SURVEY OF TRAFFIC NOISE REDUCTION PRODUCTS, MATERIALS, AND TECHNOLOGIES

Final Report 584

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16. Abstract

Noise is one of the most pervasive forms of environmental pollution. It is everywhere and affects our lives at home, work and play. By definition, noise is any unwanted or excessive sound. Highway traffic noise is a major issue for transportation agencies. The objective of this study was to identify noise reduction products, materials, and technologies currently available and that may have potential as noise mitigation alternatives. The literature review and survey identified measures that are being used by U.S. transportation organizations as well as international efforts. Some key findings from the literature review show the following best practices:

- Pavement Noise Reduction Products – noise or sound walls dominate this category and have been used for decades in the U.S. Findings from the literature revealed a variety of materials to choose from that are both aesthetically attractive, and effective in reducing sound from tire pavement noise. The cost of installing products will need to be evaluated on a case by case basis with the vendor or for each applicable product.
- Pavement Noise Reduction Materials – The operating speed of the roadway should be factored into the roadway design for quiet pavements. European studies show that higher porous mixtures tend to clog under slower speeds. Two layer-porous mixes have been found to be effective in Europe and the US. An important attribute for consideration in two layer-porous mix design and placement is aggregate size.
- Pavement Noise Reduction Technologies - use of thin-textured surfacings with a negative pavement depression are recommended for urban or low-speed roadway sections. Diamond grinding enhances noise reduction on concrete surfaces in sensitive locations.
- Other Pavement Noise Reduction Measures – looking forward, transportation officials are encouraged to develop an integrated approach to roadway noise reduction. Instead of relying on a single measure, the recommended forward strategy is to develop the ability to model the effectiveness of a number of different measures to achieve greater noise reduction.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: Volumes greater than 1000L shall be shown in m^3.			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000lb)	0.907	megagrams (or "metric ton")	mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE AND PRESSURE OR STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	Square millimeters	0.0016	square inches	in^2
m^2	Square meters	10.764	square feet	ft^2
m^2	Square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	Square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	Cubic meters	35.315	cubic feet	ft^3
m^3	Cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
mg	megagrams (or "metric ton")	1.102	short tons (2000lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE AND PRESSURE OR STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380

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Glossary

Abbreviations

e-mail	electronic mail

Symbols

ρ	density
λ	lambda (wavelength)
μ	micro

Units of Measurement

Sound

AC	absorption coefficient
c	speed of sound
CCA	chromated copper arsenate
CNEL	Community noise equivalent level
dB	decibels
dBA	decibels, A-weighted sound level
ITC	Indoor Transmission Class
L	level
L_{dn}	Day-night noise level
L_{eq}	Equivalent noise level
L_{max}	Maximum noise level
L_x	noise level exceeded by “x” percent
NHDOT	New Hampshire Department of Transportation
NRC	Noise Reduction Coefficient
PSL	pressure sound level
SEL	single event level
STC	Sound Transmission Class
STL	Sound Transmission Loss

Other units of measurement

^{o}C	degree Celsius
^{o}K	degree Kelvin
cm	centimeter
f	frequency
ft	feet
h	hour
Hz	hertz
in	inch

kg	kilogram
km	kilometer
km/h	kilometer/hour
LF	linear feet
m	meter
m^2	square meter
m^3	cubic meter
mi	mile
mm	millimeter
MPa	10^6 or 1 million Pascal
mph	mile/hour
N	Newton
Pa	Pascals
rms	root mean square
s	second
SF	square feet
sq. yd.	square yard
SQRT	square root
P	pressure
PLF	pound per linear foot
pcf	pound per cubic foot (lbs/ft^3)
psi	pound per square inch (lbs/in^2)
psf	pound per square feet (lbs/ft^2)
W	Watt

<u>Acronyms</u>

AASHTO	American Association of State Highway and Transportation Officials
ACPA	American Concrete Paving Association
ADOT	Arizona Department of Transportation
AMT	Advanced Masonry Technology
ASI	Acoustical Solutions, Inc.
ASTM	American Society for Testing and Materials
ATRC	Arizona Transportation Research Center
CPX	close proximity
CRCP	continuously reinforced concrete pavement
CSI	Concrete Solutions, Inc.
DGAC	dense graded asphalt concrete
DOT	Department of Transportation
EAC	exposed aggregate concrete
EPA	Environmental Protection Agency
FHWA	Federal Highway Association
FMCSA	Federal Motor Carrier Safety Administration

HARMONOISE	Harmonized, Accurate, and Reliable Prediction Methods for the EU Directive on the Assessment and Management of Environmental Noise
HITEC	Highway Innovative Technology Evaluation Center
HMA	hot mix asphalt
IPG	Innovation Program (Netherlands)
ISU	Iowa State University
IST	International Scanning Team
GVWR	Gross Vehicle Weight Rating
KDOT	Kansas DOT
MDOT	Minnesota DOT
NCAT	National Center for Asphaltic Technology
NCHRP	National Cooperative Highway Research Program
NGOGFC	new generation open graded asphalt friction course
OBSI	on-board sound intensity
OGFC	open graded asphalt friction course
OSHA	Occupational Safety and Health Association
PERS	porous elastic road surface
PIARC	Permanent International Association of Road Congresses – the previous name for the organization that is now known as the World Road Association
PCC	Portland cement concrete
PFC	porous friction course
PWRI	Public Works Research Institute (Japan)
QPPP	Quiet Pavement Pilot Program
QUASH™	QUASH, a trademark of the Dow Chemical Company for a large cell polyethylene foam product that is typically used for sound absorption.
RFI	reflective cracking interlayer
RFP	request for proposal
SILVIA	Silenda Via Project
SIRIUS	Silent Roads for Urban and Extra-Urban Use (European Union)
SMA	stone matrix asphalt
SPL	sound pressure level
TAC	Technical Advisory Committee (ADOT)
TLPA	two layer porous asphalt
TxDOT	Texas DOT
UK	United Kingdom
UV	ultra-violet
WIDOT	Wisconsin DOT

Section 1

Introduction

Noise is one of the most pervasive forms of environmental pollution. It is everywhere and affects our lives at home, work and play. By definition, noise is any unwanted or excessive sound. It is an unwanted by-product of our modern way of life. While noise emanates from many different sources, transportation noise is one of the most difficult sources to avoid in society today. Highway traffic noise is a major contributor to transportation noise.

Considering the impacts of traffic noise on members of the public, the Arizona Department of Transportation (ADOT), sought the services of a qualified firm or individual to perform a survey of traffic noise reduction products, materials, and technologies. Prophecy Consulting Group, LLC (hereafter referred to as Project Researcher) provided these services under Contract No. T0549A00028.

The Department provided the following objectives for the traffic noise reduction study:

a. Identify noise reduction products, materials, and technologies currently available and that have potential as noise mitigation alternatives.

b. Compile available performance information and discuss whether a full-scale testing program by the department is recommended.

This report provides the results of this research study and recommends future work or activities on this topic.

1.1 Scope of Work

A project approach was initially provided in the request for proposal (RFP) document. The Work Plan agreed upon by the Technical Advisory Committee (TAC) and the Project Researcher identified seven project tasks. :

Task 1: Develop Work Plan

A draft work plan was developed by the Project Researcher and distributed to members of the TAC prior to a project meeting on March 18, 2005. Elements of the draft work plan were discussed during this meeting.

The draft work plan was updated to include the recommended changes by the TAC during the meeting and subsequent comments. The work plan was approved on April 5, 2005.

Task 2: Conduct Literature Review

A literature review was performed. Existing work in the field of noise reduction products, materials, and technologies was reviewed. Research tools used included technical journal indices and abstracts, other periodicals, newspapers, text books, handbooks, directories, the internet, and technical societies.

The TAC recommended that the Project Researcher prioritize the research into three areas of noise reduction approaches: Products, Technologies, and Materials. For each relevant reference, the researcher was to document: the work that was done, the organization that conducted the research, the date of the study, the research outcome or findings, ease of implementation and associated costs.

Task 3: Survey Government and Non-government Organizations

Using the results of the literature review, a survey was developed and sent to government and non-government agencies. To better meet the requirements of the task, a question on the survey queried the organization on its expected future use of any noise reduction product, material, and/or technology.

The list of government and non-government agencies was developed by the Project Researcher with input from the ADOT Project Manager. Contacted agencies were encouraged to submit the survey by email.

Task 4: Assess Growth of Alternative Noise Reduction Products, Materials and Technologies

An assessment of the expected growth in the acceptability and use of alternative noise reduction products, materials, and technologies was made based on the findings in Tasks 2 and 3.

Task 5: Recommend Next Steps

Using the information obtained in Tasks 2 thru 4, the Project Researcher provided ADOT with a list of recommended next steps for future work in the area of noise reduction products, materials, and technologies. This list was developed by assessing available performance data, scalability, and application of each proposed product, material or technology. Arizona's diverse climate, traffic, and roadway conditions were also considered in the development of these recommendations.

Task 6: Submit Final Report

This document constitutes the Project Final Report. A separate four-page summary was also prepared as a "Research Note" for ADOT. The final report was prepared in accordance with the ATRC document, "Guidelines for Preparing ATRC Research Reports, September 2003".

Task 7: Make Oral Presentation to Research Council (Optional)

If requested, the Project Researcher will make a presentation to ADOT's Research Council, or another group of stakeholders.

1.2 Report Organization

Section 1 – Introduction

Section 1 summarizes the scope of work for this research study, includes information on noise control regulations at the federal, state, and local levels, and provides an outline of the Project Final Report.

Section 2 – Literature Review

A summary of the literature on pavement noise reduction products, materials, and technologies is provided in Section 2. The information and data presented is representative of significant work that has or is being done in this area.

Section 3 – Survey Development

Section 3 provides information on the survey development and the process used to identify and distribute it to potential respondents.

Section 4 – Survey Results

Results of the pavement noise reduction survey are summarized in Section 4.

Section 5 - Potential Growth of Pavement Noise Reduction Measures

Section 5 identifies those measures that are reasonably easy to implement and are most likely to be used by ADOT and other transportation organizations in the near future based on the findings of this research.

Section 6 – Conclusions and Recommendations

Conclusions of the research findings are provided in Section 6 along with recommendations for future work or analysis on this topic.

A cross section of traffic noise reduction products identified in the literature survey is provided in Appendix 3. No doubt this is not an exhaustive list but includes a wide array of applications described in the literature.

Section 2

Literature Review

A review of the literature on pavement noise reducing products, materials, and technologies was conducted to identify current and emerging methods and practices. Findings from the literature review are reported by noise reduction category. The references in this section highlight significant work done in the area.

2.1 Pavement Noise Reduction Products

For purposes of this study, a noise reduction product is considered an item that is readily available on the market. The most commonly adopted noise reduction product that has been used in the U.S. is noise walls. One of the attributes of a noise wall is that it has the ability to reduce all noise coming from the roadway regardless of source.

Noise walls are built between the highway and the adjacent neighborhood. These structures are expensive to build (often $1 to $2 million per mile) and to maintain (graffiti is a major problem). In addition, sound waves can bend over and around objects, and spread out with distance, therefore noise barriers may be limited in their usefulness to distances of less than 400 m (436 yd) from the roadway.[1] Effective noise barriers can reduce noise levels by 5 to 10 dB, cutting the loudness of traffic noise by as much as one half. For example, a barrier that achieves a 10 dB reduction can reduce the sound level of a typical tractor trailer pass-by to that of an automobile.

Barriers can be formed from earth mounds or "berms" along the road, from high vertical walls, or from a combination of earth berms and walls. Earth berms have a very natural appearance and are usually attractive. They also reduce noise by approximately 3 dB more than vertical walls of the same height. However, earth berms can require large areas of land to construct, especially if they are very tall. Walls require less space, but they are usually limited to eight meters (25 feet) in height for structural and aesthetic reasons.[2]

To effectively reduce the noise coming around its ends, a barrier should be at least eight times as long as the distance from the home or receiver to the barrier. Noise barriers can be constructed from earth, concrete, masonry, wood, metal, and other materials. To effectively reduce sound transmission through the barrier, the material chosen must be rigid and sufficiently dense (at least 20 kg/sq. m, or 36.9 lbs/sq. ft).[3] All noise barrier material types are equally effective, acoustically, if they have this density.

Two characteristics that distinguish one noise reduction product from another are the Noise Reduction Coefficient (NRC) and the Sound Transmission Class (STC).[4] NRC is a single-number index for rating how absorptive a particular material is. Although the standard is often abused, it is simply the average of the mid-frequency sound absorption coefficients (250, 500, 1000 and 2000 Hertz rounded to the nearest 5%). The NRC gives no information as to how absorptive a material is in the low and high frequencies, nor does it provide a relationship to the material's barrier effect or STC.

STC is a single-number rating of the barrier effect of a material or assembly. Higher STC values are more efficient for reducing sound transmission. For example, loud speech can be understood fairly well through an STC 30 wall but should not be audible through an STC 60 wall. The rating assesses the airborne sound transmission performance at a range of frequencies from 125 to 4000 Hertz. This range is consistent with the frequency range of speech. The STC rating does not assess low frequency sound transfer. Special consideration must be given to spaces where the noise of concern is something other than speech, such as mechanical equipment or music.

Even with a high STC rating, any penetration, air-gap, or "flanking" path can seriously degrade the isolation quality of a wall. Flanking paths are the means for sound to transfer from one space to another other than through the wall. Sound can flank over, under, or around a wall. Sound can also travel through common ductwork, plumbing or corridors. There are no federal requirements specifying the materials to be used in the construction of highway traffic noise barriers.[2] Individual State DOTs select the materials when building these barriers. The selection is normally based in part on factors such as aesthetics, durability, maintenance, cost, and the desires of the public.

2.1.1 Noise Wall Expenditure and Materials

For the year ending December 31, 2004, 45 State DOTs and the Commonwealth of Puerto Rico constructed over 2,205 linear miles of sound barriers at a cost of over $3.4 billion in 2004 dollars. Five states (Alabama, Mississippi, Montana, Rhode Island, and South Dakota) and the District of Columbia did not construct noise barriers for the same period.[3] Total noise barrier areas by material type are shown in Table 1, and a summary of noise barrier data for the United States is provided in Table 2.

Table 1
Total Noise Barrier Area by Material Type (through 2004)[3]

		Combination Barriers	
Material	Square Feet (Thousands)	Material	Square Feet (Thousands)
Concrete/Precast	67,926	Wood/Concrete	4,281
Block	33,993	Berm/Wood	2,990
Concrete/ Unspecified	13,715	Concrete/Block	2,154
Wood/Post & Plank	5,912	Other	1,930
Berm Only	4,281	Berm/Concrete	1,863
Metal/Unspecified	4,279	Metal/Concrete	1,786
Wood/Glue Laminated	3,701	Berm/Metal	1,439
Absorptive	3,629	Berm/Block	795
Wood/Unspecified	3,055	Concrete/Brick	586
Other	1,812	Wood/Metal	464
Brick	1,152	Berm/Wood/ Concrete	348
		Wood/Block	283
		Berm/Wood/ Metal	171
		Block/Brick	8
Total	143,455	Total	19,098

Table 2
Noise Barrier Data for United States (through 2004)[3]

State	Square Feet (Thousands)	State	Linear Miles
California	30,644	California	482.8
Virginia	11,227	Arizona	155.1
Arizona	11,226	Virginia	127.5
New Jersey	9,440	Ohio	112.4
Ohio	8,675	New Jersey	96.9
Maryland	8,422	Colorado	92.5
Minnesota	7,187	New York	90.7
New York	7,011	Pennsylvania	87.0
Florida	6,700	Minnesota	83.7
Pennsylvania	6,415	Maryland	81.8
10 State Total	**106,946**		**1,410.4**
	Actual Cost (Millions)		2004 Dollars Millions
California	$399.6	California	$592.8
Arizona	258.7	Arizona	284.6
New Jersey	202.4	New Jersey	277.5
Maryland	200.9	Maryland	253.6
Virginia	169.6	Virginia	225.3
New York	165.9	New York	207.3
Pennsylvania	159.6	Pennsylvania	197.8
Florida	150.7	Florida	175.9
Ohio	117.2	Ohio	139.0
Colorado	80.0	Minnesota	107.7
10 State Total	**$1,904.5**		**$2,461.4**

Note: California did not supply barrier data for 1998-2004.

2.1.2 Noise Wall Treatments and Coatings

Appendix 3 provides a sampling of traffic noise reduction products. While this is not an exhaustive list, it does cover a wide array of potential applications found in the literature. A recent concept in noise barrier design is the placement of sound absorptive materials on top of barriers. Sound absorptive materials have been applied either on a large portion of the surface area of the barrier, or at specific locations to reduce sound reflection off the barrier surface. During the early 1970s, it was first proposed that lining the region in the immediate vicinity of the edge of a barrier with sound absorptive material could result in a potential reduction in sound pressure in the shadow zone.[5]

Shadow zone is a term commonly used in oceanography or geology. Refraction produces shadow zones that sound waves do not penetrate because of curvature. However, if the object has a diameter greater than the acoustic wavelength, a “sound shadow” is cast behind the object where the sound is inaudible. (Note: Some sound may be propagated through the object depending on the material).

Acoustic treatments on the road side of barriers have been used to reduce the noise reflected off the walls. The results of full scale experiments show that the performance of a 2m (6.56ft) high barrier was reduced by 4 dBA when another reflective barrier of a similar height was present on the other side of the road.[6] However, the researchers later reported that the measured effects of applying absorptive materials to roadside barriers are generally less than 1 dB on the A-weighted equivalent noise level, L_{Aeq}, and the A-weighted noise level 10% of the time, L_{A10}. Sound absorptive barrier tops or “top treatments” have been studied in theory as well as application with noise reductions reported from 1 to 5 dBA.[6]

The Institute for Safe, Quiet, and Durable Highways studied various shapes of sound absorptive “caps” and two alternative materials - glass fiber and polyolefin foam with closed cells (QUASH). This wall “capping” concept was studied both in the laboratory and on a section of sound barrier along US 20 in Elkhart County, Indiana.[7,8] Actual field measurements showed that when the QUASH add-on device was attached to the existing barrier edge, the benefit of the sound barrier increased between 2 dB and 5 dB at frequencies from 2000 to 5000 Hz.

Although limited work has been done with barrier treatments, if an effective method could be found, the possibility for greater noise reduction or *deflection* could be significant in Arizona based on the amount of investment in noise barriers, and future maintenance needs.

2.2 Noise Reduction Materials

The contribution to roadway noise created by tire-pavement interaction on the road surface, pavement smoothness, and pavement texture is at issue here. In this subsection, pavement noise reducing materials are defined as aggregate and other materials that are applied to the surface as a part of the roadway design. As examples, these materials include asphalt surfaces, portland cement concrete, sand and gravel.

Rubberized pavement, asphalt-rubber, and rubberized asphalt are often used synonymously to describe a blend of asphalt cement, reclaimed tire rubber and certain additives. The rubber component in this blend is at least 15% by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber.[9] Interestingly, this non-proprietary, non-patented public process was developed in the 1960's by a City of Phoenix engineer and has been routinely used in the U.S. by transportation agencies in Arizona, California, Texas and Florida. The blend also has been used on five continents. The higher binder content (between 8 to 10%) allows for more coating on the aggregate and produces a longer lasting pavement. Smoother ride and noise reduction are two major benefits of asphalt-rubber hot mix pavements.

2.2.1 Pavement Treatments

The work done by European countries in using pavement surface type as a noise reduction strategy has been well recognized and documented. Research by Kandhal[10] shows that numerous studies were conducted in Europe in the 1980s and 1990s to determine comparative noise levels of dense-grade hot mix asphalt (HMA), open-graded asphalt friction course (OGFC), Portland cement concrete (PCC) pavements, and stone matrix asphalt (SMA). The general conclusions drawn from these studies are provided in Table 3.

Table 3: Noise From Different Pavement Surface Types (International Studies)[10]

Country/Agency (Year Reported)	**Surface Type Evaluated***	**General Conclusions**
British Columbia, Canada (1999)	HMA, OGFC	After three years in service, the OGFC is quieter than the HMA by 3.5 to 4.0 dBA.
Italy (1998)	HMA, SMA	As much as 7.0 dBA reduction in noise level has been reported at 110 km/h when SMA was compared to HMA
Germany (1991 and 1998)	HMA, SMA	SMA was 2.5 and 2.0 dBA quieter than HMA.
Nordic Countries (1994)	HMA, OGFC	A joint Nordic project determined OGFC to be quieter than HMA by 3 to 5 dBA.
Belgium (1994)	HMA, OGFC, PCC	HMA was quieter than PCC (old pavement) by 3.4 dBA, OGFC was quieter than PCC by 7.5 dBA, OGFC was quieter than transverse grooved PCC by 10.5 dBA.
World Road Association – *formerly PIARC* (1993)	HMA, OGFC, PCC, Chip Seal	The following ranges of noise levels have been reported in this extensive report: OGFC 69-77 dBA, HMA 72-79.5 dBA, and PCC 76-85 dBA.
United Kingdom (1993)	Rolled Asphalt, OGFC, PCC	OGFC was quieter than rolled asphalt surface (used in UK) by 4 decibels. OGFC was quieter than PCC by 6-7 decibels.
Danish Road Institute (1992)	HMA, OGFC	OGFC was quieter than HMA by 4 dBA.
Italy (1990)	HMA, OGFC	OGFC was quieter than HMA by 3 dBA
Germany (1990)	HMA, OGFC	OGFC was quieter than HMA by 4 to 5 dBA.
Sweden (1990)	HMA, OGFC	OGFC was quieter than HMA by 3.5 to 4.5 dBA.
France (1990)	HMA, OGFC	OGFC was quieter than HMA by 3 to 5 dBA.
Netherlands (1990)	HMA, OGFC	OGFC was quieter than HMA by about 3 dBA.

* HMA = dense-graded hot mix asphalt, OGFC = open-graded asphalt friction course, PCC = Portland cement concrete, SMA = stone matrix asphalt

Similarly, Khandal provides a summary of some noise level studies conducted in the U.S. for pavement surfaces made of HMA, OGFC, PCC, and SMA in Table 4. Using dense-graded HMA as the base reference, the average comparative noise levels for these pavement surface materials are OGFC = -4 dBA, SMA = -2 dBA, HMA = 0 (reference) and PCC = +3 dBA.

Table 4: Noise From Different Pavement Surface Types (National Studies)[10]

State Agency (Year Reported)	Surface Type Evaluated*	General Conclusions
Texas (2003)	HMA, PCC	An existing continuously reinforced concrete pavement (CRCP) was overlaid with asphalt-rubber OGFC. On average, the roadside noise was reduced from 85 to 71 dBA. The reduction of 14 dBA is very high and is possibly the largest noise reduction ever recorded on a Texas DOT project.
California (2002)	HMA, OGFC	After four years in service on I-80 near Davis, the OGFC is quieter than the HMA by 4 to 6 dBA.
Michigan (2002)	HMA, SMA, PCC	A limited number of pavements were tested by close proximity method. Considering the noise data obtained at 60 mph with an aggressive tire pattern, the following noise levels were recorded in dBA: SMA = 98.3, HMA = 98.9, and PCC = 98.9 to 100.8. For PCC, the quietest surface was the diamond ground with 98.9 dBA, which was about equal to HMA.
Michigan (2000, 2001)	HMA, OSMA, PCC	The first study (2000) was conducted on I-275, west of Detroit. It indicated Superpave HMA was 4 to 5 dBA quieter than PCC. The second study (2001) conducted on I-94, west of Ann Arbor, showed that a 12.5 mm SMA was approximately 4 dBA quieter than 12.5 mm Superpave HMA.
Wisconsin (1997)	HMA, PCC	The noise from HMA pavements was about 2 to 5 dBA less than PCC pavements.
U.S. DOT (1995)	HMA, OGFC, PCC	Volpe National Transportation Center (U.S. DOT) made numerous noise measurements in multiple states to collect data for FHWA's noise model. For automobiles, PCC pavements were about 3 dBA quieter than dense-graded HMA. OGFC was about 1.5 dBA quieter than dense-graded HMA. (Note: These OFGC data do not represent European type new-generation OGFCs that are now used in the U.S. and are significantly quieter.)
Minnesota (1995, 1987, and 1979)	HMA, OGFC, PCC	OGFC was found to be quieter than HMA in the 1979 study. HMA was found to be quieter than PCC in all three studies.
Oregon (1994)	OGFC, PCC	Compared to PCC pavements, the OGFC were 5.7 to 7.8 dBA quieter.
Maryland (1994)	HMA, SMA	Average noise level of SMA was 1 dBA lower than HMA.
New Jersey (1994)	HMA, SMA, PCC	One PCC pavement and one HMA pavement were overlaid with SMA. Noise levels were determined before and after the overlays. Measurements during the afternoon rush hours showed SMA to be quieter than PCC by 2.0 dBA before overlays.
Wisconsin (1993)	HMA, SMA	Similar to Maryland, the average noise level of SMA was 1 dBA lower than HMA.
Maryland (1990)	OGFC, PCC	The OGFC was quieter by 2.3 to 3.6 dBA than the PCC pavement.
FHWA (1975)	HMA, OGFC, PCC	Noise level studies were conducted in Arizona, California, and Nevada. Based on average dBA values, OGFC was quieter than HMA by 2 dBA, and quieter than HMA by 2.1 dBA. The HMA pavement was quieter than PCC by 2.0 dBA before overlays.

* HMA = dense-graded hot mix asphalt, OGFC = open-graded asphalt friction course, PCC = Portland cement concrete, SMA = stone matrix asphalt

2.2.1.1 OGFC for Noise Reduction

The current rubberized asphalt that is being used in Europe and a few south-western states is OGFC.[10] California DOT and Texas DOT (TxDOT) have been actively involved in quiet pavement studies utilizing OGFC. OGFC is referred to as porous friction course (PFC) in Texas. TxDOT's first PFC was placed in 1999. As of 2004, 25 additional PFC projects had been completed. PFC mixtures have gained popularity as a paving material due to their ability to reduce the risk of hydroplaning, reduce the amount of splash and spray, reduce pavement noise, improve visibility of traffic striping in wet weather, and improve ride quality.[11]

Data reported in Table 4 for the State of California is the result of a three-year study to determine if the noise attenuation benefits of OGFC decreased over time. A nine kilometer (5.59 mile) portion of pavement on I-80 near Davis, CA was repaved in June 1998. The new pavement cross section consisted of a 60 mm dense graded asphalt concrete (DGAC) leveling course that was overlaid with 25 mm (0.98 in) of OGFC. Immediately after applying the DGAC base, roadside noise levels declined by 3 to 4 dBA from baseline conditions. After application of the OGFC, roadside noise levels declined by about 5 dBA from the baseline condition. Noise levels continued to be 4 to 6 dBA lower than baseline condition over the entire study period.[11]

Although OGFC provides a number of pavement noise reduction benefits, one of the concerns reported at the SILVIA conference[24] is that it is not porous, it is not pervious to rainwater, and it does not perform well in colder climates. This is problematic for those areas of Arizona at higher elevations and which experience colder winters than lower elevation areas like metropolitan Phoenix and southern Arizona.

New generation OGFC (NGOGFC) is also gaining popularity as a safe pavement, especially for winter weather conditions. NGOGFC contains approximately 20 percent more asphalt (by volume) than conventional or first generation OGFC. NGOFC is designed to have a minimum of 18 percent air voids. The design of conventional OGFC did not focus on air voids. However, conventional OGFC mixtures typically contain between 10 and 15 percent air voids.[11] At lower air voids percent levels moisture can get trapped within the void matrix of the conventional OGFC. The void structure of NGOGFC allows the mix to be more permeable and less likely to trap water.

A TxDOT report to their research management committee notes the following benefits of NGOGFC:

- overall good friction and lower noise, in wet weather conditions - higher visibility
- reduced splash and spray
- reduced hydroplaning, and
- reduced night-time surface glare.

Also noted in the report are some of the common problems encountered with OGFC – lack of durability (raveling in 6 to 8 years), accumulation of frost and ice, and clogging of pores. NGOGFC is also reported to be 22.5% more expensive than OGFC.[12]

Transportation officials in The Netherlands have more than five years of experience with second generation porous asphalt surface courses with rubberized asphalt binders, ranging from test sections to large scale use. The new concept consists of a double-layered porous asphalt construction, made up of a bottom layer of fine-graded porous asphalt (aggregate size 4 to 8 mm / 0.16 to 0.32in). The binder in both layers is rubberized asphalt. The fine texture of the top layer causes a reduction of traffic noise, from 3 to 4 dBA at 50 km/h (31mph) up to 5.5 dBA at 100 km/hr (62mph).[11]

In 2005, the FHWA, American Association of State Highway Transportation Officials (AASHTO), and the National Cooperative Research Highway Program (NCRHP), sponsored a scanning study of European quiet pavement systems. A cross-section team of 14 state, federal, academic, and industry representatives visited five European countries: Denmark, France, Italy, the Netherlands, and the United Kingdom (UK). All countries have policies that require the use of quiet pavement or other measures to reduce traffic noise. Each country is also conducting research on quiet pavement technologies.[13] The focus of the tour was the three technologies below:

- Thin-surfaced, negatively textured gap-graded asphalt mixes (e.g. Novachip, micro-surfacing, and some SMA),
- Single- and double-layer highly porous asphalt mixes (greater than 18% voids),
- Exposed aggregate concrete (EAC) pavements.

The Danish government has experimented with both single- and double-layer porous mixes and thin-layer mixes as pavement noise reducing strategies. The porous mixes have the greatest potential to reduce noise by 3 to 5 dB, but have performance problems with clogging and durability. Thin mixes are more cost-effective and appear to be more durable. However, noise reduction achieved is lower at 1 to 3 dB. In some cases two-layer OGFC or porous asphalt is being used as a noise-reducing strategy in place of sound walls. Denmark requires porous mixtures to be at least 18 percent air voids. The proposed system incorporates a large stone mix (16 or 22 mm / 0.62 or 0.86 in) in the lower layer, and a smaller stone mix (5 or 8 mm / 0.20 or 0.31 in) in the upper layer. This pavement system has added benefits in that it prevents the OGFC from clogging during service.[10, 13]

France employs the following techniques for pavement noise reduction:[13]

- Use separate structural and surface characteristics,
- Use best-quality aggregates,
- Adjust pavement dressing to noise characteristics,
- Use smaller aggregate size for best adhesion (skid resistance).

French transportation officials acknowledge the use of thicker surfacing (5 to 8 cm / 1.95 to 3.12 in) and continuous grading to ensure good waterproofing of the pavement. However, very thin (2 to 3 cm / 0.78 to 1.17 in) and ultrathin (1.5 cm / 0.59 in) mixes developed to improve the surface characteristics (skid resistance, noise) are being used today. The grading composition of mixes is 0 to 6 mm (0.23 in) and 0 to 10 mm (0.39 in) gap graded. These surface mixes are usually 25 to 30 mm (0.98 to 1.17 in) thick with 5.7

to 5.9% asphalt. Gap grading appears to increase the raveling potential for these pavements. The addition of 7 to 10% sand mortar has helped to resist raveling.

In the UK, plans are underway to resurface 60 % of the strategic road network with quieter materials for a 10-year period ending in 2010.[13] Transportation officials have experimented with EAC finishes, but thin-layer quiet surfaces are now the paving materials of choice because they are more cost effective, even on concrete pavements.

2.2.1.2 Concrete Treatment for Noise Reduction

Kansas DOT (KDOT) rehabilitated eight miles of I-435 with 3-inches of asphalt laid over a 1-inch reflective cracking interlayer (RCI). The interlayer was a polymer with a heavy oil content – a modified emulsion as a tack coat between the two lifts. The finished HMA overlay reduced the noise level from the original transverse tined PCC pavements by about 7 dB. The National Center for Asphalt Technology (NCAT) tested the pavement surface for noise levels before and after the project.[14] Local residents described the noise levels before and after the project as a "difference between night and day".

Similarly, Wisconsin DOT (WIDOT) tested Italgrip, a very thin surface treatment consisting of a two-part polymer resin, and found it to be a suitable and cost-effective technique to enhance the safety and drainage characteristics of their roadways. The Italgrip system is designed to improve the frictional characteristics of a pavement surface. It is primarily intended for application in heavily trafficked short sections of roadway with friction problems or high accident rates.[15] A 3 mm (0.12 in) Italgrip aggregate was applied to both eastbound lanes, while a 4 mm (0.16 in) aggregate was applied to the westbound lanes near I-94.

The following steps were followed after diamond grinding of the roadway section:

- a two-part polymer adhesive was carefully applied to the pavement surface,
- the Italgrip aggregate was then back-spread over the polymer,
- after setting for a few hours, the surface was vacuum swept and re-opened to traffic.

The following outcomes were observed from the WIDOT study:

- grinding of the PCC pavement and application of the Italgrip resulted in no major shift in frequency spectrum when comparing the tined PCC pavement, ground PCC pavement and ground PCC pavement with Italgrip;
- a 3 dB decrease in the noise level due to diamond grinding, an additional 1 dB reduction in noise level when the Italgrip is compared to the ground PCC pavement at 96 km/h and 104 km/h (60 mph and 65 mph), and a 2 to 3 dB decrease in noise level when the Italgrip is compared to the ground pavement between 1,550 and 2,000 Hz;
- a noticeable change in sound to the ear;
- no significant change in noise level at 112 km/h (70 mph) between Italgrip and the ground pavement;
- no significant noise level difference between the 3 mm and 4 mm (0.12 and 0.16 in) aggregate.

Prior to 1999, the Italgrip System had never been used in the United States. However, the system had been in use in Italy for 10 years.

Although EAC pavements are commonly used in European countries, the technique has not been routinely used in the United States. EAC pavements are normally constructed using a two-layer "wet on wet" paving process. The top layer thickness typically ranges from 38 to 70 mm (1.5 to 2.75 in.). The mix contains fine siliceous sand and a high-quality coarse aggregate with an ideal maximum size of 6 to 12 mm (0.24 to 0.48 in.). Aggregates used in the lower layer of the pavement can be of more modest durability and commonly include recycled materials that help reduce the overall cost of the concrete. Studies have shown that the use of smaller aggregates provided better noise reduction levels.[16]

The only large-scale EAC pavement project in the U.S. was completed in 1993 on Interstate 75 in downtown Detroit, Michigan. The exposed aggregate concrete pavement was comprised of a 254 mm (10 in.) jointed concrete pavement constructed in two lifts. The top layer of the pavement was 64 mm (2.5 in.) thick with polish-resistant aggregates, and the bottom layer was 191 mm (7.5 in.) thick with conventional aggregates. The lifts were bound using a "wet-on-wet" procedure. When compared to a conventional jointed reinforced concrete pavement textured with transverse tines spaced 25 mm (1.0 in.) apart, the section provided a reduction of only 0.4 dBA in exterior noise levels, although similar European projects reported noise reductions between 4 and 5 dBA.[16]

Researchers believe that the disappointing values may have resulted from too much macrotexture on the exposed aggregate surface, combined with excessive spacing between the coarse aggregate particles. This excessive spacing was a result of large sand particles. Perhaps the difference in the U.S. and European experiences with EAC was a motivating factor for the renewed interest in EAC pavements on the recent 2005 FHWA scanning tour.

EAC pavements also exhibit properties associated with pavement texturing due to the size of aggregates used and the texture depth of the stones. This material is also discussed in Section 2.3, Pavement Noise Reduction Technologies.

Pervious or porous concrete is a material with large voids that are intentionally built into the mix. The resulting permeability allows water (and air) to flow readily through this material. When used in highway applications, pervious concrete is typically used as a top layer (wearing course), providing both low noise emission and good drainage capacity. The pervious concrete typically overlays a conventional (dense) concrete pavement using a "wet-on-wet" process. Noise reduction in this composite system is a result of the pervious material's acoustical absorption, while strength and durability are improved by the presence of the underlying concrete pavement layer.[16]

Porosity levels for pervious concrete pavements typically range between 15% and 20%. To attain good noise reduction characteristics, porosity should be at least 25%. Research from Purdue University's Institute of Safe, Quiet, and Durable Pavements has reported that sound absorption levels were improved when higher porosity was used.

When pervious concrete pavement was first constructed in Belgium, it was found to exhibit undesirable durability in freezing weather. Subsequently, polymer additives were used along with higher cement content. The result was a significant improvement in the service life.[13, 16] A policy that is currently being pursued in Japan is to replace all pavements with pervious systems due to their safety and riding comfort. To change over their existing concrete pavements to a pervious system, the preferred option is thin-bonded pervious concrete overlays.[16] Laboratory simulation tests have demonstrated that pervious concrete pavements can resist rutting and have a higher wear resistance to tire chains than porous asphalt.

Since 1993, Japan's Public Works Research Institute (PWRI) has been developing a new low-noise pavement that is referred to as "Porous Elastic Road Surface" (PERS). Potential noise reduction levels in Equivalent Noise Level (L_{eq}) exceed 10 dBA. PWRI has already solved several of the problems with PERS such as insufficient adhesion between the pavement and the base course, low skid resistance, and poor fire resistance. PERS was first constructed on Japan's National Highway Route 46. However, noise reduction levels measured in the field were less than expected due in part to the small size of the construction area. The noise reduction levels measured at the site are lower than those measured at the PWRI test facility. The noise reduction effect of PERS was found in the 1/3-bandwidth frequency of 800 Hz and over.[17]

In a separate study, pervious concrete pavements were evaluated in Japan with two experimental concrete sections, 200 mm (7.9 in) in thickness. When compared to dense asphalt pavements, they displayed noise reductions of 6 to 8 dBA for dry surfaces and 4 to 8 dBA for wet surfaces. This study was conducted with cars traveling at speeds from 40 to 75 km/h (25 to 45 mph). For heavy trucks, noise reduction values were 4 to 8 dBA and 2 to 3 dBA for dry and wet surfaces, respectively.[18]

One disadvantage of using pervious concrete pavements is the clogging of the pavement's pores. The pores clog over time due to depositions in the voids of dirt and dust from the road surroundings, from wear of the pavement itself, and from tires.[13, 16]

2.3 Noise Reduction Technologies

For the purposes of this research study, a pavement noise technology may be a part of the process, equipment, or machinery that is used to apply the paving material to the road surface. It does not include paving materials.

2.3.1 Pavement Texturing

Pavement texturing can be designed and built into a pavement or placed upon hardened concrete pavement by equipment. The National Concrete Pavement Technology Center at Iowa State University (ISU), FHWA, ACPA, and other organizations have partnered to conduct a multi-part, seven-year Concrete Pavement Surface Characteristics Project.[16] Part 1, Task 2, of the ISU-FHWA project, addressed the noise issue by evaluating conventional and innovative concrete pavement noise reduction methods in Europe and the U.S.

In the U.S., conventional concrete pavement surface options for controlling tire-pavement noise fall into two categories:[16]

- Conventional texturing (performed while concrete is still in a plastic state)
  - Drag textures (including artificial turf and burlap drag)
  - Tined textures (including transverse and longitudinal)
- Diamond grinding (performed on hardened concrete pavement)

A brief definition is provided for each category along with examples and outcomes of field studies or applications that relate to pavement noise reduction. A summary of the pavement texture options presented in this subsection is provided in Table 5 on page 23.

2.3.1.1 Drag Texturing

Broomed surface textures are created by dragging a handheld or mechanical broom along the surface of the pavement, creating a ridged surface. This texture typically consists of 1.5 to 3mm deep (0.06 to 0.12 in.) grooves, either longitudinal or transverse to the centerline of the roadway.

Artificial turf drag surfaces are similarly created by dragging an inverted section of artificial turf along the surface of the pavement. This technique often employs a device that controls the time and rate of texturing, most commonly a construction bridge that spans the pavement. Grooves of 1.5 to 3 mm (0.06 to 0.12 in.) in depth are typically created. Burlap drag (also known as Hessian drag) texturing is created by dragging moistened, coarse burlap across the surface of the pavement, typically creating grooves with depths between 1.5 and 3 mm (0.06 and 0.12 in.).

Studies have shown that dragged textures are sufficient for roadways with speeds below 72 km/h (45 mph). More recent pavement evaluations in Minnesota have concluded that the use of drag texturing results in comparable noise levels and surface friction to conventional HMA pavements. The required texture depth specification in Minnesota is reported to be 1.0 mm (0.04 in.)[16]

According to Cackler et al.,[16] the majority of concrete highway systems in Germany are finished using a burlap drag texture. The burlap drag finish provides adequate friction and minimizes air pumping. However, the frictional characteristics of the pavements often decrease due to pavement wear. Use of larger sand particles may increase the texture life by up to six years. The larger sand on the other hand may also reduce the concrete's workability.

Drag texturing techniques may provide a less costly and often quieter pavement than other alternatives. Measures should be taken to ensure adequate friction, both initially and during the service life. This can be achieved by selecting materials and mixes with improved wear resistance.

2.3.1.2 Tined Texturing

Transverse tining is the most common texture on high-speed road and highway pavements in North America.[19] It is produced by a mechanical device equipped with a tining head (metal rake) that moves laterally across the width of the paved surface. For smaller areas, a hand rake is often used. Optimal dimensions vary from 10 to 40 mm (0.4 to 1.6in) spacing for random tines with no more than 50% above 25 mm (1.0in), 3 to 6 mm (0.12 to 0.24in) tine depth, and 3 mm (0.12in) tine width.[14,19] Skewing of tines has been found to reduce tire-pavement interaction noise.

Favorable friction qualities of transverse tining are particularly pronounced in wet weather conditions. Deep macrotexture is capable of reducing the water film thickness resulting in reduced potential for hydroplaning. Depending on the properties of the concrete mixture, transverse tining can provide beneficial frictional qualities over the life of the pavement.

Transverse tining has also been known to exhibit undesirable noise emissions due to the interaction between the pavement and vehicle tires. Noise emissions from transverse tined textures depend on tine spacing, depth, and width. A study conducted by WIDOT in 2000 concluded that wider and deeper transverse tine textures often produce greater noise.[15,16]

A 1977 Minnesota DOT (MDOT) report to the state legislature discussed the testing of different anti-skid groove spacings on PCC pavement. By changing the spacing from 1.5 to 1.0 inch, roadside noise levels were reduced 2.5 to 4.0 dB.[20] Using results from a Wisconsin study, MDOT was able to reduce its spacing to 0.75 inch achieving a further reduction of 1.5 to 3.5 dB and an overall reduction of 4.0 to 7.5 dB. Wisconsin and Minnesota also conducted noise studies on different types of bituminous pavements that resulted in even greater noise reductions. Although no details are available about the data collection process or the data analysis, it is assumed that transverse tining was the texturing process applied to the PCC pavement in this study.

Uniform transverse tine spacings typically range from 12.5 to 25 mm (0.5 to 1 in). “Wheel whine” is often associated with uniformly spaced tines. While the dBA level of a tined surface may not necessarily be higher than other texturing methods, the tonal nature of the whine makes this pavement texture objectionable to many. To help mitigate the tonal qualities, random tining is recommended. A broad range of random tine spacings, between 10 to 76 mm (0.4 to 3 in.) has been reported to reduce noise emissions. In situations where concrete finishing conditions are unfavorable (e.g., objectionable weather conditions and lack of equipment control), random spacings of 10 to 51 mm (0.4 to 2 in.) are recommended. The FHWA has recommended two random tining patterns, averaging 13 mm and 26 mm (0.52 in. and 1.04 in.), respectively.[16] The shorter spacings have been recommended to mitigate the high noise levels reported by some states that have tried or adopted random spacings.

Skewing of transverse tining involves forming the grooves at an angle, rather than perpendicular to the centerline. This is a complementary method that has demonstrated benefits related to tire-pavement noise while providing the friction commonly associated with transverse tined pavements. Research by Cackler et. al. identified a skew with a recommended longitudinal-to-transverse ratio of 1:6.[16]

Longitudinally tined textures are constructed in a manner similar to that of transverse tining, except that the tining device is moved longitudinally along the direction of paving. Although longitudinal tining is not used as frequently as transverse, it has been used extensively in some states, including California.

Longitudinal tining is commonly reported to exhibit lower noise characteristics thereby increasing its popularity and use. However, some transportation agencies have been cautious to use this texturing technique because the data shows longitudinally tined surfaces to have lower friction numbers when compared to transversely tined pavements, all else being equal. One possible explanation of this may be the shape of the grooves with respect to the traction forces of the tire (compared to transverse tining). It should be noted, however, that longitudinal tining on horizontal curves has been shown to prevent vehicle skidding and thus improve safety.[16] Some DOTs report that if adequate cross-slope exists, the differences between the surface drainage on transverse and longitudinal tining are minimal.

Research shows that the long-term effectiveness of longitudinally tined surfaces is impacted by the design of the pavement mix. Data have shown that longitudinally tined pavements should contain a minimum of 25% siliceous sand to improve the level and durability of the friction capacity.

The WIDOT study further concluded that among all of the concrete pavements evaluated, those with longitudinal tining provided “the lowest exterior noise while still providing adequate texture”. When the texture is properly designed and constructed, longitudinally tined pavements can achieve friction characteristics and durability comparable to either transversely tined concrete pavements or dense-graded HMA pavements.[16]

Volpe assisted California DOT in a comparison of three PCC test sections: longitudinal tining, burlap dragged, and broomed tining. Volpe also assisted ADOT in comparing uniform longitudinal tining, uniform transverse tining, and randomly spaced transverse tining. Their findings showed that the quietest surface treatments were CA burlap dragged, CA broomed, and AZ uniform longitudinal tining.[11]

2.3.1.3 Diamond Grinding

Diamond grinding is a technique that removes a thin layer of hardened concrete pavement using closely spaced diamond saw blades. The diamond saw blades are stacked side-by-side and generally remove between 3 and 20 mm (0.12 and 0.8 in) from the surface. The blades are gang-mounted on a cutting head and can generate 164 to 197 grooves/m (50 to 60 grooves/ft). Although diamond grinding has traditionally been used to rehabilitate existing pavements by restoring smoothness, it has also been found to reduce tire-pavement noise and restore pavement friction. The grinding procedure results in the development of macrotexture. Furthermore, directional stability is more easily controlled, making diamond grinding more appealing to drivers than longitudinal tining.

In one study conducted to compare transverse tining to longitudinal diamond-grinding, test sections were constructed and evaluated for safety, noise, and other pavement characteristics.[20] Diamond grinding was used to remove a thin layer of the concrete surface. In some cases, thin fins of concrete were left behind and were subsequently broken off by a blade. Each grinding head consisted of 166 saw blades, 3.18 mm (0.125 in.) separated by spacers with a thickness of 2.67 mm (0.105 in).

It has been reported that the key variables of diamond grinding are cutting blades, cut depth, equipment horsepower, and the properties (e.g., hardness) of the aggregates used. In a 2001 study by Burgé, Travis, and Rado, the grinding rate was approximately 0.6 lane-km (0.4 lane-mi.) per day In addition, there was a specified minimum curing time of seven days before grinding. KDOT conducted a study in 2004 and concluded that smaller blade spacings led to reduced noise levels.[16]

The study concluded that the longitudinal ground pavement was quieter than the transversely tined pavement by 2 to 5 dBA (measured on the side of the road).[16] When noise measurements were conducted a year later, there was no real change in noise levels. When comparing different vehicle types, the ground surface led to a 5-dBA noise improvement for light trucks and automobiles, and a 2-dBA improvement for medium and heavy trucks. The lower noise reduction for larger vehicles is believed to be due to differences in the noise emission source; larger vehicles generate a greater percentage of noise from the engine and exhaust systems (as compared to tire-pavement noise emissions).[16] Prior to making a decision on a pavement surface technology, the percentage of heavy vehicles should be considered in determining overall effectiveness of surface treatments.

Several states, including Arizona, California, New Jersey, North Dakota, and Virginia have experience with tined and textured surfaces of PCC pavements in addressing roadway noise. A partnership has been formed between California and the Western States-ACPA on the I-280 pavement rehabilitation project in San Mateo County. Noise from old longitudinally tined pavement will be compared to noise from a PCC pavement with diamond grinding, a PCC pavement with texture grinding, and a PCC pavement overlain with 30 mm (1.17 in) of OGFC.[20] Noise measurements will be made for three to five years to assess the longevity of noise reduction benefits.

The 2005 European scanning team recommended investigating and optimizing diamond-grinding blade configurations to enhance the noise-reducing properties of existing concrete surfaces in noise-sensitive locations. To achieve noise reduction texture should always be negative (pavement depressions). Positively textured pavements, such as chip seals, increase noise. Positive texture is the magnitude of texture that exists above a planar surface (the riding surface). Positive texture almost always produces greater noise with increasing texture depth. Chippings on concrete or exposed aggregate surfaces could be considered the extreme case of positive texture.

Negative texture refers to the magnitude of the texture that exists below a planar surface. A longitudinally grooved pavement would represent a negative texture. Negative textures do not “interfere” with the tire, resulting in less vibration and noise than a positive texture. Therefore, the effect of negative texture is different from the effect of positive texture.[21] This is another reason why texture depth alone cannot be used to correlate noise across different pavement types.

2.3.1.4 Exposed Aggregate Concrete (EAC)

EAC was discussed in the previous section as a concrete pavement treatment that is usually applied using a two-layer “wet on wet” paving process. It is the combination of aggregates used in the top layer that determine its surface characteristics and texture. Texture depths, curing solutions, and concrete finishing techniques are used to determine the best combinations for optimal performance.

During the 2005 FHWA scanning tour, UK transportation officials reported that they experimented with EAC finishes and found thin-layer quiet surfacings to be more cost effective. Belgium uses EAC pavements and SMAs. Both have been optimized for noise. The porous surfaces provide a slightly better noise benefit than SMA and EAC, but officials believe that the latter provides a better blend of durability and noise reduction.

The Dutch province of Noord-Brabant conducted a study intended to further determine the surface characteristics of EAC pavements. Various aggregates, texture depths, curing solutions, and concrete finishing techniques were used in the study to determine the combinations that provided optimal performance. Two Dutch aggregates, Dutch stone and Graukwartsiet, were used in the study. The Graukwartsiet possessed a higher polished stone value than the Dutch stone aggregate. Several texture depths were evaluated. The standard depth was considered to be one-quarter of the maximum aggregate size. Different retarding agents were evaluated, including lemon, acid solutions, and various combinations of retarding agents and curing compounds. One- and two-layer paving systems, as well as a super smoother (finisher) were also evaluated in the study.[16]

Several key measurements and observations were made after construction. Texture depth was found to be affected by the use of a super smoother, which resulted in a maximum texture depth of 1.8 mm (0.07 in). When not used, texture depths were not as great, with values commonly between 1.1 and 1.6 mm (0.04 and 0.06 in). The super smoother was shown to produce positive effects in regards to noise emission, possibly due to a reduction in megatexture. The selection of the retarding agent did not appear to make a difference on the results. It was concluded that lower noise levels were measured when smaller maximum aggregates were used.

A Swedish Study tested several concrete and HMA pavements for abrasion resistance, friction, and noise under heavy traffic. The test sections were constructed with exposed aggregates in the surface on both jointed plain and continuously reinforced concrete pavements. Two different maximum aggregate sizes were used in the design of the concrete pavements, 8 and 16 mm (0.31 and 0.63 in). Noise was measured using the close proximity (CPX) method. In comparison to the HMA pavements constructed on the same job, initial tests revealed that the EAC pavements with 16 mm (0.63 in) and 8 mm (0.31 in) stones provided noise levels that were 1.0 to 1.5 dBA and 3.0 to 3.5 dBA lower.[16]

The noise emissions of the 16 mm (0.63 in) EAC and HMA sections were found to be identical after one year. However, the 8 mm (0.31 in) EAC section actually produced quieter noise levels after a year. Three years after construction, the noise levels from all of the pavements had deteriorated. Also of interest was that during the winter season concrete pavements produced noise levels about 1 dBA higher than the HMA pavements.

2.3.1.5 Pervious Concrete Pavements

Pervious concrete pavement was also discussed in the previous subsection as a pavement treatment. A relationship between sound absorption and aggregate size was identified in the research. In one study, a pavement with decreased aggregate size exhibited improved sound absorption. A combination of #4 and #8 aggregates in the mixture exhibited improved acoustic absorption characteristics when compared to straight gap grading. A Belgian study reported sound reduction using pervious concrete as well, with a 5 dBA decrease using a pervious concrete pavement with only 19% porosity.[16]

Durability is commonly regulated by the interface of the two concrete layers and the presence of pores. Once ice forms at the entrance of small pores and water is unable to move, damage occurs very quickly. In pervious concrete, freezing tends to originate at the top of the pavement and infiltrate into the lower depths of the layer. Differences in the properties of the pervious and dense concretes can lead to stress concentrations at the interface. The damage may take the form of an adhesion loss between the pervious concrete and the conventional concrete. To combat this problem, continuous maintenance and cleaning can be conducted to help preserve and restore the pavement's acoustical performance.

Double-layer pervious concrete has also been demonstrated as a possible solution where a top lift with smaller aggregates is placed over a larger stone mix. The resulting system may help to minimize infiltration of debris that causes clogging. The added cost of constructing pervious concrete pavement must be taken into consideration. The long-term effectiveness of this technique is still under debate. In one report by the Belgian Road Research Centre it is noted that compared with a conventional concrete 22 cm (8.7 in) thick a 4 cm (1.6 in) pervious concrete laid over 18 cm (7 in) of conventional concrete has associated extra costs estimated at 40%". However, no significant cost difference was found with an equivalent structure including porous asphalt. The cost of constructing quiet pervious concrete pavements in New Zealand has been reported at US $132 per m² (US $111 per sq. yd.). In the United States, pervious concrete projects have been reported to cost 40% more.[16]

2.3.1.6 Innovative Pavement Texturing Solutions

In his research on concrete pavement noise reduction methods, Cackler identified several innovative texturing solutions that were either being researched or were in experimental stage.[16]

- Stamping, Brushing, and Other Texturing Techniques: Other proposed alternative texturing techniques are proposed to conventional tining, but will be designed with better surface characteristic properties.

- Sprinkle Treatment: This technique is similar to EAC and distributes partially embedded, small, polish-resistant stone chips on fresh concrete surface. This technique was previously used in the U.S. in the 1970s and 1980s; however, the equipment was rented from England, and therefore not available for wide-spread application. Equipment will need to be developed or purchased.

- Shot Peening (or shotblasting): Special equipment is used to propel tiny steel shots onto the pavement surface. The shots make an imprint on the surface and remove a thin layer of mortar and aggregate, exposing coarse aggregate. An open porous surface texture is created increasing skid resistance and reducing noise levels.

- Use of Helmholtz Resonators: Originally developed at the University of Göttingen in Germany, euphonic pavements were designed as "quiet tire/road combination" pavements, incorporating "Helmholtz resonators underneath a perforated but planed aluminum structure". Helmholtz resonators are designed to absorb low frequencies, typically ranging between 100 to 250 Hz.

Other potential texturing techniques identified by Cackler include:[16]

- Paving concrete that possesses inclusions (e.g., fiberglass, foam, and rubber particles) to increase acoustical absorption,
- Application of acoustically absorptive materials for concrete shoulders (as opposed to traffic lanes), allowing for noise of all sources to be absorbed en route to the receiver and also reducing surface wear and clogging issues,
- Quiet joint designs, addressing the significant factor of wheel "slapping" at the joints in overall noise levels,
- Dimpling, waffling, or other innovative geometries of fresh concrete texture,
- Textured profile pans, e.g. a corduroy pattern, for example, might be machined into the profile pan of a slip-form paver to construct a surface similar to that resulting from diamond grinding.

Table 5: Summary of Concrete Pavement Texture Options[16]

Texture	Description	Current Use and Perception
Artificial turf drag	Produced by dragging an inverted section of artificial turf from a device that allows control time and rate of texturing. Usually a construction bridge that spans the pavement typically produces 1/16 to 1/8 inch deep striations.	Artificial turf drag textures have shown sufficient friction characteristics for many roadways, as well as reduced noise relative to many transversely tined pavements. Minnesota has used this type of texturing to reduce noise on high-speed roads.
Burlap drag	Produced by dragging moistened coarse burlap from a device that allows control of the time and rate of texturing, usually a construction bridge that spans the pavement; typically produces 1/16 to 1/8 inch deep striations.	Burlap drag textures provide sufficient friction characteristics for many roadways, especially those with speeds less than 45 mph, and reduced noise relative to many transversely tined pavements. This texture is used on Germany's high-speed Autobahn system.
Transverse tining	Produced by moving a mechanical device equipped with a tining head across the width of the paving surface laterally or on a skew. Consistent concrete mixture and constant forward movement of the paving train at a uniform speed is required for a consistent tining depth.	For tined pavements, texture depth and groove width are important parameters in tire-pavement noise generation. Pavements with uniformly spaced transverse tining generally, but not always, exhibit undesirable "wheel whine" noise. Artificial turf or burlap drag texture precedes many projects.
Longitudinal tining	Achieved by a mechanical device equipped with a tining head (metal rake) pulled in a line parallel to the pavement centerline. For consistent tining depth, maintain a consistent concrete mixture and move the paving train forward constantly at a uniform rate of speed. Most projects precede with an artificial turf or burlap drag texture.	Tined texture depth and groove width are important parameters in tire-pavement noise generation. Longitudinal tining is often quieter than transverse tining. Narrower time spacings might be used to reduce vehicle tracking and possibly reduce noise even further. Lateral stability of narrow-tired vehicles may also benefit from this.
Diamond grinding	Longitudinal, corduroy-like texture made by equipment using diamond saw blades gang-mounted on a cutting head. About 50 to 60 grooves/ft. are produced by the cutting head 1/8 to ¾ inch is removed from the pavement surface.	Diamond grinding has traditionally been used to restore pavement smoothness, but has also been shown to reduce tire-pavement noise and improve friction in the short term. Diamond ground pavements do not affect vehicle tracking as much as widely spaced longitudinally tined pavements.
EAC pavement	European practice includes applying a set retarder to the new concrete pavement and then brushing or washing away mortar to expose durable aggregates. Other techniques involve the uniform application of aggregates to the fresh concrete.	Regarded as an effective method for reducing tire-pavement noise while providing adequate friction. Smaller aggregate sizes have been reported to provide larger noise reductions, while aggregates with a high polished stone value increase durability. Only one large-scale EAC pavement project has been completed in U.S.
Pervious concrete pavement	When used in highway applications, pervious concrete is typically used as a top layer (wearing course), providing both low noise emission and good drainage capacity. The pervious concrete typically overlays a conventional (dense) concrete pavement using a "wet-on-wet" process.	Sound absorption increases with higher porosity levels for pervious concrete, and also results from smaller aggregate sizes. Use of pervious pavements for high-volume, high-speed facilities is still in its infancy and will require more testing. Regular maintenance and cleaning may be needed to prevent clogged pores and to preserve the pavement's acoustical performance. Research on durability is ongoing in wet, hard-freeze areas.

2.3.2 Other Innovative Pavement Solutions

Traditionally, two-layer porous asphalt is laid in two passes – one pass per porous layer. As a part of a Noise Innovation Program, equipment will be tested in the Netherlands to construct two-layer porous asphalt in one pass – both layers being laid at the same time.[26] This technique is already in use in Germany with thin top layers. The objective of the research is to determine if the "one-pass placement" will increase the performance of the two-layer pavement materials.

As a part of its *Road to the Future* program,[22] transportation researchers in the Netherlands are focusing on long-term effects and the placement of pavement materials using innovative and/or fast construction techniques. Six experimental test sections have been constructed:

a. The Very Silent Sound Module – this design has a functionally and physically modular system. The sound-reducing functional modules contain Helmholtz resonators. The road surface on top of the sound-reducing resonators is made of a thin porous top layer. This single layer of asphalt has optimized surface properties, such as low sound generation and a high skid resistance.

b. The Way of No Resound – this road design has three layers. Two top layers with a combined thickness of 30 mm (1.2 in), are assembled in the factory as one roll-up layer. The bottom layer is made up of concrete elements with a high supporting power in which cavities that function as Helmholtz resonators are included. The prefabrication of the top layer promotes a pavement surface without irregularities in the macro-texture. This results in reduced vibration of a vehicle's tires.

c. The Bonding Road – this design has a prefabricated asphalt mat on a roll that can be bonded to or removed from the substrate very quickly by utilizing an "on-off switching" bonding system. Prefabrication of the paving materials ensures a consistent high quality end product. The bonding between the asphalt mat and the substrate can be switched *on* or *off* by electromagnetic waves without any physical contact.

d. ModieSlab – the top layer of this road design consists of a 15 mm (0.6 in) open concrete layer, followed by another open concrete layer with coarsely broken gravel that is 35 to 55 mm (1.4 to 2.2 in) thick. The thickness of the lower layer decreases from the right to left lanes. Sound absorption is expected to match the type of lane traffic.

e. Quiet Transport – this road surface has porous asphalt with a very silent top layer. During construction a special layer is installed to absorb engine noise. The pavement design objective is to absorb both truck engine and tire noise.

f. Tapis Tolerance – the road construction for this pavement design includes a soft top layer, a perforated compression layer, and an absorption layer of honeycomb profiles in mineral wool. Due to the number of noise reducing elements, the expected noise reduction potential is high, and more than likely the cost of road construction will increase.

Initial results for the pavement types tested under the Road to the Futures program are shown in Table 6. These results reflect light vehicle traffic at 100 km/h (62 mph). The initial noise reduction levels reported for all pavement techniques vary between 5 and 7 dBA. The claimed reductions for some of the pavement techniques exceeded 10 dBA. However, optimization of new pavement techniques may produce higher reduction levels.

Table 6: Initial Noise Reduction Levels for Light Vehicles
Road to the Future Project[22]

Pavement Technique	Noise Reduction, dBA
Very Silent Noise Module	5
The Way of No Resound	6
The Bonding Road	6
ModieSlab	6 to 7
Quiet Transport	5 to 7
Tapis Tollerance	7 to 8

The 2005 FHWA Scanning Team noted the use of a single two-lift paver by Wirtgen during their visit to Belgium. The Wirtgen paver allows for the use of lower-quality aggregates in the base while using higher quality aggregates on the top surface.[13, 16,23] The two-lift process is not new to the U.S. and has been around almost as long as concrete pavement. The two-lift paving technique was implemented extensively from 1950 to 1990 in many states to facilitate the placement of mesh in concrete during interstate pavement construction. This pavement consisted of two layers placed wet on wet, with the top layer consisting of a special surface mix. Beginning in the 1970's the concrete paving industry moved away from a mesh dowelled design to a plain pavement design, and shortening panels eliminated the need to pave with a two-lift process. Today there are still some rare instances where the two-lift process is used in airport construction to facilitate the placement of mesh between dowel baskets.

The two-lift process is used in Europe to develop a strong base pavement and a superior, but thin, wearing surface. In France, continuous reinforced concrete pavement was placed on two traffic lanes of highway A71 using the two-lift paving method.[23] The top layer of this pavement, approximately 2 inches in depth, was made up of harder aggregates. These aggregates provided low noise and high friction for the pavement surface.

In Austria, the aggregate is secured with cement and then a two-inch layer of asphalt is placed on top. The recycled aggregate is then mixed into the bottom 8.5 in deep concrete layer, while the top 1.6 in deep layer was composed of a harder, higher quality aggregate. The purpose of using a higher quality concrete for the top layer was to reduce noise and increase friction, while keeping cost low by using a lower quality concrete for the bottom layer. The case is very similar in Germany. Two-lift paving is often used to reduce noise and increase friction. Germany also uses this method to reduce cost and achieve a smoother profile. In addition, Germany has somewhat drastic climate changes, which require the use of higher quality aggregate in the top layer to resist freezing and thawing effects.[23]

The renewed interest in the two-lift process appears to be growing in the U.S. Implementation of a two-lift system could help some agencies around the country consume growing recycled asphalt piles, since most asphalt specifications only allow up to 40% recycled asphalt in their product and generally only on the lower sections. If recycled asphalt is available, it could be used to reduce costs as less of the more expensive aggregates would need to be imported.

2.4 Other Considerations for Noise Source Reduction

Some methodologies that are being considered for pavement noise reduction do not fit in any one of the three categories of interest identified in this study. Examples of such methodologies include; developing a better understanding of the pavement attributes that reduce noise generation for different vehicle types, evaluating pavement performance with age, developing maintenance techniques that preserve the noise reducing characteristics of pavement, and developing quieter tires without compromising safety.

At the InterNoise 2003 Conference,[22] transportation officials from The Netherlands reported developing several projects under the Noise Innovation Program (IPG) that focused on the use of silent roads, improvement of tires and vehicles, optimization of barriers, knowledge management, and facilities assessment methods. Their total budget for noise abatement of road traffic is about 50 million euro. Looking to the future, one of the keys to noise reduction from tire-pavement interaction on roadways in Arizona may be the ability to model the effectiveness of combining several measures for a particular application.

Sandberg identifies seven noise influencing road surface parameters (Table 7) in an international presentation to SILVA.[24] More interestingly, he notes that European pavements are *designed* to be quiet, whereas California and Arizona pavements are *off-the-shelf.*

Table 7: Noise Influencing Road Surface Parameters[24]

No.	Parameter	Degree of Influence
1	Macrotexture	Very high
2	Megatexture	High
3	Microtexture	Low-moderate
4	Unevenness	Minor
5	Porosity	Very high
6	Thickness of layer	High, for porous surfaces
7	Adhesion (normal)	Low/moderate
8	Friction (tangent.)	See microtexture
9	Stiffness	Uncertain (?), moderate

A significant finding reported by the 2005 FHWA Scanning Team is that the source level of quiet pavements is being incorporated into existing highway noise prediction models using varying methods. This effort falls under the Harmonised, Accurate, and Reliable

Prediction Methods for the EU Directive on the Assessment and Management of Environmental Noise (HARMONOISE). The common EU model being developed will incorporate pavement type in the prediction, along with other advanced prediction parameters such as meteorological effects.[13] Pavement noise reductions of as little as 2 dB are being used in integrated noise strategies.

Under the European Union's Environmental Noise Directive, adopted June 25, 2002, all member countries are to:

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.

All member countries were to complete strategic noise maps and adopt actions plans on or before June 30, 2007.

Many European highway paving projects are bid based on performance specifications. The selection process is based on best-value contracting methods. Pavement vendors have responded to agency performance criteria with innovative solutions that often carry unequal risk, but if effective, can be held as proprietary for future project applications.

There appears to be large disagreement within the EU regarding effective maintenance of negatively textured and highly porous pavements. Some countries require pressure washing and vacuuming of the pavement at least twice a year, while others consider these practices useless, or even harmful. Some countries have stopped using highly porous pavements in snow and ice regions, and instead use SMA pavements with small aggregate.

In the area or pavement noise research, an extensive amount of research on quiet pavement technology is underway in the European Union and appears to be embedded in the culture of the organizations. A research partnership exists between the transportation agency and industry, and even with private entities. As an example, under the SIRIUS program, companies are encouraged to submit innovative ideas that are judged by a panel of topical experts. The best ideas are constructed as experimental sections. The selected projects are highly sought after by companies as a marketing tool.

One of the recommendations from the 2005 scanning tour for US transportation organizations was to consider reducing the aggregate size in the wearing surface of the pavement to realize an immediate improvement in the noise-reducing properties of mixes. In Europe, the aggregate sizes for quiet surfacing mixes are 4 to10 mm (0.16 to 0.4 in). Most State DOTs use the Superpave aggregate gradings of 19, 12.5, or 9.5 mm (0.76, 0.5, or 0.38 in). 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.[13]

The emerging trend is to use thin-textured, gap-graded mixes with small aggregate in urban or low-speed areas or areas subject to severe winter snow and ice accumulation. The highly porous mixes are recommended for rural and high-speed roads with moderate winter conditions. 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 roads and produces exceptionally quiet pavements. Porous mixes should not be placed in urban areas where the operating speed drops below 72 km/h (45 mi/h) since highly porous mixes tend to clog under slow traffic.

Section 3

Noise Reduction Survey

A survey questionnaire was developed to gather information from government and non-government agencies regarding; a) current use and practices in the area of noise products, materials, and technologies, b) current research on noise reduction methods, and c) potential future use of noise reduction products, materials and/or technologies. This section of the report documents the methodology used to develop the survey questionnaire, potential respondents targeted by the survey, and the execution of the survey. The survey questionnaire results are discussed in Section 4.

3.1 Development of Questionnaire

The survey was designed to be short with no more than 10 questions. It was also designed as an electronic survey to be distributed via email. Recipients had the option to mail back the survey as a hard copy, if desired. The questions were arranged in the following order:

Leading Questions

Questions 1 through 4 were developed as *leading questions* that ask the potential survey participant or "respondent" about his/her knowledge of different noise products, materials, and technologies that were found in the literature review.

Budget

Question 5 asks the potential respondent to identify the amount (or percentage) of funds the their organization allocates for noise reduction projects on an annual basis.

Cost Benefit

Question 6 asks if a minimum reduction in decibels (dB) is required before a noise reduction project can be considered for implementation by the respondent's organization.

Attribute

Question 7 asks how important certain attributes are when deciding to implement a noise reduction project. Question 8 asks what attributes are important in deciding against the implementation of a noise reduction measure or project?

Research

Question 9 asks whether the respondent's organization was conducting any research on the effectiveness of new noise reduction products, materials or technologies.

Contact Information

In the event the research team had follow-up questions or needed clarification, each respondent's contact information was requested in Question 10.

3.2 List of Potential Respondents

One of the findings from the literature review was that the work of pavement noise reduction has been primarily done by state transportation agencies, transportation related organizations, universities, and consultants. This is not surprising, especially since the nature of most road and highway work falls under the jurisdiction of state and local governments. This narrows the list of potential respondents from a large sample population to a very small one.

A list of potential survey respondents was created from state transportation organizations, universities with transportation centers, professional associations, and vendors and suppliers of noise reduction products. A list of 77 potential survey respondents was created.

3.3 Preliminary Noise Survey

A preliminary noise survey questionnaire was developed as a Microsoft Word document and then converted to portable document format (pdf). A cover letter and preliminary survey questionnaire was e-mailed to 16 pre-survey respondents on February 24, 2006. The 16 pre-survey respondents were selected from the list of 77 potential survey respondents. A follow up response was sent to non-respondents about three weeks later. The objective of the preliminary survey was to gain feedback/input regarding the survey form itself. Development of a preliminary survey prior to distribution of the full survey allowed the study team to identify ambiguous questions, address formatting issues, and correct possible deficiencies that may have been overlooked.

Each pre-survey respondent was asked to complete the attached preliminary survey questionnaire and provide the study team with comments or other information regarding its content and/or structure. Another objective of the preliminary survey was to validate e-mail addresses and other contact information for the pre-survey respondents.

If the pre-survey respondent had the ability to write to a pdf document, answers to the preliminary survey questions could be made on the document, and emailed back to the study team. If not, the pre-survey respondent was instructed to print a copy of the preliminary survey, complete it and fax or mail it to the study team.

Two pre-survey respondents completed the preliminary pavement noise reduction survey form and five pre-survey respondents provided comments. Each of the five pre-survey respondents indicated that their organizations were not involved in noise reduction research.

3.4 Noise Reduction Survey

Minor changes (mostly editorial or format related) were made to the preliminary pavement noise survey questionnaire based on comments received. The final pavement noise reduction survey was developed and e-mailed to the remaining 61 potential respondents as well as the nine (9) pre-survey respondents who did not respond to the preliminary survey.

The first survey questionnaire was e-mailed on May 5, 2006 and a follow up mailing was sent on May 16, 2006. Due to low response, a third e-mail was sent on June 28, 2006. All non-respondents were called after the third mailing and encouraged to return the survey questionnaire. If the individual was not in the office, a message was left on their voicemail.

Copies of the initial and follow-up cover letters and noise reduction survey questionnaire are shown in Appendix 1.

Section 4

Survey Results

This section provides a summary of the responses received from respondents who completed the noise reduction survey questionnaire.

4.1 Overall Response Rate

Sixteen survey questionnaires were returned from the group of 77 potential respondents. This represents a 20.9% overall response rate for the sample population. Of the 16 surveys that were returned, two surveys were missing significant data. To not skew the data results, these two surveys were eliminated from further analysis. Therefore, the effective sample size for the noise reduction survey is 14 respondents.

4.2 Sample Validation

When a mail survey is conducted, there is no way to ensure that 100 percent of those surveyed will respond to a questionnaire. For the Noise Reduction Survey, an e-mail survey was considered to be the same as a regular postage mail survey. For some surveys, it is necessary to conduct statistical tests to ensure that respondents are representative of the population, that there is a minimum likelihood of response bias, and that the data are reliable. Statistical methods are used to develop these answers. Due to the small sample population (77) and the even smaller effective sample size (14), the data obtained from the Pavement Noise Reduction Survey is statistically indeterminant. However, this in no way implies that the data obtained from the survey is not useful to ADOT or other organizations.

This study utilizes the C*onvenient Survey* methodology to assess respondents' knowledge and familiarity with products, materials, and technologies that are effective in reducing highway noise. A Convenient Survey is very similar to a focus group that solicits opinions about a particular product or service. It is less dependent on the sample size since one of its primary purposes is to acquire knowledge and information related to a particular topic or subject matter. Thus, the results from the 14 respondents in this study are comparable to what a targeted focus group would provide.

4.3 Survey Results

Appendix 2 provides a detailed summary of the survey results.

Section 5

Potential Growth of Noise Reduction Measures

One of the findings of the literature review in Section 2 is the identification of several noise reduction measures that are currently in use or undergoing research. Several European countries have been engaged in pavement and other noise reduction measures associated with roadway traffic since the 1980s or earlier. This comment was noted by several of the respondents in the survey.

The results of the survey are documented in Section 4. Although limited, a few survey respondents identified areas of future research and adoption by State DOTs with regard to traffic noise products, materials, and technologies. In addition, these respondents indicated that a few states such as California and Arizona have been at the forefront in researching noise reduction methods. They noted that it is just recently that some of the other states have begun to consider similar research activities in their transportation plans.

The objective of Task 4 of the Work Plan is to develop an assessment of the expected growth in the acceptability and use of alternative noise reduction products, materials, and technologies. This assessment is based on the findings from the literature review and the survey. Due to the limited response from the survey, the assessment is largely based on findings from the literature review.

5.1 Products

Noise wall barriers or sound walls have dominated this category for traffic noise reduction in the United States, with approximately 165 million square feet of barriers as of 2004. Although this category has shown growth over the years, continued growth of this traffic noise mitigation measure is not expected in the future. The effectiveness of some sound walls has been called into question, and is heavily tied to location and surrounding terrain.

Projected Growth: Replacement and repair of existing sound walls is required as part of routine or ongoing maintenance. Growth in the variety of materials that can be used for sound walls will continue, including the use of recyclable components. Those products that have been tested for sound reduction with satisfactory results and are cost effective will continue to attract users.

Top coats and treatments for sound walls have been studied with mixed results. Further study in this area is recommended for the potential to enhance the effectiveness of existing sound walls. Use of modeling tools to enhance the design of existing and future noise walls is strongly recommended.

5.2 Materials

The noise reducing properties of OGFC, SMA, and HMA are well documented in the literature. OGFC, which has been used in the warmer regions of Arizona, has a number of pavement noise benefits. However, some of the shortcomings of this paving material are that it is not pervious to rainwater, is not porous, and does not perform well in colder climates.

Projected Growth: The FHWA International Scanning Team (IST)[13] provided a number of recommendations for immediate implementation by transportation departments and other organizations following their visit to five European countries in 2005 to review quiet pavement practices. Two recommendations that were cited by the IST for immediate implementation are:

1. Two-layer Porous Mixes – early evaluation results in Europe indicate that TLPA appears to have potential application on high-speed roadways and produces exceptionally quiet pavements. Porous mixes should not be placed in urban areas where the operating speed drops below 72 km/hr (45 mi/h) because highly porous mixes tend to clog under slow traffic.

2. Reduce Aggregate Size – European practices show the aggregate sizes for quiet surfacing mixes are between 0 and 4 mm (0.16 in) up to 0 and 10 mm (0.4 in). Interestingly, most State DOTs use the Superpave aggregate gradings of 19 mm, 12.5 mm, or 9.5 mm (0.76, 0.5, or 0.38 in). Therefore, IST recommends a drop in routine aggregate mix size to the next smallest gradation that could produce noise reductions of 1 to 3 dB.

Since most of the quiet pavement work that has been completed to date in the U.S. has in some way involved FHWA, those states that are just beginning to consider pavement noise reduction projects are expected to seek guidance at the federal level and from other more experienced State DOTs.

The benefits of NGOGFC were cited by TxDOT – good friction, lower noise, and in wet weather: higher visibility, reduced splash and spray, reduced hydroplaning, and reduced nighttime surface glare. ADOT and other State DOTs that are currently using OGFC should also consider NGOGFC. NGOFC contains approximately 20% more asphalt by volume than OGFC and has a minimum of 18% air voids. The void structure of NGOGFC allows the mix to be more permeable and less likely to trap water. NGOGFC appears to last twice as long as conventional OGFC. Although the problem of freezing in colder climates has not been eliminated with NGOGFC, the pavement may hold up better in cooler climates due to its more open graded mixture and thicker placement (1.5 to 2 inches vs. 1-inch for OGFC). NGOFC is 22.5% more expensive than OGFC. However, the benefits and longevity may outweigh the additional costs.

The Netherlands has significant experience with double-layered porous asphalt construction.[11] Double-layer paving material consists of a bottom layer of coarse porous asphalt (single-grained gradation, aggregate size 11 to 16 mm (0.44 to 0.64 in) and a top layer of fine-graded porous asphalt, aggregate size 4 to 8 mm (0.16 to 0.32 in)). Rubberized asphalt is used as the binder in both layers. The double-layer porous mixture may also have applications for colder climates.

Although the extent of testing and application are limited, two materials that deserve more investigation for their noise reducing properties are Italgrip and RCI. Each product has been used with PCC to reduce highway levels. KDOT placed 3 inches of asphalt over a 1 inch RCI layer across an eight-mile stretch of I-435. Noise reduction levels of 7 dB were reported. Italgrip is a very thin surface treatment consisting of a two-part polymer resin placed on the pavement surface and covered with a man-made aggregate of re-worked steel slag 3 to 4 mm (0.12 to 0.16 in) in size. In a cooperative effort with the Highway Innovative Technology Evaluation Center (HITEC), several states with different climatic conditions will test and evaluate the Italgrip System. When available, ADOT should review these tests to further evaluate the effectiveness of this thin surface treatment.

5.3 Technologies

One of the results from the literature review is a list of potential texturing techniques that that may be effective in reducing tire-pavement noise. Another finding is a growing field of techniques that are being studied to impart texture to pavement surfaces. Prior to making a decision on a pavement surface texturing treatment, the percentage of heavy vehicles should be considered in determining overall effectiveness of surface treatments.

Projected Growth: Pavement texturing recommendations cited by the IST[13] are:

1. Thin-textured Surfacings – use of thin-textured surfacings with small aggregate size is recommended for urban or low-speed roadway sections. To achieve noise reduction, texture should always be negative (pavement depressions).

2. Diamond-grinding – investigate and optimize the use of diamond-grinding blade configurations to enhance noise-reducing properties of existing concrete surfaces in sensitive locations.

3. EAC – research the use of EAC for construction of new concrete pavements.

Traditionally, transverse tining has been the most common texture on high-speed roads and highway pavements in the United States. Longitudinal tining has been gaining in acceptability and use and exhibits lower noise characteristics. Pavement design of longitudinal tining (minimum of 25% siliceous sand) is important to improve long-term effectiveness.

Diamond grinding has been traditionally used to rehabilitate existing pavement and to restore smoothness with the unexpected outcome of a quieter pavement. As recommended by Cackler,[16] "only when the texture geometry can be characterized along with the corresponding noise and other pavement surface characteristics will the optimum 'whisper grind' technique be fully realized."

The technique of negatively texturing pavements, the equivalent of making a depression in the pavement, is being perfected. According to Cackler, to move into the low-noise Zone 1, the concrete pavement industry will have to embrace innovative solutions such as increasing porosity, minimizing adverse texture wavelengths, or even modifying mechanical properties, including stiffness. Successful products may include the use of pervious concrete, inclusions, and polymers. Negative textured pavements are probably the only solution in Zone 1. Zone 1 is the low noise level or "innovation" zone, with on-board sound intensity (OBSI) values at about 99 to 100 dBA and below range.

5.4 Other Measures

This report provides many examples of successful applications of traffic noise products, materials, and technologies in the United States and other countries. However, noise or sound reduction cannot be achieved by these measures alone. Effective land use planning is another important component of successful reduction in highway noise. State DOTs should consider encouraging local jurisdictions to enact noise ordinances and land use regulations to guide new, noise-compatible development adjacent to major highways.[19]

Another recommendation from IST is to update current noise policy and traffic noise models to take advantage of the benefits of an integrated approach with other noise mitigation alternatives. As reported at the InterNoise 2003 Conference,[21] transportation officials from The Netherlands were developing several projects under the IPG that focus on an integrated approach - the use of silent roads, improvement of tires and vehicles, optimization of barriers, knowledge management and facilities and assessment methods – to achieve greater noise reduction. A similar approach is strongly encouraged at the State DOT level.

Section 6

Conclusions and Recommendations

This research study was undertaken to compile information on traffic noise reduction products, materials, and technologies that are currently available, and if appropriate to this transportation agency's needs, to assess what could be implemented with reasonable effort. A review of the literature was undertaken. The research quickly identified large volumes of information on traffic noise reduction measures. Traffic noise is defined here as sound from the roadway that is heard as a result of vehicle use.

The regulation of many sources of noise, such as engine noise, blowing horns, noise from residential or commercial buildings, etc. is outside the jurisdiction of a state transportation agency. Most of the focus of this study was traffic noise reduction products such as sound walls and sound wall treatments, as well as pavement noise materials and technologies.

The literature review and noise survey identified measures that are being used by U.S. transportation organizations as well as international efforts. Some key findings from the literature review show the following best practices:

- Traffic Noise Reduction Products – noise or sound walls dominate this category and have been used for decades in the U.S. The effectiveness of sound walls has at times been called into question. Better design parameters are needed to ensure that noise is properly deflected away from receptors. However, existing noise walls have to be maintained and sometimes replaced. Findings from the literature revealed a variety of materials to choose from that are both aesthetically attractive, and effective in reducing noise from highway vehicle use. The cost of installing products will need to be evaluated on a case by case basis with the vendor or for each applicable product.

- Traffic Noise Reduction Materials – The operating speed of the roadway should be factored into the roadway design for quiet pavements. European studies show that higher porous mixtures tend to clog under slower speeds (less than 72 km/hr, 45 mph).

- Two layer-porous mixes have been found to be effective in Europe and the U.S. An important attribute for consideration in two layer-porous mix design and placement is aggregate size. Most State DOTs use the Superpave aggregate gradings of 19 mm, 12.5 mm, or 9.5 mm (0.76, 0.5, or 0.38 in). Current recommendations are to drop the routine aggregate mix size to the next smallest gradation, with an expectation of reducing noise levels 1 to 3 dB.

- Pavement Noise Reduction Technologies - use of thin-textured surfacings with a negative pavement depression are recommended for urban or low-speed roadway sections. Diamond grinding enhances noise reduction on concrete surfaces in sensitive locations.

- Other Pavement Noise Reduction Measures – looking forward, transportation officials are encouraged to develop an integrated approach to roadway noise reduction. Instead of relying on a single measure, the recommended strategy is to develop the ability to model the effectiveness of a number of different measures.

EAC and pervious concrete pavements have been identified as promising innovate concrete solutions. These technologies require further study or specification development before becoming part of paving practices in the United States.

Looking forward, a number of innovative traffic noise research programs are currently underway, both in the United States and Europe. As an example, the Netherlands is developing several silent pavement projects under their Noise Innovation Program. These projects not only focus on pavement materials or texturing techniques, but also improvement of tires and vehicles, knowledge management, and assessment methods. The outcomes of these projects should be documented to determine if they are applicable and cost effective for use on Arizona's highways.

Many State DOTs' noise reduction programs are in their infancy. Those states that have established programs for noise reduction within the last decade (including Arizona) will be sought after for their expertise in the area, including pavement noise reduction.

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Appendix 1

Selected Noise Reduction Survey Documents

PROPHECY

Consulting Group, LLC

February 22, 2006

Dear Transportation Official/Professional:

Prophecy Consulting Group, LLC (PCG), a contractor for the Arizona Department of Transportation (ADOT), is conducting research on pavement noise reduction products, materials, and technologies. One of the tasks for this project is to develop a survey of pavement noise reduction practices. Your agency or firm has been selected to receive a preliminary survey of pavement noise reduction products, materials, and technologies. Your assistance is requested.

PCG is requesting that you:

1. complete the attached preliminary survey, and
2. provide us with additional comments regarding the contents and/or structure of the preliminary survey.

Your comments are very important to us and will be used to develop the final survey on pavement noise reduction products, materials and technologies. If another person in your organization is more knowledgeable of pavement noise reduction practices, please forward the preliminary survey to this individual(s) for completion. Please email your completed survey to us at azdotsurvey@att.net on or before March 2, 2006.

Should you have questions about the preliminary survey, please contact me, Vi Brown, at 480.345.2580 T and vi.brown@att.net E, or my associate, Nelson Moore at 602.980.1247 T and nelmoo@att.net E. Thank you in advance for your time and consideration in completing this request.

Sincerely,

Violette J. Brown

Vi Brown, Principal

cc: Nelson Moore
Tom Kombe, ADOT Project Manager

Knowledge • Vision • Value
480.345.2580 T 480.755.0855 F 480.205.2616 M vi.brown@att.net
2005 S. Henkel Circle Mesa, AZ 85202-6564

PROPHECY

Consulting Group, LLC

May 16, 2006

Dear Transportation Official, Professional, or Researcher:

Recently, I emailed you a survey asking for your knowledge of pavement noise reduction products, materials, and technologies. To date, many valuable replies to the survey have been received - but yours is not among them. If your reply came in while this note was being posted, please consider it a sincere "Thank You!" for your help.

If another person in your organization is more knowledgeable of pavement noise reduction practices, please forward the survey to them for completion. Should you have questions about the survey, please contact me at 480.345.2580 T and vi.brown@att.net E, or my associate, Nelson Moore at 602.980.1247 T and nelmoo@att.net E. Once again, thank you in advance for your time in completing this request.

Sincerely,

Violette J. Brown

Vi Brown
Study Director

(Prophecy Consulting Group, LLC is a contractor for the Arizona Department of Transportation)

Knowledge • Vision • Value
480.345.2580 T 480.755.0855 F 480.205.2616 M vi.brown@att.net
2005 S. Henkel Circle Mesa, AZ 85202-6564

Arizona Department of Transportation
Transportation Research Center

Pavement Noise Reduction Survey

1. How Familiar are you with the following Sound Abatement Products, Materials or Technologies?

	Don't Know	Not Familiar	Somewhat Familiar	Familiar	Very Familiar	Extremely Familiar
Pavement Alterations						
- Dense grade asphalt						
- Rubberized pavement						
- Portland cement concrete						
- Other						
Traffic Noise Barriers						
- Sound Absorbing Noise Walls						
- Earth Mounds or Berms						
- Other						
Traffic Noise Barriers Treatment & Coatings						
- Crumb rubber						
- Innovative noise barrier design						
- Other						
Receptor Controls						
- Land Use Planning						
- Window Treatments						
- Other						

2. How effective are the following Products, Materials, or Technologies in reducing pavement and traffic noise?

	Don't Know	Not Effective	Somewhat Effective	Effective	Very Effective	Extremely -Effective
Pavement Alterations						
- Dense grade asphalt						
- Rubberized pavement						
- Portland cement concrete						
- Other						
Traffic Noise Barriers						
- Sound Absorbing Noise Walls						
- Earth Mounds or Berms						
- Other						
Traffic Noise Barriers Treatment & Coatings						
- Crumb rubber						
- Innovative noise barrier design						
- Other						
Receptor Controls						
- Land Use Planning						
- Window Treatments						
- Other						

3. If you are familiar with the following brands or products listed below, how would you rank their effectiveness in reducing highway pavement noise?

	Don't Know	Not Effective	Somewhat Effective	Effective	Very Effective	Extremely Effective
Products						
SoundSorb	☐	☐	☐	☐	☐	☐
Whisper Wall	☐	☐	☐	☐	☐	☐
Quilite Walls	☐	☐	☐	☐	☐	☐
Carsonite Sound Barrier System	☐	☐	☐	☐	☐	☐
Paraglas Sound Stop	☐	☐	☐	☐	☐	☐
AcoustaCrete	☐	☐	☐	☐	☐	☐
Crumb Rubber Coatings	☐	☐	☐	☐	☐	☐
Top Treatment (for sound barriers)	☐	☐	☐	☐	☐	☐
NOISHIELD	☐	☐	☐	☐	☐	☐
Starkustic	☐	☐	☐	☐	☐	☐
Soundblox	☐	☐	☐	☐	☐	☐
Broad Band Sound Absorber	☐	☐	☐	☐	☐	☐
Perma Delta Sound Barrier	☐	☐	☐	☐	☐	☐
Coustivew	☐	☐	☐	☐	☐	☐
Materials						
Porous Friction Course (PFC)	☐	☐	☐	☐	☐	☐
Dense Graded Hot Mix Asphalt surfaces (DGAC)	☐	☐	☐	☐	☐	☐
Stone-Matrix Asphalt Concrete(OGAC)	☐	☐	☐	☐	☐	☐
Street absorbing Membrane Interlayer	☐	☐	☐	☐	☐	☐
Portland Cement Concrete	☐	☐	☐	☐	☐	☐
Technologies						
Hot Mix Asphalt	☐	☐	☐	☐	☐	☐
Surface Texturing	☐	☐	☐	☐	☐	☐
Bonding Road	☐	☐	☐	☐	☐	☐
Modieslab	☐	☐	☐	☐	☐	☐

4. Do you know other noise reduction Products, Materials, or Technologies not listed above? Please list their names below.

Materials:	Products:	Technologies:

5. On the average, what percentage of your highway budget is allocated for noise reduction measures in highway projects?

____ Percent of Budget (on the average)

6. Does your Agency require a "noise benefit factor" before implementing sound reduction measures? Example, a noise benefit of three (3) decibels is required before implementing sound reduction measures in a highway project.

☐ Yes ☐ No ☐ Varies by Project

7. How important are the following in considering and implementing sound abatement measures in your highway projects:

	Not Important	Somewhat Important	Important	Very Important	Extremely Important
Cost Effectiveness	☐	☐	☐	☐	☐
Technology Maturity	☐	☐	☐	☐	☐
Durability	☐	☐	☐	☐	☐
Low Cost and Convenience in Installation	☐	☐	☐	☐	☐
Low Cost, Convenience in Maintenance & Repair	☐	☐	☐	☐	☐
Aesthetics	☐	☐	☐	☐	☐

8. When it come to your agency NOT using hot mix asphalt and other Technologies to abate traffic noise, how important are:

	Not Important	Somewhat Important	Important	Very Important	Extremely Important
Cost effectiveness	☐	☐	☐	☐	☐
Technology Maturity	☐	☐	☐	☐	☐
Durability	☐	☐	☐	☐	☐
Low Cost and Convenience in installation	☐	☐	☐	☐	☐
Low cost and Convenience in Maintenance and repair	☐	☐	☐	☐	☐
Federal Guidelines No QPPP approved	☐	☐	☐	☐	☐
More Research and Testing needed	☐	☐	☐	☐	☐

9. Is your Agency currently conducting research or studying the effectiveness of new noise reduction Products, Materials or Technologies?

☐ No ☐ Yes if yes, List names of Materials: ______

List names of Products: ______

List names of Technologies: ______

10. May we contact you in the future, concerning noise reduction, Products, Materials or Technologies?

Name of Organization: ______

Contact Person: ______

Phone Number: ______

Email Address: ______

Thank you very much for your time and consideration in this project.

Please send completed survey to AZDOTSURVEY@ATT.NET

Appendix 2

Noise Reduction Survey Resposes

ADOT Transportation Research Center

Figure A2-1: Noise Reduction Survey
Summary of Responses

1. How familiar are you with the following Sound Abatement Products, Materials or Technologies?

	Don't Know	Not Familiar	Somewhat Familiar	Familiar	Very Familiar	Extremely Familiar
Pavement Alternatives						
- Dense grade asphalt	1	2	0	8	2	1
- Rubberized pavement	0	2	5	3	4	0
- Portland cement concrete	0	0	4	4	6	0
- Other	7	1	3	3	0	0
Traffic Noise Barriers						
- Sound Absorbing Noise Walls	0	0	1	6	5	2
- Earth Mounds or Berms	0	0	0	7	5	2
- Other	8	3	1	1	1	0
Traffic Noise Barrier Treatment & Coatings						
- Crumb rubber	0	6	4	1	2	1
- Innovative noise barrier design	1	4	4	3	2	0
- Other	8	3	1	1	1	0
Receptor Controls						
- Land Use Planning	0	0	8	1	3	2
- Window Treatments	0	4	7	2	1	0
- Other	8	4	0	2	0	0

2. How effective are the following Products, Materials, or Technologies in reducing pavement and traffic noise?

	Don't Know	Not Effective	Somewhat Effective	Effective	Very Effective	Extremely Effective
Pavement Alternatives						
- Dense grade asphalt	1	2	1	7	2	1
- Rubberized pavement	0	1	7	4	1	1
- Portland cement concrete	1	1	4	6	2	0
- Other	7	3	2	0	1	1
Traffic Noise Barriers						
- Sound Absorbing Noise Walls	2	2	2	6	1	1
- Earth Mounds or Berms	1	1	3	4	1	4
- Other	8	3	2	0	1	0

Traffic Noise Barrier Treatments & Coatings						
- Crumb rubber	6	0	1	6	0	1
- Innovative noise barrier design	1	4	1	2	6	0
- Other	8	5	0	0	0	1
Receptor Controls						
- Land Use Planning	1	0	6	3	1	3
- Window Treatments	1	3	7	3	0	0
- Other	2	6	4	0	1	1

3. If you are familiar with the following brands or products listed below, how would you rank their effectiveness in reducing highway pavement noise?

	Don't Know	Not Effective	Somewhat Effective	Effective	Very Effective	Extremely Effective
Products						
SoundSorb	8	0	0	4	0	0
Whisper Wall	10	0	1	1	0	0
Quilite Walls	11	0	1	0	0	0
Carsonite Sound Barrier System	8	0	1	2	1	0
Paraglas Sound Stop	9	0	0	3	0	0
AcoustaCrete	10	1	0	1	0	0
Crumb Rubber Coatings	9	0	1	2	0	0
Top Treatment (for sound barriers)	11	0	1	0	0	0
NOISHIELD	12	0	0	0	0	0
Starkustic	12	0	0	0	0	0
Soundblox	10	0	1	1	0	0
Broad Band Sound Absorber	11	0	0	0	1	0
Perma Delta Sound Barrier	12	0	0	0	0	0
Coustiview	12	0	0	0	0	0
Materials						
Porous Friction Course	2	0	3	4	2	2
Dense Graded Hot Mix Asphalt	2	1	7	2	1	0
Stone-Matrix Asphalt Concrete	5	1	2	3	2	0
Street Absorbing Membrane Interlayer	10	0	0	2	0	0
Portland Cement Concrete	2	4	3	3	1	0
Technologies						
Hot Mix Asphalt	3	2	5	0	2	1
Surface Texturing	3	0	3	4	2	1
Bonding Road	11	0	2	0	0	0
Modieslab	12	0	0	1	0	0

4. Do you know other noise reduction Products, Materials, or Technologies not listed above? Please list their names below.

	Products	Materials	Technologies
Other 1	Durisol Evergreen Wall Nova Chip	Precast Concrete	Planting buffers Recycled plastic
Other 2	Hoover Wall (wood)	No response	Site design
Other 3	No response	No response	No response

5. On the average, what percentage of your highway budget is allocated for noise reduction measures in highway projects? 10 respondents reported a range of 1 to 5% (average of 2.1%) of their highway budget is allocated for noise reduction measures.

6. Does your Agency require a "noise benefit factor" before implementing sound reduction measures? Example, a noise benefit of three (3) decibels is required before implementing sound reduction measures in a highway project.

10 respondents said "Yes", 1 respondent said "No", and 2 respondents said it "Varies by Project"

7. How important are the following in considering and implementing sound abatement measures in your highway projects:

	Not Important	Somewhat Important	Important	Very Important	Extremely Important
Cost Effectiveness	0	0	0	11	3
Technology Maturity	0	1	6	4	3
Durability	0	0	2	6	6
Low Cost and Convenience in Installation	0	5	3	5	1
Low Cost, Convenience in Maintenance & Repair	0	4	3	5	2
Aesthetics	0	0	9	5	0

8. When it come to your agency NOT using hot mix asphalt and other Technologies to abate traffic noise, how important are:

	Not Important	Somewhat Important	Important	Very Important	Extremely Important
Cost Effectiveness	1	0	4	5	2
Technology Maturity	1	1	4	4	2
Durability	1	0	2	8	1
Low Cost and Convenience in Installation	1	3	2	5	1
Low Cost and Convenience in Maintenance & Repair	1	2	4	4	1
Federal Guidelines (not QPPP approved)	4	0	4	2	1
More Research and Testing Needed	0	2	5	2	3

9. Is your Agency currently conducting research or studying the effectiveness of new noise reduction Products, Materials or Technologies?

13 respondents said: No = 5, Yes = 8, No Response = 1

If yes, list:

	Products	Materials	Technologies
Item 1:	Durisol Sound Absorptive - 1 Nova Chip - 1	Rubberized pavement - 1	Texturing - 2 OBSI* - 1
Item 2:			
Item 3:		Pavement types - 1	

*OBSI – On board sound intensity (for noise measurement)

10. May we contact you in the future, concerning noise reduction, Products, Materials or Technologies?

Name of Organization: ____________________

Contact Person: ____________________

Phone Number: ____________________

Email Address: ____________________

Thank you very much for your time and consideration in assisting us with this project.

A discussion of the Pavement Noise Reduction Survey is presented in this appendix. A summary of the responses to the Pavement Noise Survey questionnaire is provided in Figure A4-1.

A.2.1 Knowledge of Products, Materials, or Technology

Question 1: How familiar are you with the following Sound Abatement Products, Materials or Technologies?

Most of the respondents reported being somewhat to extremely familiar with each pavement noise reduction product, material or technology listed under Question 1.

The most responses were reported for:

- Pavement Alternatives: Dense grade asphalt – 8 Familiar (57.1%)
- Traffic Noise Barriers: Earth mounds or berms – 7 Familiar (50.0%)
- Receptor Controls: Land use planning – 8 Somewhat Familiar (57.1%)
- Receptor Controls: Window treatments – 7 Somewhat Familiar (57.1%)

No additional responses were provided for "Other" pavement alternatives, traffic noise barriers, traffic noise barrier treatment and coatings, or receptor controls.

Question 2: How effective are the following Products, Materials, or Technologies in reducing pavement and traffic noise?

Respondents were asked to identify the effectiveness of each noise reducing product, material, or technologies listed:

- Pavement Alterations:
  - Dense grade asphalt – 7 Effective (50.0%)
  - Rubberized pavement – 7 Somewhat Effective (50%)
- Traffic Noise Barriers: Sound absorbing noise walls – 6 Effective (42.9%)

  Additional Comments: TxDOT has only used absorptive treatment on an experimental basis. The research work focused on construction techniques rather than acoustical properties. TxDOT has rarely considered/used earth mounds/berms due to insufficient right-of-way for construction.

- Traffic Noise Barrier Treatment and Coatings:
  - Crumb rubber – 6 Don't Know (42.9%) and 6 Not Effective (42.9%),
- Receptor Controls: Window Treatments – 7 Somewhat Effective (50%)

  Additional Comments: TxDOT has developed a comprehensive presentation on "Noise Compatible Land Use Planning."

No additional responses were provided for "Other" pavement alternatives, traffic noise barriers, traffic noise barrier treatments and coatings, or receptor controls.

<u>Question 3: If you are familiar with the following brands or products listed below, how would you rank their effectiveness in reducing highway pavement noise?</u>

A list of some of the pavement noise reducing products, materials or technologies identified in the literature review were included in this question. Not surprisingly, most respondents checked "Don't Know" for the list of products. Four (28.6%) of the respondents indicated that the noise barrier product, *SoundSorb*, is somewhat Effective.

For the Materials listed, 7 (50%) identified dense graded hot mix asphalt (DGAC) as "Somewhat Effective" at reducing pavement noise, and 10 respondents (71.4%) chose "Don't Know" when asked about the effectiveness of a street absorbing membrane interlayer.

Although HMA is considered a paving material, it is also included as a technology due to the process used to place the pavement. Five (5) respondents identified HMA as "Somewhat Effective" as a pavement noise reduction technology.

<u>Question 4: Do you know other noise reduction Products, Materials, or Technologies not listed above? Please list their names below.</u>

When asked about the respondent's knowledge of other pavement noise reduction products, materials, or technologies that were not listed in Questions 1 to 3, only three of 14 respondents provided additional information. Some items provided by the respondents are improperly categorized, e.g. planting buffers and site design are not technologies, however, these responses are included in information reported in the literature review

Question 5: On average, what percentage of your highway budget is allocated for noise reduction measures in highway projects?

Eleven (78.6%) of the 14 respondents reported that 1 to 5% (average of 2.1% for survey) of their department's budget is allocated for noise reduction activities (see Figure A4-2).

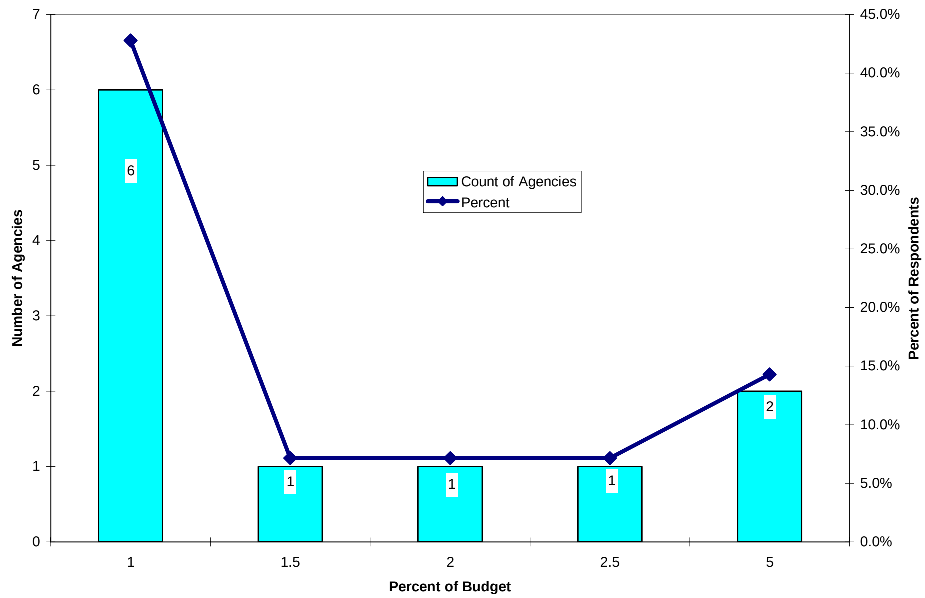


Figure A2-2: State DOT Departments and Percent of Budget Allocated For Highway Noise Reduction Measures

Question 6: Does your agency require a "noise benefit factor" before implementing sound reduction measures? Example, a noise benefit of three (3) decibels is required before implementing sound reduction measures in a highway project.

This question was designed to assist the study team in understanding if a transportation agency uses specific criteria to identify benefits of a pavement noise reduction measure(s) prior to making a decision to include the measure(s) in a highway project.

- Ten (71.4%) of the respondents answered "Yes" to this question.
- One (7.1%) respondent answered "No".
- Two (14.3%) respondents indicated that the noise benefit factor varied by project.

A total of 13 (92.9%) respondents provided an answer to this question.

Question 7: How important are the following in considering and implementing sound abatement measures in your highway projects?

A list of six attributes was provided and the respondent was asked to identify how important each one is in the decision making process to pursue a noise reduction project or include it as a part of a project.

Eleven (78.6%) of the respondents indicated that cost effectiveness is "Very Important" in the decision making process, and the remainder of the three respondents (21.4%) said that cost effectiveness is "Extremely Important."

Thirteen (92.9%) of the respondents rated technology maturity as Important or higher, while all respondents (100%) considered aesthetic appearances as Important or higher.

Question 8: When it comes to your agency NOT using hot mix asphalt and other Technologies to abate traffic noise, how important are:

- Cost effectiveness?
- Technology maturity?
- Durability?
- Low cost and convenience in installation?
- Federal guidelines (not QPPP approved)?
- More research and testing needed?

Question 8 is seeking to identify which attributes are important in deciding not to select a noise abatement measure. The majority of the respondents considered each attribute listed to be "Important" to "Very Important".

Question 9: Is your Agency currently conducting research or studying the effectiveness of new noise reduction Products, Materials or Technologies?

Thirteen respondents answered this question (see Figure A4-3). Eight (61.5%) reported that their agency or organization is conducting research on new noise reduction products, materials or technologies.

The following items are being researched by some agencies:

- Products
  - Durisol Sound Absorptive Wall
- Materials
  - Nova Chip (Note: This item was originally reported under Products.)
  - Rubberized pavement
  - Different pavement types
- Technologies
  - Texturing
  - On board sound intensity (for noise measurement)

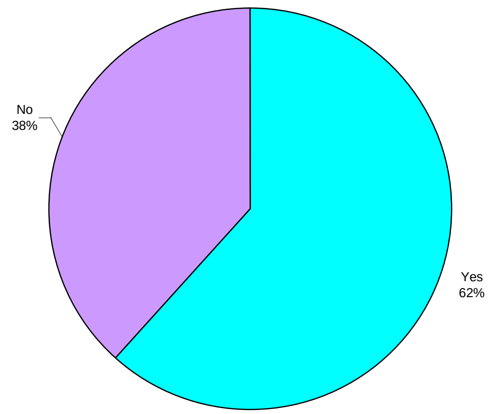


Figure A2-3: State DOT Departments Currently Conducting
Highway Noise Reduction Research

Additional Comments: TxDOT is currently in a research project to investigate the acoustical properties of various pavement types. We are working with several other state highway agencies in a cooperative effort to collect related data. The emphasis of the research is on existing pavements with the expectation that new products, materials, and technologies will be considered in the future.

Question 10: May we contact you in the future, concerning noise reduction, Products, Materials or Technologies?

Each respondent was asked to provide contact information in the event the research team needed additional information.

Appendix 3
A Sampling of Traffic Noise Reduction Products

A3-1. The Sound Barrier™ by Carsonite

The Sound Barrier™ System from Carsonite is designed for use along highways, mass transit lines, crowded residential roads and other high-traffic areas where noise is a concern. It features tongue and groove, modular sections made from fiberglass-reinforced polymer composite that are *filled with ground, recycled tire waste*. A ten-foot high, one-mile long Carsonite Sound Barrier™ consumes up to 211,000 pounds of scrap tires or about 20,800 tires. The scrap rubber used in Carsonite's Sound Barrier™ is taken from breakdown plants already in operation. Other products made from scrap tires stay in the waste stream, while Carsonite's solution removes scrap tires from the waste stream entirely.

Sound Reduction: Carsonite's Sound Barrier™ System is superior in sound reduction than conventional sound walls. When tested by Riverbank Acoustical Laboratories, the Sound Barrier™ System registered a STC of 36. This high sound transmission rating means sound levels behind the Sound Barrier™ System are significantly reduced. The Sound Barrier™ also reduces noise on its facing side. The system exceeds guidelines set for NRC and wind loads required by the AASHTO and State DOTs. It registered an NRC of 0.15 on its traffic facing side, which is more sound absorptive than concrete and significantly better than wood.

Physical Properties*:

		ASTM
Flex Strength	75,000 psi	D790
Tensile Strength	75,000 psi	D638
Compressive Strength	60,000 psi	D695
Tensile Modulus	4,300,000 psi	D638
Specific Gravity	1.88 (typ)	D792

*These properties are valid over a temperature range of -40° to +140°F

Applications: Noise reduction along highways, mass transit lines, residential roads, and other high traffic areas. Carsonite Sound Barrier™ was commercialized in 1994 and has been installed in 14 states.

Installation: The Carsonite Sound Barrier™ is lightweight and can be easily installed using a simple post and foundation design – no heavy crane is required. The modules measure up to 15 ft. wide and 6 ft. high each and are stacked on top of each other to attain the desired height. The ends are anchored in "H" shaped steel or concrete supports set into the ground. Because the Sound Barrier™ sections weigh only 7.5 pounds per square foot (PSF), no heavy crane is required for installation. This provides a significant advantage when install-ing the sound barrier on a busy roadway, because less traffic lanes need to be closed to accommodate heavy lifting equipment. And fewer installers are required. The product is available in heights of up to 28 ft. and can be manufactured in any color or color combinations.

Other Attributes: The Sound Barrier™ sections are manufactured by Carsonite using a pultrusion process which provides a strong and durable wall. The composite fiberglass material has been used for decades worldwide in demanding, outdoor applications and offers a number of key advantages over conventional sound wall materials:

- Withstands harsh weather conditions — no peeling or rotting,
- Will not corrode from chemicals or salt,
- Protected by ultra-violet (UV) inhibitors to prevent solar degradation,
- Fire resistant - classified as a Class 1 Building Material (as defined by the Uniform Building Code) suitable for indoor construction,
- Tensile and compressive strength of over 60,000 pounds per square inch (PSI).

Company Information: Carsonite International
Mailing Address: 605 Bob Gifford Boulevard
Early Branch, SC 29916
1.800.648.7916 T
http://www.carsonite.com/index.html

A3-2. SoundSorb® Licensed by Concrete Solutions, Inc.

SoundSorb® is a pre-approved precast concrete noise barrier system consisting of composite panels with sound-absorptive, cementitious material using lightweight aggregate, cement and propriety ingredients. It is an acoustic material that integrates with concrete. It is produced with patented mixing methods using cement and specific proprietary ingredients. Licensed by Concrete Solutions, Inc. (CSI), SoundSorb® provides a cost effective solution to traffic noise because it absorbs sound energy rather than reflecting it. CSI defines the uniqueness behind the product as “CSI does not make the soundwall, it makes the soundwall better” by offering a high quality sound absorptive finish along with a low cost architectural colorized texture.

SoundSorb® is designed to eliminate the refection of noise from tire and rail sounds within a frequency range of 400 to 1250 Hz. Since SoundSorb is a wet-cast product, it is easily integrated into many unique, cost-effective concrete wall designs. The products unique molding characteristics allow it to be used with almost all sizes, designs, textures, molds and colors, including customized projects.

Acoustical performance can be further enhanced by adding a textured or molded surface. This durable material is wet cast during the precast production and is integrated with the structural portion of the panel to become an AASHTO compliant barrier system with excellent sound absorptive qualities.

Sound Reduction: The sound level reduction properties of SoundSorb® have been measured using sound absorption lab test and NRC values. An average of four Hz frequency readings (250, 500, 1000, and 2000) are required with an optimal NRC value described as NRC = 1.0.

Acoustical Properties of SoundSorb®

Frequency (Hz)	125	250	500	1000	2000	4000	VALUES
ASTM C-423	0.23	0.60	1.25	0.97	0.95	0.96	NRC 0.95
ASTM E-90	39	40	45	51	58	59	STC 51

(E-90 test was done with 3 in. SoundSorb® and 2.5 in. of concrete structural backing)

SoundSorb® reaches this optimal level at a thickness of 3.5 in.

SoundSorb® ASTM C-423 NRC Ratings
Tested at a thickness of 3.5 in. = NRC 1.00
Tested at a thickness of 3.0 in. = NRC 0.95
Tested at a thickness of 2.5 in. = NRC 0.85
Tested at a thickness of 2.0 in. = NRC 0.80

Physical Properties: Absorptive Material Physical Characteristics:

- Material composition: porous, cementitious material manufactured as a wet precast product according to CSI specifications
- Weight of acoustical material: 38 - 45 pounds per cubic feet (PCF) per CSI specification and project requirements.
- Texture: a variety of textured surfaces can be provided for this sound-absorptive material.
- Weatherability: material is durable under extreme weather conditions and resists rotting, mold and mildew, rusting, and warping. Proper drainage is required at the base of the panel.

Licensed manufacturer: SoundSorb® can be produced only by a licensed manufacturer.

Applications: SoundSorb® products have been installed in the U.S., Australia, China, and Japan. Typical usage for noise abatement include all modes of transportation and industrial noise reduction, as well as commercial, residential, aviation, cooling tower, emergency generator station and generator noise. In 2003, the California DOT granted its approval of SoundSorb® for the product's use on state highway projects.

Installation: SoundSorb® can be integrated into full-size or stackable panels for easy installation. Walls and barriers do not need to be shipped long distances. Precast companies are licensed on a state or regional basis, thereby using local labor to manufacture and erect walls. Panels are installed per manufacturer's instructions. Panels are sized to suit project/site conditions. The panels vary from 24 to 72 in. in height as stackable panels but can be poured monolithically to any size requirement and up to 20 ft. in length.

Company Information: Concrete Solutions, Inc. (CSI)
Mailing Address: 3300 Bee Cave Road, Suite 650
Austin, Texas 78746
512.327.8481 T
www.soundsorb.com

A3-3. Sound Absorptive Noise Barrier by Durisol

Durisol is a proprietary material that only uses natural ingredients, is composed of specially graded raw wood shavings and chips, which are neutralized and mineralized, then bonded together with PCC. The material is very durable, particularly in harsh environments, is light weight, thermally insulating, non-combustible and sound-absorptive. It can be molded to suit any desired shape, texture and thickness.

The Durisol material was first developed in Switzerland in the 1940s. A unique chemical treatment for the wood shavings was discovered to bind wood shavings with ordinary PCC. Durisol Materials Limited obtained Canadian and US patents for the Noise Barrier Wall System in 1981.

Noise Reduction: A standard Durisol noise wall is sound absorptive on both sides: NRC from 0.70 to 0.90 depending on texture and design. The Durisol Noise Barrier System is designed to meet all State or Provincial Highway Bridge Design Codes, AASHTO, CHBDC, ASTM, CSA, etc. The product meets all requirements of CSA Z107.9 Standard for Certification of Noise Barriers and adheres to the guidelines for acceptance as outlined in the FHWA Highway Noise Barrier Design Handbook. All manufacturing is carried out under ISO 9002 Standards. Testing for structural integrity, acoustic performance, durability, (such as freeze-thaw, salt scaling, weatherometer and fire), are performed on a regular basis. Reports are available upon request.

Physical Properties: General Properties: sound absorptive, high strength to weight ratio, non-combustible, lightweight, dimensionally stable, negligible capillary suction, thermally insulating, highly resistant to freeze thaw and deicing salts.

Applications: Durisol absorptive noise walls have been used for numerous applications such as highways, rail lines, mass transit lines, industrial and commercial complexes, residential subdivisions, electric utility stations, transformer enclosures, roof top machinery surrounds and tunnel entrances.

Material Properties:

Property	**Units**	**Value**	**Specification**
Dry Density	kg/m^3	600	-
Wet Density	kg/m^3	850	-
Modulus of Rupture	MPa	1.0	ASTM C293
Compressive Strength, ultimate	MPa	2.0	ASTM C513
Modulus of Elasticity	MPa	1,500	ASTM C513
Freeze-Thaw	Cycles	300	ASTM C666 A&B
Salt Scaling	Rating	0	ASTM C672
Weatherometer	Hours	2.400	ASTM G26
Noise Absorption	NRC	0.7 to 0.9	ASTM C423
Flame Spread	Index	0	ASTM E84
Smoke Developed	Index	9	ASTM E84
Thermal Conductivity	$W/(m\text{-}^oK)$	0.083	ASTM C177
Termite Attack	-	Resistant	-
Fungus Growth	_	Resistant	-

Panel Properties:

Property	Units	Value	Specification
Thickness	mm	130 to 250	-
Sound Transmission Class	STC	35 to 50	ASTM E90
Base Concrete Core	MPa	35	ASTM C39
Mass	kg/m	100 to 400	-
Span	m	7.5 m (max)	-

Installation: The first Durisol sound absorptive noise barrier was installed in Toronto, Canada, in 1977 and is still in service today. In 1987, Durisol supplied the first US based sound absorptive noise barrier to the State of Pennsylvania. Today, Durisol noise barriers can be seen in many provinces and states all over North America. Internationally, Durisol noise barriers can be found in Asia, Europe and the Middle East. Over 12 million sq. ft. of wall has been installed throughout North America. The Durisol Noise Barrier System is essentially a post and panel system.

Durisol installed a transparent noise barrier for Alaska DOT on a heavily traveled highway in the Anchorage area. The noise barrier runs approximately 4,000 feet with heights of 10 to 17 ft. Alaska DOT initially proposed a translucent sound absorptive structure with an NRC of 0.6 and provide a minimum of 80% light transmission. The solution: a wall incorporating solid Durisol panels along the bottom to absorb sound and transparent PARAGLAS SOUNDSTOP panels along the top. The Durisol panels gave the wall an NRC of 0.8 to 0.85, exceeding the Alaska DOT specifications.

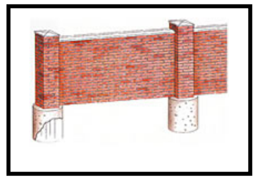
Company Information: Durisol USA, Inc.
8270 Greensboro Drive, Suite 630
McLean, VA, USA 22102
866-801-0999 T
www.durisol.com

A3-4. Masonry Sound Barriers by Advanced Masonry Technology

Advanced Masonry Technology's (AMT) prefabricated masonry sound/privacy barrier system solves two problems at once. It diverts traffic noise away from adjoining residential and commercial properties while providing an aesthetically pleasing addition to the landscape. Custom designs can be achieved through the use of AMT's prefabricated masonry barrier walls.

Custom built sound/privacy barriers are designed to coordinate with the colors, texture and patterns in the surrounding elements and landscape to create an overall harmonious look. A finished coping or sill treatment along the top edge of the wall also helps to simplify, rather than complicate, the corridor vision.

Prefabricated masonry barriers not only provide low maintenance and cost savings, they will not rust, splinter, or deteriorate and do not require additional color coatings. Prefabricated masonry privacy walls are visually elegant as well as offering security. The company is listed as an approved vendor by the Ohio DOT.



Company Information: Advanced Masonry Technology
2786 Center Rd
Brunswick, Ohio 44212
330.225.9496 T
www.advancedmasonrytechnology.com

A3-5. Fencestone® by Designer Concrete Fences

Designer Concrete Fences markets precast concrete fencing and wall systems nationwide. Their concrete fence products were developed in 1982, and trademarked as Woodcrete®, Fencestone®, Brickcrete® and Cedarcrete®, were designed to withstand deterioration related to termites and weather conditions. The precast concrete fences are designed to appear as if they are made of natural stone, crafted wood or weathered brick and should the fences be damaged by collision, they are easy and inexpensive to repair.

The concrete wall or fence products consist of professionally engineered, precision-manufactured, steel-reinforced modular concrete components that interlock during the installation process. During the manufacturing process permanent color is added to the wet concrete mix to assure that future painting will not be necessary. However, the fences can be stained or painted at a later date as a design feature.

With manufacturing locations around the country, Designer Concrete Fences is able to deliver quality products competitively and with minimum freight cost. The vendor provides customers with materials only or both materials and installation for fences and walls from 1 to 12 ft. high.

Fencestone®, the most appropriate product for a noise barrier or wall, provides the beauty of a dry-stacked ledgestone wall without the expense. Panels and posts have the same texture on both sides, providing a pleasing view for both homeowners and drivers.

Sound Reduction: For a noise barrier constructed on top of a half-mile-long berm adjacent to Interstate 75 in Naples, FL, the 18 ft. tall maintenance free wall is reported to reduce traffic noise by a minimum of 34 dB at 80 Hz.

Applications: The concrete fence products are used as screen walls, sound barriers, privacy fencing and ranch rail fencing. They are repeatedly specified by architects and developers, government agencies, community associations and individual homeowners.

Installation: Fencestone® posts are installed every 5 ft. on center in the ground. The "I" shaped posts are aligned, leveled and anchored in a concrete footing similar to other types of fence posts. The depth of the post foundations vary with soil conditions, wind loads and wall height. Once the foundation has an initial cure (typically 24 hrs), concrete panels are inserted into and down the track on either side of the post meeting in a tongue and groove interlock. Additional panels stack in place in 1-ft increments until the desired fence height is achieved. The post foundation supports the panel sections. Attaching the concrete panel cap to the top panel (and optional post cap with Fencestone®) completes the fence installation.

Company Information: Designer Concrete Fences
4925 Sepulveda Boulevard
Sherman Oaks, CA 91403
818.990.3362 T
www.designerconcrete.com

A3-6. AccoustaCrete Sound Absorptive Noise Barriers

AcoustaCrete from Faddis is a durable concrete sound-absorptive wall system designed to eliminate sound reflections from single walls and reverberations between opposing parallel walls. The product is available in single-sided or double-sided sound absorptive Stonewall Series panels or as a sound absorptive single slope barrier for rail and transit applications. The recommended ashlar and oversize-brick patterns are rugged and durable. The reverse side of the panel receives an impressed ashlar stone or brick pattern and can also be made with sound-absorptive material.

AcoustaCrete is manufactured as a monolithic concrete panel based upon the Faddis Stonewall Series. Faddis casts 16, 20 and 24 ft. wide AcoustaCrete panels at their New Castle or Downingtown, PA plants. The durable material is resistant to damage from freeze-thaw cycles and abrasion along roadways carrying high-speed traffic. Acrylic coatings provide architectural color that is durable and is an economical anti-graffiti system. Faddis can cast AcoustaCrete with integral color if required.

Sound Reduction: AcoustaCrete Sound Absorptive Concrete has an NRC between 0.8 to 1.0.

	ASTM C-423 SOUND ABSORPTION COEFFICIENTS AcoustaCrete Thickness		
Frequency, Hz	3.5 in.	3.0 in.	2.5 in.
250	0.87	0.72	0.61
500	1.23	1.10	0.97
1,000	1.04	1.10	0.99
2,000	1.02	0.96	0.87
NRC	1.05	0.95	0.85

Applications: Applications for AcoustaCrete include highway, rail and airport noise barriers airport jet blast barriers, security fencing ballistic and obscuration screens, and industrial noise barriers.

Company Information: Faddis Concrete Products
3515 Kings Highway
Downingtown, PA 19335
610.269,4685 T
www.faddis.com

A3-7. AcoustaX Sound Absorptive Noise Barriers

AcoustaX is an ultra-lightweight aluminum sound-absorptive noise barrier for mounting on structures such as retaining walls and bridges. With a weight of approximately 4 PSF and an NRC of 1.0, it can be used on a number of structures and with limited-structural support to absorb sound and provide enough sound transmission loss to keep sound from passing through the wall. A variety of perforated patterns can be produced, providing interesting architectural looks.

A super durable aliphatic urethane polyester graffiti resistant powder coating has especially been formulated for AcoustaX by Dupont. The powder coating is applied after perforating and prior to assembly.

Sound Reduction: AcoustaX absorbs a broad frequency spectrum and prevents noise transmission though the barrier:

	ASTM C-423 Sound Absorption Panel Thickness (in)	ASTM E-90 Transmission Loss Panel Thickness
	3.5	3.0
Frequency, Hz		
125	0.45	20
250	1.03	26
500	1.13	36
1000	1.02	48
2000	1.00	55
NRC	1.05	39 (Steel) ~ 34 (Aluminum)

Applications: Applications for AcoustaX include highway, rail and airport noise barriers airport jet blast barriers, security fencing ballistic and obscuration screens, and industrial noise barriers.

Company Information: Faddis Concrete Products
3515 Kings Highway
Downingtown, PA 19335
610 269 4685 T
www.faddis.com

A3-8. Absorptive Soundwalls by Pre-Stress Engineering

Prestress Engineering's Whisper Wall™ Sound Absorbing Noise Wall System is composed of recycled rubber-tire chips, specialized aggregates, additives, and cement. The mixture is compressed in forms with specialized liners. The functional use of recycled rubber chips in the sound absorbing mixture contributes to the Whisper Wall™ improved sound absorption and increased durability. A typical Whisper Wall™ Noise Abatement Panel is eight (8) inches thick, consisting of four (4) inches of sound absorptive material and four (4) inches of structural, 5000 psi, normal weight concrete. The recycled rubber chips in the mixture contribute to the wall's improved sound absorption and increased durability.

Over 7,000,000 SF of wall has been in service for 12 years. To date, no panels have been replaced due to deterioration. Prolonged exposure to moisture does not affect performance or durability. Due to the internal void structure and use of specialized aggregates, the sound absorbing mixture will not trap or wick moisture, water drains freely. Furthermore, Whisper Wall™ is insect resistant. The raw materials used in the sound absorbing mixture are not consumable by insects.

In addition, the use of recycled rubber tire chips has a positive environmental impact. A typical 8 ft. x 20 ft. Whisper Wall™ panel utilizes approximately 35 tires. On a larger scale, a 100,000 SF wall would utilize 481,250 lbs. of rubber waste, or 21,875 tires. Consequently, Whisper Wall™ takes an environmental problem and converts it into a sound solution.

Sound Reduction: Maximizing surface area and having an irregular shaped surface captures and directs more noise into the sound absorbing mixture, thus captivating and dissipating sound wave energy. Whisper Wall™ has a 0.80 NRC and a 42 STC rating.

Installation: Panels are designed to be "stacked" to the required elevation. Cast into the top and bottom of each panel is a tongue and groove keyway that aligns and interlocks the panels along the horizontal joint. A top down construction method is used when stacking panels. This allows vertical height adjustments to be accomplished by varying the height of the bottom panel thereby allowing full height panels to be placed up to the sound attenuation elevation.

Maximum panel span is 24 ft. Individual panel height varies from a minimum of 4 ft. to a maximum of 10 ft. To date, panels have been stacked as high as fifty-four 54 ft.

Company Information: Pre-stress Engineering Corporation
2220 Route 176
Prairie Grove, IL 60012
815.459.4545 T
www.pre-sress.com

A3-9. High Performance Noise Barrier by Colas

Colas, the world's leading road construction and maintenance group, and its subsidiary, Somaro, a specialist in safety equipment and road signs and signals, in collaboration with the Ecole Polytechnique, have developed a new type of noise barrier for roads with an unequalled level of sound absorption. Depending on the configuration, the barrier's performance is 30% to 50% greater than that of the most effective sound panels currently available on the market.

This innovative product, for which a patent application has been filed and which has earned the Siemens Prize for Applied Research 2003 for Ecole Polytechnique, is based on a number of theoretical and experimental studies on the properties of irregular shaped objects. It has been proven that the geometry of objects is of great importance in the deadening of noise. Resonators with a "jagged" or "ragged" geometrical shape can deliver better sound deadening properties than ordinary systems with smooth geometry.

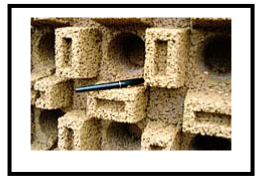
Considering these properties, and moreover, that it is very difficult to manufacture irregular shaped objects using inexpensive industrial processes (such as molding, for instance), the challenge for the team consisted in developing the morphology of an acoustically absorbent material that would be appropriate for molding.

A prototype was built in the form of a panel measuring 4 m x 4 m, associating a very sophisticated surface morphology, composed of cone and pyramid frustums arranged in repetitive fashion, with the use of wood-cement concrete.

Measurements performed in a reverberation chamber, as stipulated by the standards in force, have resulted in the classification of the new noise barriers in the "very high absorption" category, with unequalled performance.

This new high-performance noise wall is perfectly adapted to configurations of expressways and motorways and entrances to tunnels with heavy traffic, but will also prove suitable for high-speed railroads and busy airport zones. With a cost that will remain competitive and a design enabling it to blend easily into landscapes, it should soon undergo significant industrial and commercial development, for the greater benefit of neighboring residents.

Company Information: Colas Inc. of North America
10 Madison Avenue, 4th floor
Morristown, NJ 07960
973.290.9082 T
dgacolas@aol.com



A3-10. Noise Barriers by Quilite International

Quilite International, based in Los Angeles, has developed the Quilite® Noise Barrier, a factory-assembled panel system of clear polycarbonate plastic blocks enclosed in noise-trapping bezels and mounted in a steel frame. It has the appearance of glass blocks, yet reduces noise and echo anywhere from 50 – 80%. Designed by aerospace engineers, one of the unique aspects of Quilite®, however, is its ability to allow light to pass through the construction, improving the aesthetics of a necessary barrier and broadening its potential applications. At the same time, the corrugated plastic surface reduces reflected glare. And to add to the design enhancements, custom colors are available.

According to the manufacturer, Quilite® is durable from -40 to 200+ °F, is much lighter than conventional barriers (approximately 6 PSF), and can be made graffiti-resistant. Noise reduction studies addressing the use of the sound barriers for airplane shelters have also been done at San Luis Obispo Airport in California (a feeder line for turboprop aircraft), where one aviation company experienced a 90% reduction in noise complaints after constructing a noise containment structure using Quilite®.

Physical Properties:

Materials:
Block: Polycarbonate
Bezel: Noryl or Polycarbonate
Frame: Steel or Plastic
Single Panel Sections
- Thickness: 5 in.
- Height: as required in16 in. increments
- Length: up to 16 ft. between columns
- Weight: ~ 6 PSF
- Color: custom colors available

Strength:
Wind load deflection: Length to deflection ratio at 60 mph = 240

Noise Reduction[2]:

Frequency, Hz	250	500	1000	2000	4000
AC	0.21	0.64	0.88	0.72	0.58
STL, dB	23	23	24	36	36

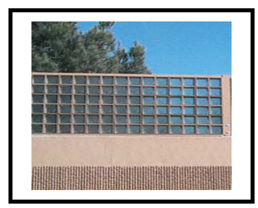
Absorption Coefficient (AC) per ASTM C 423-90a.
Sound Transmission Loss (STL) per ASTM E-413 procedure E 90-90

This product's performance has been certified by independent laboratory testing. Transmitted noise penetrating the wall was reduced by more than 80%, and a reflective noise was found to be reduced by more than 60%.

Applications: Airports, highways, sports/entertainment venues, and industrial/commercial noise barriers and shelters.

Installation: Panels are 5 in. thick and are available in modular sizes to produce walls over 30 ft. high. Their light weight permits easy handling. Installation is fast — a five-man crew can erect more than 5,000 SF in a single 8-h shift. Modular panels are easily replaceable if damaged.

Contact Information: QUILITE ® International
8616 La Tijera Blvd, Suite 509
Los Angeles, CA 90045
310.641.7701 T
www.quilite.com



A3-11. Soundcore Noise Panels by Spancrete

Spancrete's Soundcore highway noise barrier panels make up a reflexive system that essentially causes the disruptive sounds of traffic to expend energy, thereby lessening noise in the area. A variety of stains, textures, and finishes are available, making them aesthetically pleasing to residents and drivers.

Panels can span over 30 ft., requiring fewer columns and a lower total number of components. This translates into a reduced number of installation hours as well as an attractive sound wall. The barrier won't shrink, split, or spall, and requires very little maintenance. It is a cost-effective/low-maintenance wall.

Company Information: **Hanson Spancrete Pacific, Inc.**
13131 Los Angeles Street
Irwindale, CA 91706
626.962.8751 T
Fax: 626.962.8752
info@hansonspancrete.com

A3-12. Sound Fighter® Walls by Sound Fighter Systems, LLC

The Acoustical Solutions, Inc. (ASI) Sound Fighter® Wall has been a proven success in the noise abatement industry. These noise barrier walls have been used on many interstate highways, but also have industrial applications around gas compressor stations, electric transformers, cooling towers, chillers, compressors and more. The sound walls are formed of a basic building block design that meets specific noise abatement requirements without the cost of custom designs. In addition to its noise barrier values, the walls are lightweight, virtually graffiti proof, non-conductive and its modular design allows for easy assembly and disassembly.

Sound Reduction:

Sound Absorption Test (Acoustic Systems Acoustical Research Facility)
Test Method ASTM C 423 - 90a / ASTM E 795 - 92
Test Results - NRC = 1.05

Sound Transmission Loss Test (Acoustic Systems Acoustical Research Facility)
Test Method ASTM E 90 - 90 / ASTMC 423 - 90a
ASTM E 413 - 87 / ASTM E 1332 - 90
Test Results: STC = 33
Outdoor - Indoor Transmission Class (ITC) = 24

Applications: highways, interstates, bridges, truck turnarounds, shopping centers, loading docks, industrial sites, commercial sites, residential, race tracks, schools, chillers, transformers, compressors, etc.

Installation: Sound Fighter® Walls are easy to install. A crane is not necessary and two men can assemble ¼ mile of wall per day.

Company Information: Sound Fighter® Systems, LLC
P.O. Box 6075
Shreveport, LA 71136
318.861.6640 T
www.acousticalsolutions.com

A3-13. PARAGLAS SOUNDSTOP® Noise Barrier Sheet by Cyro Industries

PARAGLAS SOUNDSTOP® Noise Barrier Sheet products have been successfully used in transparent noise barriers along roads and railroads around the world for almost 30 years. It maintains natural views and aesthetics for local homeowners and off-highway commercial businesses while providing noise reduction for the community. Easy to form and fabricate, PARAGLAS SOUNDSTOP® products are extremely resistant to weathering from UV exposure and retain clarity and strength for many years. All SOUNDSTOP products are available in colorless, smoky brown and several shades of blue and green.

For bridges and overpasses, PARAGLAS SOUNDSTOP® GS CC noise barrier sheets incorporate polyamide filaments that hold a broken sheet if impacted by a vehicle, preventing fragments from falling below.

PARAGLAS SOUNDSTOP® Ready-Fit Panels are fully fabricated frame-and-panel assemblies that are adaptable to any ground-mounted noise barrier system, regardless of design or production technique. CYRO works directly with engineers, DOT and contractors to provide custom panels to fit post spacing and ensure a successful installation. The result is a “win-win” solution to visibility and noise abatement.

PARAGLAS SOUNDSTOP® TL-4 System is a lightweight noise barrier system for bridges and elevated roadway applications. It has been successfully tested under NCHRP 350 Level 4 conditions. This system incorporates PARAGLAS SOUNDSTOP® GS CC, which meets the EN1794 Standard for the performance of noise barriers.

Note: This product was used with *Item No. 3*, Durisol, for an Alaska DOT project.

Physical Properties:

Property	Test Method	PARAGLAS SOUNDSTOP®	PARAGLAS SOUNDSTOP® GS CC
Specific Gravity	ASTM C-792	1.19	1.19
Tensile Strength Elongation at Break, % Modulus of Elasticity	ASTM D-638	10,000 psi 4.5 400,000 psi	10,000 psi 4.5 400,000 psi
Service Temperature		> 160°F	> 180°F
STL	ASTM E-90	15 mm 32 dB 20 mm 34 dB 25 mm 36 dB	15 mm 32 dB 20 mm 34 dB 25 mm 36 dB
Weight, lbs per sq. ft.	0.6 in (15 mm) thick 0.8 in (20 mm) thick 1.0 in (25 mm) thick	3.66 psf 4.86 psf 6.10 psf	3.66 psf 4.86 psf 6.10 psf

Typical values: should not be used for specification purposes.
Values shown are for 0.250 in. (6mm) thickness unless noted otherwise.
Some values will change with thickness.

Company Information: CYRO Industries
100 Enterprise Drive
Rockaway, NJ 07866
800-631-5384 T
973-442-6125 T
www.cyro.com

A3-14. Plywall by Hoover Treated Wood Products

Hoover Treated Wood Products, Inc. is one of the largest producers of pressure treated wood in the United States, specializing in government specifications, high retention, and treatment of plywood. Hoover also specializes in kiln drying after treatment, which produces wood that is stronger, lighter, and pre-shrunk. Chromated copper arsenate (CCA), the preservative of choice for 60 years, is used by Hoover because it has an excellent performance record against termites and decay, excellent environmental qualities, and it's economical.

Hoover engineers and fabricates the Plywall Permanent Engineered Wood Barrier System for noise abatement and aesthetic screening. The Plywall panels have been tested in accordance with ASTM E-90. The manufacturer reports that a STC of 38, however, this most likely is the STL in dB for the ASTM E-90 test. Shipment is by truck and can be delivered to any point in the United States and Canada. A local contractor or a maintenance crew usually performs the installation. The cost includes shipment and all required materials delivered, ready to install.

PLYWALL is engineered for any specified wind load, expressed as PSF. Typical design wind loads range from 20 to 40 PSF. PLYWALL can be adaptable to different heights, soils, climates and terrain. It is aesthetically pleasing and well received by the public because of the warm, natural appearance of wood. The economical advantages are beneficial in comparison to competitive barriers that are constructed with other materials such as concrete and steel.

PLYWALL is "neighborly" because it is identical in appearance and attractiveness from either side with no unsightly backside. In spite of its lighter weight, PLYWALL's installed noise reduction is just as good as solid concrete or masonry. PLYWALL requires minimal maintenance due to the coloration and UV resistance provided by the CCA preservative, which gradually ages during the first few years from light green to gray. CCA also provides decades of protection against decay and termites.

If a special finish is desired, the rough texture enhances finish adhesion. Neither staining nor painting is required, however, due to the permanent protection and coloration provided by treatment. PLYWALL is easily repaired if traffic damage occurs. Repairs can usually be made with ordinary carpentry skills and new panels can be shipped in a short period of time.

PLYWALL Post and Panel consists of prefabricated pressure treated wood "sandwich" panels supported between pressure treated Parallam® PSL engineered timber posts. The panels are 2.75 in. and they are secured to the posts in channels created by pressure treated 4X4 cleats that are spiked or lagged to the posts.

Prefabricated panels are 8, 12, or 16 ft. wide, covered on both sides with pressure treated, exterior rated 4 ft. by 8 ft. Texture 1-11 plywood siding. Interior framing is sandwiched between the plywood faces to provide a stiff structural "skin" to enable the panels to resist high wind loads. Fabricated height of the 1-piece panels is variable, depending on the job requirements and panel width. Pressure-treated Parallam® PSL engineered timber posts support the panels at exposed heights to 24 ft.

Posts are embedded in the ground to a depth roughly equivalent to half the exposed height of the barrier and back-filled with crushed stone or concrete.

Application: highways, roadways, industrial sites, commercial sites, strip malls, shopping centers, zoo facilities, amusement parks, school/recreational facilities, residential developments, racetracks, airport noise/jet blast fence, etc.

Installation: PLYWALL is shipped complete and ready-to-install, including posts, panels, cleats and spikes (or lag bolts). Installation is done by a local contractor, often a commercial fence contractor. PLYWALL is also well suited for installation by general contractors or maintenance personnel. No special skills are required.

A truck-mounted auger often works well for digging the postholes. Hole diameters can be as large as 24 in., greater for the largest posts. Recommended backfill is crushed stone, which provides excellent lateral support and allows easy removal for future relocation. Concrete footings are not required at lower heights.

Parallam® posts are set on center to center spacing of the panel width plus the post width, plus one inch. The unique panel-to-post attachment method, using spiked or lagged 4X4 cleats to create a channel, provides an expansion joint and utilizes the exposed post face to add extra linear coverage per panel.

Individual panels are lifted into position by a crane using the built-in loops at the top of each panel. One cleat is spiked or lagged to each post with the provided hot dipped ring shank spikes or lag bolts, and then the panel is swung into position and fixed by attachment of the opposing cleat. Panels do not have to be lowered from the top of the posts. Holes are predrilled in each cleat for the spikes or lag bolts. The finishing touches are added by simply sawing off the excess post tops and cutting off the nylon web lifting loops with a utility knife.

Field cuts and modifications are easily made to PLYWALL panels to accommodate odd span widths or other field conditions where a standard panel will not fit.

Contact Information: Hoover Treated Wood Products
154 Wire Road
Thomson, GA 30824
706.595.1264 T
www.frtw.com

A3-15. Ever Quiet™ Wall by New Frontier Industries, Inc.

A sound wall comprised of planks made of 95% recycled plastic, and produced by a non-profit New Hampshire company dedicated to economically sound recycling. This is a unique product, a rare find, and an opportunity for a "win-win" solution for solid waste management and sound pollution mitigation. Working with New Frontier Industries Inc. of Milton, New Hampshire and the Department of Resources and Economic Development, the New Hampshire DOT (NHDOT) is installing several panels of the new plastic sound wall for testing in at least two locations around Manchester.

According to NHDOT, the oak-style "EverQuiet" plastic soundwall panels were installed by bridge maintenance personnel on December 14, 2004 near Route 101's Exit 1 eastbound on-ramp. A future installation will take place at the Granite Street project in Manchester.[3]

The plastic sound wall panels are easy to install and have no solid waste issues, unlike their wood counterparts. The big savings with this product may be in life-cycle costs. There are no disposal costs like there would be for pressure-treated wood. The plastic can be recycled for more products. The objective of this federally funded project SPR research is to determine if these plastics panels have characteristics of adequate noise reduction, long life, low installation and maintenance costs and natural appearance.

New Frontier Industries Inc. is a manufacturing company dedicated to finding new ways to recycle plastic that otherwise would not be recycled. It was formed as a subsidiary of Northeast Resource Recovery Association, a non-profit cooperative of 250 towns and cities in northern New England that seeks to identify and implement new recycling opportunities.

New Frontier uses state-of-the-art equipment that can manufacture one million ft. of sound barrier and two million LF of deck each year.

Physical Properties: For an 8 in. wide by 2.5 in. thick wall board:
Weight 3 pounds per LF (PLF) or 4.5 PSF
Flexural Strength = 2,000 psi*
Flexural Modulus of Elasticity = 110,000 psi*
Compression Strength = 2,500 psi*
Coefficient of Thermal Expansion = 5.77×10^{-5} in. per ^{o}F
Specific Gravity = 0.99*
Expected STC = 42
Expected sound insertion loss = 5 to 10 dBs
* Test conducted by University of New Hampshire Recycled Materials Resource Center

Installation: The product can be installed without the use of a crane or heavy equipment.

Cost: Suggested retail price:
- $4 per LF
- $6 per sq. ft.

Wholesale and bulk purchase pricing are also available. The H beams are also available in polyester-fiberglass, steel and galvanized steel with a price range from $6 to $40 per LF. Pricing for installation is also available.

Contact Information: New Frontiers Industries
PO Box 1360
Milton, NH 03851
866.637.7888
www.newfrontiersindustries.com