U.S. Department of Transportation
Federal Highway Administration

Quantifying the Benefits of Noise Abatement Measures

PART 2: EVALUATION FRAMEWORK

FHWA-HEP-24-003 | July 2023
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Notice

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Executive Summary

This report provides a framework for quantifying the benefits and costs of noise abatement measures for transportation projects. This framework is Part 2; Part 1[1] is a literature review and synthesis report documenting existing research on the various benefits and impacts of noise abatement measures and how those benefits and impacts can be quantified, monetized, and considered in benefit/cost analysis (**BCA**). This report builds on that work by providing a framework that State and local transportation agencies can apply when evaluating noise abatement measures.

BCA is a systematic process for calculating and comparing benefits and costs of a project to: 1) determine if it is a sound investment; and 2) see how it compares with alternate projects. **BCA** attempts to quantify as many benefits and impacts as possible in monetary units so they can be compared "apples to apples." To the extent that the benefits of noise reduction can be monetized, noise can be included in a **BCA** along with other monetizable benefits and costs of transportation projects, such as travel time savings, crash reduction, and emission reductions.

A process for applying **BCA** to noise abatement measures can be described in seven steps, as illustrated in **FIGURE 1**.

1. Identify the receptor population and estimate baseline noise levels for the population in the affected project area.
2. Define the potential noise abatement measures that could be applied for the project.
    a. Estimate the expected noise reductions from each measure and apply values of noise reduction multiplied by the receptor population to obtain a total dollar value of benefit.
    b. 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.
    c. Estimate the costs of the proposed noise abatement measure(s) for the specific project, including maintenance and operations as well as capital costs.
3. Compare benefits and costs for each measure being evaluated, as measured through a benefit/cost ratio (**BCR**) and/or net present value (**NPV**).
4. Provide a narrative that includes: 1) key data sources, assumptions, and uncertainties in the **BCA**; 2) a qualitative assessment of other benefits and impacts that cannot be monetized; and 3) an assessment of any equity-related considerations in the **BCA** methods and results.

[1] Federal Highway Administration (2022). Literature Review and Synthesis - Quantifying the Benefits of Noise Abatement Measures (Part 1) - FHWA-HEP-24-002

The framework report concludes with an example in which the benefits and costs of noise abatement measures are evaluated for a hypothetical project.

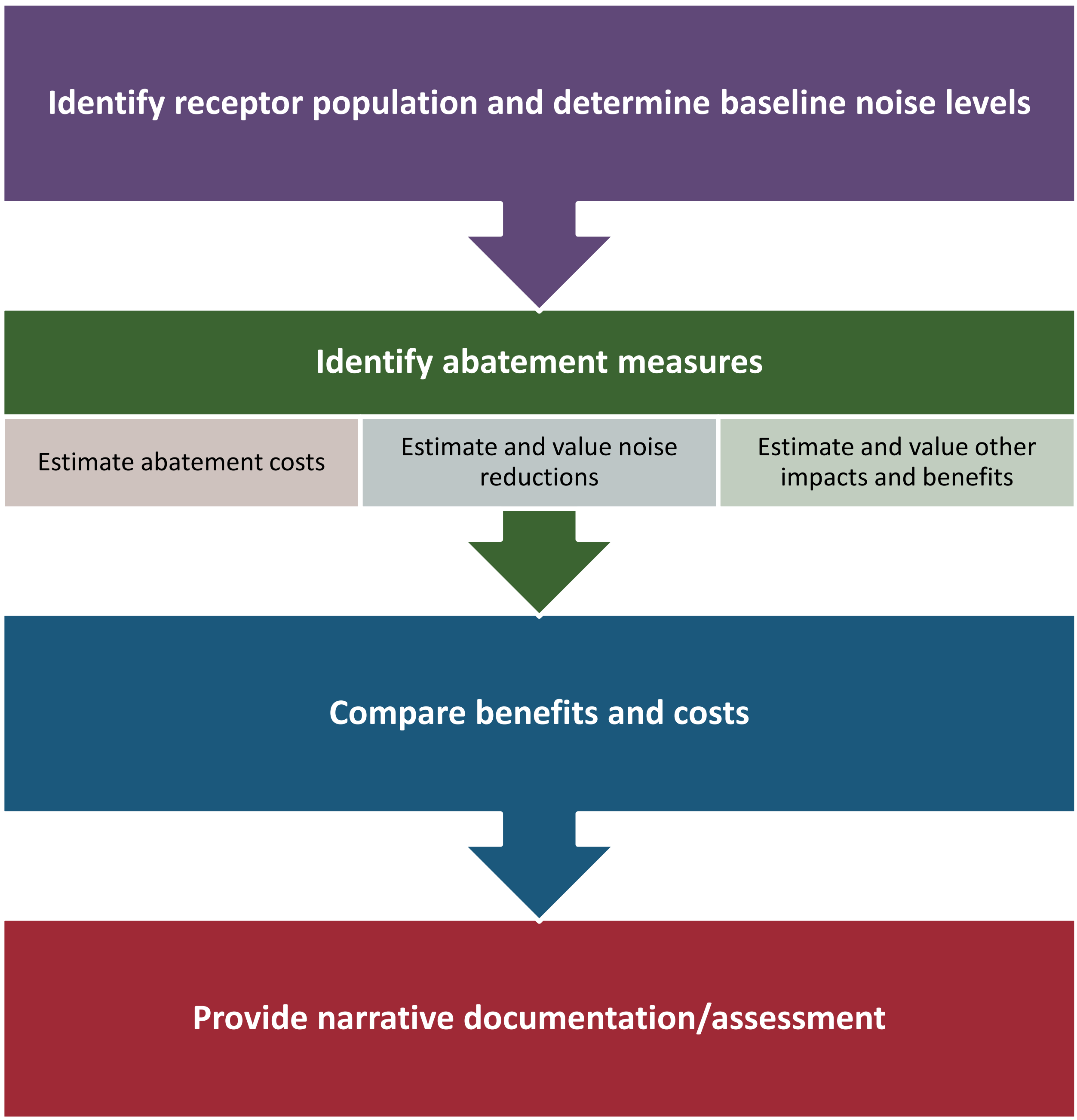

FIGURE 1. FLOWCHART. PROCESS FOR APPLYING BENEFIT-COST ANALYSIS TO NOISE ABATEMENT MEASURES

Source: Federal Highway Administration

Acronyms and Abbreviations

BCA	Benefit/Cost Analysis
BCR	Benefit/Cost Ratio
CFR	Code of Federal Regulations
dB	decibel
dB(A)	decibel A-weighted sound level
DOT	Department of Transportation
FHWA	Federal Highway Administration
mph	Miles per Hour
NPV	Net Present Value
NCHRP	National Cooperative Highway Research Program
O&M	Operating and Maintenance
ROW	Right-of-Way
TNM	Traffic Noise Model
USDOT	U.S. Department of Transportation

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I. INTRODUCTION

This report provides a framework for quantifying the benefits and costs of noise[2] abatement measures for transportation projects. Noise abatement measures, especially noise barriers, are ubiquitous along the Nation's highways, many of which are federally funded. However, in the past there has been little research or guidance to assist agencies in considering and weighing the benefits of noise abatement measures against their costs.

This framework is Part 2 of this research. Part 1[3] is a literature review and synthesis report documenting existing research on the various benefits and impacts of noise abatement measures and how those benefits and impacts can be quantified, monetized, and considered in benefit-cost analysis (BCA). This report builds on that work by providing a framework that State and local transportation agencies can apply when evaluating noise abatement measures. The Part 1 Report and this Part 2 Framework provide information on most practical noise abatement methods, including those listed in 23 Code of Federal Regulations 772 (23 CFR 772).

This framework report includes:

- An overview of the benefits and costs of transportation noise mitigation.
- A seven-step framework for a BCA of transportation noise abatement.
- Information to support each step of the noise BCA framework, such as examples of noise reduction benefits, valuation of those benefits, ranges of costs for noise abatement measures, and resources for valuing other benefits and impacts and developing a benefit-cost ratio (BCR).
- An example of a noise abatement BCA using a hypothetical project.

BCA is a systematic process for calculating and comparing benefits and costs of a project to: 1) determine if it is a sound investment; and 2) see how it compares with alternate projects. BCA determines the value of a project by dividing the incremental monetized benefits related to a project by the incremental costs of that project. BCA attempts to quantify as many benefits and impacts as possible in monetary units so they can be compared "apples to apples." To the extent that the benefits of noise reduction can be monetized, noise can be included in a BCA along with other monetizable benefits of transportation projects such as travel time savings, crash reduction, and emission reductions.

One limitation of BCA is that it may be highly uncertain as to how to monetize some benefits and impacts. For example, while there has been considerable research on how people place a

[2] Noise is a term used to describe unwanted sound.

[3] Federal Highway Administration (2022). Literature Review and Synthesis - Quantifying the Benefits of Noise Abatement Measures (Part 1) - FHWA-HEP-24-002

value on time saved, there is much less data on how they might value the aesthetic benefits of a vegetated roadside or the disbenefits of an unsightly structure. Valuation can also vary by the affected population, and there may be equity considerations related to how different population groups are affected. There is also considerable uncertainty and debate as to how to value ecological impacts (such as wildlife mortality) beyond any direct impacts to humans.

The results of a BCA should therefore always be considered within the larger context acknowledging uncertainties in the analysis and potential equity implications. A sensitivity analysis testing how benefit/cost results vary under plausible ranges of key parameters can help to justify and support findings and recommendations. As long as the limitations are understood, a properly applied BCA should provide important and useful information to inform decision-making.

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. For example, FHWA's noise criteria are based on research into communication interference. Levels above the criteria in Table 1 to Part 772 would interfere with speech intelligibility at three feet and thus with enjoyment of areas of frequent human use, such as backyards or balconies.

Transportation noise can also lead to annoyance, stress, and lack of sleep, which in turn can lead to various negative impacts on human health (**Figure 2**). How much noise causes annoyance or other effects can sometimes vary from person to person and over time.

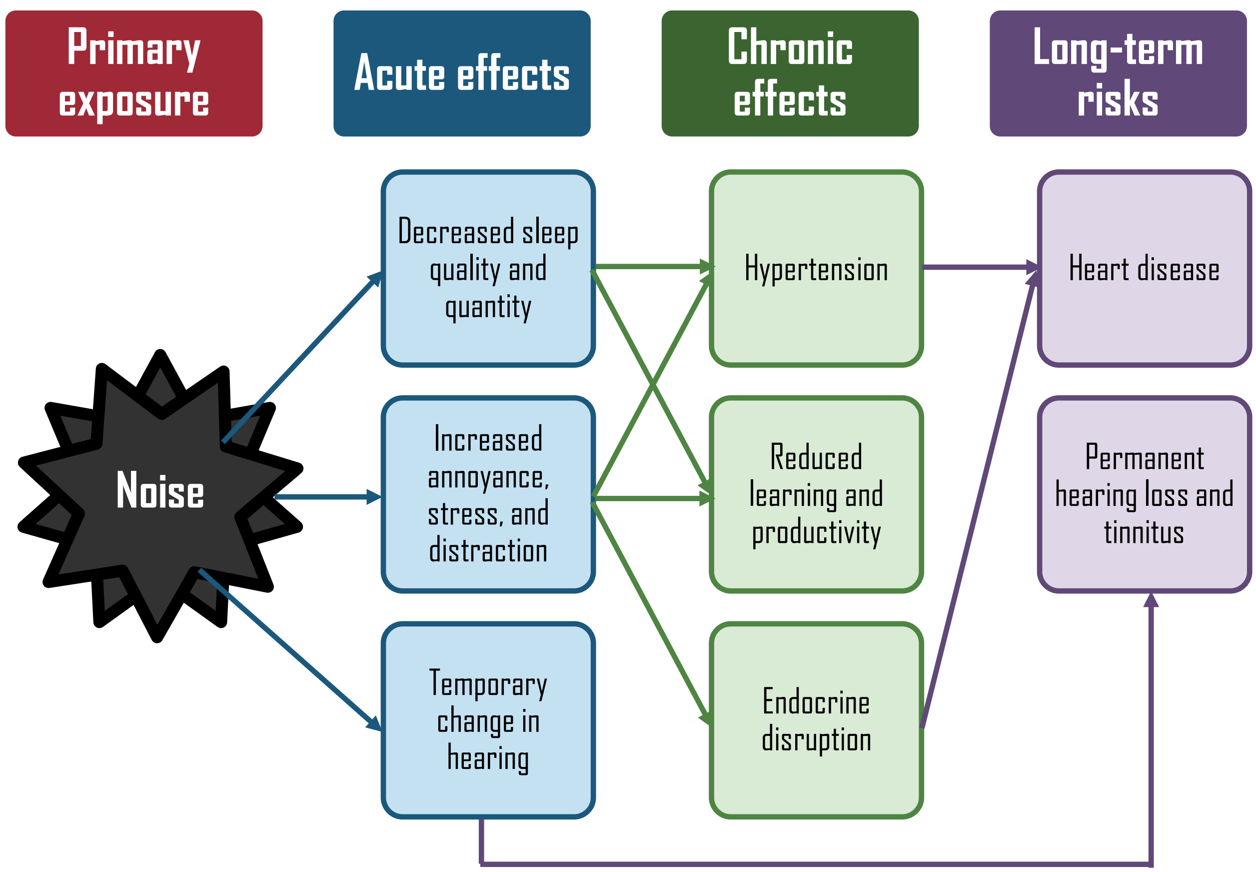

Figure 2. Diagram. Select effects of noise
Original source: Hammer, 2014; image was recreated for this report.

3. Benefit-Cost Analysis Framework

Consideration of Highway Noise Abatement Measures

This section summarizes existing U.S. Department of Transportation (USDOT) guidance on BCA; and introduces the concept of applying BCA to noise mitigation measures.

3.1. Comparison of Benefits and Costs

The USDOT provides resources to assist in valuing benefits and impacts from transportation projects. This guidance is updated regularly. This section summarizes key concepts in BCA as presented in USDOT BCA guidance [USDOT, 2021].

3.1.1. Summary Measures

NPV and BCR are two of the most commonly used summary measures that allow benefit-cost comparison in BCA. In the case of NPV, all lifecycle benefits and costs are discounted to the present, and costs are subtracted from benefits to yield NPV. Thus, if benefits exceed costs, the NPV is positive and the project may be considered economically justified. The BCR evaluates a ratio with present value of benefits in the numerator and present value of the costs in the denominator. As such, higher BCR values indicate a project or alternative with higher benefits relative to costs.

3.1.2. Inflation and Discounting

Inflation and discounting are two interrelated, but distinct adjustments required for meaningful comparison of costs and benefits.

Project studies may sometimes express data on project costs in nominal dollars from several different years for the purpose of reporting expected future costs. Nominal dollars, also referred to as “current” or “year-of-expenditure” dollars, reflect the effects of inflation over time. Meaningful comparison of benefits and costs requires that monetized terms be expressed in common terms, which means that nominal dollars must be converted to real dollars for the purpose of cost-benefit analysis. USDOT guidance recommends the use of the Gross Domestic Product (GDP) deflator to convert from nominal to real (or constant) dollars. This deflator considers the prices of all goods and services in the U.S. economy.

Discounting is the process of accounting for the time value of money; using money sooner in time, which is more highly valued, has an associated cost of diverting resources from different future uses. USDOT guidance advises applicants to USDOT discretionary grant programs to use a real discount rate (i.e., the rate after adjusting for inflation) of 7 percent per year to discount streams of benefits and costs to their present value in their BCA. Further, the guidance suggests discounting each category of benefits and costs separately for each year in the analysis period during which they accrue.

3.1.3. Analysis Period

USDOT guidance recommends selection of an analysis period that covers both the development and construction of the project as well as the subsequent operating period after completion of construction to the extent that the full benefits and costs are reflected. The magnitude of the project, type of improvement, project phasing, and other factors will determine the appropriate timeframe.

Though longer analysis periods may better or more fully capture the impact of certain projects, there are several caveats to modeling benefits and costs over very long-time scales. Uncertainty about the future, including travel behavior, travel markets, and emerging technologies, could limit the usefulness of estimates into the very far future. Additionally, discounting ensures that years further into the future are discounted more heavily; out years are less impactful on analysis findings the farther into the future they fall. USDOT recommends that projects involving the initial construction or full reconstruction of highways or similar facilities should use an analysis period of 30 years, while projects aimed primarily at capacity expansion or to address other operating deficiencies should use an operating period of 20 years. Residual value can be included in the analysis for project components with a lifespan exceeding the analysis period.

3.2. BCA Framework for Noise Mitigation Measures

To apply BCA to noise abatement measures, estimates of the following are required:

- The number of people benefitting from a specific level of noise reduction and the derived dollar value per decibel of noise reduced per person.
- The number of people benefiting or being impacted by other effects of the noise mitigation, and the value of those benefits or impacts per person; to the extent that data exists to support the quantification of these impacts.
- The lifecycle cost of the noise mitigation measure.

The level of detail and accuracy required for these estimates may vary depending upon the stage of planning/project evaluation and the overall scale of the project. For example, for planning-level analysis, or for small projects, it may be sufficient to apply general ranges of impacts or costs from other studies. For detailed project design, especially for large projects, greater investments in data collection are likely to be warranted to ensure that the end product accurately evaluates benefits and costs of the proposed mitigation measures.

A process for applying BCA to noise abatement measures can be described in seven steps, as illustrated in **FIGURE 3**.

1. Identify the receptor population and estimate baseline noise levels for the population in the affected project area.
    a. *The receptor population generally includes residents but may also include other populations such as workers, students, medical patients, or visitors with prolonged exposure to the noise source.*
    b. *Baseline noise levels may include projected noise levels as a result of a proposed transportation project without abatement measures.*
2. Define the potential noise abatement measures that could be applied for the project.
3. Estimate the expected noise reductions from each measure and apply values of noise reduction ($ per dB) multiplied by the receptor population to obtain a total dollar value of benefit.
4. 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.
5. Estimate the costs of the proposed noise abatement measure(s) for the specific project, including maintenance and operations as well as capital costs.
    a. *At the planning level, this could be done based on average or typical costs for the abatement measure.*
    b. *At the project design level, any available information describing actual project specifications (materials specifications, volumes, etc.) should be used to refine the estimates.*
6. Compare benefits and costs for each measure being evaluated, as measured through a BCR and/or net present value (NPV) (sum of discounted benefits - sum of discounted costs).
7. Provide a narrative that includes:
    a. *Key data sources, assumptions, and uncertainties in the BCA.*
    b. *A qualitative assessment of other benefits and impacts that cannot be monetized and their relative importance to these factors compared to those that have been quantified.*
    c. *An assessment of any equity-related considerations in the BCA methods and results.*

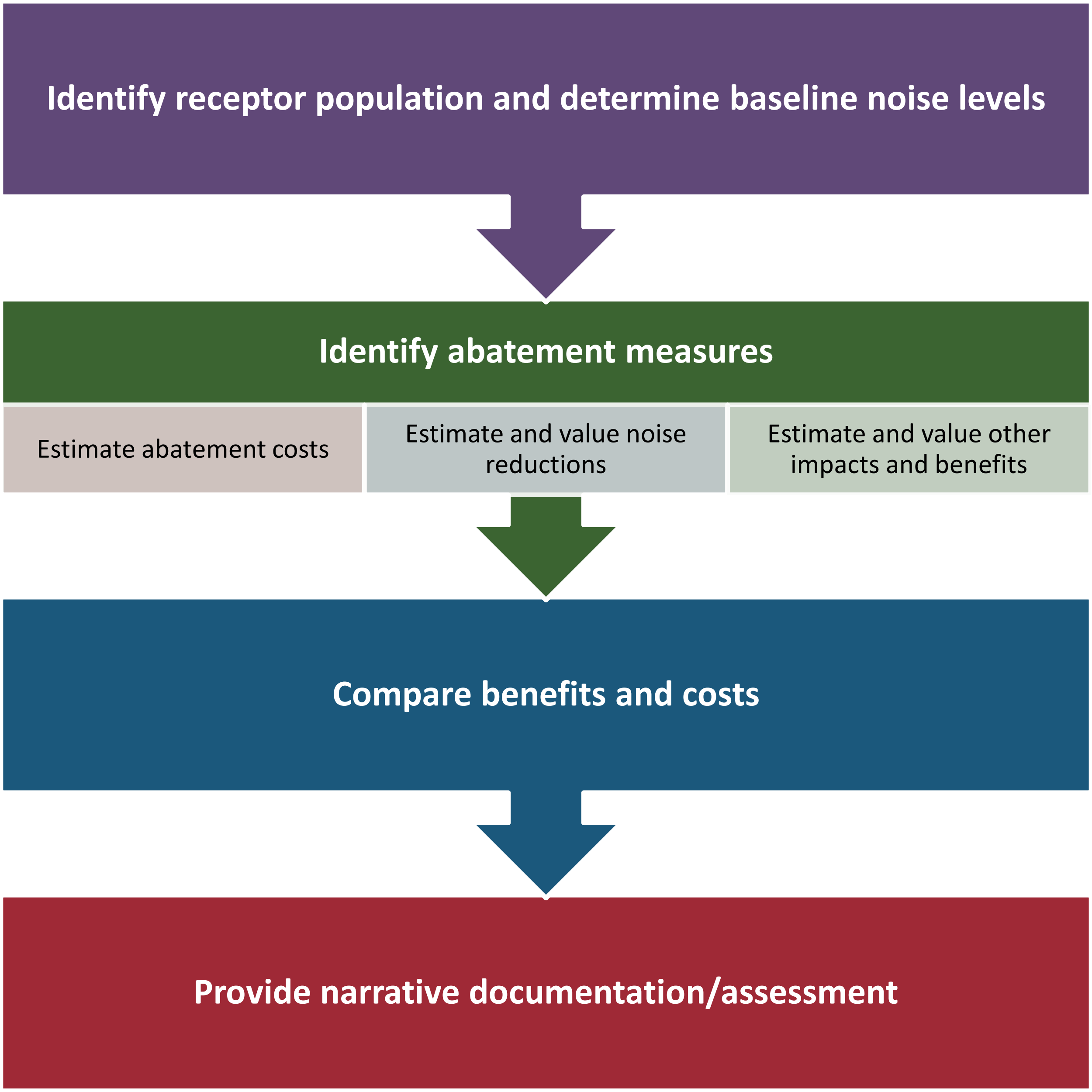

FIGURE 3. FLOW CHART. PROCESS FOR APPLYING BENEFIT/COST ANALYSIS TO NOISE ABATEMENT MEASURES
Source: Federal Highway Administration

4. Benefits and Costs of Noise Mitigation

Information to Support the Application of the BCA Framework

This section provides information to support each of the steps in the noise BCA framework presented in the previous section. In some cases, reference is simply made to existing sources of guidance and information, such as the FHWA's Noise Abatement Criteria from Table 1 to Part 772.

4.1. Potential Noise Mitigation Measures

Table 1 shows various types of highway noise abatement measures, whether FHWA will participate in funding for each type of measure, and observations regarding the potential applicability of the measure.

Table 1. Potential Noise Abatement Measures

Abatement Measure	FHWA Funding Participation?	Applicability
Barrier (wall or berm)	Yes	Widely applied.
Horizontal or Vertical Alignment Alterations	Yes	Limited application; potentially costly with significant ROW requirements.
Traffic Control (i.e. intersection controls, speed limits)	Yes	Limited application; requires the right conditions to be effective and practical.
Insulation	Yes	Limited application; does not control noise outdoors or with windows open.
Vegetation/Ground Cover	No	Limited; must have sufficient ROW for use.
Low-noise Pavement	No	Potential for wide application; need to consider the lifecycle costs.
Active Noise Control (indoors)	No	Experimental; technology for outdoor use not yet proven.
Vehicle Technology (e.g., quieter electric vehicles)	No	Limited; fleet-based strategy rather than infrastructure strategy.
Other	No	Site specific or experimental; includes measures such as use of Helmholtz resonators, noise masking, etc.

Source: Federal Highway Administration

4.2. Receptor Population and Baseline Noise Estimation

A typical noise study for a highway project will identify land uses and possible areas of frequent human use, including residential areas, that are "noise-sensitive; as well as the worst-noise hour of the day and the associated traffic characteristics.

Existing noise levels may be obtained through field measurement for new alignments, and/or modeling using the FHWA Traffic Noise Model (TNM) for either new or existing alignments. Field measurements are also generally used to validate the model before using it on the particular project. Modeling allows an analyst to estimate noise levels for hypothetical future conditions, such as for roadway changes, using forecasted traffic levels.

4.3. Expected Noise Reductions

Table 2 shows various types of highway noise abatement measures and summarizes their acoustical effectiveness. These are general ranges, and the noise reductions can vary widely depending upon the specific situation.

Table 2. Noise Reduction Expected from Different Abatement Measures in dB(A)

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

Source: Federal Highway Administration

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. In common practice, only barriers, alignment, traffic control, insulation, and pavement measures typically provide a value of at least five decibel A-weighted sound level [5 dB(A)]. This value is the minimum acoustic requirement for projects with FHWA participation.

Some measures have limited application or effectiveness. For example, insulation and active noise control are only effective inside buildings. Quieter (e.g., electric) vehicles are not an infrastructure measure, although individual agencies may be able to support this measure by purchasing fleets. For example, for roadways serving traffic at concentrated destinations (such as an airport, seaport, or intermodal terminal), the local transportation agency may be able to implement policies or incentives to support electrification of fleet vehicles serving that facility, such as drayage trucks or passenger buses.

4.4. Valuation of Noise Reductions

Considering noise reduction within a benefit-cost framework requires putting a value on a decibel (dB)[4] of noise reduction per receptor (i.e., person or household). Studies that have valued noise reduction most often rely on using property values to infer people's willingness-to-pay to avoid noise[5]. They have produced generally consistent estimates of the relationship between noise and property values.

Based on existing research, certain European agencies have issued guidance on the valuation of noise, with most sources dating from circa 2000. **TABLE 3** summarizes noise abatement values per decibel per affected person per year in 2020 dollars. The United Kingdom and Sweden assign different values at different starting noise levels. Most guidance places the value between $50 and $100 (in 2020 dollars) at higher starting noise levels. Guidance from Sweden and Switzerland indicates higher values, approaching $1,000 or more at the highest dB(A) ranges. Studies have generally found an increasing value per dB(A) as the starting noise level increases, meaning it is worth more to reduce noise from an initially high level than to reduce it by the same amount from an initially low level; and that there is little value in reducing noise below a level of 45 to 55 dB(A) [Nellthorp, 2007].

The values shown in this table are for the most part derived from hedonic price studies examining the relationship between residential property values and noise exposure, based on outdoor noise levels[6]. They might be inferred to be representative of nonresidential exposed populations, but this has not been confirmed through research. The specific noise metrics used vary based on the underlying study. The values shown are broad averages that may not capture differences in how noise is valued based on time of day, duration of exposure, noise characteristics (pitch, pattern, etc.), population (receptor) characteristics, degree of indoor versus outdoor activity, type of activities being disturbed, or other factors.

[4] A decibel is a standard measurement of sound intensity. It is logarithmic. The A-weighted sound level, dB(A), is the closest approximation to how the human ear hears and responds to sounds.

[5] Most of these studies have been conducted in Europe.

[6] The exception is the Germany study, which was based on a "stated-preference" survey method to estimate people's willingness-to-pay for noise reductions.

TABLE 3. NOISE COSTS PER DECIBEL PER PERSON PER YEAR (ROAD AND RAIL)

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]. Summary table source: Federal Highway Administration

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.

4.5. Non-Acoustic Benefits and Other Impacts of Noise Abatement Measures

While all noise abatement measures supply noise reduction benefits, some offer additional benefits, such as air quality or safety improvements; or negative impacts, such as loss of visibility, sunlight, or air circulation. Some of these effects are easier to quantify than others. It is likely that some effects are reflected 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. However, it is difficult to disentangle these effects.

Table 4 lists some of these other benefits of noise abatement measures and identifies the extent to which information is available to quantify and monetize these benefits.

Table 4. 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]
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

Abatement Measure	Benefit in Addition to Acoustic Benefits	Can Benefits be Quantified and Monetized?
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
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

Source: Federal Highway Administration

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.

TABLE 5 lists some potential negative impacts, other than cost, and considers the extent to which these impacts might be valued and monetized. ROW takings are considered a cost, as included in the subsequent section.

TABLE 5. ADDITIONAL NEGATIVE IMPACTS 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 wildlife movements (limiting range or access to preferred habitat). • Bird kills from transparent barriers	• 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 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	• Insufficient data to value wildlife/ habitat impacts

Abatement Measure	Negative Impacts for Different Noise Reduction Strategies	Can Impacts be Quantified and Monetized?
	• Can increase high frequency noise in some conditions	
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 (range or cargo capacity) compared to conventional vehicles	• May be valued through consumer preference models
Other[2]	• Masking noise may actually increase overall sound levels	• Measure-specific

Source: Federal Highway Administration

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*

4.6. Costs of Noise Mitigation Measures

While general cost ranges can be identified for each mitigation measure, the specifics will depend upon the detail of the application. For example, the material selected for a barrier can result in different costs for the same length and height of barrier; or right-of-way (ROW) must be purchased to ensure the correct placement of a barrier so that it is acoustically effective, which then results in additional costs.

Different measures may also have different relative impacts in terms of capital versus maintenance costs as well as different lifespans that will affect the total lifecycle cost of the measure. The costs provided in this report are example ranges, for more details see the Part 1 Report.

TABLE 6 identifies the relative cost of abatement for general decision-making as described in Rochat [2020] as well as illustrative cost ranges per unit of the measure as observed from the literature and practical experience.

TABLE 6. GENERAL COSTS RANKING FOR ABATEMENT INSTALLATION[1]

Abatement Measure	Measure Detail	General Cost Ranking	Cost Range per Unit[2]	Unit
Barrier	Berms	$ Moderate	$0.3–$0.5 million[3]	Linear mile
	Berms and additional ROW	$ Moderate (suburb) to $ Elevated (urban)	$0.3–$0.5 million + ROW costs	Linear mile
	Absorptive treatment	$ Average	$1–2 million[4]	Linear mile, 15’ height
	Low barriers	$ Average	$1 million[5]	Linear mile, 5’ height
	Tall barriers	$ Elevated	$3 million	Linear mile, 15’ height
	Green barriers	$ Elevated	$5 million[6]	Linear mile, 12’ height
Alignment	Horizontal	$ Average to $ Elevated	$3–$4 million[7]	New lane-mile
	Vertical alignment change (major)	$ Elevated to $ High		1 mile of fully below-grade 4-lane divided highway
	Vertical alignment change (minor)	$ Moderate	$400,000[8]	2’ depression, 5-lane arterial (incremental cost vs. at-grade)
Traffic Control	Traffic controls	$ Low	$5,000–$20,000[9]	One traffic calming application such as a traffic mini-circle, chicane, or raised crossing
		$ Moderate	$300,000–$500,000 capital less $50,000–$75,000 annual O&M savings[10]	2-lane roundabout vs. signalized intersection (incremental cost)
	Speed changes	$ Low	$200[11]	Sign (not considering enforcement)
	Vehicle restrictions	$ Low	$200	Sign (not considering enforcement)

Abatement Measure	Measure Detail	General Cost Ranking	Cost Range per Unit[2]	Unit
Insulation	Windows	$ Moderate to $ Elevated[12]	$150–300	Window (double-pane, add 10% for triple-pane)
	In-wall insulation	$ Moderate to $ Elevated	$5,000–$20,000	House (e.g., 1,000—2,500 square feet)
Vegetation/ Ground Cover	Changes to surface or in-ground treatments	$ Low to $ Moderate	Up to $300,000[13]	1 mile of WHISstone in a recessed lattice structure
	Vegetation green belts with ROW	$ Moderate (suburb) to $ Average (urban)	$0.5–$1.5 million[14]	Linear mile
	Large green belts	$ Elevated (suburb) to $ High (urban)	NA[15]	Linear mile
Pavement[16]	Diamond grinding	$ Low to $ Moderate	$50,000–$200,000[17]	Linear mile, 36’ width (2 lanes + shoulder)
	Thin overlays Open grade asphalt concrete Rubberized asphalt	$ Moderate	$100,000–$300,000[18]	Linear mile, 36’ width (2 lanes + shoulder)
Active Noise Control	Electronic equipment	$ Moderate to $ Elevated	$300–$1,500	Room
Vehicle Technology	Change to electric vehicles	$ Elevated	$100,000–$400,000[19]	Per electrified truck or bus (plus additional cost for charging infrastructure, less fuel and maintenance cost savings)

Abatement Measure	Measure Detail	General Cost Ranking	Cost Range per Unit[2]	Unit
Other	Rumble strip sinusoidal change	$ Low	$0.15 to $0.60	Linear foot (similar to conventional rumble strips after equipment change)
	Masking	NA	NA[20]	NA
	Zoning changes	NA	NA[21]	NA

Source: Federal Highway Administration

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 Source costs converted to 2021 dollars based on the consumer price index when a source cost dollar year is specified.

3 Berms are about 0.26 to 0.3 times the cost as a concrete barrier [Rochat, 2020]; calculated at 5' to 8'height.

4 [Rochat, 2020] notes that cost will vary by treatment and gives an example of $18 to $23 per square foot.

5 Based on average cost of $30.56 per square foot [FHWA, 2012], converted to $36.37 in 2021 dollars.

6 [Abbas, 2011] Based on estimated cost of "over twice" the cost of a traditional concrete barrier, $66.87 versus $30.95 per square foot. The authors note the cost would be expected to decline if the product were successfully used in practice.

7 [USDOT, 2019]. Exhibit A-1, for a minor or principal arterial on flat to rolling terrain.

8 [Rochat, 2020].

9 [FHWA, no date].

10 [Virginia Department of Transportation (DOT), 2014], based on project example showing $1 million versus $400,000 capital cost and $41,000 versus $103,000 annual operating and maintenance (O&M) cost for roundabout versus traffic signal.

11 [Moeur, 2021]. Does not include enforcement costs. Speed camera installations can cost around $100,000 per installation pus $60,000 to $100,000 in annual operating costs [USDOT, 2003], [CDC, 2015], [NYCDOT, 2017].

12 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).

13 Example for WHISstone with recessed lattice structure. Potential costs for other treatments such as grass or gravel maintenance may vary and will be geographically dependent [Rochat, 2020].

14 [Rochat, 2020]. Example for two rows planted 10 feet apart (<20 m ROW). Will be geographically dependent.

15 Geographically dependent on vegetation as well as width.

16 Time period between overlays assumed >7 years.

17 [Correa, 2001]. Estimated $0.30 to $1.10 per square foot.

18 Determining abatement costs of quiet pavement requires the consideration of lifecycle costs including initial construction cost and the type and frequency of rehabilitation required for standard versus "quiet" pavement treatments. For examples of lifecycle pavement cost analysis for noise abatement, see the National Cooperative Highway Research Program (NCHRP) Report 738 [Donovan, 2013].

19 Incremental cost of electric versus diesel medium-duty truck or bus per as estimated in Mai [2018]. Costs will vary by vehicle type and cost differentials are expected to decrease in the future. Infrastructure could add $20,000 to over $200,000 per vehicle depending upon requirements, but the vehicle owner will also realize fuel and maintenance cost savings over time.

20 Highly dependent upon the physical context and specific masking measure.

21 Modest administrative cost. Economic benefits or impacts to property owners will vary depending upon the specific change.

Some treatments will require ROW acquisition, which will range in cost depending on land use, nature of the urbanized area, and many other factors. **TABLE 7** illustrates typically land costs by area type in the United States.

TABLE 7. ESTIMATED LAND VALUE IN THE UNITED STATES

Urban Area Type	Average Value ($/Acre)
Large metropolitan area of 1+ million residents	$73,000
Small metropolitan area of less than 1 million residents	$19,000
Micropolitan area adjacent to a *large* metro area	$8,000
Micropolitan area adjacent to a *small* metro area	$5,000
Micropolitan area *not* adjacent to a metro area	$4,000

Source: [Larson, 2015]. Values are converted from 2015 dollars

For more detailed cost analysis, **TABLE 8** shows the design considerations that are likely to be most relevant in determining costs.

TABLE 8. ELEMENTS TO CONSIDER WHEN DEVELOPING COST ESTIMATES

Abatement Measure	Design Considerations Affecting Cost
Barrier	• Material • Barrier height • Topography • Need for access (doorways) • Need for additional ROW
Alignment	• New road construction (incremental cost) versus replacement cost for existing road • Length of realigned roadway versus original alignment • Width of roadway • Topography • Need for changes to intersections or overpasses • Additional ROW costs
Traffic Control	• Type of traffic control measure • New construction (incremental cost) versus replacement or retrofit cost for existing control • Number of control devices needed • Need for updating of wayfinding, route maps, upstream signage, etc. • Need for enforcement of any new traffic controls

Abatement Measure	Design Considerations Affecting Cost
Insulation	• Number of structures insulated • Size of structures insulated • Number and type of windows • New construction (incremental cost) versus replacement or retrofit cost for existing structures • Insulation type (windows and/or in-wall) • Need for additional heating, ventilation, and air conditioning components
Vegetation/ Ground Cover	• Need for any additional ROW • Planting type and costs • Maintenance costs
Pavement	• New pavement (incremental cost) versus replacement/overlay cost for existing pavement • Type of pavement • Square footage of replaced pavement • Incremental annual maintenance costs
Active Noise Control	• Number of structures affected • Number of rooms or square footage per structure
Vehicle Technology	• Number and types of vehicles replaced • Charging infrastructure requirements
Other	• Varies by measure

Source: Federal Highway Administration

5. Benefit-Cost Analysis Example

This example shows how a BCA could be applied to noise abatement measures considered for a new roadway project. The hypothetical project used in this example is the construction of a new four-lane truck haul road, one mile in length, to improve access between an Interstate highway and an intermodal terminal. A residential area about one-quarter mile square is located between the highway and the terminal (**Figure 4**). Note that a range of abatement measures are included for illustrative purposes. These measures include some that the FHWA may not participate in should Federal funding be used for the project.

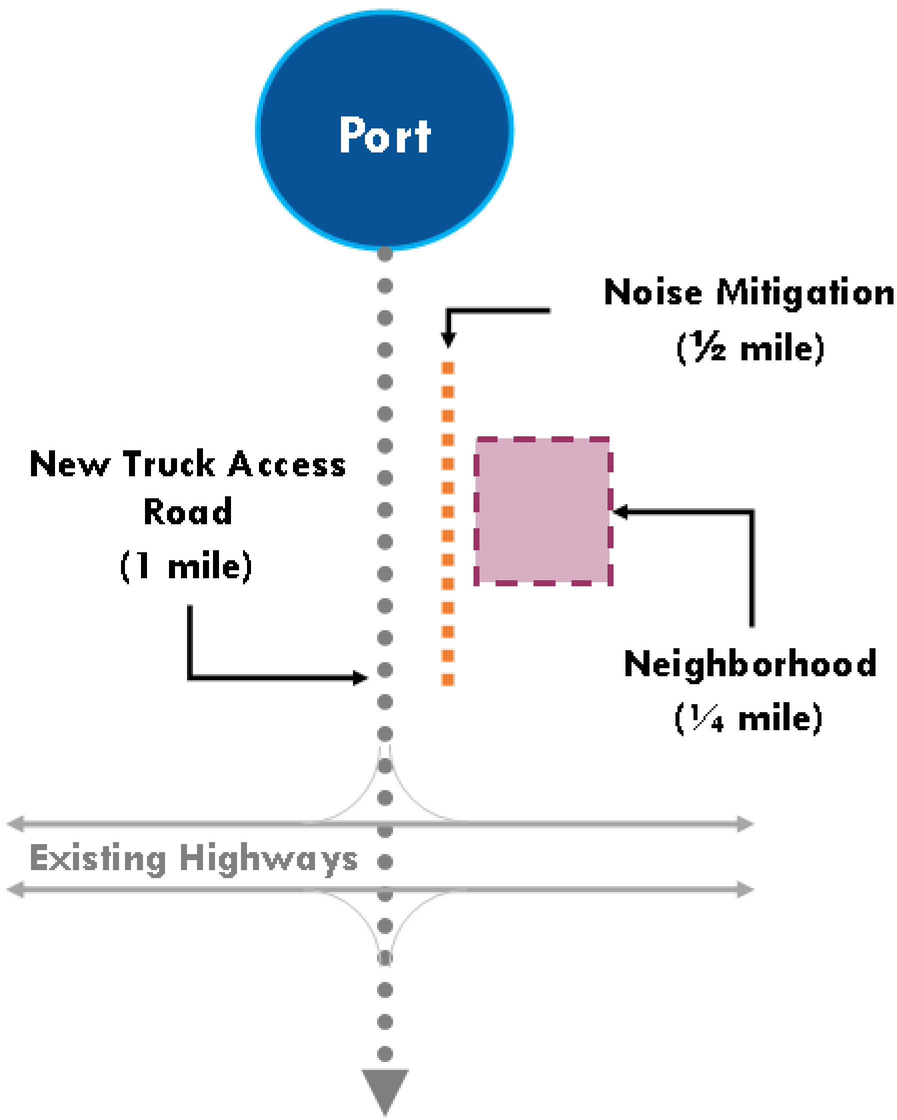

Figure 4. Diagram. Hypothetical project area schematic
Source: Federal Highway Administration

Nearby residents are concerned about potential noise impacts from the new road. Therefore, the transportation agency is considering a number of noise mitigation measures and wants to conduct a BCA of each measure.

In this example, the benefit-cost assessment of the noise abatement measures is being conducted relative to the originally proposed new roadway alternative (not relative to the no-build alternative), so all benefits, impacts, and costs are shown relative to the new road construction without any abatement measures.

5.1. Potential Noise Abatement Measures

The potential abatement measures being considered include:

- A noise barrier along the new roadway adjacent to the residential area.
- A slightly longer and more costly roadway alignment that is farther from the neighborhood.
- A depressed roadway.
- A lower speed limit than proposed based on design speed.
- Insulation of affected residential structures.
- Placement of a vegetated barrier between the road and the residential area.
- Use of a low-noise pavement material.

5.2. Receptor Population and Baseline Noise Measurement

A baseline noise study for the project identified 125 households in the affected neighborhood with a total estimated population of 350 people. Existing noise levels are approximately 55 dB(A). Modeling conducted using the TNM projects that noise at these receptor locations will increase by 3 to 8 dB(A) for the closest versus farthest residences from the road to a new value of 58 to 63 dB(A). For comparison, the social cost of this increased noise is estimated to be approximately $57,750 per year. This is based on a value of $33 per person per decibel per year at db(A) between 55 and 60 decibels per the U.K. guidance cited in **TABLE 3**, and assuming an average increase of 5 dB(A) across the affected population.

5.3. Expected Noise Reductions

TABLE 9 shows the expected noise reduction from each proposed measure, based on evidence from the literature as presented in **SECTION 4** of this framework. The expected reduction from realignment and barriers are based on modeling using TNM. For other measures, the project engineers have made judgments about the likely value considering the effectiveness of the measure in the project context as compared to other typical locations, along with effectiveness ranges found in the literature (as shown in **Table 9**).

Table 9. Expected Noise Reduction from Abatement Measures (Project Example)

Abatement Measure	Expected Reduction, dB(A)	Notes
Noise barrier	7	Concrete, 15’ height
Horizontal realignment	4	200-foot offset
Vertical realignment	10	Fully depressed roadway
Speed reduction	2	45 to 30 miles per hour (mph)
Home insulation	8	Wall insulation + triple-pane windows on 3 sides (reduction inside the home only)
Vegetated barrier	3	Dense evergreen planting, 24’ width
Low-noise pavement	5	Open-graded versus dense-graded asphaltic concrete

Source: Federal Highway Administration

5.4. Valuation of Noise Reductions

Since the value of noise reduction is being compared with a starting value of 58 to 63 dB(A) (i.e., the noise level expected after project opening under the baseline alternative), the project engineers use an average value of 60 dB(A) per person for simplicity. The reductions are then valued at $33 per person per dB(A) reduced for decibels between 55 and 60 dB(A), and a value of $22 per person per dB(A) reduced for values between 55 and 50 dB(A), based on the U.K. guidance shown in **Table 3**. With 350 people affected, the annual value of the expected noise reduction is shown in **Table 10**.

Table 10. Annual Value of Noise Reductions (Project Example)

Abatement Measure	Expected Reduction, dB(A)	Annual Value
Noise barrier	7	$73,150
Horizontal realignment	4	$46,200
Vertical realignment	10	$96,250
Speed reduction	2	$23,100
Home insulation	8	$60,638[1]
Vegetated barrier	3	$34,650
Low-noise pavement	5	$57,750

Source: Federal Highway Administration

1 *Assuming that only 75 percent of homeowners would participate in this voluntary program.*

5.5. Costs

The estimated cost of each measure and the basis for estimating the cost is shown in **Table 11**. The cost is incremental to the proposed new road as constructed without abatement measures. Incremental maintenance costs are also shown where they can be identified.

Table 11. Estimated Costs of Abatement Measures (Project Example)

Abatement Measure	Cost Basis	Approximate Capital Cost	Annual Maintenance Cost
Noise barrier	½ mile of new barrier, $36 per square foot, 12-foot height	$1,200,000	$12,000
Horizontal realignment	400 additional feet of 4-lane roadway at $10 million per mile; annual maintenance at 10% of construction cost Acquisition of an additional 530,000 square feet of ROW (200 feet offset * 0.5 mile length) at $20,000/acre	$760,000 construction + $240,000 ROW = $1,000,000	$76,000[1]
Vertical realignment	0.5 mile of fully depressed roadway at additional $25 million per mile	$12,500,000	$1,250,000
Speed reduction	No additional cost for signage $80,000 per year for automated enforcement using a speed camera at 1 location	$0	$80,000
Home insulation	$7,500 per home for blown-in insulation and triple-pane windows on three sides; 75% of homeowners participate	$700,000	NA
Vegetated barrier	½ mile of 3 rows of 5–6’ evergreens planted 8’ apart, $150 per tree Annual landscaping services (pruning, replacement of dead trees, weed control, etc.) $5/tree	$150,000	$5,000
Low-noise pavement	½ mile of roadway, 48 foot width, hot-mix asphalt plus 7-year asphalt rubber friction course overlay versus Portland cement concrete (PCC) with 20-year grind	($215,000)[2]	$17,000[2]

Source: Federal Highway Administration

1 *Incremental maintenance cost of the additional length estimated at 10 percent of incremental capital cost.*
2 *Standard pavement is PCC at $1.14 million construction cost plus $217,000 for 20-year diamond grind. Comparison quiet pavement is hot-mix asphalt at $930,000 construction cost plus 7-year asphalt rubber friction course overlay*

at 4,180,000 and 14 year mill and hot-mix overlay at $319,000. This is a simplified example based on table 3 of Donovan [2013] with costs per square foot scaled to the example project.

5.6. Other Benefits and Impacts

The project engineers worked in consultation with the affected community to identify other potential benefits and/or impacts of the abatement measures being considered. These are shown in **Table 12**. This table also describes any basis for valuing the impact quantitatively, if available, and/or provides a qualitative assessment of impacts.

Table 12. Other Benefits and Impacts (Project Example)

Abatement Measure	Benefit or Impact	Basis for Valuing
Noise barrier	Visual impacts	No quantitative basis. Barrier design will use context-sensitive materials and forms to mitigate any negative impacts.
Horizontal realignment	Additional travel time and vehicle operating cost	The realignment would add about 400 feet to the length of each one-way trip. With a speed limit of 45 mph, the round-trip travel time increases by 12 seconds per truck. With a projected volume of 1,000 trucks per day operating 300 days per year, and a value of time for commercial truck drivers of $30.80 per hour [USDOT, 2021], the annual cost of travel time would be $31,000. At a truck operating cost per mile of $0.93 [USDOT, 2021], the annual additional vehicle operating cost would be $42,000.
Vertical realignment	None identified	N/A
Speed reduction	Additional travel time	The speed limit would be reduced from 45 to 35 mph (enforcement via automated speed cameras would be implemented to ensure compliance), increasing the round-trip travel time by 46 seconds per truck. With a projected volume of 1,000 trucks per day operating 300 days per year, and a value of time of $30.80 per hour, the annual cost of travel time would be $117,000.
Home insulation	Energy savings	Most of the homes were constructed in the 1960s and are not well-insulated. A residential engineer has estimated that, in addition to reducing noise in the home, the proposed insulation would reduce the average resident’s heating costs by $250 per year. Assuming that 75 percent of owners participate in the insulation, this equates to a total value of $23,000 per year in residential energy savings.

Abatement Measure	Benefit or Impact	Basis for Valuing
	Limited effectiveness	Residents have noted that insulation will not reduce noise outside or when windows are open but are willing to make this tradeoff given the energy savings benefits.
Vegetated barrier	Visual impacts	Benefits per tree quantified based on data from a study of urban tree benefits in Los Angeles that estimated a benefit of $38 to $56 per tree per year. Residents have expressed an aesthetic preference for a vegetated barrier but only if it is comparable in effectiveness to a structural barrier.
Low-noise pavement	None identified	N/A

Source: Federal Highway Administration

5.7. Comparison of Benefits and Costs

Table 13 compares all the quantifiable benefits and costs of each abatement measure. Capital (construction) costs are annualized using a 7 percent discount rate and a 30-year project evaluation period. Capital assets with a lifespan of greater than 30 years are assigned a residual value based on a lifespan of 50 years (i.e., two out of five of the original capital cost). The NPV of costs represents the lifecycle capital, operating, and maintenance costs to the transportation agency. The NPV of social benefits and costs represents the value of the other benefits or costs to society, including noise reduction as well as (in this example) travel time increases and energy savings. The BCR is then computed as the ratio of NPV of benefits to NPV of costs.

TABLE 13. COMPARISON OF BENEFITS AND COSTS (PROJECT EXAMPLE)

Abatement Measure	Capital Cost	Annual Maint Cost	Asset Life-span (years)	Residual Value	Annual Noise Reduction Benefit	Other Annual Benefit (Cost)	NPV of Benefits	NPV of Costs	BCR
Noise barrier	$1,152,088	$12,283	50	$460,835	$73,150		$907,721	$1,155,510	0.79
Horizontal realignment	$1,000,000	$75,758	50	$400,000	$46,200	$(73,384)	($337,327)	$1,741,358	-0.19
Vertical realignment	$12,500,000	$1,250,000	50	$5,000,000	$96,250		$1,194,370	$25,204,276	0.05
Speed reduction	$–	$80,000	30	$–	$23,100	$(117,333)	($1,169,341)	$907,448	-1.29
Home insulation	$703,125	$–	50	$281,250	$60,638	$23,438	$1,043,303	$620,179	1.68
Vegetated barrier	$148,500	$4,950	50	$59,400	$34,650	$46,530	$1,007,366	$187,130	5.38
Low-noise pavement	$(215,839)	$22,652[1]	–[1]	($119,548)[1]	$57,750		$716,622	$316,952	2.26

Source: Federal Highway Administration

1 *For low-noise pavement, annual maintenance cost shown is NPV of period maintenance costs for low-noise versus standard pavement (see table 12), averaged over project evaluation period. Residual value is the remaining value of the most recent rehabilitation work (year 28 for low-noise mill/overlay, year 20 for PCC grind).*

In this example, vertical realignment is by far the most expensive measure (considering lifecycle capital, operating, and maintenance costs). Horizontal realignment is the next most expensive, followed by noise barriers, speed reduction (due to assumed enforcement costs), and then home insulation. Vegetated barriers and low-noise pavement have the lowest lifecycle costs.

Vertical realignment provides the greatest noise reduction benefit, followed by noise barriers, home insulation, low-noise pavement, horizontal realignment, vegetated barriers, and finally speed reduction. Home insulation provides additional social benefits due to its additional benefit of energy savings to homeowners. Horizontal realignment and speed reduction pose other social costs in the form of increased travel time.

A BCR greater than 1 means that estimated benefits exceed estimated costs. The low-noise pavement, vegetated barrier, and home insulation all show a BCR of greater than 1. The BCR for the noise barrier is slightly below than 1; considering uncertainty in some of the benefit and cost estimates, a BCR of near 1 may or may not reflect benefits exceeding costs. Horizontal and vertical realignment show low BCRs of much less than 1, while speed reduction shows a negative BCR due to its travel time costs that exceed the value of noise benefits.

Table 14 shows the ranking of each abatement measure on four metrics—total noise reduction, transportation agency annualized cost, social benefit, and BCR (1 is "best" and 7 is "worst" on each metric).

Table 14. Ranking of Abatement Measures (Project Example)

Abatement Measure	Noise Reduction	Annualized Cost	Annualized Social Benefit	BCR
Noise barrier	2	5	3	4
Horizontal realignment	5	6	6	5
Vertical realignment	1	7	1	6
Noise reduction	7	4	7	7
Home insulation	3	3	2	3
Vegetated barrier	6	2	4	2
Low-noise pavement	4	1	5	1

Source: Federal Highway Administration

5.8. Final Considerations

Study area residents and the port operator provided their input prior to selection of a final abatement measure by the transportation agency and FHWA. Residents expressed a general preference for home insulation measures given that the expected noise reduction was similar to that of a noise barrier and that they would realize additional benefits in terms of energy savings. Some individuals were concerned about the lack of noise benefits from insulation with open windows or when outdoors; however, they suggested that low-noise pavement could be used in addition to insulation as a low-cost measure to reduce outdoor noise. The noise barrier was considered to be an effective option and acceptable from a benefit/cost standpoint given its BCR of close to 1 but was less preferred due to its visual impacts. The horizontal and vertical realignments were rejected due to their high costs and to the horizontal realignment's limited noise benefit. The vegetated barrier was also rejected due to its limited benefits, uncertainty about maintaining those benefits in the future. Speed reduction was rejected due to its relatively small benefits and concerns about the high impact on truck drivers (as measured in travel time costs) and lack of compliance by vehicle operators.

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