,500	1
Impact damage repair[2]	$26,000	5

[1] Assumes 1% of total wall area.

[2] Assumes repair of two panels (480 ft^2) due to vehicle impact.

- Both sides of the roadway have a 12 ft high barrier.
- Initial barrier construction is conducted within the roadway right-of-way.
- Future barrier surface maintenance, graffiti removal, and impact damage repair are conducted during pavement rehabilitation and have no additional impact to user delay.
- No special provisions (e.g., moving utilities, absorptive linings, extra drainage) are required during barrier construction.

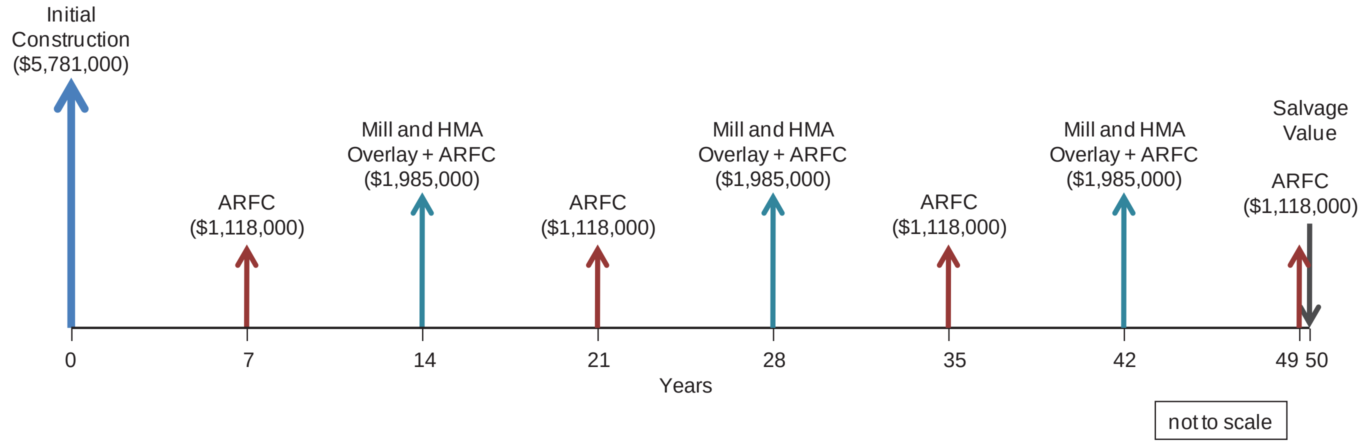
The information in Tables 2 and 3 were used to create the cost flow diagrams, shown in Figure 11, for the two primary alternatives. Both alternatives include pavement rehabilitation activities but the PCC pavement alternative also includes the construction and maintenance of a barrier. This brings the total initial construction cost to $10,545,000 for the PCC

Table 2. Summary of pavement costs, work zone duration, and performance life.

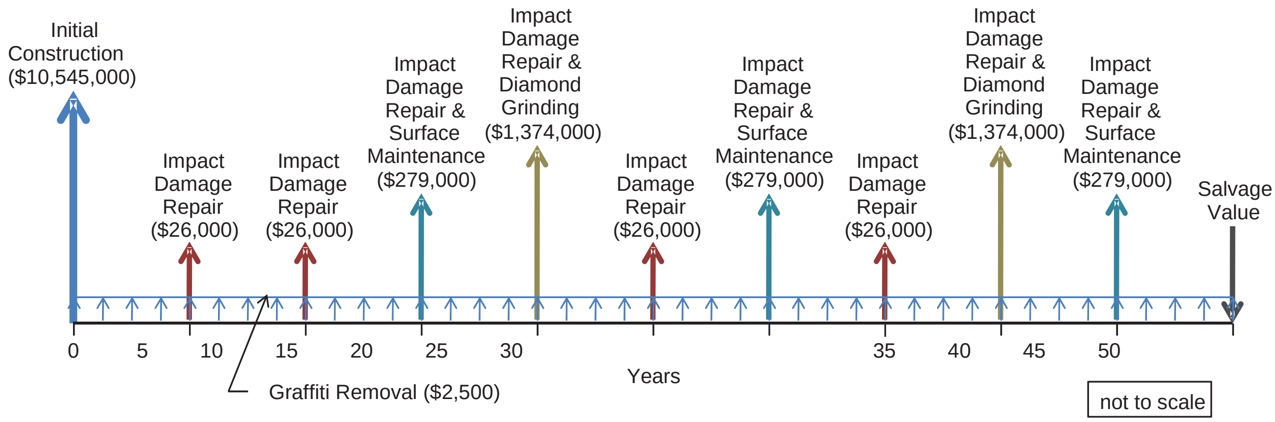
Treatment	Total Project Cost[1]	Work Zone Duration (days)	Life (years)
New construction – HMA	$5,781,000	–[2]	50
New construction – PCC	$7,124,000	–[2]	50
ARFC	$1,118,000	7	7
Mill and HMA overlay and ARFC overlay	$1,985,000	12	14
Concrete – diamond grinding	$1,348,000	13	20

[1] Cost includes all agency costs (traffic control, mobilization, sales tax, engineering, and contingencies) and are shown in 2011 dollars.

[2] Work zone duration for initial construction is assumed to be the same for both the HMA and PCC options; therefore, initial construction user costs are excluded from the analysis.



11a: HMA pavement & ARFC overlay



11b: PCC pavement & barriers

Figure 11. Pavement cash flow diagrams.

pavement alternative and $5,781,000 for the HMA pavement alternative.

LCCA Results and Discussion

Table 4 provides the results of the LCCA for the two alternatives: HMA pavement with a 7-year rehabilitation cycle and PCC pavement with two 12 ft high barriers. The undiscounted sum refers to the total agency costs over the 50-year project span, as shown in Figure 11, less the salvage value in 2012 dollars. The present value or alternatively the equivalent uniform annual cost is the amount in constant dollars that would be used by an agency to evaluate the cost of each scenario. Based on the assumptions used in this example, the HMA pavement

Table 4. Summary of deterministic LCCA results for the primary HMA and PCC alternatives.

Total Cost	Alternative 1: HMA (7-year overlay cycle)		Alternative 2: PCC (with barriers)	
	Agency Cost ($000)	User Cost ($000)	Agency Cost ($000)	User Cost ($000)
Undiscounted sum	$15,249.71	$66.34	$14,334.00	$31.47
Salvage value	$958.29	$9.53	$0.00	$0.00
Present value	$9,623.79	$24.81	$11,846.04	$9.88
Equivalent uniform annual cost	$447.99	$1.15	$551.44	$0.46

alternative yields the lowest present value of agency costs but the PCC alternative yields the lowest present value of user costs. It should also be considered that present values for the alternatives are functions of the assumed project life. With a shorter project life assumption, the Alternative 1 cost becomes even lower compared to Alternative 2. Also, the present values would be lower for a longer rehabilitation cycle. For example, a 9-year overlay cycle for the HMA pavement alternative would lower the present value to $8,539,250.

The different acoustical performances associated with the two alternatives are shown in Figure 12. The traffic noise levels were estimated using the modified version of TNM to allow consideration of the OBSI levels. Only the PCC pavement alternative with barriers would achieve the feasibility and reasonableness criteria of 23 CFR 772 when compared to TNM Average Pavement. The HMA pavement with ARFC overlay alternative provides 3 to 6 dB less reduction at moderate distances from the highway (e.g., 100 ft). Although both noise abatement alternatives initially satisfy a 5 dB feasibility criterion compared to the TNM Average Pavement prediction, the HMA alternative maintains this feasibility criterion for only 2 years after the initial construction and for 2 years after each rehabilitation application. Depending on the length of the cycle, the improvement over the TNM Average Pavement prediction falls to about 2 dB just prior to rehabilitation. The HMA alternative is not reasonable as it does not meet a 7 to 10 dB noise reduction design goal.

The present value for the PCC pavement without the barriers was estimated at $8,019,990 by subtracting the present value of the barrier ($3,826,050) from the present value for Alternative 2. Because of the lower rehabilitation costs, the present value of the PCC pavement without a barrier is lower than the HMA pavement alternative ($9,623,790) in spite of the higher initial cost of the PCC pavement.

The acoustic performance of the PCC surface, initially textured with transverse tining, is shown in Figure 13. For this texture and the barriers, the traffic noise level begins 5.5 dB lower than TNM Average predictions but is only 2.5 dB lower after the first 20 years. In this example, PCC pavement with barriers achieves an insertion loss of about 12 dB relative to the random transversely tined PCC pavement without barriers (also shown in Figure 13). However, the range of the levels in the first 20 years is about the same as for the HMA pavement alternative. After 9 years, the levels for the random transversely tined PCC pavement without barriers are about 5 dB below the TNM Average levels.

The example presented in this section demonstrates that using OBSI levels, modified TNM, and LCCA provides a framework in which pavement and barrier noise abatement options can be evaluated for economic and acoustic performance features. Evaluation of feasibility, reasonableness, effectiveness, acoustic longevity, and other economic features is discussed in Chapter 3 together with proposed revisions to the highway traffic noise abatement process.

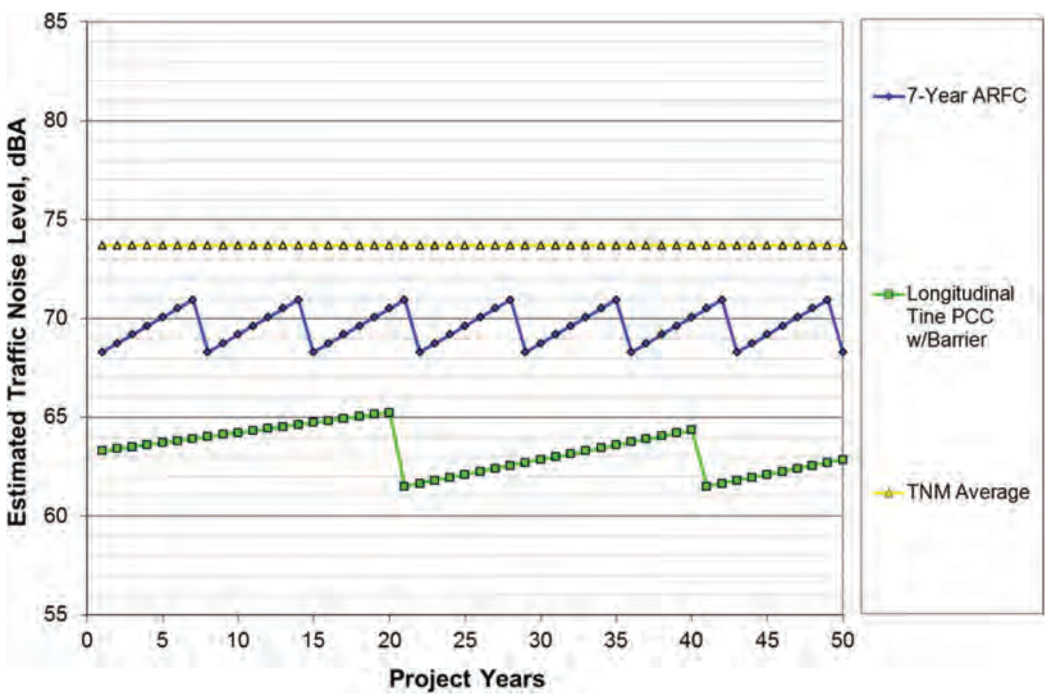


Figure 12. TNM-predicted traffic noise levels at 100 ft for longitudinally tined PCC pavement.

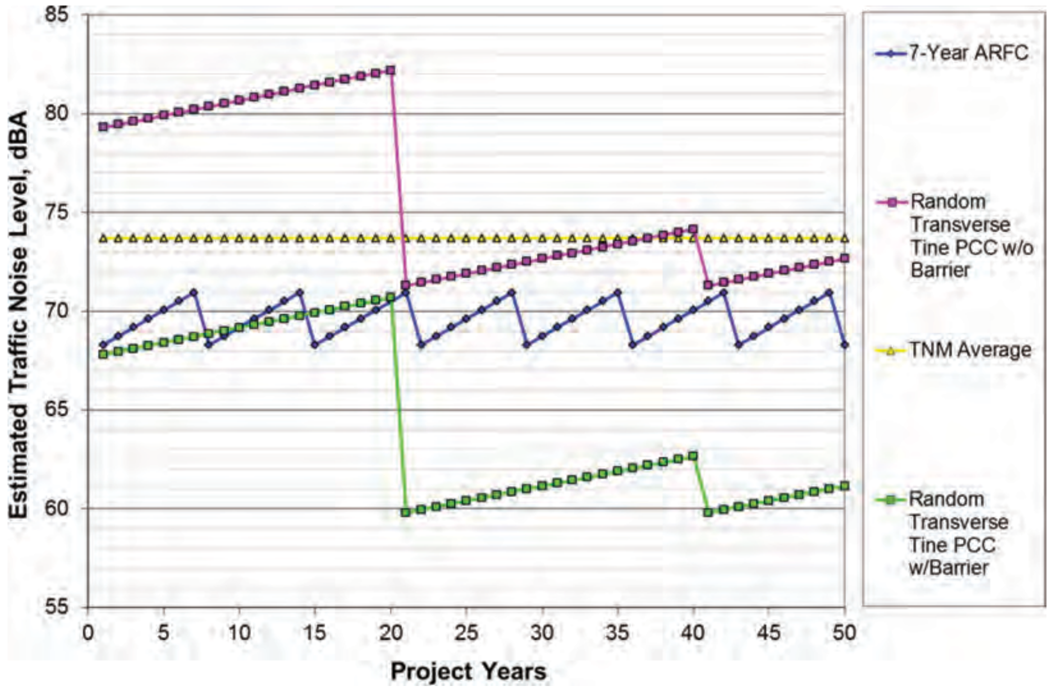


Figure 13. TNM-predicted traffic noise levels at 100 ft for random transversely tined PCC pavement.

CHAPTER 3

Evaluation Parameters

Introduction

The methodology proposed for evaluating pavement and barrier strategies for noise mitigation considers five factors: feasibility, reasonableness, effectiveness, acoustic longevity, and economic issues. Under the approach encompassed in this methodology, *feasibility* and *reasonableness* can be evaluated following basic definitions provided in 23 CFR 772 and the accompanying guidance document although some modification of these factors will be required for pavement consideration. *Effectiveness* is not addressed in the current policy and guidance document and, therefore, a definition is needed. *Acoustic longevity* is a term generally associated with pavement noise performance over time and it is therefore new to the evaluation of pavement and barrier strategies. *Economic features* are generally captured in the LCCA that evaluates and compares the initial and future costs of each pavement strategy and barrier.

The consideration of feasibility, reasonableness, effectiveness, acoustic longevity, and economic issues in evaluating noise mitigation alternatives is summarized in this section. A review of the first three topics based on the literature search performed in this research is provided in Appendix D. The case studies presented in Chapter 4 will further illustrate these concepts.

Note: The intent of this project is not to develop or recommend changes to existing FHWA and SHA policies pertaining to noise abatement options but to identify and develop a methodology for evaluating pavement and barrier strategies for noise mitigation on an equitable basis.

Feasibility

In 23 CFR 772, feasibility is discussed only in reference to barriers although other allowed alternatives may also have feasibility constraints. For barriers, feasibility consists of engineering and acoustical considerations in design, construction, and maintenance, which includes site constraints. The FHWA guidance document notes that site constraints may include topography, access to driveways, local cross streets, other noise sources, project purpose, drainage, utilities, and maintenance. For pavements, other feasibility constraints would apply as described in 23 CFR 626 (*41*) and its associated non-regulatory supplement (*42*). This regulation states that "Pavements shall be designed to accommodate current and predicted traffic needs in a safe, durable, and cost-effective manner." The supplement provides information on pavement design factors that require particular attention including traffic, foundation, shoulder structure, and engineering economic analysis. The latter item includes the use of LCCA for assessing alternative designs. The guidance document also discusses pavement rehabilitation design and safety.

According to 23 CFR 626, feasibility for the use of quieter pavement needs to include safety and durability. As a result, quieter pavement designs may not be feasible if they do not meet a SHA's existing criteria for these issues. In regard to safety, the primary concern is with skid resistance. It is stated that a SHA should have historical performance information to be certain that a proposed design is capable of providing a satisfactory skid resistance over the expected life of the pavement. Thus for a quieter pavement to be considered an option for noise abatement, either an "off-the-shelf" design is used or convincing historical information needs to be available. For pavement rehabilitation, it is also stated that, for safety reasons, traffic disruption should be minimized and adequate protection of motorists and workers should be considered. Concerning durability, the pavement design decision needs to consider traffic by vehicle classification and cumulative loading, and foundation stiffness and resistance to moisture and frost. These durability issues may influence feasibility of a quieter pavement design for a particular application.

Of special consideration is the feasibility of traffic noise reduction on bridge decks and elevated structures. Traffic noise generated on these highway elements has been the subject of several recent noise reduction projects (*43, 44*). In these cases, mitigation in the form of either added barriers or quieter overlays may not be feasible due to weight limitations on these structures. For new highway projects, the added weight would need to be considered in the design and the increase in the initial cost needs to be considered in the LCCA for the project. If these noise reduction measures are not considered in the initial design, later consideration may not be feasible. Similarly, if concrete deck thickness is designed without a provision for grinding, noise reduction by this method may not be feasible.

Under 23 CFR 772, for a barrier to be feasible acoustically, it must provide a traffic noise reduction of at least 5 dB for impacted receptors. This is based in part on the notion that "barriers which do not achieve at least a 5 dBA reduction in noise are not prudent expenditures of public funds and, therefore, should not be built" (*6*). For pavement alternatives, it may be appropriate to temper this type of notion as additional expenditure of public funds may be smaller because most Type 1 projects will include cost for some type of new pavement. An extreme example of this thinking is the recent adoption of longitudinal tining of PCC pavements by ADOT instead of the earlier uniform transverse tining. OBSI and pass-by testing showed that this change produced at least a 5 dB reduction in level for light vehicles with a somewhat lower reduction for trucks (*45*) although it would have little or no influence on the life-cycle cost. In California, less extreme cases have demonstrated positive public recognition of traffic noise reduction in several projects where PCC pavements were ground-producing source level and wayside reductions on the order of 3 dB for a mix of vehicles (*22*). Similar findings were cited in Ohio where grinding a new transversely tined concrete pavement resulted in an average noise reduction of 3.1 dB at 50 ft (*46*).

There are more dimensions of acoustic feasibility when evaluating pavement strategies, barriers, and combinations of the two. In many situations where barriers or added barrier height may not be feasible due to site geometry/barrier performance, local access, or intersections or right-of-way restrictions, the use of quieter pavement may not be physically restricted. In these cases, a noise reduction in the range of 3 to 5 dB by pavement selection may be desirable when the alternative is to provide no noise reduction at all. Reductions in this range would still need to be accountable to some reasonableness criteria. Another dimension is the relativity of the acoustic feasibility requirement. For barriers, since noise reduction is essentially independent of pavement, this concept can be unambiguously applied. For quieter pavement, the reduction depends on the performance of the less quiet pavement. It also depends on the point in time in the pavement rehabilitation cycle at which the noise reduction performance is assessed. Another dimension is the acoustic feasibility of combined barrier and quieter pavement designs. For example, if a barrier by itself will provide only 4 dB of noise reduction but, when combined with quieter pavement, will provide is 7 dB, would this become a feasible abatement alternative? These issues will become more apparent in case studies described in Chapter 4.

Reasonableness

As with feasibility, the concept of *reasonableness* in the current 23 CFR 772 can be applied to evaluating pavement strategies, barriers, and combinations of them with additional considerations for allowable cost and the noise reduction goal. In current policies, allowable cost appears to be primarily determined by barrier construction cost as estimated by each SHA. This method could be used for pavement and barrier options or combined options. For pavement only options, however, this allowance may be too large if only the initial cost of the quieter pavement is considered. When considering the life-cycle costs, the relative cost of barriers and pavement would be comparable as the acoustic rehabilitation costs of the pavement would be included while the life-cycle cost of barriers is largely in its initial cost. The case studies provided in Chapter 4 use the costs generated by the LCCA in the reasonableness analysis. The cost of barriers is considered as incremental costs over no barrier and the cost of quieter pavement is considered as an incremental cost over a not-quieter pavement, which is assumed to be of lower cost.

In the latest version of 23 CFR 772, the concept of a design goal was introduced. It requires each state to establish a design goal between 7 and 10 dB with at least one benefited receptor receiving this goal for the abatement to be reasonable. When the OBSI ground-level source correction was used for a specific set of inputs, TNM predicted 0.8 dB level change for each 1.0 dB of OBSI change (Figure 7). Thus, producing a change of 7 dB in TNM-predicted noise level (to meet the lowest level of goal design) would require an 8.6 dB change in OBSI level. For larger distances, the OBSI change would need to be even greater as illustrated by Figure 8 for a 100 ft distance. As in the case of the 5 dB feasibility criterion for barriers, a lower design goal for the use of quieter pavements may be more appropriate.

Effectiveness

The current 23 CFR 772 and accompanying guidance document do not mention the term "effectiveness" in reference to the noise abatement. Under current policy, "effectiveness" is essentially synonymous with the insertion loss provided by a barrier as there is no consideration of pavement. When the performance of different pavements is considered, "effectiveness" takes on a broader notion where overall noise reduction is of primary concern. It also has a subjective nature when effectiveness is linked to reducing complaints by residents near the highway. In this research, effective noise abatement alternatives are defined as those providing the lowest overall highway noise level with the lowest amount of variation in noise reduction performance. These concepts are developed further in this section.

Overall Performance

To understand effectiveness, it would be helpful to examine cases where noise abatement was found to be ineffective, such as those reported by the Ohio Department of Transportation (ODOT). These cases involved asphalt pavements that were replaced with transversely tined PCC pavements that resulted in unexpected higher noise levels and a rise in complaints from the nearby residents (*47*). In these cases, barriers were added along with the new (noisier) pavement. The level of tire–pavement noise that these surfaces actually produced was not known; however, the effects of not including the noise performance of the pavement can be illustrated from data shown previously. In Figure 7, the highest noise level at 108.6 dB is actually for a pavement with random transverse tines measured in Ohio (see Table 1). For the simple six-lane highway case presented in this figure, the increase in TNM-predicted level using the OBSI inclusion could be about 6.5 dB based on REMEL average DGAC and data measured in the state for DGAC. Assuming an insertion loss of 5 dB for new barriers, the resultant traffic noise levels would still be higher by 1.5 dB due to the pavement change. Additionally, with the construction of the barrier, the neighboring residents may likely expect that the noise levels would be lower. In this case, the complaints received indicated that the barriers were judged as not providing adequate abatement (*47*).

By using the methodology developed in this research, cases such as the ones encountered by ODOT would be avoided or at least anticipated in advance. In initial highway assessment, the existing noise performance of the pavement would be documented with the inclusion of the OBSI levels for the existing pavement. Using OBSI levels for the new pavement, the new, no-barrier levels would be more accurately determined to identify other options with overall lower levels (e.g., taller barriers or different surface textures or pavement types).

An alternative consideration to only evaluating relative changes in level is to consider the absolute traffic noise level after the project. Relationships between absolute level and the percentage of people highly annoyed by traffic noise have been shown (*49, 50*). Although response curves are based on day–night equivalent noise levels (L_{dn}) instead of worst hour (L_{eq}), they indicate that lower levels produce less annoyance. This suggests that the most *effective* noise abatement is the one that produces the lowest overall level within the constraints of feasibility and reasonableness.

The examples shown in Figures 12 and 13 can be used to further illustrate *effectiveness.* In Figure 13, the traffic noise levels for the transversely tined PCC pavement are predicted to be quite high for the first 20 years—about 5.5 to 8.5 dB above TNM Average Pavement. With two 12 ft high barriers, the levels are reduced by 11.5 dB. Even with this reduction, the resultant levels are about equal to those of ARFC overlay when averaged over the 20 years of the PCC rehabilitation cycle. Thus, the PCC pavement with 12 ft barriers is not more *effective* than the ARFC overlay without a barrier even though the barriers provide a large insertion loss. If the initial PCC surface was longitudinally tined, the combination of the texture and the barriers would be an effective solution compared to the ARFC (Figure 12). A PCC pavement that is ground initially and has barriers would provide the most *effective* alternative as the levels for the first 20 years would be 1.5 dB lower than longitudinally tined PCC pavement (see Figure 12). Any of these solutions would also need to be evaluated for reasonableness.

Performance Variation

Another consideration for *effectiveness* is the variation of the noise reduction over time due to environmental conditions. For example, in the greater Phoenix area, residents complained that noise mitigation in the form of barriers was not "effective" in the winter months (*51*). A followup investigation found that temperature inversions in that time of the year could produce measurable increases in traffic noise levels by as much as 10 dB. In another case in Michigan, noise complaints persisted even after a barrier was constructed (*52*). Further investigation indicated that temperature inversions were negating the normally 3 to 4 dB insertion loss performance of the barrier.

Wind is also known to affect barrier performance when the receptor is downwind of the traffic noise and the barrier is in between the two (*53, 54*). Both temperature inversions and downwind wind conditions cause sound waves to diffract downward into the shadow zone behind the barrier that normally blocks them under neutral environmental conditions. This diffraction reduces the insertion loss creating higher noise levels for receptors normally in the shadow zone. The magnitude of the increase in level depends on the specific geometry of the situation; it could be 5 dB or more. Prevailing downwind conditions and temperature inversions will also increase noise levels even when barriers are not present although the increases are generally smaller (1 to 2 dB) (*53*) and not as noticeable.

In considering pavements, wet roads have also been found to increase traffic noise levels by 2 to 4 dB at highway speeds (*55*). Although it is arguable that these time-varying effects should not be included in the impact assessment, considering them has some implications on the effectiveness of the noise abatement design. In cases where unfavorable environmental conditions (e.g., downwind wind conditions, temperature inversions, or rainy conditions) are expected to occur regularly, it may be prudent to account for those effects in the noise abatement design by increasing the height of a barrier and/or using quieter pavement to reduce the source levels. Within the constraints of reasonableness, such options will be more effective than those that do not consider these conditions.

Implementation of Effectiveness

As discussed previously, *effectiveness* would define the alternative that produces the lowest absolute traffic noise level, but, for highway modifications, it would define the abatement alternative that provides the largest reduction relative to the existing levels. Considerations for effectiveness would need to be weighed with reasonableness considerations to provide clear direction for decision making. Ideally, several different reasonable noise abatement alternatives using barriers, pavement strategies, or a combination of the two would be developed to identify the alternative that provides the lowest traffic noise level without exceeding the reasonable allowance.

With respect to feasibility, effectiveness might consider a lower reduction threshold (e.g., 3 dB). Reductions in tire noise levels of 3 dB resulting from grinding PCC pavements have been shown to produce results that are noticeable to the public and perceived as "effective" (*21*). However, such "effective" solutions would also need to pass a reasonableness requirement. The variation created by environmental conditions can be addressed by consideration of increased barrier heights, quieter pavement, or a combination of pavement and barrier. However, it would be necessary to identify a means for quantifying these environmental effects through some type of modeling.

Acoustic Longevity

One of the primary concerns associated with the use of quieter pavement for noise abatement is the increase in noise level as pavement ages. If a pavement is used as the only means of noise reduction, the amount of noise reduction will diminish with time. On the other hand, barriers typically provide the same amount of noise reduction over a long period of time even if the source levels increase as the pavement ages.

To address pavement performance issues, the changes in tire–pavement noise over time need to be quantified with OBSI data and then related to predicted traffic-noise-level changes through TNM using the modification of the GLSS as illustrated in Figures 12 and 13. OBSI measurements could also be integrated into the agency's pavement management system to indicate when pavement rehabilitation is required. For this purpose, acoustic longevity of the proposed pavement would need to be known or at least estimated from existing data so that the LCCA could be performed. Using relationships such as those of Figures 12 and 13, OBSI trigger points could be established and used in the modeled performance to indicate when acoustic rehabilitation is required.

Two methods of obtaining acoustic longevity information have been described in the literature (*56*). In one method, test sections of candidate pavements are constructed and their noise performance is measured periodically over a long period of time during which the pavement is subject to normal traffic. Because the changes from year to year may be small, time periods of 8 to 10 years are desired to allow the differences to be distinguished after a few years of service. Also, OBSI level change over time may not be linear; therefore, erroneous trends may be concluded from shorter duration studies. Other issues that need to be addressed pertain to the consistency of test methods, test tires, test vehicle, etc. over the 8- to 10-year monitoring period. Another approach to obtain longevity data is to measure the performance of pavements of different ages that were designed and constructed to the same specification. This approach requires a much shorter period of time but may have more scatter due to variations in pavement characteristics and trafficking. Both approaches have been successfully employed in quieter pavement research work (*51, 57*), but the latter appears to be more suited for agencies that are in the early stages of applying quieter pavement for noise reduction purposes and that have not yet accumulated sufficient long-term data.

If similar pavement specifications are used by agencies in regions of similar environmental conditions, it may also be possible to estimate acoustic longevity performance initially. The results of several such acoustic studies (reported in Appendix E) indicate that noise-level rates for AC surfaces increased by 0.3 to 0.8 dB/year (assuming linear trend lines and the absence of studded snow tire usage) and by 0.1 or 0.2 dB/year for PCC pavements (based on limited data).

Economic Features

Evaluating the economic features of pavement strategies and barriers will be based on LCCA. For barriers, this analysis will include the initial cost of the barriers and required maintenance and repair cost over the analysis period such as those given in Table 3. For pavements, the analysis may follow that recommended by the FHWA with an added consideration of acoustic performance in determining the rehabilitation cycle. To implement this approach for comparing strategies, it will also be necessary to perform the LCCA with and without the noise-reducing elements. For barriers, the project cost can easily be determined with and without the cost of the barrier.

For pavement, cost baseline needs to be established for a pavement that would be actually used if noise abatement was not considered in the pavement selection together with the associated OBSI level (and acoustic longevity and non-acoustic rehabilitation cycle cost if available). If acoustic performance is not considered in the LCCA, an average OBSI level of this pavement would be necessary.

For this research, cost–benefit analysis was considered a candidate method for assessing the economic features of pavement strategies and barriers. Within 23 CFR 772, benefit is monetized with a cost per benefited receptor analysis applied statewide through the policies of the SHA. Although this approach is currently applicable to barrier analysis, it could also be extended to include quieter pavement options and combinations of pavement and barriers. This approach would essentially leave the benefit side of the cost–benefit equation as it is currently defined by the SHA under 23 CFR 772 and concentrate on the cost side. A review of the status of cost–benefit analysis application to highway noise was made assuming that the monetized benefit is independent of the type of abatement to determine whether the current methods of assessing economic features are sufficient or if other cost–benefit analysis methods are appropriate (a summary is provided in Appendix F). This investigation concluded that more progress in highway noise cost–benefit analysis was needed before it could be incorporated into an acceptable methodology. However, economic features of pavement strategies and barriers could be evaluated within the framework of highway noise policy.

CHAPTER 4

Examples of Methodology Application

The Six-Lane Highway Scenario

To illustrate application of the methodology developed in this research, the six-lane new highway construction scenario used in the LCCA (Figure 10) was used to evaluate different noise exposure cases representing those of neighborhoods in three states. For this purpose, a simple flat geometry was assumed, the rows of buildings and other features were not accounted for in the analysis, and the traffic conditions were those used in the LCCA. These analyses will illustrate the application of the approach to different impact scenarios of highway projects with the same design and details. The net present value (NPV) costs developed in the original LCCA were used with some modifications to account for different barrier heights that were considered. Noise abatement analysis was conducted loosely based on the traffic noise policies of the states from which the exposure case was taken.

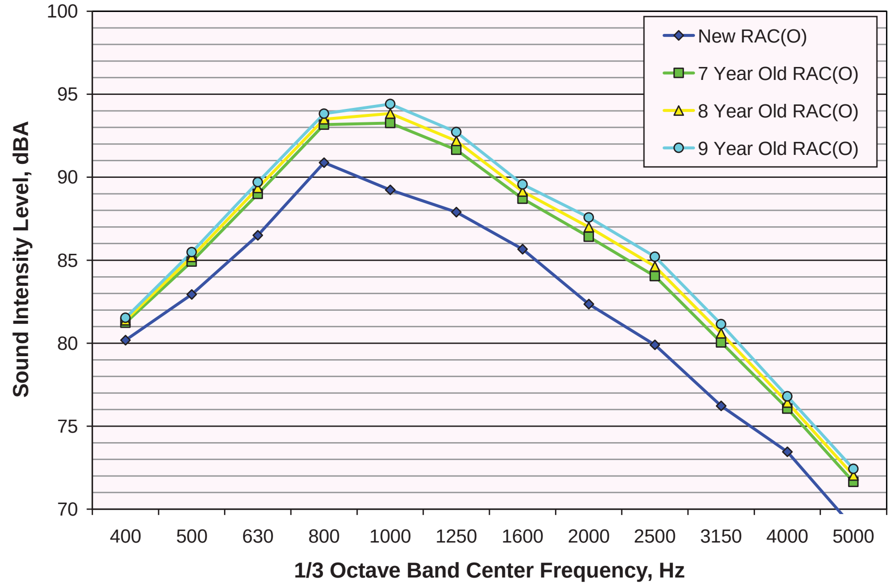
TNM-predicted noise levels were computed for the pavements and levels shown in Figures 12 and 13 as well as other pavement types using the SRTT OBSI data. The spectra and longevity data for the open-graded rubberized asphalt concrete [RAC(O)] pavement, shown in Figure 14, were taken from Caltrans Quieter Pavement Research work performed on LA 138 (*21*). The values for the ARFC pavement shown in Figure 15 correspond to levels and longevity rates found in the ADOT QPPP research (*18, 51*). The levels and longevity rates for the longitudinally tined PCC pavement were derived from the Caltrans Quieter Pavement Research work on the Mojave Bypass (*58*), the data for the ground PCC pavement were taken from test sections measured in Kansas on US 69 (*59*), and data for the random transversely tined pavement were from I-70 in Ohio (*48*); all of these are shown in Figure 16. The overall OBSI levels and the TNM-predicted levels at different distances from the highway for new and aged pavements are presented in Table 5.

These example cases are specific to the six-lane new highway case and would not apply to other highway configurations. As the number of lanes increase or decrease, the cost of quieter pavement options relative to barriers will change while achieving about the same noise reduction. Also, if receptors are equally located on both sides of the highway, the cost for barriers will be double than if receptors were only on one side, but pavement cost would remain the same. Also these examples assumed that the length of the barriers and quieter pavement will coincide, which would not necessarily occur in practice.

The TNM Average Pavement is used in the LCCA although it does not provide a specific design for which a cost can be defined. For these examples, traffic noise levels are presented for TNM Average Pavement with cost based on a generic HMA pavement without an added cost for acoustic performance. The rehabilitation cycle for this pavement is assumed to be 15 years for performance issues other than noise. In practice, a SHA would base the analysis on actual, specific pavement cost and acoustic performance. The acoustic performance of this pavement would be documented with OBSI data. A summary of the LCCA results for the HMA pavement and other pavements and barriers used in these cases is given in Table 6 (detailed information on the LCCA is provided in Appendix C). The NPV of the 12 ft high barriers was determined from the cost difference between the options with and without barriers, yielding an NPV of $3,685,000. This value was scaled appropriately for different heights and for the use of a barrier on just one side of the highway as needed. These estimated NPVs were then added to the NPV of the pavement alone. For the PCC pavements, it was assumed that texturing does not affect the life-cycle cost of these pavements. However, grinding was considered as a method of producing a quieter pavement initially after construction and as a rehabilitation method after 20 years of service. The costs for RAC(O) and ARFC pavements were determined to be similar enough such that the NPV of either type could be used.

Example 1: High-Density Case

This case is patterned after a neighborhood in Southern California along the Garden Grove Freeway (State Route 22) in the City of Garden Grove (Figure 17). In this case, one row of

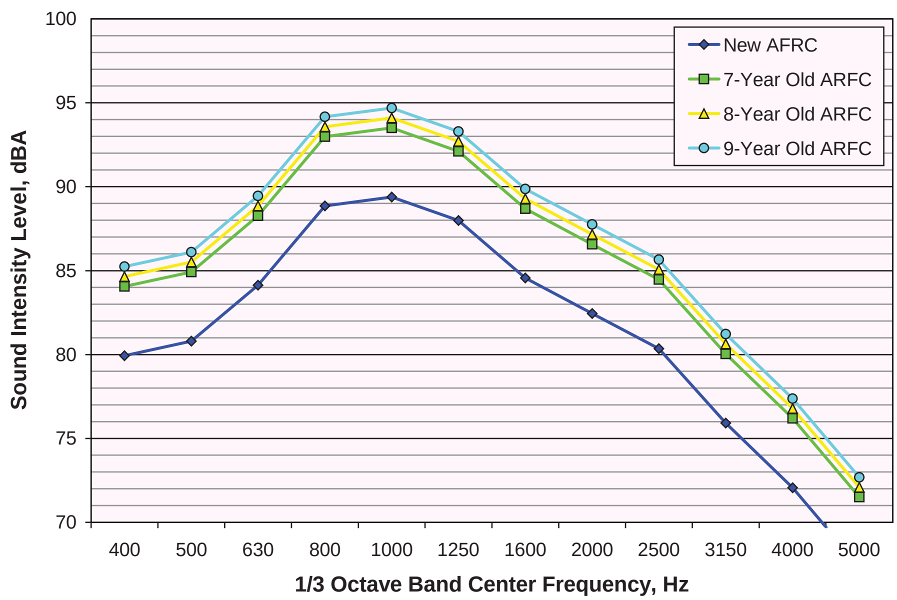


Source: Data from Thornton et al. (*20*).

Figure 14. OBSI one-third octave band spectra for RAC(O) pavement.

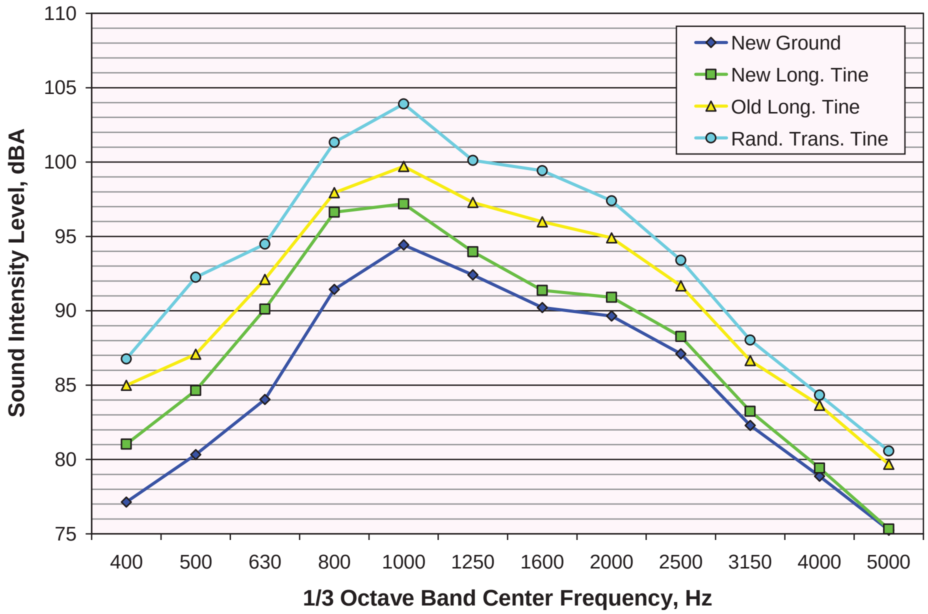
receptors is about 63 ft away from the center of the near through lane of travel and another row is at about 235 ft. The existing TNM results with receptor locations being approximated as 50 ft and 250 ft away were used for the analysis. The length of freeway shown is about 1,450 ft with 16 residences in each row. It was assumed that this pattern is repeated for at least 1 mi; thus, for the 1 mi project, receptor density is high—72 receptors in each row—and a barrier will be built on one side of the road. The following pavement alternatives were considered:

- HMA pavement with a 15-year rehabilitation cycle performing as TNM Average Pavement (designated as "HMA" in the following tables)
- HMA pavement constructed with a 1 in. RAC(O) surface layer replaced every 9 years (designated "RAC(O)" in the following tables)
- PCC pavement with longitudinal tines and rehabilitation every 20 years by grinding (designated as "LT PCC" in the following tables)



Source: Data from Donavan et al. (*18*), Scofield and Donavan (*51*).

Figure 15. OBSI one-third octave band spectra for ARFC pavement.



Source: Data from Donavan and Rymer (*58*), Donavan (*59*), Illingworth & Rodkin, Inc. (*48*).

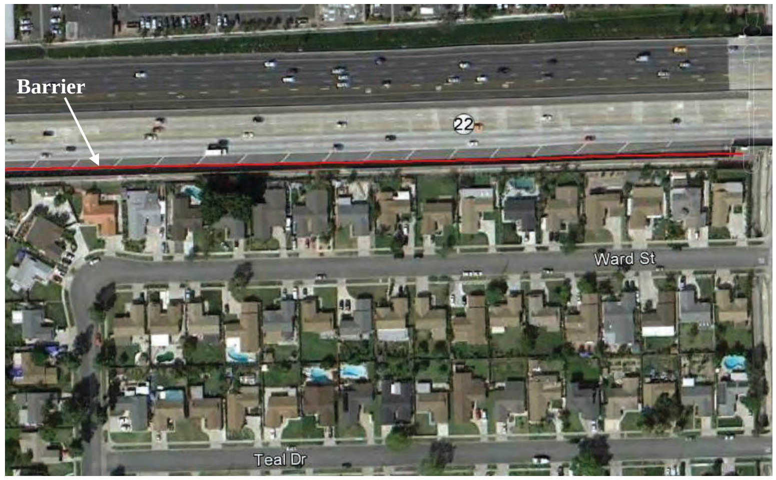
Figure 16. OBSI one-third octave band spectra for PCC pavements.

Table 5. OBSI and corresponding TNM predictions for different pavements.

Level and Distance	Pavement Type, Texture, and Age (Levels in dBA)							
	RAC(O)		ARFC		Long. Tine PCC		Ground PCC	Random Trans. Tine PCC
	New	9 yr	New	9 yr	New	Aged		
OBSI	96.0	100.2	95.3	100.6	102.4	105.1	99.6	108.6
TNM @ 25 ft	74.4	77.5	74.3	78.7	79.0	81.9	76.8	85.0
TNM @ 50 ft	72	75.1	72.5	76.9	76.7	79.5	74.4	82.5
TNM @ 100 ft	68.9	71.9	70.0	74.4	73.4	76.3	71.3	79.3
TNM @ 175 ft	65.6	68.4	67.5	71.8	69.9	72.7	67.9	75.7
TNM @ 250 ft	63.1	65.7	65.2	69.4	67.2	69.9	65.3	72.8

Table 6. Summary of NPV costs used in example cases.

Pavement Type (Rehabilitation Cycle) with & without 12 ft Barrier	Agency Cost ($000)	User Cost ($000)	Total Cost ($000)	Abatement Cost ($000)
HMA Construction (15 yr)—**Baseline 1**	6,937	10	6,947	0
HMA Construction + Barrier	10,763	10	10,773	3,826
RAC(O)/HMA (7 yr)	9,624	25	9,649	2,687
RAC(O)/HMA (7 yr) + Barrier	13,450	25	13,475	6,513
RAC(O)/HMA (8 yr)	8,985	18	9,003	2,049
RAC(O)/HMA (8 yr) + Barrier	12,811	18	12,829	5,875
RAC(O)/HMA (9 yr)	8,539	21	8,560	1,603
RAC(O)/HMA (9 yr) + Barrier	12,365	21	12,386	5,429
PCC Construction—**Baseline 2**	7,925	9	7,934	0
PCC + Barrier	11,751	9	11,760	3,826
PCC + Initial Grinding	9,273	9	9,282	1,348
PCC + Initial Grinding + Barrier	13,099	9	13,108	5,174



Source: Google Earth © 2011 Google

Figure 17. Aerial photograph of a portion of the Garden Grove Freeway in Garden Grove, California.

- PCC pavement with initial ground texture and rehabilitation every 20 years by grinding (designated as "Ground PCC" in the following tables)
- PCC pavement with random transverse tines and a 20-year rehabilitation cycle (designated as "RT PCC" in the following tables)

Although transversely tined texture is not typically used in California for on-grade pavements, it is included in this example as an alternative. For each pavement design, one or two barrier designs were considered; these barriers were assumed to be 1 mi long, of different heights, and placed on the outside edge of the near shoulder.

The analysis for the different pavement alternatives without barriers is shown in Table 7. The noise impacts were assessed by applying Caltrans and WSDOT criteria (*60, 61*) that define a benefited receptor as obtaining a 5 dB reduction and use a noise reduction design goal of 7 dB for at least one first row receptor and the Noise Abatement Criteria (NAC) of 66 dBA. Table 7 shows that although the predicted level at 50 ft ranges from 72 to 83 dBA, all receptors are impacted. At 250 ft, all receptors are impacted by all pavement alternatives except the RAC(O) and ground PCC. At the end of the respective rehabilitation cycles, the RAC(O) would reach the impact threshold and ground PCC would exceed it (when considering a 3 dB increase for the LT PCC). In terms of performance, the amount of reduction for the RAC(O) and ground PCC depends on the baseline pavement. For receptors at 50 ft, the initial reduction for the RAC(O) is 5 dB relative to HMA and LT PCC, and 11 dB relative to RT PCC. These reductions meet the 5 dB feasibility criteria relative to each of the other three pavement types. After 9 years, a reduction of 5 dB or greater would only exist relative to RT PCC. For receptors at 50 ft, the reduction for the ground PCC is 3 dB relative to HMA and LT PCC, which does not meet current feasibility criteria, but the reduction is 9 dB relative to RT PCC. The RAC(O) and ground PCC would achieve a 7 dB design goal only relative to RT PCC.

Table 7. Predicted traffic noise levels, number of impacted receptors, and NPV costs for Example 1.

Pavement	72 Receptors at 50 ft		72 Receptors at 250 ft		Total Number of Impacts	Agency NPV Cost ($000)
	Level (dBA)	Impacts	Level (dBA)	Impacts		
HMA	77	72	67	72	144	6,937
RAC(O)	72	72	63	0	72	8,539
LT PCC	77	72	67	72	144	7,925
Ground PCC	74	72	65	0	72	9,273
RT PCC	83	72	73	72	144	7,925
9-yr RAC(O)	75	72	66	72	144	8,539
20-yr LT PCC	80	72	70	72	144	7,925

The use of 8 ft high barriers on one side of the highway was considered for all pavements and 12 ft high barriers were also considered for the HMA and RT PCC pavements. The calculated traffic noise levels at 50 ft and 250 ft together with the overall pavement–barrier system noise reductions relative to the HMA, LT PCC, and RT PCC pavements are shown in Table 8.

For receptors at the 50 ft distance, the lowest absolute levels were for the HMA with a 12 ft barrier at 65 dBA followed by the RAC(O) with an 8 ft barrier at 66 dBA. Both the HMA with a 12 ft barrier and the RAC(O) with an 8 ft barrier produced the lowest levels at 60 dBA for receptors at the 250 ft distance. The insertion loss of the barriers ranged from 6 to 13 dB at 50 ft. To assess feasibility, the noise reduction relative to the baseline pavement was used instead of the barrier insertion loss alone. Relative to the LT PCC and HMA baselines, all alternatives except ground PCC with no barrier and RT PCC with a 12 ft barrier are acoustically feasible and provide benefit. For receptors at 250 ft, the insertion losses range from 4 to 7 dB. In terms of noise reduction at 250 ft relative to the HMA and LT PCC baselines, the RT PCC baseline with a 12 ft barrier does not provide benefit (it showed negative noise reduction), but the RAC(O) and ground PCC with 8 ft barriers and HMA with 12 ft barriers all provide benefit. Also, the RAC(O) pavement with an 8 ft barrier provides benefit after 9 years. Relative to the RT PCC baseline, all alternatives provide benefit at 250 ft. Relative to the HMA and LT PCC baselines, the RAC(O) without a barrier does not achieve a design goal of 7 dB, but with an 8 ft barrier, it achieves the goal for the first row of receptors. Other alternatives that did not meet a 7 dB design goal relative to the HMA and LT PCC baselines are the ground PCC without a barrier, 20-year-old LT PCC with an 8 ft barrier, and RT PCC with a 12 ft barrier.

The information presented in this section can be used to evaluate the acoustic feasibility and reasonableness performance for each alternative relative to the design goal. For the reasonableness evaluation, WSDOT uses a base barrier cost of \$51.61/ft^2 and Caltrans uses actual design costs. For LCCA, use of actual design costs is preferred but estimated costs may be used if actual costs are not available; \$51.61/ft^2 is used in this example (compared to the \$27 national average). For cost allowance, WSDOT uses a graduated scale that increases the cost allowance as the noise-level reduction increases. Caltrans uses a flat allowance of \$55,000 per benefited receptor. To calculate the reasonableness allowance for this example, the receptors are only located on one side of the highway as shown in Figure 17.

Using the results shown in Table 8, the number of benefited receptors for each alternative was estimated and is presented in Table 9 for assumed baseline noise levels of HMA or LT PCC. With only two groups of the receptors, the number of benefited receptors is either 72 or 144 depending on whether a feasible reduction was obtained at the 250 ft distance. Also shown in Table 9 are the NPV for the project together with the NPV for abatement (i.e., the cost due to quieter pavement, barriers, or a combination of the two). For each case, the NPV for the abatement is calculated relative to the NPV of the HMA pavement (without an added abatement). The acoustic performance of this pavement was taken to be that of TNM Average Pavement. The NPV of abatement for the PCC alternatives is also shown relative to a baseline of PCC pavement without abatement. For this analysis, the differences of NPV with and without abatement were compared to the reasonableness allowances

Table 8. Traffic noise levels, barrier insertion loss, and overall system noise reduction for Example 1.

Pavement Type and Barrier Height	Receptors at 50 ft					Receptors at 250 ft				
	Noise Level (dBA)	Barrier IL (dB)	dB Noise Reduction Relative to:			Noise Level (dBA)	Barrier IL (dB)	dB Noise Reduction Relative to:		
			HMA [77 dBA]	LT PCC [77 dBA]	RT PCC [83 dBA]			HMA [67 dBA]	LT PCC [67 dBA]	RT PCC [73 dBA]
HMA + 8 ft	69	8	8	8	14	63	4	4	4	10
HMA + 12 ft	65	12	12	12	18	60	7	7	7	13
RAC(O)	72	n/a	5	5	11	63	n/a	4	4	10
RAC(O) + 8 ft	66	6	11	11	17	60	3	7	7	13
LT PCC + 8 ft	69	8	8	8	14	63	4	1	1	7
Ground PCC	74	n/a	3	3	9	65	n/a	2	2	8
Ground PCC + 8 ft	67	7	10	10	16	62	3	5	5	11
RT PCC + 12 ft	74	9	3	3	9	68	5	−1	−1	5
9-yr RAC(O)	75	n/a	2	2	8	66	n/a	1	1	7
9-yr RAC(O) + 8 ft	68	8	9	9	15	62	4	5	5	11
20-yr LT PCC + 12 ft	72	8	5	5	11	66	4	1	1	7

Table 9. Predicted noise levels with abatement, number of benefited receptors, NPV costs, and reasonable allowances for various abatement scenarios (receptors on one side).

Pavement Type and Barrier Height	Predicted Noise Level (dBA)		Number of Benefited Receptors	Total Project NPV ($000)	NPV for Noise Abatement Relative to		Caltrans Reasonableness Allowance ($000)	WSDOT Reasonableness Allowance ($000)
	Receptors at 175 ft	Receptors at 375 ft			HMA Baseline ($000)	PCC Baseline ($000)		
HMA + 8 ft	69	63	72	9,374	2,438		3,960	5,126
HMA + 12 ft	65	60	144	10,593	3,657		7,920	7,978
RAC(O)	72	63	72	8,539	1,603		3,960	5,126
RAC(O) + 8 ft	66	60	144	10,977	4,041		7,920	7,978
LT PCC + 8 ft	69	63	72	10,363	3,426	2,429	3,960	5,126
Ground PCC	74	65	0	9,273	2,337	1,339	0	0
Ground PCC + 8 ft	67	62	144[1]	11,711	4,774	3,777	7,920[1]	7,978[1]
RT PCC + 12 ft	74	68	0	11,582	4,645	3,648	0	0
9-yr RAC(O)	75	66	0	8,539	1,603		0	0
9-yr RAC(O) + 8 ft	68	62	144	10,977	4,041	3,043	7,920	7,978
20-yr LT PCC + 8 ft	72	66	72	10,363	3,426	2,429	3,960	5,126

[1] Relative to RT PCC baseline only, not for HMA or LT PCC.

calculated with WSDOT and Caltrans methods; the NPV was below the allowed amount for all cases except for the ground PCC pavement without a barrier and the random transversally tined PCC pavement. In these cases, the noise reduction relative to the predicted noise levels for the HMA and LT PCC pavements shown in Table 8 was less than the required 5 dB minimum reduction. However, if a baseline noise level of RT PCC pavement is assumed, a 12 ft high barrier provides a 5 and 9 dB insertion loss at 250 and 50 ft, respectively, and the grinding produces a tire–pavement noise reduction of 8 and 9 dB. With this baseline, both options would be reasonable for cost. Based on a design goal criterion of 7 dB, the RAC(O) without the 8 ft barrier would not be reasonable.

Acoustic feasibility, cost reasonableness, and ability to meet the design goals of Caltrans and WSDOT are summarized in Table 10 for all of the pavement–barrier alternatives using

Table 10. Assessment of options under Caltrans and WSDOT policies for Example 1.

Pavement Type and Barrier Height	Caltrans			WSDOT			Effectiveness (dB)	Cost Difference ($000) Relative to	
	Feasible	Cost Reasonable	Design Goal	Feasible	Cost Reasonable	Design Goal		HMA	PCC
HMA + 8 ft	Y	Y	Y	Y	Y	Y	4	835	
HMA + 12 ft	Y	Y	Y	Y	Y	Y	0	2,054	
RAC(O)	Y	Y	N	Y	Y	N	7	0	
RAC(O) + 8 ft	Y	Y	Y	Y	Y	Y	1	2,438	
LT PCC + 8 ft	Y	Y	Y	Y	Y	Y	4	1,823	1,090
Ground PCC	N	N	N	N	N	N	9	734	0
Ground PCC + 8 ft	Y	Y	Y	Y	Y	Y	2	3,171	2,438
RT PCC + 12 ft	Y[1]	Y[1]	Y[1]	Y[1]	Y[1]	Y[1]	9	3,042	2,309
9-yr RAC(O)	N	N	N	N	N	N	10	0	
9-yr RAC(O) + 8 ft	Y	Y	Y	Y	Y	Y	3	2,438	
20-yr LT PCC + 8 ft	Y	Y	N	Y	Y	N	7	1,823	1,090

[1] Relative to RT PCC baseline only, not for HMA or LT PCC.

each agency's criteria. Effectiveness as indicated by the difference between the lowest absolute level for any of the alternatives and the level for a specific alternative and the additional cost relative to the lowest cost alternative are also shown to allow consideration of cost and effectiveness. The lowest NPV cost is the RAC(O) with no barrier, which is also acoustically feasible and cost reasonable (at least initially). However, this alternative does not provide the design goal of 7 dB reduction, is not as effective as some of the other alternatives in producing low overall traffic noise levels, and does not meet either the feasibility or cost-reasonableness criterion at the end of the 9-year rehabilitation cycle. The next least expensive alternative is ground PCC without a barrier; it is also one of the least effective alternatives and it does not provide an acoustic feasibility level of 5 dB. HMA with an 8 ft barrier is the next least expensive option; it meets a 5 dB feasibility and 7 dB reasonableness design criteria. However, the most effective solution is the HMA with a 12 ft barrier followed closely by the RAC(O) with an 8 ft barrier. These two alternatives produce twice as many benefited receptors as the HMA with an 8 ft barrier but their NPV costs are higher than the HMA with the 8 ft barrier; both alternatives are well within the allowances for Caltrans and WSDOT. The LT PCC with the 8 ft barrier is a viable option that meets all the criteria and has the lowest cost of all PCC alternatives and effectiveness similar to that of the HMA with 8 ft barrier but at a somewhat higher cost. LT PCC could be further optimized by increasing the barrier height to increase effectiveness without adversely affecting its cost advantage over the other PCC options. The cost and effectiveness of the RT PCC with 12 ft barrier is not as good as that of LT PCC with 8 ft barrier and it is feasible and cost reasonable and meets the design goal only when it is compared to a baseline of the RT PCC pavement.

When considering effectiveness in the selection process, trade-offs will be required. For example, HMA with both 8 ft and 12 ft barriers meet the feasible and reasonable criteria, but HMA with a 12 ft barrier performs better for effectiveness at a higher cost. Similarly, LT PCC with an 8 ft barrier is not as effective as ground PCC with an 8 ft barrier, but it has a lower NPV (about $1,350,000 less). In actual agency decisions, other considerations—such as blocking the view of truck exhaust stacks (e.g., 13 ft barriers for WSDOT), highway/pavement design practices, exposure to higher noise levels, and the opinions of residents affected by the abatement—may also affect the selection process.

The scenarios presented in Table 9 consider receptors and barriers on only one side of the highway. If receptors were mirrored on the other side of the highway, the NPVs for the barrier cases would increase together with corresponding increases in the reasonableness allowances as the number of benefited receptors is doubled. Table 11 shows the adjusted NPVs and allowances. In spite of the increased NPV for the barriers and allowance for receptors on both sides, all results in Table 10 will apply except for the cost differences.

The changes in the cost difference do not affect the analysis of the barrier alternatives but the RAC(O) pavement without a barrier shows much lower NPVs by about $3,300,000 to $6,700,000. For the RAC(O) with no barrier, the predicted levels at 250 ft are equal to those of the HMA with an 8 ft barrier but less effective by 3 dB at 50 ft. After 9 years, the RAC(O)

Table 11. Predicted noise levels with abatement, number of benefited receptors, NPV costs, and reasonable allowances for various abatement scenarios (receptors on both sides).

Pavement Type and Barrier Height	Predicted Noise Level (dBA)		Number of Benefited Receptors	Total Project NPV ($000)	NPV for Noise Abatement Relative to		Caltrans Reasonableness Allowance ($000)	WSDOT Reasonableness Allowance ($000)
	Receptors at 175 ft	Receptors at 375 ft			HMA Baseline ($000)	PCC Baseline ($000)		
HMA + 8 ft	69	63	144	11,812	4,876		7,920	10,253
HMA + 12 ft	65	60	288	14,250	7,313		15,840	15,955
RAC(O)	72	63	144	8,539	1,603		7,920	10,253
RAC(O) + 8 ft	66	60	288	13,415	6,478		15,840	15,955
LT PCC + 8 ft	69	63	144	12,801	5,864	4,867	7,920	10,253
Ground PCC	74	65	0	9,273	2,337	1,339	0	0
Ground PCC + 8 ft	67	62	288	14,149	7,212	6,215	15,840	10,253
RT PCC + 12 ft	74	68	0	15,239	8,302	7,305	0	0
9-yr RAC(O)	75	66	0	8,539	1,603		0	0
9-yr RAC(O) + 8 ft	68	62	288	13,415	6,478	5,481	15,840	10,253
20-yr LT PCC + 8 ft	72	66	144	12,801	5,864	4,867	7,920	10,253

will become only 2 dB quieter than the HMA baseline with no abatement. However, there is no acoustic longevity in performance of the HMA as its acoustic performance is taken to be the same as TNM Average Pavement (i.e., 0 dB/year). Caltrans Quieter Pavement Research work estimates an increase in the noise level for a dense-graded HMA of about 1 to 1.5 dB in a 9-year period (*20*). Even considering this increase, the RAC(O) alternative will not meet a 7 dB design goal and it will not meet feasibility and cost-reasonableness requirements at the end of the rehabilitation cycle.

This example case illustrates the analysis that could be done using the methodology developed in this research. In these high-density alternatives and for these agency allowances, cost reasonableness is not an issue as long as there are some benefited receptors. Other iterations of barrier height, quieter pavement life cycle, policy criterion, reasonableness allowances, pavement type, acoustic longevity, etc., could alter the results significantly. Therefore, more appropriate results will be obtained if an agency's own data, practices, costs, etc. are used in the analysis.

Source: Google Earth © 2011 Europa Technologies

Figure 18. Aerial photograph of a portion of I-475 near Grand Blanc/Flint, Michigan, used as an example case for lower density receptors.

Example 2: Low-Density Case

This example is patterned after an area along I-475 in Michigan in the Grand Blanc/Flint area. The residents are more widely spaced and set back further from the highway; the geometry of the site is shown in Figure 18. In this case, the density of the receptors is low. The first row of 13 residential receptors is about 175 ft from the center of the near lane with 3 more at a distance of about 250 ft. The second row of 11 receptors is about 375 ft from the roadway. The pavements considered are the same as those used in the high-density case. This project extends only 1,690 ft for the length of a barrier that would shield these receptors. The levels and impacts for the three receptor distances are shown in Table 12 together with the NPV of each pavement alternative. The Michigan Department of Transportation (MDOT) uses a level of 66 dBA to identify impacted receptors (*62*) (similar to Caltrans and WSDOT). With this criterion none of the receptors at the 375 ft distance would be considered as impacted initially except if RT PCC were considered as the baseline pavement (Table 12).

Similar to the previous example case, barrier heights of 8 and/or 12 ft were considered for noise abatement in combination with different pavement alternatives. The resulting noise levels are shown in Table 13 together with the barrier insertion losses (as appropriate) and the overall noise reduction compared to either the HMA and LT PCC or the RT PCC (noise reductions for the HMA and LT PCC are the same regardless of pavement type, see Table 8). The MDOT policy uses the design goal of a 10 dB reduction for at least one benefited receptor and a 7 dB reduction for 75% of all benefited receptors. If the HMA or the LT PCC levels are considered as the baseline, none of the receptors realize this goal. However, with the RT PCC as a baseline, all options meet this criterion

Table 12. Predicted traffic noise levels, number of impacted receptors, and NPV costs for Example 2.

Pavement	13 Receptors at 175 ft		3 Receptors at 250 ft		11 Receptors at 375 ft		Total Number of Impacts	NPV Cost ($000)
	Level (dBA)	Impacts	Level (dBA)	Impacts	Level (dBA)	Impacts		
HMA	70	13	67	3	63	0	16	2,220
RAC(O)	66	13	63	0	60	0	13	2,733
LT PCC	70	13	67	3	63	0	16	2,537
Ground PCC	68	13	65	0	61	0	13	2,968
RT PCC	76	13	73	3	68	11	27	2,537
9-yr RAC(O)	68	13	66	3	62	0	16	
20-yr LT PCC	73	13	70	3	66	11	27	

Table 13. Traffic noise levels, barrier insertion loss, and overall system noise reduction for Example 2.

Pavement Type and Barrier Height	175 ft Receptors				250 ft Receptors				375 ft Receptors			
	Noise Level (dBA)	Barrier IL (dB)	dB Noise Reduction Relative to: HMA/LT PCC [70 dBA]	dB Noise Reduction Relative to: RT PCC [76 dBA]	Noise Level (dBA)	Barrier IL (dB)	dB Noise Reduction Relative to: HMA/LT PCC [67 dBA]	dB Noise Reduction Relative to: RT PCC [73 dBA]	Noise Level (dBA)	Barrier IL (dB)	dB Noise Reduction Relative to: HMA/LT PCC [63 dBA]	dB Noise Reduction Relative to: RT PCC [68 dBA]
HMA + 8 ft	65	5	5	11	63	4	4	10	60	3	3	8
HMA + 12 ft	62	8	8	14	60	7	7	13	57	6	6	11
RAC(O)	66	n/a	4	10	63	n/a	4	10	60	n/a	3	8
RAC(O) + 8 ft	61	9	9	15	60	4	7	13	57	3	6	11
LT PCC + 12 ft	61	9	9	15	60	7	7	13	57	6	6	11
Ground PCC	68	n/a	2	8	65	n/a	2	8	61	n/a	2	7
Ground PCC + 8 ft	64	6	6	12	62	3	5	11	59	2	4	9
RT PCC + 12 ft	66	10	4	10	65	7	2	8	62	6	1	6
9-yr RAC(O) + 8 ft	64	7	6	12	62	5	5	11	59	3	4	9
20-yr LT PCC + 12 ft	64	6	6	12	62	5	5	11	60	3	3	8

except the ground PCC pavement without a barrier. Although the design goals are not achieved, the analysis was carried through to completion. For feasibility, MDOT requires a 5 dB reduction for at least 75% of the impacted receptors. Relative to the HMA or LT PCC baseline, the RAC(O) without a barrier, ground PCC without a barrier, and RT PCC do not meet this criterion (or that for Caltrans and WSDOT). If the RT PCC is used as the baseline, all alternatives except the ground PCC without a barrier meet the MDOT design goal of a 10 dB reduction and all alternatives meet the WSDOT and Caltrans goal of a 7 dB reduction and the feasibility requirement.

For the evaluation of cost reasonableness, MDOT uses a barrier cost of $45/ft^2 and an allowance of $41,208 per benefited receptor (i.e., those who receive 5 dB or more reduction). Table 14 shows the allowance, the number of benefited receptors, the reasonableness allowance, and the NPV for the

Table 14. Predicted noise levels with abatement, number of benefited receptors, NPV costs, and reasonable allowances for abatement scenarios – Example 2 (receptors on one side).

Pavement Type and Barrier Height	Predicted Noise Level (dBA): Receptors at 175 ft	Predicted Noise Level (dBA): Receptors at 375 ft	Number of Benefited Receptors	Total Project NPV ($000)	NPV for Noise Abatement Relative to: HMA Baseline ($000)	NPV for Noise Abatement Relative to: PCC Baseline ($000)	MDOT Reasonableness Allowance ($000)	Caltrans Reasonableness Allowance ($000)	WSDOT Reasonableness Allowance ($000)
HMA + 8 ft	65	60	16	2,901	680		659	880	771
HMA + 12 ft	62	57	27	3,241	1,021		1,113	1,485	1,168
RAC(O)	66	60	0	2,733	513		0	0	0
RAC(O) + 8 ft	61	57	27	3,414	1,193		1,113	1,485	1,168
LT PCC + 12 ft	61	57	27	3,557	1,337	1,021	1,113	1,485	1,168
Ground PCC	68	61	0	2,968	748	431	0	0	0
Ground PCC + 8 ft	64	59	16	3,648	1,428	1,112	659	880	771
RT PCC + 12 ft	66	62	27	3,557	1,337	1,021	1,113	1,485	1,168
9-yr RAC(O) + 8 ft	64	59	16	3,414	1,193		659	880	771
20-yr LT PCC + 12 ft	66	60	16	3,557	1,337	1,021	659	880	771

Table 15. Assessment of alternatives under MDOT, Caltrans, and WSDOT policies for Example 2.

Pavement Type and Barrier Height	MDOT			Caltrans			WSDOT			Effectiveness (dB)	Cost Difference ($000) Relative to	
	Feasible	Cost Reasonable	Design Goal	Feasible	Cost Reasonable	Design Goal	Feasible	Cost Reasonable	Design Goal		HMA	PCC
HMA + 8 ft	Y	N	N	Y	Y	N	Y	Y	N	4	167	
HMA + 12 ft	Y	Y	N	Y	Y	Y	Y	Y	Y	1	508	
RAC(O)	N		N	N		N	N		N	5	0	
RAC(O) + 8 ft	Y	N	N	Y	Y	Y	Y	N	Y	0	680	
LT PCC + 12 ft	Y	Y[2]	N	Y	Y	Y	Y	Y[2]	Y	0	824	589
Ground PCC	N		N	N		N	N		N	7	235	0
Ground PCC + 8 ft	Y	N	N	Y	N	N	Y	N	N	3	915	680
RT PCC + 12 ft	Y[1]	Y[2]	Y[1]	Y[1]	Y	Y[1]	Y[1]	Y	Y[1]	5	824	589
9-yr RAC(O) + 8 ft	Y	N	N	Y	N	N	Y	N	N	3	680	
20-yr LT PCC + 12 ft	Y	N	N	Y	N	N	Y	N	N	5	824	589

[1] Relative to RT PCC baseline only, not for HMA or LT PCC
[2] Relative to PCC cost only, not for HMA cost

project and the abatement strategy considering MDOT criteria (the allowances using Caltrans and WSDOT criteria are also shown). Of the alternatives that meet the feasible criteria, the HMA with an 8 ft barrier does not meet the MDOT design goal and thus is not reasonable (but it meets the goals of both Caltrans and WSDOT). Relative to the PCC NPV baseline, the LT PCC with a 12 ft barrier is reasonable according to the criteria for the three agencies. The ground PCC with an 8 ft (or increased height) barrier is not reasonable by any of the agencies' criteria. The RT PCC with a 12 ft barrier is reasonable for all agencies only if the baseline pavement is RT PCC.

The assessment of the feasibility, cost reasonableness, and achievement of design goals of the pavement–barrier alternatives is summarized in Table 15. Effectiveness is shown as the difference between the lowest absolute level for any of the options and the level for a specific option. The additional cost relative to the lowest cost option is also shown. The HMA, LT PCC, or RT PCC all with 12 ft barriers would meet the MDOT criteria but not the design goal. Of these alternatives with 12 ft barriers, the LT PCC pavement is most effective in providing the lower levels, but the HMA alternative is only 1 dB higher and only at the 175 ft receptor distance. The RT PCC alternative is less effective than the LT PCC even though the NPV is the same. Of the HMA and LT PCC with 12 ft barriers, the HMA has the overall lowest NPV by $316,000. Using the Caltrans allowances, RAC(O) with an 8 ft barrier would also be cost reasonable (in addition to the HMA and LT PCC with 12 ft barriers alternatives). The levels for the RAC(O) with an 8 ft barrier are similar to the HMA and LT PCC with 12 ft barriers with the total cost in between these two. The selection from among the RAC(O) with an 8 ft barrier, the HMA with a 12 ft barrier, and the LT PCC with a 12 ft barrier when considering Caltrans criteria may be determined by other considerations such as cost, preferred pavement type, and user costs.

Example 3: Two-Barrier Case

This example is for a six-lane new highway construction developed around the geometry shown in Figure 19 along I-93 near the Town of Medford, Massachusetts, north of

Figure 19. Aerial photograph of a portion of I-93 near Medford, Massachusetts, with receptors and proposed barriers on both sides of a highway.

Table 16. Predicted traffic noise levels, number of impacted receptors, and NPV costs for Example 3 (southbound side).

Pavement	14 Receptors at 100 ft		6 Receptors at 175 ft		10 Receptors at 250 ft		Total Number of Impacts	NPV Cost ($000)
	Level (dBA)	Impacts	Level (dBA)	Impacts	Level (dBA)	Impacts		
HMA	74	14	70	30	67	10		1,498
RAC(O)	69	14	66	20	63	0		1,844
LT PCC	73	14	70	6	67	10	30	1,711
Ground PCC	71	14	68	6	65	0	20	2,002
RT PCC	79	14	76	6	73	10	30	1,711
9-yr RAC(O)	72	14	68	6	66	10	30	
20-yr LT PCC	76	14	73	6	70	10	30	

Boston. In this case, receptors with about the same density are located on both sides of the highway. The project area is from Webster Street to Valley Street for a length of about 1,140 ft.

There are 47 receptors along the project area. On the southbound side, there are 30 receptors (the sum of those located approximately 100 ft, 175 ft, and 250 ft from the near lane of travel). On the northbound side, a total of 17 receptors are distributed over these same three distances. Tables 16 and 17 provide the predicted noise levels and impacts for the southbound and northbound sides, respectively. The Massachusetts Department of Transportation (MassDOT) defines an impact as when the noise levels are within 1 dB of the FHWA NAC (66 dBA) (*63*)—the same criteria used by WSDOT, Caltrans, and MDOT—resulting in the same number of impacted receptors. For both the RAC(O) and ground PCC pavements, the levels are below 66 dBA at 250 ft, which reduces the number of impacted receptors.

Tables 16 and 17 also provide the NPV costs for each pavement type. For this example case, the pavement NPVs apply to both the northbound and southbound directions, but the barrier NPVs apply to each side individually and are analyzed separately.

MassDOT considers acoustic feasibility to be achieved when more than 50% of the first row receptors receive a 5 dB reduction. The design goal of 10 dB is met when at least one receptor in the first row receives this reduction. For cost reasonableness, MassDOT uses an index calculation procedure that is not directly compatible with the LCCA methodology developed in this research. The cost-effectiveness index used by MassDOT is the cost of the barrier based on $50/ft^2 divided by the average insertion loss divided by the number of benefited receptors that receive a 5 dB or more reduction. In these cases, a cost allowance could not be determined, but the MassDOT-type barrier cost was used in the LCCA to determine whether the barrier met the cost-effectiveness index.

The barrier heights considered in the analysis ranged from 8 to 12 ft depending on the pavement. Cost allowances were also calculated using MDOT and WSDOT methods. The predicted levels, barrier insertion losses, and pavement–barrier noise reductions are shown in Table 18 for the different receptor distances and pavement baselines. As in the previous example, the HMA and LT PCC baselines were considered together because of their similar levels at most receptor locations and the RT PCC was considered as an additional baseline. The data in Table 18 applies to both the southbound

Table 17. Predicted traffic noise levels, number of impacted receptors, and NPV costs for Example 3 (northbound side).

Pavement	7 Receptors at 100 ft		2 Receptors at 175 ft		8 Receptors at 250 ft		Total Number of Impacts	NPV Cost ($000)
	Level (dBA)	Impacts	Level (dBA)	Impacts	Level (dBA)	Impacts		
HMA	74	7	70	2	67	8	17	1,498
RAC(O)	69	7	66	2	63	0	9	1,844
LT PCC	73	7	70	2	67	8	17	1,711
Ground PCC	71	7	68	2	65	0	9	2,002
RT PCC	79	7	76	2	73	8	17	1,711
9-yr RAC(O)	72	7	68	2	66	8	17	
20-yr LT PCC	76	7	73	2	70	8	17	

Table 18. Traffic noise levels, barrier insertion loss, and overall system noise reduction for receptors for Example 3 (both sides).

Pavement Type and Barrier Height	100 ft Receptors				175 ft Receptors				250 ft Receptors			
	Noise Level (dBA)	Barrier IL (dB)	dB Noise Reduction Relative to:		Noise Level (dBA)	Barrier IL (dB)	dB Noise Reduction Relative to:		Noise Level (dBA)	Barrier IL (dB)	dB Noise Reduction Relative to:	
			HMA/LT PCC [74 dBA]	RT PCC [79 dBA]			HMA/LT PCC [70 dBA]	RT PCC [76 dBA]			HMA/LT PCC [67 dBA]	RT PCC [73 dBA]
HMA + 10 ft	66	8	8	13	64	6	6	12	63	4	4	4
HMA + 12 ft	64	10	10	15	62	8	8	14	60	7	7	7
RAC(O)	69	n/a	5	10	66	n/a	4	10	63	n/a	4	4
RAC(O) + 8 ft	64	5	10	15	61	4	9	15	60	3	7	7
LT PCC + 12 ft	63	10	11	16	61	9	9	15	60	7	7	7
Ground PCC	71	n/a	3	8	68	n/a	2	8	65	n/a	2	2
Ground PCC + 8 ft	66	6	8	13	64	4	6	12	62	4	5	5
RT PCC + 12 ft	68	11	6	11	66	10	4	10	65	8	2	2
9-yr RAC(O) + 8 ft	66	6	8	13	64	5	6	12	62	4	5	5
20-yr LT PCC + 12 ft	65	11	9	14	63	9	7	13	62	8	5	5

and northbound sides of the highway as the results are independent of the number of receptors. For the HMA/LT PCC baseline, only the HMA with 12 ft barriers, the RAC(O) with 8 ft barriers, and the LT PCC with 12 ft barriers meet the MassDOT (and MDOT) design goal. Relative to RT PCC, all alternatives except the ground PCC meet the 10 dB design goal. In terms of acoustic feasibility, all alternatives except ground PCC meet the criterion relative to both the HMA/LT PCC and the RT PCC baselines.

The LCCA NPVs for the two sides of the highway are the same because the pavement and barrier lengths are the same; results are presented in Table 19. The allowances based on MDOT and WSDOT criteria for the southbound and northbound sides are different due to the difference in the number

Table 19. Total project and abatement NPV, number of benefited receptors, and reasonableness allowances for Example 3 (both sides).

Pavement Type and Barrier Heights	Total Project NPV ($000)	NPV for Noise Abatement Relative to		Southbound Side			Northbound Side		
		HMA Baseline ($000)	PCC Baseline ($000)	Number of Benefited Receptors	MDOT Reasonableness Allowance ($000)	WSDOT Reasonableness Allowance ($000)	Number of Benefited Receptors	MDOT Reasonableness Allowance ($000)	WSDOT Reasonableness Allowance ($000)
HMA + 10 ft	2,135	637		20	824	899	9	371	449
HMA + 12 ft	2,263	765		30	1,236	1,596	17	701	867
RAC(O)	1,844	346		14	577	1,200	7	288	550
RAC(O) + 8 ft	2,354	856		30	1,236	1,596	17	701	867
LT PCC + 12 ft	2,476	978	765	30	1,236	1,596	17	701	867
Ground PCC	2,002	504	291	0	0	0	0	0	0
Ground PCC + 8 ft	2,512	1,014	801	30	1,236	1,596	17	701	867
RT PCC + 12 ft	2,476	978	765	30[1]	1,236	1,596	17[1]	701	867
9-yr RAC(O) + 8 ft	2,354	856	643	30	1,236	1,596	17	701	867
20-yr LT PCC + 12 ft	2,476	978	765	30	1,236	1,596	17	701	867

[1] Relative to RT PCC baseline only, not for HMA or LT PCC

of benefited receptors. For the southbound side, all alternatives except ground PCC without a barrier provided sufficient allowances to be cost reasonable for both MDOT and WSDOT criteria. None of the alternatives for the northbound side (with the fewer number of benefited receptors) are cost reasonable using the MDOT allowances. Using WSDOT criteria, only the HMA with 10 ft barriers is not cost reasonable. However, the PCC alternatives are only cost reasonable when a PCC pavement NPV cost is used.

The summary provided in Table 20 shows if an alternative meets acoustic feasibility requirements, cost-reasonableness requirements, and the design goals for the southbound side when considering the MassDOT, MDOT, and WSDOT criteria. The MassDOT cost-effectiveness index was calculated for each alternative, except for the RAC(O) and ground PCC without barriers. A review of the cost-reasonableness data shows that all alternatives except ground PCC without barriers meet the three agencies' criteria but the RT PCC with 12 ft barriers only meets the criteria when the noise reduction is compared to the RT PCC without barriers. Similar results were obtained for feasibility with the ground PCC without barriers being the only alternative that did not meet the criteria. The RAC(O) without barriers did not achieve the 5 dB threshold when applied to 75% of the impacted receptors (MDOT criteria). Considering effectiveness and cost difference, the HMA with 12 ft barriers, the RAC(O) with 8 ft barriers, and the LT PCC with 12 ft barriers were nearly equal to the HMA baseline but have a slight cost advantage. As all alternatives met the feasible and reasonable criteria, other criteria will be used to select the preferred alternative.

Because of the smaller number of impacted and benefited receptors, the cost-reasonableness considerations for the northbound side are somewhat different from that for the southbound side; a summary of the results is given in Table 21. Under the MDOT criteria, none of the alternatives are cost reasonable, but the HMA with 12 ft barriers, the RAC(O) with 8 ft barriers, and the LT PCC with 12 ft barriers meet the feasibility and cost-reasonableness criteria under the MassDOT and WSDOT criteria.

This example case illustrates another feature in noise abatement analysis when quieter pavements are used. If the RAC(O) with 8 ft barriers was selected for the southbound side, it would benefit seven more receptors on the northbound side even without the barrier on that side because of the quieter pavement. Therefore, when considering MDOT criteria, the combined alternative of RAC(O) with an 8 ft barrier on the southbound and no barrier on the northbound side would become cost reasonable for both sides with some amount of noise reduction provided to the impacted receptors on the northbound side. Also, this combined alternative would be acoustically feasible and meet the goal of one receptor receiving a 10 dB reduction and 75% of the receptors receiving 7 dB reductions. When considering the other states' criteria, this combined alternative also may have merit because the RAC(O) without a barrier was also an acoustically feasible alternative. This combined alternative would provide cost savings of about $510,000 to $730,000 compared to the alternatives with barriers on both sides.

Table 20. Assessment of alternatives under different criteria for Example 3 (southbound side).

Pavement Type and Barrier Height	MassDOT			MDOT			WSDOT			Effectiveness (dB)	Cost Difference ($000) Relative to	
	Feasible	Cost Reasonable	Design Goal	Feasible	Cost Reasonable	Design Goal	Feasible	Cost Reasonable	Design Goal		HMA	PCC
HMA + 10 ft	Y	Y	N	Y	Y	N	Y	Y	Y	3	291	
HMA + 12 ft	Y	Y	Y	Y	Y	Y	Y	Y	Y	1	419	
RAC(O)	Y		N	N	Y	N	Y	Y	N	6	0	
RAC(O) + 8 ft	Y	Y	Y	Y	Y	Y	Y	Y	Y	1	510	
LT PCC 12 ft	Y	Y	Y	Y	Y	Y	Y	Y	Y	0	632	474
Ground PCC	N		N	N	N	N	N	N	N	8	158	0
Ground PCC + 8 ft	Y	Y	N	Y	Y	N	Y	Y	Y	3	668	510
RT PCC + 12 ft	Y[1]	Y[1]	Y[1]	Y[1]	Y	Y[1]	Y[1]	Y	Y[1]	5	632	474
9-yr RAC(O) + 8 ft	Y	Y	N	Y	Y	N	Y	Y	Y	3	510	
20-yr LT PCC + 12 ft	Y	Y	N	Y	Y	N	Y	Y	Y	2	632	474

[1] Relative to RT PCC baseline only, not for HMA or LT PCC

Table 21. Assessment of alternatives under MassDOT, MDOT, and WSDOT policies for Example 3 (northbound side).

Pavement Type and Barrier Height	MassDOT			MDOT			WSDOT			Effectiveness (dB)	Cost Difference ($000) Relative to	
	Feasible	Cost Reasonable	Design Goal	Feasible	Cost Reasonable	Design Goal	Feasible	Cost Reasonable	Design Goal		HMA	PCC
HMA + 10 ft	Y	N	N	Y	N	N	Y	N	Y	3	291	
HMA + 12 ft	Y	Y	Y	Y	N	Y	Y	Y	Y	1	419	
RAC(O)	Y		N	N	N	N	Y	Y	N	6	0	
RAC(O) + 8 ft	Y	Y	Y	Y	N	Y	Y	Y	Y	1	510	
LT PCC + 12 ft	Y	Y	Y	Y	N	Y	Y	Y[2]	Y	0	632	474
Ground PCC	N		N	N	N	N	N	N	N	8	158	0
Ground PCC + 8 ft	Y	Y	N	Y	N	N	Y	Y[2]	Y	3	668	510
RT PCC + 12 ft	Y[1]	Y[1]	Y[1]	Y[1]	N	Y[1]	Y[1]	Y[2]	Y[1]	5	632	474
9-yr RAC(O) + 8 ft	Y	Y	N	Y	N	N	Y	Y	Y	3	510	
20-yr LT PCC + 12 ft	Y	Y	N	Y	N	N	Y	Y	Y	2	632	474

[1] Relative to RT PCC baseline only, not for HMA or LT PCC
[2] Relative to PCC cost only, not for HMA cost

Summary and Discussion

The preceding examples illustrated the applicability of the methodology for evaluating noise abatement alternatives using barriers, quieter pavement, and combinations of both. It showed that acoustic feasibility for alternatives could be evaluated in a similar manner to that currently used for barriers alone.

For reasonableness, the methodology could be applied considering existing or modified agency criteria. For example, consideration may be given to lowering design goals to the levels achievable by quieter pavement. The concept of effectiveness based on the differences in absolute level from the quietest to noisiest alternatives was also useful in comparing alternatives when considering the economic features and the NPV of the alternatives. Also, acoustic longevity could be included in the analysis with the use of OBSI data as a performance measure at the end of the rehabilitation cycle (or other established appropriate time).

Although the specific cases presented in this chapter demonstrate that the methodology can be used within the context of existing policies, some cases (e.g., use of two barriers) require special attention. In evaluating noise abatement for barriers, currently, each case is considered individually even on two sides of a single pavement section. If receptors on both sides are impacted, it would be appropriate to evaluate them together, particularly when quieter pavement or combinations of barriers and pavement are considered.

CHAPTER 5

State Project-Based Examples

To further illustrate the approach for evaluating barriers and pavement strategies for highway noise abatement, projects from three state highway agencies (California, North Carolina, and Arizona) were analyzed. In each case, the OBSI data used was measured previously by the research team for pavements found in that state. Pavement options representing state practices were considered (these options may have been used in the original agency design and analysis). The TNM models were obtained either from the state agency or their contractors.

Example A: I-580 Lane Addition

The project consists of the addition of high-occupancy vehicle (HOV) lanes to 13.1 mi of the eight-lane I-580 between Dublin and Livermore, California. It was assumed that both eastbound and westbound HOV lanes were to be added as a single project. All eight lanes of the existing pavement are aged PCC with longitudinal tines. The additional lanes will incorporate a portion of the existing shoulder and a newly constructed pavement to provide the added lane and shoulder; the lanes are to be re-striped. The following construction options were considered for the added lane:

1. PCC pavement (as are the existing four lanes in each direction).
2. HMA pavement and overlay of all lanes with a quieter friction course.

The following pavement alternatives were considered for the LCCA:

1. Construct added HOV lanes and shoulders with PCC. The PCC of the added lanes will be longitudinally tined similar to the surface texture of the existing pavement. The existing pavement is in good condition and does not require rehabilitation at this time. Diamond grind all lanes (for noise and other considerations) 10 years after the addition of the HOV lanes and every 20 years thereafter.
2. Construct added HOV lanes and shoulders with PCC and diamond grind all lanes to reduce the tire–pavement noise levels. Diamond grind all lanes on a 20-year cycle thereafter.
3. Construct added HOV lanes and shoulders with PCC and overlay all lanes and shoulders with a 1 in. RAC(O) overlay. Mill the RAC(O) overlay and replace it every 9 years for noise performance.
4. Construct added HOV lanes and shoulders with HMA and overlay all lanes and shoulders with a 1 in. RAC(O) overlay. Mill the RAC(O) overlay and replace it every 9 years for noise performance.
5. Construct added HOV lanes and shoulders with HMA and overlay existing lanes and shoulders with a 5 in. HMA overlay. Mill 2 in. of the HMA overlay and overlay it on a 12-year cycle.

Details of the LCCA for these cases of pavement alternatives (with no barriers) are presented in Appendix F. Table 22 lists the NPV for the five pavement alternatives on a cost-per-mile basis. Only the three alternatives with the lowest NPV were considered for further analysis because they provide acoustically unique alternatives that have the low cost. Alternative 5 (all HMA) is the most expensive; it was not considered further. Alternative 4 [HMA with RAC(O) overlay] was also not considered further because it provides acoustic performance similar to that of Alternative 3, but at a higher cost.

Out of the 13.1 mi project, three smaller segments were considered, each with several potential barrier locations. For each segment, TNM was used to predict traffic noise levels for the three different pavement alternatives. For this analysis, the existing PCC pavement was used as the reference pavement. Alternative 1 (the existing eight lanes and two HOV lanes added with no further modification) provides the lowest cost. Alternative 5 (all HMA) would provide the closest acoustic performance to that of the TNM Average Pavement, but its cost would always be greater than any of the other alternatives. As shown previously in the LCCA for the six-lane example, the

Table 22. Summary of NPV results per mile for Example A.

Alternative		Agency NPV Cost ($000)
No.	Description	
1	Added PCC Lanes Only	3,691
2	Added PCC Lanes—All Lanes Ground	5,060
3	Added PCC Lanes—RAC(O) Overlay	4,668
4	Added HMA Lanes—RAC(O) Overlay	5,353
5	Added HMA Lanes—All HMA	5,466

performance of the LT PCC and TNM Average Pavement was nearly identical, but for this example, the levels for the existing LT PCC pavement are about 1 dB greater than TNM Average Pavement. Barrier and pavement analysis for each of the three segments is presented in this section. The NPV costs are the barrier LCCA costs based on $51.61/ft^2$ (scaled to height and length as needed) plus the pavement NPV costs listed in Table 22. The analysis considers Caltrans policy as of May 2011 as described in the previous examples. The acoustic performance of the LT PCC, ground PCC, and RAC(O) pavement is also the same as that used previously. Barrier heights ranging from 12 to 16 ft were considered because 12 ft was determined to be sufficient to block the line of sight to truck exhaust stacks and 16 ft is generally the maximum allowed height.

Segment 1 Cases

Segment 1 is the 1 mi section located between the freeway intersections at 1st Street and Vasco Road as shown in Figure 20. In this segment, five barriers were analyzed. Three of these barriers—SWWB6, SWEB9, and SWEB10—are new, and two are existing barriers to which height would be added to reduce noise levels at sensitive receptors to levels below the NAC. Existing barriers SWWB7 and SWWB8 are 14 ft and 12 ft high, respectively. These barriers shield two relatively densely built-up subdivisions; the other proposed barriers would shield fewer receptors (Table 23).

Source: Google Earth © 2011 Google

Figure 20. Aerial photograph of Segment 1 of an HOV lane addition project on I-580 near Livermore, California.

Results of the feasibility, reasonableness, effectiveness, and cost analyses are summarized in Table 24 for the SWWB6 barrier. The predicted levels for the existing baseline PCC pavement range from below the Caltrans NAC of 66 dBA to 80 dBA. Of 23 identified impacted receptors, 12 would be at the 80 dBA level. For this case, all three alternatives with barriers meet the feasible and reasonable criteria and are nearly equal in terms of effectiveness with only 1 dB difference among them. With respect to cost, the PCC with 14 ft barrier and RAC(O) with 12 ft barrier are quite close ($10,000 difference), while the ground PCC with 12 ft barrier is more than $100,000 higher than either of the other two. The user NPV for either of the two PCC with barrier alternatives is significantly lower than the RAC(O) alternative (see Appendix G), which could be a consideration in alternative selection. The two quieter pavement options without barriers [ground PCC and RAC(O)] do not provide enough reduction to meet the 5 dB acoustic feasibility criterion [RAC(O) provides reductions of up to 4 dB].

Summaries of the analysis results for the SWWB7 and SWWB8 barriers are shown in Tables 25 and 26, respectively.

The results of these cases are similar with none of the alternatives found to meet the feasibility requirements, cost-reasonableness requirements, or the design goal. In these cases, increasing the barrier height to the maximum height of 16 ft was considered, but it increased the insertion loss of only 1 dB to 2 dB and increased noise reduction when combined with quieter pavements by 1 to 4 dB. The higher existing barrier SWWB7 together with the quieter pavements produced reductions of no more than 1 dB while the reductions for the SWWB8 were 2 to 3 dB.

The analyses for the SWEB9 and SWEB10 barriers were essentially the same as shown in Tables 27 and 28, respectively. For these cases, the alternatives with barriers produced feasible reductions and achieved the design goal, except for the PCC with 14 ft SWEB10 barrier. However, with only two receptors in each case, sufficient allowance was not generated to allow any of the alternatives to be cost reasonable. For the

Table 23. Description and properties of proposed barriers for Example A.

Barrier Designation	Current Height (ft)	Proposed Height (ft)		Length (ft)	No. of Impacted Receptors
		LT PCC	Grd PCC/ RAC(O)		
SWWB6	0	14	12	800	23
SWWB7	14	16	16	1,375	38
SWWB8	12	16	16	2,150	31
SWEB9	0	14	12	800	2
SWEB10	0	14	12	1,100	2

Table 24. Summary of analysis results for the SWWB6 barrier.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Range (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	65–80	0	559	–	–				14
PCC + 14 ft	17	62–67	1–13	1,206	646	935	Y	Y	Y	1
PCC + Grinding	0	63–77	2–3	767	207	–	N	N	N	11
PCC + Grinding + 12 ft	18	60–66	3–14	1,321	761	990	Y	Y	Y	0
PCC + RAC(O)	0	62–76	3–4	707	148	–	N	N	N	10
PCC + RAC(O) + 12 ft	18	59–66	3–12	1,216	656	990	Y	Y	Y	0

quieter pavement alternatives, 3 and 4 dB reductions were predicted. However, these reductions do not meet feasibility requirements and, therefore, do not generate allowances.

Considering the entire segment, the use of the quieter RAC(O) pavement along the entire 1 mi distance between interchanges would produce reductions of 1 to 4 dB that would likely be noticeable at some of the receptor locations. However, it would increase the NPV of the project by about $1,000,000 in comparison with the existing PCC alternative (see Table 22) and does not appear to be a reasonable cost. However, if some form of rehabilitation of the existing pavement (e.g., grinding) was considered as part of the overall project, the RAC(O) alternative would produce slightly lower noise levels with an NPV savings of about $400,000.

Segment 2 Cases

The second segment extends from the newly built intersection with Isabel Avenue to just east of Portola Avenue as shown in Figure 21. Two barrier options SWEB6 and SWEB7

Table 25. Summary of analysis results for the existing 14 ft barrier SWWB7.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Range (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC + 0 ft	0	63–68	0	961	–	–				1
PCC + 2 ft	0	63–67	0–1	1,120	159	–	N	N	N	0
PCC + Grinding	0	63–68	0–1	1,318	357	–	N	N	N	1
PCC + Grinding + 12 ft	0	63–68	0–2	1,476	515	–	N	N	N	1
PCC + RAC(O) + 0 ft	0	63–67	0–1	1,216	254	–	N	N	N	0
PCC + RAC(O) + 2 ft	0	62–67	1–2	1,374	413	–	N	N	N	0

Table 26. Summary of analysis results for the existing 12 ft barrier SWWB8.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Range (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC + 0 ft	0	63–70	0	1,503	–	–				3
PCC + 4 ft	0	61–67	1–4	1,999	496	–	N	N	N	0
PCC + Grinding + 0 ft	0	62–69	1–2	2,060	557	–	N	N	N	2
PCC + Grinding + 4 ft	0	61–67	1–4	2,557	1,054	–	N	N	N	0
PCC + RAC(O) + 0 ft	0	61–68	1–3	1,901	398	–	N	N	N	1
PCC + RAC(O) + 4 ft	0	61–67	1–4	2,397	894	–	N	N	N	0

Table 27. Summary of analysis results for the SWEB9 barrier.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Range (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	77–80	0	559	–	–				16
PCC + 14 ft	2	71	6–9	1,206	646	110	Y	N	Y	3
PCC + Grinding	0	74–77	3	767	207	–	N	N	N	9
PCC + Grinding + 12 ft	2	69	8–11	1,321	761	110	Y	N	Y	1
PCC + RAC(O)	0	73–76	4	707	148	–	N	N	N	8
PCC + RAC(O) + 12 ft	2	68	9–12	1,261	702	110	Y	N	Y	0

Table 28. Summary of analysis results for the SWEB10 barrier.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Range (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	74	0	769	–	–				16
PCC + 14 ft	2	68–69	5–6	1,658	889	110	Y	N	N	3
PCC + Grinding	0	71	3	1,054	285	–	N	N	N	9
PCC + Grinding + 12 ft	2	67–68	7–8	1,816	1,047	110	Y	N	Y	1
PCC + RAC(O)	0	70	4	973	204	–	N	N	N	8
PCC + RAC(O) + 12 ft	2	64–65	9–10	1,861	1,092	110	Y	N	Y	0

Source: Google Earth © 2011 Google

Figure 21. Aerial photograph of Segment 2 of an HOV lane addition project on I-580 near Livermore, California.

Table 29. Description and properties of proposed barriers for Segment 2.

Barrier Designation	Current Height (ft)	Proposed Height (ft)		Length (ft)	No. of Impacted Receptors
		LT PCC	Grd PCC/ RAC(O)		
SWEB6	0	14	12	4,875	62
SWEB6p	0	14	12	2,200	60
SWEB7	0	14	12	1,375	15

were analyzed. The SWEB6 barrier is proposed in two lengths: 4,875 ft (the full barrier) and 2,200 ft (the partial barrier designated "SWEB6p"). The full barrier shields only an additional 2 residences beyond the 60 shielded by the partial barrier. The level predicted for these two receptors is about 69 dBA, which is above the Caltrans NAC. The second barrier, SWEB7, would shield 15 multi-family residential impacted receptors. Details of these barriers are given in Table 29.

A summary of the analysis results for the SWEB6 barrier is provided in Table 30. The predicted levels for the receptors range from 66 to 78 dBA (i.e., at the Caltrans threshold for impact to 12 dB above it). All of the alternatives, except the PCC with grinding only option, provide an acoustically feasible noise reduction. Of these alternatives, only RAC(O) without a barrier is cost reasonable, but it does not meet the 7 dB design criterion. If Caltrans's criteria are applied, none of these alternatives would be considered further.

A summary of the results for the partial length SWEB6 barrier is provided in Table 31. These results indicate that all alternatives with the barrier are cost reasonable and meet the design criterion and that the RAC(O) with 12 ft barrier is most effective (by 1 or 2 dB).

To provide some benefit to the two receptors that do not benefit from the SWEB6p barrier, a combined alternative may be considered that uses the RAC(O) with 12 ft high SWEB6p and the RAC(O)-only alternative for the remaining 2,675 ft that the full SWEB6 barrier would cover if used. The two receptors would both receive acoustically feasible reductions of 5 and 6 dB that qualify for cost allowance. The NPV for extending the RAC(O) would be $495,000; the total NPV cost for abatement would be $2,680,000 [$2,185,000 for the RAC(O) with a partial length, 12 ft high SWEB6p barrier and $495,000 for extending the RAC(O)]. However, the combined allowance for this alternative would be $3,410,000 (62 benefited receptors). Thus, this alternative would be feasible and cost reasonable, meet the design criteria, and provide a more

Table 30. Summary of analysis results for the SWEB6 barrier (full length).

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Range (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	66–78		3,408	–	–				12
PCC + 14 ft	49	61–68	4–11	7,347	3,939	2,695	Y	N	Y	1
PCC + Grinding	0	63–74	2–4	4,672	1,264	–	N	N	N	8
PCC + Grinding + 12 ft	62	60–67	5–11	8,048	4,640	3,410	Y	N	Y	1
PCC + RAC(O)	47	63–72	3–6	4,310	902	2,585	Y	Y	N	6
PCC + RAC(O) + 12 ft	62	59–66	6–12	7,686	4,278	3,410	Y	N	Y	0

Table 31. Summary of analysis results for the SWEB6p barrier (partial length).

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Range (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	66–78		1,538	–	–				12
PCC + 14 ft	49	61–68	4–11	3,315	1,778	2,695	Y	Y	Y	2
PCC + Grinding	0	63–74	2–4	2,108	570	–	N	N	N	8
PCC + Grinding + 12 ft	60	60–67	5–11	3,886	2,348	3,300	Y	Y	Y	1
PCC + RAC(O)	47	63–72	3–6	1,945	407	2,585	Y	Y	N	6
PCC + RAC(O) + 12 ft	60	59–66	6–12	3,723	2,185	3,300	Y	Y	Y	0

Table 32. Summary of analysis results for the SWEB7 barrier.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Range (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	69		961	–	–				9
PCC + 14 ft	15	63	6	1,913	952	825	Y	N	N	3
PCC + Grinding	0	65–66	3–4	1,318	357	–	N	N	N	6
PCC + Grinding + 12 ft	15	60–61	8–9	2,270	1,309	825	Y	N	Y	1
PCC + RAC(O)	15	64	5	1,216	254	825	Y	Y	N	4
PCC + RAC(O) + 12 ft	15	59–60	3–12	2,168	1,207	825	Y	N	Y	0

effective solution for at least two more receptors in addition to those benefiting from the partial version of SWEB6.

A summary of the analysis results for the SWEB7 barrier is presented in Table 32. As in the case of the full version of SWEB6, SWEB7 is acoustically feasible for all alternatives except the ground PCC without a barrier but attained reasonable cost only for RAC(O) without a barrier. Thus, none of the alternatives meet all the criteria and no abatement would be considered. If the 7 dB design goal requirement is not considered, only the RAC(O) meets the other feasible and reasonable criteria.

As in the previous barrier case, a hybrid alternative can be considered for SWEB7. This alternative uses RAC(O) from the western end of the SWEB6 barrier to the eastern end of SWEB7 (a total distance of 6,450 ft). The total NPV would be $1,392,000 [composed of the NPV of the additional 200 ft of RAC(O), the NPV for the RAC(O)-only alternative in the SWBE7 analysis, and the NPV for the SWBE7 barrier], compared to the original $1,207,000. Thus, the NPV cost of the additional abatement would be $185,000, and the total NPV cost of abatement for this second hybrid case would be $2,865,000 [$2,680,000 for abatement for the first hybrid alternative and $185,000 for additional RAC(O) from the end of SWEB6 to SWEB7].

The allowance for the 77 benefited receptors would be $4,235,000. As before, this second hybrid alternative is feasible and cost reasonable, meets the design criteria, and provides a more effective solution for 17 more receptors in areas where barriers were not reasonable. It also provides the most effective alternative for those shielded by the partial version of SWEB6.

Segment 3 Cases

The third segment considered extends from the Vasco Road overpass for about 0.5 mi to the east and is shown in Figure 22. In this segment, three barriers are proposed: two barriers on

Source: Google Earth © 2011 Google

Figure 22. Aerial photograph of Segment 3.

Table 33. Description and properties of proposed barriers for Segment 3.

Barrier Designation	Current Height (ft)	Proposed Height (ft) LT PCC	Proposed Height (ft) Grd PCC/ RAC(O)	Length (ft)	No. of Impacted Receptors
SWWB10	0	12	12	800	4
SWWB11	0*	14	12	900	13
SWEB11	0	12	12	900	16

*Excludes existing subdivision sound walls near residences

the westbound side, SWWB10 and SWWB11, and one barrier on the eastbound side, SWEB11. Because the existing subdivision barriers provide some noise reduction resulting in levels slightly below the NAC threshold, the residences shielded by the SWWB11 barrier do not count as impacted receptors. SWWB11 is actually proposed because a nearby park is currently not shielded and receives a predicted level of 78 dBA. However, some of the alternatives considered produce enough noise reduction to result in benefit to some of the residential receptors. Information on the proposed barriers is provided in Table 33.

A summary of analysis results for Barrier SWWB10 is provided in Table 34. Without a barrier, the traffic noise levels are predicted to range from 68 to 77 dBA, or 2 to 11 dB above the NAC. As in some of the other cases, all abatement alternatives are acoustically feasible except for the ground PCC without a barrier, and only the RAC(O) without a barrier is reasonable for cost. Therefore, none of these alternatives would be considered and no abatement is proposed.

Without SWWB11, the predicted levels range up to 78 dBA. As shown in Table 35, the three alternatives that include barriers are acoustically feasible and meet the design goal of 7 dB but only the ground PCC with a 12 ft barrier and the RAC(O) with a 12 ft barrier are reasonable for cost.

The 14 ft barrier used with the existing PCC is not cost reasonable because of the low number of benefited receptors. A 16 ft barrier was also analyzed for this alternative and found not to benefit any more receptors. Thus, only two 12 ft barriers with either of the quieter pavements meet the feasible and reasonable criteria. These two alternatives are nearly equal in effectiveness and NPV for abatement with the RAC(O) with a 12 ft barrier alternative having a small advantage.

The summary of the analysis results for Barrier SWEB11, provided in Table 36, indicates levels for the existing pavement (without any barrier) ranging from 69 to 81 dBA or 3

Table 34. Summary of analysis results for the SWWB10 barrier.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Range (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	68–77	0	559	–	–				13
PCC + 12 ft	3	66–68	2–9	1,113	554	165	Y	N	Y	4
PCC + Grinding	0	65–74	3	767	207	–	N	N	N	10
PCC + Grinding + 12 ft	4	63–67	5–10	1,321	761	220	Y	N	Y	3
PCC + RAC(O)	4	62–71	6	707	148	220	Y	Y	N	7
PCC + RAC(O) + 12 ft	4	62–64	5–13	1,261	632	220	Y	N	Y	0

Table 35. Summary of analysis results for the SWWB11 barrier.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Range (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	64–78	0	629	–	–				9
PCC + 14 ft	3	61–70	3–8	1,356	727	165	Y	N	Y	3
PCC + Grinding	0	62–75	2–3	863	233	–	N	N	N	8
PCC + Grinding + 12 ft	20	59–68	4–10	1,486	857	1,100	Y	Y	Y	1
PCC + RAC(O)	0	61–74	2–4	796	167	–	N	N	N	7
PCC + RAC(O) + 12 ft	20	59–67	4–11	1,419	790	1,100	Y	Y	Y	0

Table 36. Summary of analysis results for the SWEB11 barrier.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Range (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	69–81	0	629	–	–				12
PCC + 12 ft	10	66–71	3–10	1,252	623	550	Y	Y	Y	2
PCC + Grinding	0	67–79	2	863	233	–	N	N	N	10
PCC + Grinding + 12 ft	16	64–69	5–12	1,486	857	880	Y	Y	Y	0
PCC + RAC(O)	6	65–76	4–5	796	167	330	Y	Y	N	7
PCC + RAC(O) + 12 ft	16	62–69	7–12	1,419	790	880	Y	Y	Y	0

to 15 dB above the NAC. Also, all three alternatives with a barrier meet the feasible and reasonable criteria. Another consideration is using one of the two viable options for SWWB11 that include a quieter pavement (Table 35) directly opposite the SWEB11 barrier. In this case, the addition of the SWEB11 barrier would increase the abatement NPV by only $623,000 as the cost of the quieter pavement is already included in the SWWB11 barrier cost.

An additional benefit for some receptors would be achieved by extending the SWWB10 barrier to the east end of the SWEB11 barrier for a total pavement length of 2,275 ft. In this case, the total abatement cost would be $1,667,000 [$421,000 for the cost of the RAC(O) plus $623,000 for each of the two 12 ft barriers SWWB11 and SWEB11].

The allowance for the total 40 benefited receptors would be $2,200,000. This hybrid alternative is feasible and cost reasonable, meets the design criteria, provides benefit for four more receptors in the area, and is the most effective alternative for those shielded by the SWWB11 and SWEB11 barriers.

Observations from California Lane Addition (Example A) Cases

Several observations can be made from the cases examined in Example A for the HOV lane addition. For the six-lane idealized LCCA cases, quieter pavement alone was found not to meet a design goal of 7 dB. Noise reductions meeting acoustic feasibility requirements of 5 to 6 dB were achieved sometimes, but typical reductions were on the order of 3 to 4 dB. Additions to existing barriers were found not to be feasible or reasonable for all the considered cases even when height was extended to the maximum of 16 ft. Quieter pavements combined with low-height barriers were found to be effective at reducing noise by 1 to 3 dB. Finally, combining quieter pavement with individual barrier alternatives can provide feasible and reasonable noise reduction for highway segments where individual barriers alone would not be feasible and reasonable. Such hybrid solutions were also found in some cases to result in reduced cost and provide lower noise levels for more receptors.

Example B: Lane Addition Projects on I-40 and I-485

Two more example case studies were developed based on highway widening projects in North Carolina. For these examples, a variety of different pavement types and textures were considered: transversely tined PCC, S9.5 HMA, and diamond grind. The OBSI one-third octave spectra for these pavements are shown in Figure 23 (OBSI testing was conducted in North Carolina in September 2010 using the SRTT (*64*). The range of levels for these pavements is sufficient to identify quieter and noisier options for potential use in this project. LCCA was completed for each of these projects using construction costs supplied by the North Carolina DOT (NCDOT); the results are summarized in this section (details are provided in Appendix H). The TNM results were generated using models supplied by NCDOT but re-run with the specific OBSI adjustments as done in the previous examples.

The results of abatement analysis for each case were compared to NCDOT criteria (*65*) except in examination of cost reasonableness. NCDOT uses a threshold level for noise impact of 66 dBA approaching the federal NAC of 67 dBA. Acoustically feasible options must achieve a noise reduction of 5 dB for at least one impacted receptor. Benefited receptors for use in reasonableness determination are receptors that receive a reduction of 5 dB regardless of impact determination. The design goal is 7 dB for at least one front row receptor. NCDOT cost reasonableness is calculated on an allowed square foot of barrier area per benefited receptor up to a maximum of 2,500 ft^2 per each receptor. Similar to the MassDOT policy, this method of determining reasonableness cannot be directly applied in the LCCA in which the cost of

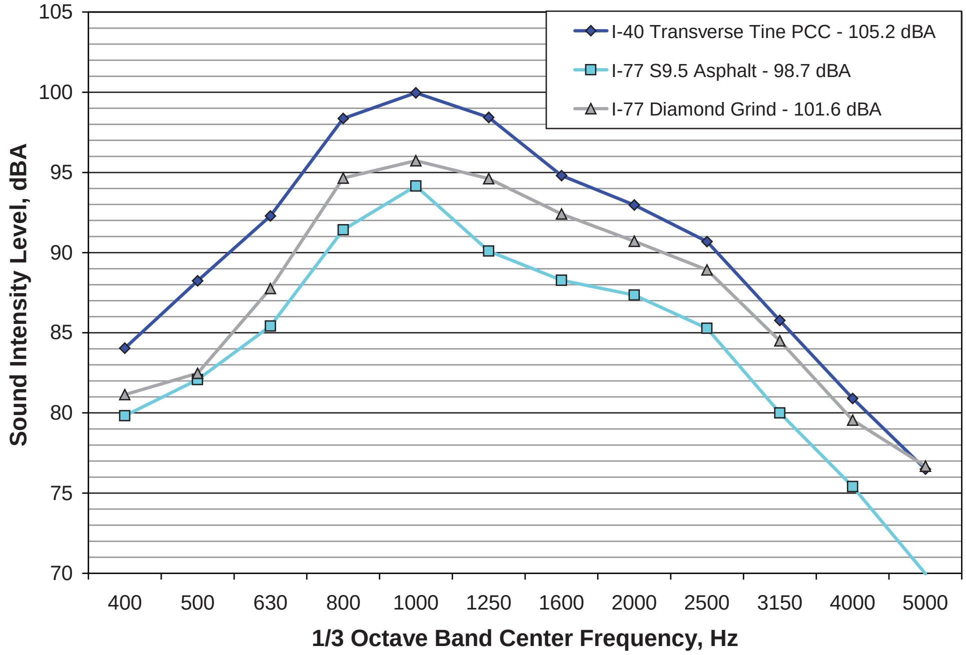


Figure 23. SRTT OBSI one-third octave band spectra for pavements used in Example B.

barriers is combined with and compared to pavement costs. An average barrier cost of $35/ft^2 and allowance of $37,500 per benefited receptor was used for this analysis.

I-40 Widening Project

The existing highway on I-40 near Raleigh has three lanes of travel in both directions and is constructed of PCC with a semi-random transversely tined texture. In this project, two additional travel lanes are to be added in the median, one in each direction of travel. The project includes the new lanes of travel and new shoulders on the median. Barriers NSA02 SB and NSA02 NB were proposed along the south and north sides of the highway, respectively, to shield primarily residential receptors. An aerial photograph of the project showing the receptors and proposed barrier locations is shown in Figure 24. Another barrier, NSA01, along a two-lane ramp that connects westbound I-40 to eastbound I-440 was evaluated as part of the project (Figure 25). Although this ramp was not altered in the project, a barrier to shield residences to the east and south of the ramp was considered.

For the widening project, the following three scenarios were considered:

1. Construction of new lanes and shoulders with PCC (transversely tined); future rehabilitation includes diamond grinding of all lanes on a 20-year cycle.
2. Construction of new lanes and shoulders with PCC, which is then diamond ground together with the existing lanes; future rehabilitation includes diamond grinding of all lanes on a 20-year cycle.
3. Construction of new lanes and shoulders with PCC and overlay of all lanes with 1 in. S9.5 mm HMA; future rehabilitation includes mill and overlay all lanes with 1 in. S9.5 mm HMA every 9 years.

Source: Google Earth © 2011 Google

Figure 24. Location of barriers on I-40 highway widening project near Raleigh, North Carolina.

Source: Google Earth © 2011 Google

Figure 25. Location of barriers for widening project on I-40 to I-440 ramp near Raleigh, North Carolina.

A summary of the costs for these options is provided in Table 37 and details of the barriers and abatement alternatives considered for the eastbound and westbound directions are given in Table 38. Details of the LCCA are provided in Appendix G.

NSA02 SB Barrier

Considering the existing transversely tined PCC as the baseline pavement, the information needed to evaluate feasibility, reasonableness, effectiveness, and costs of the NSA02 SB barrier are presented in Table 39. For this case, all of the alternatives, except for the ground PCC without a barrier, produce a feasible reduction of 5 dB or more in noise level.

To assess cost reasonableness, a $525/dB increase over the existing, current level (typically, 2 dB) per impacted receptor was added to the allowance generated by the number of benefited receptors times $37,500 (according to the NCDOT policy). In this manner, cost reasonableness was confirmed for four alternatives: PCC with a 16 ft barrier, ground PCC with a 12 ft barrier, S9.5 HMA with no barrier, and S9.5 HMA

Table 37. Summary of NPV results for I-40 lane additions.

Alternative		Agency NPV Cost ($000)
No.	Description	
1	Added PCC Lane Only	4,186
2	Added PCC Lane—All Lanes Ground	5,427
3	Added PCC Lane—S9.5 HMA Overlay	5,942

Table 38. Description and properties of proposed barriers for different pavement alternatives for I-40 lane additions.

Barrier Designation	Current Height (ft)	Proposed Height (ft)		Length (ft)	No. of Impacted Receptors
		Trans. Tine PCC	Grd PCC/ S9.5 HMA		
NSA02 SB	0	14 & 16	12	1,553	43
NSA02 NB	0	14 & 16	12	3,738	52

with a 12 ft barrier. For the existing PCC with 14 ft barrier alternative, the added height over the 12 ft barriers used for the quieter pavements does not result in a sufficient number of benefited receptors to generate the required allowance.

Only the alternatives with barriers meet the design goal reductions of 7 dB or more although the S9.5 HMA without a barrier provides reductions of up to 6 dB.

The maximum and average levels for each alternative are shown in Table 39. For this example, effectiveness in Table 39 refers to the maximum predicted levels relative to the lowest maximum level. Three alternatives meet all of the criteria: ground PCC with a 12 ft barrier, S9.5 HMA with a 12 ft barrier, and the existing PCC with a 16 ft barrier. Of these alternatives, the S9.5 HMA with a 12 ft barrier is 3 dB more effective than the ground PCC with a 12 ft barrier and 6 dB more effective than the PCC with a 16 ft barrier. The S9.5 HMA with a 12 ft barrier produces about twice the benefited receptors as any other option. However, the NPV for the S9.5 HMA with a 12 ft barrier alternative is higher than the NPV for ground PCC with a 12 ft barrier and the PCC with a 16 ft barrier by $151,000 and $273,000, respectively.

NSA02 NB Barrier

Results of the analysis for the NSA02 NB barrier are shown in Table 40. All of the alternatives, except for the ground PCC without a barrier, are acoustically feasible and all alternatives with barriers, except the PCC with a 14 ft barrier, meet the criterion for cost reasonableness. The S9.5 HMA without a barrier is under the allowance and is cost reasonable, but it does not meet the design goal requirement. The S9.5 HMA with the 12 ft barrier is most effective by 3 dB or more but it has the highest NPV cost.

Quieter Pavements with Barrier(s)

In considering the alternatives that use quieter pavements in combination with both barriers—the ground PCC and the S9.5 HMA with 12 ft barriers—the cost of the quieter pavement is common to both barrier alternatives. To analyze these alternatives, the cost of the pavement for the greatest length (3,738 ft for the NSA02 NB barrier) is added to the cost of the two barriers to produce the NPVs shown in Table 41.

Table 39. Summary of analysis results for the NSA02 SB barrier.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Max / Avg (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	77/67	0	1,231	–	–				9
PCC + 14 ft	21	74/64	3–9	2,082	851	810	Y	N	Y	6
PCC + 16 ft	29	74/63	4–11	2,203	972	1,110	Y	Y	Y	6
PCC + Grinding	0	74/64	3	1,596	365	–	N	N	N	6
PCC + Grinding + 12 ft	38	71/62	5–10	2,325	1,094	1,448	Y	Y	Y	3
PCC + S9.5 HMA	35	71/62	4–6	1,747	516	1,335	Y	Y	N	3
PCC + S9.5 HMA + 12 ft	70	68/60	7–12	2,476	1,245	2,648	Y	Y	Y	0

Table 40. Summary of analysis results for the NSA02 NB barrier.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Max / Avg (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	76/66	0	2,962	–	–				11
PCC + 14 ft	51	70/61	5–10	5,010	2,048	1,940	Y	N	Y	5
PCC + 16 ft	62	70/60	5–11	5,303	2,340	2,352	Y	Y	Y	5
PCC + Grinding	0	73/64	2–3	3,841	878	–	N	N	N	8
PCC + Grinding + 12 ft	90	68/59	7–11	5,596	2,633	3,402	Y	Y	Y	3
PCC + S9.5 HMA	33	70/61	4–5	4,205	1,243	1,265	Y	Y	N	5
PCC + S9.5 HMA + 12 ft	98	65/58	8–12	5,960	2,998	3,702	Y	Y	Y	0

Table 41. Cost and allowance results for analysis of combined pavement and barrier alternatives considering both sides of the highway.

Abatement	Abatement NPV Costs ($000)			Benefited Receptors		
	PPC + 16 ft	Grd PCC + 12 ft	S9.5 HMA + 12 ft	PPC + 16 ft	Grd PCC + 12 ft	S9.5 HMA + 12 ft
Pavement	–	878	1,243			
Barrier NSA02 SB	972	729	729	29	38	70
Barrier NSA02 NB	2,340	1,755	1,755	62	90	98
Total	**3,312**	**3,362**	**3,727**	**91**	**128**	**168**
Cost/Benefited Receptor	36	26	22			

These costs account for the barriers and the pavement (with the quieter pavement included only once) as it affects receptors on both sides of the highway. The total NPV cost for the alternatives using ground PCC and S9.5 HMA are close to the NPV of the PCC with 16 ft barriers. For the S9.5 HMA with 12 ft barriers, the combined NPV costs from Tables 39 and 40 are $4,243,000 compared to $3,727,000 in Table 41. The total number of benefited receptors for the PCC, ground PCC, and S9.5 HMA alternatives is determined from the numbers reported in Tables 39 and 40; the results are shown in Table 41. Therefore, the cost per benefited receptor is lowest for the S9.5 HMA with 12 ft barriers. Consideration of the cost per benefited receptor may be useful in comparing abatement alternatives that have relatively close NPV costs and noise reduction performance.

Another alternative to consider would be building the NSA02 NB barrier and using the S9.5 HMA pavement without the NSA02 SB barrier. The S9.5 HMA without a barrier will produce 35 benefited receptors (Table 39) and the NSA02 NB barrier will produce another 98 for a total of 133 benefited receptors for a total cost of $2,998,000 ($1,243,000 + $1,755,000). This alternative meets all criteria, has the lowest NPV, and has a cost per benefited receptor of $23,000.

NSA01 Barrier

For the NSA01 barrier (located along the ramp between I-40 and I-440), the NPV costs reflect only the cost of noise abatement as the existing pavement is considered the baseline. The NPV costs for the pavement options, shown in Table 42, consider the future rehabilitation cycle. Two barrier heights (10 and 12 ft), each 1,500 ft long, were considered for this segment. The existing PCC pavement with barrier heights of 10 and 12 ft and the ground PCC with a 12 ft high barrier were evaluated. For the S9.5 HMA, no barriers were evaluated as the levels with this pavement did not produce any impacted receptors. Barrier options were considered for the existing PCC pavement to shield 10 impacted residential receptors and for the ground PCC pavement to shield 3 impacted receptors.

Table 42. Summary of NPV results for pavements on the North Carolina I-40/I-440 ramp.

Alternative		Agency NPV Cost ($000)
No.	Description	
1	Retain Existing PCC (later rehabs)	346
2	PCC—All Lanes Ground	1,105
3	All Lanes 1 in. S9.5 HMA Overlay	876

The results of the analysis for various alternatives are shown in Table 43. All options except the ground PCC without a barrier are acoustically feasible, but only the S9.5 HMA and ground PCC with a 12 ft barrier are reasonable for cost. The ground PCC with a 12 ft barrier alternative achieves the design goal of a 7 dB reduction; the S9.5 HMA pavement does not. However, there are no noise impacts associated with the S9.5 HMA pavement. At a higher cost, the ground PCC with the 12 ft barrier is the most effective alternative in terms of level and number of benefited receptors, and the lowest cost per benefited receptor at $28,750. The S9.5 HMA without a barrier is the second most effective alternative and produces the second highest number of benefited receptors.

I-485 Widening Project

This case study involves the expansion of an Interstate in North Carolina from four lanes of travel and auxiliary lanes into six lanes of travel. As in the previous case, the new travel lanes will be added to the median on existing shoulders with new shoulders to be added to the inside. The existing roadway is an aged HMA. However, this case study will consider the existing pavement and an assumed existing old PCC pavement with transverse texture. An aerial photograph of the project area is shown in Figure 26 with the location of a proposed single barrier on the east of the highway.

Table 43. Summary of analysis results for the NSA01 barrier of the I-40/I-440 ramp.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Max / Avg (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	70/59	0	98	–	–				8
PCC + 10 ft	12	67/57	2–8	685	587	455	Y	N	Y	5
PCC + 12 ft	15	65/56	2–9	803	705	568	Y	N	Y	3
PCC + Grinding	0	67/57	2–4	314	216	–	N	N	N	5
PCC + Grinding + 12 ft	32	62/54	4–12	1,018	920	1,205	Y	Y	Y	0
PCC + S9.5 HMA	23	64/56	3–6	876	778	868	Y	Y	N	2

Source: Google Earth © 2011 Google

Figure 26. Location of barrier for widening project on I-485 near Charlotte, North Carolina.

For the project, the following five pavement alternatives are considered (two for the existing HMA and three for the assumed PCC pavement):

1. HMA—Construct new lanes and shoulders with HMA. Future rehabilitation includes mill and overlay of all lanes with 1.5 in. of HMA every 12 years.
2. HMA—Construct new lanes and shoulders with HMA and overlay all lanes with 1 in. S9.5 mm wearing surface. The wearing surface will be milled and replaced every 9 years to provide noise performance.
3. PCC—Construct new lanes with PCC (transversely tined) and the shoulders with HMA. Future rehabilitation includes mill and overlay of right two lanes with 1.5 in. of HMA every 12 years and diamond grinding of the left lane on a 20-year cycle.

Table 44. NPV results for North Carolina I-485 lane additions.

Alternative		Agency NPV Cost ($000)
No.	Description	
1	Added HMA Lanes Only	4,035
2	Added HMA Lanes—1 in. S9.5 Overlay	5,080
3	Added PCC Lanes Only	5,093
4	Added PCC Lanes—1.5 in. HMA Overlay	5,884
5	Added PCC Lanes—1 in. S9.5 Overlay	6,197

Table 45. Proposed barriers for North Carolina I-485 lane additions.

Barrier Designation	Barrier Height (ft)	Barrier Length (ft)	Barrier Area (ft^2)	No of Impacted Receptors
25 ft Constant	25	2,698	67,455	HMA - 17
Varied Height	Varies	2,698	36,538	PCC - 31

4. PCC—Construct new lanes with PCC and the shoulders with HMA, and overlay all lanes with 1.5 inches of HMA. Future rehabilitation includes mill and overlay all lanes with 1.5 inches of HMA every 12 years.
5. PCC—Construct new lane with PCC and the shoulder with HMA, and overlay all lanes with S9.5 mm wearing surface. The wearing surface is milled and replaced every 9 years for noise performance.

An LCCA was performed for these pavements (details are provided in Appendix G) and a summary of the estimated NPV costs are presented in Table 44. The acoustic performance of the 1.5 in. HMA overlay and the existing HMA pavement was assumed to be that of TNM Average Pavement.

HMA pavement noise levels were measured on NC State Route 268. Two barrier designs of the same length were evaluated: one design with a constant height of 25 ft and another with a varied height to provide a constant elevation for the top of the barrier; details are provided in Table 45.

Table 46 provides the results for the abatement analysis for the HMA pavement with and without barriers. Only the

Table 46. Summary of analysis results of I-485 for the existing HMA pavement.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Max / Avg (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
HMA	0	72/64	0	2,062	–	–				13
HMA + 25 ft	38	62/57	7–13	4,423	2,361	1,434	Y	N	Y	3
HMA + Varied Height	19	69/62	4–9	3,341	1,279	721	Y	N	Y	10
HMA + S9.5	0	69/62	2–3	2,596	534	–	N	N	N	10
HMA + S9.5 + 25 ft	46	59/55	9–16	4,957	2,895	1,734	Y	N	Y	0
HMA + S9.5 + Varied Height	41	62/57	7–11	3,875	1,813	1,546	Y	N	Y	3

Table 47. Summary of analysis results of I-485 for the assumed PCC pavement.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Max / Avg (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	74/66	0	2,602	–	–				15
PCC + 25 ft	40	64/59	3–9	4,963	2,361	1,516	Y	N	Y	5
PCC + Varied Height	21	66/62	4–11	3,881	1,279	804	Y	N	Y	7
PCC + HMA	0	74/64	2–3	3,007	405	–	N	N	N	15
PCC + HMA + 25 ft	46	62/57	9–15	5,368	2,766	1,741	Y	N	Y	3
PCC + HMA + Varied Height	39	65/60	6–11	4,285	1,683	1,479	Y	N	Y	6
PCC + S9.5	23	69/62	5–6	3,167	565	879	Y	Y	N	10
PCC + S9.5 + 25 ft	48	59/55	11–18	5,527	2,925	1,816	Y	N	Y	0
PCC + S9.5 + Varied Height	41	62/57	9–13	4,445	1,843	1,554	Y	N	Y	3

alternatives that include a barrier meet both the 5 dB acoustic feasibility criterion and the 7 dB design goal. None of the alternatives meet the cost-reasonableness criterion based on the dollar allowance per benefited receptor, but all barrier options meet the reasonableness criterion based on the barrier square feet per benefited receptor. Assuming the cost reasonableness is met using the latter calculation method, the alternative of S9.5 HMA overlay with the 25 ft barrier would provide the most effective acoustic performance based on lowest absolute level and number of benefited receptors, although it has the highest cost. The alternative of S9.5 overlay with the varied height barrier is 3 dB less effective, provides five fewer benefited receptors, and has a lower NPV cost than the same pavement with the 25 ft barrier by $1,082,000. The HMA with a varied height barrier alternative has a lower NPV cost, but it is less effective (by 7 dB) and benefits less than half of the number of receptors. The cost per benefited receptor for all the alternatives with barriers is essentially the same (within $300 of each other) but the S9.5 overlay with 25 ft barrier alternative has the lowest cost per benefited receptor. In cases where several options have similar cost and effectiveness, other considerations may be applied for the selection process.

The results for the assumed existing PCC construction with and without barriers are provided in Table 47. The S9.5 overlay without a barrier option is feasible and cost reasonable, but it falls 1 dB short of the design goal and is 10 dB less effective than the most effective alternative (S9.5 with the 25 ft barrier). All barrier alternatives meet the reasonableness criterion based on the square feet per benefited receptor and have nearly equal costs per benefited receptor. Of these alternatives, the S9.5 overlay with the 25 ft barrier provides a slightly lower cost per benefited receptor than the HMA overlay with the 25 ft barrier. As for the HMA case, other considerations may be applied for the selection process.

Observations from the North Carolina Lane Addition (Example B) Cases

In these case studies, the quieter HMA without barrier alternatives were sometimes found to be feasible and cost reasonable; other barrier options were not. In some cases, the effectiveness was found to be within 3 to 5 dB of the lowest absolute level provided by the barrier alternative. Compared to the barrier alternatives, the quieter pavement without a barrier had considerable cost advantage although it did not meet a 7 dB design goal for any of the cases. When barriers were evaluated on both sides of the highway, quieter pavements served both sides of the highway and improved cost-reasonableness considerations. In some situations, quieter pavement benefits receptors on both sides of a highway, which contributes to the barriers' cost reasonableness because of the lower combined pavement–barrier cost or the increased number of benefited receptors. In some of the cases, several alternatives with different NPV costs and effectiveness would meet all criteria. For such cases, a rational approach for trading off NPV cost and effectiveness needs to be considered. The cost per benefited receptor may be an appropriate criterion for comparing alternatives involving different numbers of benefited receptors.

Example C: New Highway Constructions and Realignments

For this example case, two projects in Arizona were considered, each involving new construction. One project is a completely new eight-lane highway and the second project is a realignment of an existing four-lane highway. PCC and HMA alternatives are considered for both cases. For PCC alternatives, the final texture is longitudinally tined or the pavement is overlaid with ARFC. The HMA alternative uses an ARFC overlay as a wearing surface. The Goodyear Aquatred OBSI data shown in Figure 27 was used. The pavement and barrier NPV costs

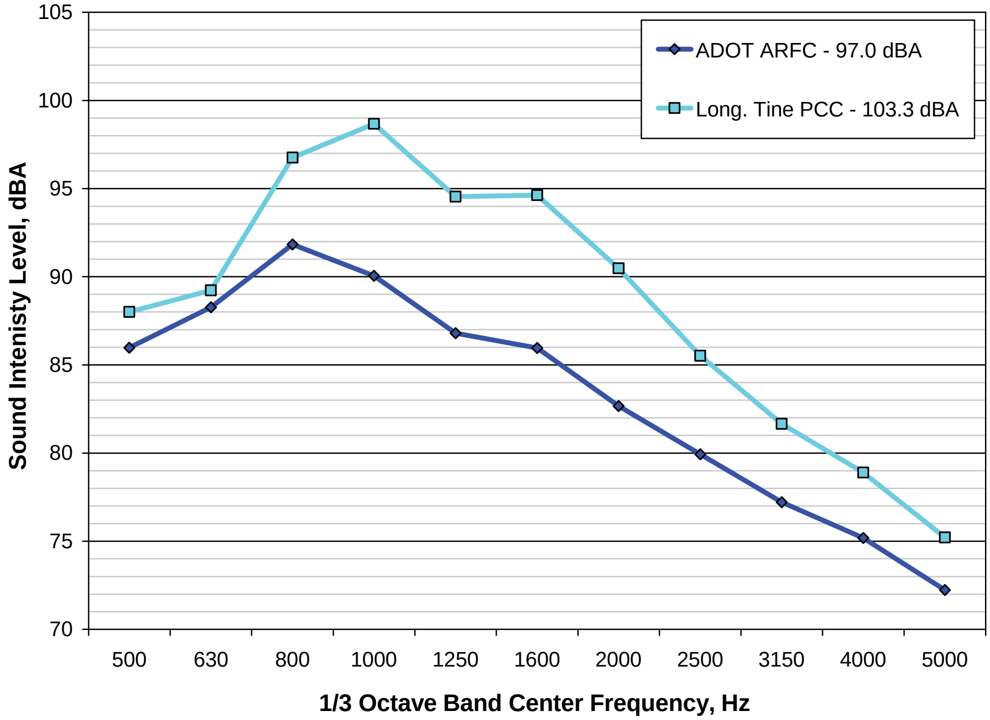


Figure 27. OBSI one-third octave band spectra for ARFC and longitudinally tined PCC pavements used in Example C.

were scaled from the LCCA of the six-lane highway scenario discussed in Chapter 4 (see Table 6). The NPV costs for the pavement (without a barrier) were multiplied by 1.333 for the eight-lane case and by 0.6667 for the four-lane case. The costs for the ARFC overlay were the same as for the RAC(O). Barrier NPV costs were scaled by height relative to the 12 ft high and $27/ft^2 barrier used in the earlier example. For the noise-level predictions, TNM results were generated by models provided by ADOT and re-run with the specific OBSI adjustments.

The analysis of each alternative for the two cases was compared to ADOT policy (*66*). ADOT defines "approaching" the NAC as 3 dB below 67 dBA or 64 dBA. For acoustic feasibility, at least half of the impacted receptors must receive a 5 dB reduction. To determine cost reasonableness, benefited receptors are allowed up to $49,000 in costs for noise abatement with the cost of barriers set at $35/ft^2 for barriers on grade. To meet the design goal, at least half of the benefited receptors in the first row should receive a 7 dB reduction.

New Construction: New Eight-Lane Highway

In this project, an existing uncontrolled access, four-lane section of state highway will be completely replaced with an eight-lane access-controlled freeway as an extension of an existing freeway. Currently, one side of the right-of-way contains a relatively high density of residential receptors in several subdivisions. This segment extends about 13,500 ft and a barrier is considered for this entire length. The opposite side of the proposed freeway does not have residential receptors, but it has a recreational use area that is considered a sensitive receptor. For this receptor, a barrier with a length of 2,632 ft parallel to the barrier on the opposite side is considered.

The following pavement alternatives are considered:

1. Construct all new lanes and shoulders with PCC (longitudinally tined). Future rehabilitation includes diamond grinding of all lanes on a 20-year cycle.
2. Construct all new lanes and shoulders with PCC and overlay all travel lanes with 1 in. thick ARFC. Future rehabilitation includes mill and overlay of all lanes with 3/4 in. ARFC every 9 years.
3. Construct all new lanes and shoulders with HMA and overlay all travel lanes with 1 in. thick ARFC. Future rehabilitation includes mill and overlay of all lanes with 3/4 in. ARFC every 9 years.

The NPV costs for the 13,500 ft long pavement alternatives of the project are given in Table 48.

For noise abatement, barriers with heights of 16 and 10 ft on both sides of the freeway are considered. With one barrier being much shorter than the other, no accounting for the quieter pavement affecting both sides is considered as there is

Table 48. Summary of NPV results for the new eight-lane highway construction.

Alternative		Agency NPV Cost ($000)
No.	Description	
1	New Construction of PCC	27,013
2	PCC & Added 1 in. Overlay of ARFC—9-Year Cycle	34,471
3	HMA & Added 1 in. Overlay of ARFC—9-Year Cycle	30,627

little impact on the cost analysis. The total number of impacted receptors is 249 when both sides are counted. For the analysis, new longitudinally tined PCC pavement that produces predicted levels about 1.5 dB higher than TNM Average Pavement is considered as the acoustic baseline. The results when compared to ADOT criteria are provided in Table 49.

The acoustic performance of the ARFC on either the PCC or the HMA pavement is the same, but the NPV of the HMA is lower than the PCC alternative. Alternatives that include a barrier meet the acoustic feasibility criterion. For the ARFC overlay without a barrier alternatives, the feasibility criterion is not met because a 5 dB reduction is achieved for only 120 receptors (125 required). For cost reasonableness, only three alternatives—the PCC with a 16 ft barrier, the PCC with a 10 ft barrier, and the HMA with ARFC overlay and 10 ft barrier—are below the cost allowance. Thus, only these three alternatives are viable under the ADOT policies. Of these, the PCC with a 16 ft barrier is most acoustically effective and the PCC with a 10 ft barrier is the least effective, but it has the lowest NPV costs. The PCC with a 10 ft barrier alternative provides the lowest cost per benefited receptor because the number of benefited receptors does not change with the decreased barrier height although the effectiveness is reduced by 5 dB. The alternative of HMA and ARFC with a 10 ft barrier comes in between the PCC alternatives in terms of cost and effectiveness, but it produces the highest number of benefited receptors.

New Construction: Four-Lane Highway Realignment

In this project, the existing four-lane highway is being realigned around an existing land use and on/off ramps are being added for an existing intersecting roadway. The highway remains four lanes and pavement construction alternatives are the same as for the previous case. The project length is 9,700 ft. The resulting LCCA NPV costs for the pavements are given in Table 50. Proposed barriers are considered along one side of the roadway for the entire length of the project. Only one barrier height of 12 ft is considered for the PCC and HMA pavements. Eighty-nine impacted receptors could potentially be benefited by these barriers.

The results of the analysis are shown in Table 51. For this case, only the alternatives with barriers meet the 5 dB acoustic feasibility criterion (the maximum reduction provided by the ARFC without a barrier is 4 dB). None of the alternatives meet the cost-reasonableness criteria and only the barrier alternatives achieve the design criterion. The most effective alternatives are the PCC/HMA and ARFC with the 12 ft barrier, although they do not meet all criteria. The ARFC overlay

Table 49. Summary of analysis results for the eight-lane new highway construction.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Max / Avg (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	80/75	0	27,013	–	–				16
PCC + 10 ft	224	72/68	10/7	33,326	6,313	10,976	Y	Y	Y	8
PCC + 16 ft	224	67/65	13/10	37,114	10,101	10,976	Y	Y	Y	3
PCC + ARFC	120	75/71	5/4	34,471	7,458	5,880	N	N	N	11
PCC + ARFC + 10 ft	249	69/66	13/9	40,784	13,771	12,201	Y	N	Y	5
PCC + ARFC + 16 ft	249	64/62	16/13	44,572	17,559	12,201	Y	N	Y	0
HMA + ARFC	120	75/71	5/4	30,627	3,614	5,880	N	Y	N	11
HMA + ARFC + 10 ft	249	69/66	13/9	36,940	9,927	12,201	Y	Y	Y	5
HMA + ARFC + 16 ft	249	64/62	16/13	40,728	13,715	12,201	Y	N	Y	0

Table 50. Summary of NPV results per mile for the new four-lane highway realignment.

Alternative		Agency NPV Cost ($000)
No.	Description	
1	New Construction of PCC	9,715
2	PCC & Added 1 in. Overlay of ARFC—9-Year Cycle	12,397
3	HMA & Added 1 in. Overlay of ARFC—9-Year Cycle	11,015

Table 51. Summary of analysis of four-lane highway realignment.

Pavement Type and Barrier Height	Receptors Benefited	Predicted Level Max / Avg (dBA)	Noise Reduction Range (dB)	Total Project NPV ($000)	NPV for Noise Abatement ($000)	Reasonableness Allowance ($000)	Feasible	Cost Reasonable	Design Goal	Effectiveness (dB)
PCC	0	72/69	0	9,715	–	–				10
PCC + 12 ft	89	66/63	7/5	14,275	4,560	4,361	Y	N	Y	4
PCC + ARFC	0	68/66	4/3	12,397	2,682	–	N	N	N	6
PCC + ARFC + 12 ft	89	62/60	11/8	16,957	7,242	4,361	Y	N	Y	0
HMA + ARFC	0	68/66	4/3	11,015	1,300	–	N	N	N	6
HMA + ARFC + 12 ft	89	62/60	11/8	15,575	5,860	4,361	Y	N	Y	0

on HMA alternative has the lowest NPV cost, but it meets none of the criteria. None of the abatement options meet the criteria largely because of the low density of the receptors over the length of the project. With only 89 impacted receptors over almost 2 mi, insufficient cost allowance is generated even though all receptors would receive a 5 dB benefit or more for all of the barrier cases. This case also presents an example in which a quieter pavement alone could provide an effective solution with a 3 to 4 dB reduction.

Observations from New Construction and Realignment (Example C) Cases

For the eight-lane new construction, viable alternatives with different barrier heights and pavements were produced, but none of these alternatives meet all required criteria. For example, the design goal of 7 dB cannot be met with the ARFC overlay alone. If the uniform transversely tined texture that was previously used by the agency is considered as the baseline, the design goal may be met because its OBSI levels are typically 3 to 5 dB higher than for a longitudinally tined PCC pavement (*67*). ARFC produces reductions of 5 dB but not for 50% of the impacted receptors.

The realignment case demonstrates the difficulty of developing any type of noise abatement when the density of the impacted receptors per length of project is low. All three barrier alternatives produce the maximum number of benefited receptors; however, none meet all of the criteria. To develop alternatives that meet the criteria, barrier height should be optimized to identify a lower height that would generate the required number of benefited receptors and reduce the NPV costs to make it viable for cost reasonableness. Depending on the concentration of impacted receptors, reducing the length of the barrier or breaking it into multiple shorter segments may also produce viable alternatives. This case also raises the issue of pavement-specific acoustic feasibility and reasonableness criteria when no abatement alternative meets a first level of criteria and receptors are impacted at levels well exceeding the NAC.

CHAPTER 6

Summary and Suggested Research

Summary

The methodology developed in this research provides a means of evaluating pavement strategies and barriers together for feasibility, reasonableness, effectiveness, acoustic longevity, and economic features. The primary elements of the approach include the following:

- The use of OBSI data to account for the effect of pavement performance on tire noise source levels
- The use of FHWA TNM with a modification to adjust for tire–pavement noise based on OBSI data
- The use of LCCA to compare the costs of barriers, quieter pavement, and combinations of pavements and barriers.

The methodology can be used immediately under the latest FHWA policy regarding feasibility and reasonableness. It can also be used directly under state policies that use a specified barrier cost per square foot in the cost-reasonableness analysis. However, if a barrier cost per square foot per benefited receptor is used, either a cost that could be used in the LCCA needs to be identified or a hybrid method for dealing with reasonableness needs to be developed. In the longer term, adjustments of the criteria for *feasible* and *reasonable* may be needed to reflect the use of quieter pavement and its noise reduction potential particularly when barriers cannot be justified. Additionally, the concept of *effectiveness* would need to be explicitly defined.

Life-Cycle Cost Analysis and Economic Features

Accounting for the cost of noise abatement in the LCCA of pavement alternatives provides an ideal means for considering the economic features of barriers and quieter pavements in the pavement–abatement selection process. This analysis allows consideration of both the initial and future costs of maintaining a specified level of noise reduction performance over time as opposed to only considering the initial cost of quieter pavement relative to barriers. Application of this approach may require collaboration between pavement engineers and environmental engineers.

However, incorporating LCCA into this approach requires actual pavement structure costs because TNM Average Pavement is not an actual pavement structure and it does not have an associated cost. Implementing the approach relies on evaluating actual pavement designs for both acoustic performance and cost. Therefore, the baseline for comparison of these two parameters would likely be that of the pavement with the lowest life-cycle cost. However, predictions based on TNM Average Pavement may be useful for reference.

The LCCA is greatly dependent on the rehabilitation cycle time and the project life, particularly for quieter pavements for which the noise performance can degrade more rapidly. In implementing the methodology developed in this research, the influence of these variables would need to be duly considered.

Effectiveness

With the integration of pavement into traffic noise abatement, *effectiveness* becomes a necessary concept. When only barriers are used for abatement, feasibility and reasonableness are based on barrier insertion loss. However, when pavement is also included, overall noise reduction becomes the primary metric for assessing the performance of abatement alternatives. In the example cases presented in this report, ranking the *effectiveness* of alternatives by amount of noise reduction provided was used as one measure of performance. However, this measure does not capture the complete concept of *effectiveness* as defined in this research. The intent of the *effectiveness* consideration is to avoid situations where post-project noise levels unknowingly become higher than the pre-project levels. This intent can be achieved by modeling the existing levels based on the OBSI levels of the actual pavement in the project area and comparing them to the levels predicted after the project is complete. However, if both the existing pavement and the candidate pavement alternatives produce higher levels, an *effective* solution will not be obtained. This situation was demonstrated in the case study in which the random transversely tined PCC pavement was found to meet the feasible and reasonable criteria only when compared to a random transversely tined PCC baseline. To set a more calibrated definition of effectiveness, it may also be appropriate to relate effectiveness criteria to TNM Average Pavement predictions or another absolute level such as the NAC.

Acoustic Longevity

Using OBSI measurements in TNM to predict traffic noise levels provides a straightforward method of considering acoustic longevity. As illustrated in some of the example cases, the increase in traffic noise due to aging of the pavement can be easily predicted by inputting the appropriate OBSI levels for a given age of pavement. Ideally, these data would be generated through research projects conducted by the agency. However, they could initially be based on data by others and then followed up by periodic measurements of the pavement in the actual projects. The rehabilitation cycle could be initially set based on these data and confirmed over time, possibly with a provision for a shorter cycle if the pavement acoustic performance deteriorates faster than anticipated.

Other Issues

The case studies considered in this research have shown that minor differences in agency requirements/criteria play a large part in demonstrating the need for noise abatement and identifying the preferred alternative. While this research was not intended to develop or propose agency policies, it identified some actions that could be taken when establishing criteria for abatement measures that would include pavements. These actions are as follows:

- Define the existing traffic noise levels based on GLSS-modified TNM levels with actual current pavement OBSI data
- Predict future noise levels based on the OBSI levels of the pavement types proposed for the project
- Encourage the consideration of quieter pavement when impacted receptors are identified and barriers are not feasible or reasonable
- Develop *effectiveness* criteria for selecting abatement options that consider the overall noise reduction of the alternatives not just insertion loss
- Reference *effectiveness* to some absolute level of performance defined by TNM Average Pavement or some other criteria such as the NAC
- Account for the benefit to receptors on both sides of the highway when pavement is considered as part of the abatement alternative

Findings from Example Cases

Although the case studies presented in this project were not intended to provide conclusions regarding the pavement type, quiet pavement versus barriers, or the specifics of the case, they revealed the following findings relevant to application of the methodology:

- A design goal criterion of 7 dB is generally not achievable with current quieter pavements alone except in extreme cases where a much quieter pavement is compared to a noisier pavement [e.g., an RAC(O) or ground PCC surface is compared to a transversely tined PCC surface].
- Quieter pavement alternatives can be both feasible and cost reasonable in some situations (even under current state agency criteria).
- Maintaining the acoustic performance of quieter pavements can result in a significant increase in life-cycle cost.
- In some situations where a barrier alone would not meet criteria, feasible and reasonable noise abatement alternatives can be obtained by combining quieter pavement with a barrier.
- Feasible and reasonable alternatives can be developed using pavements and barriers in combination, in some cases achieving comparable effectiveness.
- In some situations, a more effective and lower cost alternative can be obtained by combining quieter pavement with shorter barrier heights.
- In some instances, barriers do not meet criteria because of low receptor density or geometric factors, but the quieter pavement would provide noise-level reduction of 3 to 4 dB to impacted receptors at low enough cost.
- In cases where there are impacted receptors on both sides of a highway, it may be appropriate to evaluate them together when quieter pavement or combinations of barriers and pavement are considered.

OBSI and TNM

Based on the analysis performed in this research, it appears that using SRTT OBSI levels in the modified version of TNM offers a viable approach for accounting for differences in tire–pavement noise in traffic noise predictions. Studies have shown that the range of CTIM levels from the transversely tined PCC to ARFC is comparable to the range in OBSI levels (*17*). With the example cases, the predicted levels for the noisier and quieter pavements were about as expected relative to TNM Average Pavement.

The use the GLSS-modified TNM with SRTT OBSI data could be used in future traffic noise studies as developed in this research. Accounting for some of the effect of pavement is more desirable than not, particularly in cases where the pavement under consideration will produce levels higher than TNM Average Pavement.

Suggested Research

To advance the methodology developed in this research, interested state agencies may consider using it on a trial basis, in parallel to traditional noise studies. This trial would help the agencies familiarize themselves with the methodology and provide feedback on the approach and how it relates to the current practice. It would also provide feedback on how application of this methodology might affect the outcome of highway studies. Parallel studies would provide insight on the use of fewer and/or shorter barriers, use of quieter pavement when barriers alone are not feasible or reasonable, and use of barrier–pavement combinations.

Documenting the existing acoustic conditions for Type 1 projects that are not all new construction will help provide information for "calibrating" TNM model results to field measurements.

There is an immediate need to collect comparisons of OBSI and CTIM measurements and TNM results with the GLSS adjustment and further examine these relationships. Studies performed to date have been limited to projects that were not designed explicitly to make these comparisons and limited OBSI data using the standard SRTT test tire were available.

To better evaluate the potential of quieter pavements for noise mitigation, there is a need for a research effort to better understand the acoustic characteristics and sound-absorptive effects of the different pavement surfaces. This effort would require CTIM, OBSI, and EFR measurements and TNM calculations to quantify the effect of sound-absorbing pavement on traffic noise.

As noted in some of the example cases, current quieter pavements will not generally achieve a 7 dB design goal. Thus, there is a need for research into quieter pavement technologies to explore innovation that would produce more quieter pavement surfaces with high resistance to degrading acoustic performance with time.

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APPENDICES

The following appendices are not published herein but are available on the TRB website (http://www.trb.org/Main/Blurbs/169200.aspx):

- Appendix A: Investigations of the Effects of Porous Pavement on Traffic Noise and Traffic Noise Prediction
- Appendix B: Life-Cycle Cost Analysis
- Appendix C: Application of LCCA to Hypothetical Highway Noise Abatement Cases
- Appendix D: The Evaluation of Feasibility, Reasonableness, and Effectiveness
- Appendix E: Pavement Acoustic Longevity
- Appendix F: Evaluation of Cost–Benefit Analysis to Highway Noise Abatement
- Appendix G: Life-Cycle Cost Analysis for California I-580 HOV Lane Project Example
- Appendix H: Life-Cycle Cost Analysis for North Carolina Highway Widening Project Examples

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation