

Cost-Benefit Analysis

Noise Barriers and Quieter Pavements

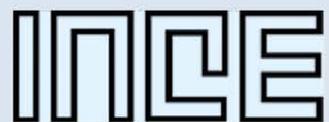
a workshop sponsored by
**The INCE Foundation, the Noise Control Foundation, and
the Transportation Research Board Committee ADC40**

organized by the
U.S. Department of Transportation Volpe Center

hosted by
The National Academy of Engineering, Washington, DC

Cori Vanchieri, Rapporteur

Eric W. Wood, George C. Maling, Jr., and William W. Lang, Editors

The logo for the Institute of Noise Control Engineering of the USA (INCE). It consists of the letters 'INCE' in a bold, stylized, outlined font. The letters are white with a dark outline, set against a light background.

Institute of Noise Control Engineering of the USA

FINAL REPORT

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**This report has been approved by the Board of Directors of INCE/
USA for publication as a public information document.**

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INCE, the Noise Control Foundation, and the Transportation Research Board Committee
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ORGANIZATIONS

Advancing Noise Control Engineering

The **International Institute of Noise Control Engineering (I-INCE)** is an international, nonprofit, nongovernmental consortium of more than 40 member organizations with interests in the control of noise and vibrations that produce noise. I-INCE was chartered in Zürich, Switzerland in 1974 on the basis of Swiss Civil Law. The objectives of I-INCE are to sponsor annual international congresses on noise control engineering in the INTERNOISE series as well as other specialized conferences, and to promote cooperation in research on the application of engineering principles for the control of noise and vibrations. I-INCE undertakes technical initiatives and produces reports on important issues of international concern within the I-INCE field of interest.

The **Institute of Noise Control Engineering of the USA (INCE/USA)** is a nonprofit, professional-membership organization incorporated in 1971 in Washington, DC. A primary purpose of the Institute is to promote engineering solutions to noise problems. INCE/USA is a Member Society of the International Institute of Noise Control Engineering (I-INCE). INCE/USA has two publications, the Noise Control Engineering Journal (NCEJ) and Noise/News International (NNI). NCEJ contains refereed articles on all aspects of noise control engineering. NNI contains news on noise control activities around the world, along with general articles on noise issues and policies.

The **Institute of Noise Control Engineering Foundation (INCE Foundation)** is a nonprofit, tax-exempt, publicly supported, charitable organization established in 1993 and incorporated in New York as a Section 501(c)(3) organization. The purposes of the Foundation are to support, promote, and advance scientific and educational activities directed toward the theory and practice of noise control engineering and to promote and support such scientific and educational activities through grants, funding, and financial assistance to various individuals, institutions, and organizations.

The **Noise Control Foundation (NCF)** was established in 1975 to provide administrative services to the newly-formed INCE/USA. It is a nonprofit, tax-exempt organization incorporated in New York as a Section 501(c)(3) organization. At the end of the century when administrative support for INCE/USA was transferred to a commercial organization, NCF was re-chartered to be devoted to the development of national and international policies as related to the technological aspects of noise control engineering.

Volpe – The National Transportation Systems Center has for over 40 years helped the transportation community navigate its most challenging problems. Part of the U.S. Department of Transportation, Volpe is a **unique federal agency** that is 100 percent funded by sponsor projects. Volpe partners with public and private organizations to assess the needs of the transportation community, evaluate research and development endeavors, assist in the deployment of state-of-the-art transportation technologies, and inform decision- and policy-making through comprehensive analyses. Home to **renowned multidisciplinary expertise** in all modes of transportation, Volpe serves its sponsor agencies with advanced technologies, research, and programs to ensure a fast, safe, efficient, accessible, and convenient transportation system that meets vital national and international interests and enhances the quality of life for the traveling public, today and into the future.

Committee ADC 40 is a committee of the Transportation Research Board of the National Research Council, part of the National Academies. Committee ADC 40 addresses noise and vibration and evaluates alternative strategies and control techniques for reducing noise and vibration from transportation systems and evaluates their environmental impact.

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Preface

The report, *Technology for a Quieter America*, (TQA) was published by the National Academies Press in October 2010 and was the result of a five-year study by the National Academy of Engineering (NAE) of the environmental noise situation in the United States. The report includes findings and recommendations for government, industry, and public actions that may mitigate or eliminate those noise sources that pose a threat to public health and welfare.

In 2011, the Institute of Noise Control Engineering (INCE) Foundation and the Noise Control Foundation established a TQA Follow-up Program to identify specific noise topics and to develop relevant recommendations aimed at improving the noise climate in the United States. The TQA Follow-up Program consists of a series of events involving experts in selected TQA topic areas to further assess specific noise issues and publish a series of recommended remediation measures.

This report presents the results of one TQA Follow-up event, a workshop titled *Cost Benefit Analysis – Noise Barriers and Quieter Pavements*, which was organized by the DOT Volpe Center and hosted by the NAE at the National Academies Keck Center, Washington, DC, on January 16, 2014. Several factors led to the workshop. First, it is well-recognized that highway noise is a quality-of-life issue in the United States. Second, the primary defense against road traffic noise in the United States has been noise barriers. However, barriers are expensive, reduce noise as it propagates (not at the source), and are not always feasible. Third, at highway speeds, the main source of noise emission is interaction between vehicle tires and road surfaces. Considerable progress has been made in understanding this noise source, and development work has shown that considerable reductions in noise emissions can be achieved by changing the design of the road surface. Fourth, to allocate costs effectively, a cost-benefit analysis of the two alternatives (quiet pavements and noise barriers) should be undertaken.

The workshop and this report respond to the above factors. The agenda for the workshop is presented in Appendix B. The wide variety of interests represented at the workshop are identified; participants offered their respective positions and recommendations. Note that participants in the workshop were invited for their experience and expertise with cost benefit analysis, noise barriers, and quieter pavement, and their participation does not indicate endorsement of the methodology discussed.

A dialog between workshop participants and related stakeholders, particularly Federal and state transportation agencies, is expected to continue.

Acknowledgements

The Steering Committee members are grateful to the many state and federal representatives and others who participated in the workshop. They shared their expertise, insights, and best ideas to establish a collegial atmosphere. A complete list of attendees and their organizations can be found in Appendix C.

Gregg Fleming and Meghan Ahearn from the Volpe Center provided invaluable support in the organization and implementation of the workshop and the preparation of this report. Funding for the production of a workshop transcript, for the rapporteur, Cori Vanchieri, and for publication of the report was provided by the INCE Foundation and the International Institute of Noise Control Engineering.

Thanks also to the staff of the NAE, which hosted the workshop. Proctor Reid, Program Director, and Jason Williams, Senior Financial Assistant, made the workshop possible through their supportive efforts to ensure that the event ran smoothly. Chapter 7 in the TQA report, Cost-Benefit Analysis for Noise Control, provided, in part, the motivation for this workshop.

Also, we'd like to express our appreciation to the NAE's Committee, chaired by George Maling, that produced the *Technology for a Quieter America* report with its numerous findings and recommendations that served, in part, to focus attention on the costs and benefits of noise barriers and quiet pavements.

Finally, thanks to the Transportation Research Board for providing support for the workshop, including funding for many state agency participants and presentations from Paul Donavan, Judy Rochat, Dana Lodico, Linda Pierce, Roger Wayson, Ken Polcak, and Adam Alexander.

The rapporteur, Cori Vanchieri, was assisted in the preparation of this report by a technical editing team consisting of Paul Donavan, Judy Rochat, Gregg Fleming, and Meghan Ahern and editors from the TQA follow-on project, Eric Wood, Bill Lang, and George Maling.

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EXECUTIVE SUMMARY

At highway speeds, the major source of noise is the interaction between tires and the road surface. Noise barriers have been used by state transportation departments for many years and are the preferred solution for reducing highway traffic noise. Federal Highway Administration regulations for highway traffic and construction noise abatement are included in the Code of Federal Regulations (23 CFR772)¹ and currently only consider noise barriers as an abatement measure for highway noise. However, pavement type can considerably reduce the noise generated from tire-road interaction. Yet considering pavement as a noise abatement measure is currently only allowed for pilot projects approved by the Federal Highway Administration. Through the end of 2010, 47 state departments of transportation and the Commonwealth of Puerto Rico have constructed more than 2,748 linear miles of barriers at a cost of close to \$5.5 billion (in 2010 dollars)².

Treatment of highway pavement is generally less costly than the construction of barriers, but the noise reduction achieved by a quieter pavement is typically less than the reduction from a well-designed barrier, at least for residents in the immediate vicinity of the barrier. However, quieter pavements produce a reduction of noise at the source, which means that it may be possible to increase the number of benefited receptors (the recipient of an abatement measure that receives a noise reduction at or above the highway agency's chosen noise impact threshold value). A combination of barrier and pavement treatment may lead to cost-effective solutions to highway noise.

To evaluate effectiveness of quieter pavements, a reliable measurement method for tire/road noise is needed. The method that is currently favored is measuring On-Board Sound Intensity (OBSI). OBSI data are collected in conformance with AASHTO TP-76,³ the American Association of State Highway and Transportation Officials Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method.

A workshop on cost-benefit analysis of noise barriers and quieter pavements was held on January 16, 2014. One objective of the workshop was to evaluate the National Cooperative Highway Research Program Report 738, "Evaluating Pavement Strategies and Barriers for Noise Mitigation". Report 738 was prepared under Project 10-76, and is typically referred to as NCHRP 10-76.⁴ The report describes a methodology for the evaluation of both barriers and pavements for noise abatement, and explores how quieter pavement technology can be incorporated into Federal and state noise policy. Three key elements of the method presented in NCHRP 10-76 involve life cycle cost analysis (LCCA), the use of a research version⁵ of the Federal Highway Administration Traffic Noise Model (TNM), and a method for the evaluation of tire pavement noise reduction, OBSI.

This report contains summaries of the presentations given during the workshop and the results of discussions identifying the challenges presented by implementing the NCHRP 10-76 methodology, especially to state departments of transportation, which carry out noise abatement

¹ Code of Federal Regulations, Title 23, Part 772, "Procedures for Abatement of Highway Traffic Noise and Construction Noise", referred to as 23 CFR772 throughout this report.

² www.fhwa.dot.gov/environment/noise/noise_barriers/inventory/summary/sintro7.cfm

³ <http://pdfstandard.net/AASHTO-TP-76-2011-PDF>

⁴ http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_738.pdf

⁵ This report refers to two versions of the FHWA's Traffic Noise Model: the public release version of TNM and the research version of TNM, which includes OBSI-related pavement assessment capabilities.

projects in cooperation with the Federal Highway Administration and in conformance with the federal requirements in 23 CFR772.

Using LCCA, planners can evaluate the initial cost of abatement using pavement and barriers as well as rehabilitation and maintenance costs. The methodology also incorporates a measure of the effectiveness of the resulting predicted level of traffic noise. Current regulations require impact determination and barrier design to be completed with the public-release version of TNM and average pavement. By using a research version of TNM and OBSI data to refine the tire-pavement interaction noise source, pavement effects could be included in the model (and therefore predictions could be more accurate and pavement type can be considered when assessing noise impact and abatement). Several examples illustrated that the NCHRP 10-76 approach can be successfully applied to real highway project studies. In some situations, a barrier-and-pavement hybrid solution can be more acoustically effective and/or cost effective than a barrier only solution and can allow for additional benefited receptors where a barrier only solution would not be feasible and/or reasonable.

Both current regulations and the public-release version of TNM require modification if the noise reduction benefits of pavements are to be realized in construction projects. The noise reduction achieved by sound propagation over sound-absorptive pavement could also be included in the public-release version of TNM.

An important part of the workshop, which was attended by noise barrier and pavement experts, as well as representatives from the FHWA and state departments of transportation, was to discuss the challenges of implementing NCHRP 10-76 methodology to state departments of transportation and to develop findings and recommendations based on these discussions. The key elements of these discussions are presented in Chapter 3 of this report.

The following recommendations appear in Chapter 4 of this report:

- Develop and document a noise evaluation process that accounts for both noise barriers and quieter pavements.
- Provide funding and implement the method presented to evaluate the abatement options on a pilot program basis to help evaluate and improve the process.
- Upgrade the public release version of TNM to include the OBSI-related pavement assessment capabilities currently available in the research version of TNM.
- Organize and make publically available national databases for OBSI and LCCA.
- Expand TNM and highway noise abatement training to include consideration of quieter pavements and enable use of the research version of TNM.
- Encourage FHWA to develop guidance on the use of quieter pavements and barriers for noise abatement.
- Incorporate noise performance into a new performance management system.
- Develop and provide a noise abatement training program for pavement engineering staff.

Other presentations from the workshop with important background information relevant to cost benefit analysis, noise barriers, and quieter pavements are summarized in Appendix A. The workshop agenda, the names of the participants, definitions of terms and a list of acronyms are provided in Appendix B, Appendix C, and Appendix D.

1 INTRODUCTION

1.1 BACKGROUND

The Federal Highway Administration (FHWA) has developed noise regulations as required by the Federal-Aid Highway Act of 1970 (Public Law 91-605, 84 Stat. 1713). The regulation, 23 CFR 772 Procedures for Abatement of Highway Traffic Noise and Construction Noise, applies to highway construction projects where a State department of transportation has requested Federal funding for participation in the project. The regulation requires the highway agency to investigate traffic noise impacts in areas adjacent to federally aided highways for proposed construction of a highway on a new location or the reconstruction of an existing highway to either significantly change the horizontal or vertical alignment or increase the number of through-traffic lanes. If the highway agency identifies impacts, it must consider abatement. The highway agency must incorporate all feasible and reasonable noise abatement into the project design.

The regulations require the following during the planning and design of a highway project:

1. Identification of traffic noise impacts; examination of potential abatement measures;
2. The incorporation of reasonable and feasible noise abatement measures into the highway project; and
3. Coordination with local officials to provide helpful information on compatible land use planning and control.

The regulations contain noise abatement criteria, which represent the upper limit of acceptable highway traffic noise for different types of land uses and human activities. The regulations do not require meeting the abatement criteria in every instance. Rather, they require highway agencies make every reasonable and feasible effort to provide noise abatement when the criteria are approached or exceeded. Compliance with the noise regulations is a prerequisite for the granting of Federal-aid highway funds for construction or reconstruction of a highway.

Through the end of 2010, 47 state departments of transportation and the Commonwealth of Puerto Rico have constructed more than 2,748 linear miles of barriers at a cost of close to \$5.5 billion (in 2010 dollars)⁶. Highway noise control projects, most for new highway construction projects, some for existing highways, include consideration of costs and benefits for barriers near residential areas.

The results of recent and ongoing well-documented studies and test programs provide compelling evidence that the use of quieter pavements alone or together with barriers could offer comparable benefits at potentially lower costs for future highway noise abatement projects.

⁶ www.fhwa.dot.gov/environment/noise/noise_barriers/inventory/summary/sintro7.cfm

1.2 SCOPE AND PURPOSE OF THE WORKSHOP

The workshop, *Cost Benefit Analysis – Noise Barriers and Quieter Pavements*, and this report review current technology and methods of cost-benefit analysis of two highway traffic noise reducing measures—noise barriers and quieter pavements. Their purpose is to address challenges and solutions for implementing a method that accounts for both and to present findings aimed at allowing state and federal agencies to expand their highway noise control cost benefit analyses to include consideration of both barriers and quieter pavements.

This report summarizes the presentations and discussions of the workshop. Chapter 2 offers detailed presentations on a new methodology for cost benefit analyses of noise barriers and quieter pavements, offering several examples of its utility. Chapter 3 lays out recommendations for solutions and next steps, based on small group discussions during the workshop. Findings and recommendations are in Chapter 4. Appendix A includes several summaries of presentations made during the workshop that offer important background information on barriers and pavements. The first section describes a 2007 workshop that addressed cost-benefit analysis of noise barriers and road surfaces. The next two summaries are specific to noise barrier utility and costs, followed by a review on quieter pavement, and finally, how the FHWA currently treats highway traffic noise analysis and abatement.

2 CBA METHODOLOGY FOR QUIETER PAVEMENTS AND NOISE BARRIERS

2.1 OVERVIEW OF THE NCHRP 10-76 METHODOLOGY

Dr. Paul Donovan, Illingworth & Rodkin, Inc.

The NCHRP 10-76 project set out to develop a methodology for evaluating the feasibility, reasonableness, effectiveness, acoustical longevity, and economic features of pavement strategies and barriers for abatement of highway noise. The current federal regulations (23 CFR 772) identify several noise abatement measures, but exclude pavements as a noise abatement measure. The purpose of NCHRP 10-76 was to show how pavement considerations could be incorporated into policy. Feasibility and reasonableness have long been parts of the policy, but effectiveness⁷ and acoustical longevity are newer dimensions.

The NCHRP 10-76 methodology⁸, published in 2013 by the Transportation Research Board, considers acoustic and economic features of both pavements and barriers. It uses (1) on-board sound intensity (OBSI) data to quantify the noise levels of existing and future pavement projects and to assess the pavement acoustic performance over time, (2) a research version of FHWA Traffic Noise Model (TNM)⁹, which uses OBSI, to determine current and future noise levels to analyze feasibility and reasonableness, and (3) life cycle cost analysis (LCCA) to evaluate the initial cost of abatement and cost of maintaining that performance over the life of the project. Using LCCA to combine pavement and barriers enables planners to account for initial costs along with rehabilitation and maintenance costs. The methodology also incorporates a measure of the effectiveness of the resulting predicted level of traffic noise.

The proposed modifications to the highway noise abatement process are depicted in Figure 2-1. The following two summaries offer examples of how the new process incorporates LCCA and OBSI.

⁷ Defined in NCHRP 738, “effectiveness” is a new term to judge the overall noise reduction provided by pavement alone or in combination with barriers.

⁸ http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_738.pdf

⁹ This report refers to two versions of the FHWA’s Traffic Noise Model: the public release version of TNM and the research version of TNM, which includes OBSI-related pavement assessment capabilities.

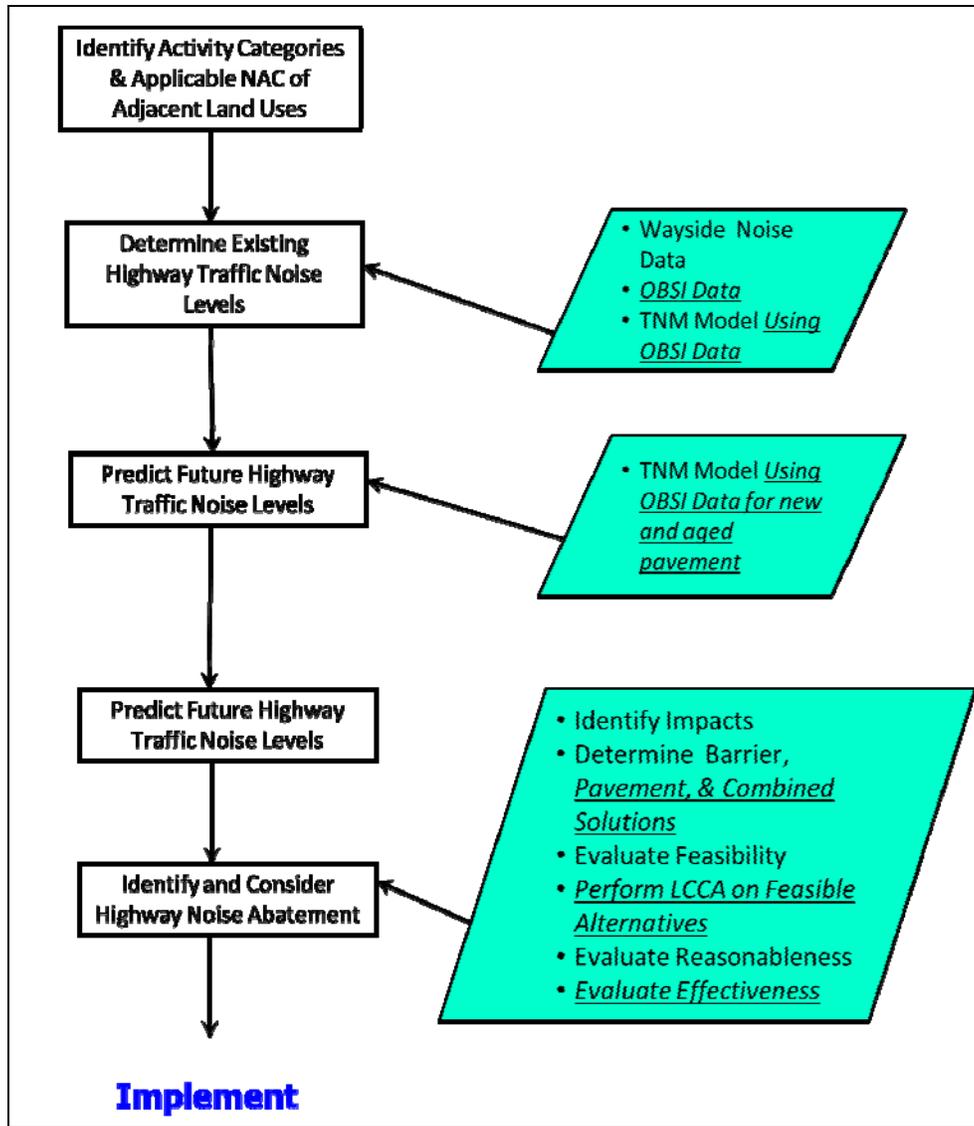


Figure 2-1. Proposed modified highway noise abatement process (changes underlined).

2.2 APPLICATION OF THE FHWA PAVEMENT LIFE CYCLE COST ANALYSIS

Dr. Linda Pierce, *Applied Pavement Technology*

Dr. Pierce described how lifecycle cost analysis (LCCA) was applied during the NCHRP 10-76 project. RealCost, developed by the Federal Highway Administration, is a user-friendly LCCA tool that is specific to pavements, but can be used to analyze other assets¹⁰. RealCost includes a deterministic as well as a probabilistic approach. The analysis discussed below uses deterministic analysis. The software incorporates both agency and user cost estimates. User costs consider costs incurred due to delay caused by lane closures during roadway construction. RealCost also includes user-specific discount rates, the difference between the market interest rate and

¹⁰ <https://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm>

inflation, using constant dollars. In LCCA, the discount rate is used to compare costs that occur at different points in time.

After describing the factors that go into the analysis, Dr. Pierce shared an example from the NCHRP 10-76 report. The analysis includes both barrier and pavement costs. For the barriers, costs included initial construction and maintenance. For pavements, costs included initial construction costs as well as rehabilitation costs for both the pavement structural needs and to maintain its acoustical performance levels. The analysis compared a concrete pavement alternative (assuming a longitudinally tined concrete pavement service, with diamond grind in 20 years) and 12-ft barriers on both sides of the roadway (including graffiti removal every year and impact damage repair every 5 years), with an asphalt alternative, asphalt rubber friction course (ARFC), applied every 7 years for acoustical performance and a 2-inch asphalt overlay applied every 14 years along with a 0.75-inch ARFC. The asphalt option example did not include barriers because of the quieter asphalt surface. The program includes the number of working days to consider user costs of lane closures during construction. The asphalt option had a lower present value cost of \$9.6 million versus \$11.8 million for the pavement plus barrier option (see Table 2-1). However, the asphalt option had a higher user cost because the asphalt had to be overlaid every 7 years, causing more frequent lane closures. The program allows a review of cash outlays with each step of the work and repair and considers salvage value of materials. It allows decision-makers to consider various alternatives and their costs.

Table 2-1. Life cycle cost analysis comparing an asphalt quieter pavement with no barriers and a concrete pavement plus barriers.

Costs (\$000)	HMA + ARFC		PCC + Barrier	
	Agency Costs	User Costs	Agency Costs	User Costs
Undiscounted Sum	\$15,250	\$66.34	\$14,334	\$31.47
Salvage Value	\$958	\$9.53	\$0	\$0
Present Value	\$9,624	\$24.81	\$11,846	\$9.88
EUAC	\$448	\$1.15	\$551	\$0.46

2.3 APPLICATION OF OBSI IN TNM

Dr. Judith Rochat, *ATS Consulting*

The Federal Highway Administration’s Traffic Noise Model (TNM) is a computer program used to predict traffic noise in the vicinity of highways to determine the noise impact and for noise barrier design. Its calculations are done in one-third octave bands (vehicle noise emission levels and sound propagation equations account for frequency content of the sound). The noise emission levels in the model represent thousands of vehicle pass-by events. Each vehicle type is represented by two sub-sources: tire-pavement interaction noise and engine or exhaust stack noise.

The current version of TNM, 2.5, includes four pavement type choices. The current Federal regulations (23 CFR 772) require use of TNM Average for noise impact determinations and barrier design. The three other types of pavement in TNM—Portland cement concrete PCC),

dense-graded asphalt concrete (DGAC), and open-graded asphalt concrete (OGAC)—are often used to validate (or calibrate) TNM input and predictions for a site. The validation process involves comparing predicted and measured existing sound levels, then refining the modeling parameters as needed to increase accuracy; the refined parameters are then used for future sound level predictions. In general, PCC is about 2 dB louder than TNM Average; DGAC is about one-half to one dB quieter than TNM Average, and OGAC is about 2 dB quieter than TNM Average.

Dr. Rochat and colleagues at the U.S. DOT Volpe Center completed the FHWA TNM Pavement Effect Implementation Study to assess options for implementing noise effects for a broad range of pavements into TNM. They used OBSI data to adjust the tire-pavement interaction noise source. The OBSI data is collected in conformance with AASHTO TP-76, the American Association of State Highway and Transportation Officials Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method. The user compares the data collected on the pavement of interest to an average DGAC OBSI level, then calculates adjustments on a one-third octave-band basis. A special research version of TNM 2.5¹¹ allows implementation of the pavement-specific adjustment.

Once these adjustments are made, the model yields the predicted sound levels, including the effect of the specific pavement type, so the user can evaluate the effects of pavement and noise barriers, separately or in combination. There are overlapping benefits of noise barriers and pavements, so their combined effect may not be the combination of each one separately.

Dr. Rochat presented one example comparing noise abatement options (asphalt rubber friction course [ARFC] and PCC with a barrier) over time. ARFC has a 7-year lifecycle. At first it is significantly lower than TNM Average, but it gets louder over time, then is repaved, gets quieter and cycles this way. PCC with a barrier starts even lower then increases over time. At 20 years it gets ground down and gets quieter. Both options initially satisfied the 5 dB feasibility criterion. The asphalt maintains it only for 2 years, and therefore is not feasible. In addition, it does not meet the 7 to 10 dB noise-reduction goal and is therefore, not reasonable. Only the PCC with barrier achieves feasibility and reasonableness criteria (see Figure 2-2).

¹¹ TNM 3.0 is expected to be available in 2015. It does not have a research version that includes the adjustment for OBSI or pavement-type effect.

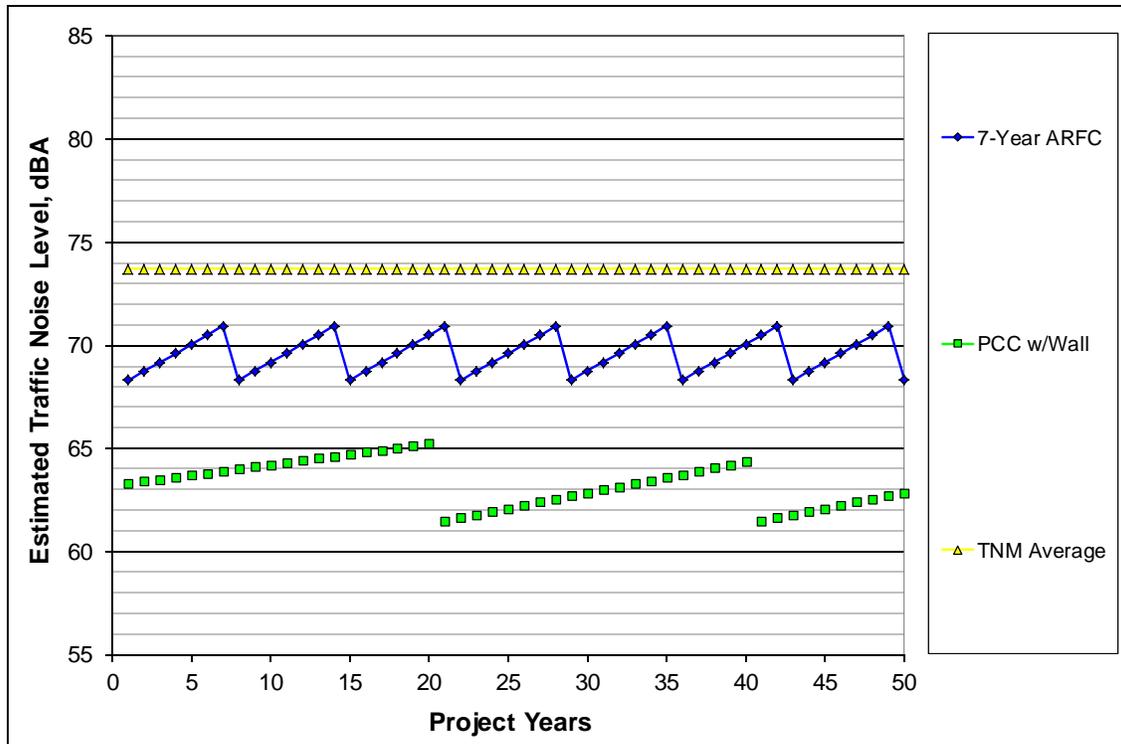


Figure 2-2. Modified TNM Predicted Noise Levels.

2.4 OBSERVATIONS FROM CASE STUDIES AND THE NCHRP 10-76 PROJECT

Example Case of New Highway Construction

Dr. Judith Rochat, *ATS Consulting*

In a new highway project in Arizona, the existing highway is a four-lane uncontrolled access state highway. The replacement highway will be a controlled access eight-lane freeway. A barrier is considered for the westbound side, where there are relatively dense residences. The eastbound side includes a large park, where a barrier is considered for just the park area.

Arizona's policies include noise abatement criteria (NAC) of 64 dB. For acoustic feasibility, 50 percent of impacted receptors must experience a 5 dB reduction. At least 50 percent of benefited receptors in the first row of residences must achieve a noise reduction design goal of 7 dB. The reasonableness allowance is \$49,000 per benefited receptor or \$35/sq ft barriers.

In this example, three options are considered:

1. Lanes and shoulders are longitudinally tined PCC with diamond grinding on a 20-year cycle.
2. Lanes and shoulders are PCC with a 1-inch thick overlay of ARFC. Every 9 years, lanes are overlaid with ¾ inch ARFC.

3. Lanes and shoulders are hot-mix asphalt overlaid with 1-inch thick ARFC. Lanes are rehabilitated every 9 years with ¾ inch ARFC.

For the TNM prediction, the acoustic baseline is the longitudinally tined PCC, which impacts 249 receptors. Therefore, to achieve acoustic feasibility, an option would have to yield a 5 dB reduction for 125 receptors. Each pavement option was considered alone and with a 10-ft and a 16-ft barrier.

Based on the calculations of the model, only three of the options met the state's criteria: PCC with a 16-ft barrier, PCC with a 10-ft barrier, and HMA + ARFC with a 10-ft barrier. Quieter pavement alone could not meet the 7 dB reduction for 50 percent of the impacted receptors. Since the three options meet the criteria for reasonableness and feasibility, one can look at effectiveness, number of benefited receptors, and cost as additional parameters to assess the options. For effectiveness, the most effective option is defined as that which achieved the lowest sound levels; for each of the other options, the sound levels are compared to the most effective option. Of the valid options in the example, PCC with a 16-ft barrier was most effective (only 3 dB higher than the most effective—although not valid—option, where 3 dB effectiveness was calculated by comparing the maximum sound levels for the two options); this option had 224 benefited receptors. Another valid option, HMA + ARFC with a 10-ft barrier, had an effectiveness of 5 dB and benefited 249 receptors. This type of information, along with cost, helps a state agency to have a clearer sense of the available options.

Example Cases of Highway Widening Projects

Dana Lodico, *Lodico Acoustics LLC*

Ms. Lodico described the application of the NCHRP 10-76 Project to two highway-widening projects.

California Project

The California project was a 13-mile segment on I-580 between Dublin and Livermore, CA, and involved adding HOV lanes to an existing eight-lane freeway. The existing pavement was aged, longitudinally tined PCC. For the complete project, 10 new and existing barriers were assessed for feasibility and reasonableness¹². For the segment of the project described in this case study, three barriers were proposed: one to shield a rural single-family residential area with four benefited receptors; the second would shield a park, behind which single-family homes are already shielded by a development wall; the third barrier shields a mobile home park (see Figure 2-3).

¹² According to CFR 772, to be considered feasible, a barrier must meet the 5 dBA noise reduction criteria at the number of receptors as defined by the State DOT and also be feasible to construct from an engineering perspective. To be considered reasonable, the barrier must be considered cost effective (based on the allowable cost of abatement as defined by the State DOT), meet the design goal, and be desirable based on the viewpoints of the benefited receptors.



Figure 2-3. I-580 Segment 3 at Livermore, CA. Red lines show three barriers under consideration.

Caltrans policies include noise abatement criteria (NAC) of 66 dBA. Receptors must receive a 5 dB reduction in noise to be considered benefited, and the design goal is 7 dB—at least 1 receptor must receive a 7 dB reduction for the barrier to be considered reasonable. California’s reasonableness allowance is \$55,000 per benefited receptor.

This case study considered five options, three that included paving the new lane with concrete and two in which the new lanes would be paved with hot-mix asphalt (HMA).

- Concrete: Longitudinally tined (LT) PCC, as currently exists
- Grind all lanes
- Overlay baseline PCC with a rubberized asphalt concrete [RAC(O)] pavement
- HMA: Overall all lanes with RAC(O)
- Overlay all with HMA

The agency cost per mile was then assessed for each option, as indicated in Table 2-2.

Table 2-2. Agency Cost per Mile

Alternative	Agency NPV Cost (\$1000)
1. Added LT PCC Lanes Only	3,691
2. Added PCC Lanes – All Lanes Grd	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

Based on costs, the two HMA alternatives were eliminated because they were the most expensive. Option 4 had noise results very similar to Option 3, but was more expensive. Based on On Board Sound Intensity (OBSI) measurements, the RAC(O) tire/pavement noise levels increase by about 4 dB over 9 years and the LT PCC tire/pavement noise levels increase by about 3 dB between new and aged pavement. Grinding typically reduces tire/pavement noise levels by 5 to 6 dB below aged LT PCC and about 3 dB below new LT PCC levels.

For barrier W10, the three pavement options were assessed with no barrier and also with a 12-ft barrier. Barrier W10 was not recommended because none of the results were found to be feasible, cost reasonable, and design reasonable (see Table 2-3).

Table 2-3. Barrier W10 on I-580 was not recommended because none of the options considered met criteria for feasibility, cost reasonableness, or design reasonableness.

Pavement Type and Barrier Height	Number Benefitted	Predicted Level Range, dBA	Noise Reduction Range, dB	Total Project NPV (\$1000)	NVP for Noise Abatement (\$1000)	Reasonableness Allowance (\$1000)	Feasible	Cost Reasonable	Design Reasonable	Effectiveness, dB
PCC No Additions	0	68-77	0	559	-	-				13
PCC + 12 ft	3	66-68	2-9	1,113	554	165	Y	N	Y	4
PCC + Grd	0	65-74	3	767	207	-	N	N	N	10
PCC + Grd +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

For barrier W11, two alternatives met the criteria—the ground PCC with a 12-ft barrier and the RAC(O) with a 12-ft barrier (see Table 2-4). The effectiveness of the two was very similar, with the rubberized asphalt offering a slight advantage. Barrier E11 had similar results.

Table 2-4. For Barrier W11 on I-580, two options that combined quiet pavement with a 12-ft. barrier met criteria for feasibility, cost reasonableness, and design reasonableness.

Pavement Type and Barrier Height	Number Benefitted	Predicted Level Range, dBA	Noise Reduction Range, dB	Total Project NPV (\$1000)	NVP for Noise Abatement (\$1000)	Reasonableness Allowance (\$1000)	Feasible	Cost Reasonable	Design Reasonable	Effectiveness, dB
PCC No Additions	0	64-78	0	629	-	-				9
PCC + 14 ft	3	61-70	3-8	1,356	727	165	Y	N	Y	3
PCC + Grd	0	62-75	2-3	863	233	-	N	N	N	8
PCC + Grd +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

The researchers then explored whether a barrier/pavement hybrid would benefit more receptors and/or be more cost effective than an individualized approach. W11 and E11 were proposed directly across the freeway from each other. As a result, any pavement costs would be shared between the two locations. If RAC(O) were applied to all of the segment of highway including the portion adjacent to proposed barrier W10 which was not found to be feasible/reasonable, and barriers W11 and E11 were constructed, the 4 receptors located behind the proposed W10 would benefit in addition to the 36 receptors that benefited with the individualized approach. This would boost the reasonableness allowance to \$2,200,000, which is higher than the estimated abatement cost of \$1,685,000 (see Table 2-5). The RAC(O) option alone offered a 2 to 6 dB reduction in noise, which would not meet the 7 dB design criteria. The barrier/pavement hybrid provided a feasible and reasonable alternative where barriers alone would not have been feasible and reasonable. In addition, the hybrid solution provided lower noise levels and benefited more receptors at a lower cost.

Table 2-5. A hybrid approach to benefit receptors behind proposed barrier W10.

Abatement	Abatement NPV Costs (\$1000)
Apply RAC(O) to all of segment (2,275 ft)	421
Build Barriers W11 & E11	1,246
Total	1,685
Hybrid Approach Adds 4 Additional Receptors (40 total)	New Allowance = 2,200

North Carolina

On a project along I-40 near Raleigh, barriers were proposed on each side of the road to protect single-family homes. Existing pavement on the six-lane freeway is transversely tined PCC. The project proposes to add one HOV lane in each direction. The North Carolina policy also has a NAC of 66 dB and benefited receptors must achieve a 5 dB noise reduction. Similar to California, at least one receptor must achieve a noise reduction design goal of 7 dB. North Carolina bases its reasonable allowance on barrier area per benefited receptor, which cannot be applied to LCCA, so they chose a barrier cost of \$35/sq. ft. and a reasonableness allowance of \$37,500 per benefited receptor.

The pavement options, listed below from least to most costly, all included constructing the new lanes with a random transverse PCC, similar to the existing pavement.

1. Add lane, texture to match existing random transverse pavement
2. Add lane, grind all lanes
3. Add lane, overlay with HMA

Based on OBSI measurements, grinding would typically reduce tire/pavement noise levels from the transverse tined PCC by 3 to 4 dB and the HMA overlay would typically reduce tire/pavement noise levels by 6 to 7 dB below the transverse tined PCC. For both the northbound and southbound barrier, the PCC only option was assessed with no barrier and with 14-ft and 16-ft barriers and the ground and HMA options were assessed with no barrier and with a 12-ft barrier. Three of the options for the southbound barrier were found to be feasible, cost reasonable, and design reasonable (see Table 2-6). The PCC option with a 16-ft barrier was the cheapest and least effective with the fewest benefited receptors, only 29. Its effectiveness was 6, meaning it was 6 dB louder than the quietest option. The HMA with 12-ft barrier was the most expensive, but also most effective with most benefited receptors, at 70. Findings for the northbound barrier were similar.

Table 2-6. The least expensive option for the Southbound barrier on I-40 was PCC + 16-ft. barrier, but it was the least effective with fewest benefited receptors. The most expensive option, PCC + HMA + 12-ft. barrier, was most effective with most benefited receptors

Pavement Type and Barrier Height	Number Benefitted	Predicted Level Range, dBA	Noise Reduction Range, dB	Total Project NPV (\$1000)	NVP for Noise Abatement (\$1000)	Reasonableness Allowance (\$1000)	Feasible	Cost Reasonable	Design Reasonable	Effectiveness, dB
PCC No Additions	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 + Grd	0	74/64	3	1,596	365	-	N	N	N	6
PCC + Grd + 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

When more than one alternative exists that meet all criteria, the cost of the entire project can be reviewed, taking into account that the pavement is effective for both sides of the freeway without adding cost to both sides. When considering benefited receptors and the cost per benefited receptor, the HMA alternative, which is the most expensive overall, actually has the lowest cost per benefited receptor due to the extra benefited receptors and the shared cost between the two sides of the freeway.

The HMA-only alternative achieved a 4- to 6-dB reduction below the traditional pavement option, which offered a considerable cost advantage and was feasible and reasonable, but it didn't meet the design criteria. Because the proposed barriers in this case were located on both sides of the same section of freeway and quieter pavement solutions serve both sides of the freeway at the same cost, cost reasonableness is improved with barrier pavement hybrid alternatives. So for cases like this, it would be helpful to have an approach that takes into account both cost and effectiveness. In this case a cost per benefited receptor approach was used.

In summary, the NCHRP 10-76 approach can be successfully applied to real highway project studies. In some situations, a barrier and pavement hybrid solution can be more acoustically effective and/or cost effective than a barrier only solution and can allow for additional benefited receptors where a barrier only solution would not be feasible and/or reasonable.

Observations from Example Case Studies and the NCHRP 10-76 Project

Dr. Paul Donovan, *Illingworth & Rodkin, Inc.*

By including OBSI, pavement performance is put into TNM to recalculate predicted noise levels. Designers can then predict different noise levels to compare different pavement, such as PCC versus rubberized asphalt. They can add in barriers and look at the cost and performance of combined abatement methods, such as PCC with the barrier or ARFC with the barrier, for an apples-to-apples comparison.

Planners can then evaluate if quieter pavement or a combined pavement/barrier system can be feasible and reasonable for the project and if they are effective in providing overall noise reduction.

However, it is difficult to reach a design goal of a 7 dB reduction compared to TNM Average Pavement with quieter pavement alone. In some cases, long barriers will not be feasible or reasonable unless combined with quieter pavement. There can be times when abatement is not going to happen unless pavement is part of the solution with a barrier. Consideration of quieter pavement extends the potential for noise reduction in areas with low receptor density or where barriers already exist, but cannot be made higher.

Other takeaways: The methodology could be applied immediately using current criteria. The current regulations will have to change to allow the use of pavement for noise abatement, however, the existing criteria used to assess barriers could also be applied directly to pavement. OBSI in TNM could be effective in calibrating noise models to actual existing traffic noise conditions. Including receptors on both sides of a highway could advance the use of quieter pavements. Accounting for pavement is worthwhile, especially when existing pavement is being replaced with noisier pavement. Finally, TNM Average Pavement should be reconsidered. It's a theoretical pavement and has no cost associated with it, which makes comparing costs of other pavements problematic. TNM Average Pavement is still a good reference point, but it may be better to choose a pavement that would perform like TNM Average with a cost associated to it.

Future refinements worth considering include: develop methods for quantifying and incorporating sound-absorbing pavements in TNM, formal definition of “effectiveness”, and continued research on quieter pavement. It is also worthwhile to work to develop even quieter pavements. All interested parties should read NCHRP Report 738, “Evaluating Pavement Strategies and Barriers for Noise Mitigation”¹³ to access more case studies, examples of LCCA in practice, and more information on the development and application of OBSI in the ground-level source strength (GLSS) modified TNM, referred to in this report as the research version of TNM.

¹³ http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_738.pdf

3 METHODOLOGY CONSIDERATIONS

Workshop participants discussed challenges and potential solutions for implementing the NCHRP 10-76 methodology. This section summarizes the key elements from these discussions, organizing them into specific topic areas.

3.1 ON-BOARD SOUND INTENSITY

On-board sound intensity (OBSI) measures tire-pavement noise using microphones mounted to the outside of a vehicle, near the tire-pavement surface.

Access to OBSI data

Challenge: Many state agencies do not have OBSI measuring capability either internally or through local consultants.

Potential Solutions: Organize a central OBSI database and make it accessible with a proper hosting service. Share OBSI data among states. Demonstrate to states the potential cost savings of considering quieter pavement to justify the cost of equipment and staffhours to collect OBSI data. Make available shared OBSI equipment to states that cannot justify the cost.

OBSI Calibration

Challenge: There is no commercially available method of calibrating an OBSI measuring system, which would be necessary to facilitate exchange of data and potentially implementing pavement noise performance specifications.

Potential Solutions: Continue to conduct OBSI “Rodeos” in which individuals measure OBSI of various pavements at the same time and under the same conditions and compare results, to compare measurements between new and current OBSI users. Develop and maintain calibration systems similar to the prototype system used within the Quieter Pavement Pooled Fund, TPF-5 (135)¹⁴. Develop regional calibration sites in the United States with documented pavement.

Use of OBSI Measurements

Challenge: There is no guidance on how to treat local irregularities in pavement due to, for example, joints or misinstalled pavement in comparison to the average OBSI level of the pavement to use as input into TNM.

Potential Solution: Obtain guidance from FHWA on how to treat these irregularities in the noise impact assessment.

¹⁴ www.wsdot.wa.gov/Business/MaterialsLab/QuieterPavement/QuieterPavementsReports.htm

Challenge: There is no guidance or policy on which year's OBSI data should be used in TNM for the noise assessment. Pavements get noisier over time and need to be assessed for future noise. How many years out is a reasonable assessment year: 7 years, 10 years, ½ pavement life, ¾ pavement life?

Potential Solution: Obtain guidance from FHWA and/or incorporate the assessment year in the state policy.

3.2 PAVEMENT

As-Built Noise Performance

Challenge: The as-built performance of the pavement may not be as good as that used in TNM for the noise assessment.

Potential Solution: Offer incentives for pavement contractors to improve tolerance and add a performance specification for noise performance.

Acoustic Longevity

Challenge: Little acoustic longevity information exists and obtaining OSBI data that is representative of a particular pavement and its durability is a challenge.

Potential Solutions: Share information between states and make existing data more accessible. Collect OBSI data on existing candidate pavements of similar construction that have different ages. Integrate OBSI data collection in FHWA's Long Term Pavement Performance (LTPP) program¹⁵ which currently includes inventory, maintenance, monitoring (deflection, distress, and profile), rehabilitation, materials testing, traffic, and climatic.

Rehabilitation

Challenge: There is little information on pavement rehabilitation cycles for noise and associated costs including maintenance.

Potential Solutions: Share information between states and make existing data more accessible. Develop a common template for tracking costs that can be used and shared across the states.

Challenge: Maintaining funding for pavement rehabilitation for noise may be difficult with respect to other state agencies' concerns.

Potential Solution: Incorporate noise performance into the new performance management system recently established by Congress, which sets standards for pavements and bridges and provides federal aid money to states for maintaining performance.

¹⁵ [http://www.fhwa.dot.gov/research/tfhrc/programs/infrastructure/pavements/ltpp/](http://www.fhwa.dot.gov/research/tfhrc/programs/infrastructure/pavements/ltp/)

Design

Challenge: Some states have little or no experience with quieter pavements.

Potential Solution: Share quieter pavement designs among states so that states without existing quieter designs can use this information to tailor designs for their own state.

3.3 TRAFFIC NOISE MODEL

Use of OBSI in TNM

Challenge: The method for entering OBSI data into TNM is not currently user-friendly or formalized.

Potential Solutions: Update the TNM interface for entering OBSI data. Develop a guidance document that explains the procedures for: 1) requesting a version of TNM that allows OBSI input; 2) processing the data for input into TNM; and 3) entering the data into TNM. Develop/formalize a template in spreadsheet format to process the data needed for input into TNM.

Pavement Sound Absorption

Challenge: The absorptive effect of porous pavements is not accounted for in TNM so some of the noise reduction produced by these quieter pavements is not included in the predicted noise level.

Potential Solution: The research version of TNM includes the absorptive effect of porous pavements by including the proper effective flow resistance (EFR). Information on implementation of the sound absorption should be included in a guidance document.

Training

Challenge: Although TNM training classes are currently available¹⁶, they do not include instruction on the research version of TNM.

Potential Solutions: When the research version of TNM (or a public release version of TNM that includes the pavement effect capabilities) is made available, add OBSI instruction to current TNM training. Conduct a webinar on the use of OBSI and pavement sound absorption in TNM.

Challenge: Broader use of TNM may require more people to be trained. Coverage of expenses for the course, travel, and staff time may be difficult to obtain.

¹⁶ <http://www.fhwa.dot.gov/environment/noise/training/>

Potential Solution: To justify the cost of training, demonstrate to states the potential cost savings that come with considering quieter pavement. In addition, limit training to those who will actually run TNM.

3.4 LIFE CYCLE COST ANALYSIS

Costs

Challenge: Determining costs for use in the life cycle cost analysis (LCCA), particularly for maintenance costs of pavements and barriers, and doing this in a consistent manner within each state can be difficult.

Potential Solution: Set up a pilot program so that a few states can use the NCHRP 10-76 methodology and start to address cost and other issues and share this experience with other states. Develop federal guidelines on what should be included in LCCA for application to quieter pavement and barriers.

Training

Challenge: Some training on the LCCA methodology is available from FHWA¹⁷, however, it is not comprehensive in the area of pavement design, although there are some pavement examples included.

Potential Solutions: Use the FHWA course as an introduction to LCCA along with other instructional material from FHWA and other sources. Set up a pilot program so that a few states can use LCCA and the NCHRP 10-76 methodology and share this experience with other states.

Challenge: Broader use of LCCA may require more people to be trained. Coverage of expenses for the course, travel, and staff time may be difficult to obtain.

Potential Solution: Justify the cost of training by demonstrating to states the potential cost savings that come with considering quieter pavement.

3.5 ORGANIZATION

Responsibility

Challenge: Within an agency, who would have responsibility for implementing a NCHRP 10-76 methodology? It requires both noise and pavement engineers, who typically do not work together.

¹⁷ <https://www.fhwa.dot.gov/infrastructure/asstmgmt/lccafact.cfm>

Potential Solutions: Provide information to the appropriate level of management where both disciplines meet on the methodology and demonstrate the potential project cost savings in potentially shorter or fewer walls if a quieter pavement is selected. Have each agency decide who is responsible and how best to implement the methodology within their organization. Set up a pilot program so that a few states can use LCCA and the NCHRP 10-76 methodology and share this experience with other states.

Workload

Challenge: Implementing the 10-76 methodology will add some additional workload to pavement engineers, noise engineers, or both as more and different data and analysis will be required as well as more collaboration and understanding of each other's issues.

Potential Solutions: Provide information to the agency on the potential project cost savings from considering barriers and quieter pavement together to staff implementation of the methodology; prepare an updated FHWA "Little Book of Quieter Pavements"¹⁸ with a portion dealing explicitly with the 10-76 methodology. Provide Federal level guidance on the use of quieter pavements and barriers for noise abatement to state agencies.

Incentives

Challenge: There is no clear incentive or penalty to encourage states to consider developing and using quieter pavements.

Potential Solutions: Provide information to the state agencies on the potential project cost savings from considering barriers and quieter pavement together. Provide Federal level guidance on the use of quieter pavements and barriers for noise abatement to state agencies.

3.6 POLICY

Effectiveness

Challenge: Unlike the terms "feasible" and "reasonable" in assessing noise abatement, the term "effectiveness" is not a well-defined term in this arena.

Potential Solution: Provide Federal level guidance on "effectiveness" so that state agencies can incorporate the definition into state policy.

Design Goal

Challenge: Quieter pavement may not achieve a 7 dB to 10 dB design goal for reasonableness, however it may produce a "noticeable" 5 dB reduction in some situations, particularly in cases

¹⁸ <http://www.tcpsc.com/LittleBookQuieterPavements.pdf>

where barriers are physically not possible or do not meet the feasible and reasonable requirements.

Potential Solution: Facilitate pilot programs so that states can use LCCA and the NCHRP 10-76 methodology and gain experience to determine if a different noise impact threshold is needed.

Public Perception

Challenge: The public may question the use of shorter or no barriers when quieter pavement is used for noise abatement.

Potential Solution: Develop a layman's version of the FHWA "Little Book of Quieter Pavements" that explains the use and performance of quieter pavement and its role in overall noise abatement and make this available to state agencies for dealing with the public.

4 FINDINGS AND RECOMMENDATIONS

States have been erecting noise barriers along highways for decades. The process is very well advanced, with clear associated costs, technologies, and decision-making analytics. Conversely, quieter pavements are a newer concept, but evidence suggests that they can contribute to noise reduction along with, or in place of noise barriers. Researchers are working to determine how to develop a decision-making analysis that incorporates both noise barriers and quieter pavements, considering the technologies available and the costs involved. The ultimate aim is to implement a method to account for quieter pavement and noise barriers in noise-impact determination and abatement design. Workshop participants reviewed one possible method, NCHRP 10-76, with a focus on what gaps remain, how it can be improved to move forward, and what factors outside of the methodology must be considered for successful implementation.

Technical and communication challenges have been identified that need to be addressed and overcome allowing both noise barriers and quieter pavements to be included in highway noise abatement design and maintenance evaluations. The method presented to evaluate the abatement options should be implemented on a trial basis to help state agencies learn and evaluate the process of the associated pavement life cycle cost analysis and traffic noise prediction methodology, including tire-pavement noise data collection for modeling input. Agencies could then evaluate cross-department (pavement and environment) communication requirements, modeling responsibilities, pavement choice and maintenance in terms of its noise-reducing capabilities, and funding challenges.

It is recommended to:

- Develop and document a noise evaluation process that accounts for both noise barriers and quieter pavements.
- Provide funding and implement the method presented to evaluate the abatement options on a pilot program basis to help evaluate and improve the process.
- Upgrade the public release version of TNM to include the OBSI-related pavement assessment capabilities currently available in the research version of TNM.
- Develop a guidance document that explains the procedures for: 1) requesting a version of TNM that allows OBSI input; 2) processing the data for input into TNM; and 3) entering the data into TNM.
- Develop/formalize a template in spreadsheet format to process the data needed for input into TNM.
- Organize and make publically available national databases for OBSI and LCCA.
- Expand TNM and highway noise abatement training to include consideration of quieter pavements and enable use of the research version of TNM.
- Encourage FHWA to develop guidance on the use of quieter pavements and barriers for noise abatement.
- Incorporate noise performance into new performance management system.
- Develop and provide a noise abatement training program for pavement engineering staff.

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Appendix A. BACKGROUND INFORMATION

Appendix A.1 REVIEW OF THE 2007 COST-BENEFIT ANALYSIS WORKSHOP

Dr. George Maling, *Chair, Technology for a Quieter America Follow-up Team*

Dr. Maling provided a summary of the February 22-23, 2007, workshop that was held at the Volpe National Transportation Systems Center in Cambridge, Massachusetts. That workshop was one in a series held in support of the preparation of the report, “Technology for a Quieter America¹,” and addressed cost-benefit analysis of noise barriers and road surfaces. The workshop was hosted by Gregg Fleming and was chaired by Ian Waitz of the Massachusetts Institute of Technology (MIT).

Dr. Maling’s summary, which begins in the next paragraph, covered the economic issues discussed in the 2007 workshop and other issues shared with him over time.

Economist Sabrina Lovell from the National Center for Environmental Economics (www.epa.gov/economics) at the Environmental Protection Agency (EPA) spoke generally of the agency’s approach to cost-benefit analysis, summarized in its “Guidelines for Preparing Economic Analyses”.² In general, the EPA takes a very broad view of benefits, considering more than monetization of benefits.

John Nelson, at the Pennsylvania State University and author of a book on noise and cost-benefit analysis in the early 1980s, presented several methods for estimating noise damage valuation on neighborhoods³. Damage valuation methods for environmental pollutants and nuisances, such as noise, include Revealed Preference methods (market surveys) and Stated Preference methods (choice surveys). Revealed Preference methods look at the value of homes near noisy highways and compare the prices of similar homes in low-noise areas. Stated Preference methods involve surveys of consumers, asking their willingness to pay for a home within various noise-climates—for example, asking them what they would be willing to pay for a lower noise level. Nelson then talked about the *noise depreciation index*, a popular metric in Europe. It is basically the percentage difference between a home value in a noisy area and one in a quiet area per decibel of the noise level. He gave one example of the noise depreciation index and its relationship to Willingness to Pay.

Judith Rochat, then at the Volpe Center, spoke about approaches to noise abatement, including barriers as well as land use planning and building insulation. She discussed the state of quieter pavements and pilot programs. She presented cost-benefit features of the Federal Highway Administration’s Traffic Noise Model (TNM). Those features include barrier costs, as both costs per square foot and per linear foot; density of housing; decibel (dB) reductions. One important idea was the use of quieter pavements in conjunction with a barrier. Perhaps a lower barrier and quieter pavements might produce the same or a larger benefit than a higher barrier alone. Note that the benefits were not expressed in terms that economists use. She gave some examples of quieter pavements.

¹ Technology for a Quieter America. 2010 http://www.nap.edu/openbook.php?record_id=12928

² Guidelines for Preparing Economic Analyses. 2010
<http://yosemite.epa.gov/ee/epa/eed.nsf/pages/guidelines.html>

³ <http://www.econ.psu.edu/papers/COST-BENEFIT%20ANALYSIS%20AND%20TRANSPORTATION%20NOISE2.pdf>

Rochat also discussed how to integrate pavement noise reductions into the TNM. Where in the model would the benefit provided by the pavement fit? In today's world, the reduction is applied to the source side of the model and not to the receiver side.

Ulf Sandberg from the Swedish National Road and Transport Research Institute spoke of European activities related to cost benefit analysis for noise abatement. He mentioned two project reports. HEATCO (Harmonized European Activities on Transportation Costs) ⁴ and SILVIA—derived from Latin for “quiet roads.”⁵

Sandberg presented one important curve, shown in Figure A-1, which describes monetary evaluation (in Swedish krona (SEK) per year) versus noise level. For example, in terms of 24-hour equivalent sound level, the Willingness to Pay is much higher (equivalent to 970 USD per person per year) at 70 dB than it is (270 USD per person per year) at 60 dB. At louder noises, people are willing to pay more for a decibel reduction of noise.

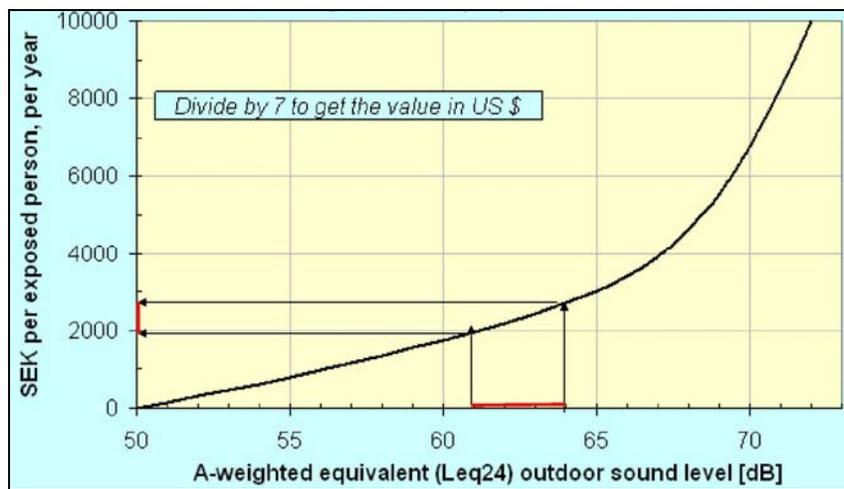


Figure A-1. Sandberg’s monetary evaluation of road traffic noise.

Paul Donovan, with the acoustics firm Illingworth and Rodkin in San Francisco, presented three papers at the workshop. He talked about barriers, cost examples, sources, pass-by levels, and onboard sound intensity. He described several projects in California and Arizona, and gave three examples of highway noise reduction: I-280 in San Mateo (California), State Route 55 and Interstate 5, and a project on a bridge deck.

Then he spoke of trucks and talked about source localization on trucks using directional microphone arrays, tire noise measurements, and then presented information on different tires and different pavements.

Michael Blumenthal from the Rubber Manufacturers Association, said that tires are designed for two purposes: safety and performance. He estimated that revising tire design would only result in a noise reduction of two to three decibels. Instead of focusing on tire design for noise reduction, the RMA has put its energy toward pavement design, including rubber asphalt concrete (RAC). His organization hasn’t been involved in sound studies since 1992, though he was aware of the states that use rubber in pavement, noting that RAC seems to be a good sell.

⁴ <http://heatco.ier.uni-stuttgart.de/>

⁵ <http://www.trl.co.uk/silvia/>

Ulf Sandberg returned to speak about the tire noise labeling in the European Union, noting that he was pretty convinced that the EU's efforts were not very effective. European manufacturers are still resisting meaningful regulations on tire noise

Mark Ferroni of the (FHWA) Highway Administration noted that, according to the National Environmental Policy Act, noise abatement measures are supposed to last in perpetuity. Therefore, life cycle usefulness must be taken into account in cost-benefit analyses. He noted that, according to 23 CFR 772⁶ code and federal regulations, at the time, pavement design was not included as an abatement measure. He had a lot of questions about the lifetime of pavements and the costs to replace them. He talked about what "reasonable" means: when the barrier costs less than a state cost index. He then talked about the current and future FHWA policies.

Mark Swanlund, FHWA, followed with a discussion about onboard sound intensity and quieter pavements. He mentioned the Transportation Pooled Fund Project number TPF-5(135)⁷, the Tire Pavement Noise Research Consortium, which began work in 2007.

Finally, Dr. Maling referred to the work of Jacques Lambert on European cost-benefit analysis studies, published in the proceedings of INTER-NOISE 2005.⁸

⁶ "Procedures for Abatement of Highway Traffic Noise and Construction Noise", Federal Register, Vol. 75, No. 133, 13 July 2010.

⁷ www.wsdot.wa.gov/Business/MaterialsLab/QuieterPavement/QuieterPavementsReports.htm

⁸ Lambert, J., Valuation of the benefits of transportation noise reduction, Proc. IN95, the 1995 International Congress on Noise Control Engineering, pp.1870-1876, Rio de Janeiro, Brazil, 1995. Available in the INCE/USA Digital Library.

Appendix A.2 NOISE BARRIER REVIEW

Dr. Roger Wayson , *U.S. Department of Transportation Volpe Center*

Dr. Wayson described how noise barriers work and what communities can realistically expect from them. Only a portion of the sound waves travel over the noise barrier, reducing noise on the opposite side in an area called the shadow zone. Two things can happen for the portion of the wave that hits the barrier: the noise can be transmitted through the barrier or it can be reflected off of the barrier. The barrier needs to be dense enough so that sound is greatly reduced that goes through the barrier, this is called transmission loss. The reflective wave can add to noise levels on the other side of the roadway. Absorptive treatment has been used to absorb a portion of the sound wave and reduce the reflected wave, reducing the impact on the other side of the roadway.

Some of the sound that travels over the barrier will immediately begin to enter the shadow zone. This frequency dependent curving of the sound wave is called diffraction.

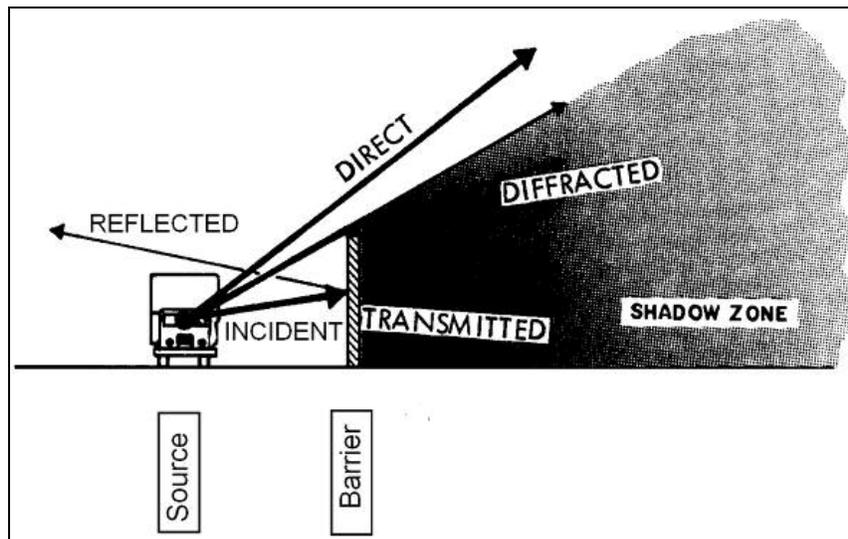


Figure A-2. Possible paths of the sound waves emitted from a vehicle in relation to a noise barrier.

One important consideration is how tall to make the barrier. Some barriers are as tall as 30 feet to try to minimize the sound waves that travel over the barrier. But there are diminishing returns as the height increases and homes become impacted by the physical presence of the barrier, so many states have begun setting limits on height.

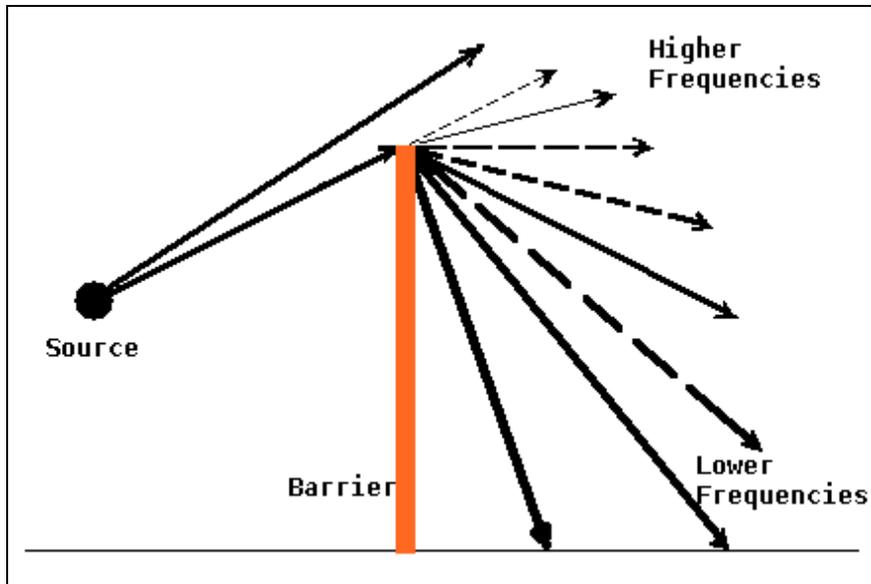


Figure A-3. Noise barriers do a better job of mitigating higher frequency noise. But the lower frequencies, which humans don't hear as well, can still travel down into the shadow zone.

The length of the barrier is also important, as sound can travel around corners. Other considerations include attenuation versus the insertion loss, weighing how much the noise changed once the barrier is in place versus the impact on aesthetics, drainage, etc. Other practical concerns include the terrain, barrier placement, aesthetics, cost, drainage, access, etc.

The people most likely to benefit from a noise barrier are those who live in the first or second row of homes behind the barrier. The negative impacts include loss of view and some consumers complain about a feeling of confinement.

Right now, noise barriers are the most effective way we have for offering noise control for the highway. Barriers have a long life span with extended acoustic durability. But they can be imposing structures. As part of a multifaceted program, they are extremely important.

Appendix A.3 NOISE BARRIER COSTS

Ken Polcak, *Maryland State Highway Administration*

Noise barriers have been erected on U.S. highways for at least 40 years. Today, building a noise barrier costs about \$1 to \$2 million per mile, though there's a large range depending on circumstances. In Maryland, barrier costs were historically \$16 per square foot, but more recent estimates have escalated, up to about \$35 to \$40 per square foot.

The Federal Highway Administration maintains the Triennial Noise Barrier Inventory, a running history of all the barriers constructed by each state. The cost data, however, are not reported in a uniform way. The inventory includes Type 1 projects, which are constructed as part of a highway project, and Type 2, which are stand-alone—a barrier built along an existing highway to deal with noise. Costs vary widely between these two, as some building costs of Type 1 projects can be subsumed in the costs of the highway construction. Costs of noise barrier production can be separated into seven categories: preliminary preparation (mobilization, clearing), drainage, excavation/grading, traffic control/MOT, utilities, barrier system, and landscaping/site restoration. Figure A-4 shows that in Maryland, there has not been a big shift in cost proportions. The barrier system itself is still about two-thirds of the costs.

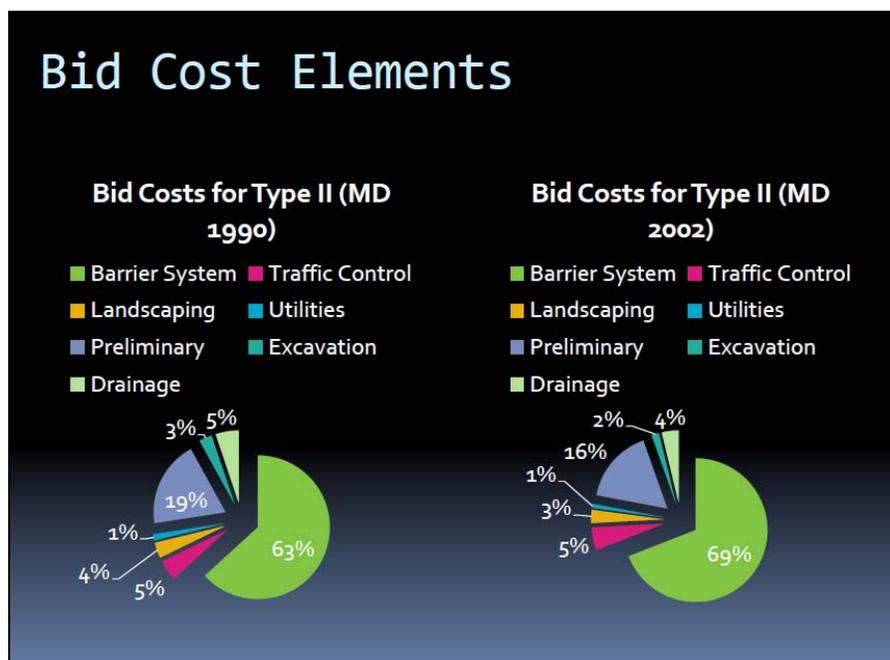


Figure A-4. Cost elements of barrier projects in 1990 and 2002 in Maryland.

Much of the variability in the cost of a project comes during the preliminary stage. Site access is a huge issue. If construction is going to be difficult, because of rock and geotechnical issues, costs will increase. Even the bidding process and competition within a given market have an impact on costs. According to the 2010 Triennial Noise Barrier Inventory, the average initial cost of a barrier was about \$27/square foot. But that figure varies state by state.

Maintenance costs are another consideration and include four factors: graffiti, repair from impact damage, structural deterioration over time, and surface maintenance. In reality, there is very little data available on maintenance costs. Polcak ended by asking: Do we need a national inventory of prevailing cost information for maintenance of noise barriers?

Appendix A.4 QUIETER PAVEMENT REVIEW

Dr. Paul Donovan, *Illingworth & Rodkin, Inc.*

How does quieter pavement work? At highway speeds, above 50 miles per hour, the tire noise dominates the noise emissions from all types of vehicles. At highway speeds, the aim is to reduce tire noise. Studies from California and Arizona indicate that there is a large range of noise performance for different pavements (see Figure A-5), a range of about 13 decibels (from 95 dB to 109 dB). As a result, addressing pavement offers big opportunities for reducing noise.

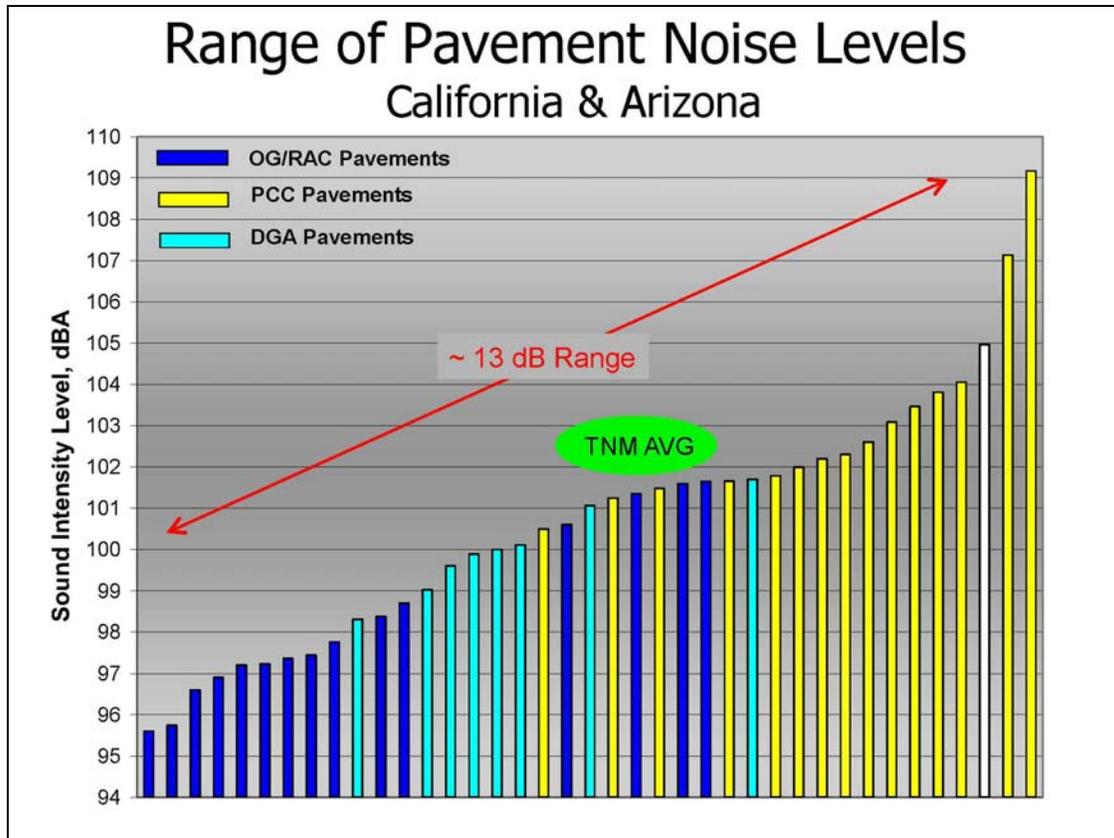


Figure A-5. Range of pavement noise levels, California and Arizona.

OG/RAC = Open-graded asphalt; PCC = Portland cement concrete; DGA = dense-graded asphalt

The noise happens primarily in three ways:

1. As the tire tread hits the pavement, it generates input to the tire, and the tire then radiates sound. This is like a hammer hitting the tire repeatedly. The texture of the pavement also plays a role. A positive texture to the roadway, rising up out of the pavement, impacts the tire and produces noise. A negative texture generates less noise. In general, a negative texture is preferred.
2. Scrubbing involves the relative motion of tread elements against pavement. The tire comes into contact with the roadway, the rubber starts to slip along the pavement and at some point, locks into the pavement. During the time it is slipping, it generates a scrubbing noise, as if rubbing hands against sandpaper. Options to reduce this noise

include increasing local friction of the pavement and increasing roughness, but not to the point of getting a positive texture.

3. Air pumping occurs as air gets rapidly squeezed out around the tread pattern itself as the tire goes in and out of contact with the roadway. It occurs at a higher frequency, like scrubbing, and can be eliminated by adding porosity to the pavement and reduced by a small amount of positive texture so the air isn't trapped as much when the tread pattern comes in contact with the pavement.

What else helps create tire noise overall? What amplifies the noise?

1. The geometry of the tire profile near the patch and pavement creates a wedge shape that is similar to a horn that amplifies the sound being radiated by the tire, particularly in the tread band area. It occurs at higher frequencies because the tire width is relatively narrow from a noise point of view. To reduce the horn effect, we add porosity to the pavement to help absorb and attenuate some of the sound.
2. Organ pipes are formed from grooves or channels in the tire footprint and these radiate sound out from the channels at mid frequencies. This can be reduced by porosity and adding negative texture to the pavement to reduce tire vibration.

Different types of pavement

Hot-mix asphalt. These include dense-graded asphalt, stone matrix asphalt, and open-graded asphalt. For quieter pavements, there are a range of materials and mixes.

Stone matrix asphalt can be one of the quieter options. With smaller stone size, modified binder, and a filler of manufactured sands and minerals, it can have a more negative texture, reducing inputs to the tire and producing less noise.

Rubberized asphalt, first used in Europe, is a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 percent by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles. Rubberized asphalt is becoming common in Arizona, California, Nevada, and Texas.

Open-graded asphalt is the most common quieter pavement. It allows some relief of noise via reduced air pumping and reduced horn effect. With voids in the pavement, air and water can penetrate it and splash and sprays can be reduced, since water can drain through the pavement. Some European countries use double layer asphalt pavement – a top layer that is relatively fine aggregate to minimize the surface texture and a larger aggregate below to maximize drainage through the pavement.

Concrete. The most common types are jointed plain concrete pavement and continuously reinforced concrete pavement. Less common are jointed reinforced concrete pavement and precast concrete pavement. Joints in the concrete can add to noise. One quieter pavement texture is longitudinally tined pavement, which is currently recommended by the Federal Highway Administration, instead of noisier transverse tine. Adding longitudinal tines is a good solution, because anytime a cement surface is poured, texture must be added, so it's inexpensive to add texture that reduces noise.

Diamond grinding is probably the quietest concrete surface texture available. This is a surface is added after the pavement is down and initially textured in some other manner. It is often used

for pavement maintenance, to reduce tire inputs at joints that can be caused by the pavement slabs warping. It can also improve skid performance of pavements that have become polished.

A newer, Next-Generation Concrete Surface (NGCS) involves a specialized grinding technique often done in two or three passes over the surface. Fine textured grinding is done in between wider-spaced grooves. A number of states have had pretty good success with this type of surface for reducing noise and for addressing safety concerns.

Noise measurement methods

How is tire pavement noise quantified? The American Association of State and Highway Transportation Officials (AASHTO) has developed a series of standards for this over the past decade.

AASHTO TP 99 — Continuous-Flow Traffic Time-Integrated Method (CTIM) Procedure measures the effect of pavement on traffic noise at a given site when a new pavement surface is installed and also provides comparison over time as the pavement ages.

AASHTO TP 98 — Statistical Isolated Pass-By (SIP) Procedure measures the average effect of pavement on vehicle pass-bys by acoustically isolating each vehicle type to get noise level as a function of speed at a fixed distance from the roadway.

AASHTO TP 76 — On-Board Sound Intensity (OBSI) Procedure measures the effect of pavement directly on tire noise with an onboard measurement, utilizing microphone pairs right at the tire-pavement interface to isolate tire pavement noise

Quieter Pavement Performance

A study measured noise after a pavement-resurfacing project on Highway 101 in Marin County, California. An old dense-grade asphalt (DGAC) was replaced with an open-grade asphalt (OGAC). Measured 60 feet away from the highway at two different heights, noise dropped about 10 to 11 decibels (dB) from previous measures (see Figure A-6). Good barrier performance is 10 dB. So the pavement improvement offered about the same noise reduction as a barrier provides.

In a second project, Interstate 80 near Davis, California, had a dense grade pavement overlaid with open-grade asphalt. The reduction was about 5 dB with the overlay, which would be a noticeable change for a neighborhood.

A more dramatic effect was seen in the Arizona Quiet Pavement Pilot Program. A transverse tine PCC was overlaid with rubberized asphalt (ARFC). A 9 dB reduction was seen. Relative to the FHWA Traffic Noise Model (TNM), which uses an average pavement for noise prediction, the new pavement was about 8 dB quieter than what would be predicted for assessing noise impact (see Figure A-7).

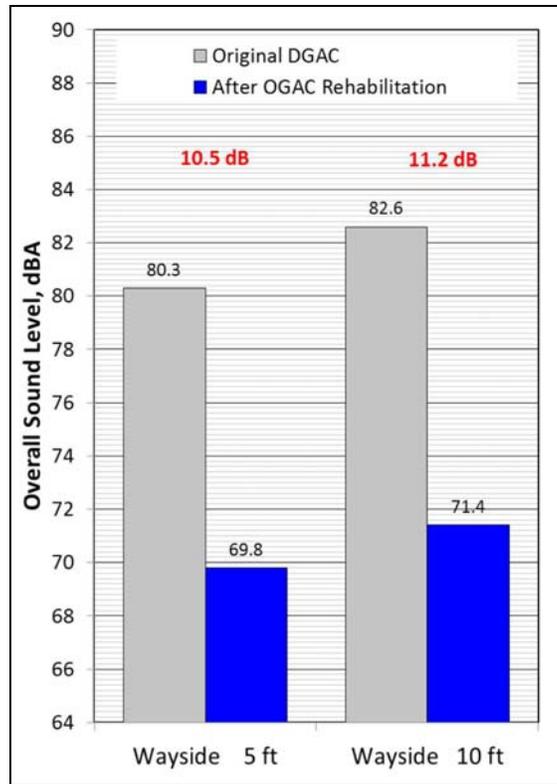


Figure A-6. Noise reduction 60 feet from the highway at two heights after a change from DGAC to OGAC.

Benefits of quieter pavement

Quieter pavement is not sensitive to site constraints that may hamper installation of barriers, such as cross streets, utilities, etc. It also addresses both sides of the freeway. Quieter pavement offers substantial savings over barrier erection in terms of initial costs (see Table A1). One drawback is acoustic longevity. Over time, quieter pavement will get noisier. So the cost benefit degrades with time.

From work in Arizona and California, quieter asphalt degrades about 0.3 to 0.8 dB per year. For concrete, degradation is less, about 0.1 to 0.35 dB per year. This depends on average traffic density—the more traffic, the higher the rate of degradation. Maintaining performance means doing rehabilitation, either overlaying or grinding concrete. Barriers, on the other hand, need less maintenance to keep up their performance.

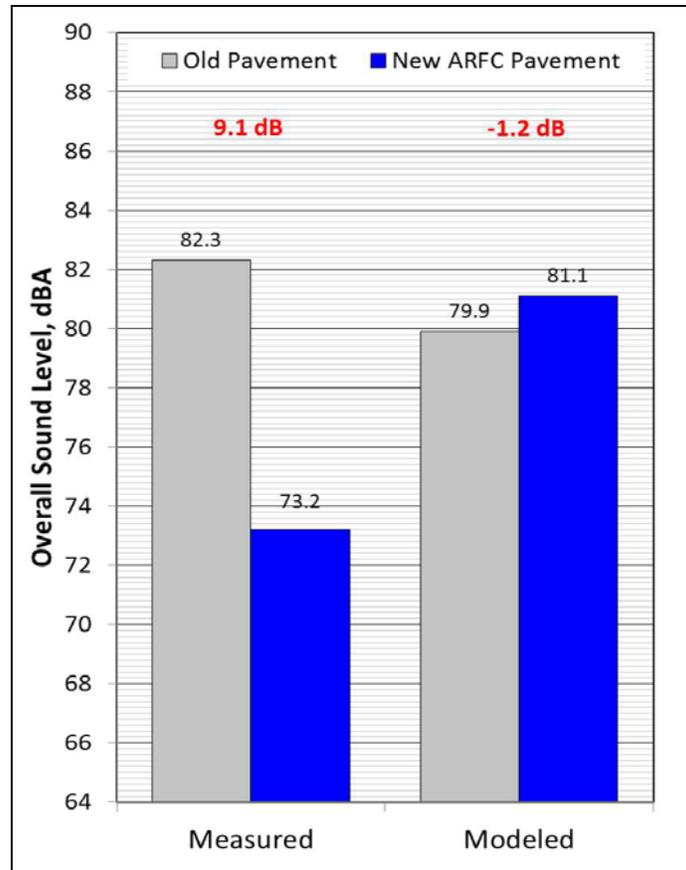


Figure A-7. Changing from older pavement to rubberized asphalt resulted in a larger noise reduction than expected from modeling.

Table A-1. Initial costs of quieter pavement vs. barrier construction

➤ Barrier application
○ 12 ft barrier, 2 sides of the highway, US average cost of \$27/sq ft
○ \$3,421,440 per mile
➤ Quieter pavement overlay (ARFC)
○ 1 inch thick, 6-lane highway
○ \$1,118,000 per mile

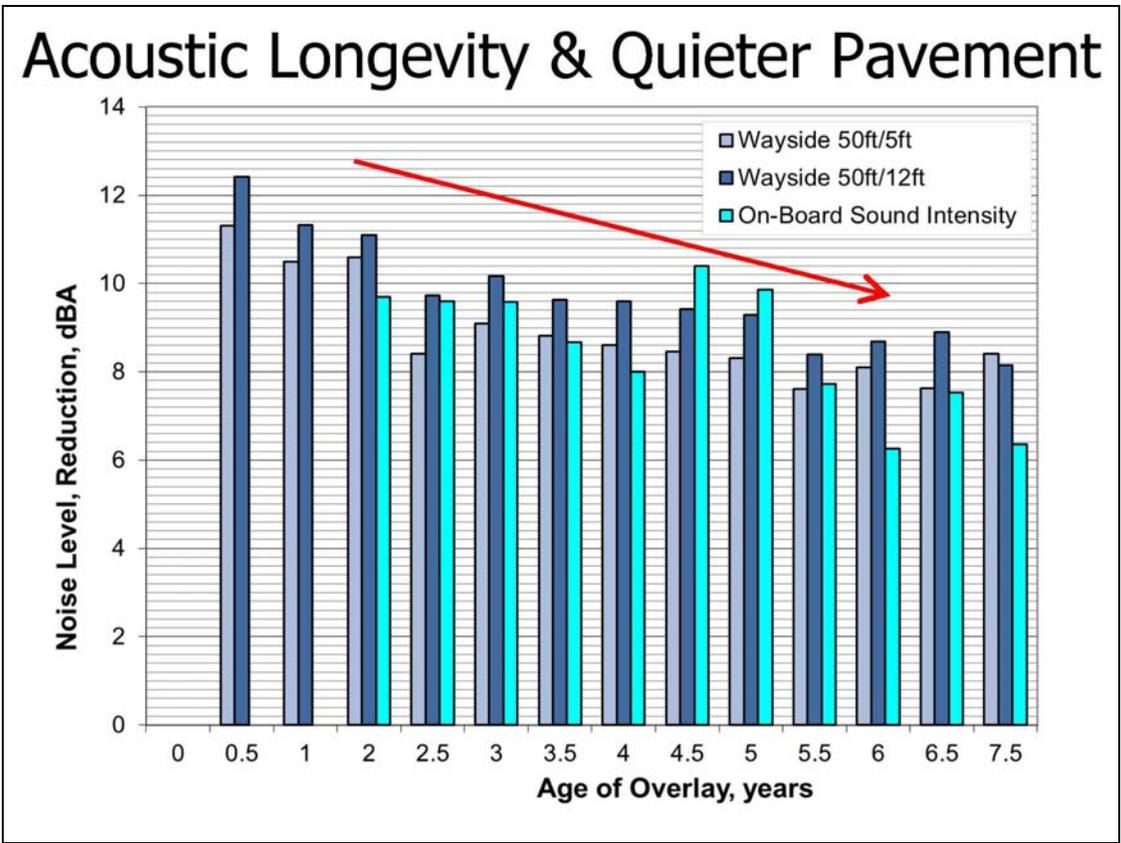


Figure A-8. Noise reduction decreases as pavement ages.

Appendix A.5 CURRENT CONSIDERATION OF COST-BENEFIT ANALYSIS FOR HIGHWAY TRAFFIC NOISE

Adam Alexander, *Federal Highway Administration*

Adam Alexander described how the Federal Highway Administration (FHWA) currently treats highway traffic noise analysis and abatement. The FHWA's determination process asks three questions:

Are Title 23 funds involved with the project? Does FHWA have to approve some component of the project? Will the project result in noise impacts? If impacts are expected, is abatement feasible (feasibility refers to the combination of acoustical and engineering factors considered in the evaluation of a noise abatement measure [23 CFR 772.5])? Is abatement reasonable?

FHWA's highway traffic noise regulation 23 CFR 772.13(A) also requires testing for reasonableness, which is the combination of the overall social, economic, and environmental effects of abatement. The reasonableness assessment on abatement is a three-part test. Is the cost reasonable? Is the design goal reasonable? What are the viewpoints of those who will benefit from abatement – business owners and residents?

A substantial reduction in noise must be accomplished. FHWA will count the number of "benefited receptors". In the regulation, a "*benefited receptor*" is defined as the recipient of an abatement measure that receives a noise reduction at or above the minimum threshold of 5 dB, but not to exceed the highway agency's reasonableness design goal. It is possible for a receptor to experience a noise impact and not receive a benefit from noise abatement and for non-impacted receptors to benefit from abatement.

Cost reasonableness is measured three ways:

1. Cost per benefited receptor. This number is established by the state in its noise policy, usually the cost of abatement divided by the number of receptors predicted to benefit. If the number is below a threshold, the abatement is approved.
2. Cost per decibel of reduction divided by benefited receptor. Massachusetts uses this calculation.
3. The newest approach aims to make a state's policies inflation-proof; they provide a quantity and square footage per benefited receptor. With this approach, decisions are consistent over time, so that even though there may be inflationary effects for the unit costs of noise abatement measures, they know from one project to the next, and year-to-year, they are offering the same opportunity for abatement on every project.

FHWA established the cost per benefited receptor option, or the value, as part of the 1995 guidance document on 23 C.F.R. 772⁹. At the time, the agency solicited the states to ask what they were spending on abatement, and the costs ranged from \$15,000 to \$50,000 per benefited receptor. So the guidance recommends that states should not spend beyond \$15,000 to \$50,000 per benefited receptor for abatement. There hasn't been a real effort to look at economic benefits of abatement beyond the historical costs.

⁹ 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 abatement measures, it does not include pavements as a noise abatement measure.

When FHWA updated its noise policies in 2011 in response to regulatory changes in 2010¹⁰ states were asked to update their cost reasonableness criteria. States were not supposed to exceed \$50,000 per benefited receptor, although 6 states did (see Table A2).

Table A-2. Cost reasonableness criteria ranges among states.

Cost Range	Number of States
\$20,000 - \$25,000	12
\$20,001 - \$35,000	10
\$35,001 - \$50,000	14
Greater than \$50,000	6
Sq. ft. per benefitted receptor	5
Cost per insertion loss ¹¹ per benefitted receptor	4

Some states use a tiered approach. For example, Tennessee starts with a basic quantity of square feet. For neighborhoods that predate the interstate or adjacent highway, the state gives a bonus quantity of square feet per benefited receptor. Indiana also uses a base of \$25,000 per benefited receptor, but increases the allowable cost to \$32,500 for any location that predates the highway. Some states allow a bonus amount to be spent in areas with noise levels predicted to be high in the future. Finally, states can average a “cost common noise environment”. For example, four neighborhoods between two interchanges might average the cost for the benefited receptor so that one location may be over the cost criteria, but it can get abatement if an adjacent neighborhood is well below the cost criteria.

¹⁰ www.federalregister.gov/articles/2010/07/13/2010-15848/procedures-for-abatement-of-highway-traffic-noise-and-construction-noise#)

¹¹ Insertion loss is defined as the difference in sound level at a receiver location with and without the presence of a noise barrier, assuming no change in the sound level of the source.

Appendix B. WORKSHOP AGENDA

**Cost Benefit Analysis - Noise Barriers and Quieter Pavements
A TQA Follow-up Workshop
Keck Center, National Academy of Engineering, Washington, DC
January 16, 2014**

8:30-8:55 am	<p>Welcome and Introductions Dr. Proctor Reid <i>Program Director, National Academy of Engineering</i></p> <p>Gregg Fleming <i>Workshop Chair Director, Environmental and Energy Systems, US DOT Volpe Center</i></p> <p>Eric Wood <i>Principal, Acentech Member, Technology for a Quieter America Follow-up Team President, Institute of Noise Control Engineering of the USA President, Institute of Noise Control Engineering Foundation</i></p> <p>Meghan Ahearn <i>Workshop Secretary US DOT Volpe Center</i></p> <p>Participant Introductions</p>
8:55-9:15 am	<p>Review of Cost Benefit Analysis Concepts From the TQA Report and 2007 Workshop Dr. George Maling <i>Chair, Technology for a Quieter America Follow-up Team</i></p>
9:15-9:35 am	<p>Noise Barrier Review Dr. Roger Wayson <i>US DOT Volpe Center</i></p> <p>Ken Polcak <i>Maryland State Highway Administration</i></p>
9:35-10:15 am	<p>Quieter Pavement Review Dr. Paul Donovan <i>Illingworth & Rodkin, Inc.</i></p>
10:15-10:35 am	<p>Current Consideration of Cost-Benefit Analysis for Highway Traffic Noise Adam Alexander <i>Federal Highway Administration</i></p>
10:35-10:50 am	Break
10:50-11:00 am	Overview of the NCHRP 10-76 Methodology

	Dr. Paul Donavan <i>Illingworth & Rodkin, Inc.</i>
11:00-11:15 am	Application of the FHWA Pavement Life Cycle Cost Analysis Dr. Linda Pierce <i>Applied Pavement Technology</i>
11:15-11:40 am	Application of OBSI in TNM Example Case of New Highway Construction Dr. Judith Rochat <i>ATS Consulting</i>
11:40-12:00 pm	Example Cases of Highway Widening Projects Dana Lodico <i>Lodico Acoustics LLC</i>
12:00-12:15 am	Observations from Example Case Studies and the NCHRP 10-76 Project Dr. Paul Donavan <i>Illingworth & Rodkin, Inc.</i>
12:15-12:30 pm	Description and organization of groups for break-out sessions. The smaller groups will discuss each topic concurrently during the break-out sessions.
12:30-1:30 pm	Lunch
1:30-2:30 pm	<u>Break-out session: Part 1 (Cafeteria)</u> Potential gaps and challenges with the NCHRP 10-76 method
2:30-2:45 pm	Break
2:45-3:45pm	<u>Break-out session: Part 2 (Cafeteria)</u> Discuss and list potential ways to address gaps and challenges in implementation
3:45-5:15 pm	Report back from break-out sessions and next steps (Room 101)
5:15-5:30 pm	Closing Meghan Ahearn <i>Workshop Secretary</i> <i>US DOT Volpe Center</i> Eric Wood <i>Principal, Acentech</i> <i>Member, Technology for a Quieter America Follow-up Team</i> <i>President, Institute of Noise Control Engineering of the USA</i> <i>President, Institute of Noise Control Engineering Foundation</i>

Appendix C. WORKSHOP PARTICIPANTS

Cost Benefit Analysis - Noise Barriers and Quieter Pavements
A TQA Follow-up Workshop
Keck Center, National Academy of Engineering, Washington, DC
January 16, 2014

Meghan Ahearn US DOT / Volpe Center	Bob Orthmeyer FHWA
Noel Alcalá Ohio DOT	Linda Pierce Applied Pavement Technology
Adam Alexander FHWA	Ken Polcak Maryland State Highway Administration
Mariano Berrios Florida DOT	Judith Rochat ATS Consulting
Nathaniel Coley FHWA	Bruce Rymer Caltrans
Paul Donavan Illingworth & Rodkin	Brian Schleppe Ohio DOT
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Appendix D. ACRONYMS AND DEFINITION OF TERMS

Cost Benefit Analysis - Noise Barriers and Quieter Pavements

A TQA Follow-up Workshop

Keck Center, National Academy of Engineering, Washington, DC

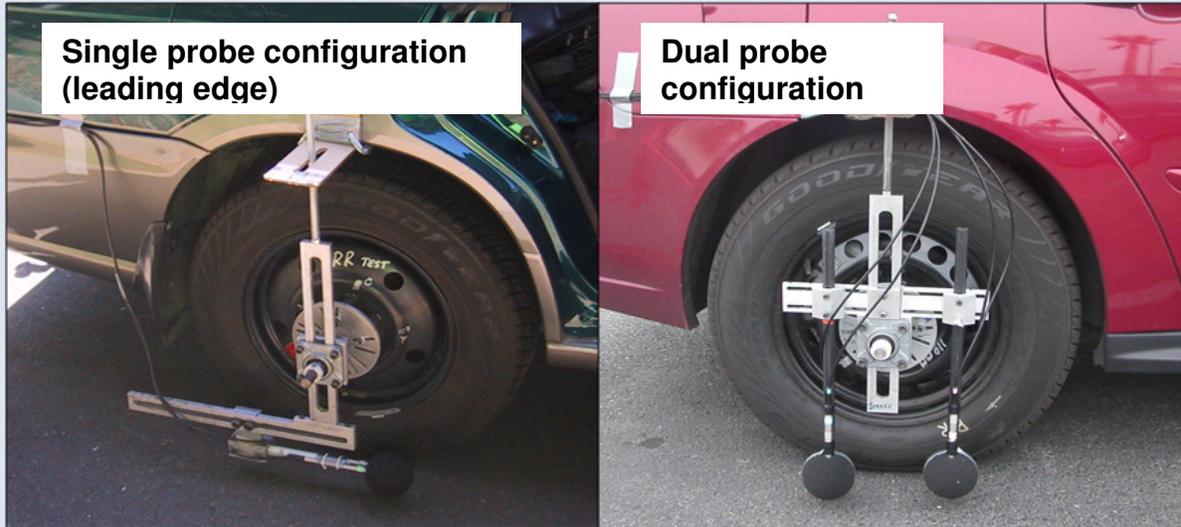
January 16, 2014

Acronyms

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ADOT	Arizona State Department of Transportation
ARFC	Asphalt Rubber Friction Course
Caltrans	California State Department of Transportation
CFI	Cost Effectiveness Index
CTIM	Continuous-Flow Traffic Time-Integrated Method
DGAC	Dense-graded Asphalt Concrete
EFR	Effective Flow Resistivity
EUAC	Equivalent Uniform Annual Cost
FHWA	Federal Highway Administration
GLSS	Ground-level Source Strength
HMA	Hot Mix Asphalt
IDOT	Illinois State Department of Transportation
LCCA	Life Cycle Cost Analysis
LT	Longitudinal Tines
MDOT	Michigan State Department of Transportation
NAC	Noise Abatement Criteria
NCHRP 10-76 Project	Methodologies for Evaluating Pavement Strategies and Barriers for Noise Mitigation
NCHRP	National Cooperative Highway Research Program
NPV	Net Present Value
OBSI	On-board Sound Intensity
ODOT	Ohio State Department of Transportation
OGAC	Open-graded Asphalt Concrete
PCC	Portland Cement Concrete
PV	Present Value
QPPP	Quiet Pavement Pilot Program
RAC(O)	Open-graded Rubberized Asphalt Concrete Pavement
REMEL	Reference Energy Mean Emission Levels
SHA	State Highway Agency
SPB	Statistical Pass-by
SRTT	Standard Reference Test Tire
TNM	Federal Highway Administration Traffic Noise Model
WSDOT	Washington State Department of Transportation

Technical Terms

Benefited receptor	The recipient of an abatement measure that receives a noise reduction at or above the highway agency's chosen threshold value.
Feasibility	The combination of acoustical and engineering factors considered in the evaluation of a noise abatement measure.
Federal Highway Administration Traffic Noise Model	The state-of-the-art computer program authorized by the FHWA for use in predicting noise impacts in the vicinity of highways including the design of effective, cost-efficient highway noise barriers. Available from the FHWA at: http://www.fhwa.dot.gov/environment/noise/traffic_noise_model/purchasing_tnm/
Microphone array	The use of multiple microphones and analysis of the signals to help define locations of specific noise sources.
Noise abatement criteria	Hourly A-weighted sound levels for various categories of land uses above which reasonable and feasible noise abatement measures are to be addressed. Noise abatement criteria represent the upper limit of acceptable highway traffic noise for different types of land uses and human activities.
Noise impact	Highway traffic noise impacts occur if the project design year predicted noise levels approach or exceed the noise abatement criteria or create a substantial noise increase over existing levels.
Noise reduction design goal	The minimum required noise reduction determined from calculating differences between future noise levels with and without abatement.
Onboard sound intensity method	The use of a pair of microphones located adjacent to the tire-pavement interface (contact patch) to quantify radiated sound.
Pavement tines	Surface texture for pavements including spacing depth, width, and direction of tine patterns. Information about surface textures for asphalt and concrete pavements is available at the FHWA website.
Reasonableness	The combination of social, economic, and environmental factors considered in the evaluation of noise abatement measures.
Reasonableness allowance	Each highway agency is required to incorporate a cost index in their highway traffic noise policy. Most highway agencies typically determine reasonable cost by using either a cost/receptor or cost/receptor/dB reduction index. Some States use a maximum square footage per benefited receptor unit.
Reference energy mean emission level database	Database of highway vehicle sound levels that have been measured and are associated with five vehicle types (automobiles, medium trucks, heavy trucks, buses, and motorcycles) as part of the FHWA Traffic Noise Model. Measurement methods are defined at the FHWA website.
Standard reference test tire	A tire that is produced, controlled, and stored in accordance with applicable standards.



On-Board Sound Intensity (OBSI) probes are used for the measurement of tire/pavement noise at the source from automobiles and trucks operating at speeds up to 60 mph (100 km/hr). Measurements using the OBSI probes are leading to better understanding of tire/pavement noise generation and radiation for a wide range of pavement types and are providing the information and insights needed for developing quieter tires and pavements.



During the past 50 years, state transportation departments have constructed more than 3000 miles of barriers along U.S. highways as a noise abatement measure

This report describes and recommends an updated noise evaluation process that accounts for both noise barriers and quieter pavements.