

International Technology Exchange Program

QUIET PAVEMENT SYSTEMS IN EUROPE



U.S. Department of Transportation
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N O T I C E

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16. Abstract Noise pollution is a growing concern in the United States. A major contributor of highway noise is at the tire-pavement interface, which means that quieter pavements could lead to reductions in traffic-generated noise. The Federal Highway Administration, American Association of State Highway and Transportation Officials, and National Cooperative Highway Research Program sponsored a scanning study of quiet pavement systems used in Europe to reduce traffic noise. All of the countries the scan team studied—Denmark, France, Italy, the Netherlands, and the United Kingdom—have policies requiring consideration of quiet pavement where noise is a concern. The focus is on three technologies—thin-surfaced, negatively textured gap-graded asphalt mixes, single- and double-layer highly porous asphalt mixes, and exposed aggregate concrete pavements. The countries are conducting extensive research on quiet pavement technology. The team's recommendations for U.S. implementation include evaluating the use of double-layer porous asphalt mixes to reduce noise on high-speed roadways, reducing the size of the aggregate used in mixes applied to the wearing surface, and trying thin-textured surfacing using a small aggregate in urban and other areas with lower traffic speeds. The team also recommends assembling a team of acoustical experts and pavement engineers to develop protocols for measuring the acoustical performance of quiet pavements.					
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**Prepared by the
International Scanning
Study Team:**

David C. Gibbs (Cochair)
FHWA

Randell H. Iwasaki (Cochair)
California DOT

Robert J. Bernhard
Purdue University

James F. Bledsoe
Missouri DOT

Douglas D. Carlson
Rubber Pavements Association

Christopher Corbisier
FHWA

Kenneth W. Fults
(Report Facilitator)
University of Texas

Thomas M. Hearne, Jr.
North Carolina DOT

Kevin W. McMullen
*Wisconsin Concrete
Pavement Association*

David E. Newcomb
*National Asphalt Paving
Association*

John H. Roberts
IGGA/ACPA CRP Division

Judith L. Rochat
U.S. DOT

Larry A. Scofield
Arizona DOT

Mark E. Swanlund
FHWA

and

American Trade Initiatives, Inc.
LGB & Associates, Inc.

for the

Federal Highway Administration
U.S. Department of Transportation

American Association of
State Highway and
Transportation Officials

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FHWA INTERNATIONAL TECHNOLOGY EXCHANGE PROGRAM

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The main channel for accessing foreign innovations is the International Technology Scanning Program. The program is undertaken jointly with the American Association of State Highway and Transportation Officials (AASHTO) and its Special Committee on International Activity Coordination in cooperation with the Transportation Research Board's National Cooperative Highway Research Program Project 20-36 on "Highway Research and Technology—International Information Sharing," the private sector, and academia.

FHWA and AASHTO jointly determine priority topics for teams of U.S. experts to study. Teams in the specific areas being investigated are formed and sent to countries where significant advances and innovations have been made in technology, management practices, organizational structure, program delivery, and financing. Scanning teams usually include representatives from FHWA, State departments of transportation, local governments, transportation trade and research groups, the private sector, and academia.

After a scan is completed, team members evaluate

findings and develop comprehensive reports, including recommendations for further research and pilot projects to verify the value of adapting innovations for U.S. use. Scan reports, as well as the results of pilot programs and research, are circulated throughout the country to State and local transportation officials and the private sector. Since 1990, FHWA has organized more than 60 international scans and disseminated findings nationwide on topics such as pavements, bridge construction and maintenance, contracting, intermodal transport, organizational management, winter road maintenance, safety, intelligent transportation systems, planning, and policy.

The International Technology Scanning Program has resulted in significant improvements and savings in road program technologies and practices throughout the United States. In some cases, scan studies have facilitated joint research and technology-sharing projects with international counterparts, further conserving resources and advancing the state of the art. Scan studies have also exposed transportation professionals to remarkable advancements and inspired implementation of hundreds of innovations. The result: large savings of research dollars and time, as well as significant improvements in the Nation's transportation system.

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ACRONYMS AND ABBREVIATIONS

AASHTO American Association of State Highway and Transportation Officials

AB Asphalt base

ADT Average daily traffic

CPB Controlled pass-by

CPX Close-proximity methodology

CRCP Continuously reinforced concrete pavement

CRTN Calculation of road traffic noise

DA Drainage (porous) asphalt

DAC Dense asphalt concrete

DGA Dense-grade asphalt

DKK Danish krone

DOT Department of transportation

DRAST Direction de la Recherche et des Affaires Scientifiques et Techniques (France)

DRI Danish Road Institute

DWW Rijkswaterstaat (Dienst Weg-en Waterbouwkunde Rijkswaterstaat, Ministerie van Verkeer en Waterstaat—Ministry of Transport, Public Works, and Water Management, the Netherlands)

EAC Exposed aggregate concrete

ECI Early contractor involvement

END Environmental Noise Directive

EU European Union

FHWA Federal Highway Administration

HAPAS Highway Product Approval System

HARMONOISE Harmonised, Accurate, and Reliable Prediction Methods for the EU Directive on the Assessment and Management of Environmental Noise

HMA Hot mix asphalt

HRA Hot rolled asphalt

IMAGINE Improved Methods for the Assessment of the Generic Impact of Noise in the Environment

IPG Innovation Program (the Netherlands)

ISO International Organization for Standardization

LCPC Laboratoire Central des Ponts et Chaussées (France)

MLS Multiple load simulator

MPD Mean profile density

NORD2000 Scandinavian traffic noise prediction model

OEM Original equipment manufacturer

PA Porous asphalt

PCC Portland cement concrete

PERS Poroelastic road surface

PIARC World Road Association

PM Pavement management

PREDIT Program of Research, Experimentation, and Innovation in Land Transport

R&D Research and development

RTF Roads to the Future program (the Netherlands)

SMA Stone mastic asphalt

SEL Sound exposure level

Sétra Service d'Etudes Techniques des Routes et Autoroutes (France)

SILVIA Silenda Via (Sustainable Road Surfaces for Traffic Noise Control)

SIRUUS Silent Roads for Urban and Extra-Urban Use

SPB Statistical pass-by

SPBI Statistical pass-by index

SRM2 Dutch noise prediction model

TLPA Two-layer porous asphalt

TRL Transport Research Laboratory (United Kingdom)

U.S. DOT U. S. Department of Transportation

VINNOVA Swedish Agency for Innovation Systems

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EXECUTIVE SUMMARY

INTRODUCTION

In the United States, the primary noise mitigation strategy for highway operations has been construction of noise barrier walls. However, these sound walls are expensive to build (often \$1 million to \$2 million per mile) and expensive to maintain. Graffiti is a major maintenance issue for highway personnel, prompting frequent complaints and requiring the redirection of precious transportation resources. In addition, the noise benefit of barrier walls is limited, often to less than 400 meters (m) from the roadway.

Prompted in part by the increasing cost of and concern about the effectiveness of sound walls, a growing number of engineers have turned their attention to attacking the noise problem at its source. Source control strategies include quieter vehicles and tires, speed control, additional building insulation, more aggressive building codes for new construction, zoning or right-of-way purchase, and quiet pavements. Many of these alternatives have been investigated with mixed results. For example, new tire designs have produced quieter tires, but the trend toward wider tires for improved handling and skid resistance has essentially negated this noise-reduction benefit. Limited use of quiet pavement in the United States has shown that this approach has potential. Quiet pavement has a longer history in Europe, and the experience of highway agencies there is valuable in determining the benefit of quiet pavements as the preferred alternative in reducing highway noise. The objective of the quiet pavements scan team was to visit countries with the most experience in quiet pavement technology and learn from their experience.

The systematic reduction of noise associated with roadway operations has been a critical issue in Europe for more than 20 years. Countries in the European Union (EU) have agreed to map noise contours along all existing roadways by 2007. These maps will be made available to the public. Each country will develop an action plan to address problems identified in the noise map. Most countries have aggressive policy directives to limit noise along newly constructed facilities.

In many EU countries, new quiet pavement alternatives are being used as one of the technologies to address noise problems.

The quiet pavements scan team was composed of a cross section of State, Federal, academic, and industry representatives. The team visited five countries over a 17-day period. The study design was based on a comprehensive desk scan of published research summarizing where the technology was most used, where it was first used, and where innovation was still being explored. Although the team had several countries from which to choose, it selected five that it visited in the following order: Denmark, the Netherlands, France, Italy, and the United Kingdom. This sequence was established in an effort to reduce travel time, maximize meeting time with experts, and visit field sites in each country. While in transit from the Netherlands to France, six team members visited several sites in Belgium. A summary of the visit to Belgium is included in Appendix A.

SIGNIFICANT FINDINGS

Although the full report explores in detail the many significant findings by the team, the following were deemed to be of high general interest to executive or policy implementation readers:

1. **Policy**—Highway pavement noise has been studied in Europe for more than two decades. Policies have been developed to mitigate noise through an integrated approach that encourages use of quieter pavements. All of the countries the team visited have implemented policies that require consideration of quiet pavement where noise is anticipated to be a concern.

In addition, on June 25, 2002, EU implemented a significant Environmental Noise Directive that requires all member countries to do the following:

- A. Determine exposure to environmental noise through noise mapping, including rural areas.
- B. Use uniform prediction methods of assessment common to the members.
- C. Ensure that information on environmental noise is made available to the public.
- D. Adopt action plans based on noise-mapping

results, with a view toward preventing and reducing environmental noise.

The directive requires all member countries to complete strategic noise maps and adopt action plans by June 30, 2007.

As is often the case in the United States, implementation budgets for the countries visited were much smaller than deemed necessary to implement the policy directive totally. The primary implementation funds were carved out of the existing construction budget, but a designated funding source did add status to the policy and direction to the program. The quieter surfacing costs were about 10 to 25 percent more than traditional surfacing.

2. **Design**—The focus of the European effort is contained in three major quiet pavement technologies: thin-surfaced, negatively textured gap-graded asphalt mixes (such as Novachip, microsurfacing, and some stone mastic asphalt (SMA)); single- and double-layer highly porous asphalt mixes (greater than 18 percent voids); and exposed aggregate concrete (EAC) pavements. The emerging trend is to use the thin-surfaced, gap-graded mixes with small aggregate in urban areas and areas subject to severe winter snow and ice accumulations. More porous gap-graded asphalt surfaces are used on rural and high-speed facilities with moderate winter conditions. EAC can be used where concrete pavement surfacing is allowed. Many highway projects are specified using performance specifications and are selected using best-value contracting methods. In many cases, pavement vendors respond to agency performance criteria with innovative solutions that often carry unequal risk, but if found effective, can be held proprietary for future project applications.
3. **Noise Analysis**—The source level of quiet pavements is being incorporated into existing highway noise prediction models using varying methodologies. HARMONOISE (Harmonised, Accurate, and Reliable Prediction Methods for the EU Directive on the Assessment and Management of Environmental Noise), the common EU model being developed, will incorporate pavement type in the prediction, along with other advanced prediction parameters such as meteorological effects. To determine the noise benefit of pavements, most countries use multiple methods, including statistical pass-by (SPB) (ISO 11819-1), close proximity (CPX) (ISO 11819-2), and various controlled pass-by (CPB) methods, along with pavement sound absorption measurements. Each method has different

strengths. In terms of vehicle types, the influence of quiet pavements on heavy vehicles is less well understood than for light vehicles; this topic is being investigated. Pavement noise benefits of as little as 2 decibels (dB) are being used in integrated noise strategies.

4. **Construction**—Normal construction equipment and technology are used to construct quiet pavements. Porous asphalt (PA) mixes are used only on pavements that are structurally sound. Other defects in the underlying pavement must be minimal. Vehicle spray reduction and improved skid resistance are the two main reasons that porous surfaces were first used in each of the five countries. Noise reduction was a side benefit in the effort to produce a safer pavement during wet weather conditions. Contrary to normal practice in the United States, factors other than low bid are considered when awarding pavement construction contracts. Also, a contractor warranty of at least 3 years is typically included in the contract.
5. **Maintenance**—Minor disagreements persist about effective maintenance of these negatively textured and often highly porous pavements. Although some countries require pressure washing and vacuuming of the pavements at least twice a year, other countries contend that the practice may not only be useless, but perhaps even harmful. The team was unable to discover any reliable data to substantiate either claim. Winter maintenance remains a challenge, especially on the highly porous pavements. Winter maintenance relies on advanced use of prewetted salt to fight formation of black ice on the highly porous pavements, resulting in a winter maintenance cost increase of 25 to 50 percent. Some countries have stopped using highly porous pavements in snow and ice regions, and instead are using SMA-type pavements with small aggregate.
6. **Research**—Perhaps the most impressive finding of the team relates to the extensive amount of research on quiet pavement technology underway in the countries visited, including Roads to the Future (RTF); Silent Roads for Urban and Extra-Urban Use (SIRUUS); Program of Research, Experimentation, and Innovation in Land Transport (PREDIT); Sustainable Road Surfaces for Traffic Noise Control (SILVIA); and HARMONOISE. It was obvious that research is a vital part of the European culture. Governments conduct much of this research in partnership with industry, and have complex relationships with private entities to

fund far-reaching research objectives. For example, under the SIRUUS program, companies are encouraged to submit innovative ideas that are judged by a panel of topical experts, and the best ideas are constructed as experimental sections. Selection of the experimental idea is a highly sought-after award and is often used as a marketing tool for other company products and services.

IMPLEMENTATION RECOMMENDATIONS

The team identified a significant number of implementation recommendations, and then categorized them into short- and long-term proposals. Following are some of the recommendations for immediate implementation:

1. The European experience demonstrates that porous mixes are effective in reducing noise when used properly. Early evaluation results in Europe indicate that two-layer porous asphalt (TLPA) appears to have potential application on high-speed facilities and produces exceptionally quiet pavements. Thus, this system appears to merit additional evaluation and research in the United States. Porous mixes should not be placed in urban areas where the operating speed drops below 72 kilometers per hour (km/h) (45 miles per hour (mi/h)), since highly porous mixes tend to clog under slow traffic.
2. For an immediate improvement in the noise-reducing properties of mixes, a reduction in aggregate size in the wearing surface should be considered. In Europe, the aggregate sizes for quiet surfacing mixes are 0/4 millimeters (mm) through 0/10 mm. Since most State departments of transportation (DOTs) use the Superpave aggregate gradings of 19 mm, 12.5 mm, or 9.5 mm, a drop in routine aggregate mix size to the next smallest gradation is recommended and should produce a noise reduction of 1 to 3 dB.
3. Thin-textured surfacings using a small aggregate size are recommended for urban or low-speed sections. To achieve noise reduction, texture should always be negative (pavement depressions). Positively textured pavements such as chip seals increase noise.
4. Diamond-grinding blade configurations should be investigated and optimized to enhance noise-reducing properties of existing concrete surfaces in noise-sensitive locations.
5. EAC pavements should be researched further and considered when constructing new concrete pavements.
6. A team of acoustical experts and pavement engineering personnel should begin the process of developing American Association of State Highway and Transportation Officials (AASHTO) protocols for measuring the acoustical performance of quiet pavements. These protocols should capitalize on the extensive work completed and ongoing in Europe, as well as other locations throughout the world. Until new standards have been developed and adopted, State DOTs should use SPB (ISO 11819-1), CPX (ISO 11819-2), and various CPB methods to monitor existing pavement noise.
7. Consider updating the current noise policy and traffic noise models to take advantage of the benefits of quiet pavement technology through an integrated approach with other noise mitigation alternatives.

CHAPTER ONE

INTRODUCTION

Noise pollution is a growing concern in the United States. Transportation engineers have tried to balance mobility, safety, and comfort for years in designing new facilities and rebuilding existing roadways. Until recently, traffic noise was remediated through construction of noise wall barriers or purchase of right-of-way buffer zones where feasible. Recently, a few States have begun looking at source control issues in an attempt to supplement or replace walls and buffers. A major contributor of highway noise is at the tire/pavement interface, which means that quieter tires or quieter pavements could lead to substantial reductions in traffic-generated noise. Arizona, California, Florida, and Texas are among the lead States investigating the noise-reducing properties of gap-graded or porous mixes. To accelerate the learning curve, an international scan sponsored by the Federal Highway Administration (FHWA) and the American Association of State and Highway Transportation Officials (AASHTO) was completed on the topic of quiet pavement systems.

This scan involved visiting and investigating innovative pavement surfaces in various European nations identified as leaders or innovators in the design, construction, maintenance, and operation of low-noise pavements. Transportation professionals from Denmark, the Netherlands, France, Italy, and the United Kingdom met with the team. After presentations based on a list of amplifying questions sent to each host country in advance, a lively and probing exchange of questions and ideas ensued. Issues discussed ranged from high-level policy issues to specific noise-modeling equations and measurement techniques.

Although a preliminary desk scan identified many of the research reports that document the initiation, implementation, and innovation of quiet pavement systems, the onsite visits proved invaluable in meeting the overall objectives of the scan. The scan will ultimately benefit the U.S. highway industry by identifying how this technology can be introduced into the United States without the trial-and-error expense that has already begun to allow optimization of the systems in Europe.

BACKGROUND

In the United States, many State and Federal transportation agencies have established the strategic goals of protecting and enhancing the environment, improving customer satisfaction with the transportation system, and making transportation improvements an asset to the community. Highway traffic noise is an increasingly important issue in many metropolitan areas and has the potential to negatively affect all of the previously mentioned goals. For some projects, highway traffic noise is the issue of highest concern to nearby residents. In fact, for all major capacity-increasing highway construction projects, a highway traffic noise analysis is required. Tire/pavement noise represents 75 to 90 percent of the total noise generated by passenger vehicles, and it could be a significant amount (yet to be determined) of the noise generated by trucks. Reductions in tire/pavement noise levels could reduce the overall traffic noise level substantially, reducing the potential requirements for expensive noise-abatement measures. While technologies now available in the United States provide modest (2-to-4-dB) noise reductions, new and innovative approaches to this problem have the potential to provide substantially greater reductions.

SCOPE

The purposes of this scan were to document the state of the practice in design, construction, maintenance, and monitoring of quiet pavement systems, and identify new and innovative practices that may be evolving from past experience with existing systems. From April 30 to May 16, 2004, the U.S. study panel visited nations that have successfully used new and innovative pavement technologies that result in substantial reductions in tire/pavement noise. In addition, the panel sought information on noise measurement methodologies and monitoring systems.

Team Sponsorship

The panel was cosponsored by FHWA and AASHTO. It was composed of 14 members representing FHWA, AASHTO, academia, and public sector professional associations.

Topics of Interest

General topics of interest to the team included issues

relating to noise policy, pavement and mix design, construction techniques, maintenance problems, modeling and measurement of tire/pavement noise, and innovative research planned or underway. Specifically, the team had an interest in onsite visits to various projects, including the following:

- Low-noise surface treatments (3-to-5-dBA (decibels A-weighted) reduction)
- Thin-surface treatments (3-to-5-dBA reduction)
- Lightweight aggregates (3-to-5-dBA reduction)
- Porous surfaces (5-to-7-dBA reduction)
- Futuristic surfaces (7-to-15-dBA reduction)

Specific questions that amplify the panel's interests in these topics are included in Appendix C.

EUROPEAN HOSTS

Before the scan trip, a desk scan was initiated to identify countries that had demonstrated materials and processes that, if studied further, may prove useful in improving U.S. practices. Desk scans are limited, office-based, information-gathering projects designed to supplement and further define scan topics that have been approved. The authors corresponded primarily by electronic mail with established contacts in Europe, Japan, Korea, Australia, New Zealand, and South Africa, as well as with several North American colleagues.

Table 1 identifies the specific locations and organizations the scan team visited.

Table 1. Organizations and locations visited.

LOCATION	HOSTS AND PARTICIPANTS	DATES
Denmark (Copenhagen)	Vejteknisk Institute/Danish Road Institute (DRI)	May 3, 2004
Denmark (Roksilde)	DRI (Site Visit)	May 4, 2004
Denmark (Copenhagen)	DRI	May 5, 2004
The Netherlands (Delft)	Dienst Weg-en Waterbouwkunde (DWW) Rijkswaterstaat, Ministerie van Verkeer en Waterstaat (Ministry of Transport, Public Works, and Water Management)	May 6, 2004
The Netherlands (Apeldoorn)	DWW (Site Visit)	May 7, 2004
France (Paris)	Ministry for Infrastructure, Transport, Housing, Tourism, and the Sea; Road Administration—Office of International Affairs; Direction de la Recherche et des Affaires Scientifiques et Techniques (DRAST); Service d'Etudes techniques des Routes et Autoroutes (Sétra); Laboratoire Central des Ponts et Chaussées (LCPC); Colas; Appia	May 10, 2004
France (Nantes)	LCPC; VIARME (Site Visit)	May 11, 2004
Italy (Rome)	Autostrade per l'Italia S.p.A. (Site Visit)	May 12, 2004
United Kingdom (London, England)	Highways Agency	May 13, 2004
United Kingdom (Crowthorne, England)	Transport Research Laboratory, Ltd. (TRL) (Site Visit)	May 14, 2004

CHAPTER TWO

In the following sections, the team arranged the material by subject area and provided details on a country-by-country basis. The team believes this arrangement provides the reader of the report with maximum accessibility to the information. For example, a reader with a primary interest in maintenance can go directly to the topic of interest and determine what each country visited has experienced or is planning to implement. To increase the readability of the report, the team decided to provide summary information by topical area as the official report.

Chapter Two begins with common issues evident in each country. All countries visited are members of the European Union (EU).

COMMON ISSUES

In Europe, research indicates that 17 percent of the population is exposed to environmental noise levels of more than 65 dBA, a level that can have negative health effects. The research involved the repeated testing of 138 people at 12 sites, and discovered that small increases in noise level matched changes in behavioral disturbance. The research used two psychometric scales to assess change in community annoyance and responses to road traffic noise due to a surface reseal (urban areas). Behavioral disturbance reduction was detected even when the reduction in noise was very small (3 dBA). The participants identified the source of noise annoyance as being the road surface interface as opposed to cars, trucks, or other characteristics, such as service covers.

These research studies appear to be the basis for Directive 2002/49/EC of the European Parliament and of the Council of June 25, 2002. Although this directive, called the Environmental Noise Directive (END), appears to be based on a correlation between noise and health, the supporting research is not considered definite and additional research is required. This EU directive requires all members to do the following:

- Determine the number of people exposed to environmental noise through noise mapping using common indices (but in the first instance based on individual member states' methods of assessment where these can be adapted to predict the required indices).
- Ensure that information on environmental noise and its effects is made available to the public.

- Adopt action plans based on noise-mapping results with a view toward preventing and reducing environmental noise where necessary, particularly where exposure levels can harm human health, and to preserve good environmental noise quality.

The critical date contained in the directive is June 30, 2007, when all member states must have completed the first round of strategic noise maps identifying areas of concern. A general principal of EU law prohibits countries from imposing stricter guidelines where an EU policy exists.

The EU directive required contour lines to be drawn for 55 to 75 dBA for daytime and 50 to 70 dBA for nighttime, in 5-dBA increments, to determine which areas are impacted by highway traffic noise. For cities with populations exceeding 100,000, major transportation actions must combine with an action plan to provide quiet zones. In addition, the directive addressed the L_{den} (day-evening-night sound level) noise metric for calculating the contours. Based on noise annoyance, this metric applied a 5-dB penalty for evening hours (6 to 10 p.m.) and a 10-dB penalty to nighttime hours (10 p.m. to 6 a.m.). The EU is investigating the application of the L_{Amax} (maximum A-weighted sound level) metric in helping to determine noise impacts.

As part of the EU, these countries will implement the use of the noise prediction methods known as HARMONOISE (Harmonised, Accurate, and Reliable Prediction Methods for the EU Directive on the Assessment and Management of Environmental Noise) and IMAGINE (Improved Methods for the Assessment of the Generic Impact of Noise in the Environment), the latter being a simpler version for the purpose of validation. HARMONOISE includes meteorological conditions, and the noise metric is an average 1-year L_{den} . Calculations are performed on a one-third-octave band basis from 25 to 10,000 Hertz (Hz). The following are the three main elements of the model:

1. Sound source—Sound power levels determined from each source from sound exposure level (SEL) (with an array of microphones), 13 classes of vehicles, and different road surfaces.
2. Propagation (includes air attenuation, ground absorption, screening, and atmospheric effects).
3. Noise reception (long-term average).

The model can account for noise sources other than highway (e.g., rail).

As early as the 1970s, many European countries had already begun their journey toward lowering roadway noise. Research, development, and implementation of noise barrier walls, building insulation, building codes, noise limitation on new roads, traffic handling, and pavement type selection were well underway in many countries based on consumer complaints of excess noise or differential noise.

For example, it is recognized that quiet pavement systems reduce the tire/pavement noise profile. However, questions remain about the duration of the noise reduction and the benefit each different system can provide. Based on the outcome of the mapping, it is anticipated that each country will begin a prioritization process to eliminate noise “hot spots.” Other EU directives provide a means of reducing vehicle and tire noise. Thus, European countries are leaning toward harmonization of technical specifications for vehicles and are performing test procedures (ISO standardization) to standardize the process of tire/pavement measurement. However, the Environmental Tire Noise Directive in particular appears to permit considerable flexibility, and most countries have indicated that they do not anticipate significant noise reduction through further vehicle improvements.

Officials noted that on a national and European level, vehicle noise emission limits were reduced between 1970 and 1996 from initial values of 92 dBA for trucks and 82 dBA for passenger cars to 80 dBA for trucks and 74 dBA for cars. These are nominal values; since measurement methods have changed somewhat over this time period,

the actual limit reductions are higher for trucks and lower for cars than the given nominal reductions. When Austria began requiring vehicles not to exceed 80 dBA at night on major highways over the Alps, vehicle manufacturers rapidly adapted to the situation and provided trucks that met the new limit, which was then 4 dBA lower than the general European limit for such trucks. Optimally, passenger

vehicles would have a limitation of 74 to 80 dBA, depending on vehicle type and engine size. Although many believe that tires can be changed easily to produce lower noise levels, reductions in tire noise by tire

manufacturers to date have been offset by the demand for wider tires, which produce more noise. One option under consideration to encourage the production of low-noise tires is to offer financial incentives. Several countries indicated that in some cases, the EU Environmental Tire Noise Directive’s flexibility might be a constraint in promoting the production of low-noise vehicles and tires. However, an additional directive is in place on low-noise tires that affects new tire types introduced in 2004, original equipment manufacturer (OEM) new vehicles in 2005, and all new aftermarket tires from 2006 through 2011. The noise regulation is based on tire width—an increase of 10 mm results in a 0.4-dB noise increase.

TOPICAL ISSUES

The team divided the general topic of quiet pavement systems into six subsets, and apportioned its members the responsibility for specific topical information. The purpose was to insure that each area of interest was properly documented. The areas of interest and team assignments were as follows:

- **Policy**—David Gibbs, Randell Iwasaki, and Chris Corbisier
- **Design**—Douglas Carlson and Mark Swanlund
- **Noise analysis**—Judy Rochat and Bob Bernhard
- **Construction**—Jay Bledsoe and Thomas Hearne
- **Maintenance**—Kevin McMullen and John Roberts
- **Research**—Larry Scofield and David Newcomb

POLICY

As noted above, all of the countries the team studied are EU members and are therefore subject to the provisions of Directive 2002/49/EC, dated June 25, 2002. However, the team found that each country is at a slightly different place in its journey to abate or attenuate roadway-generated noise. The team focused on the common denominator of quiet pavement technology as a tool in noise reduction.

DENMARK

Population—5.4 million (2003)

Highways—71,591 kilometers (km) total, including 880 km of expressways

Danish research has shown that 15 percent of the people are annoyed at noise levels above 55 dBA (A-weighted 24-hour equivalent sound level, L_{Aeq24h}). Of the 2.5 million homes in Denmark, 706,000 are exposed to noise levels exceeding 55 dBA. In response, Denmark has established noise regulatory guidelines (1984) for newly

“You can’t limit production of louder vehicles, but you can limit where they can drive.”

—Eric Vos, Ministry of Transport, Public Works, and Water Management

constructed homes and newly constructed roadways. The noise level is measured at the facade of the houses. These guidelines were designed to control noise and were not intended to limit development. Mitigation strategies include turning the rear of the houses to face the street, façade insulation, living rooms and bedrooms facing the backyard, and a maximum noise level of 55 dBA in gardens. For the past 20 years, all new houses (300,000 or 12 percent of all homes) have met the national noise guidelines (55 dBA, 30 dBA indoor).

The entire country has been noise mapped and the current focus is to expend funding on areas with the highest noise levels. There is no requirement to use noise-reducing pavement, but with the cost of noise walls approaching DKK10,000 (about US\$1,666) per meter and the commitment to using the most cost-effective strategies, the use of quiet pavement technology is becoming more attractive.

Use of low-noise surfaces is limited in Denmark, but test sections are being evaluated in active research projects. Pilot projects were built about 6 years ago, and intensive monitoring and data accumulation are being used to formulate the effectiveness of quiet pavements.

Denmark employs the following traffic-planning techniques to address highway noise:

- Through-traffic on arterial streets
- Speed and traffic reduction on roads in residential areas
- Building the overall scale of road section to reduce speed

In addition, Denmark also uses the following speed-reduction techniques to improve roadway noise:

- Displacement of driving lanes
- Road humps
- Roundabouts
- Narrowing of streets

To address roadway noise, Denmark plans the following future actions:

- Implement noise reduction on national roads.
- Produce a catalog of ideas for local agencies on noise reduction.
- Conduct a survey of annoyance from road noise.
- Implement the EU Environmental Noise Directive.
- Test noise-reducing pavements.

THE NETHERLANDS

Population—16.1 million (2003)

Highways—116,500 km total; 104,850 km paved, including 2,235 km of expressways

The Netherlands is experiencing high traffic noise because the country is densely populated, has a high

degree of infrastructure, and is highly mobile. The Noise Nuisance Act of 1979 resulted from research performed by the Health Council, which looked at noise-related sleep disturbance and annoyance. The research found that 10 percent of the population was annoyed with noise levels higher than 50 dB (greater of daytime and nighttime A-weighted equivalent sound level, L_{Aeq} , explained further in Noise Analysis section). In principle, the act stipulates that each road has noise zones and all population density within the zones must be investigated for the noise level. If the levels are exceeded, measures must be taken to reduce noise. The guidelines were 50 dBA for new locations and 55 dBA for existing locations. For the widening of existing roads, the “stand-still principle” applied, resulting in all increases in noise levels being mitigated.

In response to the Noise Nuisance Act of 1979, the Innovation Program (IPG) was created. The goal of this program, which included the Dutch Ministry of Transport and the Ministry of Environmental Affairs, was to reduce traffic noise significantly using source-related measures. The program approach was to investigate all possibilities of noise reduction. Potential results include decreased dependence on barriers and an increase in source-related measures. The mission of the IPG is to deliver noise-reduction measures ready to implement and allow noise in the Netherlands to be reduced in an affordable way.

The activities implemented under the Noise Nuisance Act and the IPG results will form the basis for the Netherlands’ approach to complying with the EU Environmental Noise Directive. Auto technology is not expected to provide a complete solution to meeting the EU requirements. Therefore, an integrated approach is proposed that includes building restrictions with noise guidelines and aggressive roadway planning.

In the Netherlands, research was initially performed on porous asphalt (PA) in the late 1970s on A28 to reduce splash and spray. A reduction of 3 dB was achieved for passenger vehicles and no reductions for trucks. Based on Noise Nuisance Act requirements, PA is required on all roads carrying over 25,000 average daily traffic (ADT). In addition, PA is required for all regular maintenance. Currently, 60 percent of the roads in the Netherlands have PA.

FRANCE

Population—60.2 million (2003)

Highways—894,000 km, including national roads of 27,000 km, motorways of 9,700 km, county roads of 360,000 km, and local roads of 595,000 km

A law on noise was passed in 1992 that provided guidance on the various sources of noise and addressed noise from a transportation viewpoint. The law also established the following noise levels (L_{Aeq} at the building façade): 6 a.m. to 10 p.m.—60 dBA (no background), and 10 p.m. to 6 a.m.—55 dBA (no background). The law also gave preference to avoidance, mitigation, and abatement, but it did not address quiet pavements.

A policy was also established that provided instructions to address black spots (greater than 70 dB during the day or greater than 65 dB at night.). This action called for treating 200,000 dwellings in 2 years, but this treatment was delayed because of lack of funding. The policy in France is to avoid all black spots on new roads. To respond to this policy, the Department of Transport has decided to use pavement products that will reduce noise, mainly in towns. The promotion of quiet pavements in France is relatively new, beginning in 1998. The Department of Transport estimates that France will see a 50 percent increase in traffic in the next 20 years.

In 1995, a decree was passed that defined the noise modifications to be carried out. Noise increases greater than 2 dB required modifications. This decree required all road systems to be mapped and required noise to be addressed in all land development.

On November 3, 2003, the French government launched a new action plan to cope with noise. The plan established a target of addressing 500 dwellings (low-income homes) in 5 years in sensitive areas or black spots (greater than 70 dB during the day and greater than 65 dB at night.).

In France, speed and traffic management is used to address noise, but this technique cannot be used in Paris, where major roads bisect the city. For the rest of the national system, agencies optimize alignment (similar to context-sensitive design—fitting alignment with existing environment), construct barriers or earth embankments (berms), or resort to façade insulation or buyouts of dwellings. Quiet pavement is an option for reducing noise in urban areas, but definitely not in Paris with its cobblestone streets. The Ministry of Culture does not allow removal or coverage of the historical sections of Paris. In addition, the French have experimented with wide bus lanes in Paris to move buses as far from the pavement edge as possible. France's Quiet Pavement Policy has been in place for about 4 years and is expected to provide a reduction of 3 to 4 dB.

ITALY

Population—58 million (2003)

Highways—479,688 km, including 6,621 km of expressways

Italy has advanced legislation in noise regulations on pavement noise. The noise law in Italy was passed in October 1995 (Law 26.10.1995) to address acoustic pollution. All noise sources—not just the noise from an improvement—that can alter the noise level limits of new roads must be addressed.

In spring 2004, the last part of the legislation was passed to address road noise, including limits. The Italians indicated that they have 3 years to complete a general plan on noise control, 18 months to complete noise contour mapping and a plan with priorities, and 15 years to implement the plan, and that they must report on the progress of implementation each March. To accomplish this task, a minimum of 7 percent of the budget has been dedicated to address noise issues.

Italian officials indicated that theirs was the first country in Europe to apply noise mapping on existing roads. Italy has 98 km of noise barriers and 1,968 km of antinoise pavement. In addition to the typical noise-reducing strategies, Italy also uses baffles, or partial or total cover of the carriageway, and recently recognized the noise-reduction ability from a 1.5-m-tall safety median barrier.

In Italy, the first use of porous pavement technology was intended to increase skid resistance and reduce wet weather spray. When it was observed that these pavements also resulted in reduced tire-pavement noise, an effort was mounted to optimize the effect without loss of safety or pavement durability.

UNITED KINGDOM

Population—60 million (2003)

Highways—371,913 km, including 3,358 km of expressways

In the past, the focus has been on providing excellent skid-resistant surfaces. However, for the past several years the United Kingdom has made an effort to find the balance between safety (skid) and noise reduction using quiet pavement technology. Quiet pavements are now widely used by the Highways Agency, which is conducting significant research into improved systems.

The 1963 *Wilson Report* brought together all issues related to noise and attempted to quantify the issues associated with different sources. The Land Compensation Act of 1973 allowed the public to claim compensation from the government for all impacts of public works (noise, air, etc.). Noise insulation regulations introduced under this act established criteria for insulating residential buildings adversely affected by noise from such works. In addition to other factors, the qualifying noise level was specified as 68 dB (sound level

exceeded 10 percent of the time, L_{10} , hours from 6 a.m. to midnight). The regulations were applied retroactively to roads built after 1969; noise barriers could be provided in the case of older roads but these locations were not addressed before 1979. More recently (since 1999) a small amount of funding was “ring-fenced” to address problems at the worst affected locations near older roads. An investigatory threshold of 80 dBA at roadside was established, with an additional criterion of an excess of noise levels above predictions of 3 dB for roads built after 1969.

In 1980, a safety policy was established requiring skidding resistance to be monitored and maintained. This policy resulted in overlays of chippings that had tended to increase tire noise. Porous asphalt pavements were introduced experimentally in the 1980s, and although they provided reduced spray and tire noise, they had durability problems because of raveling. In the mid-1990s the United Kingdom experimented with thin-layer textured mixes that were relatively inexpensive, quick to construct, and provided acceptable durability. About this time, the Department of Environment and Department of Transportation merged. Thin-surface technologies were emphasized to the new deputy prime minister and, in 1998 a policy document entitled *A New Deal for Trunk Roads* in England was published. This document outlined the routine use of quieter surfaces and said that noise barriers could be provided at hot spots meeting certain criteria (specified in 1999 in conjunction with the “ring-fenced” budget). Quieter surfaces (specified as at least 2.5 dB quieter than hot rolled asphalt (HRA)) are now used as a matter of course on new and improved trunk roads and when existing trunk roads are resurfaced.

In 2000, a 10-year plan for transport set a target for advancing noise-reduction policies on major roads. Under this plan, the U.K. Highways Agency is resurfacing particularly noisy concrete surfaces on the strategic network before the end of their normal life and plans to resurface all such pavements by the end of the plan (2011). The overall goal is to resurface 60 percent of the strategic road network with quieter materials over the 10-year period. The United Kingdom has experimented with EAC finishes, but thin-layer quiet surfacings have overtaken that technology as being more cost effective, even on concrete pavements.

Planning guidance for assessing noise impacts on new residential developments is now under review. Current guidelines are based on the 16-hour equivalent continuous free field noise level. If the traffic noise level in the area is higher than 72 dBA, then the proposal should be refused. Where traffic noise levels are above 63 dBA, if

the authority wishes to approve the proposal, the developer should be required to provide measures to reduce the noise within the building. Noise barriers are often specified in addition to insulation in such cases, although this free field level equates to the threshold of 68 dBA at the façade of an existing property specified in the noise insulation regulations for new roads.

It is anticipated that additional legislation implementing the EU END will be passed in the coming months. This will require noise maps to be generated by 2007 with 5 dB contours showing noise impacts in large urban areas and associated with major transportation links.

Future legislation is expected to specify noise calculations based on models being developed under the HARMONOISE and IMAGINE research programs. By 2008, action plans must be declared, and the U.K. noise-control policy will probably be reviewed at the same time. EU members have the right to set their criteria for action, and the United Kingdom might extend the opportunity for providing insulation where barriers and quiet pavements are less cost effective. The Highways Agency has divided its strategic road network into four regions and has developed a composite index and a value management process to prioritize maintenance actions to take into account whole-life cost, environmental benefits, safety, and traffic disruption.

DESIGN

Denmark

In Denmark, safety is the top priority. Although noise is a regulated property, pavement performance is still a very high priority. Therefore, life-cycle costs determine the use of most noise-abatement remedies.

Although surface texture (expressed as mean profile density (MPD)) has an effect on noise, the significance of this property on overall pavement noise emission is uncertain. Pavement temperature also has an effect on noise, with hotter pavements generally being quieter than cooler pavements. Also, as the air voids increase in porous pavements, the noise generally decreases. Denmark requires porous mixes to be at or above 18 percent air voids.

The Danes have measured noise stability on several experimental pavements for several years and will continue this measurement as long as the pavements perform safely. The results are shown on page 8 in tables 2 and 3.

The drainage asphalt (DA) with the smallest chip size (8 mm) and the highest percentage of built-in voids (over 22 percent) had the best noise reduction (3 to 4 dB) and retained its porosity. Thin open layers are being

Table 2. Noise reduction.

Year/ Surface	0	1	2	3	4	5	6	7
DA8 18–22%	-3.6	-4.4	-4.0	-3.7	-3.3	-3.4	-2.8	-0.7
DA8 > 22%	-3.2	-4.4	-4.3	-4.1	-4.2	-3.0	-3.3	-0.9
DA12	-1.5	-3.8	-4.0	-2.5	-2.4	-1.4	-1.0	+0.9
AB12a	+0.8	+0.6	+0.3	+0.6	+0.9	+1.2	+1.4	+2.0

Note: DA refers to drainage (porous) asphalt and the following numeric refers to the aggregate size; i.e., DA8 is a porous asphalt mix with an 8-mm maximum aggregate size. AB refers to asphalt base.

placed experimentally in urban areas to determine noise-reduction capacities while extending service life and reducing maintenance costs.

Single- and double-layer porous mixes and thin surfacing have all been used as noise-reducing pavement mixes. The porous mixes have the greatest potential to reduce noise by more than 3 to 5 dB, but have experienced performance problems (clogging, durability, etc.). The thin mixes are more cost effective and appear to be more durable, but provide only limited noise reduction (1 to 3 dB). (See figure 1 for examples of two-layer drainage asphalt.)

The Danes have completed three case studies in which they compared the cost of PA, noise barriers, and sound insulation for three road categories: city street, ring road, and freeway. They concluded, “Compared to noise barriers and façade insulation, porous asphalt gives a much higher noise reduction per invested Euro.” However, they added this disclaimer: “The test section is only 3 years old, and it therefore is still to be proven



Figure 1. Examples of two-layer drainage asphalt. From left to right: DA5 + DA16, DA8 + DA16, and DA5 + DA22.

Table 3. Trends in voids.

Wearing Course	DA8 18–22%			DA8 > 22%		
	0	2	6	0	2	6
Stones < 2 mm %	10.0	15.5	17.0	8.0	13.8	19.0
Filler, % by weight	4.5	6.4	5.8	4.8	7.7	6.8
Void, %	21.0	18.1	17.5	23.5	19.3	19.5
Permeability cm/sec	0.26	0.05	0.02	0.22	0.06	0.02

that the pavement can maintain the noise reduction throughout its entire lifetime.” (Figure 2 illustrates the use of 8-mm porous asphalt surface in Copenhagen.)

The Netherlands

All new roadway construction must not exceed a noise level of 50 dB and the noise levels of all existing roadways that are reconstructed must fall below 55 dB.

“...the cost effectiveness of silent road surfaces in general, and that of two-layered porous asphalt especially, is very high. In other words: the investment per reduced decibel is much lower for such a road surface than for sound barriers or façade isolation.”

—G. G. van Bochove, Heijmans Infrastructuur



Figure 2. Oster Sogade in Copenhagen with PA8 (8-mm porous asphalt surface).

Any widened roadway must not exceed the current noise limits (stand-still principle). Safety is still a top priority, and skid resistance is required for all new surfacing. Consideration is being given to requiring a skid warranty, and future projects may include an acoustical warranty. All pavements are now warranted for 3 years and are awarded on a low-bid basis.

In a recent comparison test of dense asphalt concrete, PA (single-layer), TLPA, and thin top layer (Microflex 0/6), TLPA was quieter at all speeds tested (30 to 130 kilometers per hour (km/h)), as much as 4 dB quieter than the next best mixes (thin layer and porous single layer) at high speed (130 km/h), and as much as 9 dB quieter than conventional dense-graded asphalt. TLPA, therefore, is especially interesting for the main highway system where traffic speeds are higher and sound reduction the greatest (see figures 3 and 4).

Another consideration noted by the Dutch was that these porous mixes do not perform as well as conventional dense mixes when there is more braking, acceleration, and turning, or “wringing” actions, as might be expected in urban areas. These considerations make a case for the following application classifications:

- National highways—PA or TLPA
- Inner-city roads—thin, semi-dense top layers

The current thin gap-graded asphalt pavements are achieving 8 to 10 years of life, while the previous dense-graded mixes lasted 10 to 12 years. Aggregate size, void structure, binder properties, skid resistance, and mix durability are all considered critical mix properties. The

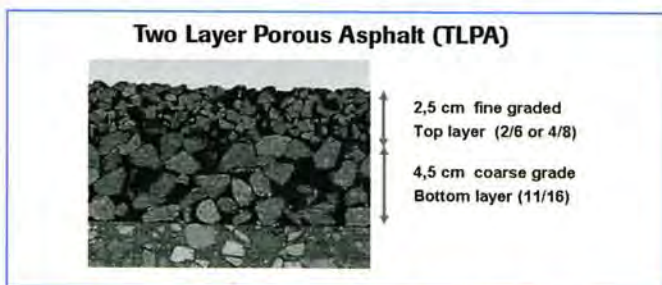


Figure 3. Two-layer porous asphalt (TLPA).



Figure 4. Experimental two-layer porous mix on A28.

porous mixes have the greatest potential to reduce noise by more than 3 to 5 dB (at greater than 30 to 55 km/h). The thin mixes are more cost effective and appear to be more durable, but provide only limited noise reductions (1 to 3 dB). However, the thin single-mix layers work better in urban (low-speed) conditions than the two-layer systems.

Although porous pavements are slightly more expensive, they produce a 50 percent cost efficiency compared to the same reduction of noise by barrier. Current barrier costs are estimated at EUR400 to EUR500 per square meter. The high costs are associated with the extensive foundation structural support needed in the Netherlands.

France

France uses several different pavement designs for noise reduction. The following techniques are employed:

- Use separate structural and surface characteristics.
- Use best-quality aggregates.
- Adjust pavement dressing to noise characteristics.
- As a general rule, use smaller grain size for quieter pavements.
- Use smaller aggregate size for best adhesion (skid).

In the past, France has used thicker surfacing (5 to 8 centimeters (cm)) and continuous grading to ensure good waterproofing of the pavement. Today, France has separated the structural function from the

surface function. Therefore, very thin (2-to-3-cm) and ultrathin (1.5-cm) mixes were developed to improve the surface characteristics (skid resistance, noise). The ultrathin mixes developed in France 10 years ago are not used as much today because these mixes cost as much as the very thin mixes. The grading composition of mixes being used today is 0/6 mm and 0/10 mm gap graded. These surface mixes are usually 25 to 30 mm thick with 5.7 to 5.9 percent asphalt. France has not experienced problems with these mixes. Figure 5 (see page 10) illustrates levels of tire-road noise with different surface mixes.

France has discontinued the use of the 0/14 mm mixes because of inferior performance in terms of adherence (not enough microtexture), and because they are too noisy. In situ noise is measured 2 to 3 months

“The difference in the noise between the reference pavement and the porous pavement increases as the distance from the pavement increases. The reverse is true for noise barrier walls.”

—Michel Berengier, *Laboratoire Central des Ponts et Chaussées*

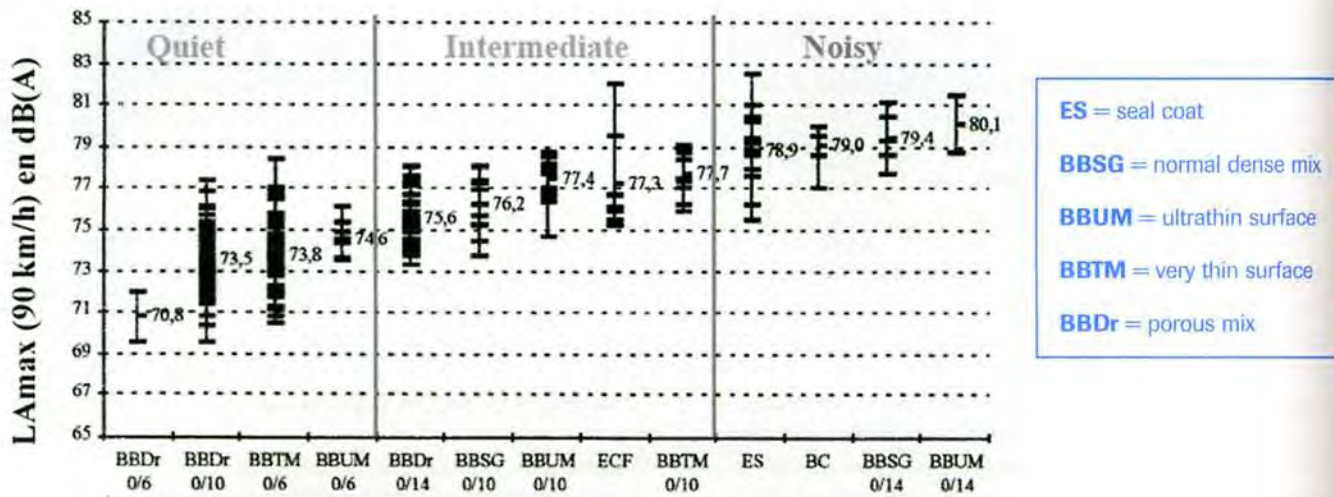


Figure 5. Tire-road noise.

after construction to determine compliance with noise criteria (60 dB during the day and 55 dB at night). If it does not meet requirements, then corrections are made. For PA mixes, the French have measured a 1-dB increase over a 6-year service life.

Safety issues are not compromised to achieve noise reduction. Skid enhancement and spray reduction are deemed more important than noise reduction. Rutting resistance, shear resistance, smoothness, and cracking are considered as critical as noise reduction. Service life performance issues are traded for improved safety and noise enhancement issues, but a program of performance enhancement continues. After much experimentation, the French have found that the 0/6-mm extreme gap is most effective at reducing noise and increasing skid (see table 4).

Table 4. Comparison of 0/6-mm mix and 0/10-mm mix.

Feature	0/6-mm mix	0/10-mm mix
Skid	++	++
Spray	++	++
Noise	++	+
Rut	++	++
Shear	--	--
Smoothness	+	+
Crack	--	--

Note: The plus (+) sign indicates an improved characteristic over conventional surfacing mixtures. The minus (-) sign indicates a negative improvement. The number of signs associated indicates a relative degree of change.

These noise-reducing mixes are considered sacrificial layers and are not given any structural value in pavement design. However, the French estimate that these mixes have about half the modulus of dense-graded mixes.

Although the service lives of the current mix formulas are anticipated to exceed 15 years, older mixes are being recycled after 10 to 12 years.

Aggregate size, void structure, binder properties, skid resistance, and mix durability are all considered critical mix properties. Gap grading seems to increase raveling potential, but the addition of 7 to 10 percent sand mortar has helped resist raveling. The wearing course is replaced within 10 to 15 years. The French also placed PA on one continuously reinforced concrete pavement (CRCP).

Lightweight aggregates (expanded clay) have been used for skid resistance in areas with few good natural aggregates. These synthetic aggregates may provide slight improvements in noise reduction. Rubber has been used in the mix binder and has reduced noise by up to 1 additional dB. The optimum rubber content is 1 to 2 percent rubber. Rubber has also been used in the very thin mixes.

Italy

About 35 percent of the Autostrade (1,868 km) was surfaced with PA by the end of 2003, but most of this PA is composed of 0/16 mm aggregate size. The new formula tends toward a smaller maximum aggregate size of 0/11 mm or perhaps even 0/8 mm.

A minimum level of skid resistance is required on all new pavements and is monitored annually under the pavement management program. Ride quality is also a

highly regulated attribute. Currently, performance and pavement life are not as good as with conventional dense-graded mixes, but performance research is a continuing program.

Some of the first porous mixes were placed in the late 1980s. A properly designed mix constructed with due care has about an 80 to 90 percent life performance, compared to a quality dense-graded mix. Aggregate size, void structure, binder properties, skid resistance, and mix durability are considered critical mix design properties. The porous mixes are specified to achieve a minimum of 23 percent air voids, and most are constructed at about 30 percent air voids.

United Kingdom

Paving contracts require the use of quiet surfaces, but contractors are allowed to decide what type of surfacing products to use for the roads they build. More than 32 approved proprietary surfacing systems meet safety and noise requirements. The approval process is known as the Highway Product Approval System, or HAPAS. To obtain HAPAS approval, the product must be proven to perform in an extensive range of quality tests, including skid resistance, drainage, and durability, with an optional test of noise generation. In addition, the products must perform in situ as indicated during HAPAS testing for at least 3 years. The British are considering an extension to this warranty period. If the product does not meet the specified minimum noise or skid requirement during the warranty period, it is removed and replaced. If it fails other requirements, the product may be permitted to remain in place at no pay. Noise-reduction properties are compared to the performance of HRA using a noise prediction algorithm. To obtain approval as a quiet pavement mixture, it must provide at least a 2.5 dB noise reduction (compared to HRA).

The British experimented with EAC, which was reported to achieve a 3 dB reduction compared with a standard brushed finish with minimum texture (1.2 mm). The British reported a 10 percent cost increase using EAC surface. Thin-layer bituminous surfacings have replaced EAC as a more cost-effective way to reduce noise. Current policy does not allow concrete pavement to be used as the finished surface. Any new concrete pavement is considered a supporting base with a required quiet pavement surfacing. Even so, 40 percent of new roads are CRCP (almost exclusive use of CRCP in England) with a thin surface layer. The public has responded favorably to the use of noise-reducing surfaces and is especially impressed by improvement in ride comfort.

The thin surfacing mixes are generically similar to

SMA, but are proprietary formulations using modified binders and a closely controlled aggregate mix. The mixes are not as difficult to construct and maintain as the PA mixes, and have reported service lives of 12 years compared to the HRAs that typically lasted 15 years. The primary differences in PAs and thin surfacings are cost (thin surfacings are about half the thickness and so cheaper and quicker to lay) and texture. PAs and thin surfacings are both negatively textured, having a relatively smooth running surface. Where PAs have interconnected voids below the surface, the aggregate particles in thin surfacings are embedded in binder. The primary failure mode of the thin surfacing mixes is raveling after the binder has started to oxidize.

The British allow the same structural design value for thin surfacings as for conventional asphalt mixes. Porous asphalt mixes are assigned 50 percent structural credit. The top layer contains the quality of aggregate needed to provide skidding resistance. The layer thickness for porous asphalt is 50 mm and for thin surfaces 20 to 35 mm. This material is reusable in future construction when the pavement is recycled.

NOISE ANALYSIS

Denmark

The highway traffic noise prediction model the Danes use is NORD2000, Scandinavian prediction code written from 1996 to 2001. NORD2000 software has a new source model developed by measuring 4,000 vehicles on 21 streets traveling from 30 to 130 km/h. The noise emission levels in NORD2000 account for vehicle category, speed, age of vehicle, size of engine, engine type, and surface texture. Plans call for incorporating quiet pavements into the model, but this will not be available for many years until the reliability of the noise-reduction effect can be verified. Meanwhile, predictions are based on a reference pavement, where supporting documentation includes a table with values to adjust for different pavements.

The metric used in the standard noise program is A-weighted 24-hour equivalent sound level ($L_{Aeq(24h)}$). The EU Environmental Noise Directive, however, will require the use of a different metric, the day-evening-night sound level (L_{den}), which applies penalties to evening and nighttime hours.

For quiet pavements, the Danes use statistical pass-by (SPB) methodology (ISO 11819-1) to determine the noise-reduction benefit and report the statistical pass-by index (SPBI). In some cases, the methodology has been modified to best represent the traffic and data collected

at the measurement sites. The data is also presented in terms of vehicle type, looking at a regression through the maximum sound levels, and recommended spectral data analysis. As part of determining noise reduction, a perceived-effect survey has been conducted in communities adjacent to pavement test sections. Close-proximity methodology (CPX) (ISO 11819-2) is used for pavement categorization. It is not used to determine noise-reduction benefits of pavements because it does not account for different vehicle types.

The only quiet pavements being tested are for research purposes, so no noise maintenance program is in place and monitoring of standard pavements is not conducted. For research purposes, the quiet pavements are tested using the SPB methodology two times a year. To date, wet pavement has not been tested.

None of the noise-abatement measures except barriers and insulation has achieved more than a 5-dB reduction. The greatest noise reduction achieved with quiet pavements is about 5 dB, for TLPA. Noise reductions are compared to their reference pavement, dense-grade asphalt (DGA) AB12.

The Danes indicated that the most important frequency range to address with quiet pavements is 800 to 1,500 Hz for light vehicles, and more broadband—peaking at a lower frequency—for heavy vehicles. The objective of the quiet pavement program is to create smooth, porous pavement with small aggregate size in a configuration that will stay clean.

The Danes have found that quiet pavements get much louder after 8 years. The noise-reduction benefit is characterized to last about 6 years, although some pavements have shown a 12-year lifetime. In the first year, the reference pavement benefit decreased 1.0 to 1.5 dBA.

The Netherlands

The prediction model the Dutch use is SRM2, although this will change to harmonize with that used by the EU. The new prediction model may be called HARMONOISE.

The prediction model accounts for quiet pavements in two ways:

1. **Simplified version**—Apply an adjustment factor to the overall sound level. The adjustments from the reference pavement (DGA 0–16), determined using SPB methodology, are determined for each pavement type.
2. **More accurate version**—Changes in spectra are accounted for during propagation. The vehicle noise emission levels are adjusted on an octave band basis for each vehicle type (light, medium, and heavy). For the more accurate version, adjustments are determined using SPB methodology. Octave band levels are compared for their reference dense asphalt to the

quiet pavement octave band levels— $L_w = A \log_{10}(V) + B$, where A is a function of octave band, and B is constant for surface and vehicle type. The adjustments are made as a function of speed.

The noise metric now applied for impact purposes is an A-weighted equivalent sound level (L_{Aeq}), measured for 24 hours. A L_{Aeq} value is obtained for daytime and nighttime hours, in which case a nighttime penalty of 10 dB is applied. The final step in determining the sound level is to take the highest of the day and night levels.

Typically, measurements have been performed using the SPB method to determine the noise-reduction benefit, although CPX and coast-by methods have also been used. In addition to the SPB index, light vehicles and heavy vehicles are examined separately. (Measurements are taken annually under similar meteorological conditions and corrected for the air/pavement temperature.) The correlation between CPX and SPB results is being investigated and consideration is being given to using just the CPX method for future determinations of noise reductions. So far, good correlation has been seen for light vehicles, but not for heavy vehicles. For the various projects in the Netherlands, different measurement methodologies are being applied. For example, the Silenda Via (SILVIA, Sustainable Road Surfaces for Traffic Noise Control) project applies both the SPB and CPX methodologies with restrictions based on conformity of performance of pavements. Sound absorption of pavements is measured using an impedance tube method and in situ testing with a loudspeaker. Both measure normal incidence sound absorption (see figure 6).

The first research was done in the 1970s, when a reduction of 3 dB was seen for passenger cars on PA. No reduction was seen for heavy trucks.



Figure 6. Danish noise-measurement trailer.

More recent research has shown that TLPA performs better at higher highway speeds and can achieve the same or more noise reduction for heavy vehicles as for light vehicles. Thin layers perform better at lower speeds (urban roadways), but do not achieve as much noise reduction for heavy vehicles as for light vehicles. Study results for specific pavements are stated below, where noise-reduction values are compared to their reference pavement, dense asphalt concrete (DAC).

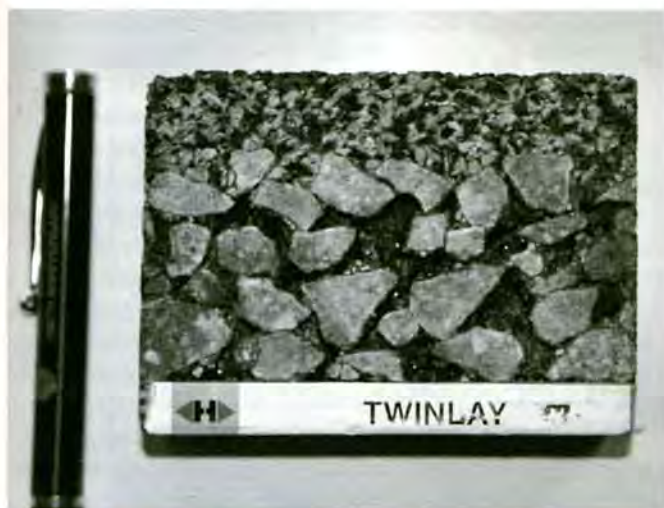


Figure 7. Twinlay mixture (twin layers of porous mixture).

At 110 km/h, the reductions achieved are about 2 dB for the 50-mm porous asphalt, 4.5 dB for the two-layer PA Twinlay (figure 7), and 6 dB for the two-layer PA Twinlay M. At 130 km/h, an approximate 8-dB reduction was achieved with the two-layer PA Twinlay M. The two-layer PA has better reduction around 600 Hz, which allows for more absorption of truck tire noise.

For the Zebra test sections, the average two-layer reduction was about 6 dB (light and heavy vehicles), although the reduction for the eight test sections varied from about 4 to 7 dB. Listed below are the pavements and their corresponding reduction from the reference DAC:

- Single layer porous, 3.5 dB
- Two-layer, 2-to-8-mm top-layer chipping, 5 to 6 dB
- Two-layer, 2-to-6-mm top-layer chipping, 6 to 7 dB
- Two-layer, 4-to-8-mm top-layer chipping (normal two-layer type), about 6 dB

These sound level values were obtained using SPB methodology on pavement aged about 2 months. The oldest section is 2 years old, where durability has been the main issue over time, not noise reduction. Measurements will continue for 7 years.

France

The model the French now use contains vehicle noise emission levels from 1980, but new vehicle noise emission levels are being implemented. The new emission levels consider noise contributions from two sources, engine and tire/pavement interaction. The work for the tire/pavement interaction noise has been completed, and the engine noise work is scheduled to be completed in 2004. The process of determining how to include the various pavements in the model and the effects for aging pavement is in progress. Calculations are performed on an octave band basis. However, it is envisioned that one-third octave band calculations will be implemented in the future. For the tire/pavement interaction noise, sound level curves have been produced as a function of speed for three different pavement categories:

- R1, low noise class (thin asphalt 0/6, 0/10, porous 0/10)
- R2, intermediate noise class (cold mix, DAC 0/10)
- R3, noisy class (cement concrete, surface dressing 6/10, 10/14, asphalt concrete 0/14, thin asphalt concrete 0/14)

France is also modeling the relationship between pavement parameters and noise. The parameters examined include acoustic absorption and impedance, porosity, specific flow resistance, tortuosity, and porous layer thickness.

For policy purposes and model validation, the A-weighted equivalent sound level is measured for daytime hours ($LA_{eq, 6h}$ to 22h) and nighttime hours ($LA_{eq, 22h}$ to 6h) at the building façade. The French are not in favor of using L_{Amax} in determining noise impacts.

To determine the noise-reduction benefits of pavement, the SPB method (ISO 11819-1) is applied. The CPB method (ISO 11819-1) is also applied (with light vehicles only). On roads with heavy traffic, the French will close the road to perform CPB measurements. With these methods, the drawbacks are that the noise level is measured at only one location, not for the whole length of the road, and site conditions for performing the measurements are stringent. LA_{eq} (time-averaged) measurements of existing traffic are performed, as is done for policy purposes, to determine noise-reduction values resulting from quiet pavements.

Although a modified (microphones mounted on the vehicle) CPX method (ISO 11819-2) is still being developed for use in France, the French would like to use the method to determine pavement benefits. The correlation between CPB or SPB and CPX has not been determined fully. Good correlation is seen with light vehicles, but not

yet with heavy vehicles. The method of instrumentation, not as a trailer but with microphones mounted on a light vehicle, is being developed. Pavement sound absorption is measured using core samples in a tube (ISO 10534-1) and the impulse multiple load simulator (MLS) technique (ISO DIS 13472-1). The latter is used in the field for both stationary and moving applications, and is the preferred method because it is nonintrusive.

Applying the SPB method compared to the reference DA pavement (BBSG 0/10), the following noise reductions are achieved:

- 5 dBA for BBDR 0/6
- 4 dBA for BBTM 0/6-T2
- 3 dBA for BBDR 0/10
- 2.5 dBA for BBTM 0/16-T1
- 2 dBA for BBTM 0/-T2
- 1 dBA for BBDR 0/14

The influence of pavement type has not been as much for heavy vehicles as for light vehicles, especially at lower speeds. For Colsoft, L_{Aeq} values are showing a 4.6-dB benefit during daytime hours and a 5.8-dB benefit during nighttime hours.

In observing spectral data for light and heavy vehicles, the following was observed:

- **Light**—Porous pavement is more absorptive starting at 400 Hz, with the largest difference at 1 kHz.
- **Heavy**—Porous pavement is more absorptive starting at 400 Hz, with the largest differences at 800 and 1,250 Hz.

France showed data results for pavement aged 1 to 5 years, with limited data out to 6 and 7 years. There was not much difference with most pavements tested, about 1 dB over 5 years. The noise for dense asphalt BBSG 0/10 did increase. The BBTM 0/6 Type 2 (18 percent voids) showed a 3 dB increase in sound after 6 years, and one data point at 7 years showed an additional 0.8 dB increase. More research is needed on aging. Long-term observations will be made over the next 10 years.

France has identified the following parameters to consider for quiet pavements:

- Reducing the chipping size can reduce tire/road noise.
- Sound absorption can be augmented by porosity.
- Discontinuous formulation is important.
- Pavement temperature influences are important (apply only to asphalt).
- Rigid pavements can be louder than flexible pavements.
- Adding rubber to pavements can reduce noise by 1 dB.

French officials believe that quiet pavements have not been defined sufficiently yet, so they have a tendency to choose traditional solutions (noise walls, insulation, etc.) for noise abatement.

Italy

Quiet pavements are measured on test sections using SPB or CPB methods and are used in the emissions model of the predictions. Italy participates in the HARMONOISE and IMAGINE projects and plans to use the prediction code when it is available.

Several acoustic models are part of the SIRUUS project: tire noise generation, sound absorption, vehicle emissions, and structural behavior of silent pavements.

For noise impact determinations, the Italians measure both a daytime and nighttime equivalent sound level (L_{eq}), and plan to switch to the day-evening-night sound level (L_{den}).

SPB is used when possible to measure pavement noise reduction, where measurements occur once each year. When SPB is not possible, the Italians use their own version of a controlled pass-by method, with at least one light and one heavy vehicle. At least one study was performed by measuring the SEL, in which noise benefits were examined according to height above the ground. Autostrade is in the process of developing a modified CPX method, in which microphones are mounted directly on the vehicle.

The absorption coefficient for pavement is measured on core samples using traditional standing wave methods or impulse methods using a speaker located above the actual pavement. The latter is used in the field for both stationary and moving applications. The impulse method has been a challenge for measuring frequencies below 400 Hz.

Noise-reduction results for various pavements from the SIRUUS research project are shown in the research section of this chapter.

United Kingdom

The prediction method used is calculation of road traffic noise (CRTN) (ISBN 0 11 550847 3), which has been implemented in privately developed computer models. Noise predictions are based on traffic flows expected 15 years after the new construction is open. Surface correction for PA is defined in CRTN as -3.5 dB (long-term). For standard quiet pavement the correction is taken as -2.5 dB (as defined in specification). EAC can be taken as having a -1.5-dB correction. These corrections are made from the HRA reference pavement (20-mm aggregate size) and are made at the source, on the overall A-weighted level (not spectrally). TRL has developed a conversion from L_{10} (sound level exceeded 10 percent of the time) to L_{den} for use with CRTN. However, as part of the EU, the United Kingdom will implement the use of computer models based on the outputs from the HARMONOISE and IMAGINE projects. The latter is intended

to provide an engineering model version for the purpose of mapping, while the former was developed for validation purposes.

For noise impacts/intervention purposes (levels exceeding 68 dB), the metric L_{10} is determined for the hours 6 a.m. to midnight. For associated noise measurements, the microphone is placed 1 m from the façade.

HAPAS determines the noise relationship of the various quiet pavement systems (the method, which also includes SPB measurements, is described in a World Road Association (PIARC) paper). Tests qualify which types of pavements are allowed for thin layers. A reduction of 2.5 dB or greater qualifies as a quiet pavement. Testing is conducted at two sites for 2 years for each thin layer. CPX (using the Transport Research Laboratory's TRITON mobile research laboratory) and coast-by methodologies (light vehicles only) are also used.

The British perform both static and dynamic noise-absorption testing. They have implemented the MLS system on a rolling vehicle, and are investigating relationships by which absorption measurements combined with CPX measurements can be used to predict SPB sound levels (see figure 8).

Standardized measurement methods that examine only one lane of traffic (SPB, CPX, etc.) may not be best for measuring the pavement noise benefits from multiple lanes of the pavement. Also, it is important to measure real traffic, since noise benefits have been seen to be less for heavy vehicles than for light vehicles.

In the 1980s, the United Kingdom began to recognize the noise benefits of PA. In the mid-1990s, researchers began to recognize the benefit of thin surface overlays. Tire/pavement noise measurement results, some showing comparisons to the reference pavement (HRA), are described below.

Exposed aggregate concrete was investigated in TRL576. In the first 12 months, the noise levels (SPB) from the 6/10-mm aggregate EAC were lower than the HRA, an average of 1.7 dBA for light vehicles and 1.3 dBA for heavy vehicles. The 8/14-mm aggregate EAC was similar to the HRA. Over time (in some cases, out to 82 months), larger increases in noise are seen with HRA (in the 500-to-1,250-Hz range for light and heavy vehicles) than with EAC (in the 1,000-to-3,000-Hz range for light vehicles and 800-to-1,250 Hz range for heavy vehicles). Additional data will be collected to support this conclusion. For SILVIA, some experiments have shown that for 20-mm aggregate PA, a 5-to-6-dB initial reduction and a 3-dB, 8-year reduction is being seen compared to 20-mm aggregate HRA.

After rainfall, traffic noise levels measured alongside both Masterpave and PA surfaces increased by 3.2 dBA



Figure 8. TRL noise test trailer.

and 3.5 dBA, respectively, when compared with dry surfaces. There was no increase in the noise for HRA.

Researchers in the United Kingdom also commented on annoyance in communities and clogging of porous pavement. Studies show that a change in the road does not follow the steady-state relationship between noise and proportion of people highly annoyed. For example, for a new road, annoyance is higher than the steady-state yields, and for a case in which a bypass was constructed (much less traffic on the existing road), the annoyance is lower than the steady-state level measurement would predict. For clogging of porous pavements, even though higher-speed roadways are self-cleaning, it is thought that most of the cleaning occurs in the tire tracks. In other locations, the pavement can clog, which causes a reduction in the noise benefit that occurs from absorption of propagating sound.

Officials generalized that for macro texture larger aggregates cause more noise, and for micro texture smaller aggregates cause more noise.

For a quiet pavement there is a reduction in block snap and air pumping mechanisms, plus absorption across porous surfaces. This last characteristic tends to deteriorate with age (about 50 percent loss of benefit overall after 5 to 6 years).

CONSTRUCTION

Denmark

Pavements must be in relatively good condition before they are considered candidates for overlay with PA. They must have very few defects with no rutting, for example, because treatments are thin. In Denmark, quiet pavement systems have been used only in experimental locations, not as a routine measure.

All projects (coarse and dense graded) are low bid, but a 5-year warranty is included in all bids. The contractor must correct any defects at the end of this time. New construction contracts are being considered that give a contractor a designated amount of money annually to maintain a project over a 15-year period. If the contractor does a good job and no maintenance is required, the contractor keeps the money. If maintenance is more than the allocation, the contractor is required to maintain the project out of its pocket. This concept applies to all warranty conditions, not just noise.

Once a new concept or product has been evaluated, the researcher turns over the details to the Standards Committee (under the Ministry of Transport), which is composed of academia, contractors, etc. The Standards Committee takes the product and draws up the standards.

The contractor tests state samples—30 to 40 projects per year with a mobile test lab as a check. No penalties are assessed for failure to achieve the design noise criteria. The Danes run a noise-absorption test on test specimens and on in situ pavement, but they question the usefulness of this test. No specialized construction equipment, training, or inspection techniques are required.



Figure 9. Construction of the rollable road.



Figure 10. Construction of the ModieSlab (two-layer porous concrete).

The Netherlands

More than 65 percent of the national highway system has been surfaced with PA. Two-layer (Twinlay) mixes are used primarily on high-speed rural areas, and single-layer mixes are proposed for lower-speed urban areas.

Construction of the two-layer system should be placed “warm-on-warm”—not allowing cooling of the first layer and eliminating the tack coat. Conventional construction requires the use of tack coat between layers when placing warm on cool. The contract requires use of insulated truck beds and covered (tarped) beds. Although the mixes are designed at 25 percent air voids, the target on the roadway is 20 percent. The first noise measurements are taken 8 weeks after construction using the CPX procedure. The reference for noise reduction is dense asphalt concrete (DAC). The initial reduction is about 5 to 6 dB for the two-layer system on high-speed facilities, and about 3 to 5 dB on low-speed (30-to-55 km/h) roadways. The pavement life or durability for PA mixes is about 8 to 10 years, compared to 10 to 12 years for DAC. The pavement warranty covers durability, but not noise. Over the pavement life, the acoustical durability is about 4 dB. The loss in acoustics is because of clogging and raveling. Including both skid resistance and noise reduction under the 3-year warranty period is under consideration for the 2005 construction season.

France

France has established a noise database of some 289 SPB measurements. PA using the 0/6-mm aggregate size is the quietest pavement at 71 dB (69 to 74). The next quietest is the 0/10-mm size at 74 dB (69 to 78). The 0/14-mm size is 75 dB (74 to 76). For comparison, the reference pavement is a 0/10-mm dense-graded mix that measures 78 dB (74 to 82), and chip seals that measure 78 dB. It is assumed that when the noise increases on a PA mix, the pavement has clogged, but there is no supporting data. The French have stopped using the 0/14-mm mixes for surfacing because of a lower skid and decreased performance for noise reduction. The French begin noise measurements 2 to 3 months after construction, and have found an increase of 1 dB after 1 to 6 years of service. New pavements are expected to maintain a maximum noise level of 75 dB during the life of the pavement. If the noise level exceeds 75 dB, some type of corrective action is required.

A number of factors are used to select a contractor. Although low bid is an important consideration, other factors may include work history, qualifications, and technical expertise. The final selection is based on a combination of these considerations. Some projects



Figure 11. Recycling a porous pavement in Italy.



Figure 12. Permeability testing of recycled mix.

have a 10-year guarantee on the total structure. The contractor is responsible for any structural failure (alligator cracking or any other distress that indicates a failure at depth in the pavement structure). This guarantee does not include normal wear of the surface course.

The thin mixes are used for most maintenance work. To begin laydown operations, the temperature must be higher than 5 degrees Celsius (C). Tack coat is considered essential between layers and is always required. The service life of these mixes is 10 to 14 years. Skid performance and noise reduction are much better for the 0/6-mm mixes, and these mixes do not clog as rapidly in urban (slow traffic speed) areas. The French do not attempt to clean porous mixes because they have not found the pressure wash and vacuum system to be effective.

Porous mixes were first used 15 years ago for spray reduction and to some extent for smoothness. However, the mixes were found to be rut resistant, skid resistant, and noise reducing. Porous mixes are not used at crossroads or other areas where severe turning actions are encountered. The primary failure mode for porous mixes is raveling. Raveling has been associated with gap grading, and 7 to 10 percent sand mortar is now used to resist raveling.

The French run a permeability test on mix specimens in the lab and in the field. Field test results cannot be predicted based on the lab results. A significant difference in noise level has also been noted using the same mixes and same contractor. By adding 1 to 2 percent rubber, a 1-dB noise reduction has been measured for the porous mixes as well as the thin mixes. Experimental

sections have been placed using lightweight aggregates for skid resistance and noise reduction, and so far the tests look good. A test is being devised to quantify spray reduction.

Italy

The Italians began recycling PA mixes in 1996 using the hot-in-place process. They favor the Martex AR 2000 and the Marini ART 220 for recycling (see figure 11). During the hot-in-place recycling operation, the contractor conducts drainage tests that consist of filling a large tube (attached and sealed to the pavement surface) with water (figure 12). The amount of water that flows into the pavement over a 10-second interval is measured (procedure is similar to a falling head permeability test). A calculated flow rate of 20 liters per minute is considered good. If the flow rate does not achieve this value, the approach taken is not clear. One technician stated that the test would be run again, while one manager indicated that the amount of virgin material added to the recycled mix would be adjusted to achieve the desired permeability.

United Kingdom

Projects are awarded differently, depending on the system of financing. About 10 percent are awarded on the basis of design-build-maintain-and-operate concessions for 30 years. In these cases, proposals submitted are reviewed and weighted 80 percent on technical merit and 20 percent on cost. Other projects are design-build-and-hand-over. The main contractors are often partnered with material suppliers, and the surfacing product used is proprietary. Material specifications for such products are

“Traffic uses the same amount of energy in the first year as the total amount of energy used for construction.”

—Robert Dudgeon,
Highways Agency

developed and owned by the contractor. The British are moving to performance-based specifications for paving materials to ensure a competitive market. The contractor is responsible for providing a quality control system.

The British have also implemented a procurement process referred to as early contractor involvement (ECI), in which the contractor is selected

before a final design is complete. This process has reduced project conception-to-delivery time from 10 to 7 years and has reduced the contractor's perceived risk (which is hoped to reduce project costs).

The British experimented with PA in the 1980s for spray reduction. They later discovered the noise-reduction benefits, but found durability problems because of raveling. One extremely hot summer destroyed many of the existing PA mixes laid in the United Kingdom, so they turned to thin surfacings in the 1990s. To meet U.K. skid-resistance requirements, development work with existing formulations for thin surfacings was needed to improve performance.

A number of products met this requirement in 1996 through modification of their mix formula. Contracts now require the use of quiet pavements but allow the contractor to select from an approved list of more than 30 products (primarily thin surfacings).

The products are warranted to maintain their quality



Figure 13. Winter maintenance on porous asphalt in Europe.

for 3 years, but longer warranty periods are being considered. Also, no incentives exist for developing products that exceed the minimum requirements. For example, a product that achieves a 5-dB reduction is not given any more credit than one that achieves the minimum 2.5-dB reduction. (A new class of higher noise-reduction performance is being launched in late 2004 to cover an emerging number of products that can now provide the extra benefit.) Thin-surface mixes are the primary quiet pavement technology now used in England. The primary failure mode is raveling. The mixes are subjected to a wheel-tracking test and warranted for 2 to 4 years.

Early use of exposed concrete pavements (Whisper Concrete 1993) proved to be successful, but current policy dictates that any concrete pavement must be covered with a HAPAS-approved quiet pavement mix. Forty percent of new roads are CRCP with a thin-surface lift, and 60 percent are constructed with concrete base. Porous concrete was never used in Britain because of excessive cost and the required construction techniques (must be placed wet-on-wet and use specific polymers).

MAINTENANCE

Denmark

Denmark cleans TLPA pavements with a high-pressure water blast (100 bar/125 pounds per square inch (psi)) followed by a vacuum to remove the fluid and solids (figure 13). Vendors using specialized equipment conduct the work. The first cleaning is conducted 3 months after construction, and cleaning is done semiannually thereafter. The water is filtered and recycled for future cleaning operations. The solids contain heavy metals, so they must be disposed of in an approved facility. To date, the benefits of cleaning have not been clearly established and the Danish Road Institute (DRI) plans to conduct future research in this area.

The Danes indicate that PA pavements begin to clog within the first year, although high-speed pavements fare better because of the cleaning action of high-speed vehicles. The Danes also indicated that if a pavement is not cleaned on a regular basis, it could become too clogged to be cleaned effectively after 2 years or less. When a pavement's permeability becomes less than 75 seconds/10 cm, the pavement is considered too dirty to be cleaned (initial permeability is less than 10 seconds/10 cm). The test sections indicate that by the fourth year the permeability of low-speed PA pavement is significantly reduced and the noise-reduction benefits are reduced.

In Denmark, porous pavements require additional maintenance during the winter because of the potential for icing conditions. This is due in part to the additional

Temperature

Surface temperature drops more rapidly and lower

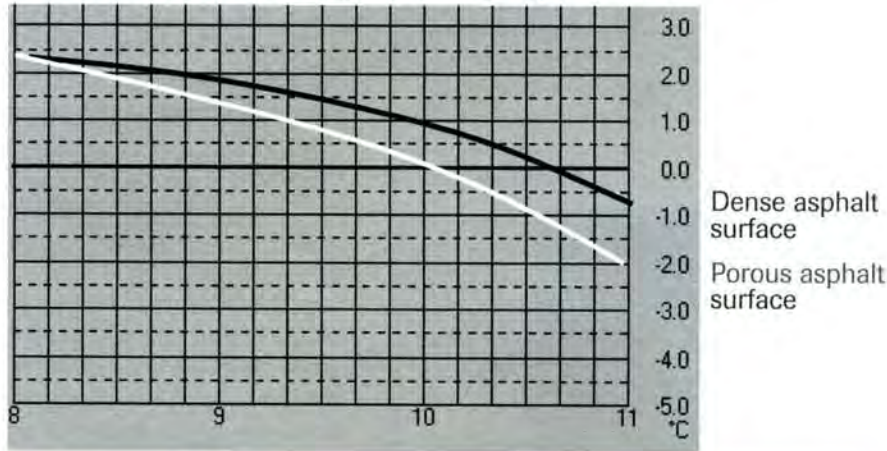


Figure 14. Comparison of surface temperatures in dense-versus-porous asphalt surfaces.

surface area, which allows the surface temperature to drop 1 to 2 degrees C faster than DGA (see figure 14).

For snow and ice control, DRI does not use friction media (sand), but instead uses a wetted salt solution (water applied at the back of the truck). DRI indicated that the formation of black ice is also an issue. However, prewetted salts seem to work well and have the added benefit of leaving the top dry but with a white coating, which results in drivers slowing down. Calcium chloride and wetted salt are used to increase the even distribution of the salt and to prevent the formation of ice hats. Ice hats form because the salt tends to wash from the top of the open-graded surfaces into the pore spaces, leaving the surface susceptible to icing (see figure 15). DRI is also looking at larger salt grains to perhaps minimize this problem. DRI indicated that the porous surfaces increase salt consumption by 50 percent and result in increased callouts for maintenance.

The Danes also expressed concerns about transitions from dense to porous surfaces because they may “spook” drivers in winter conditions, and indicated that short sections of porous surfaces should be avoided. DRI recommended not using porous surfaces in intersections because of the winter risks (see figure 16 on the following page).

The Netherlands

In the Netherlands, safety is a top priority and skid resistance is required for all new surfacings. On porous pavements, the Dutch occasionally have experienced poor skid based on the slipped wheel skid test. They do

Temperature

Different radiation compared to dense asphalt (more surface)

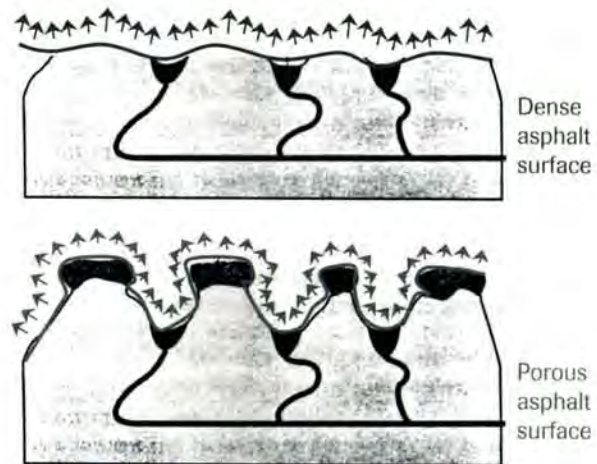


Figure 15. Comparison of radiation from dense-versus-porous asphalt surfaces.

not know why this happens, and they are considering requiring that a 5-year warranty be included to encourage the use of better aggregates and construction methods. When low friction is detected, speed reductions or post treatments are required. However, these treatments may negatively affect the acoustic properties of the porous pavement.

The Dutch also expressed concerns about acoustic durability resulting from clogging. Porous pavements are

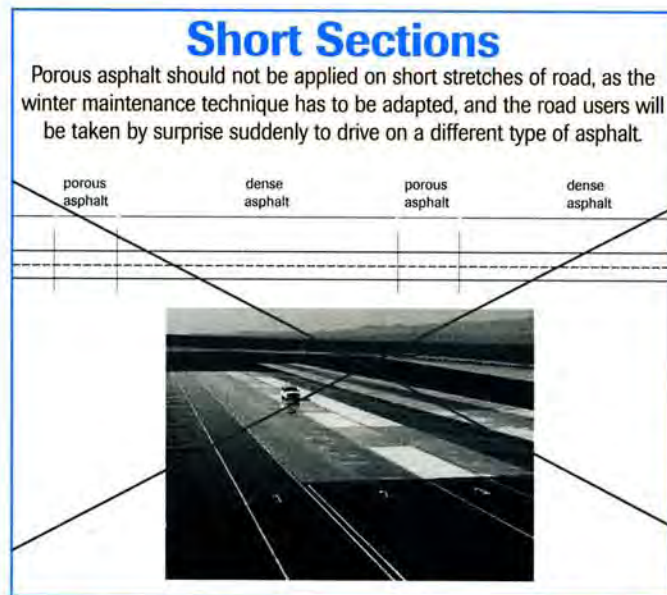


Figure 16. Short sections of porous surface.

cleaned regularly using high-pressure water blasting (100 bar/125 psi) and then vacuumed. This is done twice yearly, but it is highly dependent on traffic, speed, and other factors. If the surface becomes completely clogged, it is impossible to clean. Following cleaning, the noise reduction and permeability are worse (because material is brought up to the surface), but these properties improve shortly thereafter. The Dutch indicate that clogging begins to manifest after 6 months. However, their experience shows that clogging does not affect noise reduction as much as first thought, perhaps 1 to 2 dB. The effectiveness of pavement cleaning is still being investigated and debated.

The Dutch no longer use PA pavements in urban areas because of clogging. In rural, high-speed applications, traffic reduces clogging, so they may high-pressure wash and vacuum only the emergency lane (shoulder).

In the Netherlands, porous pavements require additional maintenance during winter weather. About 50 percent more salt applications are required. The formation of black ice, especially on the eastern side of the country, is a challenge. The best solution is the use of prewetted salt applied as soon as the pavement begins to freeze. To address winter maintenance concerns, the Dutch use communication (signage, news, weather reports), lane closures (direct two lanes onto a single lane to assist in ice break-up), and preventive actions such as presalting before storms.

Raveling is the predominant failure mechanism, and when raveling exceeds 25 percent, the surface is

replaced. The use of fog seals has not been evaluated to retard raveling.

Age hardening of the binder occurs within 6 to 8 years, but cracking or rutting is not a problem.

Test EAC sections on N279 built in 2002 are performing well. Beyond the initial roughness of the roadway, there have been no maintenance concerns.

France

In France, porous pavements are obtaining a service life of greater than 10 years. The French indicated that clogging is more of a problem in porous pavement than in very thin asphalt concrete. The French do not try to clean clogged porous pavements because they have not found cleaning to be effective. Instead, the mix design is optimized to eliminate or reduce clogging. When it is necessary to rehabilitate the pavement surface, milling is employed. If the worn surface is completely plugged, it is permissible to overlay the existing pavement. Porous pavement is no longer used in built-up areas because of fast clogging.

Although porous mixes can be used on any type of pavement, France has experienced some problems with the mixes freezing during the winter. As a rule of thumb, porous mixes are not used in France east of Paris' meridian and at altitudes above 600 m. Thin mixes are typically used east of Paris' meridian and porous mixes are used west of the meridian. Porous pavements and, to a lesser degree, very thin asphalt concrete are susceptible to the cold and can facilitate the production of black ice. In France, porous pavement surfaces fall to the frost point about 30 minutes before dense surfaces.

In the event of a prolonged winter storm, salt must be supplemented by a calcium chloride solution to remove thick ice and snowpack from the spaces in the porous surface. In France, a combination of dry salt, wet salt, wet salt enhanced with calcium, and straight calcium chloride solution is used, depending on pavement conditions (ice versus snow), preventive-versus-reactive maintenance, and wet-versus-dry surface.

Italy

In Italy, 34 percent of the Autostrade system has PA. To date, the Italians' experience with PA has been good, but they have experienced clogging issues with various types of porous pavements. Attempts to clean porous pavements have not been beneficial and the noise-reduction capability of the pavement has been reduced. However, the Italians indicated they have developed a new machine that allows them to thoroughly clean the pavements, which they plan to do every 2 years. Mill and overlay is the typical method for replacing the porous surfaces.

The Italians reported up to a 50 percent increase in salt use for porous pavements in the winter. The typical combination used is magnesium and calcium. In Italy, runoff of the salt brine is an environmental concern.

United Kingdom

The British prefer thin, noise-reducing surfacings to PA surfaces. Their experiences with PAs in the 1980s indicated these tended to clog even on high-speed motorways and were also subject to raveling after a fairly short life. Less winter salt is required for the thin surfacing because the texture of the pavement holds the salt on the road surface for a longer time period. With open-textured PA, much of the salt disappeared into the voids below the surface.

In the United Kingdom, pavement management (PM) drives the delivery needs. The target is to cover 60 percent of the system within 10 years. The British estimate this will benefit three million people living within about 500 m of the strategic network. To accomplish this goal will require the overlay of 2,000 lane/km per year. A budget of £700 million per year is dedicated to covering network maintenance costs.

RESEARCH

Denmark/Sweden

On the last day of the scan team's visit in Denmark, Professor Ulf Sandberg from Chalmers University of Technology in Gothenburg (Sweden), also affiliated with the Swedish National Road and Transport Institute, presented some of his research (see figure 17). Sandberg reported that in one of his projects, three approaches are being investigated for tire innovations for low noise emission:

1. Composite wheel (targeted reduction of 5 to 10 dB)—This is a nonpneumatic tire. Tests show a potential 10-dB reduction. The composite wheel reduces noise emission by eliminating air pumping in the tread, as well as by short-circuiting the low-frequency noise generated in the structure because of elimination of the baffle effect of conventional pneumatic tires.
2. Conventional tire with porous tread (targeted reduction of 3 to 5 dB)—Porous tires are proposed for production in Sweden using porous rubber instead of tread.
3. Design the tire by a noise model—Smaller tread block size reduces tire noise. Tire noise is reduced if a normal tread block is cut transversely, reducing the block size.

The Danes also consider at least three ways of increasing the noise-reducing properties of porous pavement:

1. Optimize the pavement texture by selecting smaller aggregates for surfacing. Aggregates greater than 11 or 12 mm tend to lose their noise-reducing characteristics.
2. Optimize the porosity of the pavement by examining the relationship between noise reduction and percentage voids per layer thickness.
3. Use a softer pavement.

The Danes have evaluated the long-term noise-reduction performance of several mixes, including single- and double-layer porous mixes using small (5 mm), intermediate (8 mm), and large (11 mm) aggregates, and several performance-graded modified asphalts. They are also evaluating thin mixes similar to Novachip and microsurfacing using the same series of aggregate sizes.

In addition, one innovative quiet pavement technology being investigated is the poroelastic road surface (PERS). This surfacing is made mainly of rubber in prefabricated panels or rolls with a porosity of about 35 percent. Although the noise reduction is good, durability has been a challenge. For example, there have been problems with snowplows scarring the pavement. Conversely, studded tire resistance is good. Another innovative design is the use of interlocking blocks (concrete blocks with asphalt surface), which has exhibited a noise reduction of about 8 dB.

The Netherlands

In response to the Noise Nuisance Act of 1979, the Dutch Ministry of Transport, Public Works, and Water Management and the Ministry of Environmental Affairs have initiated a sizeable IPG to reduce road noise. The program is charged with developing noise-reducing measurements. The goal of the program is to reduce traffic noise significantly, especially through the use of



Figure 17. Photo from Professor Ulf Sandberg's presentation. (VINNOVA, Swedish Agency for Innovation Systems)

source-related measures. In addition, the program focuses on implementing or developing the technologies and products to a level of general application. The approach to the program is to investigate all possibilities of noise reduction by road surfaces, tires and vehicles, and enhanced noise barriers. Potential results include decreased dependence on barriers and increased use of source-related measures. Strategic aims include noise reduction, affordability, readiness for implementation, and source measures. Technical aims include noise reduction (5 dB), construction durability of 8 to 10 years, cost effectiveness (50 percent reduction compared to the road), and acoustic durability (4-dB lifetime average).

Table 5. Gaps in knowledge.

	Nonporous	Porous
Car Tires	A lot is known	Some knowledge
Truck Tires	Little knowledge	Almost none

Table 6. Noise reduction results (compared to a dense-graded reference mix).

Pavement Type	Expected Noise Reduction, dB	Actual Noise Reduction, dB
Very Silent Sound Module	10	5
Rollable Road	8–10	6
ModieSlab	6–7	6–7
Adhesive Road	6–7	6



Figure 18. Test road for very silent sound module (Helmholtz resonator).

Technical clusters include silent vehicles and tires, silent roads, more efficient barriers, assessment measures, and knowledge infrastructure. The focus of the silent roads effort was the design and development of a new generation of silent roads. The expected noise reductions from this program (2003–2007) were 4 dB for road surfaces, 2 dB for tires and vehicles, and 2 dB for barriers, for a total of 8 dB. Table 5 outlines information still to be gained.

Goals for new research:

- How can porous surfaces be optimized?
- Investigate third-generation surfaces (poroelastic).

The Dutch research program includes studies on truck tires in Germany, porous surfaces in the Netherlands, truck tires on porous surfaces, and development of hybrid models that account for truck tires on porous surfaces, as well as applications of these studies.

Perhaps the most innovative research being conducted in the Netherlands is the Roads to the Future (RTF) program, launched in 1996 to improve mobility. This program tries to envision 30 years into the future and develop concepts that will be important then. There are competitions to propose ideas, the most promising of which move toward construction of test sites. The program runs in 3-year cycles and is now in the third cycle, with 30 to 32 pilot projects completed. After a theme has been chosen (e.g., maintenance) the question becomes, “What will be crucial to maintenance 30 years in the future?” Respondents are asked what they expect or what they would envision, as opposed to what they think is likely. Incremental steps are then taken toward this long-term vision.

Road Surfaces of the Future occurred in the second RTF cycle. Roads had to be modular in construction and designed for a specific purpose. The phases for RTF include long-term perspective (large-scale pilot project), development of functional specifications, construction of a pilot project, and development of improved specifications.

An RTF test section has been constructed on A50. Its features include rapid construction and removal, functional design, major noise reduction (greater than 5 dB), high permeability comparable to PA, modular construction, and room for other functions (sensors, energy production, etc.).

The test sections include the following (see table 6):

- Very silent sound module (Helmholtz resonator) (figure 18)
- Rollable road
- ModieSlab (one-to-two-layer porous concrete)
- Adhesive road

Other research programs include the following:

- Dynamic road markings, with narrower lanes during rush hour
- Floating road, similar to a floating bridge
- Safe driving—in-car monitors for speed and following distance—used for insurance reduction and other incentives
- Construction tests at the Lintrack accelerated pavement test facility

One of the more impressive test sections the team observed was a TLPA section on A28 (figure 19). The section includes eight different contractors' mixes for TLPA. The pavement was exceptionally quiet and exhibited no splash/spray during an afternoon rain event. The team also visited an EAC test site with sections ranging from 4/8 mm to 11/16 mm. EAC is generally louder for passenger cars than dense-graded asphalt, but quieter for trucks.

France

In France, the research program considers all aspects of noise—mitigation, emission, and reception at building facades. However, no formal process exists for implementing research. Contractors in France, as well as in most other European countries, are conducting product research on their own. This

process seems to be well entrenched and works well as a public/private partnership.

Italy

Experimental pavements using resonant technology (euphonic and ecotechnical), originally used by the Romans 1,700 years ago to control low-frequency noise, are being studied under SIRUUS (see figure 20 on next page). In addition, experimental sections of synthetic aggregate mixes are being tested for noise mitigation. These synthetic mixes are composed of 12 percent by weight expanded clay that has been kiln dried. To date, more than 12 million square meters have been placed with an average -2-dB noise differential from the reference dense-graded mixes. Again, these mixes were first used because of their high skid-resistant properties, but later were found to provide a noticeable reduction in tire-pavement noise.

- The ecotechnic pavement was developed for urban traffic. It is a multilayer pavement, including a top layer of PA (0/5 mm), a base layer of PA (0/24 mm), and a metallic panel disconnection layer. Performance improvement is 8.2 dB at 20 km/h and 9.1 dB at 60 km/h.
- Expanded clay has been developed as a safe and



Figure 19. Two-layer porous asphalt section on A28.



Figure 20. The "euphonic road" in Italy.

quiet addition for single-layer PA for northern Italian cities. The expanded clay was 7 to 15 percent by weight of the mix. Skid resistance rose from 50 to 60. Noise reduction was increased by 2 dB over PA. The Italians believe that the micro voids in the clay contribute to the noise-reduction benefit. Cost was 0.20/m² per cm thickness.

Many of the SIRUUS pavement concepts are variations of the euphonic pavement, which consists of two layers of PA connected to a layer with Helmholtz resonators in either the third or fourth layer. Sometimes the third layer is a transition layer. The Helmholtz resonators are designed to absorb noise over the range 100 to 250 Hz. Compared to the reference pavement, these pavements typically are 2 to 4 dB better from 80 to 250 Hz, 8 to 14 dB better from 315 to 800 Hz, and 2 to 6 dB better from 800 to 5,000 Hz.

Several acoustic models are part of the SIRUUS project: tire noise generation, sound absorption, vehicle emissions, and structural behavior of silent pavements.

United Kingdom

The United Kingdom's HAPAS road surface influence parameter has categorized standard types of road surface (when new) in the following order of decreasing noise:

1. Brushed concrete: -1.6 to +7.4 dB
2. HRA: -1.5 to +0.6 dB
3. EAC: -3.9 to -1.9 dB
4. Thin bituminous overlays: -5.8 to -0.5 dB
5. PA: -7.5 to -5.2 dB

The road surface influence is based on SPB measurements of vehicle noise. A considerable amount of research effort has been put into developing a strategy for continuous monitoring using the CPX method (TRITON mobile research laboratory) and correlating these noise data with continuous measurements of surface texture made routinely to monitor skid resistance.

EAC and thin bituminous surfacings are found to be largely self-cleaning, but PAs clog up over a period of about 5 years. Research monitoring the noise performance of PA with 20-mm aggregate showed a 5-to-6-dB initial reduction and a 3-dB 8-year reduction in pass-by noise compared to a (positively textured) conventional HRA with 20-mm aggregate. Traffic noise increases on negatively textured surfaces immediately after rainfall. Traffic noise levels measured alongside both Masterpave (thin surfacing) and PA surfaces increased by 3.2 dBA and 3.5 dBA, respectively, when compared with measurements on dry surfaces, but there was no increase in the noise on adjacent HRA monitored for comparison.

The United Kingdom is involved in the European research and development partnership called Silenda Via (SILVIA, or Sustainable Road Surfaces for Traffic Noise Control). The objective of SILVIA is to provide decision-makers with guidelines on the selection of sustainable road surfaces for noise reduction. Outputs will include a classification method, a cost/benefit analysis, sustainable solutions, integrated noise measurements, and ultimately overall guidance and advice on performance measures. Preliminary results of the SILVIA project are at www.trl.co.uk/silvia. A final report is due in 2006.

CHAPTER THREE

SIGNIFICANT FINDINGS

Policy

1. The EU Environmental Noise Directive established an overall noise policy to encourage member states to reduce the exposure of populations to noise from transportation and industry sources.
2. The EU directive required maps of noise exposure and action plans to reduce exposure to be developed and reviewed every 5 years of a 10-year plan for noise annoyance. Noise mapping must be delivered by July 2007 with identification of critical areas and action plans for these by July 2008. It supports out-of-the-box research on major highways.
3. Noise annoyance surveys of the public are being used to determine annoyance in relation to noise levels measured on the new L_{den} index.
4. Several countries visited have established abatement guidelines and limit values.
5. In several countries, noise characteristics are a critical performance indicator when selecting pavement strategies.

Design

1. Recycling of PA was performed using a hot-in-place process in Italy to renew a porous layer.
2. EAC surface has been used successfully in two countries to provide lower noise.
3. Smaller aggregate size asphalt surface mixes using a dense or semidense gradation is the technique many EU countries use to obtain low-noise pavement surfaces. These mixes are used for low- to medium-speed traffic applications.
4. PA systems with single-layer and double-layer systems are used or planned by several EU countries for significant noise reductions on high-speed facilities or facilities with significant truck traffic.
5. Safety performance of low-noise surfaces has been maintained or enhanced compared to traditional pavement systems in all countries reviewed.
6. Durability of low-noise pavement systems varies from 7 to 15 years, depending on the pavement system and the experience level of the owner agency.
7. Low-noise pavement surfaces typically are assumed not to provide a structural contribution to the pavement, but some countries use a fractional structural contribution.

Noise Analysis

Measurement

1. CPX
 - A. CPX methods vary among countries, and include the on-vehicle method.
 - B. Research is still in progress on use.
2. Wayside measurements
 - A. All countries use SPB, with some reporting results only for light vehicles.
 - B. CPB is prevalent in Europe, but is not standardized.
 - C. Some time-averaged measurements of traffic noise are used to gather SPB-like data.
3. Sound absorption
 - A. Sound absorption is being measured in many countries. Standard ISO MLS methods are used. Moving methods seem especially useful but are not fully developed.
 - B. Research is underway to develop a method for use with CPX to correlate to wayside measurements.

Modeling

1. Adjust at source in model using SPB.
2. Adjust at final level for simplified method.
3. Model the relationship of pavement texture to noise.

Performance history

1. Pavement noise-reduction benefits need to be presented with mention of the reference pavements.
2. Only some of the countries have results for ageing pavement.
3. Some countries presented spectral data.
4. The noise-reduction benefits have been shown to be different for heavy trucks than for light vehicles. It has also been shown that these compose a substantial part of the traffic noise.
5. Texture and porosity of pavements are important contributors to pavement noise.
6. No good correlation exists between permeability and noise reduction.
7. Wet pavement
 - A. Quiet pavements allowing drainage help maintain or maximize the noise-reduction benefit during wet conditions.
 - B. Retained moisture typically degrades performance for a day after rain.

APPENDIX B HOST COUNTRIES AND CONTACTS

DENMARK

**Road Directorate,
Ministry of Transport**
Danish Road Institute (DRI)
Elisagaardsvej 5
P.O. Box 235
DK-4000 Roskilde, Denmark
Phone: +45 (46) 30-7000
Fax: +45 (46) 36-7864
<http://www.vd.dk>

Primary Contacts: Hans Ertman
Larsen, Hans Bendtsen

Other Contacts:
Henning Christiansen,
Jorgen Christensen,
Bent Andersen, Stefan Sigurdsson,
Carsten Bredahl Nielsen,
Vibeke Wegan, Jorn Raaberg,
Lene Nohr Michelsen, Karin Kool
Ammitsoe, Freddy Knudsen

NCC Roads A/S
Produktion og Teknik
Fuglesangsalle 16
DK-6600 Vejen, Denmark
Phone: +45 7996 2323
Fax: +45 7996 2324
<http://www.ncc-roads.dk>
Primary Contact:
Jorn Bank Andersen

Medam AB
Svanvagen 50
611 62 Nykoping, Sweden
Phone: +46(0) 155-29 1051
Fax: +46(0) 155-29 1052
<http://www.medam.se>
Primary Contact: Mats Furen

COWI A/S
Odensevej 95
DK-5260 Odense S, Denmark
Phone: +45 6311 4900
Fax: +45 6311 4949
<http://www.cowi.dk>
Primary Contact:
Soren Rasmussen

Chalmers University of Technology
SE-412 96 Goteborg, Sweden
Phone: +46(0) 31-772 2200
Fax: +46(0) 31-772 2212
<http://www.vsect.chalmers.se>
Primary Contacts: Ulf Sandberg,
Wolfgang Kropp

THE NETHERLANDS

**Ministerie van Verkeer en
Waterstaat (Ministry of
Transport, Public Works,
and Water Management)**
Dienst Weg-en Waterbouwkunde
(DWW)
Van der Burghweg 1
PO Box 5044
2600 GA Delft, The Netherlands
Phone: +31 15 251 83 70
Fax: +31 15 251 85 55
<http://www.verkeerenwaterstaat.nl>
Primary Contact: Erik Vos
Other Contacts: Govert Sweere,
Dr. Rob Hofman, Cristo J. Padmos,
Lotje van Ooststroom,
Aad de Winter, Koos van Wieringen

M&P Raadgevende ingenieurs bv
Wolfskamerweg 57
Postbus 2094
5260 CB Vught, The Netherlands
Phone: +31 073-6589050
Fax: +31 073-6589051
<http://www.mp.nl>
Primary Contacts: Jan Hooghwerff,
Gijs Jan van Blokland

**KOAC WMD (Dutch Road
Research Laboratories)**
Schumanpark 43
NL-7336 AS Apeldoorn,
The Netherlands
Phone: +31 55 5433100
Fax: +31 55 5433111
<http://www.koac-wmd.nl>
Primary Contact:
Dr. Jacob Groenendijk

Heijmans Infrastructuur
Graafsebaan 13
PO Box 380
5240 AJ Rosmaien, The Netherlands
Phone: +31 (0) 73 528 9204
Fax: +31 (0) 73 528 9134
<http://www.heijmans.nl>
Primary Contact:
G. G. van Bochove

TNO TPD
Stieltjesweg 1
PO Box 155
2600 AD Delft, The Netherlands
Phone: +31 15 269 2467
Fax: +31 15 269 2111
<http://www.tpd.tno.nl>
Primary Contact: Foort de Roo

FRANCE

Sétra (Service d'Etudes Techniques des Routes et Autoroutes)

46 avenue Aristide Briand
BP 100
92225 Bagneux Cedex
Salle Parc n° 1
Paris, France

Phone: +33 (1) 4611 3188

Fax: +33 (1) 4611 3650

<http://www.setra.equipement.gouv.fr>

Primary Contacts:

Emmanuel Seixas, Vanessa Minard

Other Contacts: Odile Grisaud,
Yves Guidoux, Francis Besnard,
Michel Muffat, Philippe Chanard

COLAS

10 Madison Avenue, Suite 4
Morristown, NJ 07960-7303

Phone: +1 (973) 290-9082

Fax: +1 (973) 290-9088

<http://www.colasinc.com>

Primary Contact:

Francois Chaignon

LCPC (Laboratoire Central des Ponts et Chaussées)

Centre de Nantes
BP 4129-44341 Bouguenais Cedex
Nantes, France

Phone: +33 (0) 2 4084 5820

Fax: +33 (0) 2 4084 5992

<http://www.lcpc.fr>

Primary Contact: Michel Berengier

Other Contacts:

Georges Raimbault,
Philippe Lepert,
Dr. Fabienne Anfosso-Ledee

ITALY

Autostrade per l'Italia S.p.A. (Societa per Azioni)

Via A. Bergamini, 50 00159
Rome, Italy

Phone: +39 06 4363-2845

Fax: +39 06 4363-2864

<http://www.autostrade.it>

Primary Contact:

Marcello Luminari

Other Contacts: Paolo Morgera,
Domenico Sandulli, Mario Bonola,
Sandro Gervasio

Universita Degli Studi Di Trieste

34127 Trieste, Italia—

p. Le Europa 1

Phone: +0039-040-558-3591

Fax: +0039-040-558-3580

<http://www.dic.univ.trieste.it>

Primary Contact:

Professor Aurelio Marchionna

Laterlite

43045 Rubbiano di Fornovo (PR)
via Vittorio Veneto, 30
Part. IVA 02193140345

Phone: +39 02 4801 1962

Fax: +39 02 4801 2242

<http://www.leca.it>

Primary Contact: Roberto Braschi

UNITED KINGDOM

Highways Agency

Room 914, Sunley Tower
Piccadilly Plaza
Manchester M1 4BE
London, England

Phone: +44 0161 930 5579

Fax: +44 0161 930 5658

<http://www.highways.gsi.gov.uk>

Primary Contact: Mark Neave

Other Contacts: Ramesh Sinhal,
Peter Kinsey, Robert Dudgeon

Transportation Research Lab (TRL)

Old Wokingham Road
Crowthorne
Berkshire RG45 6AU
United Kingdom

Phone: +44 (0) 1344 770210

Fax: +44 (0) 1344 770356

<http://www.trl.co.uk>

Primary Contact: Dr. Mike Nunn

Other Contacts: Bob Collis,
John Chandler, Phil Abbott,
Dr. Phil Morgan, Mike Ainge,
Dr. Tony Parry, Dr. Darren Merrill,
Dr. Khaled Hassan

BELGIUM

NV Robuco

Genthof 4
B-9255 Buggehout

Phone: 052-399-199

Fax: 052-399-190

Primary Contact: Romaine Buys

APPENDIX D

SCAN TEAM MEMBERS

TEAM CONTACT INFORMATION

(Information current at time of scan)

David C. Gibbs (FHWA cochair)

Division Administrator
Federal Highway Administration
Utah Division
2520 West 4700 South, Suite 9A
Salt Lake City, UT 84118
Phone: (801) 963-0182
Fax: (801) 963-0093
E-mail: david.gibbs@fhwa.dot.gov

Randell H. Iwasaki (AASHTO cochair)

*Deputy Director, Maintenance
and Operations*
California Dept. of Transportation
1120 N Street, (MS 49)
Sacramento, CA 95814
Phone: (916) 654-6823
Fax: (916) 654-6608
E-mail:
randell_iwasaki@dot.ca.gov

Kenneth W. Fults (report facilitator)

Senior Research Fellow
Center for Transportation Research,
Suite 200
College of Engineering Research
University of Texas at Austin
3208 Red River
Austin, TX 78705-2650
Phone: (512) 232-3081
Fax: (512) 232-3070
E-mail: kenfults@yahoo.com

Robert J. (Bob) Bernhard

*Director, Ray W. Herrick
Laboratories*
*Codirector, Institute for Safe, Quiet,
and Durable Highways*
Professor of Mechanical Engineering
School of Mechanical Engineering

Purdue University
140 South Intramural Drive
West Lafayette, IN 47907-2031
Phone: (765) 494-2141/2133
Fax: (765) 494-0787
E-mail: bernhard@ecn.purdue.edu
or bernhard@purdue.edu

James F. (Jay) Bledsoe

Systems Analysis Engineer
Missouri Dept. of Transportation
PO Box 270
Jefferson City, MO 65102
Phone: (573) 751-3634
Fax: (573) 526-8052
E-mail: bledsj@mail.modot.
state.mo.us

Douglas D. Carlson

Executive Director
Rubber Pavements Association
1801 South Jentilly Lane, Suite A-2
Tempe, AZ 85281-5738
Phone: (480) 517-9944
Fax: (480) 517-9959
E-mail: dougc@
rubberpavements.org
Representing: Rubber Pavements
Association

Christopher (Chris) Corbisier

Civil Engineer, Noise Specialist
Federal Highway Administration,
HEP
400 Seventh Street, SW.
Washington, DC 20590
Phone: (202) 366-1473
Fax: (202) 366-3409
E-mail: chris.corbisier@fhwa.dot.gov

Thomas M. Heame, Jr.

Pavement Analysis Engineer
Pavement Management Unit
North Carolina Dept. of
Transportation

716 West Main Street
Albemarle, NC 28001
Phone: (704) 983-4019
Fax: (704) 983-5095
E-mail: thearne@dot.state.nc.us

Kevin W. McMullen

President
Wisconsin Concrete Pavement
Association
2423 American Lane, Suite #1
Madison, WI 53704
Phone: (608) 240-1020
Fax: (608) 240-1019
E-mail: kmcmullen@wisconcrete.org
Representing: American Concrete
Pavement Association

David E. Newcomb

*Vice President, Research
& Technology*
National Asphalt Pavement
Association
5100 Forbes Boulevard
Lanham, MD 20706
Phone: (301) 731-4748
Fax: (301) 731-4621
E-mail: dnewcomb@hotmix.org
Representing: National Asphalt
Pavement Association

John H. Roberts

Executive Director
IGGA/ACPA CPR Division
P.O. Box 58
Coxsackie, NY 12051
Phone: (518) 731-7450
Fax: (518) 731-7490
E-mail: jroberts@pavement.com
Representing: International
Grooving & Grinding Association
(IGGA)/American Concrete
Pavement Association (ACPA)
Concrete Pavement Restoration
(CPR) Division

Judith (Judy) L. Rochat*Physical Scientist*

U.S. Dept. of Transportation
 Volpe National Transportation
 Systems Center
 Acoustics Facility
 55 Broadway, DTS-34
 Cambridge, MA 02142

Phone: (310) 833-1711 (primary location) or (617) 494-6338 (Cambridge)

Fax: (310) 833-1711 (call first)

E-mail: rochat@volpe.dot.gov

Larry A. Scofield*Researcher*

Arizona Transportation Research
 Center, MD 075R
 Arizona Dept. of Transportation
 2739 East Washington Street
 Phoenix, AZ 85034

Phone: (602) 712-3131

Fax: (602) 712-3400

E-mail: lscofield@dot.state.az.us or
 lscof29749@aol.com

Mark E. Swanlund*Pavement Design Engineer*

Federal Highway Administration
 HIPT-20, Room 3118
 400 Seventh Street, SW.
 Washington, DC 20590

Phone: (202) 366-1323

Fax: (202) 493-2070

E-mail: mark.swanlund@
 fhwa.dot.gov

TEAM BIOGRAPHICAL INFORMATION

David C. Gibbs (FHWA cochair) is the division administrator for the FHWA Utah Division. He is responsible for managing and directing the Federal-Aid Highway Program with the transportation partners in Utah. In this capacity, Gibbs approves statewide environmental and engineering policies and programs. He also has a key role in advancing implementation technology and innovation with the transportation partners in Utah. Gibbs has served with FHWA for 28 years. Before becoming division administrator, he served as the assistant division administrator in the Texas Division (1995-2000) and as the director of engineering and operations for the Region 3 Office of FHWA (1993-1995) in Baltimore, MD. Gibbs has a bachelor's degree in civil engineering from the University of Florida and is a licensed professional engineer in Florida.

Randell "Randy" Iwasaki (AASHTO cochair) is the deputy director of maintenance and traffic operations for the California Department of Transportation (Caltrans). Iwasaki is responsible for managing the operation of more than 50,000 miles of State highway stretching from Mexico to Oregon and from the Pacific Ocean to Nevada and Arizona. He also is responsible for the department's research on and application of new types of pavements on California highways, including rubberized asphalt. Iwasaki has served with Caltrans for more than 20 years in a variety of high-profile management and engineering positions, including directing the department's operation in the San Francisco Bay Area where he was instrumental in initiating the \$2.6 billion replacement of the east span of the San Francisco/Oakland Bay Bridge. Iwasaki, a licensed civil engineer, earned a bachelor's degree in engineering from California Polytechnic State University, San Luis Obispo, and a master's degree in engineering from California State University, Fresno. Iwasaki belongs to the American Public Works Association and is a board member of the Foundation for Pavement Preservation.

Kenneth Fults (report facilitator) is a senior research fellow at the Center for Transportation Research (CTR) at the University of Texas at Austin. Fults is chair of Transportation Research Board Committee A2B03, "Flexible Pavement Design;" a founding member of TRB A2B09, "Accelerated Pavement Testing;" a member of AASHTO/ARTBA/AGC Task Force #45, "Asset Management Data Collection Guide;" and chair of an expert task group on pavement smoothness protocols. Before joining the CTR research staff in October 2003, Fults was the director of the Materials and Pavements Section of the Texas Department of Transportation with a staff of more than 200 and a budget in excess of \$20 million a year. He retired with more than 33 years' service in August 2003. He was chair of the AASHTO Subcommittee on Materials Tech Section 5a, "Pavement Measurement Technologies;" a 10-year member of the AASHTO Joint Task Force on Pavements; and a 6-year panel member on NCHRP 1-37A, "Development of a Mechanistic Pavement Design Guide." Fults has a bachelor's degree in civil engineering from Texas A&M University in College Station. He is a licensed professional engineer and registered public land surveyor in Texas.

Dr. Robert J. Bernhard is professor of mechanical engineering, director of the Ray W. Herrick Laboratories, and director of the Institute for Safe, Quiet, and Durable Highways at Purdue University. The Institute for Safe, Quiet, and Durable Highways has funded research efforts focused on understanding the fundamental sources of tire/pavement interaction noise and implementing improved solutions for this problem. The Purdue Tire/Pavement Test Apparatus (TPTA) is located at the Herrick Labs. Since joining the faculty of Purdue University, Bernhard's research activities include investigations of tire noise, traffic noise, numerical noise control design methods, noise source identification, active noise

and vibration control, and machinery noise control applications. He received a bachelor's degree in mechanical engineering from Iowa State University in 1973, a master's degree in mechanical engineering from the University of Maryland at College Park in 1976, and his Ph.D. in engineering mechanics from Iowa State University in 1982. He served as president of the Institute of Noise Control Engineering of the USA (INCE-USA) in 1994, and has served as secretary general of the International Institute of Noise Control Engineering (I-INCE) since 2000. He is a fellow of the American Society of Mechanical Engineers, a fellow of the Acoustical Society of America, a member of the Transportation Noise Committee (A1F04) for the Transportation Research Board, and a member of the Society of Automotive Engineers and the American Institute of Aeronautics and Astronautics.

Jay Bledsoe is the transportation management systems engineer for the Missouri Department of Transportation in Jefferson City, MO. He is responsible for the collection, processing, storage, and reporting of all pavement and traffic data, and the storage and reporting of bridge and safety data. Other responsibilities include maintenance of the Transportation Management Systems database, and all mapping, GIS, and GPS activities in the department. Bledsoe has more than 26 years' experience with MoDOT. He has a bachelor's degree in civil engineering from the University of Missouri, Columbia. He is a registered professional engineer in Missouri. Bledsoe serves as a member of the AASHTO Joint Task Force on Pavements and the NCHRP panel for Project 1-43, *A Guide for Pavement Friction*.

Douglas Carlson is the executive director of the Rubber Pavements Association. He is a graduate of Arizona State University in business administration. He served in the U.S. Marine Corps and Reserve from 1986 to 1997 as a combat engineer. Carlson has served the Rubber Pavements Association since 1998 as government relations director and deputy director. He is a member of American Society for Testing Materials and American Public Works Association, and serves as treasurer for the Arizona Highway Users Alliance. He is pursuing a master's degree in engineering at Arizona State University. He has authored and coauthored several papers on asphalt rubber-related topics published by the *Journal of Solid Waste Technical Management (JSWTM)*, the Third Joint UNCTAD/IRSG Workshop on Rubber, the Environment International Rubber Forum, Asphalt Rubber 2003, and the Arizona Department of Transportation. Carlson also serves as a reviewer for papers submitted for publication in various technical journals, including American Society of Civil Engineers journals and *JSWTM*, and for proposals submitted to the Arizona Department of Environmental

Quality and the Environmental Protection Agency (EPA) on topics related to crumb rubber and tire recycling. He is a member of the newly formed Tire Cluster, an EPA and industry group dealing with scrap tire issues. Carlson also serves on the board of directors for the Recycled Tire Research and Engineering Foundation.

Christopher Corbisier is a noise specialist on the FHWA Noise Team in Washington, DC. He helps develop national highway traffic noise policies and oversee the implementation of FHWA's noise program. The policies cover the analysis and abatement of highway traffic noise, including the use of specific pavement types and textures in analysis and as an abatement measure. He completed FHWA's 2-year Professional Development Program, including assignments with the Florida Department of Transportation (FDOT), FHWA Florida Division Office, and Volpe National Transportation Systems Center Acoustics Facility. Corbisier was a member of an FDOT noise barrier insertion loss study that measured and modeled 12 existing noise walls to determine their resulting noise reduction. Corbisier has a bachelor's degree in civil engineering from the University of Central Florida. He is a member of the Transportation Research Board Committee on Transportation-Related Noise and Vibration.

Thomas Hearne is a pavement analysis engineer for the Pavement Management Unit of the North Carolina Department of Transportation in Albemarle, NC. He is responsible for evaluating and investigating pavement structural conditions. His research emphasis includes non-destructive materials testing and evaluation of pavement smoothness during construction. He served as a roadway pavement design engineer and an area materials engineer before joining the Pavement Management Unit in 1990. Hearne is a graduate of the Citadel, the Military College of South Carolina, and holds a master's degree in engineering from the University of Florida. He is a licensed professional engineer in North Carolina, a member of the American Society of Civil Engineers and the AASHTO Joint Task Force on Pavements, and serves on several technical committees of the Transportation Research Board. He is chairman of NCHRP Project Panel D10-67, "Texturing of Concrete Pavements."

Kevin W. McMullen is president of the Wisconsin Concrete Pavement Association (WCPA) in Madison, WI. He is responsible for design, construction, maintenance, and rehabilitation technical issues and promotional activities for the concrete pavement industry in Wisconsin. He served as an industry advisor to Marquette University research titled "Noise and Texture on Portland Cement Concrete Pavements, Results of a Multi-State Study," and served on the FHWA Technical Working

Group on pavement noise and texture during the 1990s. McMullen has worked for WCPA for 8 years. Before that, he was pavement design engineer in the Central Office of the Wisconsin Department of Transportation for 5 years, and also worked as a consulting engineer. He has a bachelor's degree in civil engineering from the University of Wisconsin-Platteville. He is a licensed professional engineer in Wisconsin, sits on the board of directors of the Wisconsin Highway Research Program, and is a member of three technical committees of the Transportation Research Board. He is a former member of the board of directors of the American Concrete Pavement Association.

Dr. David E. Newcomb joined the National Asphalt Pavement Association in October 1999 as vice president—research & technology. Before that, he was an associate professor in the Department of Civil Engineering at the University of Minnesota and the technical director of the Minnesota Road Research Project since 1989. Before moving to Minnesota, he taught at the University of Nevada-Reno for 2.5 years. He received his Ph.D. at the University of Washington in 1986, after working at the New Mexico Engineering Research Institute for 3 years. Newcomb received his bachelor's and master's degrees at Texas A&M University in 1977 and 1979, respectively.

John H. Roberts is the executive director of the International Grooving and Grinding Association (IGGA), and the vice president of the American Concrete Pavement Association's (ACPA) Concrete Pavement Restoration Division. As executive director, he is responsible for managing and directing all activities associated with the proper use and advancement of concrete pavement preservation and restoration. In this capacity, Roberts is also responsible for managing and developing innovative technologies, such as diamond grinding of pavement for noise abatement. Roberts serves on several TRB, NCHRP, and FHWA-sponsored committees and is a board member of the Foundation for Pavement Preservation. Before joining IGGA/ACPA, Roberts worked for Ebasco Services, Inc., on projects ranging from radioactive cleanups to reconstruction of the Manhattan Bridge. Roberts also was the owner of a concrete contracting company in New York, where he specialized in the construction of bridges, pavements, and structures. Roberts has a bachelor's degree in civil engineering from Rensselaer Polytechnic Institute.

Dr. Judith L. Rochat is a physical scientist in the Acoustics Facility at the U.S. Department of Transportation's John A. Volpe National Transportation Systems Center. She conducts research in many areas

of transportation noise, including prediction, measurements, and analysis. Her work includes 1) support for the FHWA Traffic Noise Model (TNM), a computer program used to predict noise in the vicinity of highways and design highway noise barriers; 2) quiet pavement measurements/analysis for U.S. State departments of transportation; 3) support for FHWA's Quiet Pavement Pilot Program (QPPP); and 4) support for the Federal Aviation Administration's Integrated Noise Model (INM), a computer program used to predict noise near airports. Rochat received a bachelor's degree in applied mathematics from the University of California, San Diego, in 1990; a master's degree in acoustics from Pennsylvania State University in 1994; and a Ph.D. in acoustics from Pennsylvania State University in 1998. She is a member of the Acoustical Society of America, the American Institute of Aeronautics and Astronautics, and the Transportation-Related Noise and Vibration Committee (A1F04) of the Transportation Research Board, where she serves as the chairman of the Highway Noise subcommittee.

Larry Scofield is a researcher with the Arizona Transportation Research Center (ATRC). He manages the research conducted in the materials, construction, and maintenance areas for the Arizona Department of Transportation. He developed the work plan for the Arizona Quiet Pavement Pilot Program, and is conducting the research grade noise measurements for this program, which consists of both near-field and far-field acoustic measurement techniques. Scofield has worked for the Arizona Department of Transportation for the past 27 years. He has worked in construction, materials, and for the past 20 years at ATRC. Scofield has bachelor's and master's degrees in civil engineering from Arizona State University. He participates in numerous Transportation Research Board and National Cooperative Highway Research Program activities.

Mark Swanlund is a pavement design engineer for the FHWA Office of Pavement Technology in Washington, DC. Swanlund directs FHWA activities related to pavement surface characteristics. His priority activities include pavement evenness, tire/road noise, and pavement texture and friction. Before joining the Office of Pavement Technology in 1998, he served as the FHWA regional pavement engineer in Baltimore, MD, and in FHWA's Colorado Division Office. Swanlund has a bachelor's degree in civil engineering from Washington State University, and is a licensed professional engineer in Colorado. He serves on several committees of the Transportation Research Board, and is the English-speaking secretary of PIARC Technical Committee C1, Pavement Surface Characteristics.

Office of International Programs

FHWA/US DOT (HPIP)
400 Seventh Street, SW
Washington, DC 20590

Tel: (202) 366-9636 ■ **Fax:** (202) 366-9626

international@fhwa.dot.gov
www.international.fhwa.dot.gov

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