APPENDIX B

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Tables

Acronyms and Abbreviations

AC	Asphalt Concrete
ANC	Active Noise Control
ARFC	Asphalt Rubber Friction Course
ASAC	Active Structural Acoustic Control
AW	Alarm Value
BCA	Benefit/Cost Analysis
CD-ROM	Compact Disc Read-only Memory
CDN	Canadian Dollar
CFD	Computational Fluid Dynamics
CHF	Swiss Franc
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPX	Close Proximity
CRTN	Calculation of Road Traffic Noise
CV	Contingent Valuation
CVM	Contingent Valuation Method
dB	Decibel
DGAC	Dense-graded Asphalt Concrete
DOT	Department of Transportation

DRI	Danish Road Institute
DSF	Double Skin Glass Façades
EFR	Effective Flow Resistivity
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
ESAL	Equivalent Single-Axle Loads
EUAC	Equivalent Uniform Annual Cost
EV	Electric Vehicle
FCE	Fuel Cell Electric
FDTD	Finite-Difference Time-Domain
FHWA	Federal Highway Administration
FN	Friction Number
ft	Feet
GIS	Geographic Information System
HE	Hybrid Electric
HL3	Hot Laid 3
HMA	Hot Mix Asphalt
HPM	Hedonic Pricing Method
Hz	Hertz
ICE	Internal Combustion Engine
ICT	Illinois Center for Transportation
IDOT	Illinois Department of Transportation
IGW	Impact Value
INCE	Institute of Noise Control Engineering
IRI	International Roughness Index
kHz	Kilohertz
km/h	Kilometers per Hour
LCCA	Lifecycle Cost Analysis
m	Meters
mm	Millimeters
MPD	Mean Profile Depth

mph	Miles per Hour
NAC	Noise Abatement Criteria
NAI	Noise Annoyance Index
NCHRP	National Cooperative Highway Research Program
NDSI	Noise Depreciation Sensitivity Index
NEPA	National Environmental Policy Act
NIHL	Noise-induced Hearing Loss
NPL	Noise Pollution Level
NPV	Net Present Value
OBSI	Onboard Sound Intensity
OGAC	Open-graded Asphalt Concrete
PAC	Preplaced Aggregate Concrete
PBC	Perceived Behavioral Control
PCC	Portland Cement Concrete
PM	Particulate Matter
PW	Planning Value
RAC(O)	Rubberized Asphalt Concrete Overlay
RCNM	Roadway Construction Noise Model
REMEL	Reference Energy Mean Emission Level
ROFC	Rubberized Open Friction Course
ROGC	Rubberized Open Graded Course
RP	Revealed-preferences
RT	Reverberation Time
SC	Sonic Crystal
SEL	Sound Exposure Level
SEM	Structural Equation Model
sf	Square Feet
SHA	School Health Act
SII	Speech Intelligibility Index
SMA	Stone Mastic Asphalt
SN	Skid Number

SP	Superpave
STC	Sound Transmission Class
TDM	Travel Demand Management
TMS	Traffic Management Systems
TNM	Traffic Noise Model
TPB	Theory of Planned Behavior
UFP	Ultrafine Particle
USDA	United States Department of Agriculture
VBN	Value-Belief-Norm Theory
VGS	Vertical Greenery Systems
WTP	Willingness to Pay

Barriers

[Arenas, 2008] Arenas, J.P., Potential problems with environmental sound barriers when used in mitigating surface transportation noise, Science of the Total Environment, Volume 405, pp. 173–179.

This report from Chile examines both the beneficial and negative effects of barriers on wildlife. One beneficial effect was that a barrier prevents wildlife from entering heavily traffic areas and thus prevents road-kill. However, barriers also can restrict the natural movement of wildlife and transparent noise barriers can lead to bird kills. The negative effects on wildlife are amplified in cases of endangered species.

Arenas also evaluates effects of barriers on residents, noting that previous research shows that residents may forget the previous high noise levels and become dissatisfied with the loss of a view. Conversely, corridors with barriers can become representative of the area and give the community a unique quality with which to identify. A survey of 218 residents along an area adjacent to a noise barrier asked about both positive and negative effects. TABLE 1 provides an overview of the 126 respondents' reported effects.

TABLE 1. RESULTS OF THE PILOT SURVEY

Effects	Type of Effect	No. of respondents	%
Better sleeping conditions	Positive	78	62
Conversations in household are easier	Positive	54	43
Windows are opened more often	Positive	51	40
Increased privacy/feeling of safety	Positive	47	37
Cleaner air/reduced dust	Positive	34	27
Reduced volume when listening television/radio	Positive	29	23
Others	Positive	39	31
Loss of sunlight and lighting	Negative	83	66
Restriction of view/visual impact	Negative	72	57
Poor maintenance of the barrier	Negative	71	56
Restricted access to the other side	Negative	51	41
Loss of air circulation	Negative	36	29
Others	Negative	21	17

[Baldauf, 2008] Baldauf, R., E. Thoma, A. Khlystov, V. Isakov, G. Bowker, T. Long, R. Snow, Impacts of Noise Barriers on Near-Road Air Quality, Atmospheric Environment, Elsevier Science Ltd, New York, NY, 42(32), pp. 7502–7507.)

This highway study compares air pollution concentrations of carbon monoxide (CO) and particulate matter (PM) on a section of open field with and without a noise barrier. Measurements indicated that the noise barrier often led to pollutant concentration reductions of between 15 and 50 percent behind the barrier during certain meteorological conditions. However, under some conditions pollutant concentrations were greater behind the barrier.

[Carder, 2007] Carder, D. R., L. Hawker, and A. R. Parry, Motorway noise barriers as solar power generators, Proceedings of the Institution of Civil Engineers, Engineering Sustainability 160, Issue ES1, pp. 17–25.

This study assesses the feasibility of generating renewable energy on motorways and trunk roads. In 2004, two rows of solar barriers were installed in a cutting to the east of Junction 9 of the M27 in the United Kingdom (FIGURE 1). The trial showed that south-facing land alongside highways can successfully be used for solar barriers. In terms of maintenance, rainfall was effective in washing the panels. However, the study recommended that vegetation be cut back at least annually unless a barrier is installed in a paved area. A whole-life cost analysis showed that the electricity generated over 30 years would not pay for the cost of installing the barriers unless the price of electricity was many times its current value. There was no evidence that drivers were distracted by the barriers. In part due to the tilt of the solar panels, noise along the opposite carriageway resulting from adjacent noise barrier reflections was less than 1 dB(A).

FIGURE 1. PHOTOGRAPH. SOLAR PANELS ATTACHED TO HIGHWAY NOISE BARRIERS.

Source: Carder, 2007

[El-Rayes, 2018] El-Rayes, K, L. Liu, and E.J. Ignacio, Alternative Noise Barrier Approvals, FHWA-ICT-18-018, Illinois Department of Transportation (SPR) Bureau of Material and Physical Research.

Illinois Department of Transportation (IDOT) policies specifed that noise barriers could be constructed of earth, masonry, concrete, and composite materials. These policies specified that alternative noise barriers must meet criteria such as minimum transmission loss, noise reduction coefficient criteria, crash testing requirements, and material degradation. Research funded by the Illinois Center for Transportation (ICT) included:

- A comprehensive review of all Federal laws and IDOT policies related to noise barriers
- Interviews with IDOT officials to concisely describe current IDOT practices and policies for approving alternative noise barriers
- Recommendations from interviewed officials that could be used to streamline and expedite the approval process

Aided by a survey of other State Department of Transportation (DOT) experiences in approving and utilizing alternative noise barriers, the study reviewed noise barrier policies and approval criteria, review timelines, alternate approved noise barrier systems, and performance of noise barrier materials (including any problems). This material supported the development of recommendations providing guidance to IDOT on expediting alternative noise barrier approvals.

Recommendations and guidance included information on the following topics:

- Benefits (economic, social, well-being)
- Possible negative impacts
- Barrier characteristics and processes that allow State DOTs to expedite projects
- Maximum cost per benefitted receptor (**TABLE 2**) and maximum cost per mile (**TABLE 3**) for the approval of noise barriers
- Safety criteria, constructability, feasibility, aesthetics, and number of benefitted receptors (some front row specific)
- The performance of other materials compared to precast concrete (**FIGURE 2**)
  - Acrylic noise barriers provided a similar performance regarding construction time, aesthetics, and maintenance but slightly worse in cost and durability
  - Metallic noise barriers performed slightly worse in all criteria
  - Earth berms performed slightly worse in construction time
  - Fiberglass noise walls performed similarly or slightly better in construction time, cost, durability, and maintenance but performed slightly worse in aesthetics
- The limits to abatement, which vary by material

TABLE 2. COMPARISON OF ABATEMENT COST PER BENEFITED RECEPTOR

State	Maximum Cost per Benefitted Receptor	Number of States
North Dakota	$24,000	1
Idaho	$24,250	1
Delaware	$25,000	1
Indiana, Kansas, Kentucky, Ohio, Oregon, South Carolina, West Virginia	$35,000	7
Arkansas	$36,000	1
Nebraska	$40,000	1
Florida, Iowa	$42,000	2
Wisconsin	$47,000	1
New Jersey, Nevada	$50,000	2
Connecticut, Georgia	$55,000	2
Hawaii	$60,000	1
New York	Other - $80,000 per berm or noise insulation, 2,000 square feet (sf) per benefited receptors per wall	1
New Hampshire, North Carolina	Other - 1,500 sf per benefited receptor	2
Virginia	Other - 1,600 sf per benefited receptor	1
Tennessee	Other - 2,400 sf per benefited receptor	1
Montana	Other - $6,300 per dB per benefited receptor	1
Colorado	Other - $6,800 per dB per benefited receptor	1
Washington	Other - Cost per benefited receiver based on increasing future noise levels (no maximum)	1
Total		**28**

TABLE 3. MAXIMUM COST PER MILE FOR ABATEMENT

State	Maximum Cost per Mile	Number of States
New Jersey	$1,000,000.00	1
Ohio	$2,000,000.00	1
Florida	$2,217,600.00	1
Oregon	$3,200,000.00	1
North Carolina, West Virginia	No maximum	2

State	Maximum Cost per Mile	Number of States
North Dakota, Idaho, Delaware, Indiana, Kentucky, Arkansas, Iowa, New Jersey, Connecticut, Georgia, Hawaii	Other - Cost per receptor	11
Colorado	Other - Cost per dB per benefited receptor	1
New York	Other - Cost per berm or noise insulation	1
New Hampshire, Virginia, Tennessee	Other - Area per benefited receptor	2
Washington	Other - Cost per benefited receptor based on future noise levels	1
Total		**23**

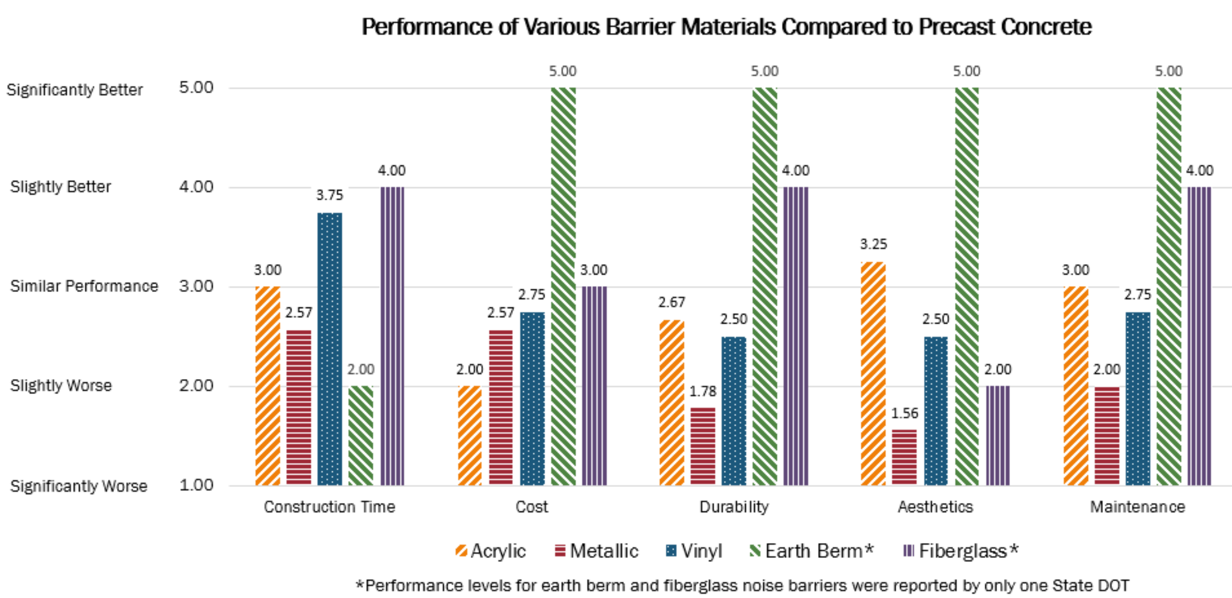

FIGURE 2. BAR GRAPH. PERFORMANCE OF VARIOUS BARRIER MATERIALS COMPARED TO PRECAST CONCRETE

Original source: El-Rayes, 2018; image was recreated for this report

[FHWA, 2000] Knauer, H.S, S. Pedersen, C.S.Y. Lee, G.G. Fleming, FHWA Highway Noise Barrier Design Handbook, FHWA-EP-00-005.

This report offers updated guidance and documents substantial changes in noise barrier design, since an original 1976 publication, "Noise Barrier Design Handbook. Report No. FHWA-RD-76-58," by Simpson. The document was comprehensive. The objectives were to provide:

- Guidelines on how to design a highway noise barrier that fits with its surroundings and performs its intended acoustical and structural functions at reasonable lifecycle cost

- A reference of common concepts, designs, materials, and installation techniques for the professional highway engineer, the acoustical and design engineers and planners, and the non-professional community participant

The guidebook emphasized that any new theory, design, material, or installation technique not addressed in the handbook should be evaluated with the general fundamentals of durability, safety, and functionality in mind. This new handbook, addressed both acoustical and non-acoustical issues associated with highway noise barrier design. The report also included two short sections on community acceptance and cost.

As far as community acceptance, opinions expressed by landowners immediately adjacent to a noise barrier typically reflected perceptions of the resulting versus expected noise levels. If a barrier provides 10 dB of reduction, but levels are still near 66 or 67 dB(A), it still may be judged as “too loud” or “ineffective” or “no better than before.” Landowners living farther from a noise barrier also may complain about noise generated by a new installation. Additionally, while noise levels may not be loud enough to require consideration of noise abatement per the noise abatement criteria, a different or new noise that occurs as the result of a new or upgraded installation may cause complaints. Closer to the installation, residents adjacent to a highway but on the opposite side of a new barrier may complain about increased noise. These issues are policy - rather than design - issues. Each state has a specific and unique policy, whether formalized or not, related to community involvement, public participation, and post-construction evaluation factors.

Regarding cost, all States have procedures for evaluating the cost and effectiveness of noise barriers. A barrier’s cost and acoustic effectiveness are factors in determining whether to provide noise abatement. Since barrier evaluations are typically performed during the design phase, they are normally based on modeled noise levels and historical barrier costs and may not necessarily reflect the true cost or effectiveness of the final barrier. A post-construction evaluation can provide a more refined cost effectiveness value by taking into account the following post-construction conditions:

- Measured noise levels
- Revised insertion loss calculations
- Costs of modifications made during construction
- Actual construction bid costs
- Actual material costs

This evaluation still may not consider all costs or benefits. In cases where projects include only noise barrier construction, agencies must determine whether to include cost items such as insurance, maintenance, protection of traffic, mobilization, etc.

[INCE, 2014] Cost-Benefit Analysis, Noise Barriers and Quieter Pavements, Institute. Office of Noise Control Engineering, Library of Congress Control Number: 2014937983.

This report summarizes an Office of Noise Control Engineering workshop held on January 16, 2014 on benefit/cost analysis (BCA) of noise barriers and quieter pavements. It provides an overview of workshop presentations and the results of discussions.

One objective of this workshop was to evaluate National Cooperative Highway Research Program (NCHRP) Report 738, "Evaluating Pavement Strategies and Barriers for Noise Mitigation," which describes a methodology for the evaluating both barriers and pavements for noise abatement, while exploring how quieter pavement technology can be incorporated into Federal and State noise policy. Three key elements of the method presented in the NCHRP report involve:

- A lifecycle cost analysis (LCCA)
- Use of a research version of the Federal Highway Administration (FHWA) Traffic Noise Model (TNM)
- Use of the onboard sound intensity (OBSI) method to evaluate tire pavement noise reduction

One important part of the process proposed above is the LCCA concept. In LCCA, the discount rate, which is the difference between the market interest rate and inflation, is used to compare costs that occur at different points in time. Using LCCA, planners can evaluate both the initial cost of abatement using pavement and barriers as well as rehabilitation and maintenance costs. It allows decisionmakers to consider various alternatives and their costs.

RealCost, developed by FHWA, is a user-friendly LCCA tool that is specific to pavements but can be used to analyze other assets.[1] RealCost includes a deterministic as well as a probabilistic approach, incorporating both agency and user cost estimates. User costs consider costs incurred due to delay because of lane closures during roadway construction. The program includes the number of working days to consider the user costs. RealCost also includes user-specific discount rates using constant dollars. It allows a review of cash outlays with each step of the work and repair, and considers the salvage value of materials. Evaluations also incorporate a measure of the effectiveness of the resulting predicted level of traffic noise.

The NCHRP project used a deterministic analysis for LCCA and a research version of TNM to model abatement measures. The example analysis included both barriers and pavement. In the asphalt example, there was no need to include barriers because of the quieter asphalt surface. The analysis compared:

- A concrete pavement alternative:
  - Longitudinally tined concrete pavement
    - Maintenance was a diamond grind in 20 years
  - 12-ft barriers on both sides of the roadway
    - Maintenance: annual graffiti removal; impact damage repair every 5 years

1 Real Cost tool (https://www.fhwa.dot.gov/infrastructure/asstmgmt/lcca.cfm).

- An asphalt pavement alternative:
  - Asphalt pavement
    - » Maintenance: asphalt rubber friction course (ARFC) applied every 7 years for acoustical performance; 2-inch asphalt overlay with a 0.75-inch ARFC applied every 14 years

The asphalt option had a lower present value cost of $9.6 million versus $11.8 million for the pavement plus barrier option (**Table 4**). However, the asphalt option had a higher user cost because the asphalt had to be overlaid every 7 years, causing more frequent lane closures.

Table 4. Lifecycle Cost Analysis Comparing an Asphalt Quieter Pavement with No Barrier and a Concrete Pavement with Barrier

Costs ($000)	Hot Mix Asphalt (HMA) + Asphalt Concrete Friction Course (ARFC)		PCC with Barrier	
	Agency Costs	User Costs	Agency Costs	User Costs
Undiscounted Sum	$15,250	$66.34	$14,334	$31.47
Salvage Value	$958	$9.53	$0	$0
Present Value	$9,624	$24.81	$11,846	$9.88
Equivalent Uniform Annual Cost (EUAC)	$448	$1.15	$551	$0.46

An analysis by Dr. Judy Rochat (**Table 5**) presents another example that considers these criteria. In this example, abatement that initially did not meet the criteria became effective through the use of changes in pavement surface and a noise barrier.

Table 5. Barrier and Pavement Options on W11 on I-580

Pavement Type and Barrier Height	Number Benefitted	Predicted Level Range, dB(A)	Noise Reduction Range, dB	Total Project NPV ($1000)	NPV for Noise Abatement ($1,000)	Reasonableness Allowance ($1,000)	Feasible	Cost Reasonable	Design Reasonable	Effectiveness, dB
PCC No Additions	0	64 - 78	0	629	–	–				9
PCC + 14 ft	3	61 - 70	3 - 8	1,356	727	165	Y	N	Y	3
PCC + Grind	0	62 - 75	2 - 3	863	233	–	N	N	N	8
PCC + Grind + 12 ft	20	59 - 68	4 - 10	1,486	857	1,100	Y	Y	Y	1
PCC + RAC(O)	0	61 - 74	2 - 4	796	167	–	N	N	N	7
PCC + RAC(O) + 12 ft	20	59 - 67	4 - 11	1,419	790	1,100	Y	Y	Y	0

Note: NPV = net present value
PCC = Portland cement concrete
RAC(O) = rubberized asphalt concrete overlay

Treatment of highway pavement is generally less costly than barriers[2], but the noise reduction achieved by a quieter pavement is typically less than the reduction from a well-designed barrier, particularly for residents in the barrier's immediate vicinity. Quieter pavements produce a reduction of noise at the source, and may allow agencies to increase the number of benefited receptors. A combination of barrier and pavement treatments may allow for cost-effective solutions to highway noise.Several examples illustrated that the NCHRP report approach can be successfully applied to real highway project studies. However, the report's recommendations discuss the challenges State DOTs face when of implementing NCHRP methodology and developing findings and recommendations. Key recommendations include:

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

  FIGURE 3 illustrates a proposed highway noise abatement process.

If TNM modeling predictions included pavement effects, agencies could develop more accurate evaluations of different pavement types when assessing noise impact and abatement. In some situations, a barrier-and-pavement hybrid solution can be more acoustically and/or cost effective than a barrier-only solution and can allow for additional benefited receptors. However, widespread adoption of this approach would require changes to both current regulation and TNM.

[2] Through the end of 2010, 47 State DOTs and the Commonwealth of Puerto Rico had constructed more than 2,748 linear miles of barriers at a cost of close to $5.5 billion (in 2010 dollars).

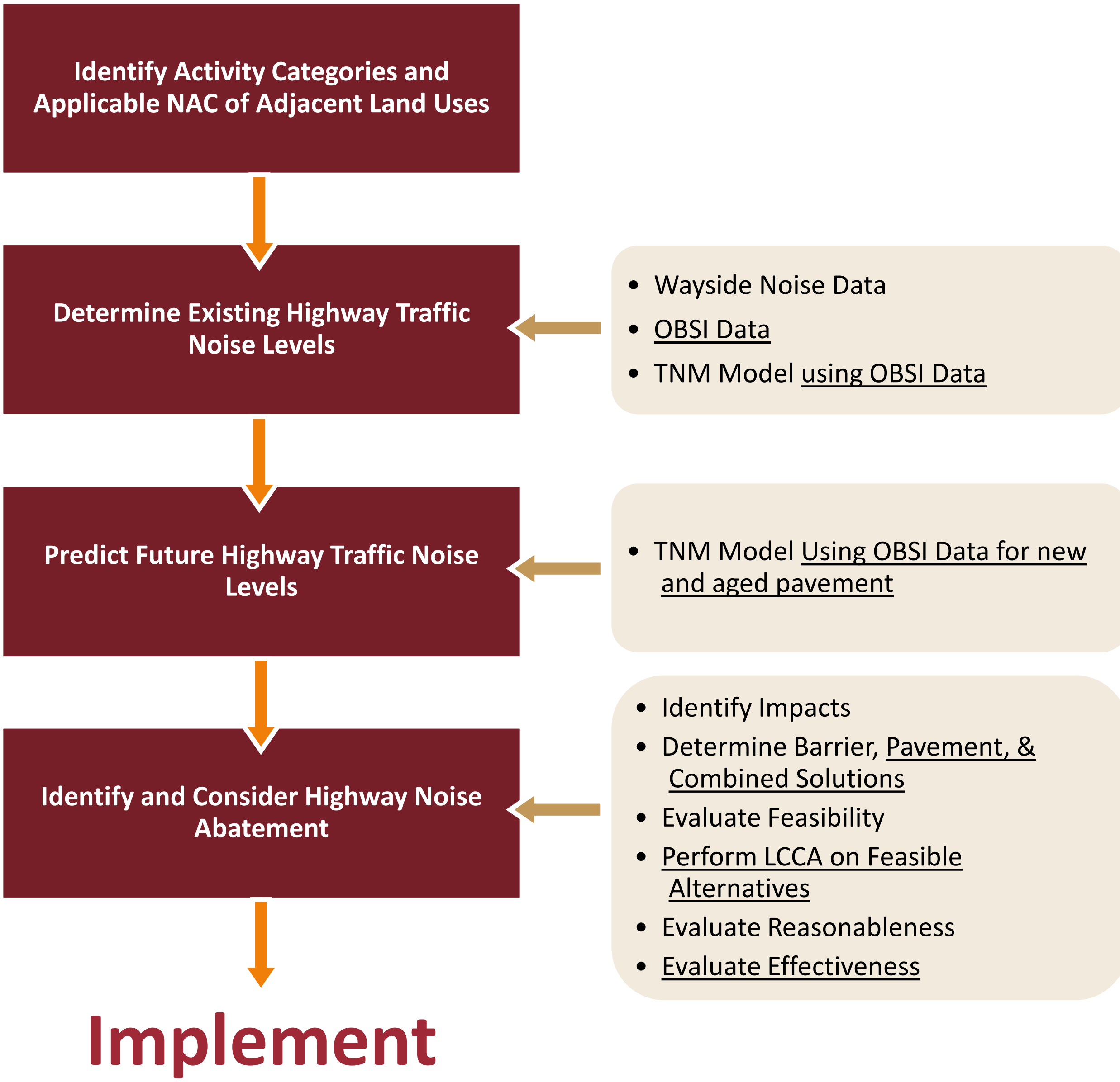

FIGURE 3. FLOW CHART. PROPOSED MODIFIED HIGHWAY NOISE ABATEMENT PROCESS (CHANGES UNDERLINED)

Original source: INCE, 2014; image was recreated for this report

[Halim, 2015] Halima, H., Abdullaha, R., Abdullah, A., Alib, A., Mohd, M.J., Nor, Effectiveness of existing noise barriers: comparison between vegetation, concrete hollow block, and panel concrete, International Conference on Environmental Forensics, Procedia Environmental Sciences Volume 30, pp. 217–221.

A study in Malaysia investigated the effectiveness of existing noise barriers - vegetation, concrete hollow block, and panel concrete - in three urban residential areas in the Klang Valley region. Field measurements followed the ISO 10847:1997 and ANSI S12.18-1994 methods to determine the insertion loss. The method requires noise measurement at a site with a barrier to determine "after" noise levels and another sets of measurements at an equivalent site without the presence of the barrier to determine the equivalent "before" levels. Simultaneous measurements ensured equivalent conditions for traffic and meteorology, but details on the barriers and vegetation were lacking. **Figure 4** provides an overview of the trends.

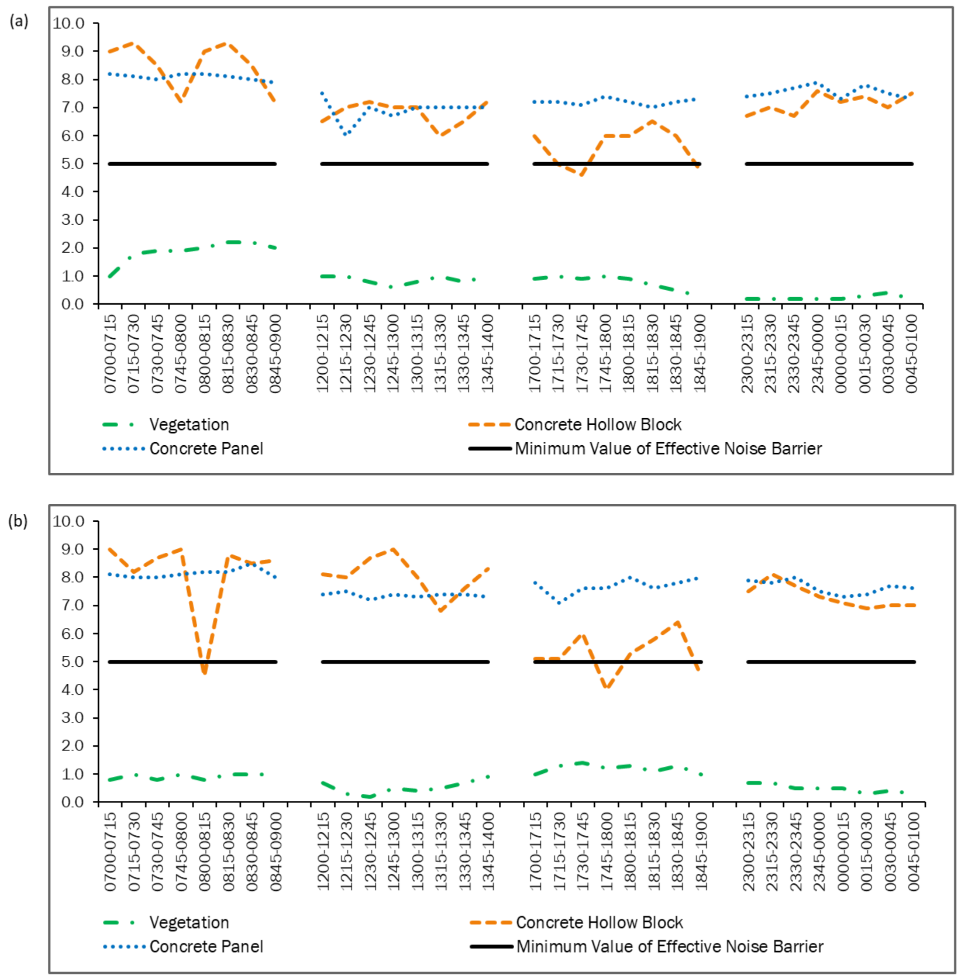

Figure 4. Line Graphs. Average of Insertion Loss of Every 15 minutes of Measurements of Three Different Types of Noise Barriers During (a) Weekdays and (b) Weekends

Original source: Halim, 2015; image was recreated for this report

As indicated in **Figure 4**, vegetation was essentially ineffective, though the only details provided were that the vegetation was "not high and dense enough to shield the receiver effectively from highway noise." Concrete hollow blocks and concrete panel barriers were far more effective, exceeding the "minimum value of effective noise" criterion of 5 dB(A). The possibility of sound leakage between the joint of the hollow blocks could have reduced the insertion loss.

[Hagler, 2010] G.S.W. Hagler, W. Tang, M.J. Freeman, D.K. Heist, S.G. Perry, A.F. Vette, Model evaluation of roadside barrier impact on near-road air pollution, Atmospheric Environment, Elsevier Science Ltd, New York, NY, 45, pp. 2522–2530.

This research suggests that roadside noise barriers will have significant effects on near-road air pollution due to difference in dispersion of traffic emissions, affecting downstream concentrations. A three-dimensional computational fluid dynamics (CFD) six-lane road model simulated the roadside barrier effects on near-road air quality.

With winds perpendicular to the road, the CFD model simulations show reduced concentrations as compared to a no-barrier situation. The near-road noise reduction shows a negative impact for on-road air pollutant concentrations, as these concentrations are likely to increase. Results also indicated that a downwind noise barrier forms a stagnant zone behind the barrier with reduced road emissions (e.g., five percent of the highway emissions strength).

Wind direction and barrier length both play a critical role. These results imply that roadside barriers may increase near-road air pollution but reduce the concentrations downwind of the barrier. However, local meteorology, the barrier structure, and the degree of lee-side emission sources are also critical factors determining the outcome.

[Hasebe, 1993] Hasebe, M., A study on the sound reduction by T-profile noise barrier, J. Acoust. Soc. Jpn, Volume 14, Issue 2.

This paper investigates the characteristics of the reduced sound field of the T-profile noise barrier through both analytical and experimental methods. The geometry under consideration is shown in **FIGURE 5**. This synopsis does not provide details of variables, but the graphic details the noise path and diffraction points for the source (S) to receiver (R).

The wide barrier has two edges, which increases the path length distance and adds an additional diffraction point. An applied solution for this particular case is often put forward. However, advancements such as the effect of finite acoustic impedance of the surface could alter the solution.

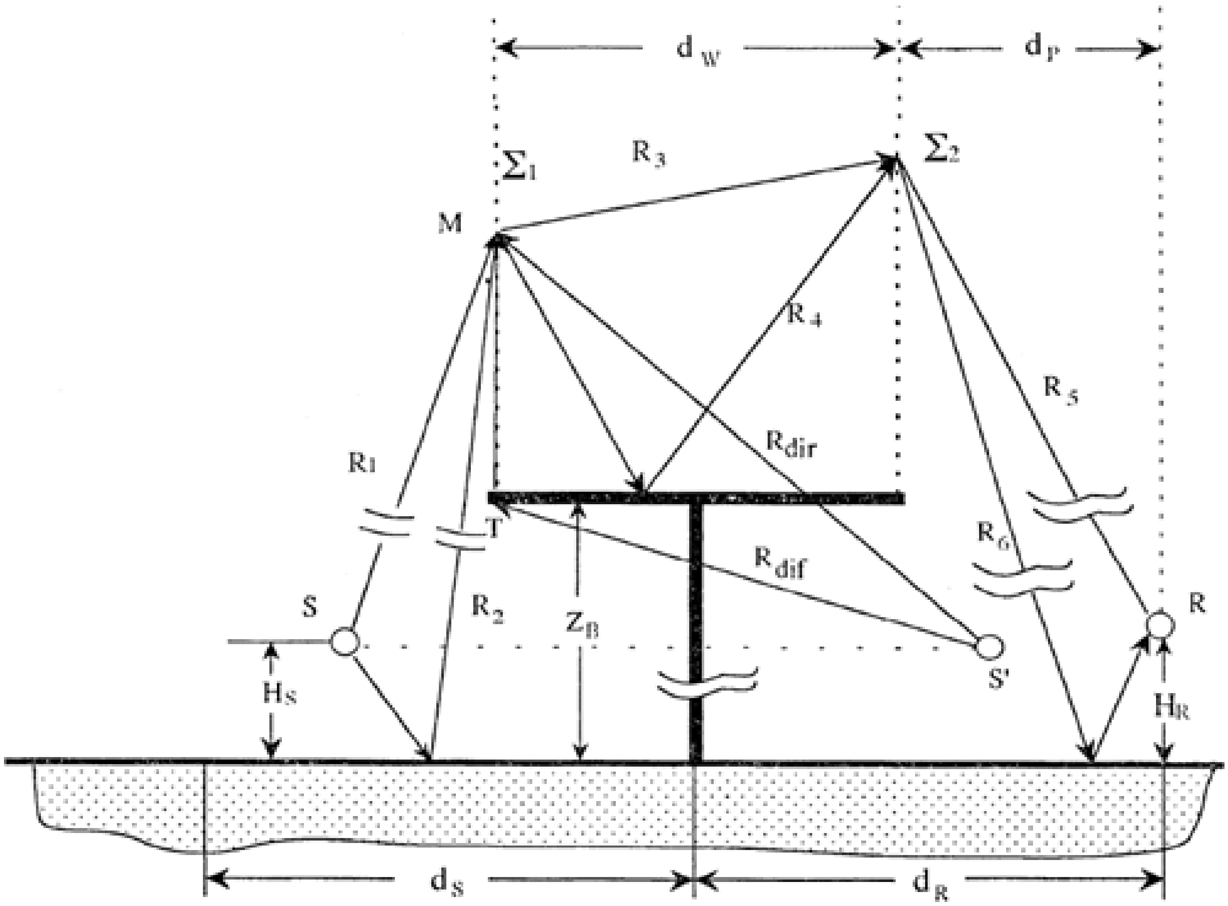

FIGURE 5. SCHEMATIC DIAGRAM. T-PROFILE NOISE BARRIER, THE GROUND, AND RECEIVER LOCATION.

Source: Hasebe, 1993

(Note: S is the real sound source; S' is the location of the image source; R is the receiver; S'TM (R_{dif}) is the path between S' and M.)

Researchers compared the T-profile barrier results to measurement using a reduced scale model in an anechoic room. The key finding (**FIGURE 6**) was that reduced-scale modeling indicated that the excess attenuation of the T-profile barrier (dashed line) significantly exceeds that of the standard thin barrier (irregular dashed line).

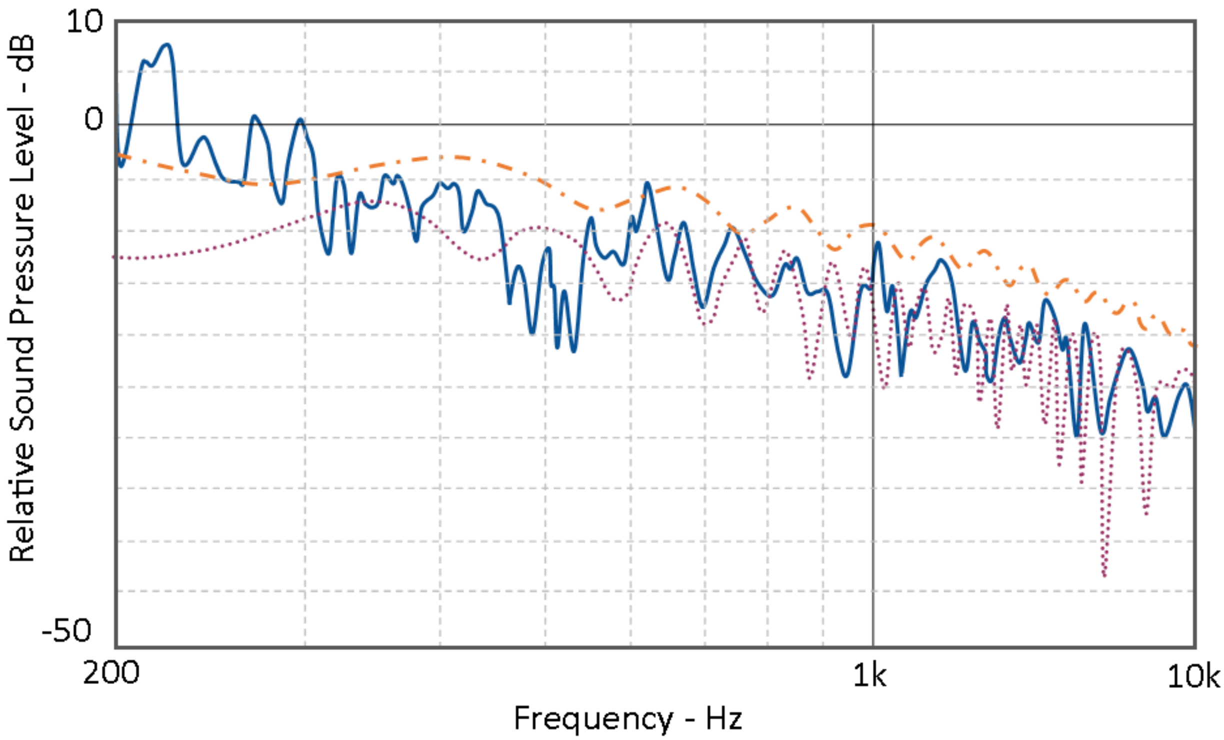

FIGURE 6. GRAPH. SOUND PRESSURE LEVEL RELATIVE TO FREE FIELD PROPAGATION

Original source: Hasebe, 1993; image was recreated for this report

(Note: The solid line is the reduced-scale model measurement; the dashed line is the results of calculations for the T-profile barrier; and, the irregular dashed line is the calculated attenuation with a standard thin barrier.)

[Kerby, 1973] Kerby, II, E.G., Highway Noise Reduction Barriers - A Literature Review, VHRC 73-R9, Virginia Highway Research Council.

This 18-page review covers the scholarship during the early stages of barrier use for noise and extend back to FHWA-issued Policy and Procedure Memorandum 90-2. While information has increased, one part of the review presented an opinion on the considerations during noise abatement planning. The report states:

> "We believe that noise barriers should be provided only as a last resort, as they result in undesirable as well as desirable effects. Some of the undesirable effects are creation of a fixed object, possible tunnel effect, and cost. Our present noise control policy in California and the proposed Federal policy recognize that when development occurs subsequent to location of the freeway, the responsibility for noise attenuation rests with others. When it is the road building agencies' responsibility to shield existing noise sensitive developments from excessive noise, protection can oftentimes be provided for less cost by acquiring an extra wide right-of-way, changing the freeway alignment to avoid the developed areas or by depressing the freeway."

[Jilkova, no date], Jilkova, I., M. Novak, The Alternate Solution of Absorptive Noise Barriers, Jour. Of Interdisciplinary Research, pp. 106–109.

While the intent of this paper was to identify benefits of absorptive barriers, it also is of note for detailing similarities in noise reduction methods from the Czech Republic and reported FHWA information.

The paper divides traffic noise control measures into two categories: active and passive. Active controls include reducing vehicle noise (a tool not available to highway analysts), reducing speed limits (**FIGURE 7**), and surface texture changes (listed as tire rolling over communication). Passive methods included vegetation (listed as greenery), the use of noise barriers (reflective, absorptive, berms), and combinations of types of noise barriers.

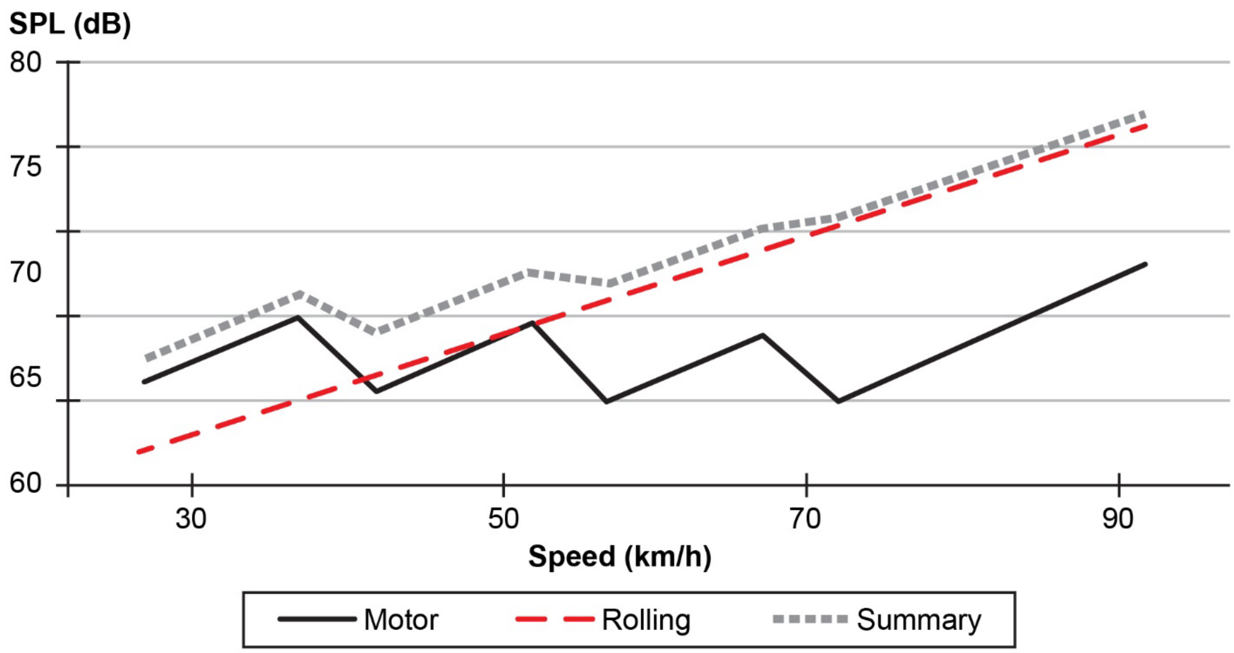

FIGURE 7. LINE GRAPH. CHANGES WITH VEHICLE NOISE DUE TO ROLLING (TIRE/PAVEMENT), MOTOR, AND SUMMARY.

Source: Jilkova, no date

[Kastka, 1995] Kastka, J., E. Buchta, U. Ritterstaedt, R. Paulsen, U. Mau, The Long Term Effect of Noise Protection Barriers on the Annoyance Response of Residents, Journal of Sound and Vibration, Volume 184(5), pp. 823–852.)

This paper reports results from a study of two parallel acoustic and psychological surveys. The surveys focus on four different barriers, four adjacent research areas, 12 experimental sites, and one untreated control area. The sites were in the outskirts of the cities Dusseldorf, Wuppertal, Krefeld, and Neuss, and results are derived from the period from 1976 to 1988. The research found that:

- There is not a simple causal relation between noise level reduction and annoyance reduction

- Barriers produce high annoyance reduction at nearby sites but produce only minimal effects beyond 150 m from the highway
- Annoyance reduction, on average, is relatively greater than noise level reduction
- Changing traffic volume on urban roads has stronger psychological effects than installing barriers
- Highway noise produces higher annoyance reactions than urban road traffic noise of the same level
- After barrier construction, the noise level influence on annoyance is weaker than before construction
- A negative experience of residents before barrier construction is not likely to be influenced by the reduced emission level after construction

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[Lee, 2018] Lee. E.S., D.R. Ranasingheb, F.E. Ahangarc, S. Aminic, S. Marad, W. Choib, S. Paulsonb, Y. Zhua, Field evaluation of vegetation and noise barriers for mitigation of near freeway air pollution under variable wind conditions, Atmospheric Environment, Volume 175, pp. 92–99.

The paper considered the effect of noise barriers on motor vehicle particulate matter emissions ($PM_{2.5}$, aerodynamic diameter ≤ 2.5 µm) and ultrafine particles (UFP) (aerodynamic diameter < 0.1 µm). There is a large variability in findings regarding the effectiveness of barriers on reducing air pollution. The characteristics of the vegetation (i.e., height, thickness, porosity, species) influence the concentrations of air pollutants near roadways. Wind speed and particle size may also contribute to the variable findings in the literature. This led to the objectives of this study to:

1. Determine the effects of a combination barrier of both the sound wall and vegetation on reducing particle concentrations near freeways, in comparison with the effects of either one alone
2. Better understand the effectiveness with respect to windspeeds and particle sizes

A series of field sampling campaigns along two major freeways in California studied concurrent measurements at three to four locations close (10 - 15 m) to the road-side barriers. Difference-in-differences analyses on the concurrently collected datasets of UFP and $PM_{2.5}$ suggested that the mitigation of UFP and $PM_{2.5}$ near freeways is more effective with a combination barrier and vegetation than with either one alone.

Specifically, the vegetation-barrier combination achieved a relative reduction in $PM_{2.5}$ concentrations of 25 - 53 percent greater than vegetation barrier alone. The additional barrier was more effective (51 - 53 percent) in the reduction of $PM_{2.5}$ when the wind speed was in the range of 1 - 2 m/s; with greater reductions of UFPs at a decreasing wind speed. The vegetation barrier was less effective for reducing $PM_{2.5}$ (0 - 5 percent) than for UFPs (5 - 60 percent).

Several key points emerged from review of other field studies. One finding using tracer gas, showed that a barrier reduced the downwind sulfur hexaflouride concentrations by 20 to 50 percent. Since the structure of a barrier modifies the wind-driven airflow field in the vicinity behind the barrier structure, the plume of vehicle-emitted air pollutants must traverse the height of the barrier or above. Consequently, the barrier helps to create additional dispersion, decreasing the level of the particulate air pollutants by 15 to 80 percent near roadways relative to an open area.

Studies on the use of vegetation were also reviewed for the potential benefit of reducing air pollution levels near roadways. Dry deposition of particulate pollutants increased due to the foliage of a vegetation barrier's large surface area. The structure of the vegetation barrier can also help increase the vertical mixing and dispersion of air pollutants. A combination of barrier and vegetation can lead to greater reduction of UFPs than a barrier alone.

Overall, the study suggests that both barrier and vegetation are effective for reducing UFPs and $PM_{2.5}$ but that mitigation effectiveness can be a complex function of particle size, wind speed, and barrier configuration.

[Nilsson, 2010] Nilsson, M.E., M. Andehn, P. Lesna, Evaluating roadside noise barriers using an annoyance reduction criterion, Journal of the Acoustical Society of America. Volume 124, pp. 3561–3567.

This research indicates that the reduction in A-weighted sound pressure level (L_A) may not be a valid indicator of the corresponding annoyance reduction. Researchers recorded road traffic noise behind a noise barrier and at a location with no barrier. Sound behind the barrier (recorded 10 - 45 m from the road) and non-barrier sound (recorded 50 - 200 m from the road) were of similar A-weighted noise level, L_A. Participants in a listening experiment found the sound behind the barrier to be more annoying than the non-barrier sound with an annoyance difference corresponding to a 3-dB increase in L_A. The Loudness level (ISO 532B) and a low frequency corrected sound pressure level (L_{*A}) were found to be better than L_A as indicators of the barrier's annoyance-reduction efficiency.

FIGURE 8 compares perceived annoyance of the road traffic noises to the corresponding A-weighted sound pressure level. Sounds recorded 10 to 45 m behind the barrier were more annoying than sounds of similar level but greater distance from the road, recorded without noise barrier.

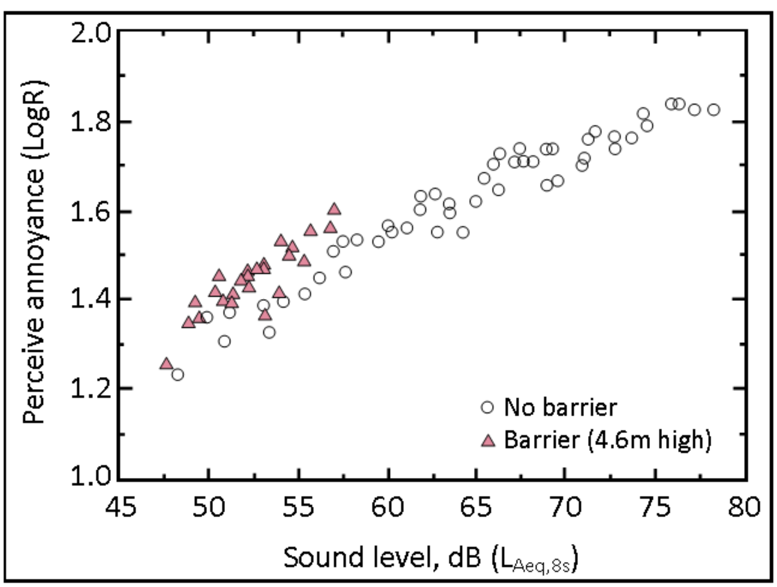

FIGURE 8. SCATTERPLOT. PERCEIVED ANNOYANCE (LOG SCALE) AS A FUNCTION OF A-WEIGHTED SOUND PRESSURE LEVEL (L_{AEQ},8S)

Original source: Nilsson, 2010; image was recreated for this report

Multiple regression analyses suggested that the low-frequency content was the main acoustical factor behind the annoyance difference between barrier and non-barrier sounds of equal L_A. A common critique of L_A is that it overcompensates for the hearing system's reduced sensitivity at low frequencies. Barrier sounds would then be perceived as louder and thereby as more annoying than non-barrier sounds, which contain less energy in the low-frequency part of the spectrum.

[Parker, 2010] Parker, G., Enhancements to noise barrier design standards for European highways, Proceedings of 20th International Congress on Acoustics, Sydney, Australia.

This paper offers an overview of proposed enhancements to the noise barrier design specification standards for highways in the European Union. Together with the growing importance of value management, increasingly costly ongoing barrier maintenance increased the importance of using durable low maintenance noise barrier systems. The paper proposes several changes to noise barrier designs to ensure that noise reductions can be sustained for the life of a barrier. These changes include:

- Defining higher categories for the specification of acoustic performance for tall barriers both in terms of sound absorption and airborne sound insulation
- Requiring outdoor noise testing of all barriers under direct sound field conditions instead of the classical indoor laboratory test regime
- Potentially using on-site acoustic testing of barrier durability as a tool for barrier maintenance and asset management

In the U.S., noise barriers are used to ensure that communities are protected from vehicle noise. In contrast, the UK's policy has historically been to offer nonenvironmental solutions such as secondary double-glazing or even compensation to residents. Neither of these interventions solve the problem, and they have been widely rejected in favor of noise barriers and low noise road surfacing.

As a result, Europe is seeing a growing need for a common set of noise barrier design specifications based on certified laboratory tested performance. This standard would help ensure that effective long-lasting barriers are built that significantly reduce noise levels. The last 15 years have seen the emergence of new European performance standards for highway noise barriers. These standards serve as the backbone for noise barrier specification and to help create a fair market for barrier products across the continent.

[Bureau Veritas, 2011] Bureau Veritas, G2G short programme project for Serbia G2G09/SB/5/5, "Reducing traffic noise in Serbia" Guidelines, Document VKa.08hi10.11r100.

While this document is primarily an implementation plan, it also includes some interesting detail on reduced barrier height with quieter pavement. The general idea is that it could be more cost effective to combine lower noise pavement and barriers. To do this, the first step is to determine the total abatement of the two measures used concurrently. This calculation is illustrated in **TABLE 6** and **FIGURE 9**.

TABLE 6. NOISE REDUCTION OF QUIETER PAVEMENT COMPARED TO TOTAL NOISE REDUCTION FOR DIFFERENT BARRIER HEIGHTS

Noise Reduction Pavement	Barrier Height (m)			
	2	3	4	5
0	2,0	3,0	4,0	5,0
1	1,7	2,6	3,4	4,3
2	1,4	2,2	3,0	3,8
3	1,2	1,9	2,5	3,2
4	1,0	1,6	2,2	2,8
5	1,0	1,3	1,8	2,4

The information in **TABLE 6** can be approximated by the equation:

$$H_{\text{barrier, new}} = 0.84—0.37\ (NR_{\text{road}}) + 0.73\ (H_{\text{barrier, original}})$$

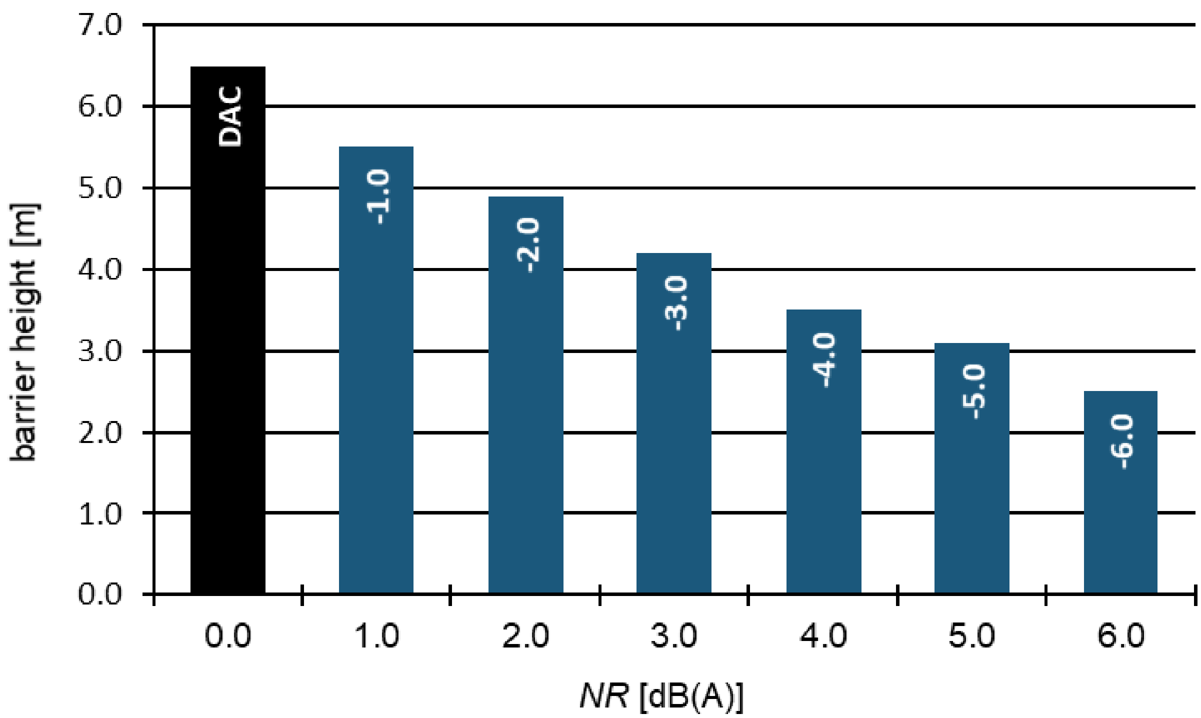

FIGURE 9. BAR GRAPH. GRAPHICAL COMPARISON OF NOISE REDUCTION OF QUIETER PAVEMENT COMPARED TO TOTAL NOISE REDUCTION FOR DIFFERENT BARRIER HEIGHTS

Original source: Bureau Veritas, 2011; image was recreated for this report

This determination considers extra costs of the lower-noise pavement (€/m^2) alongside the cost of barrier (€/m^2) to determine a total cost. **FIGURE 10** shows results of the pilot study, which indicated that the best cost is achieved with a lower noise pavement achieving a 3 dB(A) reduction. This example is offered for illustration only; real costs for paving and the barrier must be considered for any particular project.

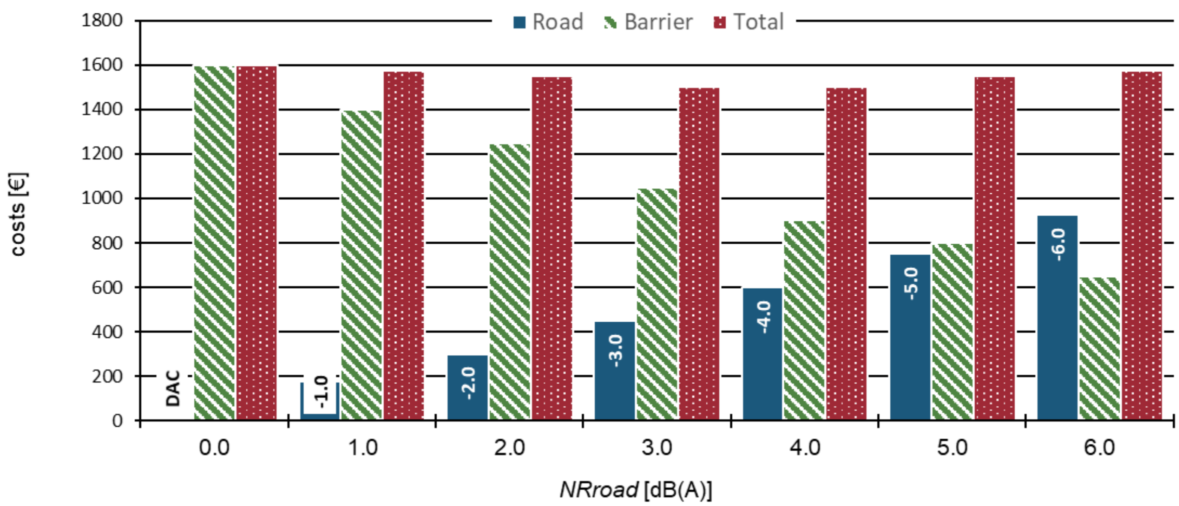

FIGURE 10. BAR GRAPH. COSTS OF LOWER-NOISE PAVEMENTS IN CONJUNCTION WITH BARRIERS.

Original source: Bureau Veritas, 2011; image was recreated for this report

[Wayson, 2003] Wayson, R., J. MacDonald, A. El-Assar, W. Lindeman, M. Berrios, Florida Noise Barrier Evaluation and Computer Model Validation, Transportation Research Record 1859 Paper No. 03-3296, pp. 72–78.

This study created a large database of on-site sound levels behind 20 barriers in Florida. Validation of TNM 2.5 and STAMINA 2.0 as used in Florida was possible with the information. Other findings included:

- Florida barriers most often provide a 5 to 10 dB benefit to first-row receivers
- Shadow zone benefits, as determined by a 5 dB:L_{Aeq} sound level reduction, were generally limited to under 400 feet (ft) (122 m) behind even the tallest noise barriers
- The use of open-graded asphalt concrete (OGAC) instead of the average pavement input type provided better results when using the FHWA TNM model
  - This is expected because Florida uses an open-graded friction mix. Although pavement type at this time could not be used as an abatement measure, appropriate pavement types were used to reduce TNM prediction errors.
- Development of an empirical relationship to estimate shadow zone length and benefited receivers
  - This approximate method allows for a better understanding of which homes are benefitted by accounting for background sound levels that are often ignored in existing computer models.

Overall, noise barriers provide substantial noise reduction for homes along Florida's highways - most first-row homes and most second-row homes. In some cases, third row homes also receive benefits. Based on this on site testing, the predictive process used to design the barriers seems to provide adequate protection to highway neighbors.

Highway Alignment/Traffic Controls

[Brown, 2015] Brown, A.L., Longitudinal annoyance responses to a road traffic noise management strategy that reduced heavy vehicles at night, J. Acoust. Soc. Am., Vol. 137, No. 1, pp. 165–176.

To control noise on an urban corridor in Brisbane, Australia, local agencies designed a traffic management strategy to reduce trucks during night-time hours. This involved removing a heavy toll for trucks on a parallel route during night-time hours (10 p.m. to 5 a.m.). The community's response to this intervention - as measured by a two-year long panel study with five repeated measurements of response - showed significant reductions in the panel's response to noise, both for night-time annoyance and for interference with activities. This occurred even though the intervention produced no change in conventional traffic noise indicators. Since the change in articulated truck movements occurred at night, the benefit was attributed to reduction in the number of noise events from heavy vehicles with counts occurring in parallel with reported noise effects. This indicated that noise effects at night depend on the number of noise events experienced, not only on the overall level of traffic noise. Normal indicators do not relate to this strategy. Indicators used in this research included traffic flows on the study corridor, road traffic noise levels adjacent to the study roadway, and responses of residents living along the corridor to road traffic noise.

[Covaciu, 2015] Covaciu, D., D. Florea, J. Timar, Estimation of the Noise Level Produced by Road Traffic in Roundabouts, Applied Acoustics, November/j.apacoust.2015.04.

This article presents a study comparing a hypothetical signalized intersection and a roundabout using traffic flow speeds for passenger cars measured in real conditions. The traffic flow data were detailed near and inside the intersection. The analysis utilized noise mapping software for Romania. Results indicate that there are differences in the resulting noise levels when the intersection is studied in more detail and these differences may affect the measures that can be undertaken by the local authorities for noise abatement.

FIGURE 11 provides some examples of speed and distance variation for three scenarios: vehicles traveling through an intersection, vehicles traveling through the same intersection signalized with traffic lights, and vehicles traveling through the intersection when converted into roundabout. The curves represent passing the intersection in the forward direction in all cases. In the case of the signalized intersection with traffic lights, there is one stop followed by a continuous accelerating sequence up to the cruise speed of the next road segment. In the case of the roundabout, there are more stops or slowing down sequences, determined by the pedestrian crossing before and after the roundabout, and the actual entrance into roundabout. Though speed is lower, there are more accelerating sequences than in the cross intersection. The overall trend changes depending on location of the receiver.

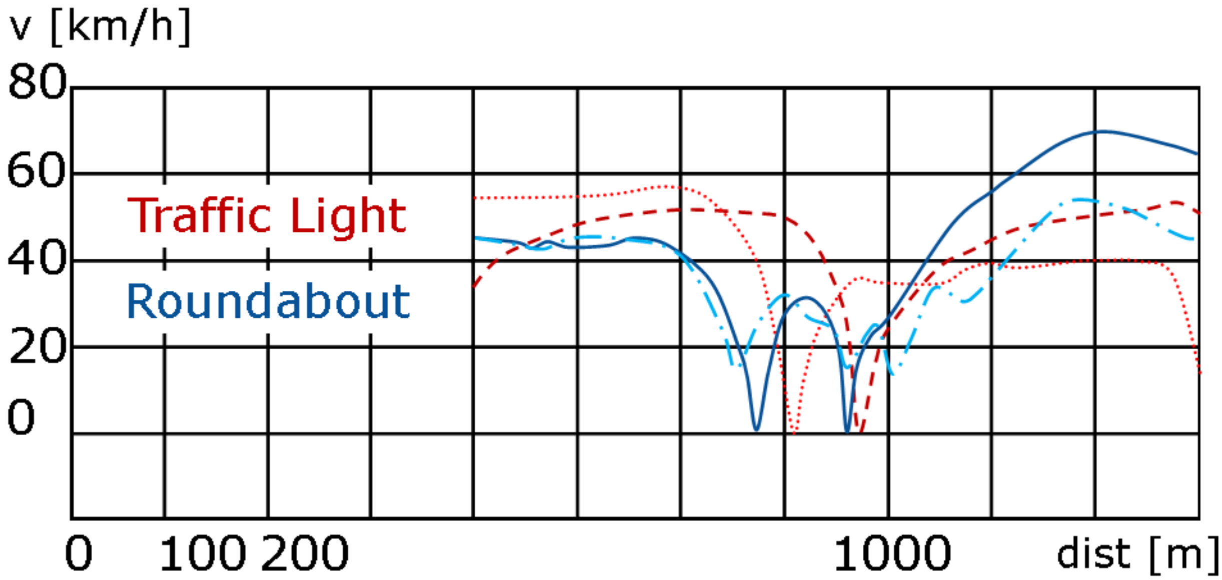

FIGURE 11. LINE GRAPH. SPEED VERSUS DISTANCE DIAGRAM FOR VEHICLES TRAVELING THROUGH AN INTERSECTION

Original source: Covaciu, 2015; image was recreated for this report

The article also highlighted several conclusions from existing literature, including:

- An additional 2 - 3 dB(A) increase may occur to the noise level average of the two adjacent segments taking into account the transverse traffic. The improvement of the traffic fluidity (e.g., by roundabouts) can reduce this noise by 2 - 4 dB(A). However, the authors tend to dispute this finding because flow is still not completely continuous at a roundabout.
- Some models/standards give a 0 - 3 dB penalty near signal-controlled junctions according to distance, while others recommend a penalty of up to 7 dB for crossroads with traffic lights.
- The noise level close to a signal-controlled junction was 2.4 dB(A) higher than a continuous equivalent traffic, according to a Japanese report. Another report from Europe noted a 2.2 dB(A) reduction.
- The optimization of traffic fluidity by traffic light control can gain up to 2 dB(A) as compared to stop-go-stop traffic.
- The transformation of an intersection regulated by traffic lights or stop signs into roundabout can result in a reduction of 1 dB(A).
- The noise reduction of cars that approach the roundabout while slowing down (-5 to -10 dB(A)) is compensated by the noise increase of those that accelerate by leaving it (+3 to +8 dB(A)).

This research finds that for the area near an intersection, the roundabout adds a noise level higher by about 1 dB(A). This finding is in contradiction to the conclusion of other studies. The difference is small and can be neglected when large areas without houses are near intersections, even without sidewalks for pedestrians (e.g., on the outskirts of towns).

[Decký, 2012] Decký, M., M. Trojanová, Noise Pollution From Roundabout Traffic in the Outer Environment of Built-Up Areas of Towns, 12th International Multidisciplinary Scientific GeoConference SGEM, pp. 927–934.

The paper begins with descriptions of how roundabouts can lower the noise pollution created by traffic on urban intersections, then describes noise level reduction after reconstruction of intersection to roundabouts in cities of Slovak Republic and Czech Republic, and concludes with a simple method of monetizing the benefits resulting from the noise level reduction.

Monetization of the socioeconomic benefit of the road infrastructure investments depended primary on lowering of traffic users, travel time, and vehicle operating costs. Other monetized benefits are related to lowering the accident rate. The cost of the environmental effects can be reflected in the depreciation of property values based on studies showing a linear relationship between noise level and change in property value. This calculation process helped determine a yearly socioeconomic benefit from noise reduction for a 30-year period.

Noise exposure creates various degrees of negative impact. The magnitude of this impact was evaluated through a social survey. The survey asked respondents to express their experience on a predetermined scale. The magnitude of noise impact was defined as the sum of annoyance scores experienced by all the residents within that area using a noise annoyance index (NAI). One NAI equals "one extremely annoyed person," two persons moderately annoyed (where annoyance score = 0.5), and so on. Based on the consensus in east European countries that the "cost" of one extremely annoyed person (1 NAI) is approximately 1,600 € per year, the cost of a moderately annoyed person (0.5 NAI) equals 800 € per year, and so on.

Census data and registry of residences information helped estimate the number of people living within different 5 dB noise intervals, with the mean annoyance score for each exposure interval calculated for the mid-points. The annoyance index per exposure interval is then the product of the number of people multiplied by the mean annoyance score, and the total annoyance index is the sum of annoyance indexes for all intervals. This process created two areas with constant noise intervals. One zone had 252 apartments and two houses and was inhabited by approximately 890 people. The second zone had 310 apartments and four houses and approximately 1,100 inhabitants.

Noise measurements taken at the intersection before and after the roundabout indicated a reduction of 2.5 dB;L_{Aeq} for the two types of intersections. This reduction was accompanied by a change in frequency components, primarily in the lower frequencies. The monetized benefits from lower noise was then assumed to be the difference between net value of noise costs for a classic intersection and the net value of noise costs for a roundabout. In this case, the difference is estimated to be about 3,991,440 €. The paper noted that a more in-depth analysis could include the fluctuation of inhabitants in the area.

[Kacprzak, 2018] Kacprzak, D., Effect of Traffic Calming Devices on Improvement of Acoustic Climate, 18th International Multidisciplinary Scientific GeoConference SGEM, pp. 533–540.

Traffic calming devices have been used in entry zones for years to reduce the adverse effect of road traffic. The success in speed reduction and improvement of acoustic climate is dependent on the type of devices, their location, and how frequently they are distributed along the pedestrian crossing.

Researchers measured road conditions in several villages located along throughways where single-sided chicanes were introduced in entry zones, examining the zones following a long stretch of a straight road. Measurements were taken of traffic volume, speed, and road noise simultaneously on five road sections both before and after the traffic calming devices. The physical obstacles required motorists to change trajectories and then return to the original trajectory. Measurements determined "before" and "after" speeds and the change in noise levels before and after the chicane. The difference between "before" and "after" traffic noise is proportional to the speed reduction. Hence, to reduce the adverse effects of traffic noise on inhabitants of neighboring houses located in entry zones, it is important that the traffic calming device reduces speeds.

Analysis of tests showed variation in the noise levels before and after the chicanes (**Table 7**). The applied chicanes did not significantly improve the acoustic climate in two of the five analyzed road sections.

Table 7. Static Test Results of the Effect of Chicanes on L_{EQ} Traffic Noise Reduction[3]

Measure	Treatment	Mrzeżyno[4]	Skibienko	Trzebusz	Dębostrów	Uniemyśl
Leq, dB(A) noise level before and after chicane	Before chicane	69,8	69,7	68,5	66,3	64,6
	After chicane	66,4	68,0	66,8	65,7	64,2
Differences of ΔLeq, dB(A) noise levels		3,4	1,7	1,7	0,6	0,4

L_{eq} traffic noise reduction is closely linked to how effectively the chicane can reduce speed, as shown in **Table 8**. The speed reduction reduces noise in the vicinity of a road and improves the road's acoustic climate.

[3] Column headings in table modified to comply with Section 508 of the Rehabilitation Act of 1973.

[4] These are the five different roadway sections.

TABLE 8. MEASUREMENT RESULTS WITH CORRELATION COEFFICIENTS

Road section	Traffic volume, P/h	Percentage of heavy vehicles, %	Speed difference Δv_{85}, km/h	Speed difference Δv_{av}, km/h	Speed difference Δv_{av}^{pp}, km/h	ΔLeq difference, dB(A)
Mrzeżyno	532	4,5	14,30	13,20	15,30	3,40
Skibienko	340	3,5	11,10	8,60	10,50	1,70
Trzebusz	530	1,5	9,40	10,80	4,50	1,70
Dębostrów	374	2,1	3,10	3,80	1,00	0,60
Uniemyśl	212	2,4	3,00	3,10	4,40	0,40
Correlation coefficients:	R(ΔLeq, N) **0,76**	R(ΔLeq, u_c) **0,73**	R(ΔLeq, Δv_{85}) **0,95**	R(ΔLeq, Δv_{av}) **0,94**	R(ΔLeq, Δv_{av}^{pp}) **0,89**	

[King, 2011] King, E. A, E. Murphy, H. J. Rice, Evaluating the impact on noise levels of a ban on private cars in Dublin city centre, Ireland, Transportation Research Part D: Transport and Environment, Volume 16, Issue 7, October, pp. 532–539.)

Public transport services in Dublin's city center experience significant time delays during peak travel periods due to traffic congestion. In an effort to alleviate traffic congestion and increase the efficiency of public transport in the area, the City introduced a "bus gate" to one particularly sensitive area in the city center to restrict private vehicles from accessing the area during peak traffic hours (7 to 10 a.m. and 4 to 7 p.m.). The aim was to generate not only significant journey time-savings for public transport users but also reduced noise levels. Noise levels were monitored prior to and after the introduction of the scheme to estimate the impact on noise exposure levels in the Dublin city center.

The analysis considered two noise monitoring locations (L_{Aeq} and L_{A10} in five-minute intervals):one at a busy interchange within the ban (Movement 1) and the other along a street which approached the entrance to the "bus gate." At the second location, vehicles could enter the center (Movement 2) or turn to avoid (Movement 3). Measurements were taken at each location for 14 days prior to the introduction of the scheme and for an additional 28 days after the introduction of the scheme. The Calculation of Road Traffic Noise (CRTN) prediction method from the UK Department of Transport further evaluated the noise levels.

The following were associated with Movement 1 during the morning period:

- A decrease of approximately 90 percent in the volume of cars
- A decrease of approximately 88 percent in HCVs
- A slight decrease (8.5 percent) in buses
- A slight increase in the movement of other modes of transport

Accounting only for cars, buses, and HGVs and applying CRTN would correspond to a decrease in 2.7 dB(A) for each hour, assuming the sign posted speed limit (50 kilometers per hour (km/h)) and an average variation per hour. This methodology allowed prediction of the variation in the basic noise level for each movement (TABLE 9). The apparent increase in noise levels associated with Movement 3 is a result of increased traffic levels taking this path to avoid the “bus gate.”

TABLE 9. PREDICTED REDUCTION IN NOISE LEVELS AT LOCATION 1[5]

Movement	Morning Period [dB(A)]	Evening Period [dB(A)]
Movement 1	2.7	1.7
Movement 2	2.2	1.4
Movement 3	-1.6[1]	-1.9[1]

[1] *A negative value indicates a predicted increase in noise levels*

The foregoing analysis yielded the conclusion that a ban on private cars in a city center region would lead to reduced noise levels.

On a practical note, if traffic were to be diverted onto different streets, it is clear the noise levels on these streets would experience increased noise levels. However, from this simple study, it is reasonable to assume that were the ban to be geographically expanded to encompass more streets, or expanded to include more hours throughout the day, the benefits in terms of noise levels would be increased.

If the gates for private cars were in effect over a complete 24-hour period, the model predicted that noise levels in Dublin’s city center would be reduced between 2 - 3 dB(A). If noise levels are considered over a 24-hour period and expressed in terms of L_{den}, the associated impact on noise levels would be minimal.

It also is interesting to note that a complete ban on private cars does not automatically imply a significant reduction in noise levels; HGVs and buses are key contributors to the noise level on a street that creates a change in vehicle mix. The use of quieter buses could improve these results.

[Makarewicz, 2010] R. Makarewicz, Prediction of noise reduction through vehicle path rerouting, J. Acoust. Soc. Am. 127 (1), pp. 216–222.

In this rigid mathematical analysis, traffic noise produced by moving vehicles, is described in terms of the day-night average sound level L_{dn} and the day-evening-night level L_{den}. Noise levels depend on the path of noise sources, and the noise source path is most often rectilinear. In this analysis, the rectilinear relationship was substituted for using a circle arc of radius R for the straight path segment. This yields noise reduction $D_L = D_{Ldn} = D_{Lden}$. The relationship between D_L and the radius can be derived by assuming that noise propagation is governed by geometrical spreading, air absorption, and ground effect. For example, replacement of a straight road at the distance of 100 m with the road of radius 270 m and an angle of 68° yields the noise reduction of 4 dB. In the case of road traffic noise, the presented results seem to be a viable alternative to barrier construction.

Substitution of the circle arc for a straight path segment yields a noise reduction D_L in terms of the L_{dn} and the L_{den} because the sound must travel a greater distance. Instead of approaching and passing a location, the curved path now takes the vehicle “around” the location. D_L is a function of the angle and

[5] Column headings in table modified to comply with Section 508 of the Rehabilitation Act of 1973.

the radius R = d/cos. While the paper author does not explicitly state this, the paper concludes with a statement that, presumably, the new path would be cheaper than building noise barriers.

[Prekop, 2016] Prekop, M., Martin Dolejs, Do Bypass Routes Reduce Noise Disturbances in Cities? Case Study of Cheb (Western Bohemia, Czech Republic), Geographia Technica, Vol. 11, Issue 2, pp. 78 to 86.

The construction of bypasses is a common strategy to avoid negative impacts, such as increased noise disturbances, on society. The authors state that the benefits of these bypasses are disputable in many respects.

One of the most-used traffic junctions in the Czech Republic is in the City of Cheb, where diverting traffic from the arterial route has been solved by constructing a bypass route. The paper focuses on evaluations of noise loads from inhabitants of the center city living along the former arterial route. The evaluation is based on direct measurements that took place before and after the construction of the bypass.

Although there was a marked difference in the traffic volume, especially that of trucks (50 percent in the morning phase and 26 percent in the afternoon phase); the study also identified induced demand in the area, where the traffic volume was spatially redistributed and the mix of vehicles changed. Thus the reduction in the freight traffic volume alone on the city arterial route did not result in an adequate reduction in noise.

The measurement results indicate both decreases and increases in the sound levels after the bypass. The overall average of all measurement locations indicated a slight increase in noise levels after the bypass in the city center; however there were no statistically significant changes in noise before and after the construction of the bypass. Additionally, there were complaints from the new bypass area.

Considering that the changes described above were found to be insignificant for human perception, it could not be stated that there was a marked decrease in the disturbance to the population due to noise. Only by fully excluding freight traffic and reducing car traffic could any major noise decrease occur.

Noise Insulation

[Amundsen, 2011] Amundsen, A.H., R. Klaeboe, and G.M. Aasvang, The Norwegian Façade Insulation Study: The efficacy of façade insulation in reducing noise annoyance due to road traffic, Journal of the Acoustical Society of America, vol. 129, 3: pp. 1381–1389.

This study examines façade insulation's efficacy in providing an improved indoor noise environment and in reducing indoor noise annoyance using a socio-acoustic before-and-after study. The study found that the façade insulation, in the form of upgraded exterior wall insulation, upgraded windows, or upgraded ventilation systems, generated an average equivalent noise reduction inside dwellings of 7 dB(A). Whereas 42 percent of the respondents were highly annoyed prior to insulation installation, this value dropped to 16 percent post-installation, indicating that the façade insulation provided a substantial improvement in the indoor noise environment. With respect to indoor noise annoyance, the advantage of having the bedroom facing the least noise-exposed side of the dwelling corresponded to a 6 dB(A) noise reduction. The changes in annoyance from noise reduction due to the façade insulation aligned with the exposure-response curves obtained pre-installation. A total of 637 respondents participated in the before-study. Of these, 415 also participated in the after study. Indoor and outdoor noise exposure calculations for each of the dwellings were undertaken before and after façade insulation installation.

[Davy, 2004] Davy, J.L., Insulating Buildings against Transportation Noise, Proceedings of Acoustics 2004, pp. 447-454, November 2004, Gold Coast, Australia.

Transportation noise contains significant low frequency components. It is difficult to insulate buildings for sound from transportation noise because wal cavities are only effective in increasing sound insulation above the mass-air-mass resonance frequency. Stud walls also can have a major structural resonance in this low frequency range, although it is not yet clear if this is significant in the field. Low frequency sound insulation has a large uncertainty in both laboratory and field measurements. This paper provides typical diesel electric locomotive traffic noise, road traffic noise, aircraft traffic noise, and other rail traffic noise spectra. The paper examines the sound insulation of measured wall sound insulation spectra against these typical transportation noise spectra using A-weighted sound level reduction.

[Diaz, 2009] Diaz, C. A. Pedrero, An experimental study on the effect of rolling shutters and shutter boxes on the airborne sound insulation of windows, Applied Acoustics, vol. 70: pp. 369-377.

A room's façade is usually composed of different construction elements, one of which is the window. The window fulfils both an aesthetic function and of course closes the wall opening. To improve thermal behavior and control solar radiation, the window may be fitted with different protection features, such as shutters. In climate zones with many hours of sunlight, windows in residential buildings may incorporate a rolling shutter. Traffic noise and higher standards of energy saving, comfort, durability, and sustainability in buildings means that windows now must comply with stricter requirements, including sound insulation from airborne noise. This work contains a summary of studies carried out on the sound insulation from airborne noise in several types of windows (e.g., double side-hung casement, double horizontal sliding sash) with built-on shutters and prefabricated boxes. For each type of window, an analysis sought to determine the effects of the interior finishes in the shutter box, the shutter position (whether fully retracted or extended), and the weighted sound reduction index of windows for traffic noise.

[El Dien, 2004] El Dien, H.H. and P. Woloszyn, Prediction of the sound field into high-rise building façades due to its balcony ceiling form, Applied Acoustics, vol. 65: pp. 431-440.

This study presents the noise reduction performance of tall building façades close to roadways due to a balcony configuration and with an inclined ceiling. The Pyramid Tracing model enabled testing of three inclined angles (5º,10º, and 15º) with different balcony depths. The results in terms of A-weighted sound pressure level reduction were expressed in free field into the balcony back wall. The protection level, defined as the difference in noise levels before and after inserting the proposed balcony form, has been used to assess the reduction offered by that configuration. A maximum reduction due to using these forms was obtained at higher floors and at balconies of 2 m depths and more. It was possible to use simulation results to calculate the prediction of protection levels from the 10^{th} to 15^{th} floors from an empirical equation.

[Fausti, 2019] Fausti, P., S. Secchi, and N.Z. Martello, The use of façade sun shading systems for the reduction of indoor and outdoor sound pressure levels, Building Acoustics, vol. 26, 3: pp. 181-206.

External shading devices are widely used in recent buildings because they reduce the greenhouse effect due to the solar irradiation through transparent surfaces and reduce the glare effects inside buildings. The acoustic effects of these devices have not been well investigated in the literature. In this article, a bi-dimensional pressure acoustics finite element model of a shading device attached to a building façade was used, in frequency domain, to analyze the effects both in the indoor and outdoor environments. The finite element model was validated with experimental measurements carried out in a semi-anechoic chamber and then extended to an urban scale to evaluate the effect in the reduction of outdoor traffic noise. A sound absorbing material was added to the bottom side of each louver to improve the acoustic effect of the shading device. Results of the simulations showed that external shading devices tend to increase the sound pressure level over the building façade, while the introduction of the sound absorbing material behind each louver reduces this problem. A finite element model investigated the dependencies of the sound pressure level reduction to the geometrical factors of the shading device were investigated. The installation of louvers on a building façade also can affect the sound pressure level over a façade of a building placed 20 m away, across a road. This article analyzes both the effect over the façade of the opposite building and the effect over the urban area between the two buildings.

[Garg, 2011a] Garg, N., O. Sharma, and S. Maji, Design considerations of building elements for traffic and aircraft noise abatement, Indian Journal of Pure & Applied Physics, vol. 49: pp. 437-450.

The paper presents various design components based on the review of previous studies and presents a database and design aspects of sandwich material combinations for applications in building elements. This included various wall and roof constructions to combat traffic and aircraft noise. Researchers were able to evaluate building elements based on two sources: 1) a series of laboratory experiments carried out in reverberation chambers designed to test the sound insulation properties of sandwich drywall partition panels, and 2) published laboratory results on masonry and drywall sandwich. The work provides a database and physical understanding of theoretical phenomena proposed in previous studies for design and development of better sound insulative sandwich drywall constructions. These constructions may be applied in building façades, walls, ceilings, and doors for abatement of traffic and aircraft noise in Delhi, India. The paper also assimilates the design guidelines in a cause-and-effect analysis diagram. The work also envisages the significance and need for stricter building regulations with respect to sound insulation of building elements for new residential projects planned, especially in the vicinity of airport or road traffic in India.

[Garg, 2011b] Garg, N., O. Sharma, and S. Maji, Experimental investigations on sound insulation through single, double & triple window glazing for traffic noise abatement, Journal of Scientific & Industrial Research, vol. 70: pp. 471-478.

This study evaluates sound insulative sandwich window constructions of high sound transmission class (STC) value for abatement of traffic and aircraft noise in Delhi, India. Researchers develop an empirical relationship correlating with the thickness of glass for various window configurations. A significant increase in sound insulation is observed at higher frequencies when either one glazing layer is doubled or both glazing layers are doubled. Increasing the thickness of the glass pane causes the coincidence dip to shift toward lower frequencies, while increasing the air gap causes a significant improvement in sound insulation characteristics for both low and high frequencies.

[Huckemann, 2009] Huckemann, V., E.B. Leão, and Marlon Leão, Acoustic comfort in office buildings with double skin glass façades, Bauphysik 31, Heft 5.

This study acoustically evaluated nine office buildings with double skin glass façades (DSF) in Project TwinSkin at the Institute for Building Services and Energy Design in Germany. Compared to other kind of façades, double skin façades are frequently promoted to provide higher sound insulation from external noise, especially road traffic noise. The study’s objective was to thoroughly analyze the apparent sound insulation properties of DSFs in the frequency range of 50 to 5,000 hertz (Hz). DSFs offer the advantage of operable windows or doors to the cavity, which provide occupant comfort. However, this leads to questions about the impairment of acoustic effectiveness and comfort arise. A significant influence of DSF design on sound insulation properties was found. The results show high levels of weighted apparent sound reduction up to 60 dB, whereas other results were 35 dB to 40 dB. Multi-story façades tend to have better sound insulation performance in relation to the other types of DSF, with an average of 13 dB higher values. The study concludes that aesthetically favorable arrangements of DSF can provide substantial influence on sound insulation.

[Ishizuka, 2012] Ishizuka, T. and K. Fujiwara, Traffic noise reduction at balconies on a high-rise building façade, Journal of the Acoustical Society of America, vol. 131, 3: pp. 2110-2117.

This study examines the performance of balconies with ceiling-mounted reflectors on a high-rise building façade using numerical analyses and scale-model experiments. The reflectors are designed to reflect direct and diffracted waves incident on the ceiling outside the balcony. The sound pressure level reduction, provided by the reflectors, on a window surface adjacent to the balcony was evaluated at intermediate floors levels. In terms of A-weighted sound pressure levels, a balcony equipped with reflectors reduces road traffic noise by 7 to 10 dB(A) compared to an ordinary balcony, at incident angles of noise close to the angle for which the reflectors are designed. The efficiency is roughly the same as, or greater than, that of a balcony with an absorbent ceiling. However, efficiency is reduced when the vertical incident angle of the noise is smaller than the design angle of the reflectors or the horizontal incident angle is large.

[Kim, 2017] Kim, M.K., C. Barber, and J. Srebric, Traffic noise level predictions for buildings with windows opened for natural ventilation in urban environments, Science and Technology for the Built Environment, vol. 23, 5: pp: 726–735.

The aim of this research was to discuss acoustical building performance for natural ventilation systems and to predict traffic noise levels for inhabitants residing in urban settlements. Natural ventilation systems use outdoor air to improve the quality of indoor environments and can reduce energy consumption. However, natural ventilation systems create an acoustical problem. For example, if windows are opened for natural ventilation, outdoor traffic noise can disrupt people working and sleeping in the building. In this study, a new method that combines an algorithm to predict traffic noise levels with FHWA's Traffic Noise Model vehicle noise spectra predicts the properties of noise propagation and attenuation through openings in urban environments. Additionally, outdoor sound propagation, the sound reduction index, and indoor sound transmission were included in the prediction process. To develop this method, researchers analyzed various traffic noise prediction methods to calculate sound attenuation during propagation outdoors based on ISO 9613. The study includes the noise attenuation effect from surrounding elements, such as building envelope, location of openings, opening ratio, and indoor boundary conditions. The simulations indicate that the integrated noise evaluation method can successfully predict the acoustic performance of natural ventilation systems in urban areas.

[Kocsis, 2014] Kocsis, L., Sound Reduction Effects of Plastered Rock Wool Slab Façade Thermal Insulation Systems, Bulletin of the Polytechnic Institute of Iasi, t. LX(LXIV), f.2: pp. 104-110.

Insulating exterior walls is one of the most important tasks in the energy efficient modernization of old buildings. Depending on material and structural design, the new layers can increase or decrease the sound reduction ability of the original supporting wall. If attention is given to the noise protection during the design, the plastered rock wool slab façade thermal insulation systems can result in better sound insulation performance for the exterior walls. In some cases, the insulation performance can increase the acoustic comfort in the rooms of buildings exposed to exterior ambient transportation noise. On the basis of the relevant features of the components of the complete outer wall, with the available detailed calculation method, this paper defined how the weighted sound reduction index of the original supporting wall can change, considering a spectrum adaptation term suitable for road traffic noise. With the help of praxis-oriented characteristic structural parameters, options for acoustic optimization are examined as well as the change in values available during energy and noise conscious construction.

[Mao, 2010] Mao, Q. and S. Pietrzko, Experimental study for control of sound transmission through double glazed window using optimally tuned Helmholtz resonators, Applied Acoustics, vol. 71: pp. 32-38.

This paper presents an experimental investigation of the passive control of sound transmission through a double-glazed window by using an arrangement of Helmholtz resonators (HRs), which are commonly used for narrow band noise control applications. Laboratory experiments involved placing the window between a reverberation chamber and an anechoic chamber. The window was subject to a diffuse field, approximating normal wave and oblique wave acoustic excitations. Three sets of HRs were designed and installed in the cavity of the window. Far field sound control performance was measured. The study presents and discusses the control performance from varying the number of HRs, incident acoustic field, and excitation sources (band-limited white noise and traffic noise examples), showing that a considerable reduction in transmitted sound pressure levels can be achieved around the mass-air-mass resonance frequency (50–120 Hz). The reductions in the transmitted sound pressure illustrate the potential of HRs for improving the sound insulation characteristics of double-glazed windows. The experimental results also indicate that tuning the HRs to the mass–air–mass resonance frequency does not guarantee the best possible noise reduction.

[Modra, 1985] Modra, J.D., Cost benefit analysis of traffic noise insulation for houses, Australian Acoustical Society Conference, 1985, Leura Gardens, New South Wales, pp. 48–53.

The study identifies six stages of traffic noise insulation for houses and finds five of these stages to a particular house to be justified on the basis of cost benefit analysis. The total cost of these five stages is $4,825 (1983 costs). However, to apply this package of noise insulation stages to all the houses in

Melbourne exposed to more than 68 dB(A); $L_{10(18hr)}$ would cost nearly two-thirds the annual budget for roadworks for the entire state of Victoria. It is important to note that the problem cannot be solved in the short to medium term through vehicle noise controls. Where an immediate reduction in the noise impact of arterial roads is required the only realistic option is to retrofit noise insulation measures to the houses affected.

[Mun Lee, 2017] Mun Lee, H., K.M. Lim, and H.P. Lee, Experimental and numerical studies on the design of a sonic crystal window, Journal of Vibroengineering, vol. 19, 3: pp. 2224–2233.

Four sets of numerical models helped evaluate the effects of shapes, staggering patterns, Helmholtz resonators, and array configurations on the acoustical performance of sonic crystals (SC). The study's overall design objective was to determine an efficient SC window to mitigate traffic noise levels in a student hostel of the National University of Singapore. Rectangular SCs consistently yielded the highest transmission loss for frequencies ranging from 300 Hz to 3,000 Hz compared to diamond and semi-circular SCs. Fully staggered patterns performed better than non-staggered and 50 percent staggered patterns for frequencies below 1,700 Hz. Helmholtz resonators were useful for enhancing low frequency noise mitigation. The prototype of the final designed SC window was fabricated and tested to validate the simulation result. Generally, numerical and experimental results resulted in similar trends. The maximum transmission loss of the SC window (about 18 dB) was found to occur at 900 Hz.

[Oldham, 2004] Oldham, D.J., M.H. de Salis, and S. Sharples, Reducing the ingress of urban noise through natural ventilation openings, Indoor Air 2004, 14 (Suppl 8): pp. 118–126.

For buildings in busy urban areas affected by high levels of road traffic noise, the potential to use natural ventilation can be limited by excessive noise entering through ventilation openings. This paper is concerned with techniques to reduce noise ingress into naturally ventilated buildings while minimizing airflow path resistance. It describes a combined experimental and theoretical approach to the interaction of airflow and sound transmission through ventilators for natural ventilation applications. A key element of the investigation was the development of testing facilities capable of measuring the airflow and sound transmission losses for a range of ventilation noise control strategies. A combination of sound reduction mechanisms—one covering low frequency sound and another covering high frequency sound—is required to attenuate noise from typical urban sources effectively. The paper proposes a method for quantifying the acoustic performance of different strategies to enable comparisons and informed decisions to be made leading to the possibility of a design methodology for optimizing the ventilation and acoustic performance of different strategies.

[Tong, 2011] Tong, Y.G., S.K. Tang, and M.K.L. Yeung, Full scale model investigation on the acoustical protection of a balcony-like façade device (L), Journal of the Acoustical Society of America, vol. 130, 2: pp. 673–676.

The acoustical insertion losses produced by a balcony-like structure in front of a window are examined experimentally. The results suggest that the balcony ceiling is the most appropriate location for the installation of sound absorption materials for the purpose of improving the broadband insertion loss, while the side walls were found to be the second best. Results also indicate that the acoustic modes of the balcony opening and the balcony cavity resonance in a direction normal to the window could have a great impact on the ⅓-octave band insertion losses. The maximum broadband road traffic noise insertion loss achieved is about 7 dB.

[Tong, 2015] Tong, Y.G., S.K. Tang, et. al., Full scale field study of sound transmission across plenum windows, Applied Acoustics, vol. 89: pp. 244–253.

A full-scale field measurement of the acoustical insertion loss of plenum windows was carried out. Two identical mock-up test rooms with dimensions the same as those commonly adopted for Hong Kong public housing were built side-by-side next to a busy trunk road. One of them was equipped with plenum windows, and the other with conventional side-hung casement windows. Four internal room settings were included in this study. Results show that both the room modes and the acoustic modes within the plenum window cavities were significantly affecting the low frequency sound transmission. After correcting for indoor reverberation/absorption effects, the acoustical benefit achieved by replacing side-hung casement windows with the plenum windows tested in the study was between 7.1 and 9.5 dB(A). By comparing the average equivalent sound pressure levels inside the two test rooms with the traffic noise weighted acoustical benefit, it was found that the changes of receiver room reverberation and acoustic modal effects due to such replacement would result in a reduction of plenum window sound insulation performance by 0.2 to 1.5 dB(A). The noise reduction effectiveness was better for larger rooms having more interior sound absorption.

[Yang, 2018] Yang, H., H. Cho, and M. Kim, On-site measurements for noise reduction through open windows of classrooms with different building dispositions, Applied Acoustics, vol. 139: pp. 165–173.

In Korea, mitigation measures for traffic noise at schools are implemented during the urban planning process to meet the acceptable level of less than 65 dB(A) at a building façade as stipulated by the environmental impact assessment (EIA). Meanwhile, traffic noise at schools is managed to satisfy the acceptable level of less than 55 dB(A) in a classroom with open windows as indicated by the School Health Act (SHA). This variation indicates the possibility to exceed the acceptable SHA level for EIA-approved schools if the noise reduction through open windows is less than 10 dB(A). This study was carried out using onsite measurements for noise reduction through classrooms' open windows at 19 schools to review the appropriate EIA level to meet the acceptable SHA level. The building orientations were categorized into four types:

- Parallel orientation between road and classroom (P type)
- Perpendicular orientation between road and classroom (V type)
- Cross-sectional orientation between road and classroom (PV type)
- Parallel orientation between road and hallway (H type)

The results showed different noise reduction requirements through open windows according to the type of building orientations on the order of H (16.9 dB(A)), V (9.2 dB(A)), PV (8.4 dB(A)), and P (6.7 dB(A)). This was attributed to the change in incidence angles between the road and open windows and was confirmed by measurements using a loudspeaker. It was concluded that the acceptable SHA noise level could be exceeded especially for the P, PV, and V types, indicating the need for different noise mitigation measures according to building orientations.

[Zhisheng, 2007] Zhisheng, L., L. Dongmei, et. al., Noise Impact and Improvement on Indoors Acoustic Comfort for the Building Adjacent to Heavy Traffic Road, Chinese Journal of Population, Resources and Environment, vol. 5, 1: pp. 17-25.

A good acoustic environment is essential to maintaining a high level of satisfaction and emotional health among residents. Unwanted sounds come from both indoor and outdoor sources. For residential buildings adjacent to roads with heavy traffic, outdoor traffic noise is the main source that affects indoor acoustic quality and health. Ventilation and outdoor noise prevention become contradictions for the residents in China for buildings adjacent to roads with heavy traffic. Traffic noise emission sources are mainly from the motors of trucks, buses, and motorcycles as well as brakes. In this paper, two methods of traffic noise reduction on the indoor sound environment and comfort were carried out to study and compare residential buildings adjacent to roads with heavy traffic in a city. One method was to install noise barriers on the two sides of the roadway, which consisted of sound-proof glass and plastic materials. The effect of this sound-insulation method was heavily dependent on the relative distance between the noise barrier and interior spaces. A reduction of average pressure level of 2 to 15 dB was achieved at the places within the shadow zones of the noise barriers. However, at the equivalent height of a single noise barrier, the noise reduction improvement was slight. For locations above the shadow zone of the barriers, the traffic noise was increased by 3 to 7 dB. The other method of noise reduction for buildings adjacent to roads with heavy traffic was to install soundproof windows, which also involved the conversion from natural ventilation to mechanical ventilation. A reduction of sound pressure level by an average of 5 to 17 dB was found to be achieved compared with common glass windows, using soundproof glass windows. These two methods are helpful to isolate high frequency noise but have the disadvantage of not being as effective for low frequency noise. For low frequency noise, installing thick and cotton curtains and porous carpet only decreased noise levels by 2.4 to 4.5 dB. Further study is required to reduce interior traffic noise, especially in the low frequency range.

Vegetation

[Attenborough, 2016] Attenborough, K., I. Bashir, and S. Taherzadeh, Exploiting ground effects for surface transport noise abatement, Noise Mapp. 3, pp. 1–25.

The potential traffic noise reduction using acoustically soft surfaces and artificial roughness (0.3 m high or less) was explored through laboratory experiments and outdoor measurements at short and medium ranges. The applicability of ground treatments depends on the space usable for the noise abatement and the receiver position. When acoustically soft ground replaces the acoustically hard ground, along with artificial roughness configurations, noise reduction is possible along surface transport corridors without breaking the line of sight between source and receiver. This could be a useful noise abatement alternative to noise barriers and reduces visual intrusion and changes in wind flow. One successful roughness design was a square lattice, found to offer a similar insertion loss to a regularly spaced parallel wall arrays of the same height but with twice the width. The lattice design has less dependence on azimuthal source-receiver angle than parallel wall configurations. **Table 10** shows results of multiple scenarios of ground treatment while **Table 11** shows results if 100 percent soft ground is used. The ground treatment also results in a change in the frequency spectra.

Table 10. Insertion Losses Compared to Smooth, Hard Ground for Receivers at 50 to 100 meters and 1.5 to 4 meters of Height on a Two-lane Road with 95 percent Cars and 5 percent Trucks at 50 Kilometers per Hour

Ground treatment	Insertion loss dB			
Receiver distance from road edge m	50		100	
height m	1.5	4	1.5	4
Replacing a 47.5 m- or 97.5 m-wide strip of hard ground by high flow resistivity grassland	5.5	1.7	7.3	4.5
Replacing a 47.5 m- or 97.5 m-wide strip of hard ground by low flow resistivity grassland	7.6	2.0	12.1	6.3
Replacing a 50 m- or 100 m-wide strip of hard ground by low flow resistivity ground growing 1 m-high dense crops	13.1	6.7	16.7	12.2
Replacing 25 m of hard ground nearest road by gravel (flow resistivity 10 kPa s m^{-2} at least 0.1 m deep)	9.1	3.0	9.3	7.5
Replacing 25 m of hard ground nearest road by alternating 1 m-wide strips of hard ground and gravel (flow resistivity 10 kPa s m^{-2} at least 0.1 m deep)	7.3	2.8	6.9	6.3
1.65 m-wide array of 9 parallel walls 0.3 m high, 0.05 m thick, 0.2 m centre-to-centre spacing	5.8	5.4	5.2	5.7
3.05 m-wide array of 16 parallel walls, 0.05 m thick, 0.2 m centre-to-centre spacing	6.6	5.6	6.1	6.5

Ground treatment	Insertion loss dB			
Receiver distance from road edge m	50		100	
height m	1.5	4	1.5	4
12.05 m-wide array of 61 parallel walls 0.3 m high, 0.05 m thick, 0.2 m centre-to-centre spacing	8.6	5.1	8.5	8.2
1.53 m-wide 0.3 m-high 0.2 m-square cell lattice	5.9	5.6	5.3	5.8
3.05 m-wide 0.3 m-high 0.2 m-square cell lattice	7.2	6.1	6.5	7.0
12.05 m-wide 0.3 m-high 0.2 m-sqare cell lattice	10.5	6.1	10.0	9.6

TABLE 11. REDUCTIONS IN OVERALL LEVELS DUE TO THE INTRODUCTION OF 100 PERCENT "SOFT" GROUND NEXT TO A ROAD

Prediction scheme	Reduction dB			
width of soft ground from nearest road edge m	47.5		97.5	
Receiver height m	1.5	4.0	1.5	4.0
CRTN	5.5	3.3	7.0	4.8
ISO 9613-2	4.0	2.8	4.5	4.0

This research points out that ground effects can be exploited for noise control. Other advantages of exploiting ground effect is there is no impassable division between communities and offers the opportunity of adding to the "green" in cities. The planting of vegetation also can increase the influence of ground effect other than the seasonal effect of the vegetation as a result of creating root zones. Significant reductions in surface transport noise (up to 10 dB) can be obtained by the deliberate introduction of an at least 3 m wide strip of 0.3 m high roughness on flat hard ground. A favorable cost benefit analysis of the deployment of lattices alongside and in the central reservation of a four-lane road suggests a useful alternative to traditional noise barriers particularly when used in combination with low noise road surfaces.

[Aylor, 1972] Aylor, D., Noise Reduction by Vegetation and Ground, Journal of the Acoustical Society of America, vol. 51, 1 (Part 2): pp. 197-205.

Transmission of random noise through dense corn, a dense hemlock plantation, an open pine stand, dense hardwood brush, and over-cultivated soil was measured. The relation between attenuation and frequency in these diverse cases suggested models that permit the prediction of attenuation in any configuration of vegetation and soil. The corn crop had an excess attenuation of 6 dB/100 ft for each doubling of frequency between 500 and 4,000 Hz. The stems of the hemlock, pine, and brush all reduced noise by only about 5 dB/100 ft at 4,000 Hz. Bare ground attenuates frequencies of 200 to 1,000 Hz, and the frequency of maximum attenuation depends on the soil permeability to air. Thus, tilling the soil reduced the frequency of peak attenuation from 700 to 350 Hz and increased maximum attenuation at 52 m from the source by nearly 80 percent. This also indicates that earlier conflicting reports of noise attenuation by vegetation appear reconciled if ground attenuation is considered. Scattering and ground attenuation are the principal factors in sound attenuation by vegetation. Both factors attenuate relatively less sound as distance from the sound source increases. Hence measurements far from the source can underestimate the effect of a narrow band of vegetation or soil.

[Bashir, 2015] Bashir, I., S. Taherzadeh, H. Shin, and K. Attenborough, Sound propagation over soft ground without and with crops and potential for surface transport noise attenuation, Journal of the Acoustical Society of America, vol 137, 1: pp. 154–164.

Growing demand on transportation, road, and railway networks has resulted in increased levels of annoyance from road traffic. Optimized use of green surfaces in combination with vegetation may be desirable as a method for reducing the noise impact of road traffic in urban and rural environments. Sound propagation over soft ground and through crops has been studied through outdoor measurements at short and medium ranges and through predictions. At lower frequencies, the ground effect is dominant and there is little or no attenuation due to crops. At higher frequencies, above 3 to 4 kHz, the attenuation in crops is dominant. It also was found that the ground effects and the influence of crops can be treated independently and can be added to obtain the total effect. Sound attenuation by crops is the result of multiple scattering between the stems and leaves, loss of coherence, and viscous and thermal losses due to foliage. The major contribution is associated with viscous and thermal losses. A model for sound attenuation by vegetation was proposed. Insertion losses for a typical road traffic noise source have been calculated for either replacing hard ground with different types of acoustically soft ground or by growing crops along the roadsides.

[Defrance, 2019] Defrance, J., P. Jean, and N. Barrière, Can trees and forests help improve the sound environment?, Public Health 2019/HS(S1), pp.187-195.

In the case of a wooded strip along a road infrastructure, it was recommended that this strip, sufficiently long, have a thickness of at least 25 meters and a density of at least 0.25 tree/m^2 (average trunk diameter of at least 0.2 m) to have a significant attenuating effect (3 dB(A)). The higher the density and thickness, the greater the sound attenuation. It also was recommended that densifying the first few meters above the ground as much as possible by combining trees and shrubs creates more effectiveness. For deeper wooded strips (100 m) and therefore greater propagation distances, the "negative" meteorological effects (for example, clear night without wind) can be almost canceled with the trees becoming a "climate screen."

For the acoustic efficiency of a woodland strip to be effective throughout the year, planting hardwoods or a combination of hardwoods and evergreens was recommended. Regarding the soil, cultivating it before planting trees and adding decomposed organic matter to it was recommended, so that it remains acoustically absorptive. In the case of a row of trees planted behind a noise barrier and whose canopy extends widely above it, a significant attenuation effect can be observed but it remains limited to downwind conditions (sound source to receiver). If the receivers (pedestrians or homes) are located less than 20 m behind the screen, it is not recommended to plant a row of trees whose canopy extends beyond the screen head, so as not to degrade the diffracting nature of the protection by the additional diffusion of noise by the branches, in particular at high frequencies. Concerning noise barriers, it is advisable to plant trees and shrubs on slopes, with the rule that their crown does not exceed the upper part of the protection. Trees in the heart of the City have a very small impact on the overall reduction in road noise. However, they participate by sound diffusion effects of the branches and leaves and lessen the reverberating character of certain mineral squares or streets and boulevards where urban roads are bordered by buildings arranged on both sides in a continuous fashion. The change to the noise environment was reported to be positively perceived in this case. Additionally, the tree's presence improves the visual quality of the urban environment.

[Embleton, 1963] Embleton, T.F.W., Sound Propagation in Homogeneous and Evergreen Woods, Journal of the Acoustical Society of America, vol 3: pp. 1119–1125.

The sound attenuation due to trees was measured (under atmospheric conditions requiring no corrections) at about 20 locations representing four selected types of woods. A constant excess attenuation of 7 dB/100 ft was found at frequencies below 2,000 Hz, in disagreement with previous reporting. With the sound source in the open at the edge of the woods, effects due to change of medium were observed, with an increase of sound pressure level in the woods and a distinctive S-shaped curve of attenuation versus frequency. This is suggestive of resonant absorption, although a theory developed according to such a hypothesis, while having the correct frequency dependence, fails to predict the magnitude of the observed results by a factor of 10. Transverse modes of vibration of the branches were shown to be the oscillators active in the frequency range of interest, which is 250 Hz in the lower branches to about 1,100 Hz near the top of the tree, indicating that trunk resonances also may be important.

[Fan, 2019] Fan, J., H. Hao, and R. Fan, Noise Reduction Effect of Plant Landscape in City Zoo Based on Animal Protection, Revista Cientifica, FVC-LUZ, vol. 29, 5: pp. 1180–1188.

Through this measurement study, the following conclusions were drawn about the noise reduction function of the urban zoo plant landscape:

- Shrubs, ground cover, and soil produce better attenuation effects on higher frequency sounds above 2,000 Hz. Ground cover plants and soil better attenuation effects on medium frequency sounds of 500–2,000 Hz. Low frequency sounds are relatively difficult to reduce, although soil and ground cover plants can have a certain attenuation effect. The performance of coniferous species needs further experiments to prove effects.
- Plants suitable for use in noise-reducing green space include: sycamore, Liriodendron, coral, palsy, white peony, sweet gum, rough-leaved tree, double-yang wood, huangshan eucalyptus, ginkgo, magnolia, camphor, Lechang Xiaoxiao, Du Ying, Nuwa, Coral Tree, Photinia, Manyuanchun, Camellia, Huzizi, Oleander, Mosquito Tree, Rhododendron, Octagonal Golden Plate, Chinese Ivy, and Dawu

Wind Grass. Saxifrage Cascades such as cedar, cedar, and metasequoia also can be used with broad-leaved trees, but the collocation method remains to be studied.

- Planting in a noise-reducing forest belt is the best spacing with one crown, while spacing on the level parallel to the sound source can be larger and use two or three crowns. When the planting density of the plant is high, the staggered, aligned or scattered planting forms may be adopted, depending on the noise reduction requirements and the landscape effect requirements, preferably two or three rows. When the density is low, it is suitable to adopt the scattered pattern which allows the leaves of the middle plant to cover the entire green belt to the maximum extent.
- The noise reduction effects of plant communities are related to their structure. Coniferous forests and evergreen broad-leaved forests have the best noise reduction effects. The noise reduction effect of plant communities is significantly better than that of open space. The noise attenuation value of plant communities during growth period is 4–5 dB greater than the radiation period.

[Gratani, 2013] Gratani, L. and L Varone, Carbon sequestration and noise attenuation provided by hedges in Rome: the contribution of hedge traits in decreasing pollution levels, Atmospheric Pollution Research, vol. 4: pp. 315–322.

Hedges are ubiquitous green elements in many European cities. The selection of hedge types characterized by different traits can be suggested for urban greening projects to decrease pollution levels. To this end, carbon dioxide (CO_2) sequestration and noise attenuation capability were analyzed in the following hedge types: *Laurus nobilis*, *Nerium oleander*, *Pittosporum tobira* and *Pyracantha coccinea*, largely used as green infrastructure in Rome (Italy). Representative hedges for each species were selected in high level traffic streets in the City center. Traffic density was monitored simultaneously with CO_2 concentration and noise level in each of the considered city center locations. The multiple regression analysis predicted noise attenuation by a linear combination of total leaf area, total leaf density, and leaf mass area of the considered hedge types. All the considered species, being evergreens, were active all year long, including winter, when CO_2 emissions from road transport peaked. Nevertheless, among the considered hedge types, *P. tobira* and *L. nobilis* were the most efficient species in both monthly CO_2 sequestration capability and noise attenuation. The results give insight on the use of hedges to mitigate pollution effects. Moreover, this method can be used to monitor hedge contribution to air quality, in relation to various elements in the City (i.e., traffic density, increased traffic, application of management projects, and local laws).

[Harris, 1986] Harris, R.A., Vegetative Barriers: An Alternative Highway Noise Abatement Measure, Noise Control Engineering Journal, vol. 27, 1: pp. 4–8.

It was reported that excessive highway noise levels affect almost 40 percent of the U.S. population. Efforts to solve a problem of this magnitude require a significant expenditure of funds, unless innovative noise abatement measures are utilized. The ability of vegetation to reduce highway noise levels has long been ignored. A primary goal of this paper was to present evidence that vegetation can be used as an effective highway noise barrier under certain circumstances. The results of previous studies on the effects of vegetation on highway traffic noise, as well as onsite field measurements conducted by the author, are presented. In addition, an actual situation where vegetation was selected as an alternative highway noise abatement measure is described.

[Harris, 1985] Harris, R.A, and L. F. Cohn, Use of Vegetation for Abatement of Highway Traffic Noise, J. Urban Plann. Dev., vol. 111, 1: pp. 34–48.

The high cost of conventional highway noise abatement methodology (i.e., free-standing walls) has made mitigation of many impacted sites economically infeasible. A solution that may prove more economically reasonable for those locations is the use of strategically planted evergreen vegetation to form a dense barrier between the highway and impacted area. Field measurements were made on vegetative barriers planted only for visual screening purposes. The results of these measurements indicate that a 2 to 3 dB decrease in noise levels is possible with a narrow [30 ft (9.1 m)] belt of vegetation. These measurements are supported by the literature review, which indicates that an even further reduction may be possible with vegetation planted and maintained in such a way as to encourage maximum density growth. When coupled with the non-quantifiable psychological effects of blocking the highway from view and the low construction cost, the potential for solving uneconomical abatement problems is clear.

[Horoshenkov, 2013] Horoshenkov, K.V., A. Khan, and H. Benkreira, Acoustic properties of low growing plants, Journal of the Acoustical Society of America, vol. 133, 5: pp. 2554–2565.

The plane wave normal incidence acoustic absorption coefficient of five types of low growing plants was measured in the presence and absence of soil. These plants are generally used in green living walls and flower beds. Two types of soil are considered in this work—a light-density, man-made soil and a heavy-density natural clay base soil. The absorption coefficient data are obtained in the frequency range of 50 to 1,600 Hz using a standard impedance tube of diameter 100 millimeters (mm). The equivalent fluid model for sound propagation in rigid frame porous media is used to predict the experimentally observed behavior of the absorption coefficient spectra of soils, plants, and their combinations. Optimization analysis is employed to deduce the effective flow resistivity and tortuosity of plants which are assumed to behave acoustically as an equivalent fluid in a rigid frame porous medium. It is shown that the leaf area density and dominant angle of leaf orientation are two key morphological characteristics which can be used to predict accurately the effective flow resistivity and tortuosity of plants.

[Hosseini, 2016] Hosseini, S.A.O., S. Zandi, A. Fallah, and M. Nasiri, Effects of geometric design of forest road and roadside vegetation on traffic noise reduction, J. For. Res., vol. 27, 2: pp. 463–468.

Geometric design of forest roads and design of their landscapes can reduce noise pollution and its harmful effects on human health. The effects of technical and biological parameters, such as geometric road design and various roadside tree stands on reducing noise pollution according to tree density and distance from roadways in Darabkola Forests, Sari, Iran, were investigated. The noise generated by a car

(Land Rover) relative to changes in longitudinal slope, horizontal curve radius and type of road pavement was measured. Also measured were noise levels according to roadside tree density and stand type (coniferous and hardwood) in 40 rectangular plots of three widths (25, 100 and 300 m) and 50 m length that were randomly demarcated along forest roads. The changes in noise level were recorded using a decibel meter with an accuracy of ±1.5 dB and resolution of 0.1 dB. Noise levels were greater alongside unpaved roads than alongside paved roads. There was an inverse relationship between the measured noise level and horizontal curve radius. The noise levels on horizontal curves with radii less than 30, 30 to 45 m and more than 45 m were 64.8, 70.8 and 75.9 dB, respectively. The noise level increased with the increasing longitudinal slope of the road. There was a significant difference between the noise level on slopes less than 3 percent (67 dB) and 3 to 8 percent (71.2 dB) in comparison with slopes greater than 8 percent (77.8 dB), ($p<0.05$). Pinus brutia L. reduced the noise levels (about 6 dB) in stands of ⅓ density of mixed hardwoods within 25 m from the middle of the road. Careful design of geometric properties of forest roads as well as planting coniferous trees with hardwoods was found to be a suitable solution for reducing noise pollution.

[Jang, 2015] Jang, H. S., H. J. Kim, and J.Y. Jeon, Scale-model for measuring noise reduction in residential buildings by vegetation, Building and Environment, vol. 86: pp. 81–88.

This paper proposes an evaluation procedure using a scale model to assess the noise reduction effects of vegetated façades for sustainable urban building designs. The absorption coefficients of the scale-model materials were measured to fit the absorption characteristics of real vegetation. The ground impedance of asphalt also was measured to deduce the acoustical properties of ground surfaces and to select the ground material. To assess the reduction of road traffic noise, a line source for a 1:10 scale model was modeled using ribbon tweeters that generated high frequencies ranging from 1 kHz to 40 kHz. Accordingly, the effects of adding vegetated façades were evaluated in the scale model of a street canyon. The noise reduction due to the vegetated façades was less than 2 dB at pedestrian level in a two-lane street canyon. The scale model results were compared with geometric computer simulation results and both evaluation methods showed similar results. The suggested modeling method can be useful for evaluating noise reduction in street canyons by vegetation considering realistic features such as the absorption, scattering, and diffraction associated with the materials and sound sources according to the shape of the vegetation.

[Jang, 2015] Jang, H.S., S.C. Lee, J.Y. Jeon, and J. Kang, Evaluation of road traffic noise abatement by vegetation treatment in a 1:10 urban scale model, Journal of the Acoustical Society of America, vol. 138, 6: pp. 3884–3895.

A 1:10 scale of a street canyon and courtyard was constructed to evaluate sound propagation when various vegetation treatments, including trees, shrubs, vegetated façades, and green roofs were installed in the urban environment. Noise reductions in the street canyon and courtyard were measured for both single and combined vegetation treatments. Vegetated façades mitigated the overall noise level up to 1.6 dB(A) in the street canyon, and greening façades were effective to reduce low frequency noise levels below 1 kHz. Trees increased the noise level at high frequency bands to some extent in the street canyon, while the noise level over 1 kHz decreased in the courtyard after installing the street trees. This is due to the tree crowns diffusing and reflecting of high frequency sounds in the street canyon. Green roofs offered significant noise abatement over 1 kHz in the courtyard, while the vegetated façade was effective to reduce noise levels at low frequencies. In terms of the integrated effects of vegetation treatments, a combined vegetation treatment was less effective than the sum of single treatments in the street canyon. The maximum noise reduction observed for all combinations of vegetation treatments provided 3.4 dB(A) of insertion loss in the courtyard.

[Karbalaei, 2915] Karbalaei, S.S., E. Karimi, et. al., Investigation of the Traffic Noise Attenuation Provided by Roadside Green Belts, Fluctuation and Noise Letters, vol. 14, 4: pp. 1–9.

This study reviewed the potential role of greenbelts of three different widths (25, 50 and 100 m) along the roadside for noise attenuation using various tree species. The reduction of noise level was statistically analyzed and showed significant differences between stations. The results indicated a positive correlation that the greenbelts has a significant effect on the attenuation of noise pollution. In different testing, a mixture of conifers and broadleaves of 100 m in width and 50 m width were tested. Noise levels existed between 40 dB(A)–44 dB(A). However, the actual reduction values, after corrected for the control case, ranged from 7–17 dB(A). The maximum noise level reduction compared to the open area was for trees and shrubs of 100 m in width. The results can be used as guidance for construction of tree belts for noise attenuation in environmental planning and management.

[Kim, 2014] Kim, M. H. Yang, and J. Kang, A case study on controlling sound fields in a courtyard by landscape designs, Landscape and Urban Planning, vol. 123: pp. 10–20.

Courtyards surrounded by buildings often have acoustic defects such as strong flutter echoes and long reverberation time (RT) that can increase noise annoyance. Therefore, it is important to absorb and diffuse sound energy propagating in such places. The aim of this paper is to investigate how applicable landscape designs can contribute to controlling sound fields in a courtyard, with attention to the acoustic effects of vegetation. Through a case study, differences between courtyard sound fields were examined by in-situ measurements before and after applying a practical landscape design using vegetation, wood decking, and street furniture. In addition, computer simulations were carried out to explore the acoustic effects of applicable landscape designs using vegetation, including climbing ivy, green wall, grass, and bedding plants. The results for the in-situ measurements showed reductions in sound levels and RT at 500 Hz of 3.1 dB and 40 percent (1.0 s), respectively. The results for the computer simulation showed that the green wall on the façade can reduce speech levels and RT at 500 Hz by 9.3 dB(A) and 81 percent (2.1 s), respectively. The bedding plants on the ground decreased the speech level by 2.2 dB(A) and increased RT at 500 Hz by 12 percent (0.3 s). At different floor levels in the accommodation building, the speech level and RT at 500 Hz were decreased by the vegetation by up to 5.5 dB(A) and 66 percent (1.1 s), respectively.

[Koprowska, 2018] Koprowska, K., E. Laszkiewicz, J. Kronenberg, and S. Marcińczak, Subjective perception of noise exposure in relation to urban green space availability, Urban Forestry & Urban Greening, vol. 31: pp. 93–102.

Increasing green space availability can create a natural buffer to the adverse effects of living in an urban environment. These positive effects of urban green space can be directly related to an objective reduction of noise levels and—indirectly—to the subjective perception of noise exposure. In this study carried out in Lodz, Poland, the relationship between objective noise levels and the subjective perception of noise exposure by urban residents in relation to urban green space availability was explored. Objective noise exposure was expressed as geographic information system (GIS) modeled L_{den} derived from noise maps (compliant with the Environmental Noise Directive, 2002/49/EC), and subjective (self-reported) perception of noise exposure as declared in a questionnaire-based survey. The percentage of green space in a buffer, the objectively measured noise level, and the perceived exposure to noise were compared to find the most appropriate radius of the green space buffer. The green space coverage (which is not correlated with an objective noise level) was chosen to avoid potential multi-collinearity in regression models. This contrasts with most studies, in which the radius of the buffer is set a priori. The selected buffer of green space coverage—300 m (representing green space availability)—was thus compared with perceived noise exposure. The direct effect of objectively measured noise levels, education, the presence of noisy neighbors, and building characteristics were found to be the most important variables influencing the self-reported perception of noise by urban residents. The indirect effect of green space availability on noise perception was not strong, yet statistically significant. Although this study does not provide clear-cut evidence, it indicates that the indirect, psychological effects of urban green spaces can positively affect the life satisfaction of urban residents.

[Koptseva, 2018] Koptseva, E and A. Zaytsev, Noise Reduction Properties of Urban Green Spaces in Saint-Petersburg, Green Technologies and Infrastructure to Enhance Urban Ecosystem Services, Proceedings of the Smart and Sustainable Cities Conference 2018, pp. 145–150.

Noise-proof properties of green spaces were studied on the streets with heavy road traffic in Saint-Petersburg. Noise reduction was considered depending on the species composition and planning concept of the plantings. It has been shown that planning concepts such as number of rows or widths of tree planting are more important for noise reduction than species composition of trees and shrubs. The double-row planting of deciduous trees with a green band width of more than 18 m and crowns overlapping of neighboring trees by 60 to 70 percent has the best noise protection features.

[Kotzen, 2004] Kotzen, B., Plants and Environmental Noise Barriers, Proceedings IC on Urban Horticulture, Acta Hort 643, pp. 265–275.

Since the introduction of more effective and stringent noise legislation across Europe, environmental noise barriers have become ubiquitous features along many road corridors. Barriers to mitigate noise and views of traffic may be located wherever there is development and human activity, along inner-city routes, suburban byways, and along more rural routes where villages and recreational areas require protection. It must be recognized that noise barriers are significant architectural features and that they should be designed to fit into their local environments. Barriers not designed for each individual location, could remain alien visual elements and diminish landscape character and landscape quality. The authors stated that noise barrier design should include the appropriate manipulation of elements, materials, and most importantly incorporating the use of plants. Plants not only help to integrate the barrier into its surroundings, by reducing apparent scale and screening elements, but they also can provide an aesthetic contribution by softening appearance and providing architectonic form. A great depth of soil is not a necessary requirement. Plants can indeed form an integral part of noise barrier design in what are termed "bio-barriers." The earth mound (berm) is the simplest effective environmental noise barrier. Reinforced earth mounds can be used where space is limited but a natural looking barrier is required. Bio-barriers may be divided into four generic types—the "A" frame and vertical, the box wall, woven-willow, and stack and crib bio-barriers. Many studies have been undertaken to indicate whether plants themselves reduce noise and this appears possible in certain situations.

[Li, 2010] Li, H.N., C.K. Chau, and S.K. Tang, Can surrounding greenery reduce noise annoyance at home?, Science of the Total Environment, vol. 408: pp. 4376–4384.

Annoyance has been identified as the most important psychological impact from noise. Beside socioeconomic status, residing neighborhood characteristics such as greenery have been shown to be able to reduce noise annoyance. To study the effects of these potential annoyance modifiers, 992 responses were collected through face-to-face interviews via questionnaire surveys. Among them, 688 responses were collected along with adequate dwelling information which enabled a more accurate prediction of home noise levels. Data were analyzed using an ordered logit model. Results indicate that greenery perception exerts considerable influence on noise annoyance rating while at home. Wetland parks and garden parks were shown to be able to reduce noise annoyance to a greater degree than grassy hills. The effects of the perceived amount of greenery on noise annoyance reduction while at home were reported to differ according to the setting of greenery participants perceived from individual homes.

[Li, 2019] Li, M., T. Van Renterghem, J. Kang, and D. Botteldooren, Sound absorption by tree bark, Proceedings of the 23rd International Congress on Acoustics, pp. 582–587.

Scattering of sound waves by tree trunks is part of the noise reducing potential of tree belts and it has been previously shown that the absorbing properties of the trunks are relevant in this respect. Detailed information on bark absorption currently is very limited. Therefore, laboratory experiments were conducted with an impedance tube to measure the bark sound absorption of various species, including variations in bark thickness, tree age, density, and trunk diameter. Preliminary measurements were made to define the relevant part of the trunk for its acoustic absorption and to come to a reproducible sample handling procedure. The measurements show that the absorption (at normal incidence) is generally below 0.1 for the deciduous species measured with only a small variation.

[Ow, 2017] Ow, L.F. and S. Ghosh, Urban cities and road traffic noise: Reduction through vegetation, Applied Acoustics, vol. 120: pp. 15–20.

This study was carried out to determine the effect of roadside vegetation on the reduction of road traffic noise under varying planting intensities. Roadside vegetation ranging from minimal planting through to moderate and dense plantings were used. The results showed that traffic noise was reduced by 50 percent when vegetation was enhanced from a minimal to moderate planting intensity, and no enhancement in noise reduction was observed as vegetation was further increased to a dense intensity. A 5 m depth of vegetation barrier was found to be an ideal depth for traffic noise reduction. On average, vegetative barriers (moderate to dense) were able to reduce traffic noise by 9 to 11 dB(A). Trunk size was found to be linearly related to traffic noise abatement and synthetic barriers were found to be inferior to tree belts both psychologically and in absolute values of noise. This report also investigated the effectiveness associated with setbacks where it was found that the greater the setback distance, the higher the level of noise amelioration and a 10 m depth identified as the threshold for an effective tree belt.

[Pérez, 2016] Pérez, G., J. Coma, et. al., Acoustic insulation capacity of Vertical Greenery Systems for buildings, Applied Acoustics, vol. 110: pp. 218–226.

Vertical Greenery Systems (VGS) are promising contemporary green infrastructure which can contribute to ecosystem enhancement at both building and urban scales. Vegetation has been used to acoustically insulate urban areas from traffic noise. With the introduction of vegetation in buildings, using VGS, experimental data was gathered on its operation as acoustic insulation tool in the built environment. In this study, the acoustic insulation capacity of two VGS was conducted through in-situ measurements according to the UNE-EN ISO 140-5 standard. From the results, it was observed that a thin layer of vegetation (20 to 30 cm) was able to provide an increase in sound insulation of 1 dB for traffic noise (in both cases, Green Wall and Green Facade) and an insulation increase between 2 dB (Green Wall) and 3 dB (Green Facade) for pink noise. Recommendations for further work on the vegetation's contribution to sound insulation included the influence of factors such as the mass (thickness, density, and composition of the substrate layer) type of modular unit of cultivation, the impenetrability (sealing joints between modules) and structural insulation (support structure).

[Price, 1988] Price, M.A, K. Attenborough, and N.W. Heap, Sound attenuation through trees: Measurements and models, Journal of the Acoustical Society of America, vol.84, 5: pp. 1836–1844.

Measurements obtained at three British woodlands for the frequency-dependent attenuation of broadband sound with distance under neutral atmospheric conditions were compared with modeling predictions obtained by summing the separate contributions of the ground, trunks, branches, and the foliage. The two latter contributions are predicted by an empirically modified multiple scattering approach. The principal features of the measured spectra, as compared to the low-frequency peak for excess attenuation below 500 Hz was a gradual increase of attenuation with frequencies above 1 kHz. being predicted by the composite model and were observed differences in acoustic propagation for the three different woodland areas.

[Pudiowati, 2013] Pudjowati, U.R., B. Yanuwiadi, R. Sulistiono, and S. Suyadi, Effect of Vegetation Composition on Noise and Temperature in Waru-Sidoarjo Highway, East Java, Indonesia, International Journal of Conservation Science, vol. 4, 4: pp. 459–466.

Infrastructure development tends to minimize green open space. This decrease in green open space could result in a noise and temperature rise due to the increasing amount of residential development, the number of motor vehicles, and industrial facilities using fossil fuels. It could be mitigated by planting along highways. Vegetation as a natural abatement, can help to reduce noise and temperature. Evaluated vegetation composition existing along the highway included tree-shrub-bush composition, no vegetation, just tree composition, and tree-shrub composition. This study's goals were to compare the percentage of noise reduction and a decrease in the temperature for each vegetation composition existing along the highway. The results of the study showed that vegetation composition which consists of trees, shrubs and bushes was more effective to reduce the noise (up to 12.25 percent) and to decrease temperatures (up to 8.18 percent). It was recommended that Waru-Sidoarjo highway management plant a tree-shrub-bush vegetation composition to reduce the noise that occurs along the highway and help decrease temperatures.

[Reethof, 1973] Reethof, G. Effect of Plantings on Radiation of Highway Noise, Journal of the Air Pollution Control Association, vol. 23, 3: pp. 185–189.

Based on the extensive literature and the tests performed by the author, trees and shrubs were found to be effective as noise reducing media for road transportation equipment. The planting should be as dense as practical consisting of deciduous or coniferous trees with as much underbrush or dense branch structure as possible. Analysis of the data does not indicate any major differences between species. The process of attenuation appears to be a combination of diffusion by scattering and absorption. Tree height, depth of planting, and particularly density, appear to be the dominant variables. Attenuations of up to 8 dB(A) for 100 ft deep tree belts can be achieved for dense 40 to 50 ft high plantings with a visibility of about 50 ft or less.

[Reethof, 1976] Reethof, G., L.D. Frank, and O.H. McDaniel, Absorption of Sound by Tree Bark, USDA Forest Service Research Paper NE-341.

Laboratory tests were conducted with a standing wave tube to measure the acoustic absorption of normally incident sound by the bark of six species of trees. Twelve bark samples, 10 cm in diameter, were tested. Measurements of the sound included seven frequencies between 400 and 1,600 Hz.

Absorption was generally about 5 percent and exceeded 10 percent for only three samples, and then only at 1,250 Hz or above. No general trend was evident in the variation of absorption with frequency.

[Samara, 2011] Samara, T. and T. Tsitsoni, The effects of vegetation on reducing traffic noise from a city ring road, Noise Control Engineering Journal, vol. 59, 1: pp. 68-74.

This study was designed to investigate the reduction of road noise by vegetation along the ring road of Thessaloniki. Road noise was measured at two sites, one through a belt of trees and the other on grass-covered ground. A total of 245 measurements were taken from each location over a two-month period and expressed as differences in L_{Aeq}. Traffic measurements of the number of vehicles per minute, the type of vehicles, and analytic description of vegetation were taken at both location. The results showed higher noise reductions through the belt of trees than over the grass-covered ground. According to the results of this research, the largest reduction (6 dB(A)) was seen with the *Pinus brutia* belt of trees, 60 m away from the road. This noise reduction was considered satisfactory due to the tree belts extending on both sides of the ring road.

[Tyagi, 2006] Tyagi, V., K. Kumar, and V.K. Jain, A study of the spectral characteristics of traffic noise attenuation by vegetation belts in Delhi, Applied Acoustics, vol. 67: pp. 926-935.

Traffic noise attenuation in one-third octave band frequencies were measured at three vegetation locations and a control site in Delhi, the capital city of India. The study indicates that attenuation generally increases with frequency. At low frequencies (between 315 and 400 Hz.), maxima relative attenuation is observed (between 10 and 16 dB). Greater relative attenuation (>20 dB) is observed in the high frequency range between 10 and 12.5 kHz. A significantly higher relative attenuation of more than 24 dB was observed characteristically at 3.15 kHz at all the vegetation sites. The results indicate that vegetation belts could be used as effective barriers for traffic noise control along roadsides.

[Tyagi, 2913] Tyagi, V., K. Kumar, and V.K. Jain, Road Traffic Noise Attenuation by Vegetation Belts at Some Sites in the Tarai Region of India, Archives of Acoustics, vol. 38, 3: pp. 389–395.

Noise measurements of the reduction due to vegetation belts have been carried out at 11 different sites located in three prominent cities of the Tarai region of India. The vegetation bels were 15 m along the roadsides. Attenuation per doubling of distance was computed for each site and excess attenuation at different ⅓ octave band frequencies was estimated. The average excess attenuation was found to be approximately 15 dB over the low frequencies (200 to 500 Hz) and between 15 dB and 20 dB over the high frequencies (8 kHz to 12.5 kHz). Over the critical middle frequencies (1 to 4 kHz), the average excess attenuation was between 10 to 15 dB, and though not as high, is still significant, with several sites showing an excess attenuation of 15 dB or more at 1 kHz. The results indicate that sufficiently dense vegetation belts along roadsides may prove as effective noise barriers and significant attenuation may be achieved over the critical middle frequencies (1 to 4 kHz).

[Van Renterghem, 2015] Van Renterghem, T., J. Forss´en, K. Attenborough, D. J. Philippe, J. Defrance, M. Hornikx, J. Kang, Using natural means to reduce surface transport noise during propagation outdoors, Applied Acoustics, 92, pp. 86–101.

This paper reviewed reducing surface transport noise by natural means. It was pointed out that the noise abatement solutions of interest can be easily (visually) incorporated in the landscape or help with greening the (sub)urban environment. Included were vegetated surfaces (applied to faces or tops of noise walls and on buildings' façades and roofs), caged piles of stones (gabions), vegetation belts (tree belts, shrub zones and hedges), earth berms, and various ways of exploiting ground-surface-related effects. The ideas presented in this overview were tested in the laboratory and/or numerically evaluated in order to assess or enhance the noise abatement they could provide. When well designed, such natural devices would seem to have the potential to abate surface transport noise, possibly by complementing and sometimes improving common (non-natural) noise reducing devices or measures. The applicability of the different measures strongly depends on the available space reserved for the noise abatement and the receiver position.

This work concentrated on new ideas since many of the stated findings are well-known, such as barrier reflectance. New ideas presented that would affect decisions of a highway noise analyst include:

- The use of green walls to reduce reflections.
- The use of vegetated caps to increase barrier attenuation.
- Use of trees behind barriers to decrease wind flow to decrease the effects of downwind refraction over a barrier.
- Using different berm shapes to increase attenuation.
- Using rough berm surfaces to increase attenuation.
- The use of vegetated low-height noise barriers on urban streets to provide noise reduction.
- The use of gabion walls as noise barriers.
- Use of strips of forests to reduce refraction effects.
- Changes to smooth-hard ground surfaces to become more absorptive and create destructive interference.
- The use of multiple impedance discontinuities to reduce noise propagation.
- The use of building envelopes of vegetation to decrease noise levels at the building.

[Van Renterghem, 2015] Van Renterghem, T., Exploiting Supporting Poles to Increase Road Traffic Noise Shielding of Tree Belts, Acta Acustica, vol. 101: pp. 1–7.

A tree belt bordering a road can be a useful and environmentally friendly noise abatement measure when specific guidelines are followed. However, biological limitations regarding biomass density largely limit the shielding efficiency of tree belts. This is especially true in the case of recently planted belts with juvenile and thus thin trunks with small acoustical efficiencies. The current study is a further elaboration on a previously performed large set of full-wave numerical calculations of tree belt planting schemes, where the effect of the presence of supporting poles is numerically investigated. It is shown that such poles can be used to give a juvenile non-deep tree belt a reasonable noise abatement and that specific configurations of supporting poles in between the trees can further optimize shielding. Making such poles absorbing could strongly increase road traffic noise abatement.

[Van Renterghem, 2014] Van Renterghem, T., Guidelines for optimizing road traffic noise shielding by non-deep tree belts, Ecological Engineering, vol. 69: pp. 276–286.

This paper discusses that a non-deep tree belt along a road can be an interesting solution to achieve road traffic noise reduction. Noise shielding is mainly obtained as a combination of multiple scattering in the tree trunk layer and the presence of an acoustically soft soil. A large dataset of full-wave and highly detailed numerical simulations, based as much as possible on measured input data, shows that high biomass density should generally be a goal. However, this conflicts with practical limitations regarding access to light, nutrients and water for the trees. Some interesting approaches have been identified to relax the need for high biomass density, without affecting noise shielding to an important extent. Rectangular planting schemes, where the spacing orthogonal to the road can be increased, omitting full rows parallel to the road length axis, and thinning inside the belt are examples of such measures. The specific choice of a planting scheme could make a tree belt along a road a more efficient noise reducing measure.

[Van Renterghem, 2002] Van Renterghem, T. and D. Botteldooren, Effect of a Row of Trees Behind Noise Barriers in Wind, Acta Acustica, vol. 88: pp. 869–878.

An experiment was set up along a highway to measure the effect of a row of trees (in leaf) behind a noise barrier in wind. Measurements were compared to a location without trees behind a noise barrier were compared. This continuous monitoring lasted from the middle of the summer until the middle of fall. It was shown that for downwind sound propagation for an orthogonal incident wind, the efficiency of the noise barrier with trees becomes increasingly better compared to the noise barrier without trees, with increasing wind speed. The improvement by the trees is only slightly affected if the wind direction is not perfectly orthogonal to the barrier. Upwind sound propagation is affected only to a small degree by tree placement. Diffraction on the canopy of trees did not result in an increased total A-weighted sound pressure level due to the typical low-frequency spectrum of traffic noise. This leads to the conclusion that the contribution of wind-induced vegetation noise to the recorded noise levels can be neglected for highways with common dense traffic.

[Van Renterghem, 2018] Van Renterghem, T. and D. Botteldooren, Landscaping for road traffic noise abatement: Model validation, Environmental Modeling & Software, vol. 109: pp. 17–31.

Deliberately changing terrain undulation and ground characteristics ("acoustical landscaping") is a potential noise abatement solution near roads. However, there is little research regarding the validity of sound propagation models to predict its effectiveness. Long-term continuous sound pressure level measurements near a complex road traffic and sound propagation case were performed. Three types of modeling approaches were validated, covering the full spectrum of available techniques. A two-dimensional full-wave technique (the finite-difference time-domain (FDTD) method) and an advanced engineering model (the Harmonoise© point-to-point model), provided accurate transmission loss predictions, both in ⅓ octave bands and for total A-weighted sound pressure levels. Two common and widely used semi-empirical engineering methods (ISO9613-2 and CNOSSOS) yielded rather inaccurate results, notwithstanding the short propagation distance. The sensitivity to input data was assessed by modeling various scenarios with the FDTD method. Detailed ground effect modeling was shown to be of major importance.

[Van Renterghem, 2013] Van Renterghem, T., B. DeCoensel, and D. Botteldooren, Loudness evaluation of road traffic noise abatement by tree belts, Proceedings of InterNoise 2013.

Detailed full-wave numerical calculations, partly based on measured input data, show that tree belts can be much more efficient than commonly thought. For road traffic noise applications, the trunks and the forest floor are responsible for the main part of the noise shielding. The choice of planting scheme and tree belt depth also are essential parameters at realistic tree densities. The noise attenuation provided by a tree belt was discussed in relation to the attenuation obtained by traditional thin rigid noise walls. The reference ground type between the edge of the road and the receiver showed to be an important parameter in this comparison. In the case of rigid soil, a 30-m deep optimized tree belt could give a similar A-weighted sound pressure level as a 4-m high noise wall at receiver distances exceeding 50 m. For grass-covered ground, the equivalent noise screen height is typically lowered by roughly 1 m. Although both types of noise abatement change the frequency balance in a different way, the course of A-weighted sound pressure levels versus Zwicker loudness is rather similar.

[Van Renterghem, 2012] Van Renterghem, T., D. Botteldooren, and K. Verheyen, Road traffic noise shielding by vegetation belts of limited depth, Journal of Sound and Vibration, vol. 331: pp. 2404–2425.

Road traffic noise propagation through a vegetation belt of limited depth (15 m) containing periodically arranged trees along a road was assessed by means of three-dimensional (3D) FDTD calculations. The computational cost was reduced by only modeling a representative strip of the planting scheme and assuming periodic extension by applying mirror planes. With increasing tree stem diameters and decreasing spacing, traffic noise insertion loss is predicted to be more pronounced for each planting scheme considered (simple cubic, rectangular, triangular and face-centered cubic). For rectangular schemes, the spacing parallel to the road axis was predicted to be the determining parameter for the acoustic performance. Significant noise reduction was predicted to occur for a tree spacing of less than 3 m and a tree stem diameter of more than 0.11 m. This positive effect is in addition to the increase in ground effect (near 3 dB(A) for a light vehicle at 70 km/h) when compared to sound propagation over grassland. The noise reducing effect of the forest floor and the optimized tree belt arrangement were found to be of similar importance in the calculations performed. The effect of shrubs with typical above-ground biomass was estimated to be at maximum 2 dB(A) in the uniform scattering approach applied for a light vehicle at 70 km/h. Downward scattering from tree crowns was predicted to be smaller than 1 dB(A) for a light vehicle at 70 km/h, for various distributions of scattering elements representing the tree crown. The effect of the presence of tree stems, shrubs and tree crowns is predicted to be approximately additive. Inducing some (pseudo) randomness in stem center location, tree diameter, and omitting a limited number of rows of trees seem to hardly affect the insertion loss. These predictions suggest that practically achievable vegetation belts can compete with the noise reducing performance of a classical thin noise barrier (on grassland) with a height of 1 to 1.5 m (in a non-refracting atmosphere).

[Van Renterghem, 2014] Van Renterghem, T., K. Attenborough, et. al., Measured light vehicle noise reduction by hedges, Applied Acoustics, vol. 78: pp. 19–27.

The acoustical effects of hedges result from a combination of physical noise reduction and their influences on perception. This study investigated the physical noise reduction to enable estimation of its relative importance. Different in-situ methods were used to measure the noise shielding by hedges. These included a statistical pass-by experiment where the real insertion loss of a hedge could be measured, three controlled pass-by experiments using a reference microphone at close distance, and transmission loss measurements using a point source. The evaluated hedges varied in thickness between 1.6 and 2.5 m and in height between 1.6 and 4 m. Thick dense hedges were found to provide only a small total A-weighted light vehicle noise reduction at low speeds. Measured insertion losses ranged from 1.1 dB(A) to 3.6 dB(A). The higher noise reductions were found to be associated with an increased ground effect.

[Van Renterghem, 2013] Van Renterghem, T., M. Hornikx, J. Forssen, and D. Botteldooren, The potential of building envelope greening to achieve quietness, Building and Environment, vol. 61: pp. 34–44, 2013.

Reduction of noise is one of the multiple benefits of building envelope greening measures. The potential of wall vegetation systems, green roofs, vegetated low screens at roof edges, and combinations of such treatments, have been studied by means of combining two-dimensional (2D) and 3D full-wave numerical methodologies. This study was concerned with road traffic noise propagation towards the traffic-free sides of inner-city buildings (courtyards). Preserving quietness at such locations has been shown to be beneficial for the health and well-being of citizens. The results in this study show that green roofs have the highest potential to enhance quietness in courtyards. Favorable combinations of roof shape and green roofs have been identified. Vegetated façades are most efficient when applied to narrow city canyons with otherwise acoustically hard façade materials. Greening of the upper stories in the street and (full) façades in the courtyard itself is most efficient to achieve noise reduction. Low-height roof screens were shown to be effective when multiple screens are placed, but only on conditions that their faces are absorbing. The combination of different greening measures results in a lower combined effect than when the separate effects are linearly added. The combination of green roofs or wall vegetation with roof screens seems to provide the best results.

Tire/Pavement

[Ahammed, 2010] Ahammed, M.A., S.L. Tighe, Pavement surface friction and noise: integration into the pavement management system, Can. J. Civ. PEng. 37, pp. 1331–1340.

In this document, the authors suggest timelines for complete pavement lifecycles considering local conditions. Of importance here is the work related to noise management. Key points included:

> "As the pavement surface characteristics play a key role in roadway noise generation, it provides a window for noise reduction by altering the pavement surface."
>
> It was suggested that over 5 to 10 years, all pavements in dense urban and other noise sensitive areas (e.g., hospital, school) should be of noise-reducing types.
>
> It was suggested that in the timeframe of over 10 to 15 years (typical service life of the asphalt concrete (AC) overlays or period until the first rehabilitation of new AC pavements), no pavement in the road network should remain in the very noisy pavement class. For Portland cement concrete (PCC) pavements, a 20- to 30-year timeframe may be reasonable.
>
> It was suggested that over 10 to 15 years, all pavements in the suburban areas (and small towns) should be of noise-reducing or less noisy types.
>
> A recommendation was that road surface shall be inspected for any unusual increase in the noise (e.g., in response to noise complaint). Appropriate repair and (or) remediation measures shall be taken within two to five years, depending on the road network size, if the noise increase is associated with pavement surface deterioration.

The authors went further and included additional parameters. For surface friction, the suggested management strategies were:

> No transportation agency in Canada or the U.S. has set standards for minimum surface friction for safety while some agencies outside North America provide standards for minimum surface friction. In the U.S. and Canada, this is probably because of litigation risk that may arise from skidding accidents. Accordingly, any evaluation can only be on a comparative basis in the U.S. Figure 12 shows skid number (SN) value for various pavements.
>
> Over 10 to 15 years, no pavement should have skid resistance below the desired minimum SN value.
>
> Over three to five years, all high speed (‡100 km/h) and highly traveled facilities (annual design lane equivalent single-axle loads (ESAL) > 3 million) should have surface friction exceeding the desired minimum SN.
>
> Over five to 10 years, all high speed (‡90 km/h) and highly traveled facilities with annual design lane ESALs of 1–3 million should have surface friction exceeding the desired minimum SN.

Over two years, all black spot locations on (i) sharp curves ‡48 for 100 km/h speed limit, ‡68 for 80 km/h speed limit, and ‡98 for 60 km/h speed limit; (ii) steep grades of > 4 percent; (iii) merges; and (iv) approaches to stop signs and traffic signals should have surface friction exceeding the desired minimum SN.

Surface friction-related problem at all spot locations other than specified in the previous item should be solved within two to five years with appropriate treatment or rehabilitation.

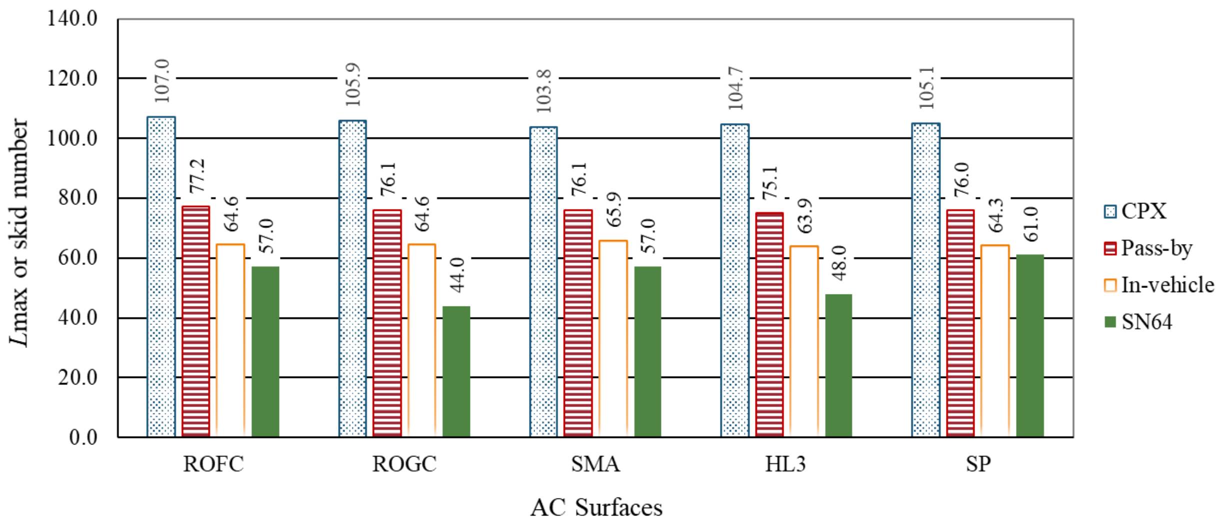

FIGURE 12. BAR GRAPH. COMPARISON OF SURFACE FRICTION AND TIRE-ROAD NOISE LEVELS

Original source: Ahammed, 2010; image was recreated for this report

Note: asphalt concrete (AC); rubberized open friction course (ROFC); rubberized open graded course (ROGC); stone mastic asphalt (SMA); hot laid 3 (HL3); Superpave (SP); close proximity (CPX); skid number at 64 km/h (SN64)

FIGURE 13 shows a relative framework for selecting a SN for the rehabilitation decision while **FIGURE 14** shows a general framework for design noise level for a new surface.

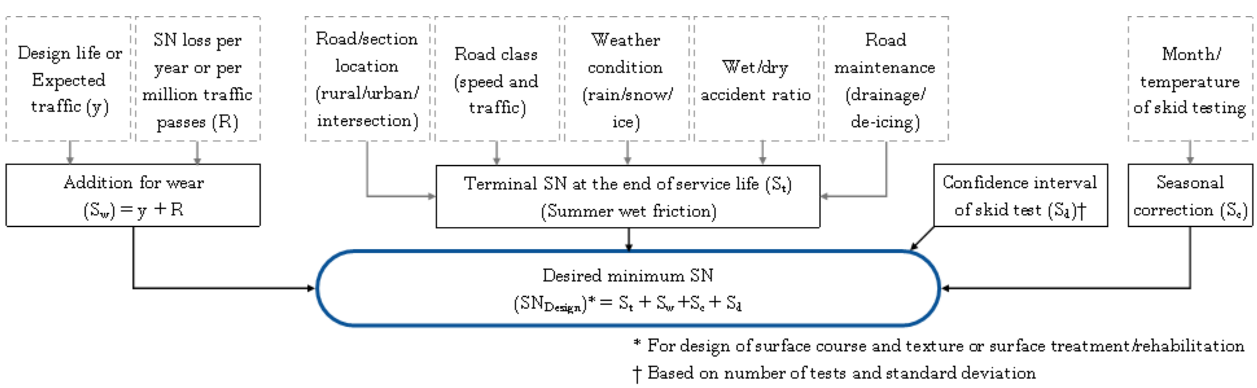

FIGURE 13. FLOW CHART. GENERAL FRAMEWORK FOR SELECTION OF DESIGN SKID NUMBER (SN) OR FOR REHABILITATION DECISION

Original source: Ahammed, 2010; image was recreated for this report

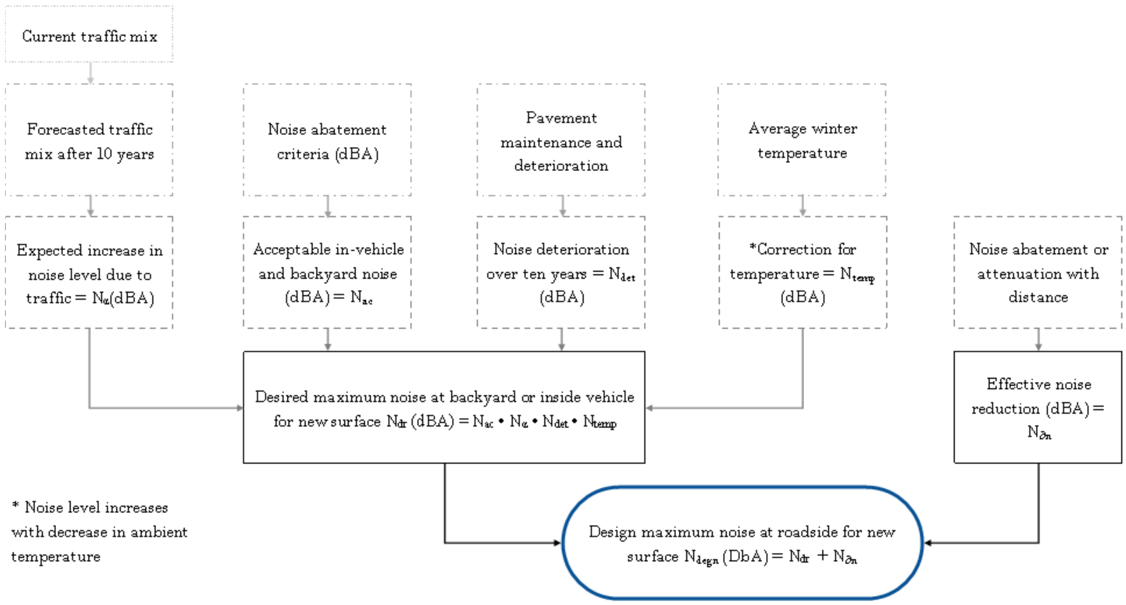

FIGURE 14. FLOW CHART. GENERAL FRAMEWORK FOR DESIGN NOISE LEVEL FOR A NEW SURFACE

Original source: Ahammed, 2010; image was recreated for this report

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[Bendtsen, 2006] Bendtsen, H., and Schmidt, B., Integrating noise in pavement management systems for urban roads, NORDIC Road and Transport Research Publication, 3: pp. 26–27.

The Danish Road Institute (DRI) and Road and Hydraulic Engineering Institute in the Netherlands cooperated on a noise abatement program for Thin Layer Pavements with an annual daily traffic around 80,000. Full scale test of different types of noise reducing thin layers on a highway in Denmark with speed limits of 110 km/h for passenger cars and 85 km/h for heavy vehicles were carried out. The purpose of this experiment was to document the noise reducing effect and attempt to determine the acoustical and the structural lifetime of the thin layers. Safety in the form of friction was measured as well as Statistical Pass By levels, CPX (Close Proximity Method), and surface texture by using DRI's laser equipment. Criteria for evaluation was determined and shown in **TABLE 12** and **TABLE 13**.

TABLE 12. GUIDELINE FOR EVALUATION OF PAVEMENT SURFACES BASED ON CRITERIA OR LIMITS

Overall Noise Level with Respect to the Maximum Acceptable Limit	Pavement Classification	Action by Agency
>5 dB(A) higher	Very noisy	Actively consider surface change and (or) treatment to reduce the noise level.
3–5 dB(A) higher	Noisy	Candidate for surface change and (or) treatment.
Within ±2 dB(A)	Normal	Check at two-year interval for potential increase.
3–5 dB(A) lower	Less noisy	Check at five-year interval for potential increase.
>5 dB lower	Noise reducing	No action is needed.

TABLE 13. VALUE-ENGINEERING APPROACH FOR SELECTION OF SURFACE AND PAVEMENT TYPE

Pavement attributes	Weights	Criteria for ranking the attributes
Initial construction cost and cost effectiveness	30	Based on bid price for alternative pavements or surfaces and expected benefits.
Lifecycle maintenance cost	10	Based on historical costs for similar pavements and (or) surfaces.
Structural capacity and (or) durability	20	Based on design and (or) actual service life.
Safety (skid resistance, splash and spray) over the service life	20	Based on ranges of average skid resistance value and (or) accident record on similar surfaces over the service life.
Exterior or interior noise over the service life	10	Based on average roadside or in-vehicle noise levels over the service life for alternative surfaces, depending on roadway location.
Smoothness and rolling resistance over the service life	10	Based on average international roughness index (IRI) of alternative surfaces over the service life.

[Bendtsen, 2010] Bendtsen, H., E. Kohler, Q. Lu, B. Rymer, California–Denmark Study on Acoustic Aging of Road Pavements, Transportation Research Record 2158, National Academy of Sciences, pp. 122–128.

Several conclusions were put forward regarding acoustical changes with time. These included that the increased noise level on asphalt pavements with time occur continuously and before significant pavement deterioration with raveling and cracking begins. This is shown in both U.S. and Europe and studies and a linear regression gives a good fit to the increases in noise level. Results for linear regression fits are shown in TABLE 14.

TABLE 14. AVERAGE NOISE INCREASE FOR MULTIAXLE HEAVY VEHICLES FOR FOUR PAVEMENT GROUPS EXPRESSED AS THREE INDICATORS: ΔL_{AGE}, ΔL_{ADT}, $\Delta L_{Mix25/75}$

Pavement Type	ΔL_{Age}	ΔL_{ADT}	$\Delta L_{Mix25/75}$ [dB/mix]
All average	0.27	0.15	0.18
Dense-graded asphalt concrete (DGAC)	0.23	0.17	0.19
Open-graded asphalt concrete (OGAC)	0.12	0.11	0.11
Thin open	0.44	0.16	0.23
Preplaced aggregate concrete (PAC)	0.22	0.17	0.18

There also is a change in the frequency components during the pavement life. Spectral analyses provided the following general information based on four pavement types:

> For DGAC, the higher-frequency air pumping noise increases in the first years, indicating that the pavement surface becomes denser (after compaction). After some years there also is an increase in the lower frequencies below 1,600 Hz, indicating that the pavement surface becomes rougher with an increase in the tire vibration noise.
>
> For OGAC, the tendencies are not as clear.
>
> For the thin open pavements, the noise increases for both the lower and higher frequencies. This indicates that the pavement surface becomes rougher with an increase in the tire vibration noise and that the pavement surface becomes denser, causing increased higher-frequency air pumping noise.
>
> For PAC, in the second year, clogging begins, and this increases the higher frequency noise over 1,000 Hz because of increased generation of air pumping noise. As the porous pavements age, there is an increase in the low-frequency noise (under 1,600 Hz), indicating increased tire vibration noise caused by a rougher pavement surface structure.

[Chalupnik, 1992] Chalupnik, J.D., D.S. Anderson, The Effect of Roadway Wear on Tire Noise, Washington State Transportation Commission, Final Report.

While the intent of this work was to try and establish time limits on the change in acoustic properties with time, Chalupnik made other key statements in this work that have become common place “rules of thumb.” One of these was the speed at which pavement/tire noise starts to be a dominant noise factor: 25 miles per hour (mph). While this varies by vehicle type, it provides detail on when pavement texture changes may be of importance. While not stated in the work, it can be concluded that the use of quieter pavements on collector streets in neighborhoods would be of limited value. Additionally, since the pavement/tire noise is directly related to speed of the vehicle, it also implies that an important mitigation measure could be as simple as reducing speed limits.

For the change in noise effectiveness of the pavement surface wear, when dealing with asphaltic pavement, Chalupnik’s work established a conclusion that is often referred to when discussion pavement surface benefits. This was that the results of multiple studies seemed to show that due to wear, aging, and environmental effects, that after seven years, the noise benefit is significantly diminished. The far-reaching implication of this is that if noise surface texture is used as a noise abatement measure, it will require increased frequency of pavement maintenance.

[Donavan, 2006] Donavan, P.R., Comparative Measurements of Tire/Pavement Noise in Europe and the United States—NITE Study, FHWA/CA/MI-2006/09.

Donavan conducted studies in different States which allows a direct comparison of the results. **FIGURE 15** shows a comparison of OBSI measurements from California and Arizona for three general pavement types. These results, similar to other State results, shows the general trend in pavement types with the asphaltic pavements showing the lower levels. This points to the possibility of choosing surface textures during the design phase to assist with noise control.

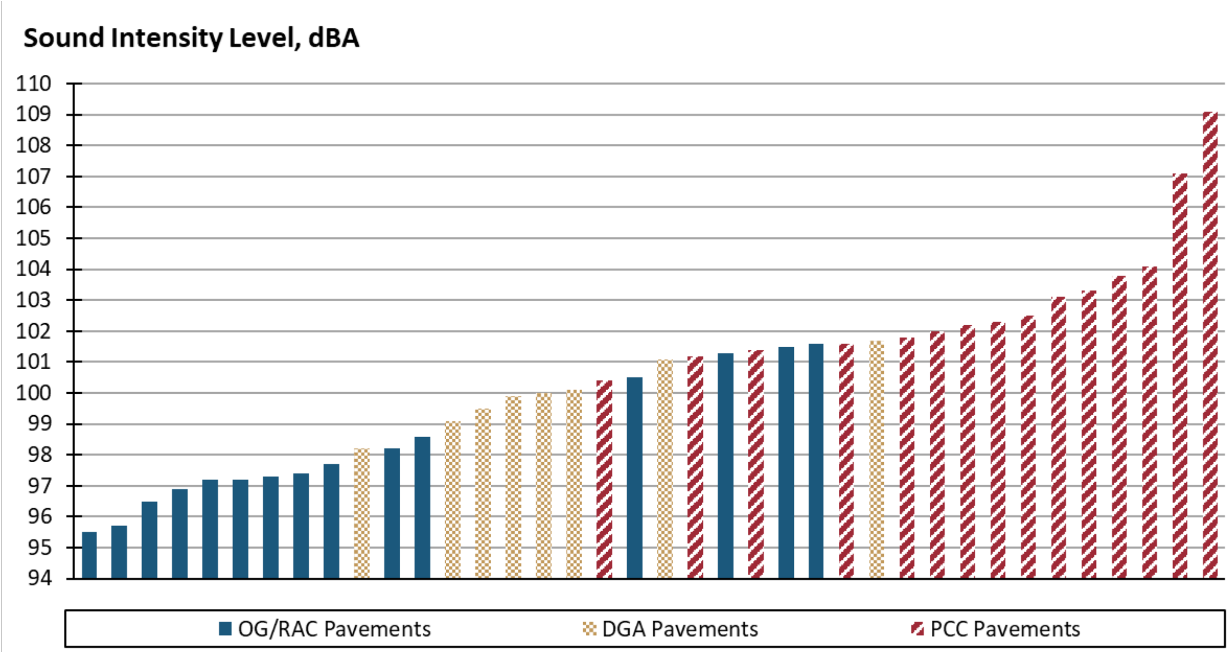

FIGURE 15. BAR GRAPH. COMPARISON OF DIFFERENT PAVEMENT SURFACE SOUND INTENSITY LEVELS FROM CALIFORNIA AND ARIZONA

Original source: Donavan, 2006; image was recreated for this report

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[Donavan, 2013] Donavan, P.R., L.M. Pierce, D,M. Lodico, J. L. Rochat, H.S.Knauer, Evaluating Pavement Strategies and Barriers for Noise Mitigation, NCHRP Report 738, Transportation Research Board, National Academy of Sciences.)

This report presents a methodology for evaluating feasibility, reasonableness, effectiveness, acoustic longevity, and economic features of pavement strategies and barriers for noise mitigation. Life-cycle cost analysis is used to examine the economic features of mitigation alternatives, the FHWA Traffic Noise Model to integrate the noise reduction performance of pavements and barriers, and onboard sound intensity measurements as input to the prediction model. This approach provides a rational basis for evaluating alternatives for noise mitigation. **FIGURE 16** shows an overview of the existing and proposed inputs to the overall process.

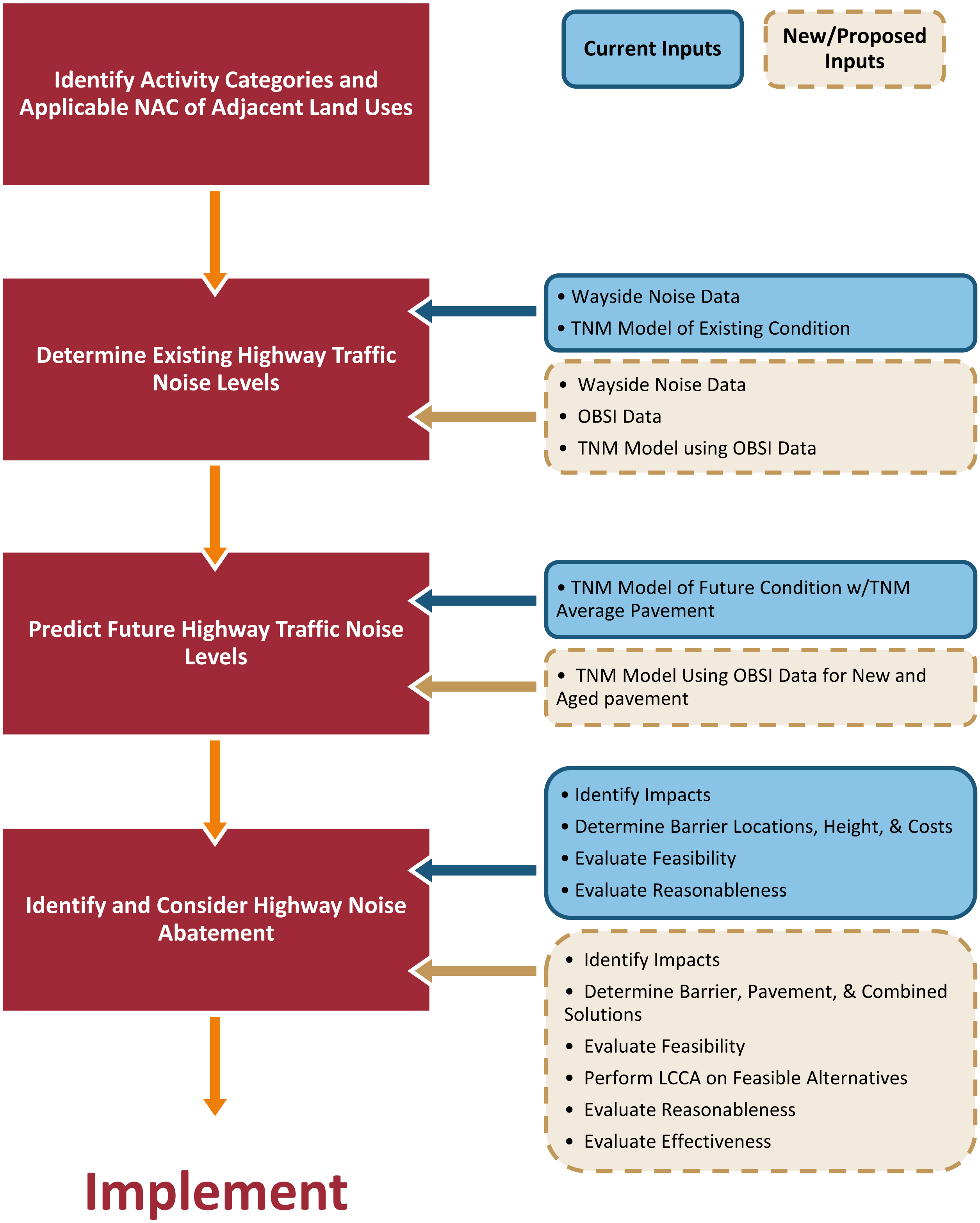

FIGURE 16. FLOW CHART. HIGHWAY NOISE ABATEMENT PROCESS - CURRENT AND REVISED

Original source: Donavan, 2013; image was recreated for this report

The integration of OBSI allows a more accurate assessment of the actual pavement and a process is described. Due to the current methodology of using average pavement in TNM analysis, this has not become commonplace. More work is needed.

The additional of the LCCA also is a large change from the current methodology. A critical component for evaluating quieter pavement strategies and barriers is comparing costs of the two mitigation methods on an equivalent basis. The cost of barriers is part of the initial cost of the project and expected to provide a fixed amount of noise reduction throughout the project life while the noise level for a “quieter pavement” is harder to define over the project life. To maintain performance, rehabilitated should be conducted on a shorter cycle than would normally be required. The recurring cost must be considered. Using LCCA, the cost of different pavement alternatives over the life of the highway project can be considered, which can vary over a range of years. The rehabilitation cycle would need to account for acoustic longevity cycle (which would need to be determined) to maintain noise reductions and ensure that the FHWA criterion of maintaining the noise abatement “in perpetuity” is met. Costs of each rehabilitation event during the analysis period were added together along with periodic maintenance costs and initial construction costs. Using equivalent dollars this allows estimation of the total lifetime cost and pavement design alternatives to be compared on an equal basis. User costs (e.g., time lost due to delays and vehicle damage) also can be included. Due to these additional considerations, the LCCA must be slightly altered to analyze pavement and barrier strategies for noise abatement that are commonly used now. The initial barrier costs would be less due to the quieter pavement, and must be determined and added to the cost of the appropriate pavement choice. Maintenance costs for the barrier (e.g., graffiti removal) also should be included in the analysis. The cost of periodic monitoring of the pavement’s acoustic performance also might be included in the analysis. Pavement reductions and barrier heights should be matched. Examples of this process were presented, including at the State level.

The examples showed that acoustic feasibility for alternatives could be evaluated in a similar manner to that currently used for barriers alone. Reasonableness depends on the methodology agency criteria. If receptors on both sides are impacted, it would be appropriate to evaluate together, particularly when quieter pavement or combinations of barriers and pavement are considered.

[Dravitzki, 2002] Dravitzki, V.K., D. Walton, C.W.B. Wood, Effects of Road Texture on Traffic Noise and Annoyance at Urban Driving Speeds, New Zealand Acoustics, Volume 15, Number 4, pp. 7–15.

This paper concludes that insufficient allowance is being made for road surface effects on New Zealand traffic traveling approximately 50 km/h. A greater benefit in reducing community annoyance noise in urban may exist than previously concluded. Using a drive-by technique to measure both the noise level and a spectral distribution of the noise from test vehicles and actual vehicles, the noise from a range of road surfaces was reported. It was found that chip surfaces were 3 to 6 dB(A) noisier for cars and 0 to 2dB(A) noisier for trucks. A survey found that the effects on people may be larger than was previously considered. It was found that even changes in the noise levels of less than 2 dB(A) were significant for annoyance and behavioral scales.

[EPA, 1974] Environmental Protection Agency, Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety, U.S. Environmental Protection Agency, EPA/ONAC 550/9-74-004.

This early document was extremely comprehensive and even now is one of the most referenced documents. Discussion is presented of the Noise Control Act of 1972, the effect of noise which might be expected from various levels and exposure situations, and information as to the levels of noise "requisite to protect the public health and welfare with an adequate margin of safety." Sound descriptors are defined, and considerable material was gathered from scientific publications and other sources, both from the U.S. and abroad.

[FHWA, 1995] Federal Highway Administration, Highway Traffic Noise Analysis and Abatement, Policy and Guidance, Office of Environment and Planning, 1995.

Although superseded by updated FHWA documentation, this documented provided the FHWA policies and guidance for the analysis and abatement of highway traffic noise and many of the concepts are still in use. Topics covered included land use planning, information on truck emission levels, a listing of noise abatement still in use today, a primer on noise fundamentals, information on the version of 23 CFR 772 that was in use at the time of publishing, an overview of States definition of "substantial," a description of the traffic noise impact requirements, abatement details (such as **TABLE 15** for insulation and **TABLE 16** for barriers), and details for environmental documentation.

TABLE 15. BUILDING NOISE REDUCTION FACTORS TO INSIDE NOISE LEVELS

Building Type	Window Condition	Structure
All	Open	10 dB
Light Frame	Ordinary Sash (closed)	20 dB
	Storm Windows	25 dB
Masonry	Single Glazed	25 dB
	Double Glazed	35 dB

Note: The windows shall be considered open unless there is firm knowledge that the windows are in fact kept closed almost every day of the year

TABLE 16. BARRIER ATTENUATION

Reduction in Sound Level	Reduction in Acoustic Energy	Degree of Difficulty To Obtain Reduction
5 dBA	70%	Simple
10 dBA	90%	Attainable
15 dBA	97%	Very Difficult
20 dBA	99%	Nearly Impossible

[Enríquez-de-Salamanca, 2019] Enríquez-de-Salamanca, A., Environmental impacts of climate change adaptation of road pavements and mitigation options, International Journal of Pavement Engineering, 20:6, pp. 691–696.

The author puts forward the premise that climate change affects road pavements, making adaptation measures necessary even though these measures also may produce environmental impacts. The two main adaptation impacts put forward were more frequent pavement replacement and acoustic impacts related to pavement type change. It was thought possible to mitigate the impacts using more resistant materials, in situ recycling of pavements, materials with a lower carbon footprint and machinery with greater energy efficiency. Additionally, it was stated that it is essential to include the acoustic performance in decisionmaking for road pavement adaptation, avoiding changes that imply an increase of road traffic noise.

[Lodico, 2013] Lodico D.M., P.R. Donavan, Using Onboard Sound Intensity Measurements to Interpret Results of Traffic Noise Modeling, Transportation Research Record No. 2362, Transportation Research Board of the National Academies, pp. 9–15.

This paper discusses the use of OBSI results to interpret TNM predictions. Ideas included:

- OBSI levels for each lane of travel should be measured, especially in areas where the pavement changes from lane to lane.
- Use of a moving average OBSI level, as opposed to discrete samples, would allow for the correlation of a localized OBSI level for each measurement location.
- Use of the Volpe National Transportation Systems Center’s modified version of the TNM would allow for the contribution of the pavement to be directly calculated within the model, leading to more sophisticated results.

The model currently allows for the use of only one additional (other than TNM average) pavement to be applied for any single run. Therefore, for sections of roadway where more than one pavement type is used, additional calculations would still be required. Potentially, the use of OBSI adjustments also could enable practitioners to account for changes in pavement type under future conditions.

[Nijland, 2005] Nijland H.A., G.P. Van Wee, Traffic Noise in Europe: A Comparison of Calculation Methods, Noise Indices and Noise Standards for Road and Railroad Traffic in Europe, Transport Reviews, Vol. 25, No. 5, pp. 591–612.

This paper points out that it has become increasingly essential to compare and assess international data on noise. Questions are raised if international data on noise can be compared with the different national calculation methods and metrics. Metrics noted that are in use included L_{Aeq}, $L_{Aeq\text{-}5}$, $L_{Aeq,12h}$, $L_{Aeq,24h}$, L_{10}, $L_{10,18h}$, L_{50}, and L_{max}. Concentrating on international data for noise from road and railroad traffic it was shown that possible differences in the outcome of noise calculations using different national methodologies can be up to 15 dB(A). The national noise indices and noise standards differences make it even more difficult to compare data on noise exposure. Harmonization of calculation methods and noise indices, as initiated by the European Commission, is suggested as a necessary first step. L_{Aeq} type indices are recommended. The overall objective is to quiet sources of noise, preferably at the source. Reduction of tire noise by tightening emission limits is the most promising option with integrating noise into spatial planning as the most cost effective option at the local level.

[Rasmussen, 2007] Rasmussen, R.O., R.J. Bernhard, U. Sandberg, E.P. Mun, The Little Book of Quieter Pavements, FHWA-IF-08-004, Federal Highway Administration Office of Pavement Technology, HIPT-1.

This FHWA publication provides a good primer for pavement/tire noise and abatement. It is recommended for individuals just beginning to study the topic.

[Rochat, 2012] Rochat, J.L., A.L. Hastings, D.R. Read, M. Lau, FHWA Traffic Noise Model (TNM) Pavement Effects Implementation Study: Progress Report 1, DOT-VNTSC-FHWA-12-01.

As noted in this report, there are measurable noise level differences among roadway pavement textures and the selection for a highway results in a different impact regarding the amount of noise received by nearby communities. While it has been traditional for noise prediction models to use a reference pavement it has become evident that the current understanding should lead to an investigation of the implementation of different pavement effects into their models for reasons such as reducing the under- or over-predictions in sound levels.

Questions remain to be answered (e.g., amount of community benefit, longevity of benefit) for a large array of specific pavement types. Because of these concerns, FHWA requires a national average pavement type for future highway noise predictions when using the FHWA Traffic Noise Model. TNM is directly linked to 23 Code of Federal Regulations, Part 772. This study was initiated to help determine how to incorporate a broad range of pavement effects into the FHWA model TNM.

Three implementation options were considered with one changing the model and the other two used in post-processing. These were:

- Integrating new data into the FHWA TNM vehicle noise database (REMEL) for specific pavement types while also adjusting the roadway effective flow resistivity (EFR, a measure of sound absorption).
- Adjusting the existing tire/pavement source level in the TNM using OBSI data while also adjusting the roadway EFR.
- Applying a pavement type offset adjustment value to the predicted sound levels (post FHWA analysis).

The first two options were found to be valid, but each required additional data before implementation. Implementation of the final option was determined not to be valid since current efforts established that pavement effects are distance-dependent and site-geometry dependent, and therefore, adjusting predicted sound levels by a single decibel offset or adjustment value would be inaccurate.

[Sandberg, 1999] Sandberg, U., Low noise road surfaces-A state-of-the-art review, J. Acoust. Soc. Jpn. (E) 20, 1, pp. 1–17.

This article summarized the current state of knowledge at the time for the design and performance of low noise road surfaces. Noise generation mechanisms, mechanisms causing noise reduction by surface design, and measurement procedures were explained. Design guidelines were presented along with details on noise reducing methods. It was stated that the best traffic noise reduction attainable with such surfaces is around 8 dB(A) in new condition, using small chippings in the top layer. It also was noted that regular cleaning operations may be required for porous surfaces used for lower speeds but in applications where speeds are 90-130 km/h, there is a significant self-cleaning making the acoustic lifetime acceptable even without cleaning. It was concluded that road surfaces will be used frequently to reduce traffic noise and can give substantial effects but this could mean serious economic tradeoffs, other problems, with the long-term noise reduction efficiency still a problem for most designs.

This paper provides an excellent overview or review of the basic principles and concerns. It also points out that new approval procedures were underway in some European countries.

[Sandberg, 2002] Sandberg, U., J.A. Ejsmont, Tyre/Road Noise Reference Book, Informex publishing, Poland.

This book, once referred to as the “bible” on the subject, includes general information on highway sound, historical perspectives, and characteristics of the pavement/tire noise on vehicles, tires, pavement types, generation, control, driver variables, construction details, measurement details, modeling, guidelines, perception, regulations, cost/benefit, measurement data, and other details.

It is recommended that anyone interested in tire/pavement noise review this book. So much information makes a short synopsis literally impossible and is not attempted here with one exception; an analysis of cost. Based on stated parameters within the book, an important conclusion was that if a 10 meter wide roadway (two lanes) needed to be paved every other year to maintain a 5 dB(A) noise reduction, the cost would be equal to the barrier cost needed to supply the same amount of attenuation. If repaving were to occur every fourth year, this cost would of course be cut in half. Also, if wider roadways or other conditions are considered, the cost would vary accordingly.

[Sohaney, 2013] Sohaney, R., R. O. Rasmussen, P. Donavan, J. L. Rochat, Quieter pavements guidance document, Natural Resource Technical Report NPS/NSNS/NRTR—2013/760, National Park Service, Fort Collins, Colorado.

The National Park Service has identified quieter pavements as a possible solution to reduce road noise in the National Parks. There is still a need for information regarding which quieter pavements might work based on site-specific factors, including weather, traffic, available materials and construction expertise. This document provided guidance and recommendations on quieter pavements to help park personnel select pavement surfaces that minimize tire-pavement noise. It also included a synopsis of ongoing work in multiple States. TABLE 17 to TABLE 20 provide a concise summary of collected information.

TABLE 17. QUIETER HOT MIX ASPHALT PAVEMENT DESCRIPTION, ELEMENTS, AND TYPICAL NOISE LEVEL RANGE

Pavement	Description	Elements of a Quieter Pavement	Typical Noise Levels (OBSI, dBA)	
			New	Aged
OGFC	• Open-Graded HMA • Mixture including significant quantity of air voids, typically used as a surface course	• 15 to 25% porosity • Nominal maximum aggregate size ≤ 0.375 in (9.5 mm)	96 - 100	98 - 104
SMA	• Gap-graded HMA • Mixture providing stone-on-stone contact and thus including high-quality stone	• Nominal maximum aggregate size ≤ 0.375 in (9.5 mm)	98 - 102	100 - 106
DG HMA	• Dense-graded HMA • Conventional mixtures, most commonly used today	• Nominal maximum aggregate size ≤ 0.375 in (9.5 mm)	98 - 102	100 - 106
ARFC	• Open-graded HMA with crumb rubber additive • Reduced air voids compared to OGFC, since binder content is higher	• Nominal maximum aggregate size ≤ 0.375 in (9.5 mm)	96 - 99	98 - 104
Bonded wearing course	• NovaChip® or similar product • Thin wearing course	• Nominal maximum aggregate size ≤ 0.375 in (9.5 mm)	98 - 102	100 - 104

TABLE 18. QUIETER HOT MIX ASPHALT PAVEMENT CLIMATIC CONSIDERATIONS AND REGIONS USED

<table>
<tr><th rowspan="2">Pavement</th><th colspan="2">Climatic Considerations</th><th rowspan="2">Regions Used</th></tr>
<tr><th>During Construction</th><th>Long Term</th></tr>
<tr><td>OGFC</td><td>Minimum temperature during construction commonly specified</td><td>Potential freeze-thaw issues
Increase in black ice formation possible
Studded tires and/or chains can lead to premature raveling
Use of sand for winter maintenance may diminish acoustical benefit by clogging pores</td><td>Typically used in warmer climates found in southern States</td></tr>
<tr><td>SMA</td><td>No special considerations</td><td>No special considerations</td><td>Many. Commonly specified to provide additional frictional performance in colder climates</td></tr>
<tr><td>DG HMA</td><td>No special considerations</td><td>No special considerations</td><td>All</td></tr>
<tr><td>ARFC</td><td>Minimum temperature during construction commonly specified</td><td>Potential freeze-thaw issues
Increase in black ice formation possible
Studded tires and/or chains can lead to premature raveling</td><td>Typically used in warmer climates found in southern States</td></tr>
<tr><td>Bonded wearing course</td><td>Minimum temperature during construction commonly specified</td><td>No special considerations</td><td>Many</td></tr>
</table>

TABLE 19. QUIETER CONCRETE PAVEMENT DESCRIPTION, ELEMENTS, AND TYPICAL NOISE LEVEL RANGE

Pavement	Description	Elements of a Quieter Pavement	Typical Noise Levels (OBSI, dBA)	
			New	Aged
Diamond ground	• Hardened concrete surface ground using diamond grinding head • Final texture has “corduroy” appearance	• Blades and spacers selected as a function of concrete aggregate type to minimize presence of “fins” • Narrow joints	98 - 102	100 - 104
Drag textured	• Wet concrete surface finished by dragging burlap or artificial turf	• Narrow joints	99 - 103	101 - 105
Longitudinal tined	• Wet concrete surface tined (raked) in the longitudinal direction	• Tine grooves spaced 0.5 or 0.75 in (12.5 or 19 mm) and ≤ 0.125 in (3 mm) deep • Narrow joints	100 - 104	101 - 106
Transverse tined	• Wet concrete surface tined (raked) in the transverse direction	• Tine grooves spaced ≤ 0.5 in (12.5 mm), and ≤ 0.125 in (3 mm) deep • Narrow joints	101 - 105	102 - 108
Pervious	• Concrete mixture containing significant air voids	• 20 to 30% porosity • Maximum aggregate size ≤ 0.375 in (9.5 mm) • Smooth surface (negative texture)	96 - 100	98 - 104

TABLE 20. QUIETER CONCRETE PAVEMENT CLIMATIC CONSIDERATIONS AND REGIONS USED

<table>
<tr><th rowspan="2">Pavement</th><th colspan="2">Climatic Considerations</th><th rowspan="2">Regions Used</th></tr>
<tr><th>During Construction</th><th>Long Term</th></tr>
<tr><td>Diamond ground</td><td>No special considerations</td><td>No special considerations</td><td>Many</td></tr>
<tr><td>Drag textured</td><td>No special considerations</td><td>No special considerations</td><td>Many</td></tr>
<tr><td>Longitudinal tined</td><td>No special considerations</td><td>No special considerations</td><td>Many</td></tr>
<tr><td>Transverse tined</td><td>No special considerations</td><td>No special considerations</td><td>Many</td></tr>
<tr><td>Pervious</td><td>No special considerations</td><td>• Potential freeze-thaw issues
• Increase in black ice formation possible
• Studded tires and/or chains can lead to premature raveling
• Use of sand for winter maintenance may diminish acoustical benefit by clogging pores</td><td>• Most
• Primarily parking lot and shoulder application</td></tr>
</table>

[Tao, 2017] Tao H., C. Chen1, P. Jiang, S. Huang, Review of Cement Concrete Pavement of Noise Reduction Method, MATEC Web of Conferences, 100, 03029.

This paper is a good reminder of the world-wide interest in quieter pavement and that it applies not only to flexible pavements but rigid pavements as well. Noted is that highways are the lifeline of the national economy, as well as supporting regional development, defense, and stable transport. Roadways in good repair are needed in order to ensure that vehicles quickly and safely transverses the roads. Results of a survey noted that noise has a negative impact on the human psychology and the body at the same time, can be particularly harmful to the nervous system and cardiovascular system, and can damage children's brains and limit intellectual development by approximately 20 percent. China's continued growth and greater number of motor vehicles has led to increases of concrete pavements but due to its stiffness, traffic noise has become more obvious.

The problem of cement concrete pavement noise pollution has become more of a concern for residents which has led to developing effective measures to reduce traffic noise pollution to maintain a good acoustic environment along the road. Other abatement measures mentioned included sound barriers and greenbelts, but the development of quieter roads and work continues. It was noted that the research for cement pavement noise reduction measures can create a better living and working environment for residents, and that noise reduction measures can be divided into the pavement structure and other noise reduction measures.

[Vaitkus, 2018] Vaitkus, A., T Andriejauskas, J Gražulytė, O Šernas, V Vorobjovas, R Kleizienė, Qualitative criteria and thresholds for low noise asphalt mixture design, IOP Conf. Series: Materials Science and Engineering, 356.

The paper is based on feasibility studies that low noise asphalt pavements are cost efficient and cost effective alternative for road traffic noise mitigation if compared to noise barriers, façade insulation and other known noise mitigation measures (see **FIGURE 17**). While not stated in the paper directly, it appears the costs are for quieter pavement (blue), barriers (green), and insulation (red) based on the pictures in the figures. Note that barriers are not used in the city streets. Based on these studies, the quieter pavement costs are lower. It is also mentioned that it may be less expensive to achieve required noise reduction effect by using a combination of low noise pavements and noise barriers than only barriers in a longer treated distance.

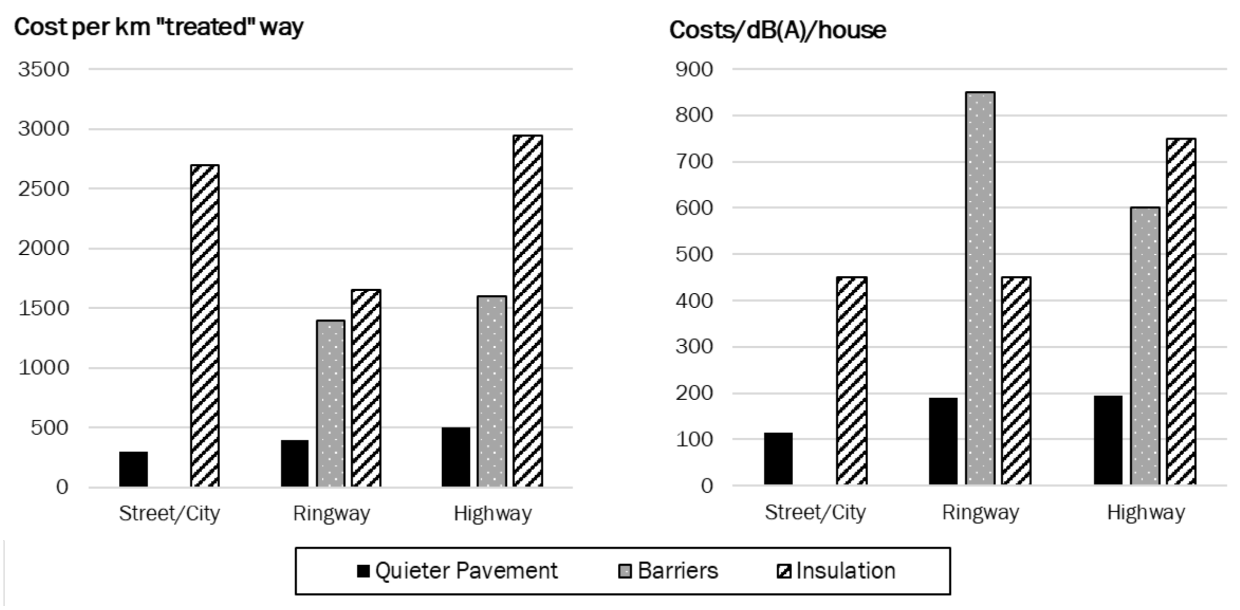

FIGURE 17. BAR GRAPHS. COSTS FOR THE ABATEMENT MEASURES OF QUIETER PAVEMENT, BARRIERS, AND INSULATION

Original source: Tao, 2017; image was recreated for this report

But the design of low noise asphalt mixtures strongly depends on climate and traffic peculiarities of different regions. These differences require criteria for implementation. Severe climate regions may experience short durability of low noise asphalt mixtures and traffic volumes. This results in a need to find a balance between mechanical and acoustical durability as well as to ensure adequate pavement skid resistance for road safety purposes. This paper analyzes the qualitative criteria and design parameters thresholds of low noise asphalt mixtures for different asphalt mixture composition materials and relevant asphalt layer properties with the pavement suitability for durable and effective low noise pavements being the goal. The paper includes an overview of requirements, qualitative criteria, and thresholds for low noise asphalt mixture design in severe climate regions.

The paper then lists qualitative items of concern when selecting the pavement type, including pavement considerations (road surface texture, aggregate properties, air void content, pavement stiffness, pavement color, pavement age and deterioration), tire characteristics (number of tires, tire dimensions, tire internal structure, tire inequality, rubber hardness, tread pattern and structure, age and wear, tire type, studded tires), environmental factors (moisture, wind, temperature, water on the surface, dust) and factors controlled by driver (driving speed, tangential forces, acceleration, tire load and pressure). However, although items of concern and relative costs are presented, no real procedure is defined.

[Walton, 2004] Walton, D., J.A. Thomas, P.D. Cenek, Self and others' willingness to pay for improvements to the paved road surface, Elsevier, Transportation Research Part A 38, pp. 483–494.

A contingent valuation study is described that was undertaken to measure motorist's self and perceived others' willingness to pay (WTP) for improvements to the paved road surface. While noise benefits to abutting properties were not included, the three benefits considered were: (1) improved fuel efficiency, (2) reduced interior noise and (3) reduced stopping distance in wet conditions. With a goal to assess the perceived relative importance of the improvements, 1200 motorists received one of 18 versions of a questionnaire outlining a road surface scenario with different levels of the benefits. It was found that motorists were willing to pay for improved fuel efficiency and reduced interior vehicle noise. Noise improvements and fuel efficiency are considered a function of road texture with smoother roads being quieter and more efficient. It must be noted that in New Zealand, estimates of road surface roughness related vehicle depreciation, repairs and maintenance, constitute approximately 6 percent of vehicle operating costs, leading to one WTP parameter. However, motorists showed no significant WTP for a reduction in vehicle stopping distance. No systematic bias is detected in perceptions of self/other WTP for road surface improvements and perceived other WTP presents the same pattern of results. However, of interest are these findings are contrasted with the finding that the Government spend additional petrol taxation on safety benefits.

Two sets of conclusions were stated to follow from these findings. First, WTP for road surface improvements co-varies with use of the road. WTP estimates suggest reductions to fuel consumption are valued most; reduction in noise is also valued, but a 15 percent reduction in stopping distance in wet conditions is not valued. These findings seem to contradict a preference for the Government to allocate resources to safety considerations above economic considerations. Rather, participants have no economic regard for as much as a 15 percent reduction in stopping distance. Though the mechanism that underlies this is not understood, the findings illustrate the importance of investigating the thought processes underpinning responses to contingent valuation (CV) questions. Second, comparisons reveal that WTP for road surfaces is modulated by perceptions of the Government, reasonableness of taxation mechanisms and age. Additionally, a higher WTP aligns with a greater concern to reduce the environmental impacts of travel.

[Wayson, 1998] Wayson, R.L., Relationship Between Pavement Surface Texture and Highway Traffic Noise, Report No. 268, National Cooperative Highway Research Project, National Research Council, National Academy Press.

A synthesis on the relationship of pavement surface texture and highway traffic noise was created in 1998 and summed the technical aspects to that date. A brief synopsis of findings from that synthesis are presented here.

In 1998, over 30 years of measurements had been made of pavement/tire noise using both the trailer and the pass-by methods. Since that time, significant correlation between the methods had been shown although it changes by pavement surface type. Certain trends seem clear from a literature review of this period. PCC pavements have the advantage of durability and superior surface friction when compared to dense-graded asphaltic pavements. However, PCC pavements generally create more noise along the highway although experimentation using different surface preparation show promise. Transverse tining seems to cause the greatest sideline (pass-by) noise levels. It also appears that the surface texture of uniform transverse tining, especially if spaced over 26 mm (1 in.), generates the most tire/pavement noise and the most annoying tones. Researchers have reported that random spacing may reduce and even eliminate the annoying pure tone generated by transverse tining. Longitudinal tining was found to reduce the overall noise levels, but at a cost of reduced surface friction when compared to transverse tining. Also, surface friction decreases more rapidly over time for longitudinal tining than transverse tining. There was conflicting data in the United States suggesting that other surface characteristics, such as tine spacing, construction techniques, and aggregate size, must also be considered concurrently.

Results from the U.S., Australia, and Europe show that the exposed aggregate surface appears to provide better noise quality characteristics than tined pavement. This surface also has good frictional characteristics and could provide durability as well as noise reductions. For example, an exposed aggregate surface with a top layer containing a maximum 8 mm (0.31 in.) aggregate size, showed a 5 dB(A) reduction when measured by the trailer method. A frequency analysis showed important reductions in the 500 to 2,000 Hz range that can cause annoyance as well. A significant noise reduction or frequency shift was not shown when U.S. researchers compared a transverse tined surface (26 mm (1 in.) uniform spacing)) with a European exposed aggregate texture design. Two states showed only a 1 dB(A) reduction. Construction techniques were thought to be the problem, especially aggregate size used in the final course.

Asphaltic pavement surfaces, such as open-graded, stone mastic and rubberized asphalt may offer a more significant noise abatement option. Smaller aggregate sizes, less than 10 mm (0.39 in.), are needed for asphaltic surfaces to provide adequate frictional effects and result in reduced noise levels. In general, when dense-graded asphalt and PCC pavement are compared, the dense-graded asphalt is quieter by 2 to 3 dB(A) and even more benefit is shown if the dense-graded asphalt is compared to transversely tined PCC pavements. However, these pavements suffer from plugging, deterioration with freeze/thaw cycles, and reduced effectiveness when using deicing agents. Noise benefits of the asphaltic pavement are also reduced with surface wear. Also, the dense-graded asphalt frictional characteristics are less than for PCC pavements and have a shorter service life.

[Wayson, 2014] Wayson, R.L., J.M. MacDonald, A. Martin, Onboard Sound Intensity (OBSI) Study, Phase 2, FDOT Project No. BDT06, Florida Dept. of Transportation.

This report was a continuation effort of previous research pertaining to the noise created at the tire/pavement interface. The topic continues to gather considerable interest because of the potential benefits and a general desire by the public for quieter highways. Key findings from both reports (Phase 1 and Phase 2) are included and a detailed examination of the collected data is included. Additionally, the overall equipment was described as well as data collection procedures.

The report included a large number of pavement texture ranking based on measurements (see figure 18) as well as analysis of the different pavement variables that changed the noise content and amplitude. Open graded pavements were found to represent the quieter pavements in use in Florida. Three variables that seem significant in the pavement texture in terms of noise control are mean profile depth, aggregate size, and friction number. These variables were selected for analysis because of the general use in pavement design, availability, and are thought to act for surrogates of the acoustic parameters. Both the amplitude and frequency spectra change with changes to these mix variables.

An overall difference of 32.5 dB(A) was measured with a standard deviation of 1.62 dB(A) when comparing noise levels from the OBSI method and pass-bys and concurrently measured noise levels at the defined reference energy mean emission level (REMEL) position (50 feet from the centerline of the near lane and 1.5 feet above the pavement surface). The difference or delta consistency allows a general first order approximate method to approximate wayside sound levels if OBSI measurements are made. This general first order approximation is:

Wayside SPL [dB(A)] = OBSI Level—32.5

The uncertainty is 3.5 dB(A). To provide more flexibility, a transfer function was derived that should improve the estimation process. The final function was:

$$\Delta = 32.57 + 0.0349(\mathrm{FN}) + 18.094(\mathrm{MPD}) - 0.0493(\mathrm{AG4})$$

(R^2 = 0.7328) with a residual standard error of 1.0 dB(A)

> Where: Δ is the difference to be subtracted from the OBSI level to REMEL position, FN is friction number, MPD is mean profile depth, and AG4 is an aggregate designation defined during testing and by Florida standards.

Surface textures over a long span allowed the aging reduction of sound qualities to be quantified (~0.2 dB/year).

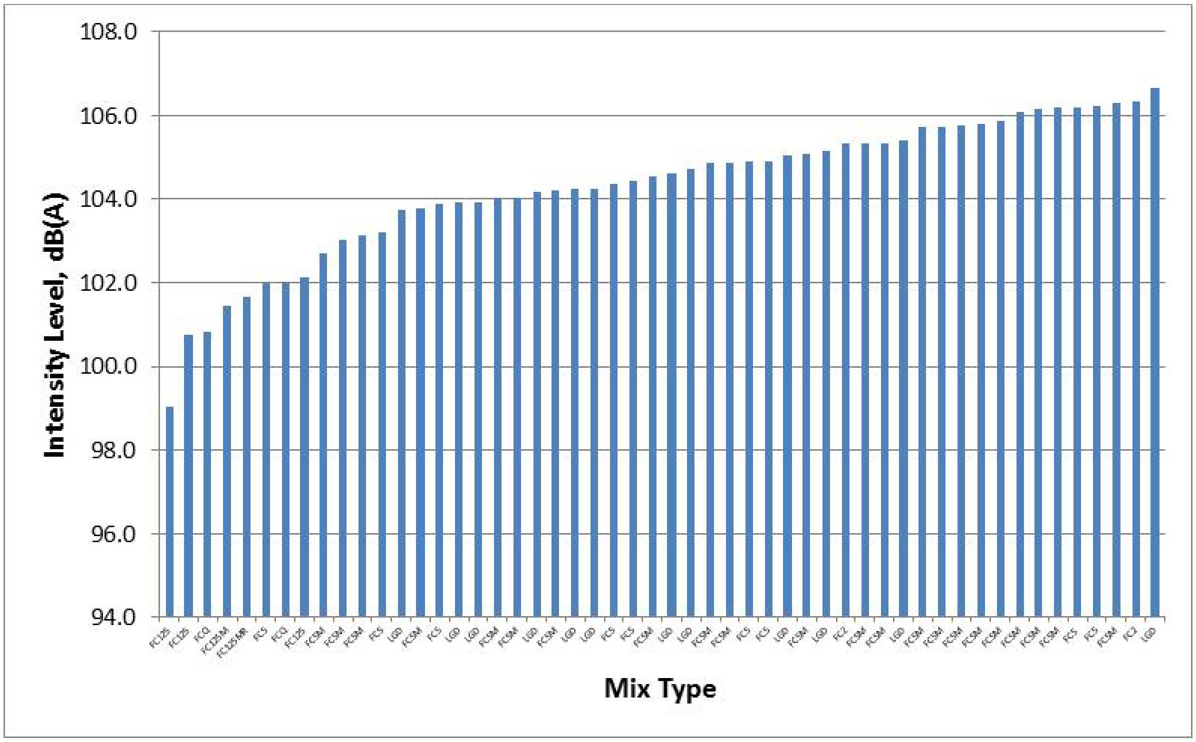

FIGURE 18. BAR GRAPH. PAVEMENT RANKINGS IN FLORIDA BY PAVEMENT SURFACE TYPE

Source: Wayson, 2014

Active Noise Control

[Cha, 2011] Cha, S. and A.G. Troshin, Active noise control barrier for national road in South Korea: Part I Preliminary noise study and electro-acoustic hardware design, Electronic Journal Technical Acoustics, 2011, 6.

Traffic noise annoyance in dwelling areas such as private houses and apartments is becoming a very important issue in South Korea. In this paper, frequency analysis of the traffic noise near highways was performed. Based on sound pressure level analyses and their frequency content, specific requirements for the components of active noise control systems were formulated. An active compensational loudspeaker, microphone front end and digital signal processor design were analyzed, considered and proposed. Required components specifications and design solutions for electro-acoustic hardware were verified using an experimental technique.

[Dehandschutter, 1998] Dehandschutter, W. and P. Sas, Active Control of Structure-Borne Road Noise Using Vibration Actuators, Journal of Vibration and Acoustics, vol. 120: pp. 517–523.

Structure-borne road noise is generated by road-induced excitation forces. The control approach presented here relies on the use of vibration actuators to modify the vibration behavior of the car body such that its noise radiation efficiency is decreased (Active Structural Acoustic Control - ASAC). The controller is optimized using laboratory experiments and numerical tools to simulate the performance in a complete vehicle control setup. Road tests yielded a 6.9 dB noise reduction in the 75 to 105 Hz range at the error microphone and a 6.1 dB noise reduction in the same frequency range at the passenger's ear.

[Duhamel, 1998] Duhamel, D. and P. Sergent, Active Noise Control of an Incoherent Line Source, Journal of Sound and Vibration, vol. 212, 1: pp. 141–164.

In this paper, outdoor active noise control of the sound pressure created by an incoherent line source was studied. Such a source is a model for the noise generated by road traffic or by trains and consists of a continuous distribution of uncorrelated point sources. By using this model, the possibility of generating quiet zones for environmental noise was examined. For this purpose, the statistical properties of the sound pressure are first studied. Then the efficiency of active control by point sources is calculated as a function of both frequency and position and comparisons are made between finite and infinite length primary sources. Finally, the investigation is extended to the calculation of the pressure crossing an aperture in a rigid plane to simulate the energy entering a room through an open window. The energy crossing the aperture is calculated with and without control to determine the noise reduction potentially provided by active control. The efficiency of the system was limited to low frequencies and to a local area assuming predictable source characteristics, which are not the case in real highway noise environments.

[Feist, 2006] Feist, J.P., R.J. Bernhard, and L.G. Mongeau, Estimation of speech intelligibility for road traffic tollbooth attendants using active noise control and directional microphones, Noise Control Engineering Journal, vol. 54, 3: pp. 177–186.

The effects of active noise control (ANC) on speech communication in a high traffic noise environment near a tollbooth were examined. Speech intelligibility was evaluated by means of the Speech Intelligibility Index (SII). The SII was computed for measured traffic noise spectra for continuous and idling traffic, using standard speech levels. The impact of active noise control systems on the SII was estimated by adding measured insertion gain data to noise and speech levels for four different active noise control systems. It was postulated that improvements in speech intelligibility may be obtained through a reduction of low frequency masking. Noise at tollbooths were studied. However, it was found that in-band masking was dominant. Thus, the ANC systems provided minimal improvement. The theoretical performance of alternative ANC systems featuring directional microphones and filters were then investigated. The results suggested that the use of a sealed ANC headset with a dipole directional microphone will offer improved speech intelligibility for truck noise. The predicted performance of similar systems improved as the order of the directional microphone was increased.

[Gäbel, 2018] Gäbel, G., J. Millitzer, et. al., Development and Implementation of a Multi-Channel Active Control System for the Reduction of Road Induced Vehicle Interior Noise, Actuators, vol. 7, 3: pp. 52–59.

Optimized driving comfort with a low interior noise level is an important component for the passenger car development process. The interior noise level caused by the dynamic interaction between rolling tires and the rough road surface which is transmitted via the car-body is a significant component of the overall noise level inside the car. To reduce the road-induced interior noise, in general, the chassis system has to be optimized. Passive measures often induce a tradeoff between vehicle dynamics and driving comfort. To overcome this disadvantage in this paper, the development and realization of an active measure was proposed. For the purpose of active mechanical decoupling, an active control system was developed, the feasibility of the integration was investigated, and its noise reduction potential was identified by vehicle tests. In a first step, a classical multi-channel and experimental-based structure-borne transfer path analysis of the full vehicle was completed to determine the dominant transfer paths. The concept for the active mount system (active mounts, multi-channel control system, sensors) is developed and parametrized by system-level simulation. Mechanical components and power electronics of the active system were designed, manufactured, and tested in the laboratory. The entire active system was integrated into the vehicle. The broadband adaptive feedforward algorithm was extended by certain measures in order to improve robustness and performance. Full vehicle tests were used to quantify the required specifications and the achieved effectiveness of the active vibration control system.

[Li, 2018] Li, H. and S. Zhang, Research on Active Control System of Vehicle Noise Caused by Pavement Excitation, IFAC PapersOnLine, vol. 51, 31: pp. 467–472.

To reduce the interior noise caused by road excitation, a finite element modal analysis method was used to analyze the interior space and then to get the frequency response curve of the corresponding nodes in the car. Through the establishment of an adaptive neural network active noise control system, the simulation experiment was carried out. The experimental results show that the active control system of neural network noise control in the 0 to 50 Hz frequency band has an average noise reduction of 4.3 dB. At 86 Hz, the maximum noise reduction was 9.8 dB, and the system can control the low frequency noise produced under the excitation of the road.

[Kwon, 2013] Kwon, B. and Y. Park, Interior noise control with an active window system, Applied Acoustics, vol. 74: pp. 647–652.

An active noise control window system to reduce the impact of exterior noise sources, such as traffic and construction noise which enters through open windows was proposed. The proposed system uses a feedforward control method for active noise control so as not to place the sensors and control sources inside the interior space of the building. For noise reduction throughout the interior room, the control gains for feedforward control were calculated to minimize the total acoustic power of the new source. The performance of the proposed system for directional exterior noise was confirmed with a scale-model experiment. The experimental results show that the proposed system may achieve a noise reduction of up to 10 dB for the entire room of the scale model, in the 400 to 1,000 Hz range, regardless of the direction of the incident wave.

[Sahib, 2017] Sahib, M.A. and Streif, S., Design of an Active Noise Controller for Reduction of Tire/Road Interaction Noise in Environmentally Friendly Vehicles, Proceedings of IEEE SPA 2017, pp. 59-62.

This paper contributes to the development of enhanced, environmentally friendly vehicles by proposing an effective tire/road interaction noise mitigation method based on active noise control (ANC). ANC methods can reduce the noise directly at the tire/road contact points by installing loudspeakers inside the vehicle fenders. The proposed method will also reduce the noise propagating inside the vehicle and will hence eliminate the needs for passive noise reduction measures. As a result, the weight of the vehicles can be significantly reduced, thus requiring less resources for production and more efficient fuel consumption during operation.

[Sakamoto, 2015] Sakamoto, K. and T. Inoue, Development of Feedback-Based Active Road Noise Control Technology for Noise in Multiple Narrow-Frequency Bands

and Integration with Booming Noise Active Noise Control System, SAE International Journal of Passenger Cars-Mechanical Systems, vol. 8, 1.

When a vehicle is in motion, noise is generated in the cabin that is composed of noise in multiple narrow-frequency bands and caused by the road surface. This type of noise is termed low-frequency-band road noise and reducing this noise will increase occupant comfort. The research used feedback control technology as the basis for the development of an active noise control technology to simultaneously reduce noise in multiple narrow-frequency bands. Methods of connecting multiple single-frequency adaptive notch filters, a type of adaptive filter, were investigated. Based on the results, a method of connecting multiple filters that would mitigate mutual interference caused by different controller transmission characteristics was proposed. This method made it possible to implement controllers with amplitude and phase characteristics in multiple narrow-frequency bands corresponding to design values. This allowed achievement of the target noise reduction. Additionally, in feedback-based road noise control, the amplitude of the control output signal changes drastically depending on the frequency characteristics of the road surface. This technology was integrated with the already-commercialized booming noise control system to permit a method to adjust the range of each controller output automatically. The system allowed balancing noise reduction performance under normal conditions with control stability when the vehicle passes over a large-input surface. Noise reduction values inside the vehicle of up to 5 dB at 45 Hz. and 125 Hz. were realized in field tests.

[Sano, 2001a] Sano, H., Inoue, T., et. al., Active Control System for Low-Frequency Road Noise Combined with an Audio System, IEE Transactions on Speech and Audio Processing, vol. 9, 7: pp. 755–763.

An active control system for low-frequency road noise in automobiles combined with an audio system was developed as a commercial application and installed in a station wagon. The purpose of this paper is to provide an outline of the system and describe the newly developed cost-reduction technology. The reduction of system costs is a major reason that active noise control technology could successfully be applied in a commercial product. The methods used to reduce costs include utilization of feedback control, implementation by analogue circuits, and common use of audio system speakers. This system reduced low-frequency road noise in the front seats by about 10 dB in the 35 to 45 Hz range and improved audio system listening experience while driving.

[Sano, 2001b] Sano, H, Inoue, T., et. al., Development of active control system for low frequency road noise: Solutions for practical use and system configuration, Acoustical Science & Technology, vol. 22, 5: pp. 378–379.

Recent years have brought increased emphasis on vehicle weight reductions in order to achieve increased fuel economy in automobiles. However, countermeasures for reducing noise in automobiles have resulted in an increased weight. Active noise control technology reduces noise by adding anti-phase noise to potentially solve these contradictory issues. Significant research in ANC application to automobiles has been taking place. However, ANC has not achieved widespread application because of its unfavorable cost performance. To improve cost performance, lowering the cost of an ANC system was evaluated. As a result, an active control system for low frequency interior road noise (drumming) combined with an audio system was developed and installed in a mass-production station wagon.

[Wang, 2017] Wang, B. and D. Duhamel, On the design and optimization of acoustic network resonators for tire/road noise reduction, Applied Acoustics, vol. 120: pp. 75–84, 2017.

A numerical method for the calculation of resonant network frequencies was proposed along with an optimization method based on genetic algorithms which allow targeted resonant frequencies of the network resonators. Parameters of the network structure (such as junction types and end positions) can be optimized. Experiments were conducted on optimized wooden network resonators to validate the method. Good agreement was found between the measured and targeted resonant frequencies. Applications to tire/road noise were considered.

[Zhu, 2004] Zhu, H., X. Yu, R. Rajamani, and K.A. Stelson, Active control of glass panels for reduction of sound transmission through windows, Mechatronics, vol. 14: pp. 805–819.

This paper explored the development of thin glass panels that can be controlled electronically to act as transmission preventers that block the propagation of sound. Small rare earth voice coil actuators are used to control glass panel vibrations. The development of the control system is based on the use of a wave separation algorithm that separates incident sound from reflected sound. The incident sound serves the important purpose of providing an acoustic reference that is unaffected by the action of the control system speaker. This reference signal was used in an adaptive feedforward control system to drive the transmitted sound to zero. Detailed experimental results were presented showing the efficacy of the algorithms in achieving real-time control of acoustic transmission. The glass panels effectively blocked transmission of sound, reducing sound transmission by up to 15 dB in the case of tonal frequencies and by up to 10 dB for broadband noise below 600 Hz. The glass panels can potentially be of great value in the development of noise-blocking glass windows for homes close to airports and noisy highways.

Vehicle Trends

[Campello-Vicente, 2016] Campello-Vicente, H., R. Peral-Orts, N. Campillo-Davo, E. Velasco-Sanchez, The effect of electric vehicles on urban noise maps, Applied Acoustics, 116, pp. 59–64.

While the main purpose of this paper was to present the assumptions and experimental tests developed to integrate the electric vehicle (EV) as a noise source in a traffic noise prediction model, as well as the expected effect of those vehicles on a noise map under different traffic conditions, it provides some good information for the overall abatement process. A comparison of the noise frequencies due to tire/pavement noise as shown by FIGURE 19 during coast-by conditions. There is quite a bit of similarity implying similar noise from the tire/pavement action regardless of engine type. Since the sound is dominated by the tire/pavement noise above approximately 40 km/h, the real difference in noise levels only occurs at lower speeds.

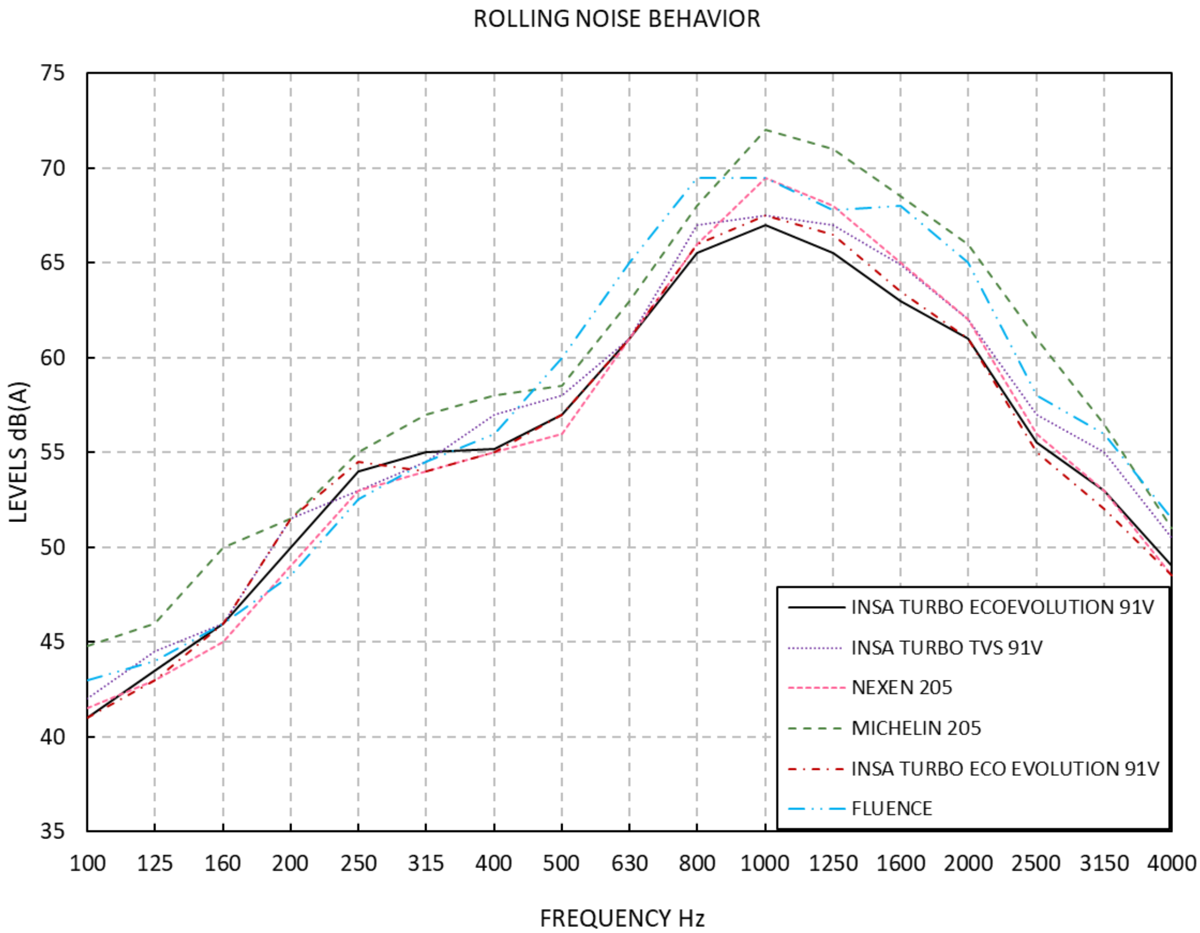

FIGURE 19. LINE GRAPH. COMPARISON OF SOUND EMITTED BY AN ELECTRIC VEHICLE VERSUS INTERNAL COMBUSTION ENGINE VEHICLES TIRE/ROAD NOISE

Original source: Campello-Vicente, 2016; image was recreated for this report

An analysis of the noise emitted by a free field traffic lane of vehicles was used to assess the variations in the emitted sound pressure levels by changing the proportion of electric vehicles in the traffic flow. A road with a constant traffic flow of conventional internal combustion engine (ICE) vehicles was implemented, simulated and validated with real traffic noise measurements. The total number of light vehicles was varied and the sound level emitted by the traffic lane was calculated. The optimal sound power level of the warning sound of the EV was integrated into the model. On a representative low speed (e.g., 30 km/h) the difference between a traffic lane of ICE vehicles and the same one running only EVs is 2 dB. The difference approaches zero with speeds higher than 50 km/h. These findings change when heavy vehicles are considered in the traffic flow. If 5 percent of the total traffic is heavy trucks, the decrease generated for electric vehicles is lower than 2 dB in any case, and at 30 km/h it is only 1.2 dB.

This led to the general conclusions that:

- At speeds above 50 km/h, the benefits are poor or negligible due to the dominant contribution of rolling noise.
- When the entire flow of EVs running at 30 km/h is studied in a free field lane, the estimated reduction of the sound pressure level is 2 dB but if electric vehicles use warning sounds to improve the security of pedestrians, the result is 1 dB without heavy vehicles in the traffic flow.

[Hastings, 2015] Hastings, A., M. Ahearn; C. Guthy-McInnis, R. Garrott, L. Garay-Vega, Acoustic Data for Hybrid and Electric Heavy-Duty Vehicles and Electric Motorcycles, DOT HS 812 225, National Highway Traffic Safety Administration.

Measurements for two electric motorcycles and one electric vehicle delivery truck were conducted along with screening data for four hybrid and electric heavy-duty vehicles. It was noted that results obtained may deviate appreciably from the results obtained using specified conditions. Regardless, as reported in two appendices, noise levels for these two vehicle types are available. While octave band data is available, only the overall noise levels are reported in this review and were:

- Motorcycles:
  - Ranged from 28.5 to 64.2dB(A) when stationary
  - Ranged from 59.6 to 66.5 dB(A) at 30 km/h
  - Intermediate speeds were between these values
  - Deceleration and acceleration were between these values
- Heavy Vehicles:
  - 55.4 at idle to 75.2 dB(A) at 30 km/h
  - Intermediate speeds, acceleration and deceleration were within this range

[Laib, 2018] Laib, F., A. Braun, W. Rid, Modeling noise reductions using electric buses in urban traffic. A case study from Stuttgart, Germany, Transportation Research Procedia, 37, pp. 377–384.

Buses are heavy vehicles with high noise emissions in urban areas. This case study examines to what extent noise reduction can be achieved in urban areas using electric buses. Using sound measurements on three different bus types with conventional and electric drive concepts, the noise profiles were implemented into a sound propagation model and the noise levels were determined along bus routes in the City of Stuttgart, Germany.

The measurements included the recording of sound pressure levels at standstill and the pass-by levels of buses on a test track at constant speeds of up to 50 km/h at a distance of 7.5 m. This allowed the authors to conclude that the maximum pass-by sound pressure levels at constant speed (see figure 20) reveal that the studied fuel cell electric bus (FCE-bus) is up to 14 dB(A) quieter than the conventional combustion bus (IC-bus) at a constant speed of 20 km/h. At a constant speed of 20 km/h about 25 FCE-buses are as noisy as one conventional IC-bus. The studied hybrid electric bus (HE-bus) is up to 7 dB(A) quieter than the studied conventional IC-bus at this speed. The noise level differences between the studied buses become smaller at higher speeds. The maximum noise level difference is determined at a constant speed of 20 km/h with no noise level differences found between the buses at 50 km/h. This is a consequence of the greater influence of rolling and air-regenerated noise at higher speeds.

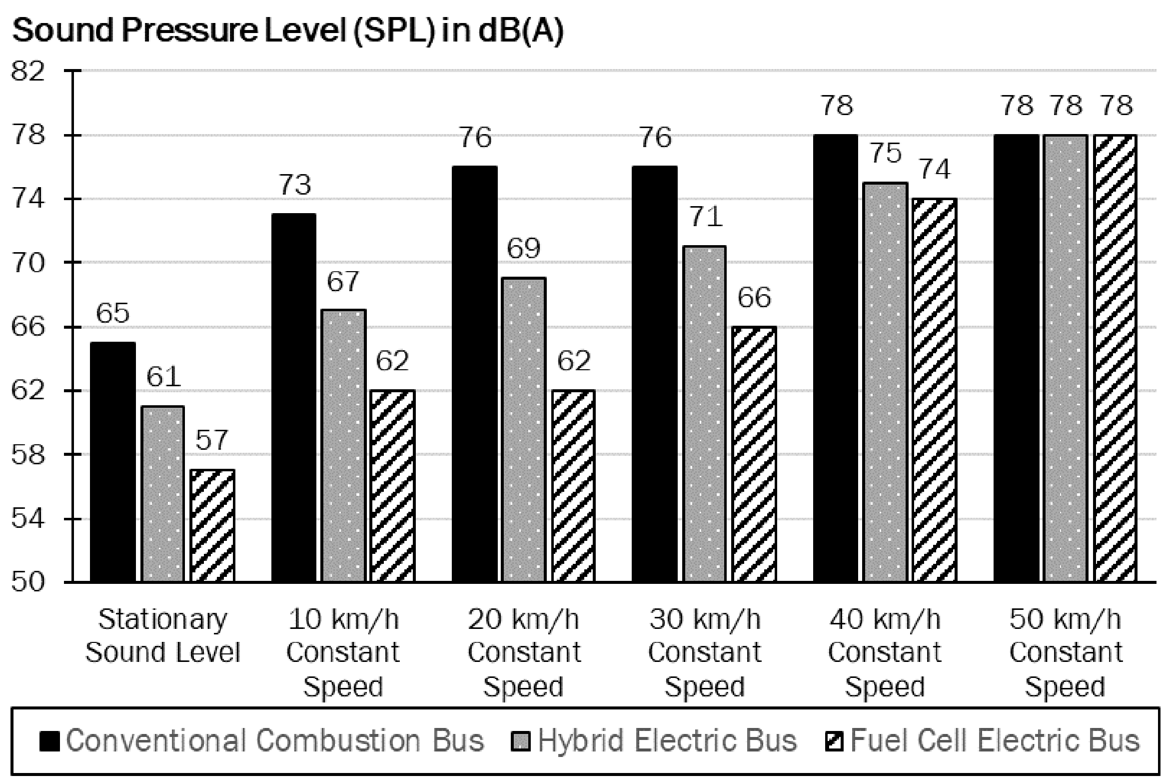

FIGURE 20. BAR GRAPH. STATIONARY AND PASS-BY AT 7.5-METER SOUND LEVELS OF EXAMINED BUSES

Original source: Laib, 2018; image was recreated for this report

This work was then applied to bus stops and bus routes. Accounting for other traffic on exemplary bus routes resulted in almost no noise reduction using the electric buses on heavily trafficked roads. By contrast, in a quiet residential area, the average noise reduction when using electric buses were as high as 5 dB(A). Results indicate that there is a great potential for noise reduction when using electric buses on routes with a high bus share of total traffic, low average travel speeds and a low percentage of other heavy traffic and especially at bus stops.

[Pollard, 2012] John K. Pollard, J.K., C. Guthy, A. Hastings, M.D. Stearns, L. Garay-Vega, Evaluation of Sounds for Hybrid and Electric Vehicles Operating at Low Speeds, Proc. of the Human Factors and Ergonomics Society 56th Annual Meeting, pp. 2206–2210.

Auditory cues may be needed for electric vehicles and hybrid electric vehicles (HEVs), operated at low speeds to alert pedestrians (e.g., pedestrians with sight difficulties or legally blind) of on-coming traffic. This field study compared the auditory detectability of numerous synthetic sounds that could be used. Testing occurred with a noise background of 58 - 61 dB(A) and test signals of 59.5 and 63.5 dB(A), approximately the levels from ICEs. Detection at 72 and 85 feet from the best alert signal sound were found for the two noise levels. Since the idea is to alert pedestrians, sounds designed according to psychoacoustic principles were used.

[Skov, 2015] Skov, R.S.H, L.M. Iversen, Noise from electric vehicles—Measurement, Danish Road Directorate, Institute of Transport Economics, Norwegian Centre for Transport Research.

In general, it was found that EVs are 4 - 5 dB quieter than similar ICE vehicles at low, steady speeds. At about 30 km/h, the difference in emitted noise is not significant due to tire/road noise dominance with similar tires and pavement textures. During decelerations, the engine braking noise for EVs is 2 - 4 dB quieter than for ICEs at low speed. At higher speeds the difference is much less due to the tire/pavement noise. The authors concluded that EVs will reduce the traffic noise on streets where the velocity of the vehicle will be under 30 km/h. In urban areas where the speed it often above 30 km/h the introduction of EVs will not have as great of influence. In some EV types there are narrow peaks in the spectra at low speed which are possible to hear and could be described as annoying.

The authors considered the overall impacts as the percentage of EVs increase in local traffic based on modeling. **FIGURE 21** illustrates their findings. As can be seen, there is a large potential reduction at 10 and 20 km/h, whereas the reduction at 30 km/h is not significant until higher percentages of EVs enter the fleet. By changing 100 percent of the fleet from ICEs to EVs, the reduction was computed to be only at 0.6 dB at 30 km/h and essentially non-existent at higher speeds.

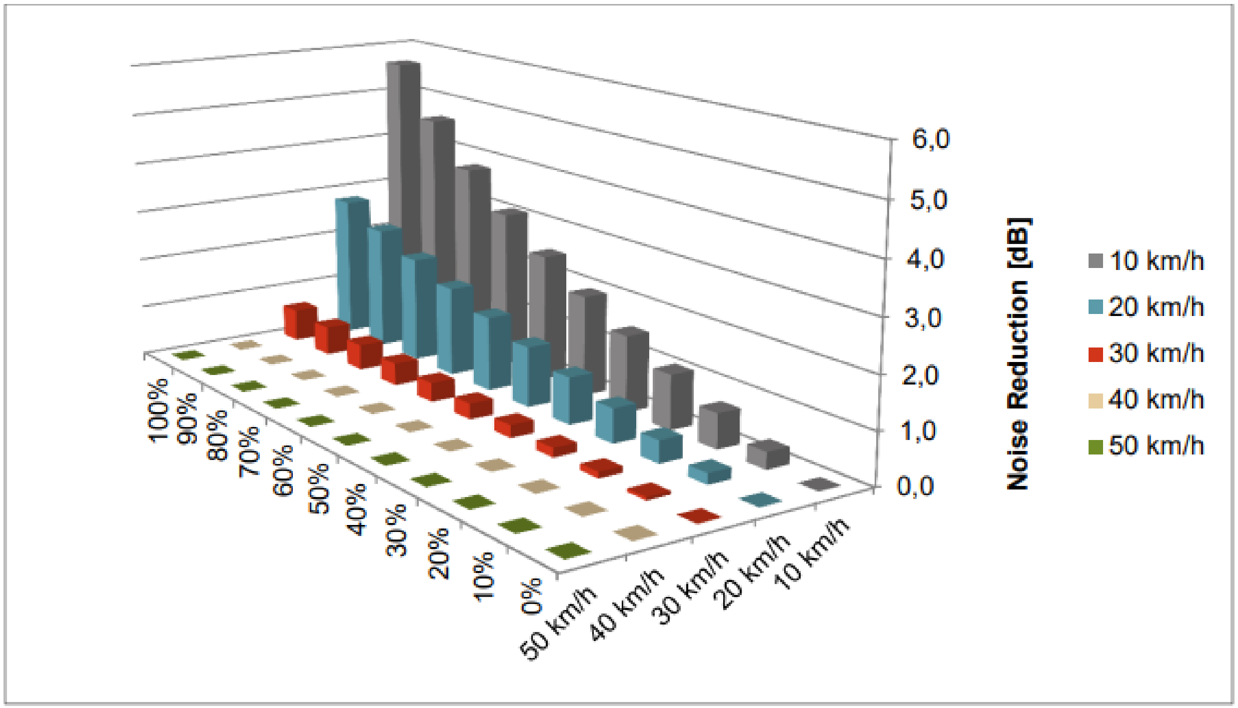

FIGURE 21. GRAPH. NOISE REDUCTION AT DIFFERENT SPEEDS BY REPLACING PERCENTAGES OF THE VEHICLE FLEET

Source: Skov, 2015

Cost Analysis and/or General Information

[Becker, 2003] Becker, N., D. Lavee, The Benefits and Costs of Noise Reduction, Jour. of Environmental Planning and Management, 46(1), pp. 97–111.

This paper attempts using a BCA to evaluate a stricter noise abatement program for noise originating from roads in Israel. Using the hedonic price method for three large cities and suburban area transactions, a benefit was found from noise reduction. The social cost–benefit analysis used a measure of benefit derived for 1 km of road as compared with the cost of noise reduction under different types of road structures. The present study performs social BCA with respect to two proposed alternative noise standards in Israel - 64 decibels and 59 decibels - while the current standard is 67 decibels. The cost of the project (i.e., noise reduction) was estimated through engineering data regarding the cost effective solution to reach a specified target. The benefits were estimated according to differences in property values due to different noise levels. The results of the study do not provide a clear-cut solution but provide some guidelines for decisionmakers with respect future impacts.

Two main features characterize noise abatement: 1) it does not accumulate; and 2) impacts varies from person to person. A social BCA should accompany each standard or proposed change in a standard. With respect to benefits, there are four major techniques for measuring the economic benefits of noise reduction.

- *Cost of abatement.* It was assumed that the cost of abatement is a minimal estimate of the noise damage. This is based on revealed behavior. If the individual was willing to pay $100 for the insulation process, then the benefit from this action must be at least $100.
- *Cost of illness*. Productivity loss is one way to measure the cost of illness.
- *Contingent valuation method (CVM).* By asking people how much they are willing to pay (WTP) for a given amount of noise reduction, the benefit of the noise reduction method can be estimated.
- *Hedonic pricing method (HPM).* This seems to be the most popular approach to estimating the true value of noise reduction. Here the real estate market is used as a proxy for the WTP for a less noisy apartment. This method was selected for use.

The report noted past research on the differences in property values near highways.

- Anderson & Wise (1977) results show differences of U.S. $42 - U.S. $129 on a U.S. $30,000 per house (about 0.3 percent) for differences in property values in four suburbs in the U.S.
- Baily (1977) suggested a 0.3 percent change for each decibel above 55.

Other research was noted showing similar results. The majority of the research uses a correlation between a given increase in the noise level and a reduction in the property value; the Noise Depreciation Sensitivity Index (NDSI). The NDSI is the percentage of reduction in the property value with a dollar amount attached to each decibel. This means for an average NDSI of 4 percent, a +20 dB change in noise level would result in an 8 percent reduction in price. However, different initial noise levels can result in variations. This requires an assumption that the NDSI is linear. This left a problem with the defining of a noise standard in that none of these studies incorporates two features that are essential to the assessment of the policy problem, aggregation of benefits to test for a national new noise standard and estimation on a length scale (that is, 1 km of road or 1 km^2). Without these two characteristics, it is impossible to perform a national BCA and/or test a new proposed standard. This study attempted to overcome these two problem areas.

The authors attempted to include all variables that affect the price of real estate properties in Israel. This resulted in inclusion of nine variables: (1) Area of apartment (m^2), (2) Age of building in years, (3) Availability of a lift, (4) Floor number, (5) Neighborhood quality, (6) View (in this case the sea), (7) View of an open space, (8) Region of transaction, and (9) Noise variable. The authors computed a NDSI in U.S. dollars. Noted were that other things affect these variables, but the list provides a good starting point for the analysis.

The acoustic costs to reach a new standard had several key parts and several assumptions that are specific to the Israel situation. But the application is of interest in that benefits as intended were applied to each km of roadway and that interpretation of results showed no clear-cut results with multiple combinations of variables passing the benefit/cost test. General patterns were shown, including buildings that are as close as 25 m from the road will never pass a cost–benefit test while buildings 100 m from the road will always pass a cost–benefit test (besides those located at intersections). Another important result was that as long as the acoustic means are 'regular' (e.g., acoustic barriers and quiet asphalt), the optimal level of noise is lower while the use of expensive acoustic means (e.g., roofed roads or triple barriers) raises the optimal level of noise. With respect to regional standards, this paper shows that the marginal valuation of reducing 1 decibel is not all that matters. Rather, it is the total benefit of noise reduction, taking into account the density factor, and compared with the cost component of reaching a given noise level.

Important cited from this author's work include:

Anderson, R.J. & Wise, D.E. (1977) The Effects of Highway Noise and Accessibility on Residential Property Values (Springfield, VA, National Technical Information Service).

Baily, M.J. (1977) Report on pilot study: highway noise and property values, unpublished paper (Baltimore, MD, University of Maryland).

[Bjørner, 2004] Bjørner, T.B., Combining socio-acoustic and contingent valuation surveys to value noise reduction, Transportation Research Part D 9, pp. 341–356.

For traffic noise the HPM is the most widely used approach to estimate the external costs. A number of studies have also relied on the contingent valuation method and other stated-preference methods. The main strength of the HPM is that it relies on actual behavior observed in the housing market, while the CV method relies on respondents' statements about what they would pay for a hypothetical reduction in noise. It is likely that the HPM provides an upwardly biased estimate of the value of noise reduction alone since traffic noise is positively correlated with other disturbances. Additionally, the house price differential calculated from the HPM only provides an upper bound on the willingness to pay for noise reductions. There are also methodological problems associated with the CV method. The CV method may produce too high of an estimate for WTP, due to its hypothetical nature. Recent studies suggest that the bias is limited, when CV responses are interpreted correctly. CV studies on noise reduction also face the challenge of explaining reductions in noise levels in a way that is scientifically correct while being understandable to the respondent. Early CV studies used scenarios with specified reductions in noise levels, typically a 50 percent reduction but with this scenario it is difficult to check whether the respondents understand what the reduction in noise would mean to them. CV researchers have adopted methods developed by noise researchers in reporting the impact of noise on the experienced (self-reported) annoyance. This has led to standardized methods for asking questions in socio-acoustic surveys about level of annoyance using a five-level annoyance scale (not at all annoyed, slightly annoyed, moderately annoyed, very annoyed and extremely annoyed).

In this work, the questionnaire combines the socio-acoustic survey tradition with CV questions on the WTP for removing the noise annoyance. By expanding the method used in these previous studies it allowed the calculation of the expected WTP per dB reduction at different noise levels. When WTP results are combined with the exposure–annoyance relationship it was found that the expected annual WTP per dB reduction increases with the noise level (e.g., 2 EUR at 55 dB to 10 EUR at 75 dB).

A sample of 2,200 respondents from the Municipality of Copenhagen was selected with the respondents living in areas with relatively high traffic levels to obtain a reasonable number of respondents exposed to medium and high noise levels. The survey consisted of four sections. In the first demographic questions were asked as warm-up. The second section asked about the level of annoyance from road traffic noise while subsequent questions asked about other disturbances from traffic (vibrations, safety, air pollution, dirt and dust) and noise annoyance from other noise sources. The third section was a hypothetical scenario and the WTP questions. The final section included questions on the socioeconomic characteristics of the respondent.

Data on noise exposure were obtained from the Environmental Protection Agency of Copenhagen based on the Nordic Prediction Method for traffic noise. The model was based on traffic levels, speed and share of heavy traffic. Combining the calculated noise at street level with GIS data allowed calculation of the distance between the noise source and each dwelling. Noise exposure was measured in dB;L_{Aeq24}. Analysis of the combined survey and noise level led to multiple results. **Figure 22** and **Figure 23** show results for age and overall annoyance levels.

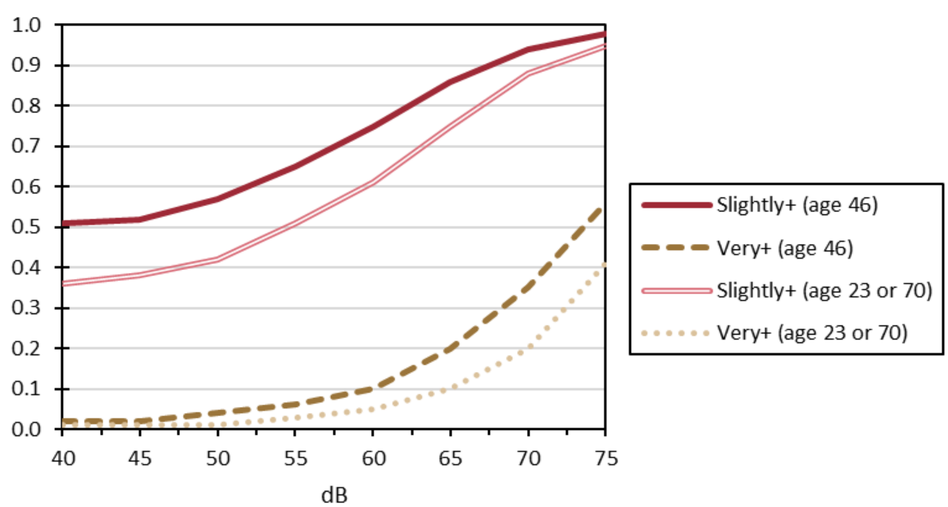

Figure 22. Line graph. Annoyance Level and Age

Original source: Bjørner, 2004; image was recreated for this report

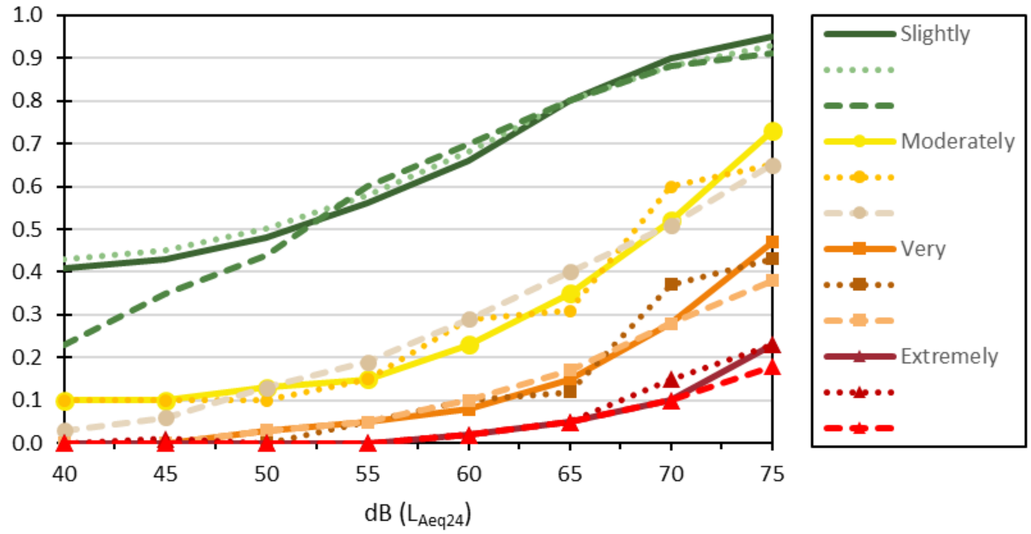

FIGURE 23. LINE GRAPH. ACTUAL AND PREDICTED ANNOYANCE LEVELS

Original source: Bjørner, 2004; image was recreated for this report

Of the 1,149 questionnaires returned 594 (52 percent) stated a positive WTP for removal of the noise annoyance. With respect to the other respondents debriefing questions were included in order to identify protest zero bids from genuine zero WTP. Genuine zero bids were obtained in 275 (24 percent) cases, protest zero bids in 202 (18 percent) cases, while item non-response was obtained in 78 (7 percent) cases. The most frequently used explanation for a legitimate zero bid, was that the respondent stated that s/he was not sufficiently annoyed by the noise. With respect to protest bids, different explanations were given (general objection against paying more tax, car drivers should pay etc.). As the share of positive bids increased with annoyance level, the share of genuine zero bids decreased. The share of positive bids reaches its peak for the moderately annoyed, while it is lower for the very and extremely annoyed but the numbers of respondents in these two categories are relatively small (132 and 83 individuals) and the differences among the shares of positive bids in the three highest annoyance categories are not significantly different at the 5 percent level according to a t-test. The willingness to pay results are shown in **FIGURE 24**.

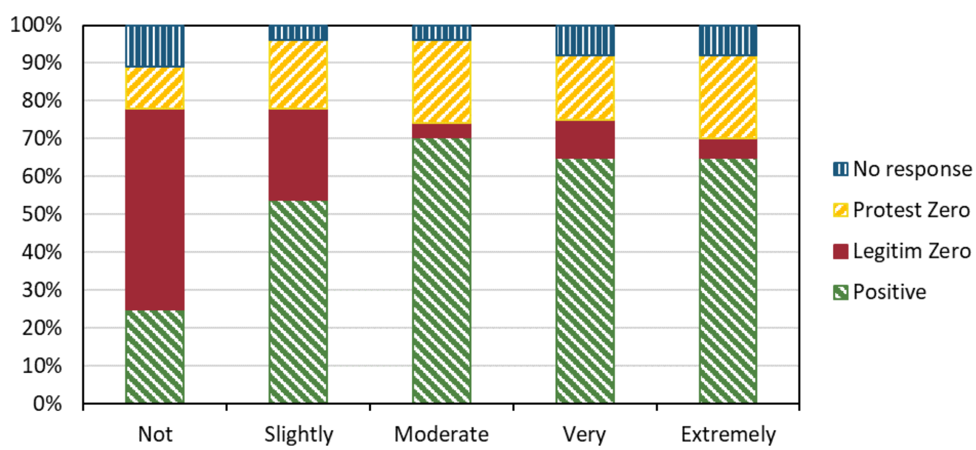

FIGURE 24. BAR GRAPH. WILLINGNESS TO PAY COMPARED WITH LEVEL OF ANNOYANCE

Original source: Bjørner, 2004; image was recreated for this report

Looking at the willingness to pay by noise level is shown in **FIGURE 24**. The results show the WTP dB reduction exceeds 10 € (EUR) per year per household at an initial noise level of 75 dB. However, the mean WTP per dB decreases with reductions in initial noise level. At 60 dB the value of a dB reduction is just below 4 €. At 45 dB the value is below 1 €.

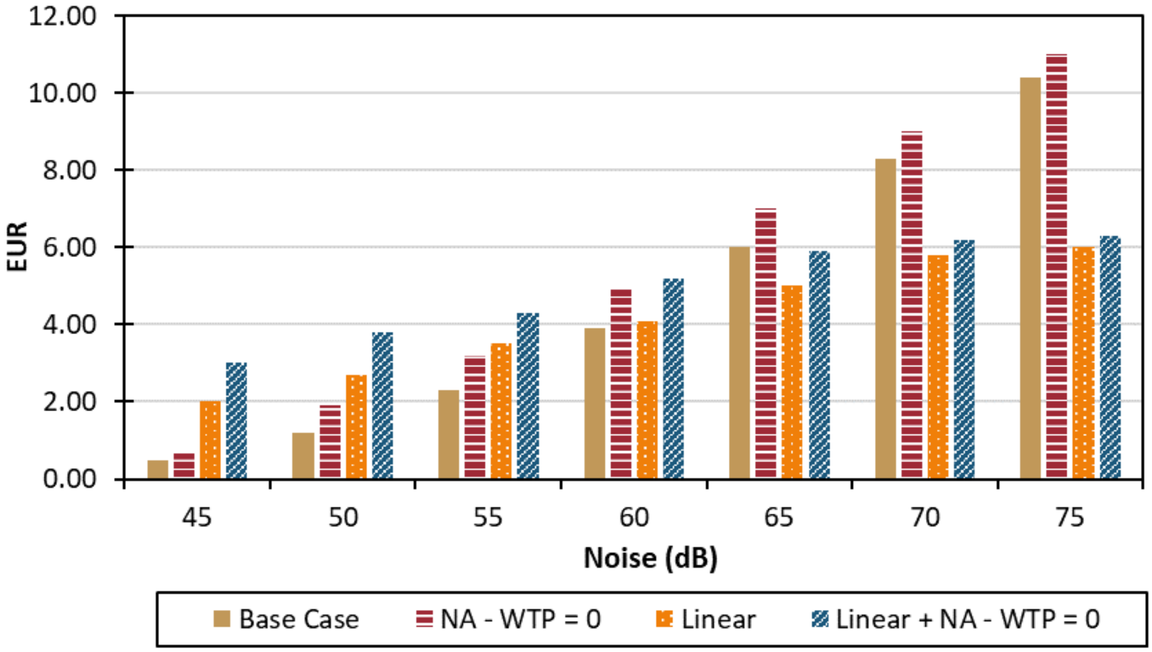

FIGURE 25. BAR GRAPH. EXPECTED WILLINGNESS TO PAY PER DECIBEL REDUCTION (€/HOUSEHOLD/YEAR)

Original source: Bjørner, 2004; image was recreated for this report

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[Brown, 2008] Brown, V., Survey of Traffic Noise Reduction Products, Materials, and Technologies, FHWA-AZ-08-584, Arizona DOT.

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 study included a literature review and survey.

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.
- Pavement Noise Reduction Materials—The operating speed of the roadway should be factored into the roadway design for quiet pavements.
- Pavement Noise Reduction Technologies—use of thin-textured surfacing 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—instead of relying on a single measure, the recommended forward strategy is to develop the ability to model the effectiveness of many different measures to achieve greater noise reduction.

Considerable description of lower noise pavement was presented but is not provided here due to intent of use. The survey included questions on respondent knowledge, budget for noise reduction on an annual basis, minimum reduction required, importance of attributes, and if research on effectiveness of new products had been accomplished. Sixteen responses were received from 77 potential respondents. Responses of interest included:

- Most of the respondents reported being somewhat to extremely familiar with each pavement noise reduction product, material or technology, including:
  - Pavement Alternatives:
    - » Dense grade asphalt - 8 Familiar (57.1 percent)
    - » Traffic Noise Barriers: Earth mounds or berms - 7 Familiar (50.0 percent)
    - » Receptor Controls: Land use planning - 8 Somewhat Familiar (57.1 percent)
    - » Receptor Controls: Window treatments - 7 Somewhat Familiar (57.1 percent)
- In terms of effectiveness replies were:
  - Pavement Alterations:
    - » Dense grade asphalt - 7 Effective (50.0 percent)
    - » Rubberized pavement - 7 Somewhat Effective (50 percent)
    - » Traffic Noise Barriers: Sound absorbing noise walls - 6 Effective (42.9 percent)
  - Traffic Noise Barrier Treatment and Coatings:
    - » Crumb rubber - 6 Do not Know (42.9 percent) and 6 Not Effective (42.9 percent)
    - » Receptor Controls: Window Treatments - 7 Somewhat Effective (50 percent)
    - » Eleven (78.6 percent) of the 14 respondents reported that 1 to 5 percent (average of 2.1 percent for survey) of their department's budget is allocated for noise reduction activities
    - » Eleven (78.6 percent) of the respondents indicated that cost effectiveness is "Very Important" in the decision-making process, and the remainder of the three respondents (21.4 percent) said that cost effectiveness is "Extremely Important"
    - » Thirteen (92.9 percent) of the respondents rated technology maturity as Important or higher, while all respondents (100 percent) considered aesthetic appearances as Important or higher

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[Cermak, 1981] Cermak, G.W., C.R. von Buseck, J.G. Cervenak, R.D. Blanchard, Analysis of traffic noise abatement strategies, Jour. of the Acoustical Society of America 69, 158.

Traffic sound levels were evaluated using computer simulations to evaluate the effectiveness of several hypothetical noise abatement strategies for traffic sound. These were performed for 28 actual census tracts in six cities and thought to be representative of the urban U.S., the results showed several key findings. These were:

- "Automobile acceleration noise standards would be only marginally effective in reducing traffic noise impact."

- "Truck acceleration noise standards would be more effective than automobile noise standards in reducing traffic noise impact; such standards would be only partially successful."
- "Rezoning of areas adjacent to major urban and suburban arterials would be more effective in abating traffic noise impact than new automobile acceleration noise standards, but less effective than current truck acceleration noise standards."
- "Traffic noise impact for one hypothetical passenger vehicle fleet with more subcompacts and diesels would not be markedly different from current impact levels."
- "Land use patterns (population density and traffic flow) are major determinants of traffic noise impact. Central business districts in their present form will continue to show relatively large traffic noise impact for any currently practical noise abatement scheme."

[FHWA, 2011] FHWA, Highway Traffic Noise: Analysis and Abatement Guidance, FHWA-HEP-10-025.

This document presents a three-part approach to highway traffic noise abatement: (1) control of land use planning adjacent to highways, (2) quieter vehicles, and (3) when feasible and reasonable, abatement of highway traffic noise for individual projects.

- *Noise Compatible Planning*. The Federal Government has no authority to regulate land use planning or the land development process on non-Federal lands. As such, FHWA encourages State and local governments to practice land use planning and control near highways. Some State and local governments have enacted statutes for land use planning and control such as California which requires local governments to consider the adverse environmental effects of highway traffic noise in their land development process. Wisconsin has a State law requiring formal adoption of a local resolution supporting the construction of a noise barrier and local land use controls to prevent the future need for noise barriers. State or local governments may not use this type of legislation to override construction of a noise barrier deemed feasible and reasonable. Other States and local governments have similar laws, but it is complicated. Since many competing considerations enter in land use control decisions, it is unlikely that land use planning and control will eliminate incompatible land development near highways.
- *Source control.* This option, except for quieter pavement types and in some cases tire regulations, is not available to the highway engineers and analysts. It is controlled by the Environmental Protection Agency (EPA) and other Federal agencies.
- *Highway Traffic Noise Abatement.* The National Environmental Policy Act (NEPA) of 1969 provides broad authority and responsibility to Federal agencies for evaluating and mitigating adverse environmental effects, including highway traffic and construction noise. The Federal-Aid Highway Act of 1970 (23 USC §109(i)) specifically addresses the abatement of highway traffic noise and mandates FHWA to develop highway traffic noise standards. The FHWA has developed and implemented regulations for the analysis and mitigation of highway traffic noise in Federal-aid highway projects in 23 CFR 772. The following is required during the planning and design of a highway project: 1) identification of highway traffic noise impacts; 2) examination of potential abatement measures; 3) the incorporation of reasonable and feasible highway traffic noise abatement measures into the highway project; 4) coordination with local officials to provide helpful

information on compatible land use planning and control; and 5) identification and incorporation of necessary measures to abate construction noise. Noise Abatement Criteria (NAC) for different types of land uses and human activities have been established and included. Meeting the NACs is not required in every instance and are not design standards. Rather, the regulation requires that FHWA make every feasible and reasonable effort to provide substantial noise reduction when highway traffic noise impacts occur. Local zoning and design requirements, such as height limits on fencing and walls are not acceptable limitations on the configuration or design of noise abatement.

Abatement measures as included in 23 CFR 772 are discussed. If an FHWA-approved highway traffic noise abatement measure is determined to be feasible and reasonable, then the highway agency must incorporate the noise abatement measure in the project design. The FHWA-approved highway traffic noise abatement measures include creating buffer zones, constructing barriers, installing noise insulation in buildings, and managing traffic. Discussions of each abatement measure are included to provide details. For barriers, three general types are listed: earthen mounds along the road called earth berms, vertical barriers called noise barriers, and a combination of earth berms and noise barriers.

The limitation for noise barriers as well as the acoustic benefits are covered. It is noted that in some cases, blocking the line of sight is difficult and that the possible theoretical reduction is 20 dB(A). The impact of openings in noise barriers for driveway connections or intersecting streets reduce the effectiveness of barriers and in some areas, homes are scattered too far apart to permit construction of noise barriers at a reasonable cost. The most effectiveness for noise barriers was stated to be for receivers within approximately 200 feet of a highway.

From a social perspective, it was noted that public reaction to noise barriers appears to be positive. However, it was noted that there is a wide diversity of specific reactions to barriers. Residents adjacent to barriers have stated that conversations in households are easier, sleeping conditions are improved; they have a more relaxing environment, open windows more often, and use yards more in the summer. Other perceived benefits included: increased privacy, cleaner air, improved view and a rural sense, and healthier lawns and shrubs. Negative reactions have included a restriction of view, including a visual impact of the barrier itself, a feeling of confinement, a loss of air circulation, a loss of sunlight and lighting, and poor maintenance of the barrier. Motorists have sometimes complained of a loss of view or scenic vistas and a feeling of being "walled in" when traveling adjacent to barriers. Residents near a barrier seem to feel that barriers effectively reduce highway traffic noise and that the benefits of barriers outweigh the disadvantages of the barriers. Commercial property owners may oppose noise barrier construction because the barrier may block the line of sight to the property.

Four examples for traffic management were provided: prohibiting trucks from certain streets and roads, permitting trucks to use certain streets and roads only during daylight hours, timing traffic lights to achieve smooth traffic flow and to eliminate the need for frequent acceleration/deceleration, and reducing speed limits reduces highway traffic noise levels.

The other possible abatement measures were discussed in general as well as the real versus psychological effects of vegetation and privacy fencing.

The guidance document includes important guidance on flexibility. FHWA believes that the States are in the best position to make investment decisions on the needs and priorities of their citizens and as such give highway agencies flexibility to determine the feasibility and reasonableness of highway traffic noise abatement; balancing the benefits of highway traffic noise abatement against the overall adverse social, economic and environmental effects and costs of the highway traffic noise abatement measures. Guidance on costs and determining feasibility/reasonability are included.

[FHWA, 2006] Harvey, K., S. Pedersen, C. Reherman, J. Rochat, E. Thalheimer, M. Lau, G.G. Fleming, M. Ferroni, C. Corbisier, FHWA Highway Construction Noise Handbook, FHWA-HEP-06-015, Office of Natural and Human Environment.

The FHWA Office of Natural and Human Environment, in cooperation with The John A. Volpe National Transportation Systems Center Acoustics Facility, developed the Highway Construction Noise Handbook. The handbook provides guidance to U.S. state transportation agencies in measuring, predicting, and mitigating highway construction noise and developing noise criteria. The FHWA Roadway Construction Noise Model (RCNM) is used in conjunction with this document and a user manual is included. This guidance document provided substantial improvements and changes in addressing highway construction noise since the 1977 publishing of the FHWA Special Report, Highway Construction Noise: Measurement, Prediction and Mitigation. The focus of the handbook and CD-ROM is confined to noise-related issues and not on vibration. Detailed information on all phases of construction noise prediction, effects, measurement, public involvement, and mitigation are included. Two key tables based on noise effects are shown in **Table 21** and **Table 22**.

Table 21. Summary of Human Effects in Terms of Speech Communication, Community Reactions, Annoyance, and Attitude Toward Area Associated with an Outdoor Day-night Sound Level of 55 Decibel re 20 micropascals

Type of Effect	Magnitude of Effect
Speech – Indoors	100% sentence intelligibility (average) with a 5 dB margin of safety
Speech – Outdoors	100% sentence intelligibility (average) at 0.35 meters
	99% sentence intelligibility (average) at 1.0 meters
	95% sentence intelligibility at 3.5 meters
Average Community Reaction	None evident; 7 dB below level of significant “complaints and threats of legal action” and at least 16 dB below “vigorous action” (attitudes and other non-level related factors may affect this result)
Complaints	1% dependent on attitude and other non-level related factors
Annoyance	1% dependent on attitude and other non-level related factors
Attitude Toward Area	Noise essentially the least important of various factors

TABLE 22. STEADY A-WEIGHTED SOUND LEVELS THAT ALLOW COMMUNICATION WITH 95 PERCENT SENTENCE INTELLIGIBILITY OVER VARIOUS DISTANCES OUTDOORS FOR DIFFERENT VOICE LEVELS

Communication Distance (meters)	0.5	1	2	3	4	5
Normal Voice (dB)	72	66	60	56	54	52
Raised Voice (dB)	78	72	66	62	60	58

[Forssén, 2013] Forssén J., Van der Aa, B., Initial results for traffic noise mitigation with Helmholtz resonators in the ground surface beside a road, Internoise 2013.

This paper focuses on the effect of Helmholtz resonators, buried in the ground surface alongside the road. A benefit of buried resonators is the ability to function without obstructing the accessibility to the protected area. A modeling approach using equivalent sources is described for a coupled field of resonators in an otherwise acoustically hard ground plane. The model is validated in comparison with laboratory measurements. For selected road traffic cases, using a grid pattern within a strip along the road, noise reductions of 2 - 4 dB(A) were predicted. The insertion loss increases with opening area, as expected and by frequency by the size of the opening. **TABLE 23** shows the resonant frequency by opening size.

TABLE 23. VARIATION OF TOP PLATES WITH DIFFERENT RESONATOR OPENING RADII AND CORRESPONDING RESONANCE FREQUENCIES

Top plate nr	Opening diameters	Estimated resonance frequency
1	all 6.0 mm	780 [Hz]
2	all 7.0 mm	862 [Hz]
3	all 8.0 mm	940 [Hz]
4	all 10.0 mm	1084 [Hz]
5	2.0, 3.0, 4.0, 5.0, 6.0, 7.0, and 8.0 mm	500–940 [Hz]
6	5.0, 5.5, 6.0, 6.5, 7.0, 7.5, and 8.0 mm	689–940 [Hz]

For roadside resonators of Helmholtz type, a numerical model was developed and validated by laboratory measurements. Using the model, the effect of a 4-m-wide strip of resonators buried in the ground surface, with a center-to-center spacing of 6 cm, circular openings with 20 mm diameter resulted in a common resonance frequency of about 380 Hz. Calculated sound pressure levels in the range 50 - 5,000 Hz, with and without the resonators in an otherwise hard ground, show, for two-lane road traffic cases, an estimated noise reductions of 2 - 4 dB(A). There is also an estimated noise increase at lower frequencies, at 250 Hz and below. Initial calculations show interesting results when raising a finite impedance strip to a moderate height of 0.3 m. and is planned to be investigated further for the resonators. Slightly higher insertion losses are also expected if the strip is placed closer to the road track, which should be possible in practice since the resonators are free from protruding elements.

[Garg, 2011] Garg, N., O. Sharma, V. Mohanan, S. Maji, Passive control measures for traffic noise abatement in Delhi, India, Jour. Of Scientific & Industrial Research, Vol. 71, pp. 226–234.

This research began with a socio-acoustic survey of 520 individuals less than 30 years old in Delhi. It found that more than 50 percent are disturbed by traffic and horn noise, 17 percent annoyed by aircraft noise, and that train noise had less impact than traffic noise. When exposed to traffic noise, 28 percent felt stressed, 25 percent were mentally tired, 21 percent irritated/angry, 9 percent had sleep disturbance, and 7 percent had headaches. Based on measurements, population density, and traffic volume, an $L_{Aeq,24h}$ value of 69 dB(A) was found to be the corelated disturbance parameter which is greater than existing limits. A noise abatement program was established to reduce noise levels at homes over 70 dB(A) by 100 percent, 65 dB(A) by 90 percent and 60 dB(A) with a goal of 50 percent by 2030. As shown in **FIGURE 26**, many abatement strategies were considered after identifying hot spots using GIS traffic noise predictions.

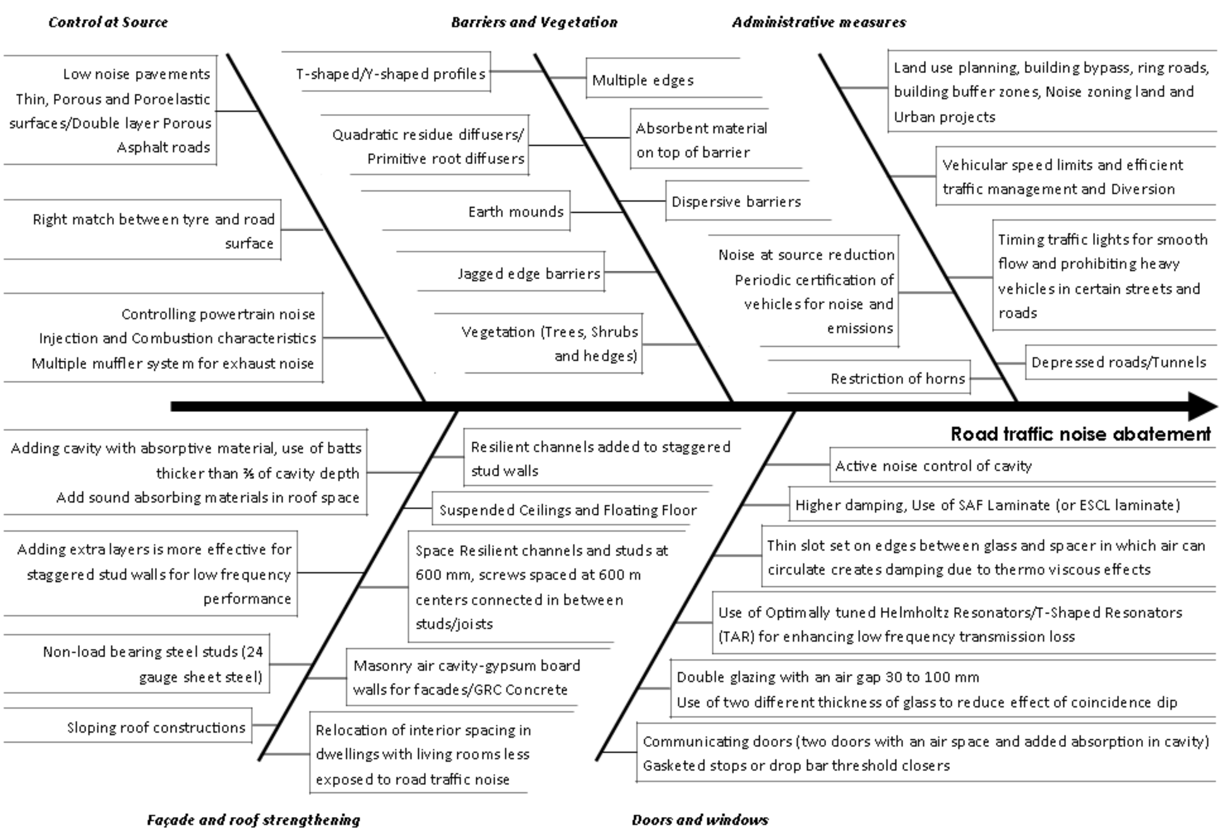

FIGURE 26. DIAGRAM. CAUSE AND EFFECT ANALYSIS DIAGRAM FOR ROAD TRAFFIC NOISE ABATEMENT

Original source: Garg, 2011; image was recreated for this report

Abatement measures reviewed in detail included multiple barrier types (ranked in **TABLE 24**), and vegetation. Others included but to lesser detail included noise zoning, restricting horn usage, traffic management, including restrictions on heavy vehicles, and regulatory incentives. Final rankings were not presented.

Table 24. Design Evaluation Matrix of a Sound Barrier

Barrier Type	Requirements from a Barrier									Normalized Weight	Closeness Coefficient Using TOPSIS Approach	Rank
	IL	Structural Integrity	Compatibility with Environment	Maintenance	Safety and Durability	Installation	Corrosion Resistance	Economic Consideration	Ventilation, Lighting, Drainage Issues and Vandalism			
T-Top barrier with absorptive material	G	F	F	MP	F	MP	F	MP	MP	0.0132	0.355	7
Y-Top/Half Y	MG	MP	F	MP	F	MP	MP	MP	MP	0.0126	0.343	8
Jagged top	MG	MG	MG	F	F	F	MG	F	F	0.0154	0.50	4
Cylindrical top	MG	F	F	MP	F	MP	F	F	MP	0.0129	0.454	5
Mushroom top	MG	F	F	MP	F	MP	F	MP	MP	0.0129	0.414	6
Multiple-edge top treatment	MG	F	F	MP	F	F	F	MP	MP	0.0132	0.454	5
Absorptive barrier	MG	MG	F	F	F	F	MP	MP	MP	0.0132	0.50	4
Transparent barrier	F	MG	G	MG	MG	MG	G	G	G	0.0176	0.586	2
Concrete barrier/ Hollow concrete blocks	MG	G	G	G	G	F	G	P	MG	0.0204	0.678	1
Reflective barrier	F	MG	F	MG	MG	MG	F	F	MG	0.0154	0.50	4
Metal/Composite/ Polycarbonate sheets/ Sintered metals/ Plastics	F	MG	G	G	MG	G	F	G	MG	0.0171	0.573	3

[Hall, 1978] Hall, F.L., B.E. Breston, S.M. Taylor, Effects of Highway Noise on Residential Property Values, Transportation Research Record, No. 686, Transportation Research Board.

Studies of highway noise have shown the price of housing varies considerably with location. Six similar housing sites in parallel rows adjacent to major roads were identified, data on real estate transactions reviewed, and noise levels collected. Analysis of variance indicated a significant difference in price between rows of houses at the two noisiest locations. Multiple regression analysis was performed for the two nosiest sites based on the noise level. The results show that at the noisy locations (daytime L_{eq} of 73 dB(A) or higher) noise was strongly related to differences in housing prices and is valued at approximately $650–$700 per dB. At less noisy sites (daytime L_{eq} less than 70 dB(A)), noise was not significantly related to difference in housing prices. The highest dollar-per-decibel value, $646, occurs at the lowest noise pollution level (NPL), 80 dB(A). The other three sites have NPL readings over 85 and dollars-per-decibel values of less than 150. These results suggest that some noise impacts are not a linear function of sound level and that noise reduction at very noisy locations is more important that at less noisy ones.

[Hammer, 2014] Hammer, M.S., T.K. Swinburn, R.L. Neitzel, Environmental Noise Pollution in the United States: Developing an Effective Public Health Response, Environmental Health Perspectives, Volume 122, No. 2, pp. 115–119.

Some of the most serious health effects associated with noise were summarized based on published estimates and extrapolations from those estimates. It was estimated that 104 million individuals had annual $L_{eq,24\,h}$ levels > 70 in 2013 and were at risk of noise induced hearing loss. It has been estimated by EPA in 1981 that 100 million people (about 50 percent) may be at risk of heart disease and other noise-related health effects. It was stated that direct regulation, altering the informational environment, and altering the built environment are the least costly, most logistically feasible, and most effective noise reduction interventions. Other effects were also noted (see **FIGURE 27**).

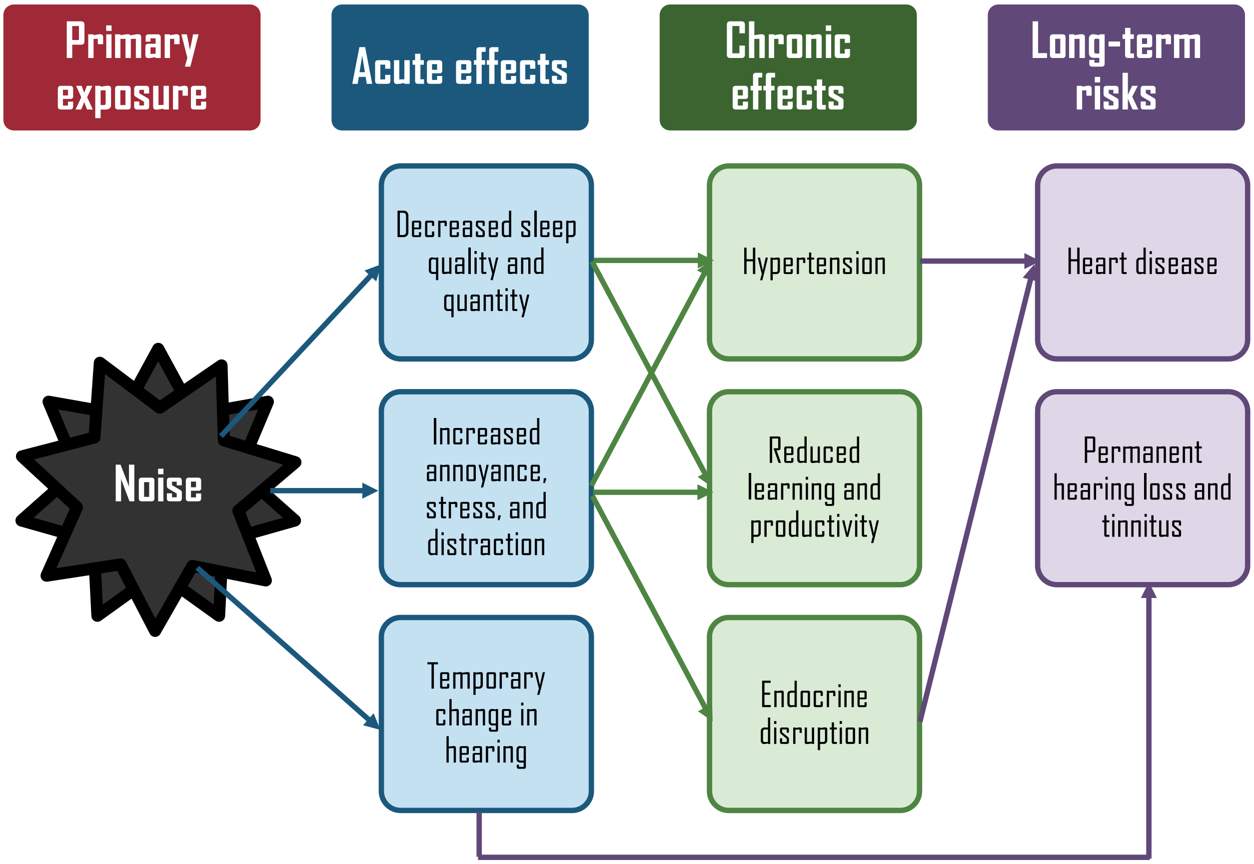

FIGURE 27. FLOW CHART. SELECT EFFECTS OF NOISE

Original source: Hammer, 2014; image was recreated for this report

- *Sleep and heart disease*. People in noisy environments experience a subjective habituation to noise, but their cardiovascular system does not. The cardiovascular system still experiences activations of the sympathetic nervous system and changes from deep sleep to a lighter stage of sleep in response to noise. Decreased quality and quantity of sleep elevates cardiovascular strain, which manifests as increased blood pressure and disruptions in cardiovascular circadian rhythms.
- *Stress.* The effects of noise on conscious subjects are insidious and result in part from increased psychosocial stress and annoyance. Annoyance from continuous sound appears to vary substantially by individuals. Annoyance increases sympathetic tone, especially in noise-sensitive individuals, and may be the non–sleep-mediated pathway that is present in individuals with high occupational noise exposures who subsequently develop heart disease. Children in noisy environments may have poor school performance.
- *Noise-induced hearing loss (NIHL).* Long-term exposures to noise levels > 75 dB(A) as stated by the U.S. EPA can cause metabolic changes in sensory hair cells within the cochlea, eventually leading to an increasing inability to perceive sound. Neuronal destruction may also occur in which the ability to perceive sound may remain undiminished but the ability to understand the meaning of sound deteriorates. Extreme exposures can cause direct mechanical damage. Noise exposure is also associated with tinnitus (ringing in the ears) and hyperacusis.

[Hustim, 2013] Hustim, M., K. Fujimoto, Road Traffic Noise Reduction Using TDM-TMS Strategies in Makassar City, Indonesia, Jour. Environ. Eng., AIJ, Volume 78, No. 689, pp. 551–559.

This paper put forward ideas for using travel demand management (TDM) and traffic management systems (TMS) to mitigate road traffic noise. Strategies put forward were somewhat unique and included: ridesharing/car pooling to reduce overall vehicles, prohibition of horn blowing, and bus rapid transit. If we consider the ridesharing and bus service, this would result in fewer vehicles and reduce noise relative to the number of vehicles reduced. Noise reductions from reduced traffic volumes were computed to be small with a maximum value of 2.8 dB. It should be noted that this also provides other benefits such as reductions in capacity needs and reduced air pollutants. The bus service reductions were small with a maximum of 3.9 dB predicted. It was also noted that combination of all three methods resulted in average reductions of 4.7 dB with a maximum of 6.2 dB.

[INCE, 2014] Institute of Noise Control Engineering of the USA, Inc., Cost-Benefit Analysis: Noise Barriers and Quieter Pavement, Workshop sponsored by The INCE Foundation, the Noise Control Foundation, and the Transportation Research Board Committee ADC40.

The importance of this workshop was the final recommendations that were developed after an extended discussion of the issues. These recommendations, repeated verbatim, are:

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

[Jha, 2009] Jha, M.K., P.E., M.W. Kang, GIS-Based Model for Highway Noise Analysis, J. Infrastruct. Syst., 2009, 15(2), pp. 88–94.

Elevated noise levels due to vehicular traffic can significantly reduce property values. Most of the highway noise literature has been focused in predicting noise levels, estimating cost of installing noise barriers, and assessing effectiveness of noise barriers in reducing the amount of noise.

A solution to the problem of automatically identifying highway segments along which installation of noise barriers may be warranted due to elevated noise levels can be accomplished by integrating GIS spatial modeling capability with the FHWA Traffic Noise Model (TNM) methodology. In this paper, a GIS-based model to perform that function was presented. In addition to automatic identification of problem segments, the method also calculates effective length of noise barriers to be installed. An example is included using Maryland's GIS database to demonstrate the capability of the proposed model. Several enhancements remain to be included in the future.

[Martin, 2006] Martın, M.A., A. Tarrero, J. Gonzalez, M. Machimbarrena, Exposure–effect relationships between road traffic noise annoyance and noise cost valuations in Valladolid, Spain, Applied Acoustics 67, pp. 945–958.

A social survey was conducted to identify the main sound sources, evaluate the annoyance, and analyze the main effects of noise on people. The survey was distributed to a sample of people living approximately in the corners of an imaginary 250 m grid placed over the map of the City (Valladolid, Spain). Measurements were performed at these locations. The noise levels (L_{eq}, L_{max}, L_{10}, L_{50}, L_{90}, L_{min}) were measured in dB(A), using an averaging time of 10 minutes. At each of the 490 measurement points, eight measurements were made as follows: two during a working day period, two during a holiday day, two during the night of a working day, and two during the night of a holiday. Measurements took place on different months, days of the week and time during the corresponding period.

Using approximately the same locations as measurements, a survey was structured to obtain different information, including: 1) Dwelling location; 2) Data concerning the person being surveyed; 3) Dwelling description-characteristics; 4) Environment description-characteristics; 5) Annoyance due to the different sound sources; 6) Effects produced by noise on the population being interviewed; 7) Actions taken to reduce noise; and 8) Economical valuation of noise reduction. Of the 490 points, 296 came back as valid. To evaluate the cost, a contingent valuation technique was used based on answers given by citizens when they are asked about how they value the object under analysis with the intent to investigate how much a citizen is willing to pay in order to reduce such noise. This method is questionable and raises certain controversy since citizens are asked to value something that they do not fully understand or may not have experienced. Age distribution, sex, and education were considered. People in the survey were asked about the degree of annoyance produced by several different sources. The greatest annoyance was ''general traffic noise''. Allocating 5 points to the answer ''very much'', 4 to ''much'', 3 points to ''so-so'', 2 points to ''little'' and 1 point to ''not at all'', results were analyzed. An example of the responses is shown in **FIGURE 28** while **FIGURE 29** looks at just the values when people were highly annoyed (much or very much). Of note is that L_{dn} was found to be the best metric.

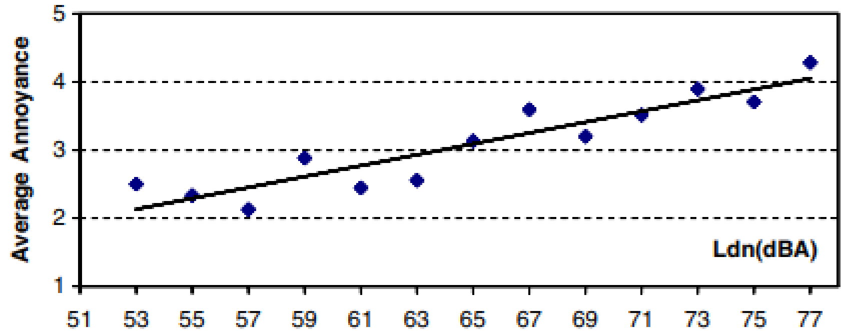

FIGURE 28. LINE GRAPH. AVERAGE ANNOYANCE PRODUCED BY TRAFFIC NOISE AS A FUNCTION OF THE L_{DN} IN DECIBEL(A); CORRELATION COEFFICIENT R = 0.92

Source: Martin, 2006

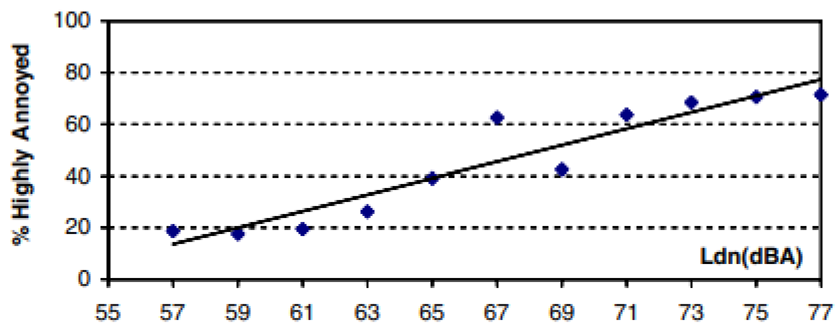

FIGURE 29. LINE GRAPH. PERCENTAGE OF PEOPLE HIGHLY ANNOYED BY TRAFFIC NOISE AS A FUNCTION OF THE L_{DN} IN DECIBEL(A); CORRELATION COEFFICIENT R = 0.94

Source: Martin, 2006

The following conclusions were drawn:

- The spatial distribution of ''people highly annoyed by noise'' and points with L_{dn} above 65 dB(A) is very similar (both plots present a high degree of coincidence).
- L_{dn} relates very well to the annoyance. The relation is better when considering people highly annoyed than when considering average annoyance.
- L_{max} also related fairly well to annoyance, but in this case the relation improves when considering average annoyance.
- The population prefers to live in silent environments even if this means living in house of a lower economical value, increasing the distance to their working places or even paying a higher price for the house.
- Fifty percent of the population are willing to pay money in order to reduce noise contamination.
- Many of the people that had high annoyance have undertaken some actions. Twenty-nine percent have insulated their dwelling in some way and 30 percent have placed a complaint or a demand against the disturbing source.

[McNerney, 1999] McNerney, M.T, B.J. Landsberger, Validation of Cost-Effectiveness Criterion for Evaluating Noise Abatement Measures, Report No TX-99/3965-1, Texas Department of Transportation.

This project from the Texas Department of Transportation includes information about the effects of the current cost effectiveness criterion. The project reviewed (1) the cost effectiveness criteria used by other states, (2) the noise barrier construction history of the other states, and (3) the effect the cost effectiveness criteria on noise barrier construction. Decisions regarding noise barrier construction during recent years were reviewed and typical residential scenarios were evaluated to determine when the cost effectiveness criterion indicate the need for constructing a noise barrier. Recommendations were made on the optimum monetary level for that criterion.

Required of every noise barrier project is a method to determine reasonable and feasible. Case studies in Texas revealed that in most cases where noise mitigation was feasible it can be accomplished within the criteria cost. The main reason for a no-build decision was access requirements with cost second. Through modeling, the following results were concluded:

- A long continuous barrier is the most cost effective.
- Only under ideal situations can single or double residences be protected due to cost.
- Gaps lead to significant reductions in effectiveness.
- The current criteria at the time ($25,000 per benefitted receiver) is valid.

This led to the following conclusions and recommendations:

- The cost criteria were sufficient at that time but should be evaluated every 5 years.
- Complete records of noise analysis should be kept and maintained.
- Trends in other States should be monitored.
- A Texas database of design details should be established and maintained

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[Nellthorp, 2007] Nellthorp, J., A.L. Bristow, B. Day Introducing Willingness-to-pay for Noise Changes into Transport Appraisal: An Application of Benefit Transfer, Transport Reviews, 27:3, pp. 327-353.

In many industrialized countries including the UK, noise costs and benefits are still not incorporated into appraisals for most transport projects and policy changes. This paper describes the actions taken in the UK to address this issue and includes: research based on the City of Birmingham (see **Figure 30**), an international review of willingness-to-pay evidence; the development of values using benefit transfers over time and locations; and integration with appraisal methods.

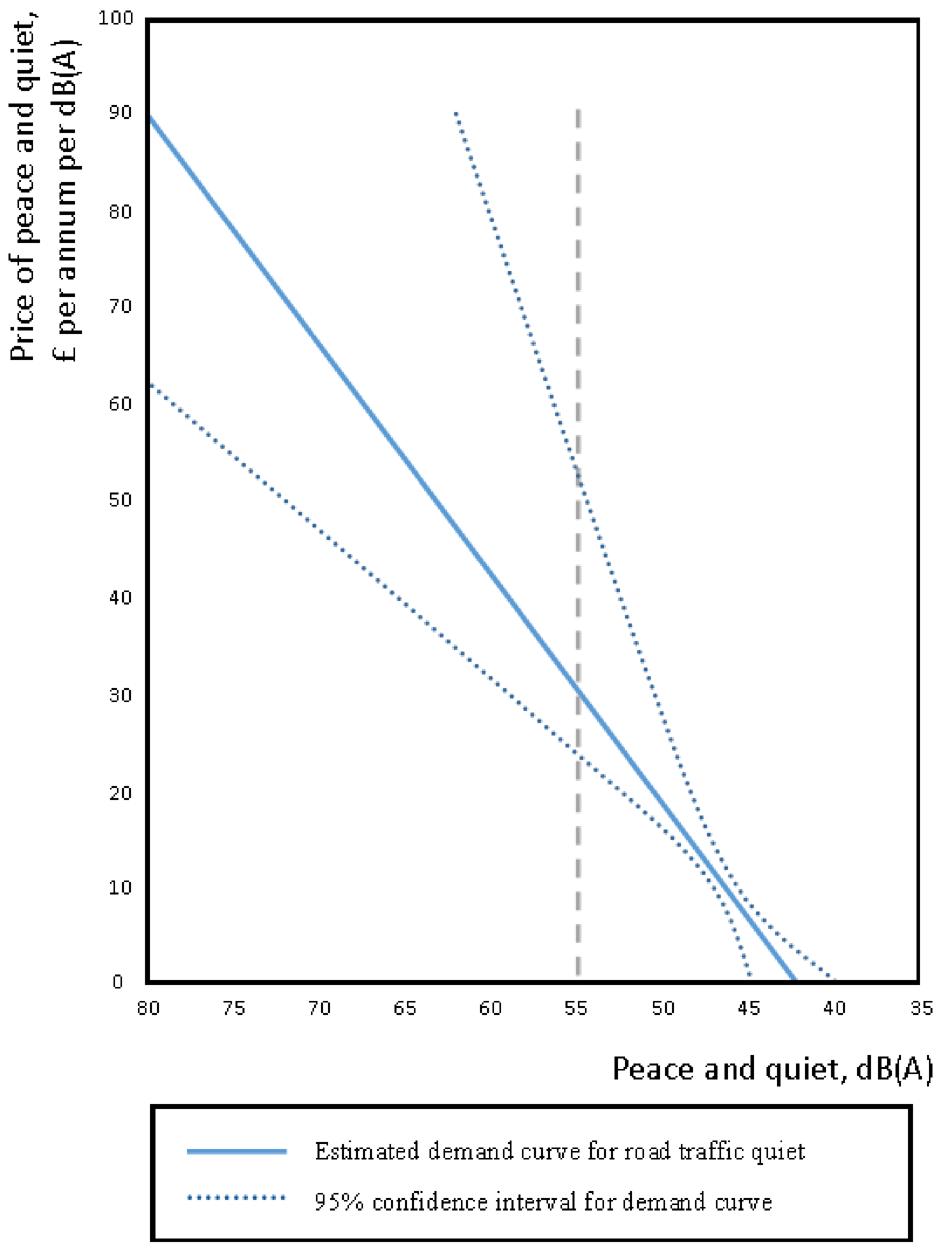

FIGURE 30. LINE GRAPH. DEMAND CURVE FOR PEACE AND QUIET IN RELATION TO ROAD NOISE IN BIRMINGHAM (AND 95 PERCENT CONFIDENCE INTERVAL)

Original source: Nellthorp, 2007; image was recreated for this report

The findings included:

- The willingness-to-pay estimates derived for the UK are broadly comparable with those used in appraisal elsewhere in Europe.
- A case was made for a lower threshold at 45 dB(A) $L_{eq,18h}$ rather than the more conventional 55 dB(A).
- Values per dB(A) increase with the noise level above this threshold with significant issues over the valuation of rail versus road noise, the neglect of non-residential noise, and the valuation of high noise levels in different countries.

In describing the Birmingham study, information from across Europe on house prices versus road traffic noise was also presented. This is summarized in **Table 25** and **Table 26**. The study findings in the UK were provided and **Table 27** includes the final results.

Table 25. Percentage Change in House Prices with Respect to a 1 dB(A) Change in Road Traffic Noise Levels

Reference	Location	Threshold (db(A))	Percentage Change (NSDI)
Wilhelmsson (2000)	Stockholm	56 (implicit)	0.60
Lake *et al.* (1998, 2000)	Glasgow	54	0.20
		68	1.07
Rich and Nielsen (2004)	Copenhagen:		
	• houses	50	0.54
	• apartments	50	0.47
Bjørner *et al.* (2003)	Copenhagen	55	0.47
Bateman *et al.* (2004)	Birmingham	55	0.21 - 0.53

Table 26. Road Traffic Noise: Willingness-to-Pay per Decibel(A) per Household per Annum, €, 2001

Reference	Method	Location, study year, scenario	€
Pommerehne (1998)	CVM	Basle, Switzerland, 1988, percentage change	99
Soguel (1994)	CVM	Neuchâtel, Switzerland, 1993, percentage change	60 - 71
Sælinsminde (1999)*	SP	Oslo and Akershus, Norway, 1993, percentage change	48 - 96
Vainio (1995, 2001)	CVM	Helsinki, Finland, 1993, elimination of annoyance	6–9
Thune-Larsen (1995)	CVM	Oslo and Ullensaker, Norway, 1994, percentage change	19
Wibe (1997)	CVM	Sweden (national study), elimination of annoyance	28
Wardman and Bristow (2004)*	SP	Edinburgh, UK, 1996, percentage change	37 - 55
Navrud (1997)	CVM	Norway (national study), 1996, elimination of annoyance	2
Navrud (2000)	CVM	Oslo, Norway, 1999, elimination of annoyance	23 - 32
Barreiro et al. (2000)	CVM	Pamplona, Spain, 1999, eliminiation of annoyance	2 - 3
Lambert et al. (2001)	CVM	Rhônes-Alpes Region, France, 1999, elimination of annoyance	7
Arsenio et al. (2006)*	SP	Lisbon, Portugal, 2001, change to level in a known location	55

Source: Values are derived from Navrud (2004, table 1), except where indicated (*)

TABLE 27. UK-BASED VALUES FOR TRANSPORT-RELATED NOISE, 2002 PRICES AND VALUES

Noise Change in the Interval (dB(A)) Low	High	£ per household per annum for a 1 dB(a) change within the stated interval	£ per person per annum for a 1 dB(a) change within the stated interval
< 45		0.0	0.0
45	50	13.7	5.8
50	55	26.9	11.4
55	60	40.1	17.0
60	65	53.2	22.6
65	70	66.4	28.1
70	75	79.6	33.7
75	80	92.8	39.3
> 80		98.0	41.5

[Parris, 2015] M. Parris, K.M., Ecological impacts of road noise and options for mitigation, Handbook of Road Ecology, First Edition, Chapter 19, John Wiley & Sons, Ltd.

Consideration of the impact of traffic noise on local ecology, both during construction and when a road is open to traffic, includes the impacts for animals and mitigation of road noise to protect animals and their acoustic environment. Road noise has a variety of ecological impacts, including effects on the physiology, behavior, communication, reproduction and survival of animals that live in or move through the noise-affected areas. While further research is required to better understand the ecological consequences of introducing road-construction and road-traffic noise to a given habitat, measures to mitigate the known impacts of road noise on wildlife should be implemented as part of new road projects. One important part of the description of each of these impacts was the note that the animals do not hear in the same way humans do, both in amplitude and frequency.

[Rochat, 2020] Rochat, J., S. McKenna, D. Barrett, K. Cubick, S. Riffle, L. Samples, R. Rasmussen, Breaking Barriers: Alternative Approaches to Avoiding and Reducing Highway Traffic Noise Impacts, Summary of Noise-Reducing Strategies, NCHRP 25-57, National Cooperative Highway Research Program.

National Highway Cooperative Research Program Project 25-57 examined strategies other than traditional noise barriers to reduce highway traffic noise. A literature review was conducted and investigated over 13 alternative strategies. **TABLE 28** shows the strategies investigated. Extracted information included traffic noise reduction, associated construction costs, maintenance costs, and the context-appropriateness for highway design and management. An online survey was distributed to noise professionals through the American Association of State Highway and Transportation Officials and the Transportation Research Board and interviews were conducted to provide additional information.

Highlights of the findings were presented along with relative cost estimates ($-$$$$$). These are presented here without edits to ensure the correct meaning is conveyed.

On-road design choices:

- "($$-$$$$) For bridge decks[6], diamond ground pavement surfaces ($$) or polyester overlays ($$$$) may provide up to 10 dB reduction (acoustic longevity needs to be considered)
- ($$$-$$$$) For bridge joints, patterned joint cover plates may provide up to 9 dB reduction
- ($-$$$) For rumble strips, sinusoidal patterns may provide up to 7 dB reduction
- ($$-$$$$) For quieter pavements[7], the most promising pavements/surfaces are diamond grinding ($$-$$$) (up to 7 dB reduction), open-graded or rubberized asphalt ($$-$$$$) (up to 9 dB reduction), and thin bonded asphalt overlays ($$-$$$$) (up to 6 dB reduction)

TABLE 28. INVESTIGATED ALTERNATIVE NOISE-REDUCING STRATEGIES

Noise-Reducing Strategy Category	Subcategory
On-road design choices	1. Quieter bridge decks and joints
	2. Quieter rumble strip design
	3. Quieter pavements for travel lanes and/or shoulders
Highway design choices	4. Horizontal and vertical alignment
	5. Solid safety barriers in lieu of guardrail
	6. Separation zones between vehicle travel lanes and side paths for nonmotorized users
Right-of-way design choices	7. Low berms
	8. Vegetated screens
	9. Vegetated swales and retention basins
	10. Sound-absorbing ground surface and ground treatment adjacent to the highway
Operations management strategies	11. Speed or truck restrictions
Implementations by receptors or local governments	12. Approaches that can be implemented by subdivision developers, homeowner associations, special districts, or local governments
Sound absorptive treatment	13. Sound absorptive treatment or retaining walls or other surfaces

[6] Acoustic longevity needs to be considered

[7] Acoustic longevity needs to be considered

Other (added to original list)	14.	Low barriers and diffractors
	15.	Solar panels

Highway design choices:

- "($$$$-$$$$$) For horizontal and vertical alignments[8], alignment shifts may provide up to 10 dB noise reduction, although there may be limitations due to space or cost (horizontal higher in cost in most cases)
- ($$) A solid safety barrier in lieu of guard rail[9] may provide up to about 7 dB reduction for an arterial road, but only up to 2.6 for a highway
- ($) For separation zones, there is minimal benefit from improving sound absorption in the separation zone between a roadway and path, however properly modeling paths/separation zones may increase accuracy up to 1.6 dB

Right-of-way design choices:

- "($-$$$) Low berms (≤ 1.8 m or 6 ft) may provide up to 10 dB or more noise reduction, with favorable topography (e.g., receivers lower than roadway). For a ~1 m (3 ft) berm roadside and/or in median, up to 5 dB reduction may be achieved. The availability of the material affects the price.
- ($-$$$) A wide belt of vegetation/trees (> 20 m (65.6 ft)), may provide up to 10 dB or more noise reduction. Right-of-way space needs to be considered. A narrower vegetated belt may provide up to 6 dB reduction. Of special note, a row of trees behind a noise barrier may reduce negative downwind effects, a vegetated belt may reduce the likelihood of a temperature inversion layer, and vegetation may help improve perception of highway traffic noise.
- ($) A vegetated basin can have up to a 2.4 dB effect for a two-lane road but the effect can be minimal for wider highways.
- ($$-$$$) Acoustically soft ground may reduce noise more than 2 dB if very highly sound absorptive (e.g., gravel), although greater noise reduction could be achieved with extension of the material beyond the right-of-way for multi-lane highways. This strategy is less effective as receiver height increases.
- ($$$) In-ground treatments/structures may reduce noise 2 dB for a lattice structure about 1 m (3.3 ft) wide and up to 8 dB if the width is substantial (24 m or 79 ft), based on two-lane roadways.
- ($$-$$$$) Above-ground treatments/roughness, particularly a low (0.3 m or 1 ft high) lattice structure, may reduce noise up to 11 dB for a width of 12 m (30 ft) (wider would be more effective and likely required for meaningful reduction for a multi-lane highway). The strategy effectiveness is not affected by receiver height or distance."

Operations management strategies:

- "($-$$) A reduction in speed of 16 km/h (10 mph) may result in a 2 dB noise reduction.

[8] Site topography and vehicle types need to be considered

[9] Site topography and vehicle types need to be considered

- ($-$$) Truck restrictions may reduce maximum noise levels up to 10 dB and L_{Aeq} values 1-6 dB, although effectiveness is based on multiple factors. Strategies implemented by receptors or local governments:
- ($) Site planning strategies include creating a wider buffer zone (up to 3 dB reduction per doubling of distance) and shielding with privacy walls or other structures (up to about 10 dB reduction).
- ($) For building design, placing the sensitive rooms farthest from the highway may provide up to 13 dB reduction.
- ($$-$$$$) Construction methods/materials may provide up to 35 dB reduction for interior noise levels."

Sound absorptive treatment:

- "($$-$$$) Absorptive treatment applied to retaining walls may provide 1–2 dB reduction for receptors on the opposite side of a single wall, 2.5 dB reduction for parallel walls, and 4 dB reduction for wall-truck reflections. In addition to decibel reduction, the character of the sound changes, potentially reducing adverse effects of reflections.
- ($$-$$$$) Absorptive treatment applied to bridge understructures may provide up to 5–11 dB noise reduction. Tuned vibration dampers on steel bridge structures may help to reduce low frequency noise.
- ($$-$$$$) Absorptive treatment applied to tunnels may provide up to 4–10 dB reduction, and surface roughness up to 4 dB reduction.
  - Acoustical treatments may be tuned/engineered to provide reduction at key frequencies.
  - Green wall systems can be considered for reflecting facades and rooftops.
  - Wall curvature needs to be considered in focusing/de-focusing and scattering sound."

Other:

- "($$) Low barriers with diffractors on top can provide up to 9 dB noise reduction. They are most effective close to the source and may be most applicable to two-lane roads, although application to multi-lane highways could be investigated.
- ($$-$$$$) Solar panels in a single row or arrays can provide more than 11 dB reduction, although gaps at the row/array ends and panel angles need to be considered.

When combining highway noise reducing strategies, one should consider the following:

- Addressing multiple locations: at the source, in the propagation path, and at the receptor. The combination of addressing more than one of the locations can be additive. In general, most of the strategies can be combined with the on-road design choices. As an example, if quieter pavements are used in combination with above-ground right-of-way treatments/roughness, the combined noise reduction would likely be greater than either strategy alone. Other source location strategies are sound absorptive treatment (source being the reflection) and speed or truck restrictions.
- Addressing the same location: The combination of addressing the same location can also be additive. For example, sound absorptive pavement combined with sound absorptive treatment on structures can help to reduce multiple reflections for bridge and tunnel applications. Also, soft ground combined with low structures within the right-of-way can help further reduce the noise.

- Considering frequency content: the frequency range of reduction for a particular strategy may be the same as another strategy or in a different range. If the frequency range is the same, one needs to consider that the strategies may not be additive in terms of the broadband noise level, particularly if the reduction from a single strategy alone causes the broadband sound level to be dominated by frequencies outside that range. For example, quieter pavement and noise barriers each reduce noise most effectively in the mid to high frequency range. If a receptor is in an area well-protected by a noise barrier and the diffracted traffic noise is dominated by lower frequencies, any reduction due to the quieter pavement will likely be minimized considering the broadband noise level. If the frequencies being reduced are in different ranges for the different strategies being combined, it's possible that their combined effect could be greater than either strategy alone, particularly if both frequency ranges are contributing to the broadband sound level. Even if one of the reductions does not contribute to the broadband sound level, it could change the character of the received sound, making it more acceptable."

[Sanchez, 2018] Sanchez, M., N. Lopez-Mosquera, F. Lera-Lopez, J. Faulin, An Extended Planned Behavior Model to Explain the Willingness to Pay to Reduce Noise Pollution in Road Transportation, Jour. of Cleaner Production 177, pp. 144–154.

In the European Union, 30 percent of the population is exposed to noise levels greater than 55 dB, L_{Aeq}, with road transportation responsible for 93 percent of the environmental costs. There has been an increasing use of social and psychological models to explain individual behavior towards the environment. This study made use of an extended Theory of Planned Behavior (TPB) which includes personal values to determine the influential variables in willingness to pay for the reduction of noise pollution generated by road transportation. A Structural Equation Model (SEM) was applied in the European Pyrenees region, an area that has high traffic pollution due to road transport.

A project goal was to determine whether the environmental profile of individuals determines their WTP to reduce the noise pollution from road traffic in areas with significant impacts. Different combinations of TPB and Value-Belief-Norm Theory (VBN) components were used to reach this goal. An additional goal was centered on the analysis of the problem in the rural context, which is less studied. This study uses data from a survey carried out with 1612 residents in 74 localities located in the Spanish Pyrenees: Navarre, the Basque Country and Catalonia (Spain) in December, 2012. It was important to provide empirical evidence to explain WTP while combining the two different theoretical perspectives, TPB and VBN, and to apply this framework for the first time to explain noise externality due to road transportation.

This work uses the TPB as the reference theory due to its greater predictive value and greater flexibility to include extra variables. The TPB model was completed with the inclusion of the multidimensional construct of biospheric, altruist, and egoistic values, which are also present in the VBN model. These three values play a key role in the individual attitude configuration, and in the WTP predictions. With the combination of both models, a better explanation of the psychological and social background which determines the pro-environmental behaviors was expected.

The first studies were focused on the analysis of different psychological determinants of everyday pro-environmental behavior. It was found that attitudes, value orientations, environmental beliefs and norms have an influence on those individuals who show clear pro-environmental behaviors. According to TPB, the most proximal predictors of behavior are behavioral intentions, which in turn are preceded by: a) attitudes which reflect an individual's positive or negative appraisal of a behavioral option; b) subjective norm (SN) as the social pressure or influence people feel when faced with a behavioral choice, and c) perceived behavioral control (PBC) which refers to the perceived ease or difficulty of finally undertaking a particular behavior and considered to reflect past experiences and anticipated impediments and obstacles. As a rule of thumb, the more positive attitude and subjective norm and the greater perceived behavioral control, the greater should be an individual's intention to perform the behavior under consideration. Multiple hypotheses were assumed. The null hypotheses for tests was that the attitude is positively correlated to WTP. These were:

- Attitude has a positive influence on WTP
- Subjective norms show a positive influence on WTP
- Perceived behavioral control has a positive influence on WTP
- Biospheric and altruistic values have a positive influence on WTP, and egoistic values have a negative influence on WTP
  - Individuals tend to express in their WTP judgments a predisposition to pay for the environment (attitudes), beliefs about whether others consider they should pay (subjective norms) and their own ability to pay (perceived behavioral control)
- Subjective norm has a positive influence on attitude
- A subjective norm has a positive influence on perceived behavioral control and some values could precede the attitudes manifested by individuals in relation to environmental goods or services
- Biospheric, egoistic and altruistic values have an impact on attitude, perceived behavioral control, indirectly influence WTP through attitudes, and indirectly influence WTP through perceived behavioral control
- A subjective norm shows indirect influence over WTP through attitudes and perceived behavioral control.

A statistical test was used and contrasted survey data.

The noise levels were measured in the selected localities in September and October 2012. Two measurements a day were carried out in each locality deleting the noise produced by sources not related to road traffic. These measurements allow definition of two dissimilar zones per locality, called A and B, with significant differences in noise level. Zone A was defined as the area in each locality with people suffering noise levels above the noise legal limit in residential areas in Spain (65 dB in daytime). Zone B was defined as the area with noise levels between 65 dB and 50 dB. Zone A indicated an area next to the road causes clear discomfort for the people living there. The response rate was close to 80 percent and the final sample included 1,612 respondents. Approximately 50 percent of the surveys were carried out in zone A and the other 50 percent in zone B in each locality. The sampling error was 2.42 percent with a 95 percent confidence level.

On the basis of the final sample, the following characteristics of the respondents were observed: 40.9 percent men and 59.1 percent women, aged 49.68 years on average (with a standard deviation of

16.03), 36.0 percent had completed secondary school studies and 54.4 percent had a medium income level (ranged from 1,701 € to 2,800 €).

TABLE 29 shows a description of the contrasted hypotheses and their final statistical results. This highlighted attitudes and the perceived control as the main determinants of WTP. Additionally, the subjective norm effect and the universal values in the attitudes have been revealed along with their perceived control.

The results highlight the importance of psychological aspects and show that positive attitudes towards the environment and adequate perceived behavioral influence can increase WTP. Moreover, there is an indirect effect of biospheric and altruistic values on WTP by means of other variables such as the perceived behavioral control. This implies that public performances and educational policies that improve environmental sensitivity and reduce environmental impact could help to achieve a collective effect on the environment and a unified struggle in favor of environmental protection.

TABLE 29. RESULTS SUMMARY OF THE TESTS OF HYPOTHESIS CONTRAST

Hypothesis	Result
Direct effects	
H1. Attitude has a positive influence on WTP	✓
H2. Subjective norm has a positive influence on WTP	x
H3. Perceived control has a positive influence on WTP	✓
H4. Biospheric, egoistic, and altruistic values impact on WTP	x
H5. Subjective norm has a positive influence on attitude	✓
H6. Subjective norm has a positive influence on perceived control	✓
H7. Biospheric, egoistic, and altruistic values impact on attitude	✓
H8. Biospheric, egoistic, and altruistic values impact on perceived control	✓
Indirect effects	
H9. Subjective norm indirectly influences WTP through attitude and perceived control	✓
H10. Biospheric, egoistic, and altruistic values indirectly influence WTP through attitudes[1]	✓
H11. Biospheric, egoistic, and altruistic values indirectly influence WTP through perceived control	✓

[1] *Only the indirect effects of the biospheric and altruist values have been contrasted.*

[Sandberg, 1995] U. Sandberg, U., T. Otsuka, Road Traffic Noise Abatement by Emission of Pleasant Sound?, Proceedings of the 1995 International Congress on Noise Control Engineering, Newport Beach, California, USA.

Road traffic noise annoys exposed people, like pedestrians along streets, people strolling in recreational areas, dwellers in their homes or gardens, etc. In most cases, almost exclusively selected by noise engineers, is the attempt to control the noise physically either by emission or immission measures. However, annoyance and some other adverse effects depend not only on the physical level of the noise, but also on the psychological perception by the exposed human. In most urban areas there are some roads or streets along which traffic noise exposure is unacceptably high and conventional reduction methods appear to be either inefficient, unreasonably expensive or impossible to use. In such cases, unconventional methods may be applied to possibly reduce the nuisance. One such unconventional way is to produce sound which is regarded by most exposed people as being pleasant and defer attention away from disturbing traffic noise. This idea is anticipated to work only when the main adverse effect of the noise is annoyance and where it is expected affected individuals will find the artificially produced sound pleasant or interesting. Attractive spin-off effects may also be the concept of "acoustical art" or assignment of certain local and identifiable sound character to a place or town.

Few types of sounds are useful for third purpose, especially since sound is very subjective to different people. A particular sound may be pleasant or interesting only for limited time or for limited number of repetitions. In our daily environment, most of us are exposed to sounds which are intended to either increase our quality of life or make us notice something in positive way. Examples include church/temple bells playing melody, outdoor clockwork bells, jingle bells and sound from musical instruments. Another frequently used sound in recent years is the "ticking" sound at pedestrian crossings. This is hardly a pleasant sound but does serves a purpose. Our natural environment is dominated acoustically by birdsong, songs of cicadas or related insects, sound from air turbulence, sound from rattling leaves, and sound from waves or rushing water. These sounds are usually regarded as very pleasant and may be candidate sound types for use as noise "compensators."

Recent studies ranking the pleasantness of various sounds have shown that the most pleasant sounds come from musical instruments (harp, flute, music box, etc.), waves, waterfall, church/temple bells, wind bells and birds.[10] The Kashima reference also noted that the sounds typical of location could give it certain positive identity. It is important when considering the soundscape to consider not only the unwanted noise but also sounds which are carrying information or meant to provide some pleasure and, finally, the natural sounds of birds, moving waters, wind, etc. Noise engineers often neglect this.

In Japan, "soundscape" has long been an important part of environmental design. The first of them is the Nishitsuruya-bashi bridge in Yokohama, Japan, in which an interesting acoustical installation has been in operation since 1988. The pedestrian/bicycle/motor vehicle bridge crosses the Shintama River in the downtown shopping district of Yokohama. Due to the exceptional space problems in the City, an elevated and highly trafficked expressway is built on a concrete structure as a "roof" over the river. This has led to an unpleasant situation, with the understructure of the elevated expressway visually dominating the scene and very high traffic noise levels with daytime L_{eq} at the bridge being around 75 dB(A). The sound mainly originates from the expressway and is amplified by multiple reflections. Since thousands of people cross the bridge daily, something was desirable to improve the environment. The

[10] Shimai, S., A. Schick, H. Hoege, H, "A cross-cultural study of identification and pleasantness-unpleasantness of environmental sounds," Proceedings of Inter-Noise 94, Yokohama, Japan; Kashima, N., A. Tamura, R. Shima, J. Sawada, "Social survey of public opinion on sound environment in Yokohama," Proceedings of Inter-Noise 94, Yokohama, Japan.

rails on both sides of the bridge were supplemented with specially designed metallic tubes in which the acoustical installation of tiny jingle bells inside each tube, which are excited and brought to motion by road traffic vibrations. When the traffic vibrations and noise exceed certain levels, pleasant but discrete “chime” sound is emitted by the bells. This can be heard by the pedestrians and bicyclists crossing the bridge, but never dominates over the noise from the traffic in order not to disturb anybody during relatively quiet periods. The sound never contributes to the overall A-weighted sound level. The Whispering Bridge sounds like the whispering of trees. As stated on the plaque on the bridge, the purpose of the acoustical installation is to make people forget about the poor environment and remind them of a more natural setting. Unfortunately, many people hurrying over the bridge do not notice the bell sound. In corresponding future installations, higher sound level in relation to the traffic noise will be considered.

Max Neuhaus, who designed the Nishitsuruya-bashi bridge in Yokohama, is also responsible for other sound installation projects in street noise environments. Between 1977 and the mid 1980s, he had an installation at Times Square on Manhattan, which was an enormous loudspeaker and through huge cavities produced sound from beneath grillwork in the traffic island in the center of the square. The sound, partly infrasonic, was meant to interact with the buzzing street noise and give the passers-by an interesting acoustical experience. In 1983 Neuhaus installed “Time Piece” at the Whitney Museum of American Art in New York City which provided the street facade with sound picked-up from the traffic, reverberated and processed in other ways. Each 20-minute period started with this sound (or noise if you prefer) being emitted at very low level which then increased continuously until it reached a level which equaled the ambient traffic noise at the end of the period, then suddenly shut off. People on the street first did not notice the sound (noise), then generally became curious, and when the sound was momentarily shut off felt like the location suddenly became “quiet.” The idea originated in an alarm clock that Neuhaus constructed which woke people up not by sound but by silence based on the same idea.

In the City of Tama in Japan there is a mixed cultural, recreational and commercial center called Parthenon-Tama. In the heart, the “Sound Tower” has been constructed. Loudspeakers in vertical columns emit sounds which that are intended to resemble the song of larks. The Sound Tower is meant to be visual and acoustical landmark unique to the plaza and even a symbol of the City. It constitutes an acoustically pleasant and interesting counterpart to the noise of traffic to/from the center as well as the noise of other activities.

The possibilities to introduce pleasant sounds acoustic amenities in outdoor urban spaces in order to improve the well-being of individuals passing through or staying there are mostly overlooked. In Japan and other locations, the application of the soundscape concept is sometimes resulting in improvements being made to poor as well as medium environments in public places by means of artificial sound generation. The choice of sound source: character, spectral shape, sound level and the temporal characteristics, can be adapted to the particular situation, to lead to an improvement of the area and enhance the quality of life of the area.

[Sklarz, 2018] Sklarz, M., N. Miller, The Impact of Noise on Residential Property Value, University of San Diego and Collateral Analytics Research.

This paper addresses the question of whether noise measurements and the integration of a noise variable would improve the valuation of residential property. As with other factors that could influence value, it is possible to pick up proxies for these effects by carefully controlling the location of observations used as input to a valuation model. Data from airport noise and highway noise were used. Most studies of residential property value impacted by a particular feature or attribute have used hedonic pricing models. However, depending on the variables used these studies have had different overall results. From this study, the authors found that flight noise had the most negative effect on housing prices and road and train noises had similar but smaller effects. It could be that high levels of intermittent noise are worse than high levels of steady noise, which humans can sometimes filter out as white noise if it is not too severe.

Noise data was collected generated from roads and the airport. Data was geocoded by latitude and longitude and merged for San Diego county. **FIGURE 31** shows a general trend. Note that higher noise generally implies lower values but the variance at higher noise levels reflects the high valued urban land areas where noise levels may be high, but the land value is also high.

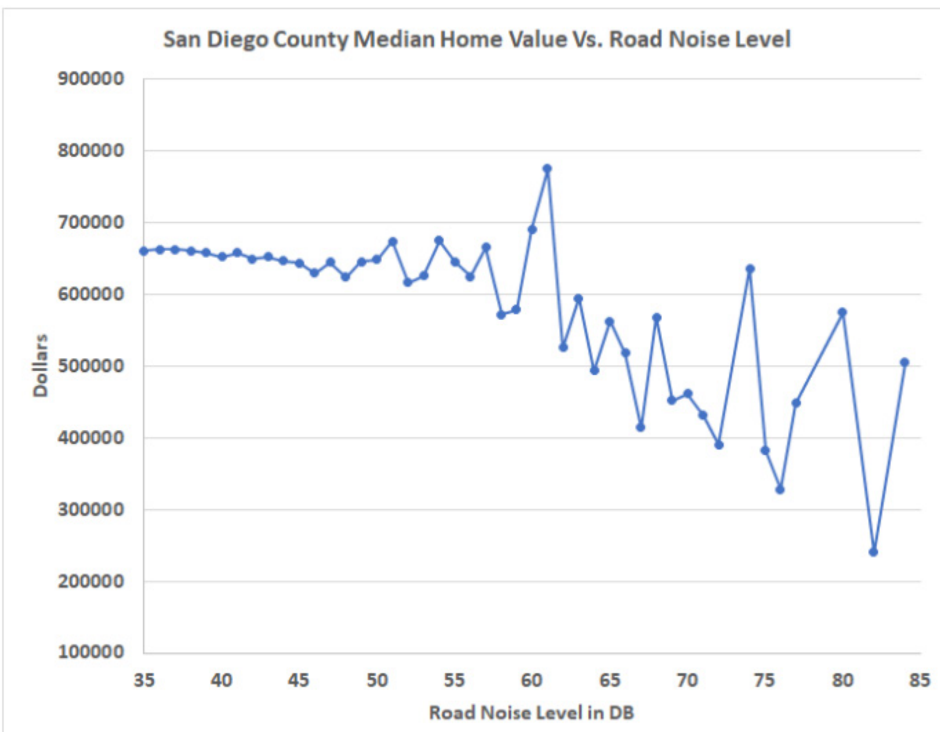

FIGURE 31. LINE GRAPH. NOISE AND HOME PRICES
Source: Sklarz, 2018

Using the average home prices, plots were made and color coded based on noise and house prices. As expected, many of the home prices were lower near roads but other factors such as relationship to the ocean also made a big difference.

To capture many of these other influences such as physical size, age, features and location amenities, a separate, simple valuation model was used. A challenge is that the impact of noise must consider similar locations and similar homes to provide a definitive separation of the noise impact. This led to problems in a perfect paired comparison. As such, a general analysis of potential marginal effects from noise on property value was conducted. Data that were considered included both road and aviation noise in the initial test, using the highest of the two measures. 73,958 transactions based on resales of existing homes were evaluated using the methodology:

- Dependent Variable = Log natural, Ln, of the automated valuation model estimate of selling price.
- Independent variables, in log form, included living area in square feet, lot size, bedrooms, baths, age in years, noise in dB, and a constant.

Noise levels were grouped to allow for the possibility of nonlinearity resulting in an R^2 of 0.78 with a control model that included living area, lot area, age, bedrooms, baths, and a constant. A break down by noise level provided the following:

- 0.93 of 1 percent of the observations had noise levels above 60 dB, while 5.8 percent were in the 50 to 60 dB range and over 80 percent were in the 40 to 50 dB range.
- The results found the highest noise levels are positive, but the location of these properties tend to be near the downtown, so a location control may be needed.
- Still, the conclusion is that noise matters, and while hard to measure, will likely exert a nonlinear effect on property values.

It was concluded that noise matters and the effects are likely to be nonlinear based on prior studies. Also, design and construction might be used to partially mitigate the effects of noise. Impacts from noise at the highest decibel levels are not found and the location and value of land matters. This makes it harder to separate out conclusions from a central urban location. With better location controls, it might show that the significance of noise influencing the values of any given site and property.

[Stoecklin, 2019] Stoecklin, A., T. Saurer, E. Bühlmann, Options for cities to reduce noise levels while promoting good quality of life through effective management of noise and spatial planning, 26th International Congress on Sound and Vibration, Montreal.

Every seventh person in Switzerland is exposed to excessive noise levels. Increasing population and mobility as well as the densification of cities and towns will further aggravate the noise problem. Spaces with good acoustic quality and protection from excessive noise is recognized as a valuable resource while also constituting a significant locational advantage. The aim of this work was to illustrate practical examples of noise abatement enforcement practices in the Canton of Basel-Landschaft and evaluate the effectiveness in reducing noise levels and in improving the quality of life. The paper shows how road traffic noise can be effectively reduced at the source by low-noise pavements and speed reductions and by measures in the propagation area. Based on the abatement, effectiveness accounting for the number of people benefiting from the measure a benefit/cost ratio was computed.

As defined in the counties' environmental protection law, the polluter-pays principle is applied in general. Therefore, for existing or considerably changed facilities (e.g., roads, noise emitting factories) which exceed noise limits, measures were considered at the cost of the owner of the facility. By ordinance and the Swiss spatial planning act, the type of facilities permitted are defined by zone. For each zone, a maximum tolerated noise limit is established and the sensitivity levels (ES) are defined by how much noise is allowed in any given area. A distinction was made between four levels:

- ES I: increased need for noise protection (e.g., recreational zone, hospitals)
- ES II: residential zone in which no substantial noise emitters are allowed
- ES III: mixed zones in which moderately disturbing noise emitters are allowed
- ES IV: industrial zones in which substantial noise emitters are allowed

Table 30 shows the planning value (PW), impact threshold (IGW), and alarm value (AW) for each zone.

Table 30. Sensitivity Levels for Road Noise

ES	PW day [dB]	PW night [dB]	IGW day [dB]	IGW night [dB]	AW day [dB]	AW night [dB]
I	50	40	55	45	65	60
II	55	45	60	50	70	65
III	60	50	65	55	70	65
IV	65	55	70	60	75	70

Evaluation of the noise abatement measure was provided for low noise pavement, speed reduction, noise barriers, and sound insulation (where other measures would not possible or proportional). The measures evaluated were 4,572 meters of speed reduction length, 2,483 meters of noise barriers, 75,000 meters of low noise pavement, and 3,542 windows treated. Requirements for abatement required:

- Proportionality must be ensured (max. CHF/CDN 5,000.- per decibel-reduction and person).
- The noise barrier must have an acoustic effect of at least 5 dB.
- The noise barrier must not be higher than 2.5 m.
- The street side of the noise barrier must be greened and covered with a sound-absorbing material.

Implementation of the abatement measures resulted in 5,562 people out of approximately 28,000 falling below the immission threshold and 344 below the alarm threshold after implementation. The estimated number of people protected per implementation category were:

- speed reduction = 1,600
- noise barrier = 900
- low noise pavement = 15,100
- sound-insulated windows = 2,600

The cost per resident of ≥ 1 dB was 2,223 CHF for the noise barrier, 743 CHF for the low-noise pavement, with no cost given for speed reduction, and 2,200 CHF for window replacement.

The conclusion based on cost and benefit is that the low noise pavements show the best benefit/cost ratio, due to the extensive effect on both sides of the road as well as vertically, resulting in a larger number of people being directly benefitted.

Noise optimization by the arrangement of the buildings is also a key factor in the planning of buildings and superstructures and required in the area. This is not discussed further here in that the highway analyst does not control this aspect in the U.S.

[Van Leeuwen, 2006] Van Leeuwen, H.J.A, Road Traffic Noise in Urban Areas—Annoyance and Reduction Measures, INTER-NOISE 2006.

The dose-effect relationship to annoyance for people living in a high noise level area is relevant and brings up multiple questions:

- Are these dose effect relations the same for continuously flowing traffic as for interrupted flows? Driving behavior may be important.
- What about cars with a damaged exhaust or motorcycles and mopeds?
- Traffic management may be a noise reduction measure, but what will be the effect?

This paper discusses the annoyance and noise reduction measures to successfully enhance the quality of life in a living unit and in the environment, based on a large number of presentations, discussions, noise calculations used during the making of noise maps/noise measures and consultancy work for local authorities. Included was the development of the Amsterdam Action Plan where annoyance was the starting principle and a measurement campaign for the Dutch Ministry of Traffic and Infrastructure for the "New Driving Force" project.

Key information from this work is presented from **FIGURE 32** through **FIGURE 35**.

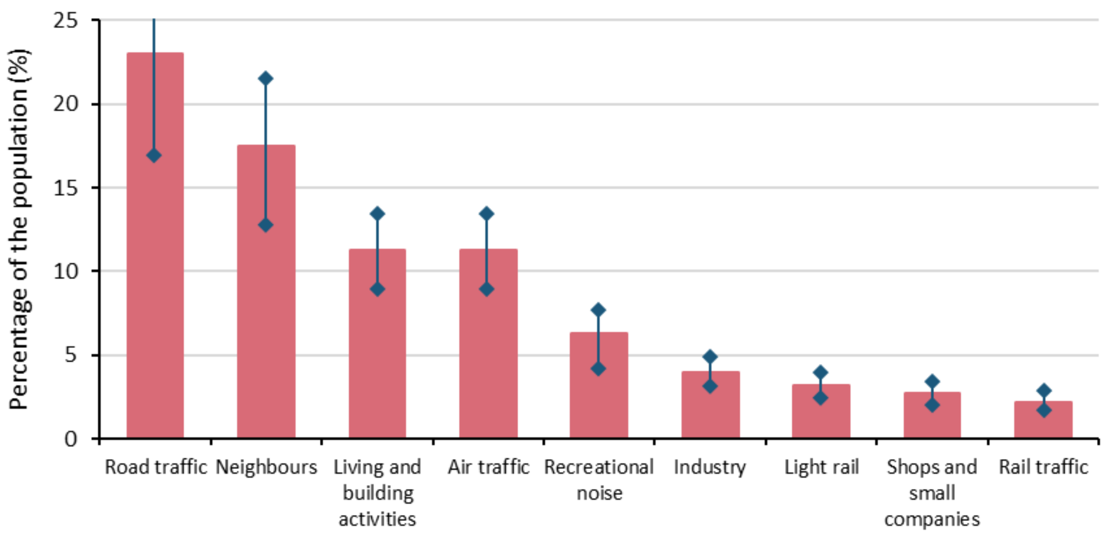

FIGURE 32. GRAPH. THE PERCENTAGE OF THE POPULATION ANNOYED BY A CERTAIN NOISE SOURCE

Original source: Van Leeuwen, 2006; image was recreated for this report

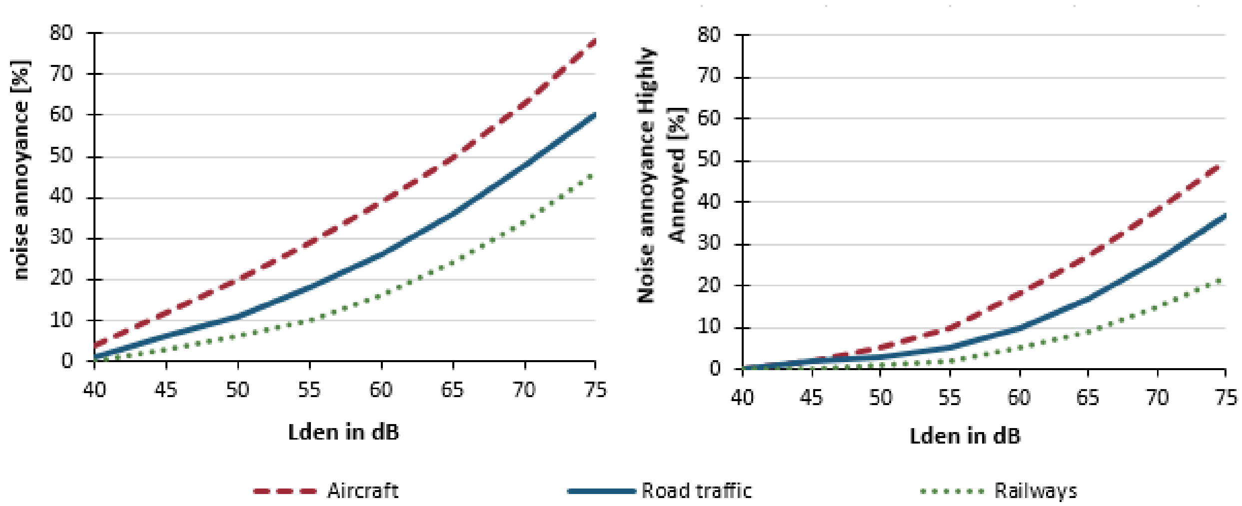

FIGURE 33. LINE GRAPHS. THE PERCENTAGE OF ANNOYED OR HIGHLY ANNOYED PEOPLE AS A FUNCTION OF NOISE LEVEL

Original source: Van Leeuwen, 2006; image was recreated for this report

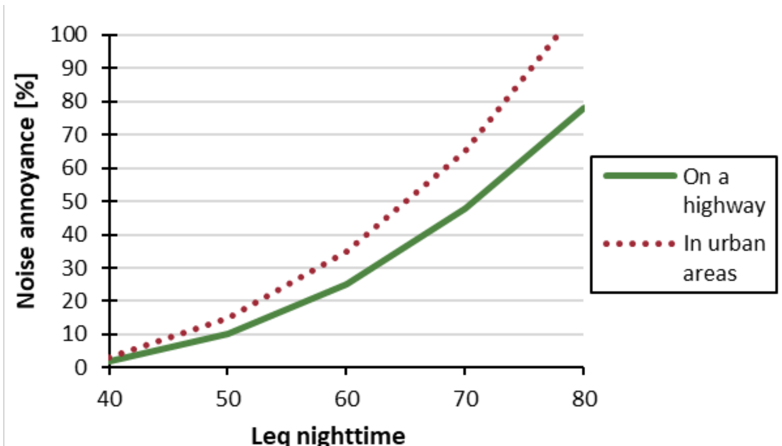

FIGURE 34. LINE GRAPH. THE PERCENTAGE OF THE POPULATION ANNOYED AS A FUNCTION OF THE NOISE LEVEL FROM ROAD TRAFFIC NOISE ON A HIGHWAY AND FROM ROAD TRAFFIC NOISE IN URBAN AREAS

Original source: Van Leeuwen, 2006; image was recreated for this report

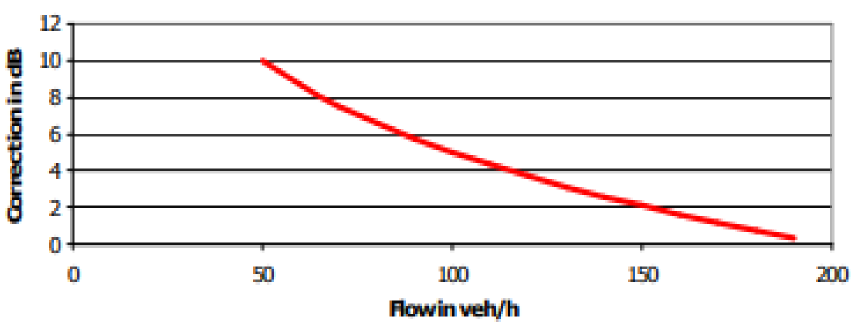

FIGURE 35. LINE GRAPH. GRAPHIC WITH THE LOW FLOW CORRECTION FROM THE CALCULATION OF ROAD TRAFFIC NOISE METHOD

Source: Van Leeuwen, 2006

This work also offered the following conclusions:

- Accelerating traffic at junctions, traffic lights, or road bumps/speed ramps, creates more engine noise. Tire road noise is of minor importance.
- More aggressive driving increases noise up to 7 dB(A) in relation to ecodriving. Vehicles with a damaged exhaust can increase noise by 15 to 20 dB(A). For motorbikes this can be much higher.
- Engine noise has many pure tones and harmonic components. It has also more low frequency noise. This is especially true for heavy trucks and even more for the chopper bikes (two-cylinder low revolution-bikes) where there is much more low frequency energy.
- Barriers and facade isolation have a lower reduction potential at lower frequencies. This results in more low frequency noise inside a dwelling in relation to the complete noise level.
- Human perception for recognizable harmonic tones results in more annoyance in relation to pure random noise or pseudo random noise such as tire road noise.
- Ecodriving is one of the possible measures but this is very difficult to implement. The road environment and other factors can affect driving behavior.
- It was pointed out that electric cars and busses or a hybrid engine will give different effects.

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