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Quantifying the Benefits of Noise Abatement Measures

PART 1: LITERATURE REVIEW AND SYNTHESIS

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13. ABSTRACT (Maximum 200 words) This report provides a synthesis of available research related to transportation noise abatement measures and methods to evaluate and/or quantify the benefits of these based on an extensive literature review. The report considers: the harm caused by transportation noise; the various types of noise mitigation measures available; their effectiveness at reducing noise; other benefits and impacts of the mitigation measures; the costs of the noise mitigation measures; how benefits and impacts might be quantified and valued; and whether a framework exists or might be developed for benefit/cost analysis of noise mitigation measures. Benefit/cost analysis has mainly been applied to noise mitigation measures in Europe and there appears to be a basis for valuing noise mitigation benefits. Other benefits and impacts of noise mitigation measures may be valued and included to varying degrees based on the impact. The report concludes that a framework could be developed for applying benefit/cost analysis to noise mitigation measures in U.S. practice.			
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Executive Summary

Report Objectives

Noise barriers are ubiquitous along highways in the United States of America (USA). However, the Federal Highway Administration (FHWA) does not currently provide methods or information on how to evaluate or quantify the costs versus the benefits of providing noise abatement, including noise barriers.

This report provides a literature review and synthesis on various noise mitigation measures, including how well they reduce noise, potential positive benefits and negative impacts of the measure, and generalized costs for the type of measure. This report also evaluates whether research exists on how to quantify the benefits of noise abatement, and whether quantification methods are widely applicable.

The report summarizes the following findings:

- The possible harms caused by transportation noise
- The various types of noise mitigation measures available
- Their effectiveness at reducing noise
- Other potential benefits and impacts of the mitigation measures
- How benefits and impacts might be quantified and valued
- The expected costs of the mitigation measures
- How benefits relate to costs
- Whether a framework exists or can be developed for valuing noise mitigation measures as part of a benefit-cost analysis (BCA)
- How such a framework could be applied in practice

The Impacts of Transportation Noise

Transportation is one of the major sources of community noise and is often loud enough to disturb the daily activities of the general public. Noise from transportation may cause chronic hearing loss, but the most common impact is annoyance which can indirectly lead to other effects including impacts on health. Highway traffic noise can also cause direct impacts to human health even in the absence of annoyance.

Noise Abatement Measures: Types, Benefits, and Impacts

This study is based upon a comprehensive literature review of noise abatement measures. This review considered both existing and new approaches to highway traffic noise abatement and defined the possible benefits and negative externalities of those approaches.

Table 1 shows the types of noise abatement measures considered in this study and summarizes their acoustical effectiveness. These are general ranges, and the noise reductions vary widely depending upon the specific application. FHWA currently only participates in funding for a subset of these measures (see: 23 CFR 772 [FHWA, 2010]); and noise barriers are the most commonly used abatement measure for highway noise mitigation in the USA.

Table 1. Noise Reduction Expected from Different Abatement Measures in dB(A)

Abatement Category	Maximum Practical Reduction	In Practice Reduction
Barrier	20	7
Alignment	4 - 10	4–5
Traffic Control	4	2
Insulation	20	7 - 10
Vegetation/Ground Cover	8	3
Pavement	13	3 - 9
Vehicle Technology[1]	6	1 - 2
Active Noise Control	10	0
Other[2]	7	3

[1] *Vehicle technology information presented for electric vehicles.*

[2] *"Other" includes experimental or site-specific abatement measures such as masking, sinusoidal surfaces for rumble strips, and use of buildings as barriers.*

For outdoor noise control, barriers provide the most attenuation. Only barriers, alignment, traffic control, insulation, and pavement measures typically provide a value of at least 5 decibel (dB)(A). Some measures have limited application; for example, insulation and active noise control are only effective inside buildings, and quieter (e.g., electric) vehicles are not an infrastructure measure.

It is possible to identify general cost ranges for different types of abatement measures by considering materials, construction, maintenance, and other associated costs for each measure. Noise abatement measures also can have a variety of other benefits and impacts, such as effects on aesthetics, air pollution, safety, airflow/ventilation, and wildlife. These are specific to the measure, and the degree to which they can be quantified and valued varies.

Benefit-Cost Analysis

While there are a number of methods for valuing benefits of traffic noise reduction, the primary methods used are to evaluate property values as they relate to noise and other property characteristics to infer people's willingness-to-pay to avoid noise. While some studies have been conducted in North America, most have been located in Europe. These studies have produced generally consistent estimates of the relationship between noise and property values (on a percentage basis). One important finding is that the value per decibel of noise reduction increases as the baseline level of noise increases.

The results from these studies have formed the basis for estimating the benefit of noise mitigation measures and comparing costs with benefits, primarily in European contexts. European agencies have issued guidance on valuation of noise, with most sources dating from circa 2000. **TABLE 2** summarizes noise abatement values per decibel (dB) per person per year in current dollar values. Most guidance places the value between $50 and $100 (in 2020 dollars) at higher starting noise levels.

TABLE 2. NOISE COSTS PER DECIBEL PER PERSON PER YEAR (ROAD AND RAIL), CONVERTED TO 2020 U.S. DOLLARS ($)

Country	Differentiation	Year	Any	>45 dB(A)	>50 dB(A)	>55 dB(A)	>60 dB(A)	>65 dB(A)	>70 dB(A)	>75 dB(A)	>80 dB(A)
Austria	Only road noise	1997	$77								
Germany	Noise exposure in built-up areas	1998	$94								
Sweden	Only road noise	2001			$8	$121	$261	$450	$1,011	$2,419	
Switzerland	Annoyance in dwellings	2000	$955								
Hungary	Annoyance from road noise	2002	$51								
United Kingdom	Annoyance from road noise	2002		$11	$22	$33	$44	$55	$66	$77	$81

Primary data sources: Odgaard (2005); U.K. from Nellthorp (2007)

Note: Based on rates per unit of native currency in the original study, converted to 2020 United States dollars (USD) at exchange rates and inflation as of November 2020.

Options for a Noise Valuation Framework

The data to support a basic benefit/cost framework for noise abatement methods appears to exist, and BCA of noise abatement has been performed in European transportion project studies. The noise abatement benefits of any measure can be monetized as long as the noise reduction due to the measure can be estimated across the receptor population. Benefits can then be compared with costs.

Other effects specific to each measure could be included in a BCA, although some effects (such as aesthetic effects) will not have data to support quantification. Planning-level estimates could use rough estimates of benefits and costs typical for a particular type of measure, while more detailed engineering estimates can provide location or project-specific noise estimates and costs.

An approach to benefit-cost analysis for noise mitigation measures in project studies would therefore be as follows:

1. Define the potential noise abatement measures that could be applied for the project
2. Identify the receptor population
    a. Measure baseline noise levels for the population in the affected project area
3. Estimate the expected noise reductions from each measure
4. Apply standard values of noise reduction ($ per dB) multiplied by the receptor population to obtain a total dollar value of benefit
5. Identify other benefits and negative impacts for the proposed measure(s) in the specific project context
    a. Identify any that can be quantified/monetized and assess these
    b. Provide a qualitative assessment of other benefits and impacts
6. Estimate the costs of the proposed noise abatement measure(s) for the specific project, including maintenance and operations as well as capital costs
7. Compare benefits and costs for each measure being evaluated, as measured through a benefit-cost ratio and/or net present value

A framework based on this approach would outline, explain, and illustrate the above steps, and provide the following additional supporting information:

- Typical ranges of noise reductions, in decibels, for various noise abatement measures

- Standard values of noise reduction (e.g., $ per dB per person, based on the starting noise level)
    - A description of how to apply them to specific project situations
- An enumeration of the various other benefits and impacts of each type of abatement measure
- Information to assist in quantifying and monetizing these other benefits and impacts, to the extent such information has been identified
- Cost estimate ranges for noise abatement measures based on a planning-level assessment, before a detailed engineering study is performed
- Guidance on appropriate benefit-cost thresholds when using Federal funds for noise abatement
- References to tools or real-world results that could be used to support quantification of any project or program-specific measures

Future research could include developing additional supporting tools and data. For example:

- Expanding consideration of abatement measures in the Traffic Noise Model
- Developing sample benefit-cost calculations for hypothetical project abatement measures illustrating the magnitude of various benefits and impacts and which ones are most important and/or uncertain
- Providing a threshold dollar value per receptor benefited (which might vary based on the measure and its context) to streamline the use of BCA

Acronyms and Abbreviations

BCA	Benefit/Cost Analysis
CHF	Swiss Franc
CV	Contingent Valuation
dB	Decibel
DFA	Damage Function Approach
DNL	Day-Night Level
DOT	Department of Transportation
ECU	European Currency Unit
EPA	Environmental Protection Agency
ERF	Exposure-Response Function
EV	Electric Vehicles
FHWA	Federal Highway Administration
ft	Feet
GBP	British Pound Sterling
HEATCO	Harmonised European Approaches for Transport Costing
HP	Hedonic Price
HUF	Hungarian Forint
Hz	Hertz
ICE	Internal Combustion Engine
INCE	Institute of Noise Control Engineering
kHz	Kilohertz
km/h	Kilometers per Hour
m	Meters
mm	Millimeters
mph	Miles per Hour
NAC	Noise Abatement Criteria
NCHRP	National Cooperative Highway Research Program

NDI	Noise Sensitivity Depreciation Index
NSDI	Noise Sensitivity Depreciation Index
OBSI	Onboard Sound Intensity
PCC	Portland Cement Concrete
PVB	Present Value of Benefits
RP	Revealed-preferences
SEK	Swedish Kronor
SP	Stated-preferences
STC	Sound Transmission Class
TNM	Traffic Noise Model
US	United States of America
USD	United States Dollar
USDA	United States Department of Agriculture
WTP	Willingness-to-Pay

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1 Introduction

Noise barriers are ubiquitous along highways in the United States of America (USA). However, the Federal Highway Administration (FHWA) does not currently provide methods or information on how to evaluate or quantify the costs versus the benefits of providing noise abatement, including noise barriers.

This report provides a literature review and synthesis on various noise mitigation measures, including how well they reduce noise, potential positive benefits and negative impacts of the measure, and generalized costs for the type of measure. This report also evaluates whether research exists on how to quantify the benefits of noise abatement, and whether quantification methods are widely applicable.

The report summarizes the following findings:

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The remainder of this report is organized as follows:

- **Section 2** provides an overview of the impacts of noise from transportation and why transportation noise is a concern.
- **Section 3** summarizes a literature review of the noise effects and other benefits, impacts, and costs of eight types of noise abatement measures.
- **Section 4** discusses how noise benefits have been valued and how this information has been used in BCA for noise mitigation measures.
- **Section 5** summarizes the benefits, negative effects, and costs of the various noise abatement measures reviewed.

- **SECTION 6** presents options for a noise valuation framework
- **SECTION 7** provides a list of references.
- **APPENDIX A** contains definitions of terms used in noise analysis.
- **APPENDIX B** provides a detailed literature review with information from approximately 150 relevant sources.

2 IMPACTS OF TRANSPORTATION NOISE

Human Health and Quality of Life

Transportation is one of the major sources of community noise and is often loud enough to disturb the daily activities of the general public. Although noise from transportation could cause chronic hearing loss [Hammer, 2014], [Swinburn, 2015]; the greater impacts are those related to annoyance and stress.

Transportation noise became a growing concern in the 1950s. Although the level of noise that leads to annoyance or other side effects can vary from person to person, in 1978 Schultz put forward a curve charting annoyance versus sound level. As shown in **FIGURE 1**, there are a wide range of responses to local transportation noise levels; annoyance ranges from nonexistent to levels of high irritation. The study is based on similar, previous work by the U.S. Environmental Protection Agency (EPA) [1973]; which provided the basis for the EPA's criteria on transportation noise [EPA, 1974] and FHWA's noise abatement criteria (NAC). FHWA's NAC are based on research into communication interference. Levels above the criteria in [Table 1 to Part 772] [FHWA, 2010] interfere with speech intelligibility at three feet and thus with enjoyment of areas of frequent human use, such as backyards or balconies.

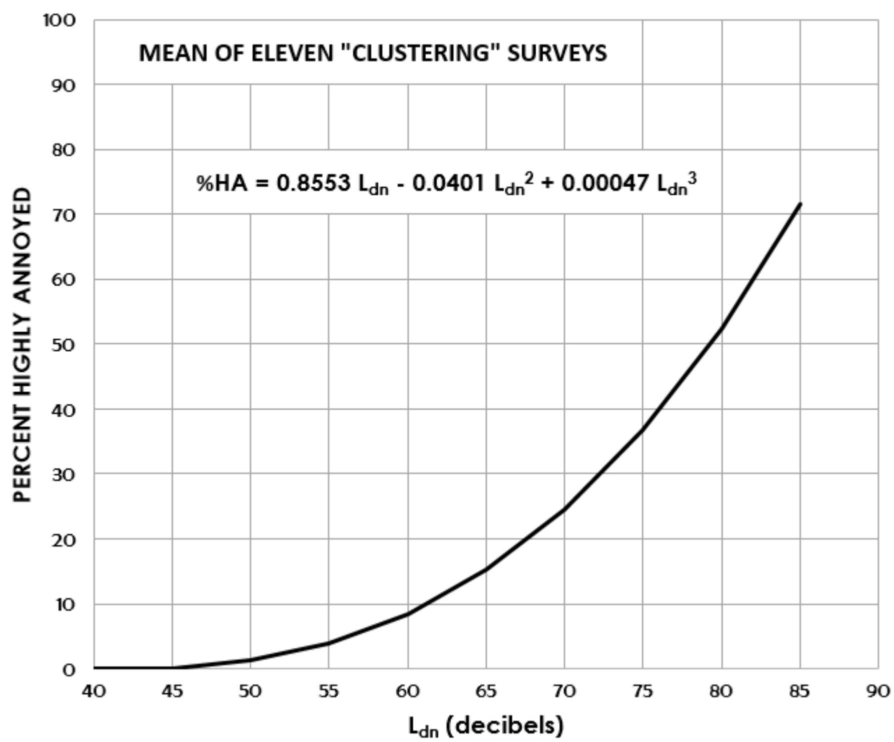

FIGURE 1. LINE GRAPH. SYNTHESIS OF CLUSTERING SURVEY RESULTS DUE TO TRANSPORTATION NOISE
Original source: Schultz, 1978; image was recreated for this report

These initial direct effects (decreased sleep, annoyance, and stress) can in turn indirectly generate other impacts, including those related to chronic health effects. **FIGURE 2** indicates how noise may cause a range of effects.

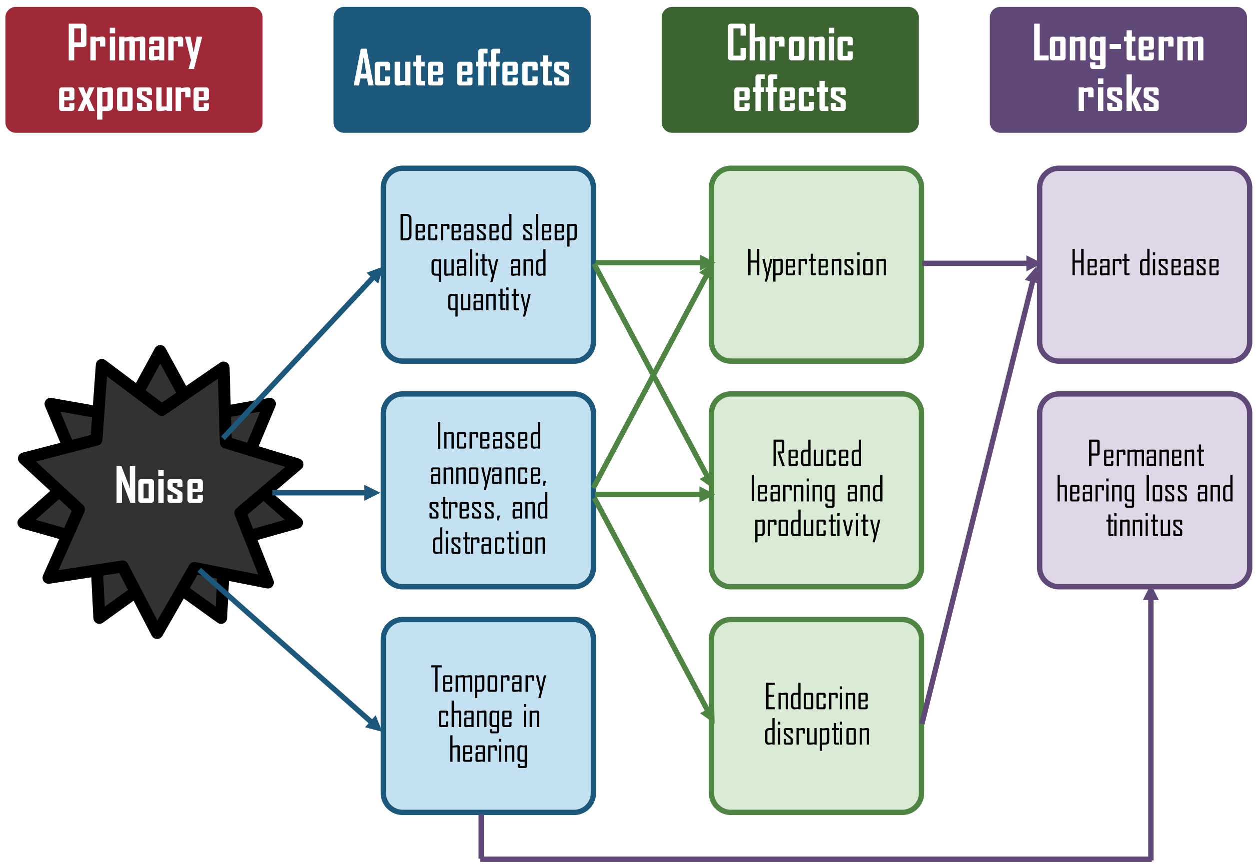

FIGURE 2. FLOW CHART. SELECT EFFECTS OF NOISE
Original source: Hammer, 2014; image was recreated for this report

Transportation-related noise incurs known costs to society in the form of harming public health and reducing productivity. The social costs of noise exposure can be divided into three groups [Andersson, 2013]:

1. *Resource costs* in the form of medical and health care. These include costs financed by taxes and direct payments by the individual.
2. *Opportunity costs* in the form of loss of production. These include market services (workplace productivity) as well as "non-market services" carried out in the household and lost recreation time.
3. *Disutility* in the form of other negative influences resulting from noise exposure. Disturbances in different forms and increased concern about the after-effects because of exposure are two examples.

Highway agencies work to manage the negative externalities related to traffic-generated noise by providing abatement. Different members of the general public may want different solutions depending on the situation. A business owner may not feel noise is an important factor when at work; or may prioritize store access and visibility over a noise barrier; but in their residential neighborhood or local park, they may desire noise mitigation and lower noise levels. In some cases, noise abatement enables people to live in areas that would be extremely difficult to tolerate without the reduced noise levels.

As noted by Arenas [2008], reduced noise levels due to noise abatement measures generate many social benefits, including better sleeping conditions, less impact on conversations, ability to open windows, elevated feeling of privacy/safety, less interference with activities such as listening to the radio or television, and others. Reduced noise levels also generate indirect benefits such as increased productivity, improved learning environment, better long-term health, and diminished stress. Certain abatement measures can also contribute to reduced air pollution.

2.1 Non-human Impacts

Consideration of impacts on local ecology including the impacts on wildlife is even more complex. Ecological effects depend on the physiology, behavior, communication, reproduction and survival of animals that live in or move through the noise-affected areas. These effects are not well defined and more research is needed [Parris, 2015].

3 LITERATURE REVIEW: NOISE ABATEMENT METHODS

Methodology and Results

This literature review on noise abatement measures considers various approaches to highway traffic noise abatement and defines the possible benefits and negative externalities of those approaches. This was a global review, allowing for a more comprehensive scan that explores mitigation options outside those in common use in the United States of America.

The literature review began with FHWA rules and policies. As described in 23 CFR 772 [FHWA, 2010], the FHWA will participate in funding for the following types of abatement:

- Noise barriers, including acquisition of property rights if needed for the construction of these (Type I on new alignment or Type II retrofit)
- Traffic management measures (Type I or II)
- Alteration of horizontal or vertical alignments (Type I or II)
- Acquisition of real property to serve as a buffer zone (Type I only)
- Noise insulation of certain land use facilities (Type I or II)

Of this list, noise barriers are the most commonly used measure. There are other measures beyond those specifically listed above, which can be implemented on a voluntary basis by State and local agencies. These include but are not limited to such avoidance measures as municipal zoning, placement of building structures, orientation of buildings, and abatement measures such as use of lower noise pavement, and innovative barrier designs.

The literature review of noise abatement measures was divided into the following categories:

- Noise barriers
- Highway alignment
- Traffic controls
- Insulation
- Vegetation
- Pavement
- Active noise control
- Vehicle technology (limited to electric vehicles)

- Other abatement measures

Our understanding of noise impacts and the science of noise abatement is dynamic. Gaps in the knowledge base remain, advances occur, and public attitudes change, requiring FHWA to be active in research to aid decision-makers.

The review process began with a computer search that resulted in over 4,000 papers, articles, and books being identified. A quick review of titles and abstracts reduced this list to just over 1,200. When multiple documents covered essentially the same information, reviewers selected a representative document. This process resulted in the selection of approximately 150 documents from around the world to consider in this report. Each of the remaining documents was reviewed in detail. **Appendix A** includes a synopsis of each of these documents, including some tables and figures not presented in the main text.

The remainder of **Section 3** contains, for each category of mitigation, a description of the measure followed by four parameters:

- The impact of the abatement measure on noise levels, and how this impact might vary under different circumstances
- Other non-acoustical potential benefits of the abatement measure
- Potential negative impacts of the abatement measure
- Generalized costs of the abatement measure

Evidence on "other benefits" and negative impacts is presented in quantitative terms where possible, including how these benefits and impacts might be valued in a benefit-cost analysis. In many cases, however, these benefits and impacts are difficult to quantify and may need to be described in qualitative terms.

Note that the absence of a particular benefit in any given abatement category subsection does not necessarily indicate that the measure does not provide the benefit. Rather, the benefit may have been described in sufficient detail in another section already.

This review also describes cost information qualitatively, with some quantitative data presented for measures for which costs are more clearly defined.

3.1 Noise Barriers

Barriers are by far the most used abatement measure for highway noise in the U.S. and consist of various shapes and materials including walls (the most common application) and earthen berms. FHWA reported that over $8.6 billion had been spent on constructing noise barriers from the beginning of the program through the end of 2019 [FHWA, 2021][1]. This support has continued to expand the use of barriers nationwide, as indicated by the following trends:

- By 2019 States had constructed over 269 million square feet of noise barriers (all types)
- By 2019, barriers totaled 3.537 linear miles in length
- Total construction costs from 2017 to 2019 were approximately $624 million, representing 7 percent of total expenditures since the first barrier listing from 1963 in the dataset
- The average noise reduction for these 2017-2019 barriers was 7.43 decibels [dB(A)]
- Absorptive materials were used on at least 18 percent of the barriers built this period

Since the last collection in early 2020[2], many more miles of barriers have likely been built.

3.1.1 Noise Reduction

Noise barriers reduce noise through diffraction, which causes noise to bend around an object. The amount of noise reduction depends on several parameters including barrier material, height, length, design used, and placement.

Material: Highway noise barriers have been made of earth (berms), concrete, masonry block, brick, metal, wood, transparent materials, plastics, fiberglass, and composites [FHWA, 2000]. Rock, as gabion walls, has also been used [Van Renterghem, 2015]. Material type (density) and thickness control noise that might pass through the barrier (transmission). Most highway barriers have over 30 dB(A) of transmission loss, so the diffraction effect is not degraded. The material can also result in sound absorption at the surface, resulting in reduced reflective noise. In some cases, other more absorptive materials or even vegetation may be applied to the main barrier material to reduce noise reflections. Berms have this added benefit. See also **Section 3.5.1** regarding the acoustic effects of vegetation on/near noise barriers.

Height: The effectiveness of a barrier depends on the degree of diffraction afforded and depends on the path length difference - the difference in the distance around the top of the barrier from source to receptor minus the direct line-of-sight from source to receptor if there were no noise barrier - and the wavelength of the sound. In general, breaking the line-of-sight between the source and the receiver results in a 5 dB(A) attenuation. The taller the barrier, the

[1] The available dataset begins with a listing for a barrier built in 1963; however, there are several large gaps in the information, particularly for older listings before the late 1990s, including missing cost data.

[2] This data is collected from States every 3 years and the most current dataset is available online at: [Inventory - Noise Barriers - Noise - Environment - FHWA (dot.gov)]

greater the path length difference and the more noise is reduced. Higher frequency sounds, with their shorter wavelengths, show greater attenuation.

Length: The extent to which sound circumvents the ends of a barrier is affected by the length of the barrier. The longer the barrier in relation to the source/receptor direct line-of-sight, the more attenuation. If a barrier is too short, it may degrade the attenuation achieved by height.

Design: The most common barrier design is a free-standing wall. However, a range of designs are used with reported differences in diffraction. Designs are generally differentiated based on their treatment of the top of the barrier or the curvature of the barrier, and these characteristics affect the diffraction levels. For example, the T-top barrier creates a greater path length over the barrier and has been shown to provide an additional 2.5 dB(A) but can be greater in some situations [Hasebe, 1993]. **FIGURE 3** provides some examples of different barrier-top designs. Barriers can also be slanted or tilted away from the roadway to increase effectiveness. Openings in the barrier for access or drainage considerations, even if small, can degrade a barrier's performance.

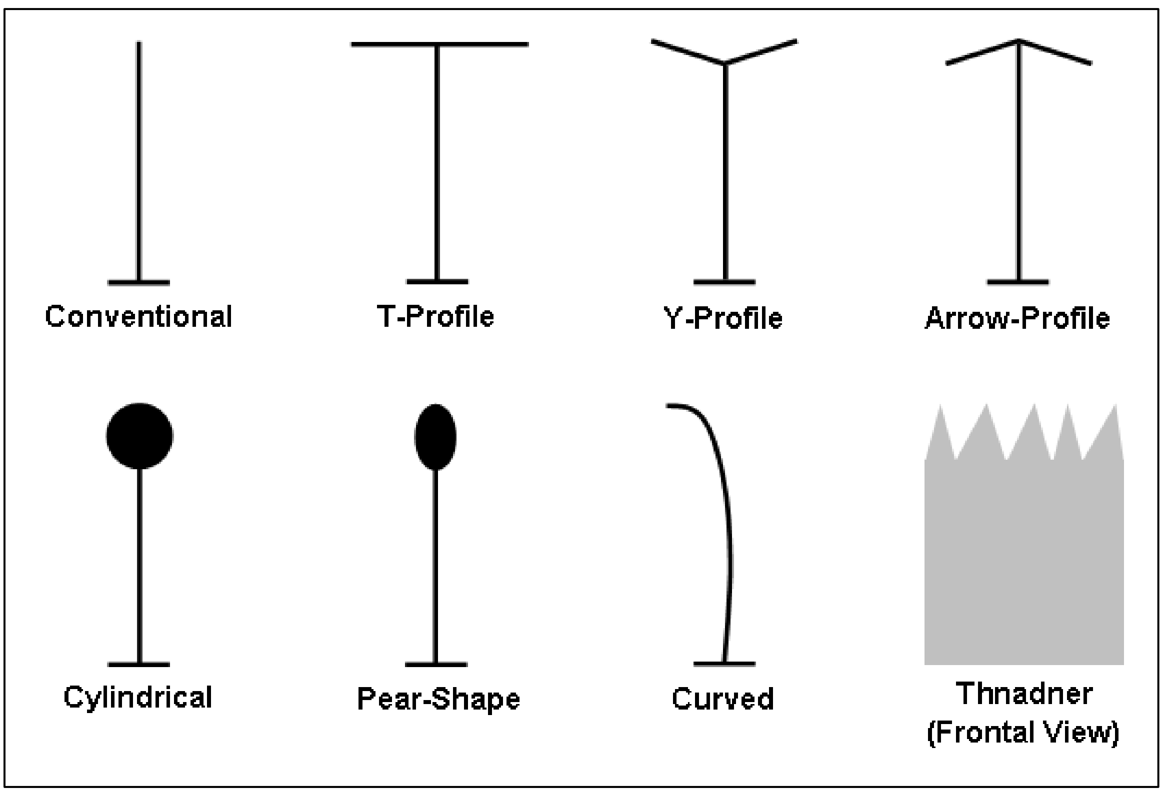

FIGURE 3. DRAWINGS. DIFFERENT BARRIER TOP DESIGNS
Original source: FHWA, 2000; image was recreated for this report

Placement: Due to changes in path length, which changes the diffraction angle, a barrier is more effective if placed close to the source or the receptor. Local terrain can have significant effects on the effective barrier height which is the barrier height plus or minus any height due to the terrain it is on, or any structure it may be on. The area of diffraction (the "shadow zone") diminishes with distance behind the barrier. A study of 20 barriers in Florida indicated that shadow zone benefits, as determined by a 5 dB:L_{Aeq} sound level reduction, were generally limited to under 400 feet (ft) (122 meters (m)) behind even tall noise barriers. Additionally, reflections may cause increased noise levels on the opposite side of a highway or, in the case of parallel barriers, degradation of the barrier effectiveness on both sides of the highway. In such cases, it can be important to consider the absorptive treatments previously described.

The overall effect of these parameters is a large range of barrier attenuations, unique to the application, that can result in a range of social and ecological benefits and impacts. A practical application range of attenuation is from 5 to 20 dB(A), with the level of acoustic benefits being directly related to the barrier construction parameters: height, length, material, placement.

3.1.2 Other Benefits

A primary benefit from noise barriers as compared to other abatement options is the acoustic longevity of the design attenuation. Although attenuations of greater than 30 dB(A) are possible, in practice, 20 dB(A) is difficult to achieve. Even so, noise barriers generally provide large and long-lasting noise reductions for the outdoor environment. Even the replacement of a guardrail with a solid barrier could provide up to 2.6 dB [Rochat, 2020]. Barriers require only a small cross-sectional footprint to achieve these reductions and so do not require normally generate additional right-of-way costs.

However, Nilsson [2010] compared noise acceptance behind a barrier and at a greater distance without a barrier, finding that the noise behind the barrier was more annoying to people when compared to the same levels at a non-barrier site. This demonstrated the importance of lower frequency sound to human annoyance and responses to noise. This evidence indicates that the benefit of decreased annoyance is directly related to the characteristics and level of the sound after the final attenuation. Unfortunately, this is generally not a linear function due to the subjective nature of individual responses [Sanchez, 2018].

Barriers are generally large structures that can also offer additional benefits. One common secondary use, for example, has been the addition of short light poles on the top of barriers. These shorter poles are less expensive but provide the same height and light projection area when placed on top of tall barriers.

In the United Kingdom [Carder, 2007], a somewhat more uncommon beneficial use was the use of barriers as a support for solar panels. Carder's work suggests that the presence of solar panels did not cause driver disturbance. Another benefit was that the angle required to effectively expose the panels to sunlight, particularly to the south, resulted in less noise reflection to the other side of the roadway. However, a whole-life cost analysis indicated that though the power generation provided a positive benefit, recouping the cost of the barriers in this location would take over 30 years.

Studies have indicated that barriers can also change the dispersion and concentration of air pollution from highways and in some cases can reduce pollutant concentrations at homes on the other side of the barrier.

Noise barriers may also affect wildlife. The benefits of noise reduction can include better habitats and more audible communication for various species. Wildlife collisions are dangerous for both the wildlife itself and human motorists; barriers can help prevent road kills by blocking access to the road. This second benefit is also accompanied by the negative impact on animal movements and is discussed in the next section.

Barriers can also create more desirable conditions for living and recreation by reducing noise levels over large areas with a minimal footprint. As a result, there is a general tendency for property values to increase [Decký, 2012], [Becker, 2003].

Additionally, barriers can be aesthetically designed so that they can either blend into the background (e.g., the use of vegetation or the same outer textures as nearby buildings) or add to the landscape (e.g., use of shape, color, graphics, and textures)[Knaeur, 2000]. In some cases, barriers have become a method of creating community recognition (e.g., city emblems embedded into or on barrier panels, the use of local art, or showcasing important local history or preferences).

3.1.3 Negative Impacts

A pilot study of 218 residents conducted in Chile [Arenas, 2008] found that large percentages of the respondents noted negative impacts from barriers. Each of these areas are discussed below with additional references of key information included:

- **Loss of sunlight and loss of air circulation:** The large size of barriers both in height and length leads to landscape impacts. The normal breezes close to the surface will be blocked and, if the barrier is on the western side of a location, the sun sets a little earlier. In the case of the change in surface air circulation, research from the U.S. EPA has also shown that this may be either a negative impact or benefit in that roadway air emissions may be reduced or increased depending on the given conditions [Baldauf, 2008]. Similar results have come from modeling fluid dynamics, which showed that the highway-side air pollutant concentrations may increase and negatively affect drivers, especially those with open windows [Hagler, 2010]. Roadside barriers may or may not mitigate air pollution on the home side of the barrier, depending on the local meteorology, the barrier structure, and the degree of lee-side emission sources.

- **Visual Impacts:** As stated, barriers are large objects and can be a visual intrusion if they are not designed, built, or maintained properly. In addition, a barrier's size can create the sense of further dividing a community by blocking the viewshed to the other side of the roadway.
- **Access:** Good acoustic performance depends on reducing gaps in barriers, which means that allowing driveway openings and cross street traffic are not feasible. This need for a solid, continuous surface can also lead to problems with local drainage, utility placement, and community connectivity.
- **Wildlife:** Barriers can interfere with normal animal movements, both locally and regionally, resulting in reduced range of motion and blocked paths to water and/or food sources. This exacerbates the impacts from the highway itself dividing habitats and migration routes. If wildlife can go around the ends of a barrier, it could also trap that wildlife on the road side of the barrier. Birds fatalities also occur due to collisions with transparent barriers [El-Rayes, 2018].

3.1.4 Costs

Barriers can add considerable costs to highway construction. FHWA [2021] reports that for the period from 2017 to 2019, the overall average unit cost, combining all materials, was $53.39 per square foot; for the last 10 years it was $37.36 per square foot. Since 1963, 48 States and Puerto Rico have constructed at least 3,537 linear miles of barriers at a total cost of over $8.6 billion, in 2019 USD.

Providing wildlife overpasses for animal crossings adds considerable cost to a project, though these are rarely if ever provided solely due to a noise barrier blocking animal movements; and are more likely added to projects to mitigate impacts from the presence of the roadway itself.

Mitigating the negative visual impacts of a barrier can also increase the cost to initially build and then maintain that barrier. There are different funding mechanisms and agreements that can be engaged to minize the cost impact to any one agency or organization.

Maintenance will also require the ongoing use of public funds. The frequency and amount of such expenditures vary by material (e.g., concrete, metal, wood, brick), surface treatment (e.g., paints, absorptive materials, other aesthetic treatments), and over time. Such maintenance to the barrier itself includes repairing normal wear and tear; as well as unexpected repairs due to sudden vehicular, storm, or malicious damage from things such as collisions, vegetation growth or breakage, or vandalism.In an effort to lessen these costs, research from Europe [Parker, 2010] explored the use of durable low maintenance noise barrier systems. Maintenance typically also requires access to the community side of the barrier, and in some cases, doors and overlapping barriers have addressed this issue, but these solutions can still lead to possible degradation of the barrier's acoustical performance and create additional costs.

3.2 Highway Alignment

Alignment changes generate noise reductions by shifting traffic further away. The shifts include moving the highway either horizontally, to create distance between the source and the receptor; or vertically, to break the line-of-sight.

3.2.1 Noise Reduction

Horizontal changes: Horizontal changes in alignment move the highway farther from a sensitive receptor to provide or maintain a greenbelt area; which not only provides a buffer zone but offers reduced noise levels and aesthetic relief. Horizontal alignment shifts may provide only small noise benefits when those shifts must occur within an existing right-of-way. Shifting an alignment horizontally so that the highway is about twice as far from the receptor can reduce noise levels by approximately 3 - 4 dB(A). On a smaller scale, based on a simplified approach of geometric spreading (reduction with distance), each doubling of distance could result in a noise decrease of up to a 4.5 dB(A).

An extreme horizontal change would be to move the roadway to an entirely new location elsewhere. Makarewicz [2010] studied moving vehicles "around" an area using a curved roadway rather than past an area using a direct path. Noise levels for replacement of a 100 m straight road with a 270 m radius road at a 68 degree angle yielded a noise reduction of 4 dB L_{dn}. The study concluded that the cost to change the roadway alignment could even be less than that of installing noise barriers for comparable benefits.

Vertical changes: Vertical alignment changes may include changing a roadway to a tunnel, depressing a section with an open top, elevating a roadway, or fully converting the alignment to a bridge. The barrier effect from open-top depressed roadways can enable up to 10 dB of reduction [Rochat, 2020]. In the case of the elevated roadway, the alignment increases noise at greater distances due to loss of ground effects but results in quieter conditions close to the structure. In the case of joint noise, abatement measures such as the use of finger joints are important to allow a transition between bridge decks. Finger joints can generate up to 9 dB of noise reduction from structures [Rochat, 2020]. Barriers may also be used on elevated structures to provide more noise reductions.

3.2.2 Other Benefits

Changes in alignment can lead not only to noise reductions but also to fewer crashes if the new geometry improves safety. Harmful emissions may also be reduced (if traffic flows more smoothly) or at least moved farther from receptors. Alignment changes such as depression of a highway below grade can reduce visual impacts of the highway and help to reconnect communities by making it easier to cross the alignment via bridges or decks.

3.2.3 Negative Impacts

Horizontal changes: Bypasses could result in impacts to other communities; or to natural areas and wildlife. Prekop [2016] looked at the use of bypasses, finding that there was a marked difference in the traffic volume once a bypass was built, especially that of trucks. The bypass induced demand, the traffic volume was spatially redistributed, and the vehicle mix changed. Measurements indicated 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, although it was not statistically significant. Additionally, there were complaints from people in the new bypass area.

Vertical changes: Changing from an at-grade roadway to a depressed or elevated roadway could create drainage and other problems. Depressed roadways can divide neighborhoods, and elevated roadways can create visually intrusive structures. With certain building techniques, elevated roadways can be aesthetically unpleasant, blocking visibility, generating structure noise, especially from joints, and decreasing airflow.

3.2.4 Costs

Horizontal changes: If a new roadway is being built, the incremental cost of a noise-reducing alignment may vary compared to the cost of other alternatives. An example analysis of a project in Central Ohio considered the cost of a 50 foot alignment shift to move an arterial roadway away from noise sensitive sites; the additional construction cost for shifting 1,750 feet of roadway was estimated to exceed $2 million.

Aiming to achieve large reductions by shifting an existing roadway horizontally could have significant land costs. Costs may include right-of-way acquisition in addition to construction. The resulting greenbelt could also generate maintenance costs.

Vertical changes: Vertical alignment shifts may be less costly and more realistic if existing right-of-way is sufficient [Rochat 2020]. However, changing the alignment of an existing roadway vertically can also be very expensive, especially if new structures are required. Walkways to reconnect communities over a depresesd typical section would incur an additional cost to the project. Means to control structure noise from bridges, such as the use of finger joints, is crucial to minimize noise increases to nearby receptors, but would also be an additional project cost for construction and maintenance.

3.3 Traffic Controls

Traffic controls for noise include reducing speeds, redirecting traffic flows, changing vehicle mix, and using different control devices or configurations.

3.3.1 Noise Reduction

Traffic Speed: Reducing vehicle speed reduces noise. A speed reduction will almost always result in noise reduction because vehicle noise increases with increased speed. Tire and pavement noise is the greatest noise source for speeds above 25 to 30 miles per hour (mph); engine noise may increase slightly at these speeds as well.

FIGURE 4 illustrates the relationship between speed and sound level in the U.S., indicating that reducing the vehicle speed from 45 mph to 30 mph, for example, reduces the noise by approximately 2 dB(A) [Rasmussen, 2007]. Speed reduction is a particularly good strategy on local streets, where driveway access makes the use of barriers infeasible. The greatest noise reductions would be unlikely to occur on local streets, though; **FIGURE 4** also illustrates the dominance of pavement and tire noise above 30 mph, which means that the greatest reductions would occur at higher speeds.

Trucks have much more acoustic energy than passenger cars; as such, implementing Traffic Controls targeted to heavy trucks can have a notable impact on local traffic noise levels. **FIGURE 4** shows the effects of truck traffic on overall noise levels due to propulsion noise, which have been reported in the Czech Republic (**FIGURE 5**). It appears that a practical limit for the reduction of propulsion noise would be approximately 3 dB(A).

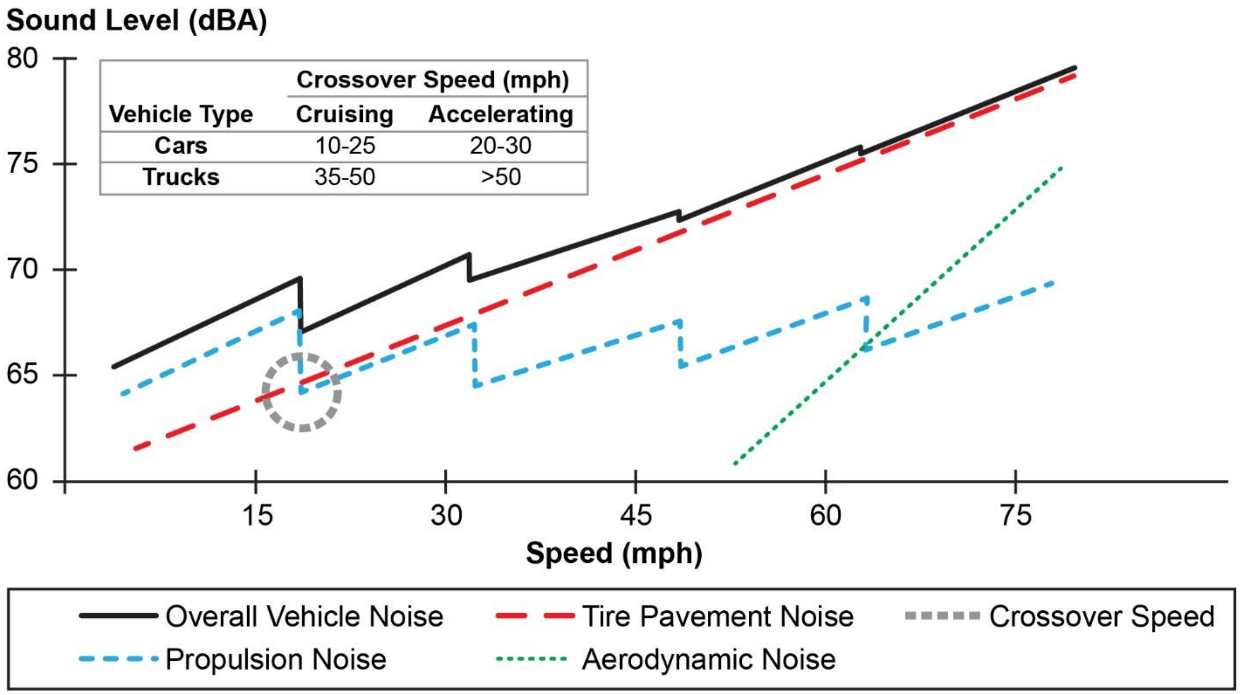

FIGURE 4. GRAPH. SPEED EFFECTS ON VEHICLE NOISE SOURCES AND CROSSOVER SPEED

Source: Rasmussen, 2007

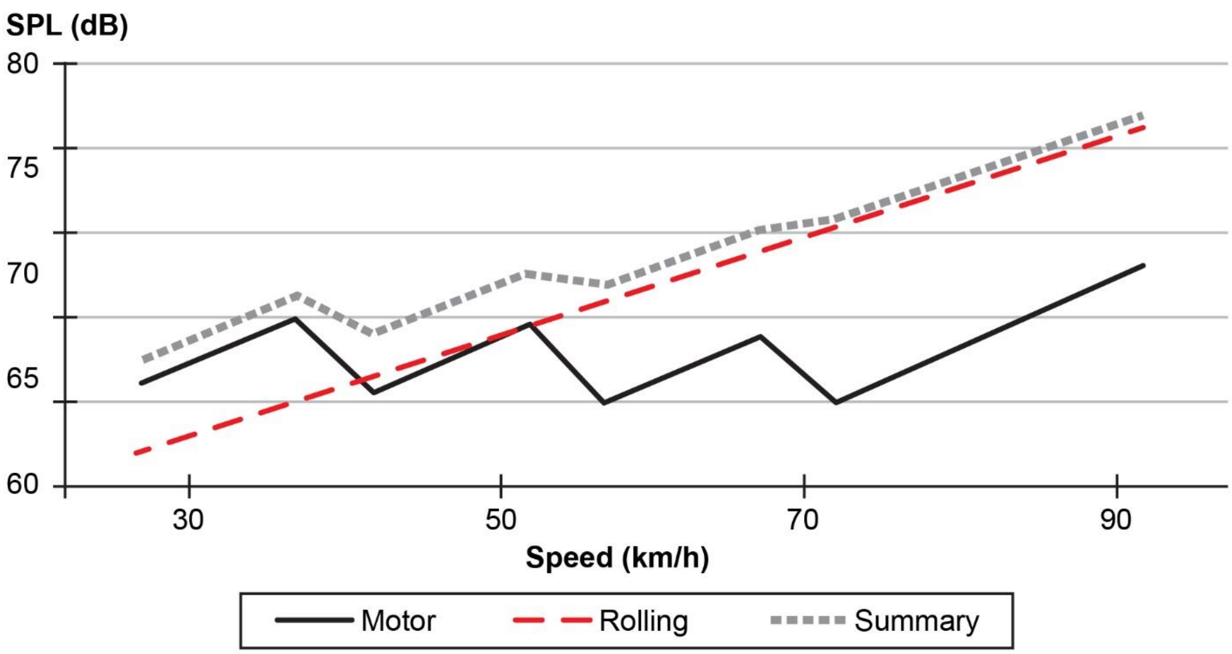

FIGURE 5. GRAPH. SPEED EFFECTS ON VEHICLE NOISE

Source: Jilkova, no date

Traffic Calming Devices: Kacprzak [2018] reports that improvement of the acoustic climate is dependent upon the type of devices, location, and frequency of use of calming devices. When single-sided chicanes, which are artificial narrowing or turns in a road, were introduced in entry zones to several villages to test the noise reduction, the measured noise reduction was proportional to speed changes. For speed changes of 1 to 15.3 kilometers per hour (km/h), the noise level change was 0.4 to 3.4 dB L_{eq}, respectively.

In some cases, the use of an alternate control configuration (e.g., a roundabout rather than an intersection) can result in lower noise levels due to smoother traffic flow. Changing a cross intersection to a roundabout can decrease the noise level by eliminating what research has found to be the more disruptive noise associated with traditional intersections [Covaciu, 2015]. In several research locations, 1 - 4 dB(A) reduction was possible due to the improved fluidity. Authors doubted, though, that the continued flow could be maintained. Results such as those from the Slovak and Czech Republics [Decký, 2012] also show noise reductions associated with the construction of roundabouts. Decký's research found that roundabouts generated both environmental and socioeconomic benefits. Noise measurements from before and after the construction of a roundabout showed a 2.5 dB L_{Aeq} noise reduction.

Traffic Flow and Mix: Changes in vehicle mix can also affect overall noise levels. If traffic volumes in sensitive areas can be diverted to other areas, the reduced volume will also generate noise decreases. In Ireland, a ban on private cars in the city center during peak traffic hours allowed researchers to track noise impacts [King, 2011]. Through both measurements and modeling, it was found that banning private vehicles did indeed reduce noise levels by up to 2.7 dB(A) during certain times of the day but also increased noise levels at other locations and times by up to 1.9 dB(A). To accrue real benefits of between 2 to 3 dB(A), the rerouting would have to take place over the entire 24-hour period.

Timing: The proper timing of control devices is also an important factor. Traffic controls such as routing restrictions can also be targeted by time of day to reduce noise when it is most impactful. Rather than move the vehicles, Brown [Brown, 2015] looked at reducing heavy vehicles volumes in the evening in Brisbane, Australia using a heavy toll for trucks between 10 p.m. and 5 a.m. Data over a two-year period show significant reductions in surrounding community's reported 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. The study attributed the change as being directly related to the reduction in the number of noise events from heavy vehicles. Noise effects at night, the study found, depend on the number of noise events experienced, not only on the overall level of traffic noise.

3.3.2 Other Benefits

Reducing traffic speed improves safety; for example, the probability of a motor vehicle-pedestrian collision resulting in a fatality to the pedestrian increases from 20 percent if the vehicle is moving at 20 mph, to 40 percent at 30 mph, to 80 percent at 40 mph [U.S. DOT, 2000]. It may also reduce emissions, if the speed reductions are from high levels (above 65 mph) into moderate speed ranges (30–65 mph) [Barth and Boriboonsomsin, 2009].

Restricting or rerouting traffic may also improve safety and reduce emissions in proximity to receptors, but the specific effects will depend upon the shift in traffic.

Restricting traffic and reducing speed are also used to create walkable commercial and recreational zones, reconnect communities, or create gathering points for people. Such zones can have positive effects to the surrounding area and to visitors, both at the individual and community level.

3.3.3 Negative Impacts

In some cases, calming devices (such as roundabouts) can show conflicting results in terms of noise effects. While most roundabout cases showed noise reductions, Covaciu [2015] noted that an increase in noise levels might occur. Slower speeds may also cause more annoying truck sounds at very low speeds as the engine noise continually rises and falls due to acceleration/deceleration (**FIGURES 5 AND 6**).

Traffic calming can also have non-noise negative impacts. Though reducing speed reduces vehicle noise and improves safety, it also increases travel time. Emissions also tend to increase at low speeds (below 25-30 mph [Barth and Boriboonsomsin, 2009]), with the specific effects depending upon the pollutant and vehicle characteristics. Rerouting traffic to other locations may result in noise complaints in the new area.

Other calming devices, such as chicanes, may cause movement and access problems for vehicles such as larger trucks. This could be an important issue in commercial areas where encouraging pedestrian accessibility must be balanced with vehicular needs for activities such as food delivery or trash collection.

3.3.4 Costs

Costs for implementing certain types of traffic controls, including speed limits and routing or time of day restrictions, can be minimal, only requiring changes to signage and possibly other information sources. However, some ongoing enforcement costs (either manual or automated) will also likely need to be incurred if the strategy is to be effective.

The costs of roadway design elements can range from very modest (a few thousand dollars) for some traffic calming devices to much more significant (in the millions) for strategies such as replacing a signalized intersection with a roundabout.

3.4 Insulation

Although there is a vast amount of published data on the sound insulation properties of building materials, a limited amount has been published on sound insulation specifically related to traffic noise. As sound insulation properties of building materials are well-established, this review focused on current innovative designs in building envelope as they relate to traffic noise control. It should be noted that insulation and barriers can be used concurrently, especially in cases where reflective noise from barriers on the opposite side of the roadway cause increases at higher floor levels that are not protected by the near-side barrier [Zhisheng, 2007].

3.4.1 Noise Reduction

Noise reduction from typical building materials is limited because of the significant low frequency composition of traffic noise combined with building component resonances [Davy, 2004]. Design considerations should therefore be focused on choosing thickness and depth of air space to bring the mass-air-mass resonance frequency below 100 hertz (Hz). Increasing air space above 100 millimeters (mm) (4 inches) increases sound insulation at low frequencies more than at high frequencies due to the mass-air-mass resonance being lowered. However, standing wave resonances may affect the attenuation of high frequency insulation.

Windows: The limiting component of most exterior wall systems is glazing, as glazing systems have inherently lower sound transmission loss ratings than other building envelope materials. A double-paned window provides better insulation as compared to single glazing, especially for low frequencies, mainly due to the air space between panes. Double glazing helps considerably and in some cases the use of different shapes and Helmholtz resonators can be arranged to provide further reductions [Mao, 2010], [Mun Lee, 2017]. See also **Section 3.9.1**.

FHWA provides estimates of how much noise reduction could be expected for different building types and window conditions, whether open or closed. Per the FHWA guidance [FHWA, 2011]:

- A frame house with open windows can be expected to provide about 10 dB(A) of traffic noise reduction to the building interior
- A light frame home with ordinary, closed sash windows would provide 20 dB attenuation
- A light frame home with storm windows would provide 25 dB attenuation
- A masonry house with single glazed windows would also provide 25 dB attenuation
- A masonry house with double glazed windows would provide the most attenuation, at 35 dB

These values can vary by the orientation of the windows with respect to the roadway. The guidance also states that for insulation to be effective, the windows should remain closed. A more recent study showed open window noise reduction results varying between 7 and 17 dB(A) [Yang, 2018]. This is somewhat in conflict with findings by Zhisheng [2007] where noise reduction of 5 to 17 dB(A) required closed windows. While, Amundsen [2011] reported that a 6 dB reduction might be expected if a room is placed on the opposite side of a building from the highway.

Changing the window type can also be beneficial. Plenum windows were found to provide up to 9.5 dB(A) more reduction than side-hung windows [Tong, 2015]. Plenum window design offers a variation of double-skin façades for which two layers of windows are separated by a significant airspace with individual open window segments staggered to provide ventilation without a direct airflow line-of-sight to the outdoors. These have been shown to provide a 7 to 10 dB(A) traffic noise reduction improvement over a single layer of partially open windows, depending on interior room size and finishes.

There is also a significant increase in the effectiveness of sound insulation for higher frequencies when either one glazing layer is doubled or both glazing layers are doubled [Garg, 2011b]. 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.

Exterior walls can also be a problem area for transmission of noise to interior spaces. Insulating exterior walls is also one of the most important tasks in the energy efficient modernization of old buildings. Depending on their material and structural design, the new layers can increase or decrease the sound reduction ability of the original supporting wall [Kocsis, 2014]. See also **SECTION 3.5.1** on providing a thin layer of vegetation to the building envelope.

Building Façade: As reported by Amunndsen [2011], noise reductions of 7 dB(A) can occur from façade insulation including wall insulation, upgraded windows and upgraded ventilation systems. An upper practical limit would seem to be 20 dB(A). If openings in exterior walls or windows cannot be avoided, special designs such as double-skin façades are typically needed to achieve noise reduction goals of 20 dB(A) [Huckemann, 2009].

Double-skin façades, comprised of two layers of materials separated by a 1- to 2-meters (m) open cavity, can be effective in traffic noise insulation for all types of buildings, especially when both layers are closed (since one layer is often open for ventilation requirements). When both layers are closed, insulation ratings equivalent to exceeding sound transmission class (STC) 60 were measured, while STC ratings below 30 were measured when both layers were open.

Balconies: The use and enjoyment of exterior balconies, especially in apartment units, can be heavily compromised due to traffic noise. 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 are found to be the second best [Tong, 2011]. According to theoretical models, exterior balconies having inclined or acoustically absorptive ceilings can provide an additional 0.5 to 10 dB(A) of noise reduction, depending on floor level, balcony depth, and ceiling incline angle. Greater attenuation has been shown to occur at higher floors with inclined ceilings [El Dien, 2004]. Ceiling incline angles of at least 10° and balcony depths of at least 2 m are required for minimal reductions. Ceiling mounted reflectors have also been examined and reductions of 7 - 10 dB(A) reported [Ishizuka, 2012].

Ventilation: Ventilation requirements for areas requiring open windows provide significant noise reduction challenges. Even venting for clothes dryers or fireplaces can increase interior noise. 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 [Oldham, 2004]. Oldham proposed a design methodology for optimizing the ventilation and acoustic performance.

Other: An application combining active noise control for low frequency traffic noise control and absorptive lining for high frequency traffic noise control has been proposed as a noise control solution for exterior building walls that require ventilation openings. Although potentially effective in theory, active noise control is not effective over the wide frequency range and constantly varying nature of traffic noise. This topic is covered in greater detail in **Section 3.7 Active Noise Control**.

Shutters [Diaz 2009] over windows and sun shading systems [Fausti, 2019] have also been evaluated for noise control. However, shutters provide little, if any, additional sound insulation for traffic noise. The sun shading systems, without absorptive treatment, can even increase the noise sound level over the building façade and can cause reflective noise to other buildings.

3.4.2 Other Benefits

Proper insulation allows for a comfortable indoor environment for homes near highways that would otherwise be much less tolerable. The value of having quieter indoor social environments that provide spaces for effortless communication, less sleep interference, reduced learning disabilities, increased productivity, and reduced annoyance, extends to having fewer chronic stress-related illness and emotional effects.

Insulation also generally provides the benefit of energy savings. The decreased gaps and air leaks results in better heating and cooling insulation depending on the amount of increased insulation. To provide sufficient insulation for noise may require additional space to better attenuate low frequency noise as compared to what is needed just for energy savings.

Further, the value of this peace of mind combined with the potential monthly energy savings, could also increase the property values of the insulated homes; especially in near-road environments or where climate realities can generate large seasonal energy bills.

3.4.3 Negative Impacts

Installing acoustical insulation can restrict natural ventilation, especially when more than 20 dB(A) of reduction is required. But if windows are opened for natural ventilation, outdoor traffic noise can disrupt people relaxing, working, or sleeping in the building [Kim, 2017]. If windows remain closed, mechanical ventilation is needed, and this can create its own noise.

Another limitation is related to not being able to control low frequency noise as these frequencies require more space and/or special measures (such as resonators or active noise control). A significant drawback to using building insulation as noise control is that the control is limited to indoor areas, and the use of outdoor areas may still be hampered by intrusive noise levels. While not actually a negative impact, this failure to provide abatement in outdoor areas is a failure to achieve complete noise control.

3.4.4 Costs

The cost of installing insulation represents a significant portion of the expenditures related to home and building construction. Garg [2011a] noted that in many cases, regulations, ordinances or building codes may need to be changed in order to require the use of insulation in homes and other noise-sensitive buildings. Without these requirements, builders may be reluctant to spend additional funds on insulation. However, insulation methods may be the only feasible alternative [Modra, 1985] to reduce noise levels at certain locations where other mitigation measures cannot be provided.

To put the cost in perspective, Modra noted six stages of traffic noise insulation for houses and used a cost benefit analysis to show that the application of five of these stages to a single house can be justified. The total cost of these five stages in 2020 dollars was $11,677 - a value less than the allowed cost for a barrier per benefitted receiver used by many State DOTs. However, Modra found that applying this package of noise insulation stages to all houses in Melbourne exposed to more than 68 dB(A) $L_{10(18\ hr)}$ would cost nearly two thirds the annual budget for roadworks for the entire State of Victoria, Australia due to the large number of homes in high noise zones.

Additionally, the costs are by individual receptor. Unlike other abatement measures (e.g., barriers) that supply attenuation along a stretch of highway, insulation usually applies to only one indoor area or building. Mechanical ventilation systems, such as air conditioning and heating units, cost money up-front to install, can add to the homeowner's monthly energy costs, and also require ongoing maintenance to ensure they provide the correct ventilation and air temperature. Variations in the designs of balcony ceilings can also provide traffic noise attenuation but at a cost to the builder, which may be passed on the homeowner/purchaser.

3.5 Vegetation

Vegetation of can provide some traffic noise attenuation. This effect is primarily connected to vegetation in the line-of-sight, where it is able to cause diffraction. However, vegetative surfaces can also reduce traffic noise by ground attenuation and scattering [Aylor, 1972], [Van Renterghem, 2012], [Van Renterghem, 2018]. Other authors note that the noise reduction properties of vegetation are linked to the maturity of the vegetation, the width, the height, orientation, and the type or seasonality of the species present.

Means of controlling of highway noise [Van Renterghem, 2015] with vegetation 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 and the effects of downwind refraction over a barrier
- Use of different berm shapes as well as rough berm surfaces to increase attenuation
- The use of vegetated low-height noise barriers on urban streets to provide noise reduction
- Use of strips of forests to reduce refraction effects
- Changes to smooth-hard ground surfaces to become more absorptive and create destructive interference

3.5.1 Noise Reduction

Aylor (1972) states that scattering and ground attenuation are the principal factors in sound attenuation by vegetation, though different frequencies are affected differently by vegetation [Price, 1988]. Although sound attenuation generally increases as distance from the sound source increases; for vegetation, the attenuation occurs primarily from ground absorption in the lower frequency range and diffusion and scattering from leaf foliage, stems, and trunks at higher frequencies.

Foliage/Trunk Diffusion and Scattering: Even the leaf orientation can change the attenuation effects [Horoshenkov, 2013]. Deciduous trees without leaves mostly provide scattering through diffusion, creating different frequency and attenuation effects, but with the disadvantage of being seasonal. Most studies involved measurements taken at sample full-scale and at established sites, although several studies involved scaled models (especially for evaluating building absorption in urban canyon and courtyard studies). Researchers have compiled both empirical and theoretical data on the noise attenuation effects of different types of vegetation.

For road traffic noise applications, tree bark is characterized by absorption ranging from approximately 5 percent to as high as 10 percent [Reethof, 1976], indicating that absorption by the trees was not the dominant factor in noise reduction. However, more recently, Van Renterghem (2013) reported that absorption from the tree trunks and the forest floor are responsible for the bulk of the noise shielding from highway noise.

Aylor [1972] provided a diverse database by measuring through dense corn, a dense hemlock plantation, an open pine stand, dense hardwood brush, and over-cultivated soil. The corn crop provided an excess attenuation of 6 dB/100 ft for each doubling of frequency between 500 and 4000 Hz. However, the stems of the hemlock, pine, and brush all reduced noise by only about 5 dB/100 ft at 4,000Hz. At higher frequencies above 3 to 4 kilohertz (kHz), the attenuation due to crops is significant [Bashir, 2015].

When breaking the line-of-sight, especially for solid vegetation belt depths of more than 15 meters, the level of attenuation is comparable to that of noise walls, but in most cases it provides less. FHWA's noise guidance [FHWA, 2011], continuing guidance that was first adopted in 1995, states that noise reduction cannot be obtained for an extended period of time using vegetation. Example figures in the guidance show that a 61 meter (200 feet) width of dense vegetation could reduce noise by 10 decibels.

With Barriers: For downwind sound propagation with an orthogonal incident wind noise barrier, attenuation with trees becomes increasingly better with increasing wind speed as compared to the noise barrier without trees but improvement by the trees is affected less if the wind direction is not perfectly orthogonal to the barrier [Van Renterghem, 2002]. Additionally, barriers provide a slight improvement in noise reduction when trees are on the downwind side of noise walls, but there is no improvement when trees are on the upwind side.

With Buildings: Building envelope greening measures [Van Renterghem, 2013] and a thin layer of vegetation can provide up to 3 dB of insulation to buildings [Pérez, 2016], [Jang, 2015]. Reverberation noise in courtyards can be reduced with vegetative landscaping with trees and shrubs in urban canyons. Courtyards have lower reverberation and flutter echo effects through diffusion and absorption of vegetation, improving acoustical conditions in those areas [Kim, 2014], [Li, 2019].

Other vegetation noise studies found the following attenuations[3]:

- Hedges with a thickness between 1.6 and 2.5 m and heights between 1.6 and 4 m provided 1.1 to 3.6 dB(A) [Van Renterghem, 2014].
- A wooded strip 25 m thick provided attenuation of 3 dB(A) [Defrance, 2019].
- A 2 to 3 dB decrease in noise levels is possible with narrow [30 ft (9.1 m)] belts of vegetation [Harris, 1985].
- An attenuation of 6 dB for stands of 1/3 density of mixed hardwoods within 25 m of the road centerline [Hosseini, 2016].
- Reductions of 6 dB L_{Aeq} from a *Pinus brutia* belt of trees 60 m away from the road [Samara, 1976].
- An 8 dB(A) reduction for 100 ft deep tree belts of dense 40 to 50 ft high plantings with a visibility of about 50 ft or less [Reethof, 1973].
- A reduction of 9 to 11 dB(A) for moderate to dense vegetative barriers [Ow, 2017].
- Noise level reductions for trees and scrubs (mixture of conifers and broadleaves) of 25, 50, and 100 m in width were compared to an open area and found to be 7, 13, and 17 dB(A) greater, respectively [Karbalaei, 2015].
- The largest reduction was over 15 dB for 15 m vegetation belts [Tyagi, 2013], [Tyagi, 2006].

Attenuation level appears to be limited by many factors, including tree size (overall height and trunk diameter), the presence of foliage, the size, orientation, and density of leaves, the spacing of trees, the depth of the tree belt, and the presence of low brush. Koptseva [2018] noted that the number of rows or widths of tree planting may be more important for noise reduction than species composition of trees and shrubs.

Ground Absorption: Aylor also found that the noise attenuation by vegetation needs to be normalized by using the ground attenuation to determine impact of the standing vegetation. Other research affirmed this point in finding that at lower frequencies, the ground effect is dominant. Aylor [1972] found that bare ground attenuated sound at frequencies of 200 to 1,000 Hz, while 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.

Following up on the idea of increased attenuation due to ground effects, Forssén [2013] studied burying Helmholtz resonators alongside the road. See also **SECTION 3.9.1**. While, Attenborough [2016] looked at using acoustically soft ground surfaces and increased surface roughness for

[3] Some studies may report unusually high insertion loss results due to not compensating properly for control cases. Additionally, ground effects and those from vegetation should be considered separately.

highway noise reduction. Reductions of up to 10 dB were reported for 12 m wide areas with 0.3 m high, 0.2 m square lattices versus 5 dB with just soft ground.

3.5.2 Other Benefits

The benefits of using vegetation for traffic noise control are clear in terms of acoustic, visual and psychological perceptions. A study from Poland indicated that "indirect, psychological effects of urban green spaces can positively affect the life satisfaction of urban residents" [Koprowska, 2018]. One author noted that vegetation enhances barrier aesthetics while stating that the main aspects of good noise barrier design is the appropriate manipulation of elements and materials and, most importantly, incorporating the use of plants [Kotzen, 2004]. A reporting based on 688 responses of face-to-face interviews and using an ordered logit model evaluation indicated that greenery perception exerts considerable influence on noise annoyance rated at homes [Li, 2010]. FHWA's noise guidance [FHWA, 2010] states that "the planting of trees and shrubs provides psychological benefits by providing visual screening, privacy, or aesthetic treatment".

Infrastructure development tends to minimize green open space, which could result in noise and temperature rise due to the increasing amount of residential development and the number of motor vehicles and industrial facilities using fossil fuels. Planting along highways could help to reduce this impact by absorption from the vegetation [Pudiowati, 2013].

3.5.3 Negative Impacts

The most significant negative impact associated with using vegetation for noise control is the potential sacrifice of open space to create the vegetative zones between roadways and noise-sensitive locations. Time can also be an issue, since newly planted trees and shrubs take years to mature to the size and density at which they provide noise attenuation. High biomass density is ideal but can be difficult to achieve due to practical limitations regarding access to light, nutrients, and water for the vegetation [Van Renterghem, 2014], [Van Renterghem, 2015]. In arid regions, watering could also be required.

Vegetation zones could also attract unwanted wildlife if not maintained which could lead to undesirable effects such as increased vehicle-animal collisions or wildlife that creates a nuisance for humans by disrupting gardens, trash, etc.

Trees may increase high frequency noise levels in street canyons because tree crowns diffuse and reflect high frequency sounds back into the street canyon. This would require construction changes to abate the high frequency noise and could be an important impact for residential or office units in tall buildings that may suffer from increased annoying noise levels and the associated health and productivity effects.

3.5.4 Costs

Economic costs associated with adding vegetation are minimal (a fraction of those associated with noise walls). The real cost is the purchase of additional right-of-way, which in urban areas could be significant. If the project also requires irrigation or other ongoing maintenance, the cost could continue to climb over time. Likely, the most practical application of vegetation is for evergreens in non-urban areas, where ample space is available to establish, or preferably maintain, buffer zones of trees and shrubs between roadways and noise-sensitive locations.

3.6 Quiet(er) Pavement

Highway surface textures have a significant effect on traffic noise generation. The pavement micro-, macro-, and mega-texture can be quite important in increasing or reducing noise generation and propagation. Quieter pavements work to minimize noise along a highway by reducing tire excitation and eliminating a “mirror reflection” of the sound by diffusing the direct reflection and absorbing sound energy during the reflection.

However, quieter pavement must be designed not only for noise but for safety and durability. Pavement design and choices are generally led by the need to provide safe travelling ways for the public, not by the desire to reduce noise levels. Surface friction, an important safety parameter, depends heavily on the surface texture of the pavement and is directly related to noise generation and propagation.

As of 2020, there have been over 50 years of measurements in the realm of pavement/tire noise using both at-the-source and the pass-by methods. Measurements at the source can be the close-proximity or OBSI method, which measure noise with microphones very close to the tire/pavement patch or moving with the tire along the roadway. The pass-by method uses fixed noise-meter locations along the highway to measure the sound level as a vehicle passes. There is significant correlation between the methods although differences occur by pavement surface type. Certain trends seem clear from various literature reviews [Wayson, 1998], [Sandberg, 1999], [Sandberg, 2002], [Rasmussen, 2007]. These trends are highlighted below.

3.6.1 Noise Reduction

Concrete Pavements[4]: Rigid pavements such as Portland cement concrete (PCC) offer 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. This noise can potentially be reduced by using different surface preparations [Tao. 2017]. Random spacing may reduce the particularly annoying pure tones caused by uniformly-spaced

[4] There is conflicting data in the U.S. suggesting that other surface characteristics, such as tine spacing, construction techniques, and aggregate size, must also be considered when evaluating PCC texture-generated noise.

transverse tining. Longitudinal tining also reduces the overall noise as compared to transverse tining.

Results from the U.S., Australia, and Europe show that "exposed aggregate surface appears to provide better noise quality characteristics." 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. However, when U.S. researchers compared a transverse tined surface[5] with a European exposed aggregate texture design they did not find a significant noise reduction or frequency shift. Two States showed only a 1 dB(A) reduction [between what? compared to what?]. Construction techniques may have been the problem, particularly the aggregate size used in the final course.

Texture depth also seems important to noise levels from PCC pavements. Australian test results showed that an increased depth led to a slight noise benefit [amount of benefit?], while trends for U.S. data showed even more benefit from increased depth [amount of depth, amount of benefit?]. Use of diamond grinding to change the surface texture of PCC pavements can also provide noise reductions at a smaller overall cost than repaving. Reductions up to 7 dB are reported [Rochat, 2020], although other reporting [cite] shows only about half this value.

Asphalt Pavements: Asphaltic pavement surfaces, such as open-graded, stone mastic and rubberized asphalt may offer more significant noise abatement. The use of open-graded pavements (friction courses) may provide more reductions, but a shorter lifespan (see: **NEGATIVE IMPACTS**). Aggregate sizes of less than 10 mm (0.39 in.) are needed for asphaltic surfaces to provide both adequate friction and reduced noise levels. In cases where the roadway design necessitates the use of chip and seal, varying the thickness of the chip seals could reduce the noise.

In general, when dense-graded asphalt and PCC pavement are compared, the dense-graded asphalt is quieter by 2 to 3 dB(A); the difference is even greater if the dense-graded asphalt is compared to transversely tined PCC pavements. A review of the information shows up to a 13 dB(A) reduction when comparing PCC and open graded pavements. A more practical reduction is approximately 6 dB(A), while general reporting indicates reductions by as much as 9 dB for open-graded asphalt [Rochat, 2020]. Noise reductions could also potentially be achieved from thin overlays, which would allow greater frequency of paving [Bendtsen, 2006]. Up to 6 dB of noise reduction has been reported for thin, bonded asphalt overlays [Rochat, 2020].

FIGURE 6 shows differences in measured OBSI sound intensity levels [Donavan, 2006] in California and Arizona for various pavement types, while **FIGURE 7** shows these trends from Florida [Wayson, 2014]. Research indicates similar trends in Europe, Asia, and South Africa.

[5] 26 mm (1 in.) uniform spacing.

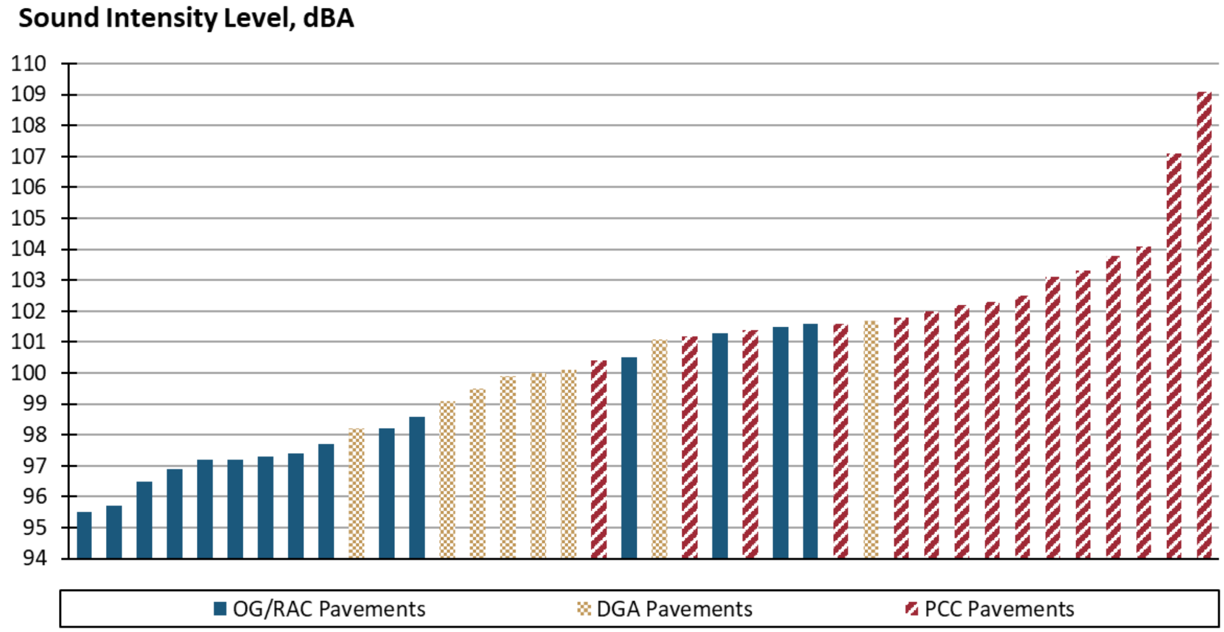

FIGURE 6. GRAPH. COMPARISON OF DIFFERENT PAVEMENT SURFACE SOUND INTENSITY LEVELS FROM CALIFORNIA AND ARIZONA

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

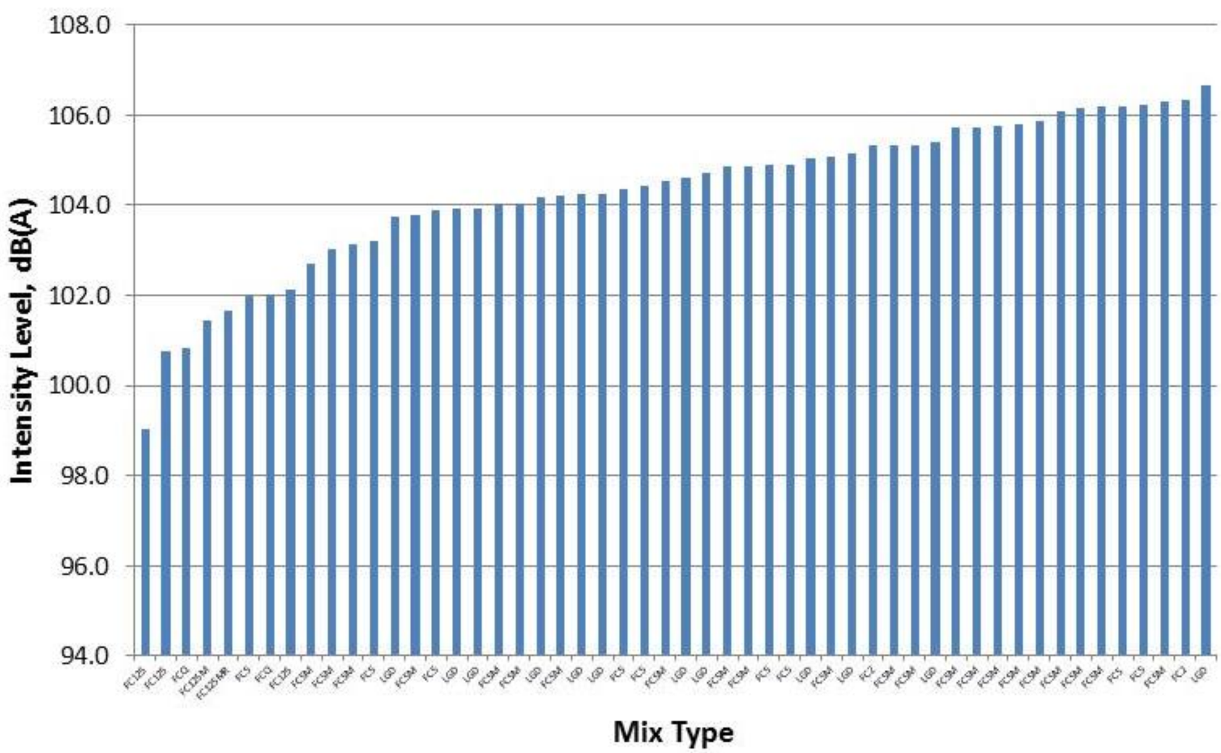

FIGURE 7. GRAPH. PAVEMENT RANKINGS IN FLORIDA BY PAVEMENT SURFACE TYPE

Source: Wayson, 2014

3.6.2 Other Benefits

Safety benefits include better splash/spray during wet weather and increased friction when open-graded pavements are used versus PCC or dense graded pavement. Exposed aggregate surface also has good frictional characteristics and could provide durability as well as noise reduction.

While not actually additional "benefits," low noise pavement avoids some negative impacts as compared to some other mitigation measures. It does not block airflow or cause shading. The National Park Service prefers lower noise pavement because it has no visual intrusion [Sohaney, 2013]. Also, unlike barriers, it provides noise reduction on both sides of the road. Unlike insulation, it does not require any work to occur on or in private buildings. Nor does it require the acquisition of additional right-of-way for its construction. In addition, it should not intrude upon or impact utilities or drainage patterns if installed and maintained properly.

3.6.3 Negative Impacts

While quieter pavements benefit adjacent noise-sensitive receptors, they may also increase noise levels inside the vehicle, leading to driver annoyance. However, the largest negative impacts are safety concerns related to surface friction and the loss of noise reductions over time.

The frictional characteristics of dense-graded asphalt are less than for PCC pavements; and for PCC pavements, longitudinal tining reduces surface friction when compared to transverse tining. The frictional characteristics of dense-graded asphalt have a shorter service life. The use of open-graded pavements (friction courses) may provide more reductions. However, these pavements may suffer from plugging, more rapid deterioration especially with freeze/thaw cycles, reduced effectiveness when using deicing agents, and a general increase in noise levels with surface wear. Chip seals, to improve the pavement, may be louder by up to 6 dB(A) for cars and 2 dB(A) for trucks [Dravitzki, 2002].

The noise reductions, especially for asphaltic pavements, seem to decline with surface age. As a general rule, after 7 years the noise benefit diminishes significantly [Chalupnik, 1992]. This effect varies by individual studies, with some stating a range of 5 - 10 years [Ahammed, 2010]. While not always portrayed as a linear trend, attempts at a linear fit have also been put forward on acoustic changes with time and traffic volumes [Bendtsen, 2010] as shown in **TABLE 3**.

TABLE 3. AVERAGE NOISE INCREASE FOR MULTI-AXLE HEAVY VEHICLES FOR FOUR PAVEMENT GROUPS EXPRESSED AS THREE INDICATORS

Pavement Type	ΔL_{Age} [dB/year]	ΔL_{ADT} [dB/1 mil vehicles]	$\Delta L_{Mix25/75}$ [dB/mix]
All average	0.27	0.15	0.18
Dense-graded asphaltic concrete	0.23	0.17	0.19
Open-graded asphaltic concrete	0.12	0.11	0.11
Thin open	0.44	0.16	0.23
Preplaced aggregate concrete	0.22	0.17	0.18

Source: Bendtsen, 2010

3.6.4 Costs

In general, the cost of quieter pavements has been slightly more than conventional asphaltic pavements. However, Sandberg reports the cost of low noise pavements is often less than that of noise barriers[6]. Vaitkus [2018] affirms this point noting that the cost is less than that of insulation. **FIGURE 8** compares low noise asphalt pavements to noise barriers[7], façade insulation, and other known noise mitigation measures based on feasibility studies. In these studies, the quieter pavements are lower cost than the alternatives.

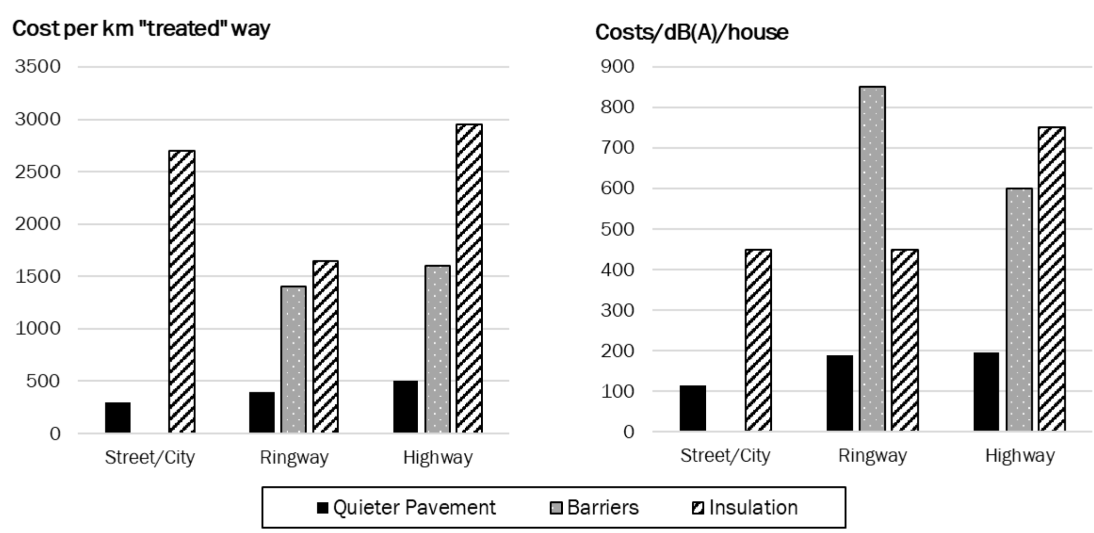

FIGURE 8. GRAPHS. COST COMPARISON OF QUIETER PAVEMENT, BARRIERS, AND INSULATION
Original source: Vaitkus, 2018; image was recreated for this report

[6] Sandberg included the initial application of the pavement surface, but not ongoing maintenance or other costs.
[7] Note the absence of barriers for city streets where access problems make them infeasible.

The cost of resurfacing and increased maintenance could affect the results of this analysis. The limited acoustic durability of quieter pavements necessitates repaving on shorter cycles, which results in increased costs of maintenance. It can also result in increased construction costs for manufacturing and supervision. However, when providing mitigation for long stretches of roadway it may be less expensive to use a combination of low noise pavements and noise barriers, rather than only barriers.

3.7 Vehicle Technology

The proliferation of electric vehicles (EV) could reduce highway traffic noise at low speeds because electric vehicle engines are much quieter than internal combustion engines. Electric vehicles might be considered as a noise reduction strategy in some situations where there is a locally based vehicle fleet (e.g., a port, warehousing area, or bus route). However, the tire/pavement noise component[8] becomes dominant when speeds are above 25 mph, so EVs are unlikely to reduce noise on major arterials and interstates with higher operational and design speeds; and they are unlikely to become part of the baseline from which further noise attenuation might be measured.

3.7.1 Noise Reduction

In general, EVs are 4 - 5 dB quieter than similar internal combustion engine (ICE) vehicles at low, steady speeds [Skov, 2015]. At about 30 km/h, the difference in emitted noise is not significant due to tire/pavement noise dominance. The tire/pavement noise trends are also very consistent with ICEs if similar tires and pavement textures are used [Campello-Vicente, 2016]. During deceleration at low speeds, the engine braking noise for EVs is 2 - 4 dB quieter than ICEs.

Skov also considered the overall changes as the percentage of EVs increase in local traffic. As illustrated in FIGURE 9 there is a large potential reduction at 10 and 20 km/h, whereas the reduction at 30 km/h is not. By changing 100 percent of the fleet from ICEs to EVs, the noise reduction is only 0.6 dB at 30 km/h and essentially non-existent at higher speeds.

[8] Differences in tire design can cause audible changes in the noise from highways and more recent model vehicles have better muffler designs and are more aerodynamic, which can further reduce noise. However, vehicle design is generally not an option for agencies considering noise abatement approaches and is not covered any further in this document.

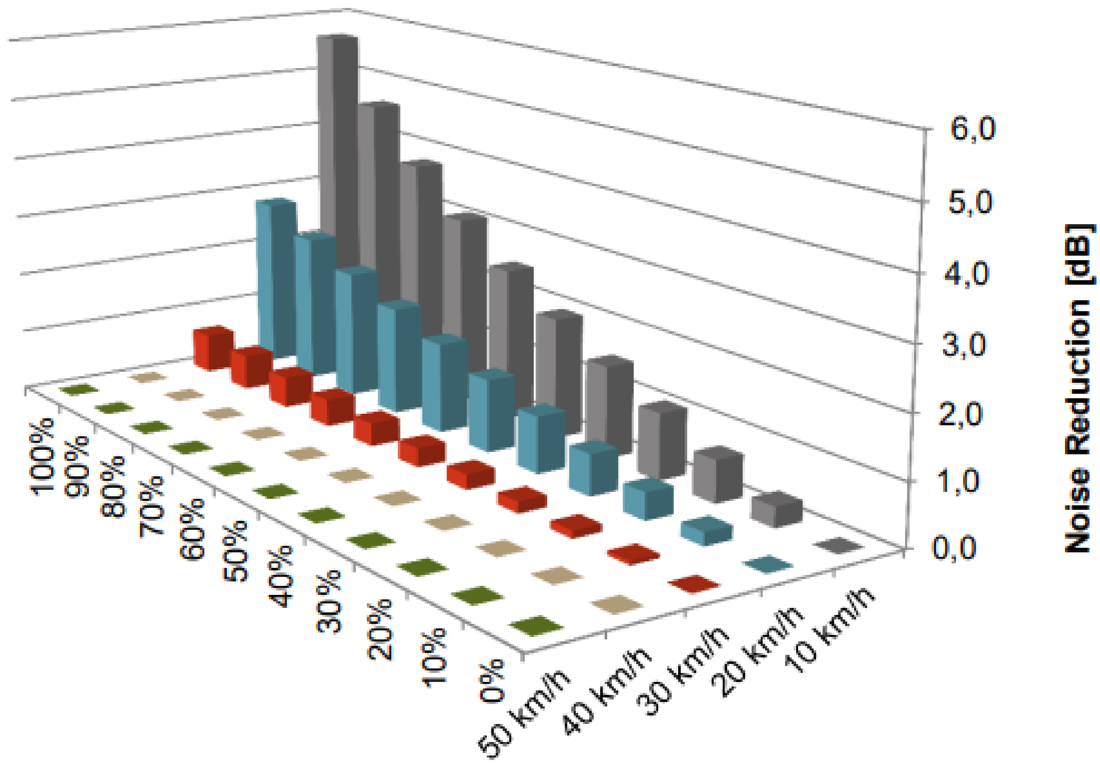

FIGURE 9. GRAPH. NOISE REDUCTION AT DIFFERENT SPEEDS BY REPLACING PERCENTAGES OF THE VEHICLE FLEET

Source: Skov, 2015

Laib investigated the electric buses' impact on noise levels [Laib, 2018] by considering three bus types: a conventional ICE, a hybrid electric, and a fuel cell electric in the city of Stuttgart, Germany. The measurements were used in a sound propagation model and noise levels predicted along bus routes.

The results show that there is a potential for noise reduction when using electric buses on low-volume routes with a high bus share of total traffic[9]. The EVs were up to 7 - 14 dB(A) quieter than the ICE buses at 20 km/h, with the fuel cell bus being the quietest. Acceleration and deceleration events are also quieter. At higher speeds, the differences became smaller when comparing the EVs and ICEs, and there was essentially no difference at 50 km/h. **FIGURE 10** illustrates these results.

[9] The results indicated almost no noise reduction when using the electric buses on heavily trafficked roads. By contrast, in a quiet residential area, the average noise reduction when using electric buses was as high as 5 dB(A).

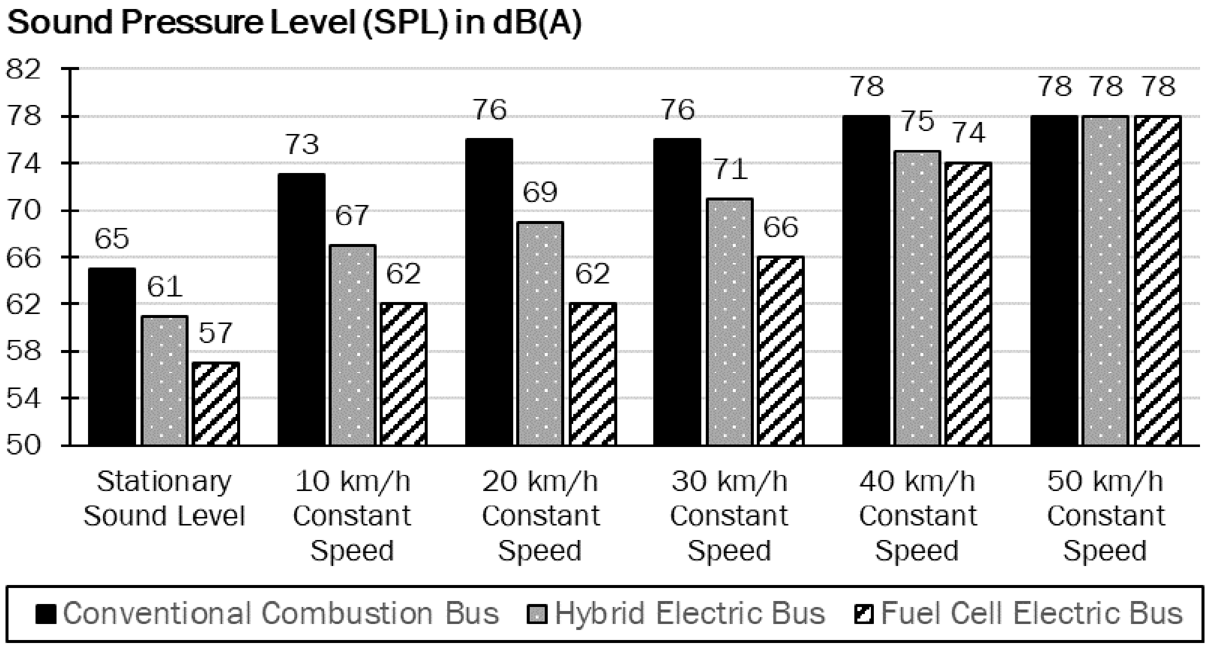

FIGURE 10. GRAPH. COMPARISON OF STATIONARY AND PASS-BY AT 7.5-METERS

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

Heavy trucks have also been evaluated [Hastings, 2015] as well as motorcycles. Measurements were conducted for two electric motorcycles and one electric vehicle delivery truck as well as collecting screening data for four hybrid and electric heavy-duty vehicles. While octave band data is available, only the overall noise levels for the EV testing are reported in this review:

- 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, acceleration, and deceleration were within this range
- Heavy Vehicles:
  - 55.4 at idle to 75.2 dB(A) at 30 km/h
  - Intermediate speeds, acceleration and deceleration were within this range

However, the benefit of the reduced noise in low speed areas may be truncated due to other requirements. The Pedestrian Safety Enhancement Act of 2010 requires rulemaking to establish a Federal Motor Vehicle Safety Standard to have an alert sound for pedestrians be emitted by all types of motor vehicles that are electric or hybrid. These auditory cues for EVs operated at low speeds alert pedestrians (e.g., pedestrians who are sighted and legally blind) to on-coming traffic. Testing using test signals of 59.5 and 63.5 dB(A), approximately the levels from ICEs, resulted in detection at 72 and 85 feet from the best alert signal sound [Pollard, 2012].

3.7.2 Other Benefits

EVs have no tailpipe emissions and would therefore reduce local air pollution and greenhouse gas emissions (this only accounts for operation of the vehicle after it is manufactured). The benefits would be greatest from diesel trucks and buses, which have higher levels of particulate and NO_x emissions.

Individual owners could benefit from fuel and potential maintenance cost savings compared to owning an ICE vehicle.

3.7.3 Negative Impacts

The requirement for a noise source to alert pedestrians would reduce benefits. Since the idea is to alert pedestrians, the sounds were designed according to psychoacoustic principles and the types of sound needed may be more annoying to local residents.

In some EV types, there are narrow peaks in the spectra at low speed that are possible to hear and could also be described as annoying.

3.7.4 Costs

Costs for electric vehicle use are owner expenses and include the charging infrastructure and the incremental purchase cost of an EV compared to an ICE. These costs would only be directly related to highway agencies when such agencies purchase fleets, construct infrastructure associated with EVs, or provide financial incentives for others to undertake these activities.

Given the nascent state of the EV market for light duty EVs and especially for trucks and buses, the Federal Government and many States and municipalities have offered various forms of incentives to subsidize the costs of EV purchase, infrastructure, and/or charging in order to "jump-start" the market. The amount of subsidy required will change over time as the technology evolves and also as a function of other economic factors such as the relative prices of petroleum fuel and electricity.

A secondary negative cost impact for highway agencies could be the loss of vehicle fuel taxes. The loss of revenue to highway agencies could have trickling effects for all road users by potentially reducing or slowing down the construction and maintenance of highways.

3.8 Active Noise Control

The premise behind active noise control is relatively simple: a mirror noise source situated 180 degrees out of phase with the original sound wave cancels the original sound wave. The application of this technology is very limited, especially for non-steady broadband sound sources due to signal processing and amplitude limitations. Accordingly, there has been limited research related to using active noise control as a traffic noise control measure due to the severe limitations of cost, signal processing, and the acoustic power required to overcome traffic noise. The researchers that have reviewed or tested the concept of active control of traffic noise outdoors have generally found its implementation is not practical given the technological hurdles.

3.8.1 Noise Reduction

For outdoor highway noise, researchers have stated that both in theory and application, active noise control efficiency is limited to the low frequency component of highway noise, which is of limited use for real highway noise environments [Duhamel, 1998]. Actual measurements conducted in California showed no decrease in sound levels. Discussions with Rudy Hendriks, previously with Caltrans, indicated the sound power coming off the road was too great to be canceled even with enormous speakers.

There has been some success with attenuation in enclosed and limited spaces such as buildings, wheel wells, and vehicle interiors. In these small areas, active noise control measures can account for tonal steady noise sources over limited frequency ranges. For example, instead of insulation in buildings, it may be possible to use active noise control [Cha, 2011]. One interesting research effort using scale modeling for an open window case [Kwon, 2013] found a noise reduction of up to 10 dB for the entire room of the scale model, in the 400 to 1,000 Hz range. Innovative ideas, such as experiments allowing the windows to vibrate to control the sound [Zhu, 2004], are as yet undeveloped.

By placing devices inside the wheel wells of cars, it may be possible to reduce the tire/pavement noise at the source [Wang, 2017]. However, Sandberg [Sandberg, 2002] noted the harsh environment would make application in the real world extremely difficult.

Multiple research efforts inside of vehicles have shown some success over limited low frequency ranges with reported reductions of 5 dB [Sakamoto, 2015], over 6 dB [Dehandschutter, 1998], over 9 dB [Li, 2018], and 10 dB [Sano, 2001a]. Research on expanding the frequency range continues [Gäbel, 2018] as well as making cars lighter with less noise deadening materials required [Sano, 2001b], [Sahib, 2017].

3.8.2 Other Benefits

The potential benefits of using active noise control for outdoor highway noise abatement are significant in theory, as effective active noise control systems would eliminate the need for noise walls or any other type of noise abatement measure. The non-intrusive nature of the control method would lead to secondary benefits such as out-of-sight, out-of-mind.

On a practical basis, the use of active noise control may provide an abatement similar to insulation for enclosed spaces. But even under the best of circumstances, the noise reductions of 10 dB for traffic noise occur only over a limited frequency range.

This was shown to be possible inside the cabins of vehicles as a practical application, but this would be of limited assistance to highway engineers or analysts except that riders would have a quieter trip (10 dB over narrow frequency bands). Since active noise control systems for vehicles could have a lower mass than typical passive noise control materials, there are also potential, but unquantified, improvements in fuel efficiency.

3.8.3 Negative Impacts

This abatement measure is impractical at this time, as current technology and cost considerations do not support an effective outdoor active noise control system for traffic noise. It is possible that negative impacts of the technology may be identified, but these cannot be fully understood until a working technology is developed.

3.8.4 Costs

The theoretical costs for the equipment needed to abate typical highway noise are significant. A single speaker of the required size and output with required electronics may be several thousand dollars. In addition, maintaining the system of electronic devices would add large maintenance costs.

3.9 Other Abatement Methods

There are several other abatement methods that can be employed to control highway noise. Right now, their use is generally very limited, or non-existent, by highway and government agencies. Summary information is provided by method.

3.9.1 Helmholtz Resonators

As briefly mentioned in **Section 3.4**, the use of Helmholtz resonators in addition to double-glazed windows can improve the noise reduction capabilities of the window [Mao, 2010], [Mun Lee, 2017]. Tuned Helmholtz resonators installed in the cavity of double-glazed windows can reduce low frequency traffic noise transmission by up to 6 dB. However, the cost makes it somewhat impractical for commercial use.

Forssén [2013] studied burying Helmholtz resonators in hard ground alongside a two-lane road. Although the resonator effectiveness is confined to frequency bands in the range of 50–5000 Hz, the study estimated noise reductions of calculated sound pressure levels of 2 - 4 dB(A).

3.9.2 Masking

In masking, other sounds are emitted to mask the traffic noise [Sandberg, 1995]. While the overall noise level would increase, the emitted sounds are usually more pleasing to humans - such as the sounds of waterfalls.

3.9.3 Quieter Rumble Strip Design

Another example, that is part of the highway design, is the use of sinusoidal surfaces to reduce the overall ambient sound created by rumble strips [Rochat, 2020]. Rumble strips are typically placed in the shoulder or along the centerline of opposing travel directions to alert drivers that they are drifting either off the roadway, or into oncoming traffic.

Quieter rumble strip designs provide 3- 7 dB of ambient noise reduction as compared with traditional rumble strips. However there could be even greater reductions inside the vehicle. The noise inside the vehicle (depending on other transfer mechanisms) is reduced but found to still be effective for safety measures intended to alert drivers so they can take corrective action.

3.9.4 Land Use Planning and Permitting

Methods outside the right-of-way controlled by highway agencies can be some of the most effective in avoiding or reducing noise impacts from highways.

Land use zoning and permitting practices by cities can have a great impact on building patterns [Stoecklin, 2019]. One such case is in Switzerland - by ordinance and the Swiss Spatial Planning Act, the type of facilities that can be permitted for construction are defined by zone. For each zone, a sensitivity level (ES) is defined for it by how much noise is allowed in that area. In each zone, different impact levels can be defined. This indirect control depends on local coordination. There are 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.

Land use planning methods also include building construction and alignment in such a way that they reduce noise or protect sensitive receptors similarly to a noise wall. For example, zoning rules by local governments to encourage such construction, the use of non-noise sensitive structures (such as parking garages or commercial buildings with solid walls) to form noise barriers, and/or alignment of these buildings to direct the noise away from sensitive receptors.

4 Literature Review: Benefit-Cost Analysis Methods

A baseline unit of measure is needed to compare a project's benefits, negative impacts, and costs in the same terms. This unit must be able to compare abatement measures internally (to their own impacts and benefits) and externally (to the impacts and benefits of other abatement options). One way to do this is to use economic terms and monetize all costs, benefits, and negative impacts using dollars.

While there are a number of methods for valuing benefits of traffic noise reduction, the bulk of the literature deals with methods that are based on evaluation of property values in relation to noise and other attributes. A number of studies have analyzed sensitivity to noise (as revealed through property values) in North America, but studies explicitly using these models to determine the benefit of noise abatement treatments have mainly been conducted in Europe. These studies have produced generally consistent estimates of the relationship between noise and property values, demonstrating that the value per decibel of noise reduction increases as the baseline level of noise increases. Providing noise reductions in a quiet setting does not provide the same level of benefits as providing the same relative noise reduction in a noisier setting.

A few studies have also considered health cost savings related to noise abatement. While this has not been a primary method for valuing noise attenuation benefits, some studies have attempted to integrate health care costs into hedonic models.

The estimates from these studies can form a basis for estimating the benefit of noise mitigation measures, although these methods have seen little application in the North American context.

4.1 Approaches to Valuing Noise Reductions

Valuation methods can consider both the direct benefit of an action, as well as other incidental benefits, and the avoided negative impacts of not taking that action (of maintaining the harmful status quo). These benefits can then be compared to the direct cost of taking the action plus the cost of incidental negative effects from taking the action.

4.1.1 Valuing the Social Costs of Exposure

As stated in **Section 2: Impacts of Transportation Noise**, the social costs of noise exposure can be divided into three groups [Andersson, 2013]:

1. *Resource costs*

2. *Opportunity costs*
3. *Disutility*

The first two groups of social costs of noise together can be termed “cost of illness” and can be estimated using market prices for health care and lost production. However, disutility can only be measured using willingness-to-pay (WTP) approaches.

WTP approaches can be separated into two categories:

- “Revealed-preferences” (RP)
- “Stated-preferences” (SP)

Revealed-preference methods analyze the actual behavior of individuals, under the assumption that consumer preferences can be revealed by examining behavioral choices; while stated-preference methods rely on asking respondents hypothetical questions about their behavior.

4.1.2 Valuing the Economic Benefits of Mitigation

Becker and Lavee [2003] detail four principal willingness-to-pay techniques for measuring the economic benefits of noise abatement. These four techniques are:

1) cost of abatement
2) cost of illness
3) contingent valuation method
4) the hedonic price method

The “cost of illness” approach directly maps to the “resource costs” identified by Andersson. The other three methods (cost of abatement, contingent valuation, and hedonic pricing) measure disutility and may also reflect opportunity and/or resource costs to the extent that these costs are considered by the people whose actual or stated behavior is measured. Contingent valuation is a stated-preference method, while cost of abatement and hedonic price analysis are revealed-preference methods.

Cost of abatement is a methodology based on revealed behavior. If an individual is willing to pay a certain amount for insulation, then the amount paid is the value of the abatement. However, this method almost certainly undervalues the benefit of abatement, which is higher than the cost of materials and labor. Furthermore, abatement treatments can have benefits beyond sound control that are not captured by this method.

The **cost of illness** approach uses health expenditures as a proxy market for the noise damage. This can be estimated by evaluating health costs in two communities—one that has been impacted by traffic noise, and a control community. Although traffic noise is unlikely to cause hearing loss, exposure to traffic noise does cause increased stress and poor sleep quality that may lead to high blood pressure and a higher risk of cardiovascular diseases over time [Andersson 2013]. At least one U.S. study developed a nationwide estimate of the health costs of noise based on previous research on this topic, as described later in this section.

The **contingent valuation (CV) method** is based on stated-preferences of a representative sample of the public who are to be affected by the new noise standard. In this method, respondents directly state their WTP for the good, here a reduction of the noise level. By asking people how much they are willing to pay for a given amount of noise reduction (for example 30 percent or half), the benefit of noise reduction can be estimated. However, the CV method may give values that are too high due to the hypothetical nature and the subjectivity of attitudes, trust, and general influences on each individual [Bjørner, 2004; Sanchez, 2018]. Futhermore, most residents lack familiarity with what a certain percentage reduction would entail and thus the results of CV can be murky.

- Since the public typically does not understand how a particular noise level relates to the decibel scale, researchers have used a four or five-level annoyance scale, e.g., not at all annoyed, slightly annoyed, moderately annoyed, very annoyed, and extremely annoyed, to characterize noise [Bjørner, 2004]. Annoyance levels can then be related to decibels based on surveys that ask people to rate their annoyance level before and after a change in noise conditions that can be quantified with field measurements. There are consensus values for east European countries that the "cost" of one extremely annoyed person (1 NAI) is approximately 1600 € per year, then the cost of a moderately annoyed person (0.5 NAI) thus equals 800 € per year and so on [Decký, 2012].
- Navarud [2002] suggests using a damage function approach (DFA) to calculate the total welfare loss from environmental noise. As part of this approach, he advances exposure-response functions (ERF) to relate between decibel levels and levels of annoyance. Examples of the ERF approach to estimating the relationship between noise exposure (measured in day-night level (DNL) or an equivalent) include Miedema and Oudshoorn [2001], who fitted their model to data from noise annoyance studies for aircraft, road traffic, and railways separately, showing the annoyance level distribution at different levels of DNL for each mode.

The most common approach to estimating the value of noise reduction is the **hedonic price (HP) method.** HP analysis is a revealed-preference method where the real estate market is used as a proxy for the willingness to pay of individuals for a home where noise pollution is reduced. The main strength of the HP method is that it relies on actual behavior observed in the housing market. In the HP method, the following equation can be used to model the impact of noise on home value:

***V* = v(*N, Z*)**

where V is the value

N represents the value of one unit of noise

Z represents all other factors

If the values of N and Z can be distinguished regarding their respective effects on V, then the coefficient of N represents the value of one unit of noise in decibels, that is, how much people are willing to pay, in terms of property value, in order to eliminate it. By studying how property prices are affected by noise exposure, while at the same time as controlling for the effects from other attributes on the prices, researchers can determine property owner preferences for noise abatement. The "noise sensitivity depreciation index" (NSDI) has evolved as the standard measure of the WTP of this literature. This is a measure of the percentage change in the price as a result of a unit change in the noise level. Even so, it is likely that HP provides an upwardly biased estimate of the value of noise reduction alone since traffic noise is positively correlated with other disturbances [Bjørner, 2004].

4.2 Findings from Benefits Estimation Studies

While there have been some significant applications of HP analysis to traffic noise in the United States to measure WTP through NSDI, this work has not necessarily been applied towards calculating benefits of noise abatement projects. A scan of the literature showed that most attempts to explicitly value the benefit of traffic noise reduction occurred in Europe. Furthermore, U.S. research in this area has focused more on valuing air transportation noise abatement benefits rather than surface transportation.

Another consideration is which noise metric performs best. In some cases [Martin, 2006], multiple metrics were measured to allow flexibility with short averaging times (L_{eq}, L_{max}, L_{10}, L_{50}, L_{90}, L_{min}) and evaluated. In the study by Martin, most results used L_{dn}, which was reported to have a high degree of coincidence and related very well to annoyance. L_{max} also related fairly well and was a better indicator for average annoyance.

4.2.1 Valuing the Acoustic Impacts of Noise

A 2014 economic assessment in the Journal of American Medicine [Swinburn et. al, 2014] estimated that 46.2 percent of Americans (145.5 million people) were exposed to average noise levels (Ldn) of 58 dBA or greater, and 13.9 percent (43.8 million people) were exposed to 65 dBA Ldn or greater in 2013. Using an analysis of previous studies linking noise exposure to cardiovascular disease and hypertension, the assessment finds that a 5 dB noise level reduction scenario would reduce the prevalence of hypertension by 1.4 percent and coronary heart disease by 1.8 percent, at an estimated annual economic benefit of $3.9 billion.[10]

Since the 1980s, relatively few benefits estimation studies have been conducted in the United States for highway noise. Nelson's 1982 meta-analysis of nine existing HP studies in North America found a mean NSDI (also referred to as NDI) of 0.40 percent per dB. Using a formal meta-analysis, Bertrand [1997] compared 16 estimates from nine HP studies. His work suggests an NDI for traffic noise as high as 0.64 percent, a figure similar to the estimate provided in the Bateman study in England. Nelson's latest meta-analysis [2008], analyzing 25 studies from around the world, produced an unweighted mean value of 0.55 percent and a median value of 0.54 percent per dB for noise stemming from road traffic.

A study in San Diego County also noted that other variables must be considered in noise impacts on housing prices [Sklarz, 2018]. Of note in this study is that a general nonlinear trend began at approximately 45 dB with higher noise levels resulting in lower median home values. **FIGURE 11** shows this information [Sklarz, 2018].

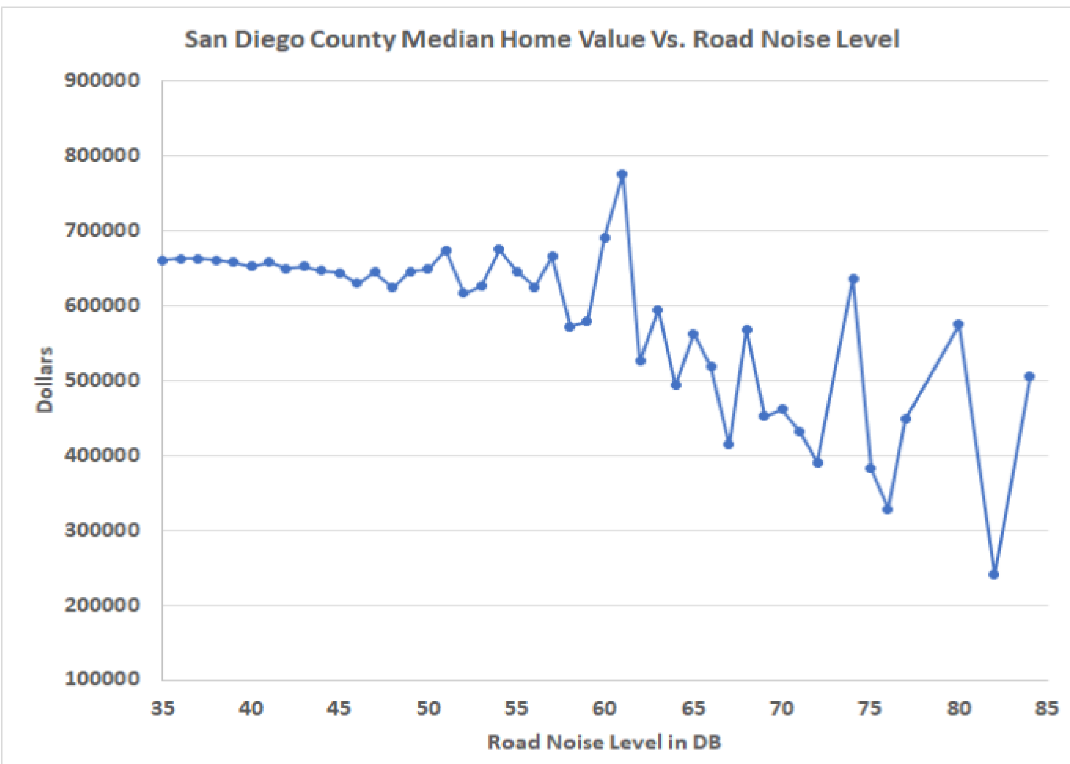

FIGURE 11. LINE GRAPH. NOISE LEVELS AND GENERAL HOME PRICES
Source: Sklarz, 2018

10 While this ostensibly seems like a large value, dividing $3.9 billion by 189.3 million affected people implies a somewhat modest annual benefit of about $21 per person. A project with a 20-year lifespan that benefited 100 people, or about 40 households, would therefore have to cost less than $40,000 to pay for itself in health benefits.

One of the most-cited studies in the literature is an HP analysis conducted by Bateman, et. al in 2004 in Birmingham, England. This study used real estate transactions data from over 10,000 properties while adding in hundreds of non-noise related characteristics (socioeconomic, locational, property) to form one of the most comprehensive datasets compiled in this area [Nellthorp, 2007]. This study reviewed noise from road, rail, and air traffic, although no significant relationship between airplane noise and property values was found.

The models revealed that a 1 dB(A) increase in road noise would reduce property prices by between 0.21 and 0.53 percent, depending on market segment (these market segments are characterized by income, ethnicity, family composition and property size). The rail noise estimates are larger in magnitude, indicating that on average a 1 dB(A) increase in rail noise will reduce property prices by 0.67 percent. These percentages represent the NSDI.

A weakness of simplified WTP models is that they produce a set of implicit prices, which only reflect the prevailing conditions in one market and its particular balance of supply and demand; this limits the efforts to broaden the applicability of any such study. Bateman's Birmingham model, however, adjusted for this by undertaking a second stage of analysis where demand curves for the value of quiet were estimated using multiple regression, controlling for household expenditure and other socioeconomic characteristics. Prices were converted into equivalent annual payments based on the empirical relationship that exists between rents and the purchase prices of houses. Mean values for road noise ranged from £31.49 per year for a 1 dB(A) reduction from a 56 dB(A) baseline to £88.76 per year for the same change from an 80 dB(A) baseline. A higher baseline of ambient traffic noise resulted in an increased willingness to pay for a 1dB(A) reduction. In fact, projecting the demand curve down below 55 dB(A) revealed marginal WTP to falls to zero at a noise level of 42.3 dB(A), meaning that households are unlikely to pay for any reduction in noise level when the baseline is at or below that figure.

Some efforts have been made to calculate WTP using both CV and HP models in the same study. Two Swiss studies [Pommerehne 1988, Soguel 1996] that combined a contingent valuation survey with a standard hedonic pricing real estate model found only slight differences in the WTP functions between the two models, with one showing a slightly higher value per reduced dB(A) of road traffic noise in the HP models, and the other showing the reverse, but each showing only marginal differences. However, a Danish study [Bjorner, 2006] using similar methodology found a much higher WTP in the HP model than from the CV survey results.

4.2.2 Valuing the Acoustic Benefits of Noise Abatement

Delucchi and Hsu [1998] created a model of the total external damage cost of noise emitted from motor vehicles in the United States, finding that the cost could range from as little as $100 million per year to approximately $5-10 billion per year. This study calculated noise costs in detail, for several different types of road and traffic conditions, in each of 377 urbanized areas and one aggregated rural area of the United States and accounted for noise reductions provided by sound barriers. While the study was not designed to explicitly calculate the value of noise abatement measures, their methodology for accounting for noise barrier impact on total value could theoretically be modified to explicitly determine noise attenuation benefits.

Nellthorp [2007] attempted to use the state-of-the-practice in HP and SP models and specifically apply it to valuing the benefits of projects that produce a noise reduction outcome. In Nellthorp, the UK Government uses the results from the Bateman study to produce a table of values for transport-related noise at different dB(A) interval levels. Nellthorp examined other studies from continental Europe and found that there was generally a rough consensus on the monetary valuation of noise, even across HP and SP studies. The *Harmonised European Approaches for Transport Costing* (HEATCO) value table for transportation-related noise [Bickel, 2006] is commonly used for continental European studies in this area. However, it is important to note that most of these studies are based on residential properties only. **TABLE 4** shows a sample of European values for noise cost estimation from the HEATCO [Odgaard, 2005] project assessment and from Nellthorp [2007] which shows that valuation can depend on context and location. **TABLE 5** shows the same values converted in to 2020 U.S. dollars.

Predictions of household noise exposure from two future years (usually 15 years apart) and data for with- and without-project scenarios are needed (along with a social discount rate) to use the WTP estimates in the table above to calculate a total net benefit for an abatement project. The present value of benefits (PVB) can be calculated using the schedule for projected value of noise over time, which assumes a time-series elasticity for the value of transport noise in income per household.

Nellthorp gives the example of the A3 Hindhead Improvement, a £240 million highway project that would remove a bottleneck on England's A3 trunk road. The project includes a tunnel that is currently divided by the road. Under the project, this section of the road would be returned to nature. Noise effects on households would result from changing the alignment of the road and from the new patterns of traffic movement and speed. Nellthorp used the UK standard to calculate WTP for 772 households in the affected area, finding a net benefit in 2012 of £43,925 for all households. After applying the expected growth rate over 15 years and social discount rate, a PVB of £1.16 million was found. Nellthorp's work demonstrates that WTP models can be used to calculate an estimate of the monetary benefits of real noise abatement projects.

One variant of HP analysis that has been used to estimate the economic value of a noise abatement project is the repeated-sales method, as used by Wilhelmsson [2005] in his study of noise abatement projects in Stockholm. In this approach, benefits are estimated by analyzing prices of houses that have been sold more than once. This method seeks to address the problem of large variations in quality among houses present in HP analysis. The price difference between the first and second sale is then compared to price changes in the overall housing

TABLE 4. NOISE COSTS PER DECIBEL (DB) PER PERSON AND YEAR (ROAD AND RAIL)

Country	Differentiation	Unit	Year	Any	>45 db(A)	>50 db(A)	>55 db(A)	>60 db(A)	>65 db(A)	>70 db(A)	>75 db(A)	>80 db(A)
Austria	Only road noise	Euro	1997	44								
Germany	Noise exposure in built-up areas	Euro	1998	55								
Sweden	Only road noise	Swedish Kronor (SEK)	2001			51	810	1,750	3,020	6,780	16,220	
Switzerland	Annoyance in dwellings	Swiss Franc (CHF)	2000	800								
Hungary	Annoyance from road noise	Hungarian Forint (HUF)	2002	8,000								
United Kingdom	Annoyance from road noise	British Pound Sterling (GBP)	2002		5.8	11.4	17.0	22.6	28.1	33.7	39.3	41.5

Source: Odgaard [2005]; U.K. from Nellthorp (2007)

TABLE 5. NOISE COSTS PER DECIBEL (DB) PER PERSON AND YEAR (ROAD AND RAIL), CONVERTED TO 2020 U.S. DOLLARS ($)

Country	Differentiation	Year	Any	>45 dB(A)	>50 dB(A)	>55 dB(A)	>60 dB(A)	>65 dB(A)	>70 dB(A)	>75 dB(A)	>80 dB(A)
Austria	Only road noise	1997	$77								
Germany	Noise exposure in built-up areas	1998	$94								
Sweden	Only road noise	2001			$8	$121	$261	$450	$1,011	$2,419	
Switzerland	Annoyance in dwellings	2000	$955								
Hungary	Annoyance from road noise	2002	$51								
United Kingdom	Annoyance from road noise	2002		$11	$22	$33	$44	$55	$66	$77	$81

Note: Converted at exchange rates and inflation as of November 2020.

market. Using a regression model (controlling for other price effects like house quality), a dummy variable can isolate the impact of a noise barrier. Applying his model to a Stockholm suburb where a noise barrier was built along a roadway in a suburban area, Wilhelmsson estimates that the construction of a noise barrier caused a 6 percent average increase in home value after the second sale. This study also finds that homes closer to the road had a greater increase in value post-abatement, an increase of 0.05 percent per meter for every meter by which distance from the road is less than 300 meters. Wilhelmsson then uses his findings to determine whether the project was economically justified by calculating the benefit value in housing price per each meter of noise barrier and comparing it to the per meter cost of construction.

As noted at the beginning of this section, cost of illness-based approaches have not gained much traction in the valuation of noise abatement, as HP and CV models have been emphasized. However, Andersson [2013] contends that most WTP studies do not capture the total social cost of noise exposure and attempted to integrate health impacts by adding in a health cost component to their model. Their study uses an "impact pathway approach" to estimate the value of health costs and add it to a WTP equation. This approach analyzes each emission source, estimates its distribution, and then estimates the final effects of emission. In this particular study, the authors used health effects of road traffic noise in a Swedish study which estimated a linear cost function between 70 and 80 dB. This function is modified to produce an equation to estimate marginal health cost at a given dB level, which can be added to the general WTP equation. The study concluded that the health cost component had a "small but not negligible" impact on overall WTP.

Even the price of abatement is not always straightforward and is project-dependent. This makes general analysis to provide guidance difficult. A National Cooperative Highway Research Program (NCHRP) project examining strategies other than barriers [Rochat 2020] overcame this problem by avoiding State absolute values and instead providing ranges. For example, truck restrictions may reduce maximum noise levels for a relatively small cost while a change in horizontal or vertical alignment is much more costly. This could lead to analysis problems if conflicts arise that are not solvable, but it does allow one to draw general conclusions.

4.2.3 Valuing Other Benefits of Noise Abatement

One thorny issue in analyzing the value of noise abatements is disentangling indirect benefits. For example, green walls and green roofs have been built as a way to decrease the intrusion of traffic noise, but these tools can also offer significant aesthetic value as well. Veisten, et. al. [2012] studied the value of green soundscape measures to determine the value of noise attenuation and "non-acoustic amenity effects" separately. They assessed a theoretical case where a green façade is applied to the front of an apartment building facing a busy road. Veisten uses the HEATCO value of 10.095 € per person per dB(A) per year, while using a value for aesthetic and other amenity effects from a meta-analysis of greenscaping studies. In their case, the authors found the amenity benefits to be over 10 times higher than the acoustic benefits. One drawback of their approach is that it simply assumes that “noise impacts are omitted from the reviewed amenity valuation of green roofs/walls, such that [one] can simply add the aesthetic/amenity valuation to the dB-change valuation,” which does not fully account for the potential overlap of amenity and acoustic benefits. However, the Veisten method marks one of the few examples of an attempt to account for both acoustic and non-acoustic benefits of noise abatement in the literature.

5 Summary of Benefits and Negative Externalities of Noise Abatement

In **Section 3**, this report presented information on the benefits and negative impacts of abatement measures, while **Section 4** noted that a benefit/cost approach requires an understanding of the various benefits and impacts of the measure, how these can be valued, and how they depend upon the project and its context. This section provides a summary of the findings for each abatement measure on noise reduction; the other types of benefits and impacts of the measure, and the extent to which these can be quantified and monetized; and the general costs of the various measures considered.

5.1 Noise Reduction Benefits

The primary purpose of any noise abatement measure is to reduce noise. **Figure 12** shows the various abatement measures[11] and the benefits of noise reduction. This figure does not list non-acoustic or other incidental benefits from the abatement measures. The absolute value of the benefits varies with the amount of noise reduction.

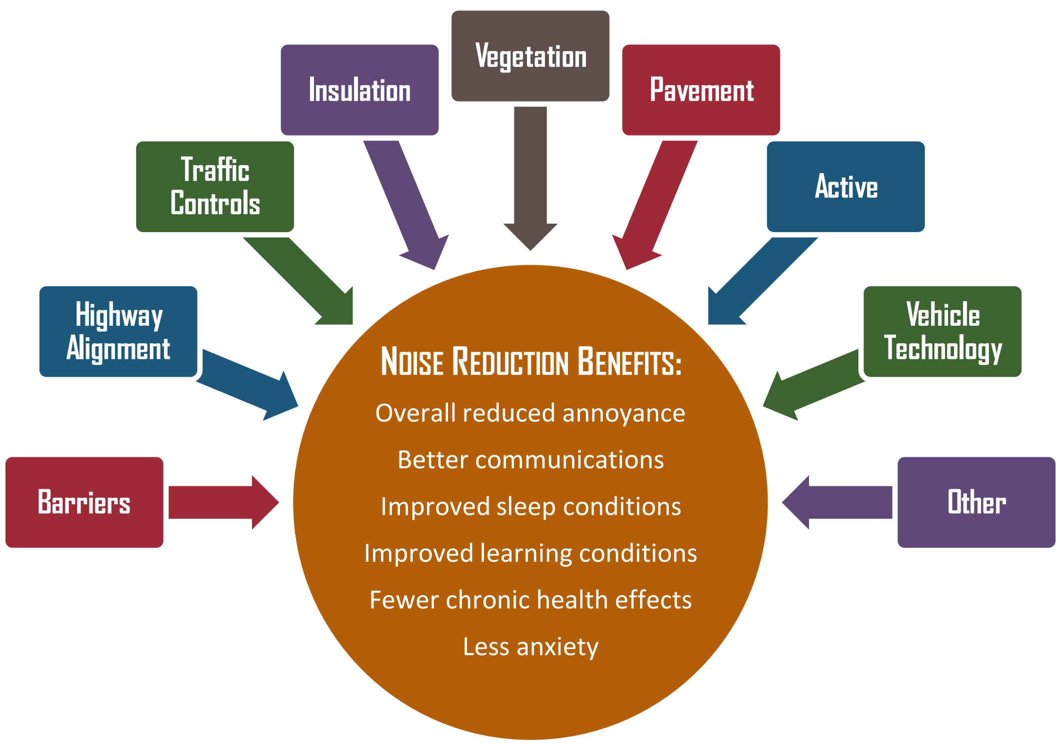

Figure 12. Diagram. Types of Noise Abatement Measures Applicable to Highway Noise
Source: Federal Highway Administration

[11] Highway alignment also includes greenbelts and acquisition of real property to serve as buffer zones.

This report identifies trends among the noise reduction literature. **TABLE 6** conveys the maximum and in-practice practical limits of noise reduction for each measure, and identifies situations which may limit the effectiveness of the meaure, or generate adverse noise impacts.

TABLE 6. NOISE REDUCTION EXPECTED FROM DIFFERENT ABATEMENT MEASURES; DECIBEL(A)

Abatement Measure	Maximum Practical Reduction	In Practice Reduction	Limitations for Noise Mitigation
Barrier	20	7[1]	• May result in increased reflected noise to some receptors
Alignment	4 - 10[2]	4 - 5	• May result in increased noise in other areas • Use of structures presents new problems with structure noise
Traffic Control	4	2	• For lower speed traffic the sound may become more erratic casuing greater annoyance • Rerouting traffic may result in increased noise in other areas causing impacts in a different area
Insulation	20	7 - 10	• Only provides indoor noise reduction • May not control low frequency noise well
Vegetation/ Ground Cover	8	3	• May be seasonal • May take long periods before growth is sufficient to produce meaningful noise reductions • Can increase high frequency noise in some conditions
Pavement	13	3 - 9[3]	• Effectiveness may degrade over time
Active Noise Control	10[4]		• Not proven in outdoor environments
Vehicle Technology	6[5]	1 - 2[6]	• May result in different noise sources or tones that could be annoying • Only valid in low speed situations
Other	3[7] - 7[8]	3	• Measure-specific

[1] *U.S. average for installed barriers, all benefitted receivers behind barrier*

[2] *Maximum value is for depressed roadways, lower value is for other alignment changes*

[3] *Actual reduction depends on pavement texture being replaced*

[4] *Indoor reduction only for small frequency ranges*

[5] *Low speed conditions with 100% replacement of ICEs*

[6] *Most probable application of EV replacement for buses*

[7] *Estimate of measures such as zoning changes*

[8] *Alterations of rumble strips*

Two conclusions are readily apparent from this table: First, for outdoor noise control, barriers provide the most attenuation. Second, using a value of 5 dB(A) as the minimum desired reduction and considering practical limits only barriers, alignment/traffic control, insulation, and tire/pavement measures would provide enough abatement. This is not to say the other abatement measures should not be used. Instead, in general, these four abatement measures result in readily apparent reductions and to receive this degree of abatement from the other measures would require more extreme applications, or application in combination with some other abatement measure(s).

5.2 Other Benefits

While all abatement measures supply noise reduction benefits, some offer additional benefits, such as air quality improvements, or negative impacts, such as loss of visibility. **TABLE 7** lists some of the other benefits and identifies the extent to which information is available to quantify and monetize these benefits.

TABLE 7. ADDITIONAL BENEFITS EXPECTED FROM DIFFERENT ABATEMENT MEASURES

Abatement Measure	Benefit in Addition to Acoustic Benefits	Can Benefits be Quantified and Monetized?
Barrier	• Ability to use structure for other purposes • Neighborhood recognition • Privacy • Air pollution—In some meteorological cases causes a reduction in pollutant concentrations on the residential side of the barrier • Reduced roadkill	• Ancillary use of structure could be quantified through cost savings for light and signage poles, etc. • Impacts on human environment might be reflected in property value studies but will be impossible to disentangle from noise benefits • Air pollution health benefits could be monetized based on dispersion and exposure modeling, but this would be resource intensive • A value could potentially be assigned to wildlife impacts based on insurance claims for animal strike damage[1]

Abatement Measure	Benefit in Addition to Acoustic Benefits	Can Benefits be Quantified and Monetized?
Alignment	• Alignment changes may reduce crash rates and may result in lower emissions or pollutant exposure • Greenbelts can form pleasing areas and habitats for desired species	• If crash risk decrease can be quantified, it can be valued based on standard crash costs • Emissions changes can be valued based on $/kg of pollutant emitted • Air pollution health benefits could be monetized based on dispersion and exposure modeling, but this would be resource intensive • Insufficient data to value greenbelt or wildlife impacts
Traffic Controls	• Speed reductions may reduce crash rates and may result in lower emissions	• If crash risk decrease can be quantified, it can be valued based on standard crash costs • Emissions changes can be valued based on $/kg of pollutant emitted
Insulation	• Less energy loss from homes • Allows construction in high-noise zones	• If energy savings can be quantified, they can be monetized based on energy costs • The added value from allowing and protecting noise-sensitive uses in high noise zones is difficult to assess
Vegetation/ Ground Cover	• Aesthetically pleasing • Privacy • Better sense of well-being • Animal habitats • Mitigation of heating and air pollution • Water runoff and flood management	• Tools exist to quantify the benefits of urban trees. Benefits that can be quantified and monetized include water runoff, reduced heating and cooling loads, air pollutant removal, and carbon storage and sequestration • There is limited data to quantify the aesthetic or habitat benefits of vegetation[2]
Pavement	• For open-graded pavements less splash/ spray	• Difficult to value
Active Noise Control	• None identified	• N/A

Abatement Measure	Benefit in Addition to Acoustic Benefits	Can Benefits be Quantified and Monetized?
Vehicle Technology	• Decrease in emissions	• Emissions changes can be valued based on $/kg of pollutant emitted
Other	• Potential addition of pleasing sounds (masking) • Other measure-specific benefits	• Measure-specific

[1] *While there is literature on valuing ecosystem services (i.e., the economic value provided by an entire ecosystem), there is no accepted approach to putting a dollar value on an individual animal death.*

[2] *Some studies have quantified the value of access to greenspace, but these have generally been based on access to urban parks rather than just individual trees or small vegetated areas. While well-managed vegetated areas in highway rights-of-way can support biodiverse habitats [O'Sullivan, 2017], it is unclear how effective highway-side habitats can be in general at supporting biodiversity since there is also some evidence that they are associated with invasive species [Trammell, 2011]. Habitat/biodiversity benefits would be site-specific and lack an accepted monetization procedure.*

As previously discussed, many of the abatement measures can be used in conjunction with others. This can improve overall noise control and if implemented with careful planning can provide more of the benefits shown in **Table 7**.

5.3 Negative Impacts

Table 8 includes a listing of negative impacts (with the exception of cost), as well as an assessment of the extent to which these impacts might be valued and monetized.

Table 8. Additional Negative Impacts Expected from Different Abatement Measures

Abatement Measure	Negative Impacts for Different Noise Reduction Strategies	Can Impacts be Quantified and Monetized?
Barrier	• Loss of sunlight • Loss of air circulation • Visual impacts • Increased maintenance • Loss of sightlines to businesses • Restricted access • Increased air pollution on roadway side of barrier • In some meteorological cases causes increased air pollution at homes	• Impacts on human environment might be reflected in property value studies but will be impossible to disentangle from noise benefits • If sightline to a business were blocked, economic impact could be estimated based on methods of valuing pass-by traffic • Air pollution health benefits could be monetized based on dispersion

Abatement Measure	Negative Impacts for Different Noise Reduction Strategies	Can Impacts be Quantified and Monetized?
	• Impacts on wildlife movements (limiting range or access to preferred habitat) • Bird kills from transparent barriers	and exposure modeling, but this would be resource intensive • Insufficient data to quantify and value wildlife impacts
Alignment	• New alignment or structure may cause visual or connectivity impacts on community	• Insufficient data to value
Traffic Control	• Reduced speeds and/or vehicle restrictions will increase travel time and may lead to complaints • Some calming devices may cause trouble with some vehicle movements	• Travel time changes can be quantified based on traffic volumes and standard values of time
Insulation	• May result in not having natural ventilation • Could cause space restrictions in buildings	• Any space reductions could be valued based on lease costs per square foot • Loss of natural ventilation difficult to value
Vegetation/ Ground Cover	• May attract unwanted wildlife or invasive species • Can increase high frequency noise in some conditions	• Insufficient data to value wildlife/ habitat impacts
Pavement	• May have safety considerations • May increase in-vehicle noise • May require new construction techniques that contractors are unfamiliar with, more material control is required • Plugging and freeze/thaw cycles may result in increased maintenance	• If crash risk increase can be quantified, it can be valued based on standard crash costs • Costs of new construction techniques or increased maintenance could be quantified
Active Noise Control[1]	• Insufficient data on negative impacts	• Insufficient data on negative impacts
Vehicle Technology	• Current-generation electric vehicles may have performance limitations	• May be valued through consumer preference models

Abatement Measure	Negative Impacts for Different Noise Reduction Strategies	Can Impacts be Quantified and Monetized?
	(range or cargo capacity) compared to conventional vehicles	
Other[2]	• Masking noise may actually increase overall sound levels	• Measure-specific

[1] *Technology has not been proven in outdoor areas*
[2] *Relies on innovation; due to infrequent use the technologies are not fully proven as effective*

5.4 Costs

This document does not attempt to include all possible cost differences but presents general cost ranges for each mitigation measure. The specific cost will depend upon the detail of the application. For example, different materials can result in different costs for the same length and height of barrier. In some cases, the purchase of additional right-of-way is needed, resulting in more costs. Different measures may also have different relative capital, maintenance, and life cycle costs. **Table 9** lists the relative cost of abatement for general decision-making as described in Rochat [2020].

Table 9. General Costs Ranking for Abatement Installation[1]

Abatement Measure	Measure Detail	General Cost Ranking
Barrier	Berms	$ Moderate
	Berms and additional ROW	$ Moderate (suburb) to $ Elevated (urban)
	Absorptive treatment	$ Average
	Low barriers	$ Average
	Tall barriers	$ Elevated
	Green barriers	$ Elevated
Alignment	Horizontal	$ Average to $ Elevated
	Vertical alignment change (major)	$ Elevated to $ High
	Vertical alignment change (minor)	$ Moderate
Traffic Control	Traffic controls	$ Low
		$ Moderate
	Speed changes	$ Low
	Vehicle restrictions	$ Low
Insulation	Windows	$ Moderate to $ Elevated[2]

Abatement Measure	Measure Detail	General Cost Ranking
	In-wall insulation	$ Moderate to $ Elevated
Vegetation/Ground Cover	Changes to surface or in-ground treatments	$ Low to $ Moderate
	Vegetation green belts with ROW	$ Moderate (suburb) to $ Average (urban)
	Large green belts	$ Elevated (suburb) to $ High (urban)
Pavement[3]	Diamond grinding	$ Low to $ Moderate
	Thin overlays Open grade asphalt concrete Rubberized asphalt	$ Moderate
Active Noise Control	Electronic equipment	$ Moderate to $ Elevated
Vehicle Technology	Change to electric vehicles	$ Elevated
Other	Rumble strip sinusoidal change	$ Low
	Masking	N/A
	Zoning changes	N/A

[1] *The following rating scheme was used in the table for the "general cost ranking" with all cost relative to other abatement costs:*

- *$ Low—Represents a low expenditure as compared to other abatement (less than $100,000 per mile)*
- *$ Moderate—Below the average cost of abatement (around $100,000 to $1 million per mile)*
- *$ Average—Near the average cost of abatement (around $1 to 2 million per mile)*
- *$ Elevated—Above average cost of abatement (around $3 to 5 million per mile)*
- *$ High—At the high end of cost for abatement ($5 to 10 million per mile or more)*

[2] *Cost rankings for treatments applied to receptor locations rather than to the highway will vary depending upon the density of receptors, with higher cost rankings for a higher density of receptors. For example, for 50 treated residential structures per mile of road at a cost of $10,000 per structure the total cost will be $500,000 ($ Moderate). For 500 residential structures per mile the cost for the same treatment would be $5 million ($ Elevated).*

[3] *Time period between overlays assumed >7 years.*

The use of more than one abatement measure can often be synergistic and reduce costs. For example, combining low noise pavement and shorter barriers could reduce the overall costs.

The abatement costs presented in **TABLE 9** are a simple approach but only part of a meaningful cost analysis. Accordingly, **SECTION 6** is dedicated to describing a potential noise valuation framework that is based on benefit/cost analysis.

6 Options for a Noise Valuation Framework

Data exist to support a basic benefit/cost framework for noise abatement methods. Studies from the United States and Europe have identified a general range of the monetary values of noise reduction per dB, mainly as revealed through hedonic price studies of property values. This value varies with the baseline noise level, with the benefit of noise reduction increasing at higher starting noise levels. Research supports the establishment of standard monetary benefits of a given noise change per person affected, and researchers and practitioners have applied these values to estimate the costs versus benefits of noise abatement projects in European countries.

The noise abatement benefits of any measure could be quantified using this approach as long as the noise reduction due to the measure can be estimated across the receptor population. This literature review has also established that noise reduction estimates exist for a range of measures, including noise barriers, highway alignment and traffic controls, insulation, vegetation, and pavements. The actual level of reduction achieved will depend upon measure and context-specific characteristics such as barrier design or the type of vegetation or pavement.

The literature review identified a variety of other benefits and negative impacts associated with mitigation measures. Some are easier to quantify than others. For example, methods exist for valuing speed changes based on the value of travel time. Impacts such as the aesthetic benefits of vegetation or the negative impacts of noise walls are more difficult to quantify. These other considerations could be included or excluded from the benefit/cost analysis based on the availability of supporting data. It is likely that these considerations are reflected to some degree in existing valuations; for example, studies of the property value impacts of noise barriers are likely influenced not only by noise but also by aesthetic considerations. It is difficult to disentangle these effects.

An approach to BCA for noise mitigation measures in project analysis could therefore be as follows:

1. Define the potential noise abatement measures that could be applied for the project.
2. Identify the receptor population and measure baseline noise levels for the population in the affected project area.
3. Estimate the expected noise reductions from each measure (based on literature specific to that measure).

4. Apply standard values of noise reduction ($ per dB) multiplied by the receptor population to obtain a total dollar value of benefit.
5. Identify other benefits and negative impacts for the proposed measure(s) in the specific project context. Identify any that can be quantified/monetized and assess these. Provide a qualitative assessment of other benefits and impacts.
6. Estimate the costs of the proposed noise abatement measure(s) for the specific project, including maintenance and operations as well as capital costs. At a planning level, this could be done based on average or typical costs for the abatement measure.
7. Compare benefits and costs for each measure being evaluated, as measured through a benefit/cost ratio and/or net present value.

A framework that could be applied to project-level analysis would outline, explain, and illustrate the above steps, and provide the following additional supporting information which would be based on this review:

- Typical ranges of decibel reductions for various noise abatement measures.
- Standard values of noise reduction (e.g., $ per dB per person, based on the starting noise level) and a description of how to apply them to specific project situations.
- An enumeration of the various other benefits and impacts of each type of abatement measure.
- Information to assist in quantifying and monetizing these other benefits and impacts, to the extent such information has been identified.
- Ranges of cost estimates that might be expected for noise abatement measures for planning-level assessment, before a detailed engineering study is performed.
- Guidance on appropriate benefit/cost thresholds when using Federal funds for noise abatement.
- References to tools or real-world results that could be used to support quantification of any project or program-specific measures.

FHWA might also consider developing additional supporting tools and data. For example, this might include:

- Expanded consideration of abatement measures in the Traffic Noise Model, to the degree supported and warranted.
- Developing sample benefit/cost calculations for hypothetical project abatement measures illustrating the magnitude of various benefits and impacts and which ones are

most important and/or uncertain. This would help States decide where to focus their efforts on refining data used in the benefit/cost assessment for a measure.

- To avoid the need for a BCA for every project undertaken (especially for smaller projects, which might not warrant a large-scale analysis effort), FHWA could provide a threshold dollar value per receptor benefited. This threshold might vary depending upon the effectiveness of the abatement measure being considered.

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APPENDIX A

Acoustical Terms and Symbols

A-weighted sound level, decibal (dB)(A) or L_A: Sometimes referred to as A-weighted noise level, is the response adjustment by a sound level analyzer to the overall at different frequencies in such a way as to mimic the human response to sounds.

Absorption: The changing of sound energy to heat energy.

Absorption Coefficient: The dimensionless ratio of absorbed to incident sound energy from a single interaction between a sound wave and a surface. Values range from 0 to 1.

C-weighting dB(C): C-weighting is the weighting network used by a sound level to adjust the overall sound level to better represent the effect of low-frequency sounds on the human ear and differs most from A-weighting below 1 kilohertz (kHz).

Community Noise Equivalent Level (L_{den}): A 24-hour, A-weighted average sound level for a given day, after addition of 5 dB to sound levels between the evening hours of 1900 (7:00 p.m.) and 2200 (10:00 p.m.) ("penalty" in addition of 10 dB to nighttime sound levels between the hours of 2200 (10:00 p.m.) and 0700 (7:00 a.m.) It is also known as the "day-evening-night level."

Day-night sound level (L_{dn}): The 24-hour equivalent sound level, in decibels, obtained after addition of 10 decibels to sound levels in the night from midnight up to 7:00 a.m. and from 10:00 p.m. to midnight (0000 up to 0700 and 2200 up to 2400 hours).

Decibel (dB): One-tenth the ratio of a logarithm of two powers. The human ear responds logarithmically to sound and this unit of measure is a convenience for that response. The reference pressure for acoustics is most often 20 µPa.

Diffraction: The act of sound waves traveling around obstacles or cohomogeneity in the propagation medium causing the wave front to change.

Diffusion: The act of sound waves spreading out over a wide area after reflecting off an uneven surface.

Divergence: Often referred to as geometric spreading and is the reduction in sound energy due to sound energy being distributed geometrically over greater distances for the source.

Equivalent sound level (L_{eq}): The logarithm of the ratio of a given time-mean-square, standard-frequency-weighted, sound pressure for a stated time period, to the square of the reference sound pressure of 20 µPa.

Frequency: The rate of change with time of the instantaneous phase of a sine function divided by 2π, with dimensions of cycles per second or hertz (Hz).

Ground attenuation: The change in sound level—either positive or negative—due to intervening ground between the source and receiver. Ground attenuation is a function of ground characteristics, source-to-receiver geometry, and the spectral characteristics of the source. Surfaces are often referred to as acoustically soft (greater attenuation) or hard.

Ground impedance: A frequency related function of the sound transmission characteristics of a ground surface type.

Helmholtz resonator: A reactive, tuned, sound absorber (i.e., a perforated cover or slats at the entrance to a cavity).

Hertz (Hz): A unit of frequency. One Hz is equal to one cycle per second. The unit was named to honor Heinrich Hertz.

Hourly equivalent sound level: Equivalent sound level, in decibels, over a one-hour time period.

Impedance (acoustic): The ability of a medium to restrict the flow of acoustic energy, related to the cross sectional area of the propagation path.

Impulse sound level: A very short, transient, sound, measured at 35 milliseconds (ms) on a sound level meter.

Insertion loss: Insertion loss is the difference in levels with and without a barrier. It varies from just barrier attenuation due to geometries, ground cover changes, and other parameters.

Maximum sound pressure level: In decibels, the exponential-time-average sound level obtained with a squared pressure time constant of 35 ms.

Noise: Unwanted sound.

Noise level: Same as sound level, for sound in air. Some people use "noise" only for sound that is undesirable.

Octave: In acoustics, one tone is an octave above another if its frequency is twice that of the other. Mathematically, two tones are an octave apart if the ratio of the frequencies of the tones is two to the first power. Two octaves are represented by a ratio of two to the second power, and so forth. Human response to pitch is approximately logarithmic. Ten octave bands cover the audible range for humans.

One-third octave (⅓-octave): One-third of an octave, or two raised to the one-third power (26 percent). Allows subdivision in smaller frequency bands in order to better understand the nature of noises.

Octave band: A band of frequencies $^1/_1$ or ⅓ octave wide, identified by the geometric mean frequency of the band.

Octave band level: The $^1/_1$ octave band center frequencies in the audible range are 31.5, 63, 125, 250, 500, 1,000, 2,000, 4,000, 8,000 and 16,000 Hz.

One-third octave band format: The ⅓ octave band center frequencies in the audible range are 25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, l.0k, 1.25k, 1.6k, 2.0k, 2.5k, 3.15k, 4.0k, 5.0k, 6.3k, 8.0k, 10.0k, 12.5k, 16.0k, and 20.0k Hz.

Reflection: Sound waves, impinging on surfaces that are large compared to the wavelength, will change direction where the angle of incidence is equal to the angle of reflection.

Refraction: The act of sound waves bending or changing propagation direction due to changes in medium or medium condition.

Reverberation: The trailing off of sound in an enclosed area due to multiple reflections from the boundaries.

Sound exposure: Time integral of squared, A-frequency-weighted sound pressure over a stated time interval or event. The exponent of sound pressure and the frequency weighting may be otherwise if clearly so specified.

Sound exposure level (SEL): The level of sound accumulated over a given time period or event. It is particularly appropriate for a discrete event such as the passage of an airplane, a railroad train, or a truck. Sound exposure level is not an average, but a kind of sum. In contrast to equivalent sound level, which may tend to stay relatively constant even though the sound fluctuates, sound exposure level in decibels is the time integral of A-weighted squared sound pressure over a stated time or event, with reference to the square of the standard reference pressure of 20 micro-pascals and reference duration of one second.

Sound intensity: Sound intensity is the average rate of sound energy transmitted in a specified direction at a point through a unit area normal to this direction at the point considered.

Sound level: In decibels, 20 times the common logarithm of the ratio of a sound pressure to the references sound pressure of 20 micro-pascals (0.0002 micro-bar). The frequency bandwidth must be identified.

Sound pressure: Sound pressure level is 10 times the base-10 logarithm of the ratio of the square of p_{rms} (root mean square pressure) signal, to the square of the reference sound pressure of 20 µPa.

Sound pressure level: In decibels, 20 times the common logarithm of the ratio of a vibratory acceleration to the reference acceleration of 10 micrometers per second squared (nearly one millionth of the standard acceleration of free fall). The frequency bandwidth must be identified.

Sound Transmission Class (STC): The Sound Transmission Class is an integer rating of how well a building partition attenuates airborne sound. In the U.S., it is widely used to rate interior partitions, ceilings, floors, doors, windows and exterior wall configurations. The STC rating very roughly reflects the decibel reduction of noise that a partition can provide and is useful for evaluating annoyance due to speech sounds.

Statistical sound levels (L_{xx}): The sound level that is exceed xx percent of the time. For example, L_{10} is exceeded 10 percent of the time. This holds for other levels as well such as L_{50} (exceeded 50 percent of the time) and L_{90} (exceeded 90 percent of the time).

Tone: The auditory sensation of a pitch.

Tortuosity: A measure of the geometric complexity of a porous medium. In acoustics it is used to describe sound propagation in porous media.

Wavelength: The distance between successive repeating portions of a pure tone sound wave.

Weighting: Adjustment of sound level analyzer response to achieve a desired measurement. For example, A-weighting is used to simulate human auditory response to sound and indicated as L_A or dB(A). Another weighting scheme in common use is C-weighting (L_C or dB(C)) to emphasize lower frequencies.

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