National Cooperative Highway Research Program

Project 25-57

Breaking Barriers: Alternative Approaches to Avoiding and Reducing Highway Traffic Noise Impacts

Summary of Noise-Reducing Strategies

May 4, 2020

Technical Memorandum 1, Task 2

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The summary of noise-reducing strategies reported herein was a result of information and data gathered and brief investigations conducted by the research team. The team thanks all the American Association of State Highway Transportation Officials (AASHTO) and Transportation Research Board (TRB) noise professionals who responded to our survey seeking additional information for the targeted noise-reducing strategies, those who participated in interviews, and those who provided helpful references and material. The research team also acknowledges the valuable input and direction from the project's technical advisory panel.

EXECUTIVE SUMMARY

Strategies Investigated

National Highway Cooperative Research Program (NCHRP) Project 25-57, "Breaking Barriers: Alternative Approaches to Avoiding and Reducing Highway Traffic Noise Impacts" is examining strategies other than traditional noise barriers to reduce highway traffic noise. For this literature review, the research team investigated 13+ alternative strategies (listed in Table ES-1). Additional strategies and combinations were also considered. The team extracted information on traffic noise reduction, associated construction and maintenance costs, and the context-appropriateness for highway design and management. To supplement, an online survey distributed to noise professionals in American Association of State Highway and Transportation Officials (AASHTO) and Transportation Research Board (TRB) and resulting interviews with the respondents provided additional references and information.

Table ES-1: Investigated alternative noise reducing strategies.

Noise-Reducing Strategy Category	Sub-category
On-road design choices	1. Quieter bridge decks and joints
	2. Quieter rumble strip design
	3. Quieter pavements for travel lanes and/or shoulders
Highway design choices	4. Horizontal and vertical alignment
	5. Solid safety barriers in lieu of guardrail
	6. Separation zones between vehicle travel lanes and side paths for nonmotorized users
Right-of-way design choices	7. Low berms
	8. Vegetated screens
	9. Vegetated swales and retention basins
	10. Sound-absorbing ground surface and ground treatment adjacent to the highway
Operations management strategies	11. Speed or truck restrictions
Implementations by receptors or local governments	12. Approaches that can be implemented by subdivision developers, homeowner associations, special districts, or local governments
Sound absorptive treatment	13. Sound absorptive treatment on retaining walls or other surfaces
Other (added to original list)	14. Low barriers and diffractors 15. Solar panels

Strategy Attributes

Table 9-1 in the conclusions section of this report shows the summarized results from all strategies examined as part of this research project. Highlights are presented below, including potential noise reduction values and key considerations, with relative cost estimates ($-$$$$$). Comments on strategy combinations follow the highlights.

On-road design choices:

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

Highway design choices:

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

Right-of-way design choices:

- ($-$$$) Low berms (≤ 1.8 m or 6 ft) may provide up to 10 dB or more noise reduction, with favorable topography (e.g., receivers lower than roadway). For a ~1 m (3 ft) berm roadside and/or in median, up to 5 dB reduction may be achieved. The availability of the material affects the price.
- ($-$$$) A wide belt of vegetation/trees (> 20 m (65.6 ft)), may provide up to 10 dB or more noise reduction. ROW space needs to be considered. A narrower vegetated belt may provide up to 6 dB reduction. Of special note, a row of trees behind a noise barrier may reduce negative downwind effects, a vegetated belt may reduce the likelihood of a temperature inversion layer, and vegetation may help improve perception of highway traffic noise.
- ($) A vegetated basin can have up to a 2.4 dB effect for a two-lane road but the effect can be minimal for wider highways.
- ($$-$$$) Acoustically soft ground may reduce noise more than 2 dB if very highly sound absorptive (e.g., gravel), although greater noise reduction could be achieved with extension of the material beyond the ROW for multi-lane highways. This strategy is less effective as receiver height increases.
- ($$$) In-ground treatments/structures may reduce noise 2 dB for a lattice structure about 1 m (3.3 ft) wide and up to 8 dB if the width is substantial (24 m or 79 ft), based on two-lane roadways.
- ($$-$$$$) Above-ground treatments/roughness, particularly a low (0.3 m or 1 ft high) lattice structure, may reduce noise up to 11 dB for a width of 12 m (30 ft) (wider would be more

effective and likely required for meaningful reduction for a multi-lane highway). The strategy effectiveness is not affected by receiver height or distance.

Operations management strategies:

- ($-$$) A reduction in speed of 16 km/h (10 mph) may result in a 2 dB noise reduction.
- ($-$$) Truck restrictions may reduce maximum noise levels up to 10 dB and L_{Aeq} values 1-6 dB, although effectiveness is based on multiple factors.

Strategies implemented by receptors or local governments:

- ($) Site planning strategies include creating a wider buffer zone (up to 3 dB reduction per doubling of distance) and shielding with privacy walls or other structures (up to about 10 dB reduction).
- ($) For building design, placing the sensitive rooms farthest from the highway may provide up to 13 dB reduction.
- ($$-$$$$) Construction methods/materials may provide up to 35 dB reduction for interior noise levels.

Sound absorptive treatment:

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

Other:

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

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

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

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

1. INTRODUCTION

National Highway Cooperative Research Program (NCHRP) Project 25-57, "Breaking Barriers: Alternative Approaches to Avoiding and Reducing Highway Traffic Noise Impacts" is examining strategies other than traditional noise barriers to reduce highway traffic noise. Noise barriers are an effective way to reduce highway traffic noise and are the primary abatement measure applied to address noise impacts. Noise barriers, however, have limitations and cannot always be built. Past implementations of federal regulations (23 CFR 772) and some State policies allowed for a broader examination and application of strategies to reduce noise such as construction of earthen mounds, lower speed limits, time-of-operation limits, horizontal or vertical alignment changes, or creations of buffer zones to minimize noise impacts. A broader examination of current alternative noise reduction strategies could allow States to more effectively improve the noise environment in the vicinity of major highways and local roadways.

This report summarizes findings from the literature review portion of the NCHRP 25-57 project. For later phases of the project, further investigations will be conducted for at least three promising strategies or combination of strategies. The final results will be presented in a report, associated presentation, and user-friendly practitioner resource.

1.1 Literature Review Process

For the literature review, the research team investigated 13 alternative strategies (listed in Table 1-1). Additional strategies and combinations were also considered, with two additional strategies listed in Table 1-1 in the "Other" category. The team extracted information on traffic noise reduction, associated construction and maintenance costs, and the context-appropriateness for highway design and management. Over 170 references were reviewed; both national and international references were found in published research and practice in reports, papers, and policies. To supplement the literature review, an online survey was distributed to noise professionals in AASHTO and TRB. The responses to the online survey and follow-up interviews with the respondents provided additional references and information.

Table 1-1. Investigated alternative noise reducing strategies.

Noise-Reducing Strategy Category	Sub-category
On-road design choices	1. Quieter bridge decks and joints
	2. Quieter rumble strip design
	3. Quieter pavements for travel lanes and/or shoulders
Highway design choices	4. Horizontal and vertical alignment
	5. Solid safety barriers in lieu of guardrail
	6. Separation zones between vehicle travel lanes and side paths for nonmotorized users
Right-of-way design choices	7. Low berms
	8. Vegetated screens
	9. Vegetated swales and retention basins

	10. Sound-absorbing ground surfaces and ground treatments adjacent to the highway
Operations management strategies	11. Speed or truck restrictions
Implementations by receptors or local governments	12. Approaches that can be implemented by subdivision developers, homeowner associations, special districts, or local governments
Sound absorptive treatment	13. Sound absorptive treatment on retaining walls or other surfaces
Other	Solar panels Low barriers and diffractors

1.2 Noise Reduction and Perception

To help provide insight to noise reduction values and changes in frequency content discussed for the various strategies, this sub-section provides information on human perception of traffic noise.

From the National Highway Institute course on highway traffic noise,[1] Table 1-2 shows changes in sound level relative to an original sound, and the perceived change in loudness. Loudness is a subjective term related to the magnitude of sound, and the perception changes stated here assume sounds of similar nature are being compared. As an example, highway traffic noise at 60 dBA sounds half as loud as highway traffic noise at 70 dBA. [Note for the energy loss equated to dB change, apply the equation $10*Log_{10}((1\text{-energy loss})*(pressure^2/reference_pressure^2))$, where $pressure^2/reference_pressure^2$ is the acoustic energy in this case, or more simply, use $10*Log_{10}(1\text{-energy loss})$ to calculate the decibel change (e.g., for 90% energy loss, $10*Log_{10}(1-0.90) = -10$ dB).]

Further, frequency is an objective description of what we subjectively judge to be the pitch of a sound. In reality the sounds we hear contain many different frequencies at many different levels. Human hearing is most sensitive to frequencies between 1,000 and 6,300 Hz and less sensitive is frequencies lower and higher in the unimpaired human hearing range (20 to 20,000 Hz). The same sound pressure at different frequencies will produce different hearing responses.

Table 1-2. Relative changes in loudness.

Sound Level Change	Acoustic Energy Loss	Relative Loudness Change
0 dB	0	Reference
-3 dB	50%	Barely perceptible change
-5 dB	70%	Readily perceptible change
-10 dB	90%	Half as loud as original

[1] National Highway Institute, *Highway Traffic Noise: Basic Acoustics*, NHI 142063, 2019.

-20 dB	99%	1/4th as loud as original
-30 dB	99.9%	1/8th as loud as original

Literature also discusses highway traffic noise and mitigation in relation to annoyance. Information from the HOSSANA project[2] helps to explain differences in annoyance based on frequency content. It is stated that mitigation strategies not only reduce overall noise, but they also alter the spectral content and time patterns. A study with a vegetated barrier protecting an esplanade from road noise showed that, although the annoyance reduction was fairly well predicted by the noise reduction, there was a slight tendency for the annoyance reduction to be a little less than expected from the decibel reduction. This can partly be explained by the barrier's lower reduction of low-frequency than high-frequency sounds. It was determined that the relative level in low frequency sound can affect annoyance. As a general rule of thumb, decibel reductions can be adjusted down by 0.4 dB per decibel increase in L_C - L_A caused by the barrier. L_C is the C-weighted sound pressure level, and L_A is the A-weighted sound pressure level, which emphasizes mid frequencies and de-emphasizes low frequencies based on human hearing. A more recent study showed that the adjustment should be 0.55 dB per decibel increase in the difference.[3] To demonstrate how this works, if a mitigation measure provides a measured A-weighted 4 dB reduction, the perceived reduction would be about 3 dB if low frequency sounds before and after mitigation installation differ by 2 dB (after mitigation L_C - L_A minus before mitigation L_C - L_A). The same study with the vegetated barrier also showed that, although the mitigation reduced the noise variability, measured as the difference between the levels exceeded 10 and 90% of the time, statistical analyses suggested that this did not strongly influence the perceived annoyance of sound.

Also described in the HOSANNA project,[4] measurements conducted for a tramway with sound propagation over acoustically hard and soft ground showed that there was a slight tendency for the annoyance difference to be greater than one would predict from decibel difference alone. Verbal reports indicated that the main perceptual effect was a reduction in high frequency sounds. Also discussed was consideration of masking of wanted sounds. For example, mitigation may allow birds chirping to be heard. In addition, vegetated mitigation may attract more birds, which will produce more natural sound. Visual changes were also discussed, stating that the extent to which visual changes influence auditory perception of noise is debatable, however, the sound environment and scenery independently contribute to perceived tranquility. Low sound levels combined with a view dominated by vegetation would be associated with a high degree of tranquility. Experiments with simulated environments suggest that urban streets planted with greenery were perceived as more pleasant and quieter than streets with no greenery.

[2] Chalmers University of Technology, CSTB, Canevaflor, IBBT Gent University, Muller BBM, Open University, City of Stockholm, TOI, University of Sheffield, University of Bradford, Stockholm University, Acoucite, and Hangyang University, "Novel solutions for quieter and greener cities, Brochure summarizing HOSANNA Project, 2013.

[3] Nilsson, M., M. Andehn, and Paulina Lesna, "Evaluating roadside noise barriers using an annoyance-reduction criterion," J. Acoust. Soc. Am., 124 (6), December 2008.

[4] Chalmers University of Technology, CSTB, Canevaflor, IBBT Gent University, Muller BBM, Open University, City of Stockholm, TOI, University of Sheffield, University of Bradford, Stockholm University, Acoucite, and Hangyang University, "Novel solutions for quieter and greener cities, Brochure summarizing HOSANNA Project, 2013.

1.3 Report Organization

The remainder of this report discusses the various strategies categorized by general topic. The remaining sections are as listed, discussing the associated strategies:

- Section 2: on-road design choices;
- Section 3: highway design choices;
- Section 4: right-of-way design choices;
- Section 5: operations management strategies;
- Section 6: implementations by receptors or local governments;
- Section 7: sound absorptive treatment on structures;
- Section 8: other;
- Section 9: conclusions and discussion;
- Section 10: references; and
- Appendix A: acoustic terminology.

2. STRATEGY CATEGORY: ON-ROAD DESIGN CHOICES

2.1 Quieter Bridge Decks and Joints

Table 2-1 shows a summary of the strategy quieter bridge decks and joints. The summary is based on information extracted from the references described in this subsection.

Table 2-1: Summary of strategy: quieter bridge decks and joints.

Strategy	Noise Benefit	Costs	Context Appropriateness
Quieter bridge decks using diamond grinding or polyester overlays	5 to 10 dB	Polyester overlay \$10-\$30 per ft^2, geographically dependent; diamond grinding \$1-\$3 per ft^2, geographically dependent	Bridges or other structures
Quieter bridge joints using patterned joint cover plates	6 to 9 dB	20% to 40% higher than conventional joints	Bridges or other structures with expansion joints, particularly designed seismic activity

While pavements constitute the majority of traveled surfaces, bridges and structures can also be a significant proportion, especially in dense urban areas. The type of bridge deck and the joints used on the bridge can significantly impact noise that is generated. One on-road design strategy is therefore the selection of quieter bridge decks and joints

2.1.1 Quieter Bridge Decks

Technologies to reduce the noise of bridge decks are often the same or similar to those used for quieter pavements. It is important though to recognize that there are some limitations to the materials and textures that are used on bridge decks due to their unique aspects. For example, while friction is always important, it can be paramount on bridge decks. Bridge decks can also experience large deflections and vibration amplitudes.

In a 2011 project in California,[5] two dozen bridge sections were evaluated for tire-pavement noise using On-Board Sound Intensity (OBSI). Specific bridge deck surfaces included diamond grinding, transverse tining, transverse brooming, polyester overlays, hot-mix asphalt, and burlap drag. Diamond ground decks had the lowest measured levels. Polyester overlays were also relatively quiet. Transverse tined and transverse broomed surfaces were among the highest of the measured levels.

More recently, surface textures including both diamond grooving and grinding were evaluated by Caltrans,[6] with a texture similar to the "next generation concrete surface" developed by the paving

[5] Kohler, E. and Dynatest Consulting, Inc., "Quiet Pavement Research: Bridge Deck Tire Noise Report," Research Report: UCPRC-RR-2010-04, 2011.

[6] Communication with Bruce Rymer, California Department of Transportation, 2019.

industry. Caltrans uses this texture on new bridge decks, migrating from the previously used transverse tining and brooming. As a result, noise levels from bridge decks have decreased by 8 to 10 dBA. Where polyester overlays are used to rehabilitate bridge decks, the trend is now to use longitudinally oriented texture instead of transverse, which has reduced noise on these decks.

In 2016, Kansas[7] evaluated multi-layer polymer bridge deck overlays installed throughout the state. KDOT received numerous reports about decreased noise levels on these bridges compared to tined concrete surfaces, and it was hypothesized that aggregate angularity may be one possible cause. Kansas State University evaluated the possible noise reduction using a non-standard close-proximity measurement method and confirmed a reduction in level compared to concrete bridge decks with transverse tining. Polymer overlay sections measured with an average noise level of 102.4 dBA compared to 108.2 dBA for tining.

In Minnesota[8], bridge decks are being both diamond ground and grooved. The result has been a significant noise reduction.

Washington[9] state has also recently installed longitudinal grooving on the new SR 520 bridge recently replaced and opened a couple years ago. The longitudinal grooving was confirmed quieter, and while it has not been used yet on other bridges, there is interest in doing so.

2.1.2 Quieter Bridge Joints

Impulse noise associated with bridge joints is commonly reported as a nuisance, even if total sound levels are not significantly increased.

The New Zealand Transport Agency[10] researched bridge joint noise using vehicle-mounted noise and vibration transducers. Measurements found significant variations in noise and vibration from the same nominal joint types, and these variations were greater than that between different joint types. The variation is hypothesized to be due to differences in installation and maintenance. Joints with lower noise levels were those with a more even surface across the joint. Finger joints were also measured in this study, and while the sample size was limited, the trend was towards the quieter of the joint types. Modular joints without surface plates were also evaluated and had relatively high noise levels.

In Germany,[11] a study was made of joint covers with different shapes and surface textures. The key to noise reduction was to maintain an even transition; however, it was also important to maintain joint function (expansion and contraction). Different alternatives were tested in the tire-road-interaction test-facility (PFF) of the federal highway laboratory, BASt. The facility features a drum that permitted various joint covers to be evaluated under a controlled condition. Acoustic measurements are in close proximity to the tire-road interface. Options included rhomboidal shapes, profile angles, a “mushroom” shape, and sinusoidal shapes. Overall, the treatments reduced noise compared to the untreated standard expansion joint by as much as 9 dB. Of the various patterns evaluated, no single pattern emerged as the best, since the measured noise reduction varied by tire type and speed. Texture of the covers was also important, with “grained” surfaces improving grip and further reducing sound levels.

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[7] Meggers, D., "Effectiveness of polymer bridge deck overlays in highway noise reduction," Kansas Department of Transportation, Report No. KS-15-11, 2016.

[8] Communication with Peter Wasko, Minnesota Department of Transportation, 2019.

[9] Communication with Jim Laughlin, Washington State Department of Transportation, 2019.

[10] Chiles, S., "Selection of state highway bridge expansion joints in noise sensitive areas," INTER-Noise and NOISE-CON Congress and Conference Proceedings. Vol. 249, No. 7, 2014.

[11] Glaeser, K., G. Schwalbe, and M. Zoller, "Mitigation of noise emissions from vehicles passing bridge expansion joints," Noise Control Engineering Journal, Vol. 60, No. 2, 2012.

Figure 2-1: Photographs of various joint treatments used in German study.

In 2011 in Washington[12] state, expansion joint noise reduction was evaluated by coating adjacent surfaces with noise absorptive materials. Sound was measured before the project, after the walls were constructed without absorptive treatment, and after sound absorptive treatment was added. For nearly all of the measured locations, measured sound was found to be lower in the low frequency range (generally less than 400 Hz). There is also a measurable decrease in the low and high frequency sound with the absorptive treatment added compared to the new walls alone, before absorptive treatment was added.

More recently, the SR 520 floating bridge in Washington[13] state was replaced. The bridge used modular encapsulated joints which were quieter. However, the zipper sound of the expansion joint is louder than the new quieter surface.

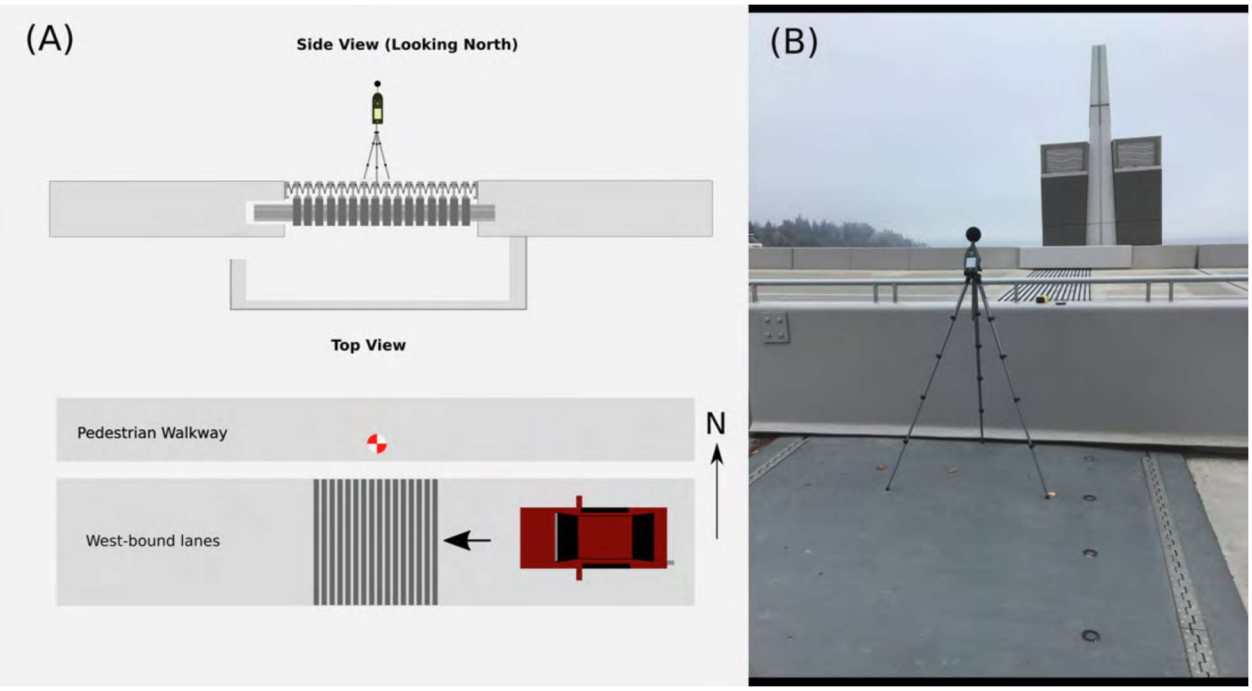

Figure 2-2: Acoustical measurements of the expansion joint on SR 520 in Washington State.

[12] Sexton, T., "Expansion Joint Noise Reduction on the New Tacoma Narrows Bridge," Report WA-RD 785.1, 2011.

[13] Communication with Jim Laughlin, Washington State Department of Transportation, 2019.

Based on the SR 520 experience, a study[14] was initiated to investigate the mechanisms responsible for the noise and identify mitigation options for control. For each option, durability, cost, and effectiveness is being evaluated for possible implementation on all existing and future bridges. The study so far has reported:

- *The majority of the noise at the bridge radiates from the top of the modular expansion.*
- *Concrete joint cavity enclosure significantly reduces the noise coming from underside of bridge.*
- *Preliminary analysis suggests that sinus plates (plates with a sine wave pattern) reduce noise levels between 400 Hz and 800 Hz by 5 dB. Further study is needed to confirm this.*
- *Filling the gaps between the center beams (with a foam or other flexible material), or the installation of sinus plates, are the two existing mitigation options that could reduce the noise on the SR520 bridge. Based on the existing information, filling the gaps is the more viable option.*
- *The quieter pavement surfaces used reduce the overall background noise of the roadway which can provide masking the noise from the expansion joints. This makes the expansion joint noise stand out from the background noise.*

Studies in California[15] have included a preliminary evaluation of a quieter joint "plate". The low-noise joint was installed on the pedestrian/bike path on the new portion of San Francisco Oakland Bay Bridge, where its movement could be evaluated over a long-term period. While it has yet to be installed under live traffic lanes, opportunities to evaluate this design further are now being sought.

Various "quiet" expansion joints are commercially available, including means to retrofit existing joints. Among options evaluated by a team in 2008[16] and further reported in 2010[17]:

- Cantilever finger joints: low initial cost, compact design with few components, lower maintenance costs; but limited longitudinal, transverse, and vertical movement, and significant moment loading
- Sliding finger joints: simple, durable, low maintenance, permits rotational and vertical moments, no large moments, easy replacement; but limited transverse movement, high initial costs, not suited for cycle traffic
- Modular joints with noise reducing plates: allows movement and rotation in all directions and about all axes, large longitudinal moments possible, good over-rolling comfort and safety; but high initial costs and complex system
- Single gap joints with noise reducing plates: good over-rolling comfort and safety, compact construction, low initial and maintenance costs; but limited transverse movement and rotation

[14] Reinhall, G. and A. Soloway, "Modular Expansion Joint Mitigation Study," Prepared for the Washington Department of Transportation, 2019.

[15] Communication with Bruce Rymer, California Department of Transportation, 2019.

[16] Spuler, T., G. Moor, and C. O'Suilleabhain, "Expansion joints with low noise emission," Walraven & Stoelhorst (Eds.), Tailor made concrete structures, 2008.

[17] Spuler, T., G. Moor, and C. O'Suilleabhain, "Expansion joints for urban bridges--quiet, reliable, and low maintenance," IABSE Symposium Report, Vol. 97, No. 4, 2010.

These "quiet" joints were found to be 6 dB quieter than conventional expansion joints, and differences in measured sound level between the roadway and each of these joints was less than 3 dB (metric not stated).

2.2 Quieter Rumble Strip Design

Table 2-2 shows a summary of the strategy *quieter rumble strip design*. The summary is based on information extracted from the references described in this subsection.

Table 2-2: Summary of strategy: quieter rumble strips.

Strategy	Noise Benefit	Costs	Context Appropriateness
Quieter rumble strips with a sinusoidal pattern	3 to 7 dB	After minor equipment modifications, costs are similar to conventionally ground rumble strips; $0.50 to $2.00 per lineal meter ($0.15 to $0.60 per lineal ft)	Outside edges of travel lanes or centerline of undivided roadway

There have been numerous initiatives over the last 20 years looking at strategies to quiet rumble strips. Doing so requires a balance of reducing sound levels externally, while maintaining adequate response within the vehicle to alert them.

Numerous agencies have explored quiet rumble strip designs. A summary of these various initiatives is summarized here.

2.2.1 Minnesota

Minnesota[18] has embraced a design for quiet rumble strips (mumble strips) after a variety of studies demonstrated their efficacy. The process includes grinding or milling the defined pattern into a pavement surface. Reduction in sound levels have been verified with wayside testing (at 15 m 50 ft), on-board passenger car measurements, and by modeling.

The process began in 2011,[19] when MnDOT implemented a policy to reduce lane departure crashes requiring centerline rumble strips (CLRS) to be installed on all rural, undivided roadways with a posted speed limit of 89 km/h (55 mph) or higher after resurfacing. To reduce external noise, research began on alternative rumble strip designs based on European trials. Test sections were installed in 2014, which resulted in a significant reduction of external nuisance noise.

[18] Communication with Peter Wasko, Minnesota Department of Transportation, 2019.

[19] "Centerline Rumble Stripe Fact Sheet," Minnesota Department of Transportation, 2015.

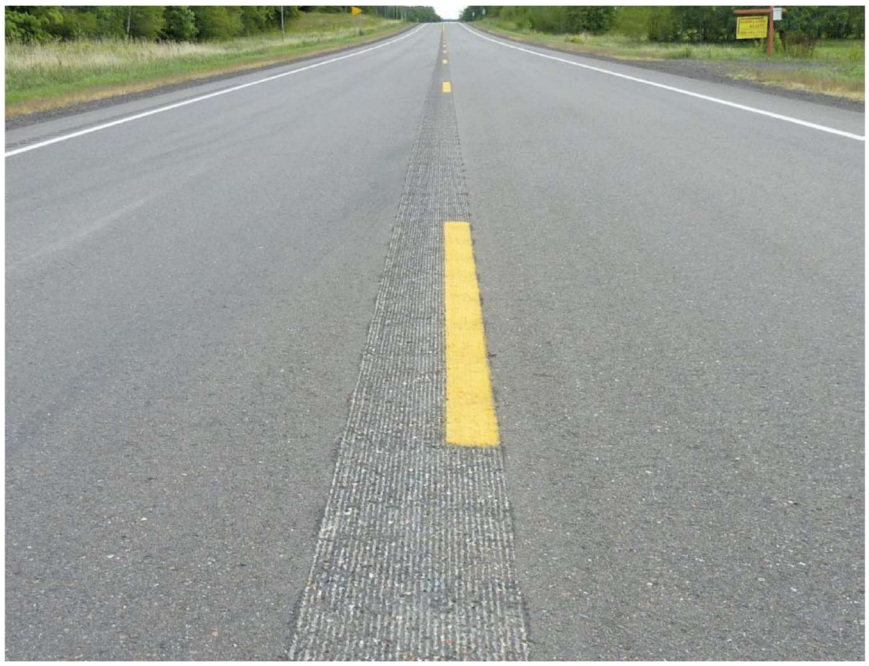

Figure 2-3: Centerline sinusoidal rumble strips installed in Minnesota.

In 2015, a Sinusoidal Rumble Design Optimization[20] research project was initiated to investigate rumble patterns. Sound levels were monitored for four types of centerline sinusoidal rumble strips installed along Highway 18 in Mille Lacs and Aitken counties in Minnesota. All four designs included a 355 mm (14 inch) wavelength sinusoidal design, but with different geometric configurations. A single strip 355 mm (14 inches) wide and a double strip of two 200 mm (8 inch) wide strips spaced 100 mm (4 inches) apart were tested, each with two different depths: 9.5 mm (3/8 inch) and 12.5 mm (1/2 inch).

Motorcycles and bicycles were used to evaluate designs at the MnROAD facility to determine rider performance. Tests on Highway 18 were performed with a passenger car, pickup truck, and tandem dump truck.

The external noise results correspond to the depth of the rumble strip design. The interior sound levels were similar for all four designs, but the actual level increase varied by vehicle type. All designs resulted in increased sound levels of 10 dBA for the passenger car, which is a desirable level. For the pickup truck, the interior sound level increased up to 6.8 dBA, and the increase for the dump truck was up to 2.7 dBA.

All four of the sinusoidal designs resulted in lower exterior sound levels compared to the standard Minnesota rumble strip design. The 355 mm (14 inch) wide, 12.5 mm (1/2 inch) deep design was recommended for further implementation by MnDOT.

2.2.2 California

California[21] has been issued a patent for its low-noise sinusoidal rumble strip design, which has emerged from numerous internal studies. The Caltrans[22,23] sinusoidal “mumble strip” meets both safety

[20] Terhaar, E., "Listening to a sine: Minnesota digs deeper into rumble strip design," Roads and Bridges, 2017.

[21] Communication with Bruce Rymer, California Department of Transportation, 2019.

[22] Caltrans, "Traffic noise generated by rumble strips," California Department of Transportation, 2012.

and acoustical targets. Details for installation remain to be finalized, but the wayside noise reduction is reportedly 6 dBA, with interior noise levels and steering column vibrations elevated to acceptable levels. The process began in 2009 with a concept paper authored by Paul Donavan. Trials then proceeded in Eureka District with spacing between peaks of approximately 355 to 405 mm (14 to 16 inches). These trials were measured again in 2013, and more recently as part of an ongoing NCHRP study. Caltrans is developing a standard plan detail sheet for the sinusoidal rumble strip, which should facilitate widespread use across the state. The Caltrans design and variations of it are currently being evaluated in an NCHRP project.

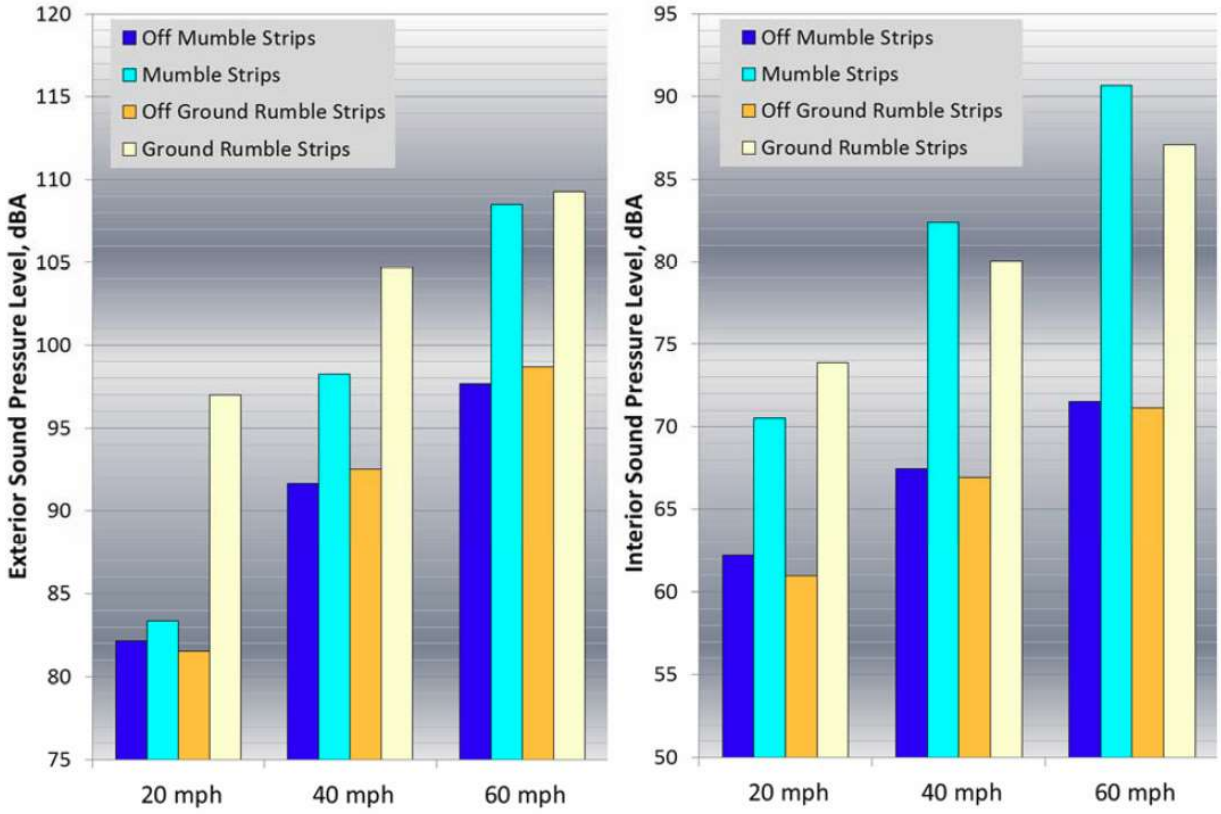

Figure 2-4: Interior and exterior overall sound level measurements for one vehicle in Caltrans study.

2.2.3 Washington State

Washington[24] state also has adopted a quieter rumble strip which can be milled in centerline or shoulder. Trials included varying spacing, width, and length, and analysis found the noise levels are reduced by changing spacing. A pilot test of a sinusoid pattern was installed in 2017, and measurements confirmed exterior noise was substantially lower. This pattern is now included as an option in the standard details.

[23] Donavan, Paul, "Design and Acoustic Evaluation of Optimal Sinusoidal Mumble Strips versus Conventional Ground-In Rumble Strips," Caltrans Report CTHWANP-RT-18-365.01.2, April 2018.

[24] Communication with Jim Laughlin, Washington State Department of Transportation, 2019.

While not used on concrete surfaces, it is used on both asphalt pavements and bituminous surface treatments (BST), principally in the Eastern part of the state. Occasionally, additional BST are installed, which tends to fill in the rumble strip, and work is ongoing to determine the impact of these overlays on measured levels.

A 2018[25] report provides additional detail of the Washington state design, including external noise measurements of conventional rumble strip designs with varying depth, width, and length. The potential for lower noise was found with shallower milling and less width. However, the sinusoidal design was found to be most promising in reducing external noise while maintaining the ability to alert the driver. For external noise, the variation between the designs that were evaluated ranged from 2 to 8 dBA, with a standard deviation within a given section ranging from 0.6 to 3 dBA. Interior noise levels increased between 7 and 13 dBA, which are all above an acceptable level to increase alertness of the driver.

2.2.4 Texas

In 2007, a Texas[26] study was initiated to determine the impact of rumble strips on exterior noise levels. Measurements were performed at 15 m (50 feet) wayside for various types of rumble strip designs. Button rumble strips increased exterior noise by 4 to 5 dB. Milled and rolled rumble strips resulted in an increase of 12 dB. Milled rumble strip applications 400 mm (16 inches) wide resulted in a 10 to 16 dB increase in the exterior noise level, while those 200 mm (8 inches) or less in width only increased the exterior noise by 4 dB or less. With respect to spacing, the increase in exterior noise was the greatest for milled rumble strip applications with 300 mm (12 inch) spacing. Rumble strips spaced greater than or equal to 450 mm (18 inches) yielded increases in the exterior noise of 8 dB or less.

2.2.5 NCHRP

As part of NCHRP Report 641,[27] it was reported that from the existing literature, milled rumble strips increase external noise levels by 5 to 19 dB and increase noise levels inside vehicles by 5 to 15 dB. Wider groove widths produce greater noise levels. External noise from sinusoidal rumble strips is 3 to 7 dB quieter than rectangular strips, which increase noise levels by only 0.5 to 1 dB. A 2004 report by the European Commission suggests that thermoplastic rumble strips decrease external noise levels by as little as 4 dB.

It was also reported that available research shows that increasing groove depth and width as well as rumble strip length increases interior noise and vibration. Milled, rolled, button, profiled and formed rumble strips produce adequate changes in sound for drivers of passenger vehicles, but only milled rumble strips produced an adequate change in sound for drivers of commercial vehicles.

Ongoing NCHRP Project 15-68 is yielding very promising results.

A literature review[28] reports on the two primary types of rumble strips: milled and raised. It discusses findings on low-noise rumble strips, bicycle and motorcycle safety, rumble strip effects on the community and drivers, and rumble strip noise and vibration data collection. Some key findings include:

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[25] Laughlin, J. and J. Donahue, "Evaluation of New Rumble Strip Designs to Reduce Roadside Noise and Promote Safety," Washington State Department of Transportation, 2018.

[26] Finley, M. and J. Miles, "Exterior Noise Created by Vehicles Traveling over Rumble Strips," Texas Transportation Institute, 2007.

[27] Torbic, D., J. Hutton, C. Bokenkroger, et al., "Guidance for the Design and Application of Shoulder and Centerline Rumble Strips," NCHRP Report 641, 2009.

[28] Rochat, J. and S. McKenna, "Effective Low-Noise Rumble Strips, Task 1: Literature Review," Cross-Spectrum Acoustics, NCHRP 15-68, 2019 (unpublished).

- Low noise rumble strips (strips with a sinusoidal shape) can reduce exterior noise levels compared to conventional designs. Studies have shown that heavy trucks may not be alerted enough by the sinusoidal rumble, but other studies suggest that making the strips wider may solve the problem. Shallower rumble strips produce lower noise levels both inside and outside the vehicle.
- The main concern for bicyclists is to have designs/placement that allow for safe travel. This includes adequate space between the rumble strip and edge of road, gaps for crossing, and a maximum depth between 6 and 10 mm (0.25 and 0.4 in), based on conclusions from various studies.
- In general, motorcyclists can safely traverse rumble strips. There may be some difficulty associated with raised strips or being unaware of centerline rumble strips. A maximum depth of 10 mm (0.375 in) is preferred.
- Rumble strips can increase noise by 5-25 dB near the road and cause annoyance and sleep disturbance in communities. The effect is dependent on distance from the road, vehicle type, and speed.
- For noise, rumble strips causing an increase of 3 to 15 dB above ambient may be required for detection, and tones should help with driver detection and perception of urgency (higher frequency)...For sinusoidal rumble strips, an optimum wavelength is 0.35 m (13.8 in) to have sufficient interior noise and vibration and minimize exterior noise.

A state-of-practice review[29] was also developed including an overview of existing FHWA guidance and other syntheses on general state-of-practice on rumble strips, including design parameters and accommodation for bicyclists. Noise control policies related to rumble strips are also included, along with low-noise rumble strip design. It finds that guidance related to rumble strip noise can be divided into 3 categories:

1. Low noise design options: sinusoidal rumble strips used in areas where roadside noise is a concern. Several States have completed studies showing sinusoidal rumble strips reduce roadside noise compared to conventional strips and recommend their construction in noise sensitive areas. No States have adopted sinusoidal rumble strips as their standard design.
2. Implementation restrictions near residences – Some State DOTs specify a specific distance from residences at which rumble strips should be discontinued. Some States do not specify a distance but do allow for an evaluation on whether rumble strips should be omitted near noise sensitive receptors. In general, States discourage the use of rumble strips in areas with relatively high levels of residential development.
3. Measures to reduce inadvertent rumble strip strikes - Some States do not place CLRS in passing zones or increase rumble strip gapping in passing zones. Some States do not place edge-line ELRS on the inside of horizontal curves where off-tracking is common and there is a greater likelihood of inadvertent strikes. Some States recommend a larger offset for shoulder rumble strips near residences to reduce the likelihood of inadvertent strikes. The drawback of these strategies is that they reduce or eliminate the safety effectiveness of RS.

A number of states allow for alternative low-noise rumble strip designs in their guidance or have carried out studies on test sections of low-noise rumble strips. Studies on sinusoidal rumble strips have shown that they reduce roadside noise while generating sufficiently high levels of noise and vibration. In general, sinusoidal rumble strips have reduced wayside noise compared to conventional strips by about 4-12 dB.

[29] Rochat, J. and S. McKenna, "Effective Low-Noise Rumble Strips, Task 2: State-of-Practice Review," Cross-Spectrum Acoustics, NCHRP 15-68, 2019 (unpublished).

2.2.6 U.S. National Park Service

In 2011, the United States National Park Service (NPS)[30] voiced concern about rumble strips being installed in locations that may affect the natural sound environment inside the park A synthesis was initiated to consolidate guidance on how to install rumble strips near or in parks while minimizing disturbances in adjacent noise-sensitive areas. Included in the synthesis is information on rumble strip noise based on the type of rumble strip, applications of rumble strips, the effects rumble strips have on various road users, including bicyclists, and also recommendations for rumble strip use and application in a park environment.

One of the studies described in the synthesis used the FHWA noise model and measurements to predict rumble strip noise levels at four different neighborhood settings. It was found that noise for vehicles driving on a rumble strip was 7 to 10 dB louder than emission levels for vehicles on standard pavement.

To minimize exterior noise, the NPS report suggests that design should include shallow depth, narrow width, large spacing, nonzero offset, and be non-continuous (gap > 0).

2.3 Quieter Pavements for Travel Lanes and/or Shoulders

Table 2-3 shows a summary of the strategy *quieter pavements for travel lanes and/or shoulders*. The summary is based on information extracted from the references described in this subsection.

Table 2-3. Summary of strategy: quieter pavements for travel lanes and/or shoulders.

Strategy	Noise Benefit	Costs	Context Appropriateness
Quieter pavement using diamond grinding	Up to 7 dB	\$2.50 to \$15.00 per m^2 (\$0.25 to \$1.50 per ft^2)	All pavement surfaces
Quieter pavement using open-graded or rubberized asphalt	Up to 9 dB	\$5.00 to \$15.00 per m^2 (\$0.50 to \$1.50 per ft^2)	All pavement surfaces
Quieter pavement using thin bonded asphalt overlays	Up to 6 dB	\$5.00 to \$15.00 per m^2 (\$0.50 to \$1.50 per ft^2)	All pavement surfaces

Over the last 40 years, numerous strategies for quieter pavements for both travel lanes and shoulders have been advanced and studied in detail. This section highlights just a few of the alternatives that have been recently reported.

[30] Cybulski, J., J. Rochat, and D. Read, "Roadway Departure Warning Indicators: Synthesis of Noise and Bicycle Research," National Park Service, Report No. DOT-VNTSC-NPS-11-24, 2011.

2.3.1 Minnesota

Minnesota[31] has been using an "innovative diamond grind" as the best management practice for a quieter pavement surface, although it is only sparsely used. Implementation includes recent use on I-394 where concrete pavement was needed but concerns over noise led to use of the innovative grind.

The goal of the I-394 Pavement Noise Study[32] was to determine whether the pavement resurfacing project resulted in statistically significant changes to noise levels in various neighborhoods adjacent to the highway. The innovative grind pavement surface was intended to reduce tire-pavement noise levels. Confirmation of this was made by measuring noise levels before and after the pavement resurfacing.

The analysis indicated some post-project neighborhood noise average levels lower than pre-project levels by statistically significant amounts. However, the differences could not be attributed solely to the I-394 resurfacing. The influence from other local sound sources is also believed to have contributed to the change. However, through an analysis of the L_{10} noise levels, paired samples do show a statistically significant average decrease of 1.3 dBA. While this decrease is statistically significant, it is small and doesn't qualify the I-394 resurfacing project to be considered as providing effective noise level mitigation.

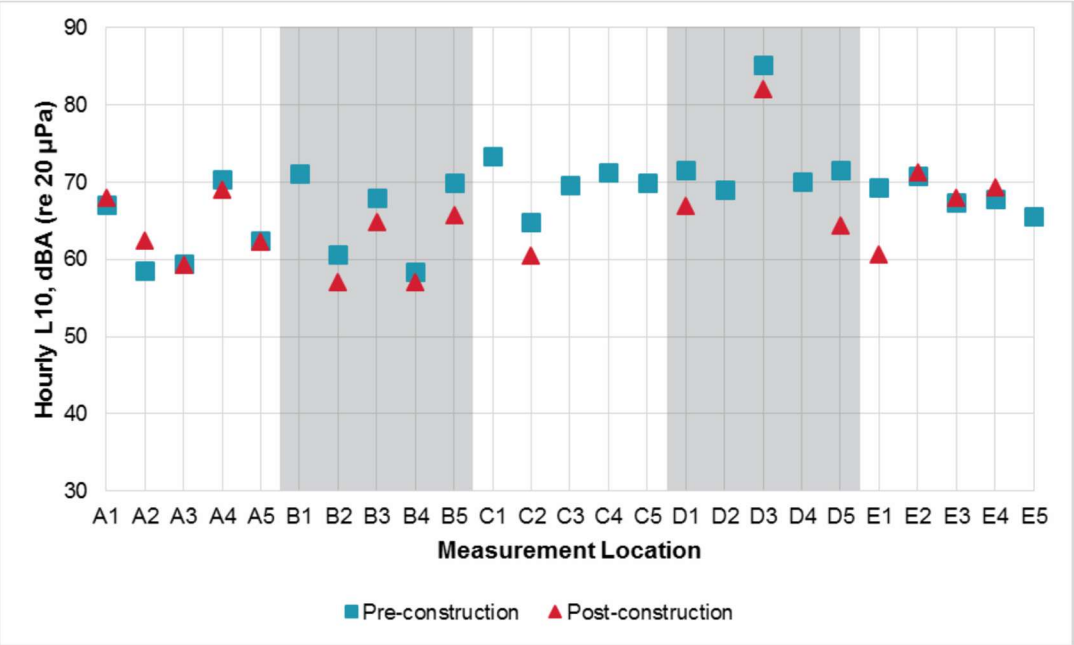

Figure 2-5: L10 measurements before and after construction on I-394 in Minnesota.

2.3.2 Florida

In Florida,[33] there has been an ongoing study to evaluate quieter pavement. The most current reporting has recommended and concluded:

[31] Communication with Peter Wasko, Minnesota Department of Transportation, 2019.

[32] HDR, "A statistical study of changes in tire-pavement noise," I-394 Pavement Noise Study, 2016.

[33] Wayson, R., J. MacDonald, and M.S. Martin, "On-board sound intensity study," FDOT Project No. BDT06, 2014.

- Continue participation in the FHWA Quieter Pavement Program.
- Validation and implementation of the OBSI system.
- Develop and populate a formal acoustic inventory of pavement surfaces used in Florida.
- Develop precision statement based on research findings.
- Conduct training for FDOT personnel on the use of equipment and analysis of data.
- A solid methodology has been defined for collection and analysis of OBSI data and turned into a guidance document.
- A tremendous database of OBSI intensity levels, matched wayside sound pressure levels, meteorological data, and field notes has been established.
- Flexible pavements appear to represent the quieter pavements in use in Florida.
- Three variables that seem significant in the pavement texture in terms of noise control are mean profile depth, aggregate size, and friction number. These variables were selected for analysis because of the general use in pavement design, availability, and are thought to act for surrogates of the acoustic parameters.
- Both the amplitude and frequency spectra were shown to be different based on the variables above.
- Rigid pavement (LGD), dense graded asphalt (FC125), and open graded asphalt (FC5 and FCQ) display distinctly different patterns in frequency spectra.

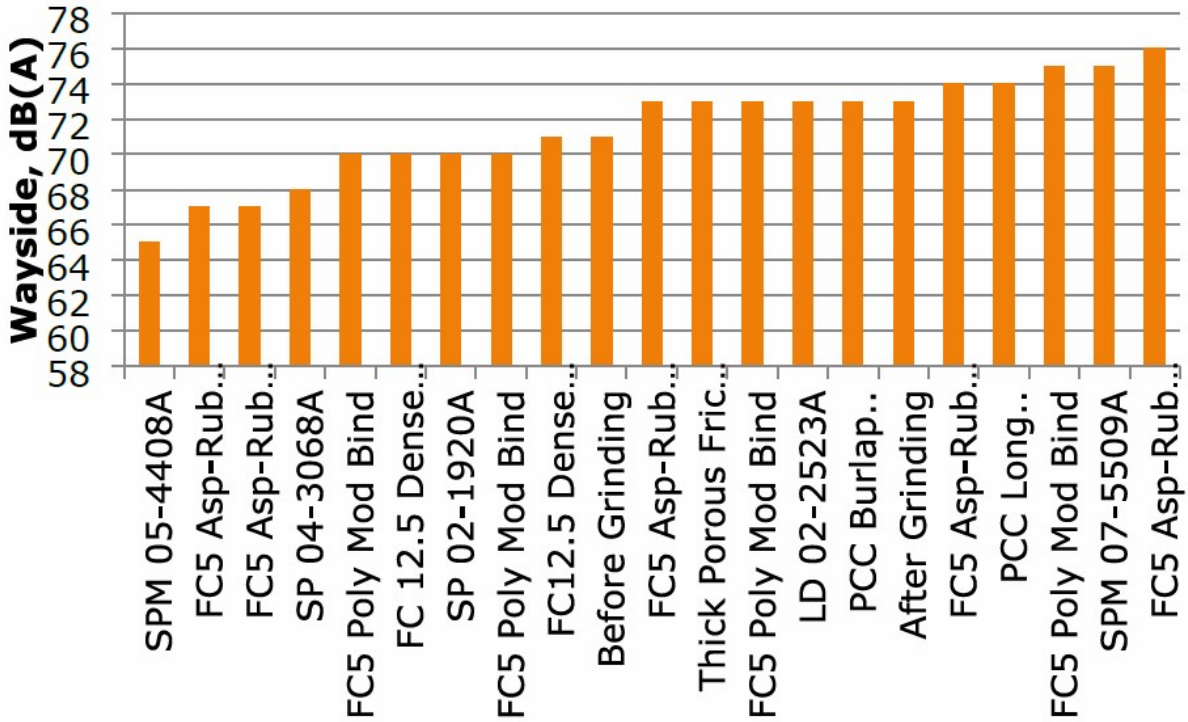

Figure 2-6: Wayside measurements of various surfaces evaluated in Florida study.

2.3.3 Arizona

In 2008, Arizona[34] conducted a study to identify noise reduction products, materials, and technologies currently available and that may have potential as noise mitigation alternatives. A literature review and survey identified measures being used by U.S. transportation organizations as well as international efforts, as follows:

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

Arizona has also been working under a Quiet Pavement Pilot Program (QPPP)[35] in cooperation with the Federal Highway Administration. Asphalt rubber friction course (ARFC) has been used on freeways in the Phoenix area, with period measurements over the last 10 years to assess ARFC as a noise abatement measure.

Tire/pavement noise measurements at the source (using OBSI) documented an average initial reduction of 8.7 dBA compared to the pavements prior to ARFC overlay, and an average increase of 0.5 dB/year afterward. Noise measurements in residential neighborhoods near the freeways using time-averaged wayside data resulted in an average initial reduction of 5.2 dBA. Noise using direct measures of traffic noise adjacent to the freeways showed an average initial reduction of 9.1 dBA compared to the pavements prior to ARFC overlay, and an average increase of 0.5 dB/year since then.

After 10 years, the ARFC overlay is providing an average reduction of 4.8 dB to locations where residents would potentially be living near the freeways with an average reduction of 8.2 dB.

[34] Brown, V., "Survey of traffic noise reduction products, materials, and technologies," Arizona Department of Transportation, Final Report 584, 2008.

[35] Donavan, P. and C. Janello, "Arizona quiet pavement pilot program: comprehensive report," Arizona Department of Transportation, SPR-577-2, 2018.

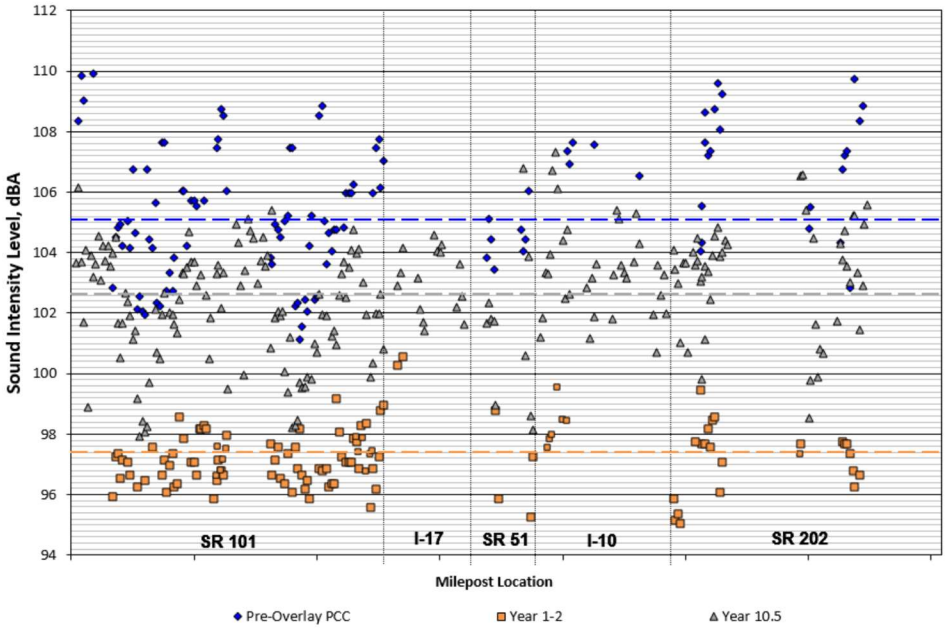

Figure 2-7: OBSI measurements of Arizona pavements evaluated over 10 years.

2.3.4 Texas

In Texas,[36] a study was conducted in 2012 to evaluate the benefits of diamond grinding of concrete pavement. In addition to a study of noise reduction were measures of surface macrotexture, skid resistance, and roughness. The effectiveness of diamond grinding in improving each of these properties was realized. An average overall reduction in noise level of 3.2 dBA was found, with a maximum reduction within frequencies 1,000 Hz to 2,500 Hz. The grinding operation produced a relatively uniform surface in terms of these properties despite the varying pre-existing conditions across the Continuously Reinforced Concrete Pavement (CRCP).

In 2016[37], another study included a comprehensive literature review of the state of the art in designing quieter pavements and all relevant contributing factors in terms of surface macrotexture, porosity, and resilience. A pavement-noise database was compiled from different pavement surfaces used in Texas, including noise measurements using OBSI. A case study documents the design and use of a noise barrier in conjunction with low-noise surfaces to address noise complaints from residents residing along a busy stretch of IH30 near Dallas.

Thin Overlay Mixes (TOM)[38] were found to have excellent noise performance and are recommended as the best mixture for low-noise surfaces. PFC mixtures also performed well, but not consistently as they were subject to premature aging and clogging that reduced their noise-attenuating properties.

[36] Buddhavarapu, P., A. de Fortier Smit, A. Banerjee, M. Trevino, and J. Prozzi, "Evaluation of the benefits of diamond grinding of a CRCP," TRB Paper 13-1515, 2013.

[37] de Fortier Smit, A., M. Trevino, N. Garcia, P. Buddhavarapu, and J. Prozzi, "Selection and design of quiet pavement surfaces," FHWA/TX-16/0-6819-1, 2016.

[38] Communication with Manuel Trevino, UT Austin, 2019.

Austin District[39] subsequently placed several thin overlay mixes solely for the purpose of mitigating noise, both on low-volume roads and major highways. Lower noise levels were perceived by drivers and in adjacent neighborhoods previously affected by highway noise. OBSI testing of the pavements were performed over approximately four years, with significant noise level reductions compared to conventional pavements as well as to other quieter pavements including PFC. Average OBSI noise levels range from 96.7 to 99.8 dBA, which is among the quietest of all pavement types (see Figure 2-8 for relative noise levels for various types of pavement).

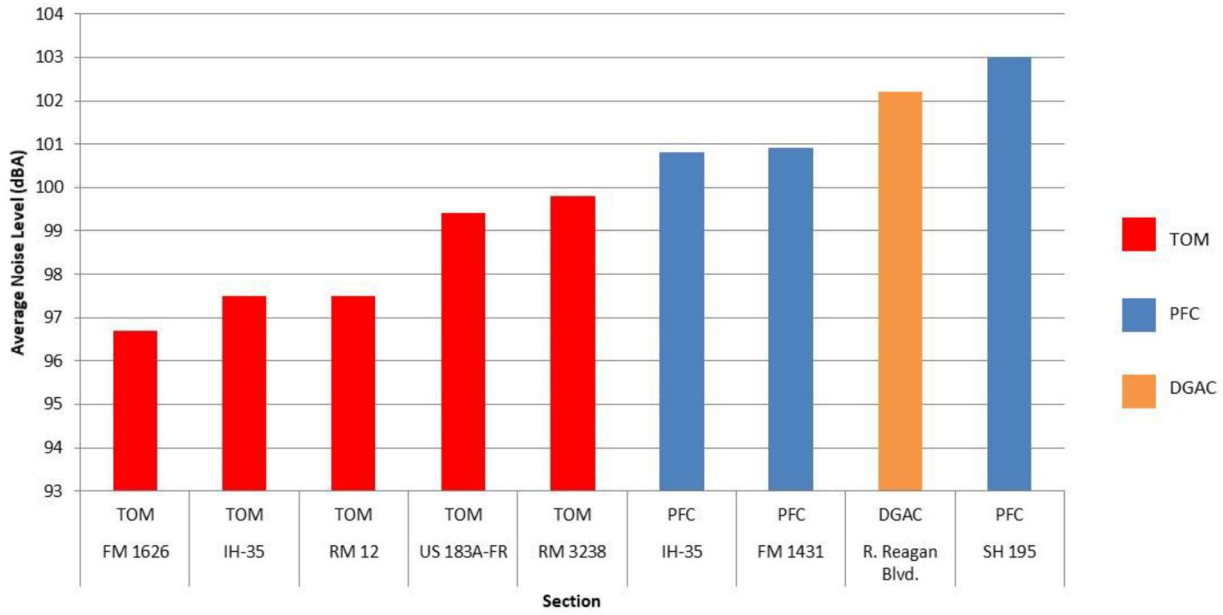

Figure 2-8: OBSI noise levels of various pavements evaluated in Texas study.

2.3.5 New Jersey

In New Jersey[40] on a Garden State Parkway project, there was interest in a new open-graded asphalt concrete (OGAC) surface. Measurements and analysis with TNM v2.5 confirmed an approximate 6 dB reduction new compared to average pavement.

2.3.6 Tennessee

In 2005, Tennessee[41] DOT conducted a pilot project on a rural freeway to evaluate both the durability and noise-generating characteristics of SMA and OGFC in addition to dense-graded asphalt. The study concluded that the A-weighted noise level differences calculated from SPB and time-averaged (CTIM) noise measurements were small, making it difficult to develop definitive conclusions. However, noise levels generated by automobiles on the OGFC pavement were determined to be 8 to 10 dB lower at frequencies above 1.2 kHz (1200 Hz). TDOT now routinely specifies OGFC for freeway projects but has not conducted any additional noise studies.

[39] Trevino, M., "OBSI tests on thin overlay mixes in Austin, Texas," San Diego Noise-Con, 2019.

[40] Communication with Leo Tidd, WSP, 2019.

[41] Communications with Geoff Pratt and Darlene Reiter, Bowlby & Associates, 2019.

2.3.7 North Carolina

In North Carolina,[42] little to no work has been performed on quieter pavement in recent years. As policy, NCDOT does not select pavement type specifically for noise, but sometimes a "quieter pavement" is selected as a result of other needs, such as to help mitigate hydroplaning.

NCDOT has previously used both open-graded friction course and diamond grinding, but formal studies of these have not been performed.

2.3.8 Washington State

The quiet pavement research program in Washington[43] was disbanded a few years ago. Pilot sections were tried using quieter asphalt overlays and new asphalt, but the longevity of each of the trials was very short, commonly requiring placement within 2 years. In general, poor acoustic durability was reported. There is ongoing interest to address heavy rutting from stud tire damage by diamond grinding, which has yielded some initial noise reduction. For new pavements, longitudinal grooving is used.

2.3.9 California

Quiet pavement in California[44] is used on occasion to address noise complaints. A lot of research and measurements have been performed over the years that have led to a number of approaches for making transportation infrastructure quieter. Caltrans issued a Quiet Pavement Design Memo in 2009 stating that Caltrans would avoid constructing loud pavement surfaces near noise-sensitive receptors. This led to the development of diamond grooving and grinding for bridge deck texture, which has also been used on some new and existing concrete pavement surfaces. Another example was an initiative to look at quiet chip seals using smaller chips. Very quiet asphalt pavement has also been identified. Most of these are OGFC, where OBSI measurements predict a decrease of 5 to 6 dBA; however, roadside measurements yield a 9 to 10 dBA reduction. High absorption of these pavements explain the additional benefits, including a particularly significant reduction within the 1600 Hz octave band. This additional benefit is similar to reports of similar products in Florida, Texas, and at NCAT. Caltrans believes that investing in absorptive pavement surface is more cost effective than placing absorptive surface on a sound wall, or even building an expensive sound wall.

In 2011, Caltrans[45] performed a tire-pavement noise survey using OBSI of various OGFC evaluated along I-80 near Davis. In this study, these pavements were ranked among other pavements previously evaluated by Caltrans. It was found that as these OGFC surfaces aged, they ranked among the highest noise levels of all asphalt pavements. However, they remained quiet compared to the majority of the PCC pavements in California. In the same study, Rubberized Asphalt Concrete (RAC) ranked among the quietest surfaces in California. Figure 2-9 shows OBSI level for various pavement types and ages.

[42] Communications with Missy Pair and Tracy Roberts, North Carolina Department of Transportation, 2019.

[43] Communication with Jim Laughlin, Washington State Department of Transportation, 2019.

[44] Communication with Bruce Rymer, California Department of Transportation, 2019.

[45] Illingworth & Rodkin, "I-80 Davis OGAC Pavement Noise Study", California Department of Transportation, May 13, 2011.

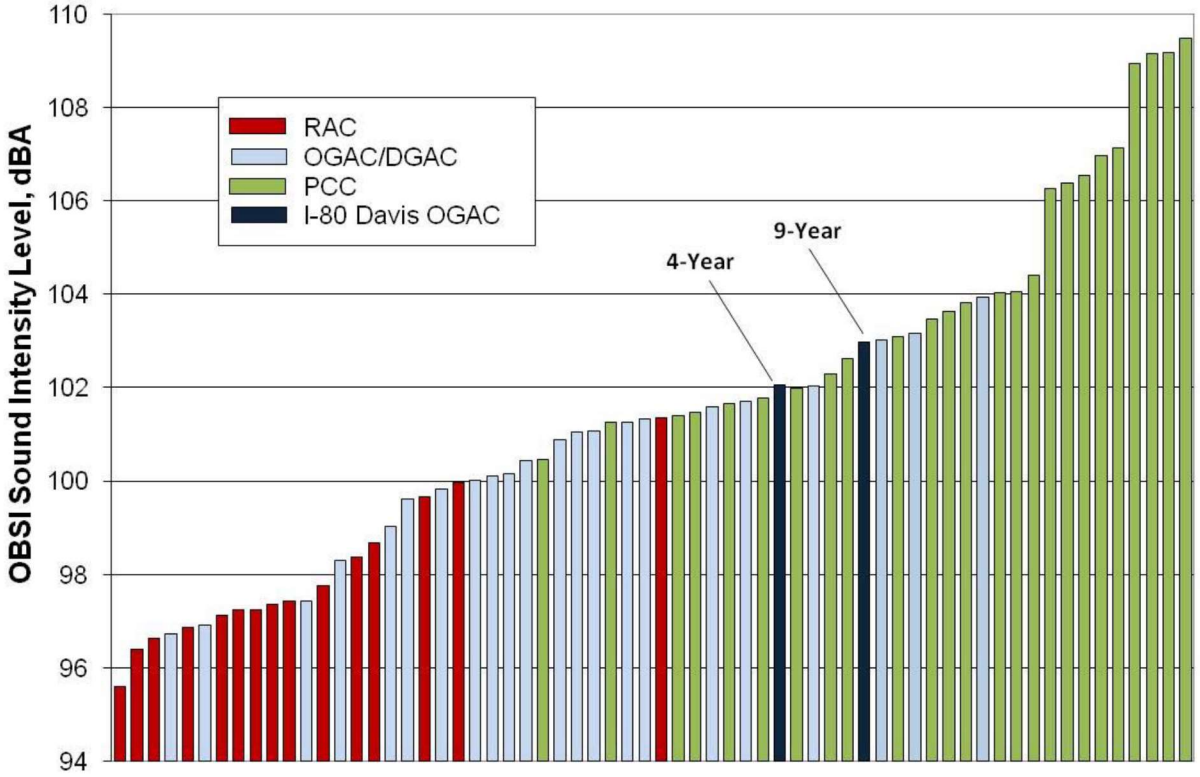

Figure 2-9: OBSI noise levels of various pavements in California.

The US DOT Volpe Center[46] evaluated select pavements in California in 2014. From wayside measurements, it was found that the acoustical durability of RAC was approximately 0.4 dB/year, and OGAC deteriorated at approximately 0.1 dB/year for the first 5 years since installation (see Figure 2-10).

[46] Rochat, Judith, D. Read, "Noise benefits of asphalt pavements—Trends at ages up to 52 months," Noise Control Eng. J. 57 (2), March-April 2009.

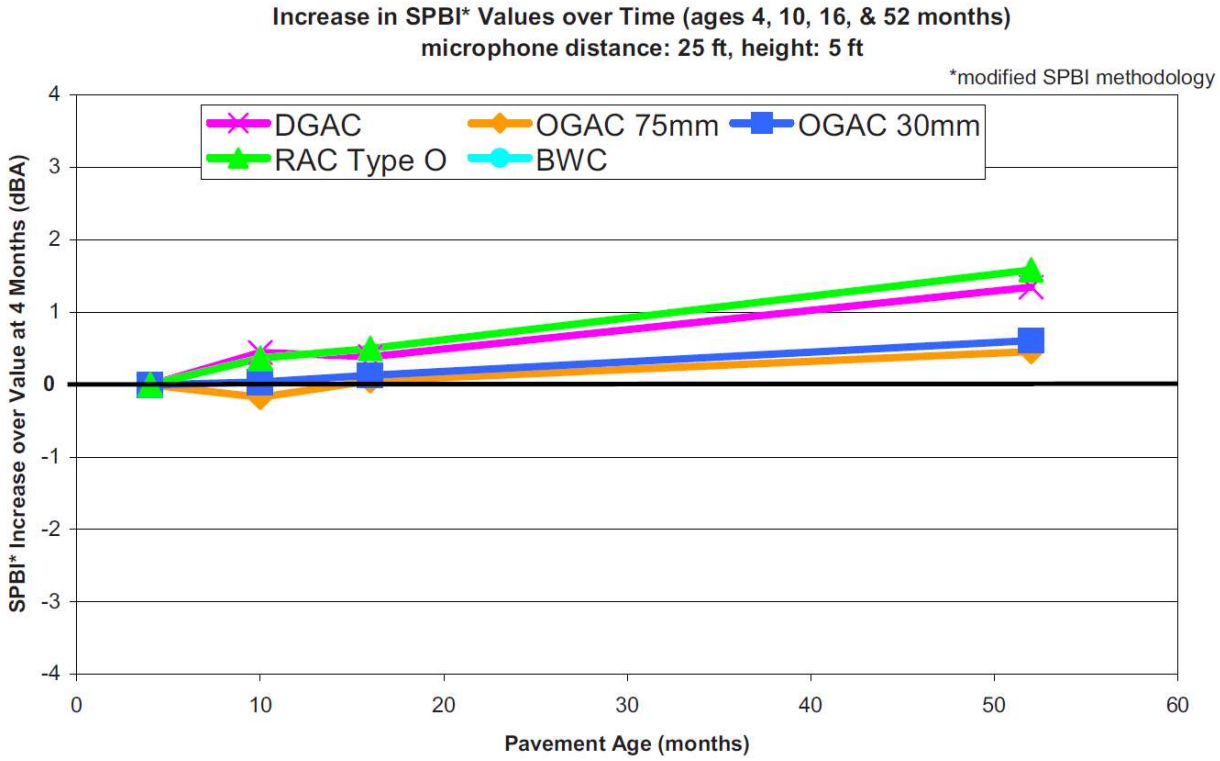

Figure 2-10: Acoustic durability of select pavements in California.

2.3.10 NCHRP

NCHRP Report 738[47] reported on a methodology for evaluating acoustic performance and life-cycle costs of various noise mitigation for a systematic and fair comparison of abatement alternatives. The resulting methodology provides a means of evaluating pavement strategies and barriers together for feasibility, reasonableness, effectiveness, acoustic longevity, and economic features.

2.3.11 U.S. National Park Service

The U.S. National Park Service and USDOT Volpe Center[48] have completed work recently in Death Valley[49] as a case study looking at four viable surface treatments including two chip seals with different size aggregates and two microsurfacing treatments with different mixtures. Each surface is commonly used, with the default surface being a 9.5 mm (3/8 inch) chip seal. Of the four options, none were exceptionally quiet, but the Type II microsurfacing and 4.75 (1/4 inch) chip seal were considered reasonably good. The range in measured sound level between all alternatives was approximately 3 dB.

[47] Donavan, P., L. Pierce, D. Lodico, J. Rochat, and H. Knauer, *Evaluating pavement strategies and barriers for noise mitigation*, National Cooperative Highway Research Program, Report 738, 2013.

[48] Communication with Aaron Hastings, USDOT Volpe Center, 2019.

[49] Rochat, J. and M. Lau, "Demonstration of using quieter pavement in Death Valley National Park," Natural Resource Technical Report, 2013.

Propagation at great distances is important in parks, and frequency content was studied. Microsurfacing resulted in higher levels of low frequency content, although some of this may be from construction defects in the form of ripples.

In 2013[50], the NPS evaluated quieter pavement alternatives with the intent to identify possible solutions to reduce road noise in some National Parks. Parks looking to reduce road noise needed information regarding which quieter pavements might work based on site-specific factors including weather, traffic, and available materials and construction expertise. The purpose of the resulting document is to provide guidance and recommendations on quieter pavements to help park personnel select pavement surfaces that minimize tire-pavement noise.

2.3.12 International

In 2013, Australia's VicRoads[51] initiated a 5-year acoustic assessment program for asphalt pavements to reduce traffic noise by selection of pavement.

After three years, the best performing asphalt is open-graded asphalt (OGA) with additional treatment by grinding. Noise levels are reported as 3 dB lower than those for standard OGA and a lesser degradation in acoustic performance over time. Acoustic durability of standard OGA is approximately +1 dB per year, resulting in noise levels within 1 dB of the SMA after two years of trial. Two double-layer systems were also evaluated, which had lower initial values compared to standard OGA, but also showed the same increase over the time of the trial.

Figure 2-11: OGA with and without grinding in Australia VicRoads project.

Australia's Roads and Maritime Services[52] has carried out low noise diamond grinding of existing concrete pavements in the Valla Beach area of the Nambucca Heads to Urunga (NH2U) project. Using both SPB and OBSI measurements, a general trend of lower noise levels after grinding was observed.

[50] Sohaney, R., R. Rasmussen, P. Donavan, and J. Rochat, "Quieter pavements guidance document," National Parks Service, 2013.

[51] Buret, M., J. McIntosh, C. Simpson, "Long-term asphalt trial: Results of acoustic tests after three years," Acoustics Australia 44.2, 2016.

[52] Sburlati, D. and A. Miller, "Low noise diamond grinding pavement noise monitoring," SLR Consulting Australia, 2019.

The diamond ground concrete pavements produced comparable noise levels to the traditionally "low noise" 10 mm stone mastic asphalt (SMA) pavement.

In New Zealand[53], long-term acoustic performance of open graded porous asphalt (OGPA) was evaluated on over 150 sections of different ages. Measurements show that through the eight to ten years of functional life, there is no sudden change in noise level, but rather a steady and shallow deterioration of acoustic performance.

Ten test sections were installed in May 2012 in Belgium,[54] with the objective of integrating Thin noise-reducing Asphalt Layers (TAL) in the Flemish road surface policy in a later stage. Eight test sections are paved with TAL with a thickness of a maximum of 30 mm and a maximum content of accessible voids of 18%. The other two sections consist of a Double-layer Porous Asphalt Concrete (DPAC) and a Stone Mastic Asphalt (SMA-10 as a reference section). Initial noise reductions were found of up to 6 dBA, but higher than expected acoustic deterioration rates and the presence of raveling led to noise reductions of a maximum of 1 dBA after almost three years.

2.3.13 Absorptive Treatments of Shoulders

Rochat in 2014[55] suggested that sound absorptive ground adjacent to transportation systems can reduce noise impacts. For the near travel lane, it was calculated that a 3 m (10 ft) sound-absorptive shoulder would influence homes at a distance of about 27 to 76 m (90 to 250 ft) from the center of the near travel lane. It is suggested to use quieter pavements combined with sound absorptive shoulders to get the best results, likely a 5-7 dB reduction compared to standard pavement/shoulders.

Staiano in 2012[56] suggested that reduced traffic flow on shoulders may permit highly sound-absorptive pavement. TNM v2.5 was used to model a two-, three-, and four-lane roadway with a shoulder, and receivers were placed 15-122 m (50-400 ft) from the center of the near travel lane. Traffic included 5% medium trucks and 5% heavy trucks. The 3.7 m (12 ft) shoulder was represented first by two pavement surfaces (sound reflective, EFR 20,000 cgs rayls, and sound absorptive, 2000 cgs rayls). An experimental ultra-soft shoulder (EFR 300 cgs rayls) was also examined and compared to the standard pavement surface. Applying an experimental ultra-soft shoulder (sound absorptive surface, 300 cgs rayls), the noise reduction compared to a standard pavement shoulder ranged from about 1-3 dB at 30 m (100 ft) to 4-6 dB at 122 m (400 ft), with the highest attenuation for the two-lane case. In summary, noise reduction of up to 3 dB for real sound-absorptive pavements and up to 6 dB for experimental (non-existent) pavements can potentially be achieved.

A 2013[57] Chalmers study reported that it is possible to combine acoustic resonators with porous road surfaces. Tuned to 1 kHz, the buried resonators can improve the noise reduction capability of new twin-layer porous asphalt by approximately 3 dBA. Pass-by measurements made on a test section show that the

[53] Lester, T., V. Dravitzki, P. Carpenter, I. McIver, and R. Jackett, "The long-term acoustic performance of New Zealand standard porous asphalt," Opus International Consultants Ltd, 2017.

[54] Vuye, C., A. Bergiers, and B. Vanhooreweder, "The acoustical durability of thin noise reducing in asphalt layers," Coatings, 2016.

[55] Rochat, J., "Using the ground to reduce transportation noise," presentation at Transportation Research Board Noise and Vibration Committee Summer Meeting, 2014.

[56] Staiano, M., "Possible benefits of sound-absorptive highway shoulders," presentation at Transportation Research Board Noise and Vibration Committee Summer Meeting, 2012.

[57] Chalmers University of Technology, CSTB, Canevaflor, IBBT Gent University, Muller BBM, Open University, City of Stockholm, TOI, University of Sheffield, University of Bradford, Stockholm University, Acoucite, and Hangyang University, "Novel solutions for quieter and greener cities, Brochure summarizing HOSANNA Project, 2013.

sound pressure level dropped 3-4 dBA for passenger cars and 2 dBA for heavy trucks for a 1.2 m (3.9 ft) high receiver at a distance of 7.5 m (24.6 ft). The reference mentions that this effect lasts for at least 3 years.

A buried resonator (like a bottle) can be tuned to a desired frequency. A 4 m (13.1 ft) wide array of such resonators placed in the shoulder and tuned to 350 Hz is predicted to reduce noise for a 1.5 m (5 ft) high receiver 40 m (131 ft) from a two-lane road (5% heavy and 95% light vehicles, 50 km/h) by 2-3 dBA.

3. STRATEGY CATEGORY: HIGHWAY DESIGN CHOICES

Highway design choices include horizontal and vertical alignment alterations, solid safety barriers in lieu of guardrails, and separation zones between roadways and side paths. All are described in this section.

3.1 Horizontal and Vertical Alignment

Table 3-1 shows a summary of the strategy *horizontal and vertical alignment alterations*. The summary is based on information extracted from the references described in this subsection.

Table 3-1: Summary of strategy: horizontal and vertical alignment alterations.

Strategy	Noise Benefit	Costs	Context Appropriateness
Horizontal alignment shift	< 1 dB to 10+ dB depending on project specifics: extent of shift, site topography, and vehicle types	Very expensive due to additional right-of-way and construction costs	Highways or local roadways with vacant land opposite the sensitive sites
Vertical alignment shift	< 1 dB to 10+ dB depending on project specifics: extent of shift, site topography, and vehicle types	May be less expensive than horizontal shift if right-of-way is sufficient	Highways or local roadways where right-of-way is sufficient

Alteration of horizontal and vertical alignments are noise abatement measures considered by some state DOTs because such changes are identified as acceptable abatement measures in United States Department of Transportation Federal Highway Administration's (FHWA) Title 23 Code of Federal Regulations, Part 772 Section 15 (23 CFR 772.15).[58] Horizontal alignment changes involve moving the roadway away from noise sensitive sites. Vertical alignment changes involve raising or lowering the roadway elevation relative to the elevation of the noise sensitive site. Based upon the research team's experience with numerous projects involving traffic noise analysis, horizontal alignment changes are frequently discounted without quantitative analysis because of the potential acquisition of additional right-of-way, the potential displacement of developed land uses such as homes, businesses, and intuitions, and the potential negative impacts to regulated natural resources. Likewise, changes in vertical alignment are discounted because of the same concerns, plus the increased cost of more complex drainage systems and extensive earth moving.

Based upon responses to the online survey and interviews conducted for this project, horizontal and vertical alignment changes have been considered regularly, but usually as abatement measures without detailed traffic noise analysis. Therefore, the extent of either type of alignment change that might be necessary to provide a specific amount of noise reduction is not well known. Several interviewees explained that noise levels related to substantially different alternative alignments were predicted with TNM (assumed to be v2.5)[59] to document the differences in potential impacts. Generally, the alternative

[58] Federal Regulations, *Procedures for Abatement of Highway Traffic Noise and Construction Noise*, 23 CFR Part 772, Fed. Reg. Vol. 75, No. 133, July 13, 2010.

[59] Menge, C., C. Rossano, G. Anderson, and C. Bajdek, *FHWA Traffic Noise Model, Version 1.0: Technical Manual*, Report No. FHWA-PD-96-010, 1998. TNM v2.5 update sheets: https://www.fhwa.dot.gov/environment/noise/traffic_noise_model/tnm_v25/tech_manual/index.cfm, 2004.

alignments were developed to avoid utility conflicts, reduce construction cost, or minimize right-of-way impacts; the alternative alignments were not developed to reduce noise. During the telephone interviews conducted for this project, Jessica Goza-Tyner (Traffic Noise Analyst at Nevada DOT) explained that trying to reduce highway traffic noise has never been the reason a roadway alignment was shifted, however, at the I-15/Starr Avenue Interchange near Las Vegas, the alignment shift away from the residences did eliminate noise impacts.[60]

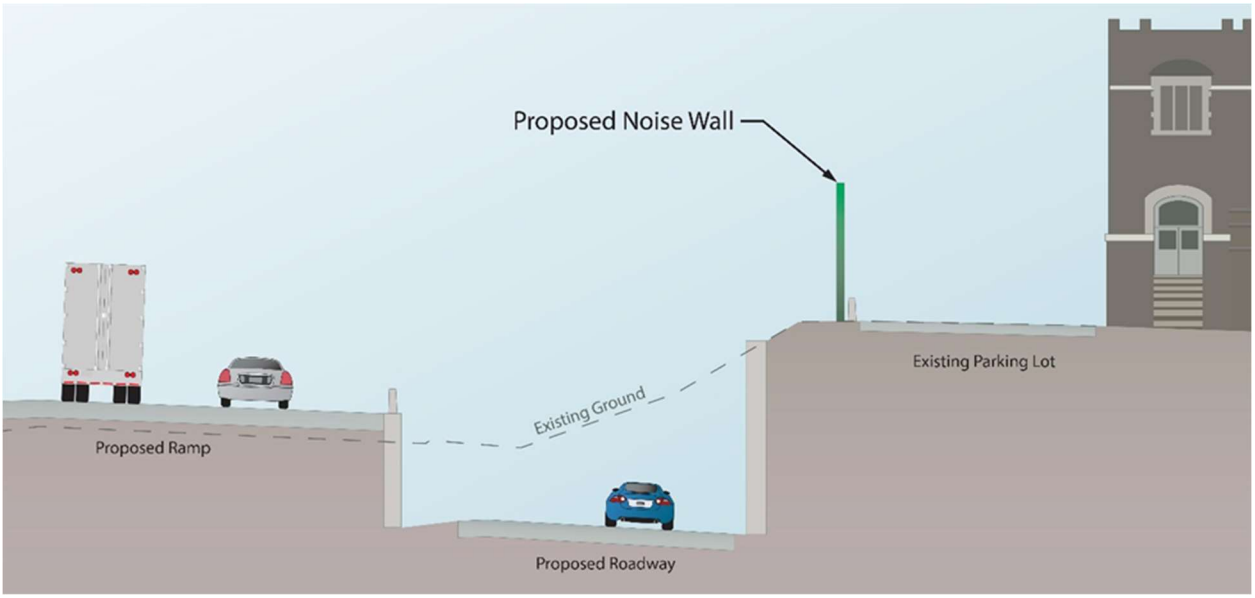

Figure 3-1: Example of vertical alignment changes (ms consultants, inc.).

An exception to the trend of looking at alignments developed for other reasons was a recent project in Arizona where, if enough space was available, the DOT examined horizontal and vertical alignment shifts during very preliminary project planning. Arizona DOT conducted simplified TNM v2.5 analyses of multiple horizontal alignments (sometimes several thousand feet) away from highly noise sensitive locations. Shifting the alignment horizontally away from the sensitive sites reduced noise levels substantially depending upon the distance involved. These analyses also considered existing and projected land use to determine if there was sufficient space to make the proposed horizontal shift. If the shifted alignment reduced noise levels at sensitive sites and had no unreasonable land use impacts, it was given further consideration.[61]

Ohio DOT's Design Manual explains that the most important considerations to horizontal alignment design are sight distance, curve radius, and superelevation. Ohio DOT's Design Manual also explains that the most important considerations to vertical alignment design are sight distance, grades, and vertical curves. These primary design considerations are directly related to safety and driver comfort. Additional design considerations involve available right-of-way, constructability, ease of maintenance, environmental impacts, and construction cost. Therefore, investigation of horizontal and vertical alignment changes to reduce noise impacts will have to take into account the complex relationship of all other design considerations. This conclusion was more simply explained in FHWA's Analysis and

[60] Communication with J. Goza-Tyner, Nevada DOT, October 2019.

[61] Communication with A. Newton, Newton Environmental Consulting, October 2019.

Abatement Guidance, "It may be very expensive to alter the alignment of a highway to reduce noise levels."[62]

In order to estimate the probable cost of horizontally shifting an arterial roadway away from noise sensitive sites, the research team conducted a FHWA Traffic Noise Model (TNM v2.5) study for a recently completed project in Central Ohio where noise impacts (noise levels 1-2 dB above impact criteria) were predicted at several 1st row homes. The roadway location, number of vehicles (traffic volume), vehicle mix, vehicle speed, and general ground type were exactly the same as used in the previously completed TNM model. It should be noted that traffic on this arterial roadway was assumed to traveling at 72 km/h (45 mph) and was primarily autos (including pick-up trucks and SUVs). Only 5% of the traffic were trucks with those divided equally between medium trucks (delivery trucks, school buses, etc.) and heavy trucks (tractor-trailer, dump trucks, etc.). The TNM model used for this study was the portion of the original study area where two cul-de-sacs backed-up to the arterial roadway and vacant land existed on the opposite side of the roadway.

The noise barriers included in the previously completed model were deleted and additional receivers were added to identify the distance between the edge of the nearest travel lane and a receiver with a noise level just below impact level. Using this model it was determined that if the roadway was shifted horizontally 15.2 m (50 ft) away from the 1st row receivers there would be no noise impact. A rough cost estimate for the additional right-of-way required to shift 533 m (1,750 ft) of roadway 15.2 m (50 ft) laterally is $350,000 based upon appraised residential land values available from the County Auditor's website.[63] Additionally, the research team reviewed the project's construction cost estimate and determined the additional construction cost required to shift 533 m (1,750 ft) of roadway 15.2 m (50 ft) laterally would exceed $2,000,000. Therefore, based upon these rough right-of-way and construction cost estimates, altering the horizontal alignment of an arterial roadway to reduce noise levels below impact criteria is very expensive and does not have merit unless there is sufficient vacant land readily available.

Given that horizontal alignment changes can nearly always be discounted because of potential right-of-way and construction costs, vertical alignment changes appear to be more realistic. As explained in Cramer 2006, when noise sensitive areas cannot be avoided by horizontal shifts, often vertical shifts can be considered to depress the highway below the grade of nearby noise-sensitive land uses and create roadway "cut-slopes" that shield the noise source from the receiver, notwithstanding potentially significant engineering considerations and repercussions.[64]

Zimmer provided specific examples of traffic noise effects related to elevated, depressed, and at-grade freeways in Texas. This report found that depressed freeway sections provide the greatest reduction in noise in areas both near to and far from the roadway, especially if the walls of the depression are sloped.[65] Case studies in Zimmer provide insight into the specific amount of noise reduction associated with vertical alignment alterations. The US 281 San Antonio case study measured noise levels at various distances from the highway in comparable elevated, depressed, and at-grade sections (See Table 3-2).

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[62] Federal Highway Administration, *Highway Traffic Noise: Analysis and Abatement Guidance Analysis and Abatement Guidance*, Appendix C, December 2011.

[63] Delaware County Auditor, http://www.delco-gis.org/auditor/.

[64] Cramer, J., R. Kolmansberger, and J. Wilson, *Statewide Investigation of Noise Abetment Alternatives*, Ohio DOT, June 2006.

[65] Zimmer, R., and J. Buffington, *Traffic Noise Effects of Elevated, Depressed, and At-Grade Level Freeways in Texas*, National Technical Information Service, Springfield Virginia, February 1997.

Table 3-2: Measured noise levels US 281 San Antonio case study.[66]

Distance from ROW Line	Distance from Center Line	At-Grade Section Noise Level	Elevated Section Noise Level	Depressed Section Noise Level
15.2 m (50 ft)	61 m (200 ft)	70.8	65.4	63.1
45.7 m (150 ft)	96 m (300 ft)	66.6	63.7	59.4
76.2 m (250 ft)	122 m (400 ft)	63.0	62.6	54.5
All noise levels are dBA Leq				

The only reference to the height/depth of the elevated/depressed sections included in the US 281 San Antonio Case Study are photographs of each section.[67] The elevated sections appear to be high enough to accommodate bridges over cross roads and the depressed sections appear to be low enough to allow cross roads to bridge over the mainline. Therefore, the research team estimates these vertical alignment changes, which provide a substantial amount of noise reduction, to be roughly 6.1 m(20 ft).

During the telephone interviews conducted for this project, Greg Smith (retired NCDOT Noise & Air Quality Supervisor) mentioned a two lane to five lane widening project in eastern North Carolina where lowering an arterial road about 0.6 m (2 ft) decreased predicted noise levels at nearby homes about 1-2 dB or just enough to get below impact criteria. However, the vertical alignment change was ultimately not advanced because the deeper ditches required by the change would reach the ground water table and the available right-of-way not sufficient.[68]

In order to estimate the probable cost of lowering an arterial roadway about 0.6 m (2 ft), the research team revisited the plans for the recently completed project in Central Ohio where noise impacts (noise levels 1-2 dB above impact criteria) were predicted at several 1st row homes. A rough cost estimate for the excavation required to lower/depress 457 linear m (1,500 linear ft) of a 5 lane arterial roadway 0.6 m (2 ft) is $101,655.[69] It was assumed that no additional right-of-way would be required and all other construction costs would be similar to the original cost estimate. Therefore, based upon excavation cost alone, lowering an arterial roadway 0.6 m (2 ft) to reduce noise levels to below impact criteria may have merit. However, sight distance, grades, driveway adjustments, stormwater drainage, utility conflicts, available right-of-way, constructability, ease of maintenance, and environmental impacts must be considered on a project specific basis.

3.2 Solid Safety Barriers in Lieu of Guardrail

Table 3-3 shows a summary of the strategy *solid safety barriers in lieu of guardrail*. The summary is based on information extracted from the references described in this subsection.

[66] Zimmer, R., and J. Buffington, *Traffic Noise Effects of Elevated, Depressed, and At-Grade Level Freeways in Texas*, National Technical Information Service, Springfield Virginia, February 1997.

[67] Zimmer, R., and J. Buffington, *Traffic Noise Effects of Elevated, Depressed, and At-Grade Level Freeways in Texas*, National Technical Information Service, Springfield Virginia, February 1997.

[68] Communication with G. Smith, AECOM, November 2019.

[69] Excavation cost assumed to be $15 per cubic yard, ms consultants.

Table 3-3: Summary of strategy: solid safety barriers in lieu of guardrail.

Strategy	Noise Benefit	Costs	Context Appropriateness
Solid safety barrier in lieu of guardrail freeway	0.4 dB to 2.6 dB depending on project specifics: distance to receiver and site topography	Minor overall project cost increase	Limited-access highways if state standards allow
Solid safety barrier in lieu of guardrail arterial	2.0 dB to 6.6 dB depending on project specifics: distance to receiver and site topography	Minor overall project cost increase	State or local roadways if state or local standards allow

In general, it is preferred to keep the entire clear zone free of fixed objects wherever economically feasible.[70] A safety barrier, either guardrail or concrete barrier, is used to shield motorists from natural or man-made obstacles located on the roadside within the clear zone. Roadside obstacles may be fixed objects or non-traversable terrain. Examples of fixed objects are bridge piers and abutments, culverts pipes and headwalls, non-breakaway sign or light supports, and utility poles. Examples of non-traversable terrain include bodies of water (where depth exceeds 0.3 m (1 ft)), transverse ditches, some retaining walls such as mechanically stabilized earth (MSE) walls, noise walls, and, most commonly, slopes. Height and steepness of slope are the basic factors considered in determining the need for guardrail or concrete barrier.

Figure 3-2: Example of guardrail, solid safety barrier, and noise wall (ms consultants, inc.).

[70] Ohio Department of Transportation, Location and Design Manual – Volume One, Section 601.1.1, October 2019.

Guardrail is a common type of safety barrier that involves a steel rail and wooden posts. The rail acts to capture impacting vehicles and dissipate energy. Guardrail posts are designed to support the rail and rotate through the soil when impacted. Guardrail can be installed along any roadway where a clearance of 1.5 m (5 ft) can be provided to allow for rail deflection. Post spacing can be adjusted to allow guardrail to be installed where only 0.9 m (3 ft) of deflection is available.

Concrete barriers are used in locations where barrier deflections are not possible such as along retaining walls and walls that connect bridge pier columns. Ohio's Single Slope Concrete Barrier Type B is 107 cm (42 in) tall, Type B1 is 145 cm (57 in) tall, Type C can vary in height from 107 cm (42 in) to 168 cm (66 in), and Type C1 can vary from 145 cm (57 in) to 206 cm (81 in) tall.[71]

The research team is not aware of traditional guardrail being considered during the noise analysis process because of the openings below the rail and between the posts. Based upon responses to the online survey and interviews conducted for this project, the influence of concrete barriers on wayside traffic noise levels has been considered occasionally including on highway projects in Arizona, New York, and Wisconsin. Members of the research team have also included concrete barriers in analysis conducted in Ohio and Pennsylvania. These concrete barriers were features of the proposed roadway and not suggested as noise mitigation.

To help estimate noise reduction due to concrete barriers along roadways, the research team conducted an FHWA Traffic Noise Model (TNM)[72] study, adding concrete barriers to previously completed noise models. Both a freeway on-ramp and an arterial roadway widening scenario were examined. The roadway and receiver locations, number of vehicles (traffic volume), vehicle mix, vehicle speed, and general ground type were exactly the same as used in the previously completed models. The noise barriers included in the previously completed models were deleted and concrete safety barriers were added as TNM barriers along the roadway shoulder.

3.2.1 New Freeway On-Ramp Scenario

This scenario involved constructing a new southbound on-ramp at an existing interstate highway partial diamond interchange. Because the new on-ramp would be supported by a retaining wall, to avoid right-of-way impacts, it would have a traditional guardrail along the outside shoulder. As shown in Table 3-4, the previously completed model resulted in noise impacts (predicted future noise levels above residential noise abatement criteria) at five single family homes. However, with a 168 cm (66 in) tall concrete safety barrier replacing the guardrail, there would be no noise impacts, and evaluation of a noise barrier would not be warranted.

Table 3-4: Predicted noise levels with concrete safety barrier: new freeway on-ramp scenario.

Receiver ID	Traffic Noise Level with Traditional Guardrail	Traffic Noise Level with 66" Tall Concrete Barrier	Difference Attributable to 66" Tall Concrete Barrier
A	66.1	65.7	0.4
B	66.1	63.7	2.4
C	67.0	65.1	1.9

[71] Ohio Department of Transportation, Location and Design Manual – Volume One, Section 603.1.4, October 2019.

[72] Menge, C., C. Rossano, G. Anderson, and C. Bajdek, *FHWA Traffic Noise Model, Version 1.0: Technical Manual*, Report No. FHWA-PD-96-010, 1998. TNM v2.5 update sheets: https://www.fhwa.dot.gov/environment/noise/traffic_noise_model/tnm_v25/tech_manual/index.cfm, 2004.

D	66.1	64.5	1.6
E	66.4	63.8	2.6
All noise levels are dBA Leq(h) predicted with TNM 2.5 by ms consultants, inc. A noise impact would occur if the noise level was 1 dB below the Noise Abatement Criteria of 67 dB (Activity Category B Residential Land Use)[73]			

3.2.2 Arterial Roadway Widening Scenario

This scenario involved symmetrical widening of an existing local roadway from one lane in each direction to two lanes in each direction. The terrain in the area was gently sloping with existing homes at one end about 0.6 m (2 ft) higher than the roadway and the homes at the opposite end about 1.2 m (4 ft) lower than the roadway. Homes in the middle were basically level with the roadway. None of the homes have driveways to the roadway which would have precluded the construction of the concrete safety barrier. As shown in Table 3-5, the previously completed model resulted in noise impacts (predicted future noise levels above residential noise abatement criteria) at 12 single family homes. However, with a 107 cm (42 inch) tall concrete safety barrier (Ohio DOT Type B) constructed along the roadway shoulder, all but one noise impact would be eliminated. Table 3-5 also shows that the studied concrete safety barrier was most effective where the homes were level with or lower than the roadway.

These results of the New On-Ramp Scenario and the Arterial Roadway Widening Scenario both suggest that including standard concrete safety barriers in TNM Version 2.5 can reduce or eliminate noise impacts associated with some projects.

Table 3-5: Predicted noise levels with concrete safety barrier: arterial roadway widening scenario.

Receiver ID	Traffic Noise Level with Traditional Guardrail	Traffic Noise Level with 42” Tall Concrete Barrier	Difference Attributable to 42” Tall Concrete Barrier
A	69.1	67.1	2.0
B	68.8	66.5	2.3
C	67.7	64.2	3.5
D	68.4	66.2	2.2
E	68.2	63.5	4.7
F	68.0	62.6	5.4
G	68.3	62.6	5.7
H	68.1	62.4	5.7

[73] Federal Regulations, *Procedures for Abatement of Highway Traffic Noise and Construction Noise*, 23 CFR Part 772, Fed. Reg. Vol. 75, No. 133, July 13, 2010.

I	67.6	61.6	6.0
J	67.4	61.4	6.0
K	67.4	60.8	6.6
L	68.1	62.7	5.4
All noise levels are dBA Leq(h) predicted with TNM 2.5 by ms consultants, inc. A noise impact would occur if the noise level was 1 dB below the Noise Abatement Criteria of 67 dB (Activity Category B Residential Land Use)[74]			

3.3 Separation Zones between Vehicle Travel Lanes and Side Paths for Non-motorized Users

Table 3-6 shows a summary of the strategy *separation zones between vehicle travel lanes and side paths for non-motorized users*. The summary is based on information extracted from work described in this subsection. This strategy is strongly tied to the strategy of using sound-absorbing ground surfaces, and although it's examined here in terms of realistic site parameters for side paths. For more information on sound-absorbing ground surfaces, please refer to Section 4.4.

Table 3-6: Summary of strategies: modeling separation zones between vehicle travel lanes and side paths for non-motorized users.

Strategy	Noise Benefit	Costs	Context Appropriateness
Adding a separation zone between roadway and side path to TNM	When the surface in the separation zone was very different from the default ground type (pavement vs. lawn), the separation zones can be modeled to accurately account for noise increases and decreases (although the decrease when switching from lawn to snow showed reductions only up to 0.3 dB). When the surface in the separation zone was similar to the default ground type, the addition of a Ground Zone for the separation zone made	Minimal for modeling effort; construction and maintenance costs would vary by ground type and geographical area	Roadways with sidewalks or shared-use paths

[74] Federal Regulations, *Procedures for Abatement of Highway Traffic Noise and Construction Noise*, 23 CFR Part 772, Fed. Reg. Vol. 75, No. 133, July 13, 2010.

	only a slight (0.1 dB or 0.2 dB) difference. Can increase accuracy up to 1.2 dB to 1.6 dB if separation zone is hard soil or pavement compared to lawn; for more absorptive surfaces than lawn, provides minimal noise reduction benefit (up to 0.3 dB). The noise reduction would be greater if separation zone is highly sound absorptive and the default ground type is not.		

As confirmed by the responses to the online survey and interviews conducted for this project, the effect of separation zones between travel lanes and side paths (sidewalks, bike trails, shared-use paths) has not been frequently considered in project specific TNM models. However, some research has shown that accurately modeling roadway shoulders and other Ground Zones can improve model accuracy. Therefore, the width and surface type within the separation zone might change the project's anticipated noise impacts. Figure 3-3 shows the conceptual location of both a sidewalk and shared-use path relative to an arterial roadway. Figure 3-4 shows a recently completed project with both a sidewalk and shared-use path. The grass covered separation zones are visible in both Figure 3-3 and Figure 3-4.

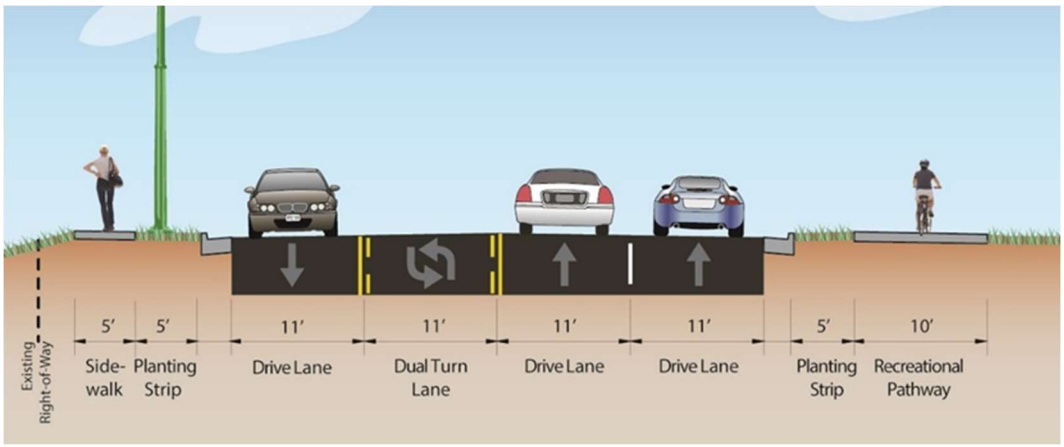

Figure 3-3: Improvement concept with 5' sidewalk and 10' shaded-use path (ms consultants, inc.)

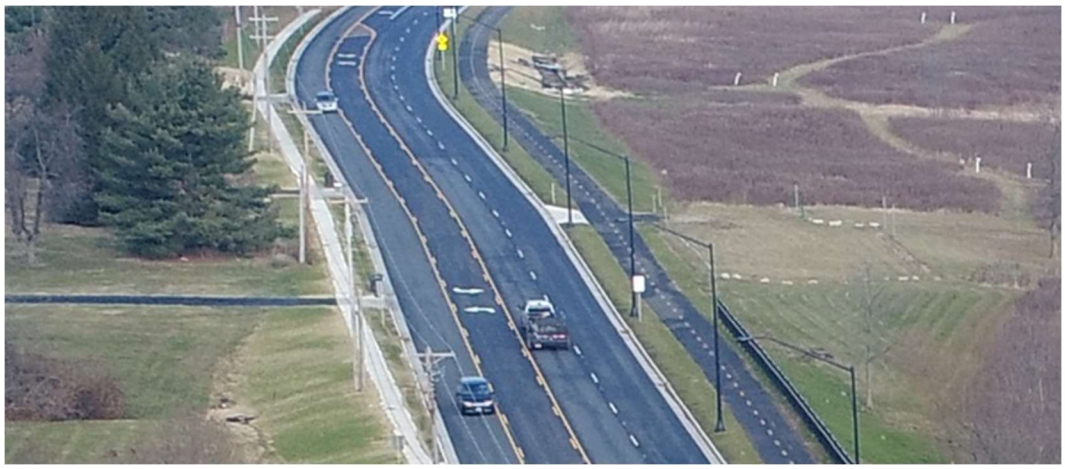

Figure 3-4: Arterial roadway with 5' sidewalk and 10' shaded-use path (ms consultants, inc.)

The minimum desirable sidewalk width is 1.5 m (5 ft) and the minimum width for a paved two-directional shared use path is 3.0 m (10 ft).[75] A 1.2 m (4 ft) wide sidewalk does not provide adequate clearance for pedestrians passing in opposite directions. A 3.0 m (10 ft) wide shared-use path is intended to serve adult bicyclists moving in opposite directions. The separation zone, also called a buffer, tree lawn, or planting strip, is between the sidewalk or shared-use path and the adjacent roadway curb or shoulder. In residential areas, which are usually the subject of traffic noise analysis, the ideal width of a sidewalk separation zone is 1.9 m (6 ft).[76] In general, a wide separation zone is recommended between a shared-use path and the adjacent roadway for both safety and path user confidence. However, the minimum recommended distance between a path and the roadway curb is 1.5 m (5 ft), and if the separation is less than 1.5 m (5 ft) wide, a physical barrier should be provided between the path and the roadway.[77]

To estimate noise reduction attributable to the width and surface type of side path separation zones along an arterial roadway, the research team conducted a FHWA Traffic Noise Model (TNM) study, adding a sidewalk, shared-use path, and separations zones with multiple surface types to a previously completed noise model from a recent project in Central Ohio (Figure 3-4). The roadway and receiver locations, number of vehicles (traffic volume), vehicle mix, vehicle speed, and general ground type were exactly the same as used in the previously completed TNM model. It should be noted that traffic on this arterial roadway was assumed to be traveling at 72 km/h (45 mph) and was primarily autos (including pick-up trucks and SUVs). Only 5% of the traffic were trucks with those divided equally between medium trucks (delivery trucks, school buses, etc.) and heavy trucks (tractor-trailer, dump trucks, etc.).

The TNM model used for this study was the portion of the original study area where two cul-de-sacs backed-up to the roadway with the sidewalk and shared-use path. This study area had single-family homes typical of 1st row, 2nd row, and 3rd row noise receivers. Noise impacts were originally predicted in the outdoor activity areas nearest the roadway at most 1st row homes. The noise barriers included in the previously completed model were deleted. To establish baseline noise levels, TNM Version 2.5 was used to predict the average noise level at the seven 1st row, six 2nd row, and six 3rd row receivers with no side paths or separation zones and with the default ground type set as Lawn or Hard Soil to simulate conditions in typical damp or dry environments (please refer to Section 4.4.1 for more information on

[75] Ohio Department of Transportation, Location and Design Manual – Volume One, Section 306.2.2, July 2019.

[76] Ohio Department of Transportation, Location and Design Manual – Volume One, Figure 306-2, July 2019.

[77] Ohio Department of Transportation, Location and Design Manual – Volume One, Section 702.2.2, January 2014.

acoustically hard or soft ground). Next a 3.0 m (10 ft) wide shared-use path positioned 3.0 m (10 ft) from the roadway and a 1.5 m (5 ft) wide sidewalk set 1.9 m (6 ft) from the roadway were added to both the Lawn or Hard Soil models as TNM roadways with no traffic. These models did not include any unique separation zones defined with a TNM Ground Zone.

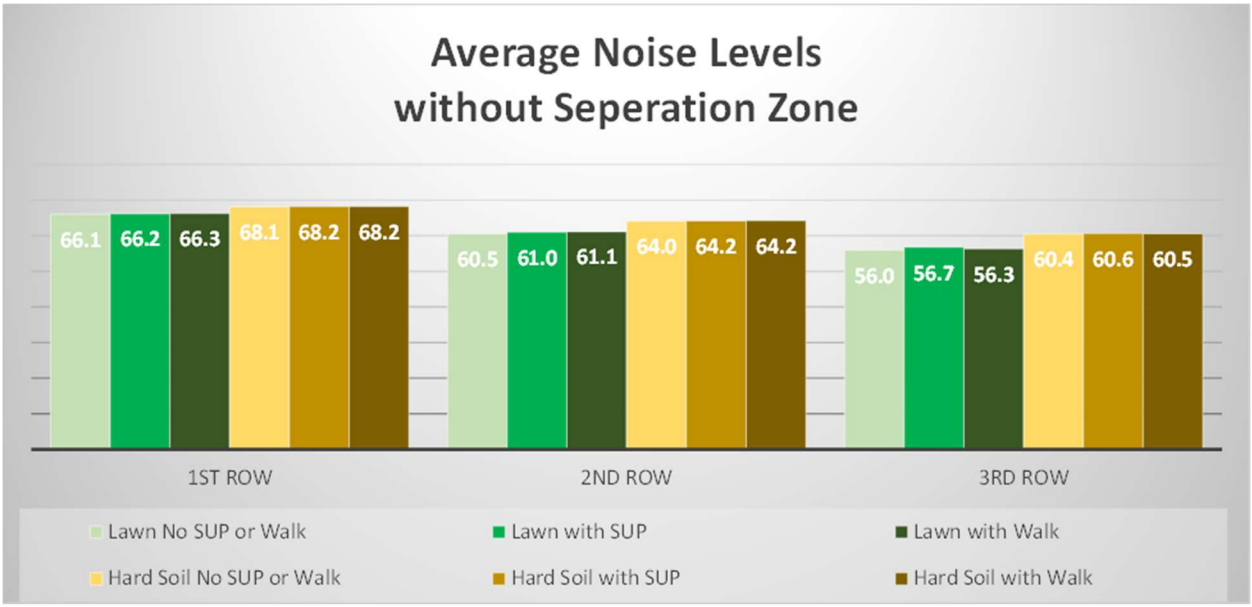

Figure 3-5: Results of baseline models without unique separations zones; Walk = sidewalk, SUP = shared-use path (ms consultants, inc.).

As shown in Figure 3-5, adding the shared-use path or a sidewalk made only a 0.1 dB or 0.2 dB difference at 1st row receivers. Adding either the shared-use path or sidewalk made a 0.5 dB to 0.7 dB difference (sound level increase) at the 2nd and 3rd row receivers when the default ground type was Lawn. When the default ground type was Hard Soil, adding the shared-use path or sidewalk made only a slight (0.1 dB or 0.2 dB) difference at the 2nd and 3rd row receivers. These results suggest side paths should be included in TNM Version 2.5 when the default ground type is Lawn or another soft surface and multiple rows of homes are involved.

After completing the baseline models, two side path separation zone scenarios were developed and modeled with TNM Version 2.5 using Lawn as the default ground type. One scenario involved a 3.0 m (10 ft) wide shared-use path separated from the roadway by a 3.0 m (10 ft) wide TNM Ground Zone. The other scenario involved a 1.5 m (5 ft) wide sidewalk separated from roadway by a 1.9 m (6 ft) wide TNM Ground Zone. For both scenarios, the shared-use path and sidewalk were added to TNM as roadways with no traffic. The separation zones were modeled as ground zones which covered the area between the roadway and shared-use path or sidewalk. Five of the ground types available in TNM Version 2.5 were used to compare noise levels in each scenario with various sound absorptive surfaces in the ground zones. The Lawn ground zone represented the conditions from the original project area, Hard Soil was a less absorptive surface than Lawn, Pavement represented the least absorptive surface, Field Grass and Soft Snow functioned as the most sound absorptive surfaces. The results of the TNM analysis were combined to show the average noise level at the seven 1st row, six 2nd row, and six 3rd row receivers for each scenario and each ground type in the separation zone.

As shown in Figure 3-6 and Figure 3-7, the various sound absorptive surfaces in the separations zones between the sidewalk or shared-use path and the roadway made up to a 1.6 dB difference in the predicted noise level in the 1st row receivers and up to a 1.9 dB difference in the 2nd and 3rd row. Compared to the default ground type of lawn for the 1st row, the 3.0 m (10 ft) path case shows a 1.3 dB increase for

pavement in the separation zone and a 0.3 dB decrease for powdered snow, ground types with the lowest and highest sound absorption in TNM, respectively. For the 2nd and 3rd rows, the difference was +1.6 dB for pavement and -0.3 dB for snow. Also comparing to lawn for the 1st row, the 1.5 m (5 ft) sidewalk case shows and 0.9 increase for pavement in the separation zone and a 0.2 decrease for powdered snow. For the 2nd and 3rd rows, the difference was +0.5 dB for pavement and -0.1 dB for snow. It follows that, when the surface in the separation zone was very different from the default ground type (pavement vs. lawn), the separation zones can be modeled to accurately account for noise increases and decreases (although the decrease when switching from lawn to snow showed reductions only up to 0.3 dB). When the surface in the separation zone was similar to the default ground type, the addition of a Ground Zone for the separation zone made only a slight (0.1 dB or 0.2 dB) difference.

These results suggest separation zones as narrow as 1.9 m (6 ft) wide should be included in TNM Version 2.5 as Ground Zones when the surface of the separation zone is intended to be very different from the default ground type. However, the addition of a separation zone with even the most sound absorptive surface (soft snow) may not eliminate the noise impacts at the 1st row receivers and the need for investigation of noise mitigation.

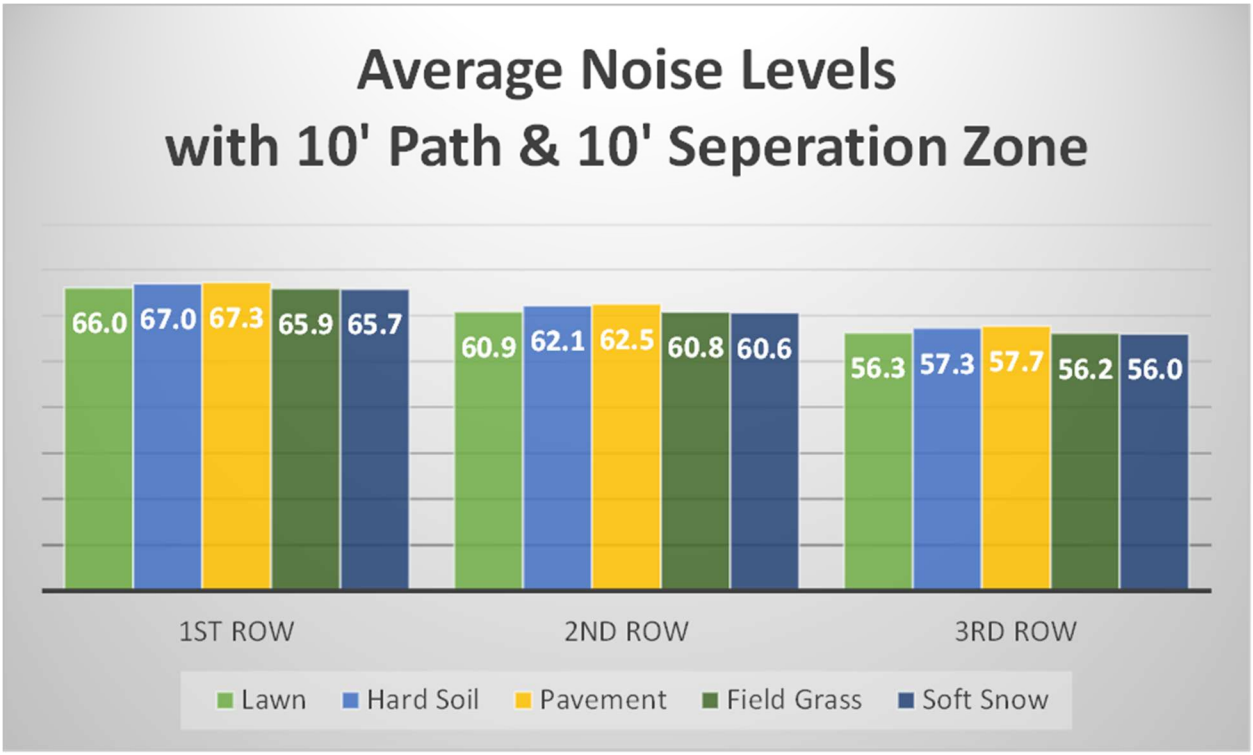

Figure 3-6: Results of 10' shared-use path model with separations zones (ms consultants, inc).

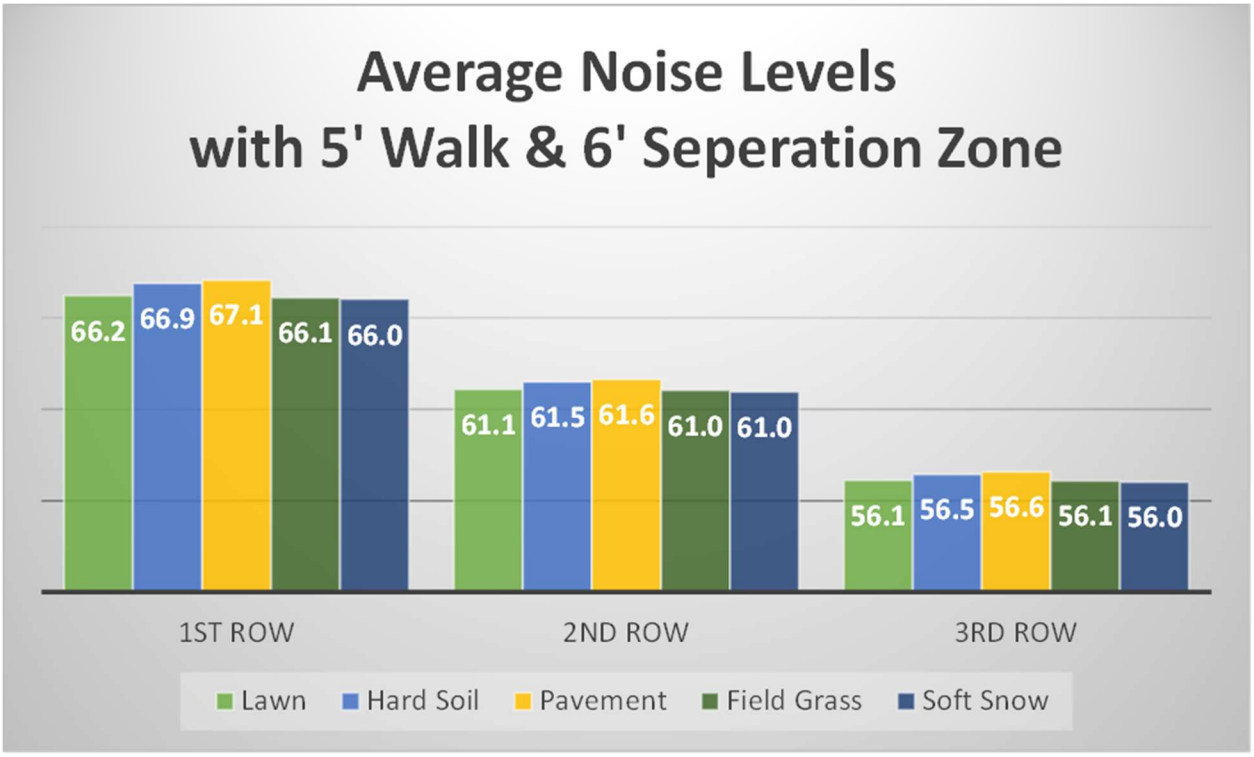

Figure 3-7: Results of 5' sidewalk model with separations zones (ms consultants, inc.).

4. STRATEGY CATEGORY: RIGHT-OF-WAY DESIGN CHOICES

Right-of-way design choices include low-height noise berms, vegetated screens, vegetated swales and retention basins, sound-absorbing ground surface and ground treatment adjacent to a highway. All are described in this section.

4.1 Low-Height Noise Berms

Noise berms are noise barriers constructed from natural earthen materials in an unsupported condition.[78] Noise berms are considered a desirable alternative to noise walls because they maintain a natural, aesthetically pleasing appearance, and they can be low-cost and low maintenance, especially if they can be constructed using surplus materials from the highway construction project. The main disadvantage of noise berms is the amount of right-of-way they require. Typically, side slopes of 2:1 (run:rise) are necessary for stability of the berm and a side slope of 3:1 or 4:1 may be preferred for mowing and landscaping.

Acoustically, noise berms and noise walls are about equally effective in terms of insertion loss, provided the berm is covered by grass or similar material.[79] Some FHWA noise barrier design guidance states that earth berms provide 3 dB more noise reduction than traditional barriers;[80] studies show this may be true if the berm is covered with a more acoustically absorptive surface (refer to Section 4.1.3). An acoustical disadvantage of noise berms is that their peak height cannot be located as close to the noise source compared to traditional walls because of their wide base.

According to the FHWA noise barrier inventory,[81] only seven of the barriers constructed since 2010 are berms. This low number is likely due to right-of-way constraints. For example, the Ohio DOT guidance is that earth berms are to be considered the first option when feasible or reasonable, and the noise abatement will have a minimum height of 2.4 m (8 ft).[82] A 2.4 m (8 ft) high noise berm would usually require a base at least 9.8 m (32 ft) wide and may require a 14.6 m (48 ft) wide base to maintain a 3:1 slope for mowing and landscaping.

Low-height noise berms are considered to be berms 1.8 m (6 ft) in height or less. These low-height noise berms would be more feasible to implement because they require less right-of-way. Table 4-1 summarizes the results from the literature survey for conventionally designed low-height noise berms and for three alternative designs: engineered berms with steeper slopes, low-height berms with absorptive ground, and low-height berms with unusual shapes.

Table 4-1. Summary of strategy: low berms.

Strategy	Noise Benefit	Costs	Context Appropriateness
Standard low-height berms	The noise benefit of low-height berms ranges from 2 dB to more	In opening year, a concrete wall is about 2.6 to 3 times	Highways or arterials with sufficient ROW space for

[78] Fleming, G. G., H. S. Knauer, C. S. Y. Lee, and S. Pedersen, "Noise Barrier Design Handbook," Federal Highway Administration, https://www.fhwa.dot.gov/environment/noise/noise_barriers/design_construction/design/, 2017.

[79] Hajek, J.J., "Are Earth Berms Acoustically Better than Thin-Wall Barriers," Transportation Research Record No. 896, Hydrology and Hydraulics: Water, Noise, and Air Quality, pp. 60-67, 1983.

[80] Federal Highway Administration, "Keeping the Noise Down: Highway Traffic Noise Barriers," Publication No. FHWA-EP-01-004, February 2001.

[81] https://www.fhwa.dot.gov/ENVIRonment/noise/noise_barriers/inventory/, updated July 2017.

[82] Ohio Department of Transportation, Highway Traffic Noise Analysis Manual, Ohio Department of Transportation Office of Environmental Services, April 2015.

(up to 6ft high)	than 10 dB. The noise benefit strongly depends on the relative elevation of the source, berm, and receiver with the greatest noise reduction for receivers situated at a lower elevation than the roadway.[83] A model of a 0.96 m (3.1 ft) high berm showed a noise reduction of 2 to 5 dB with roadside and/or median berms.[84]	more expensive than an earthen berm. This assumes no right-of-way costs or fill costs for the berm.[85] (Berms can be as or more expensive than a wall if material has to be brought in.) Maintenance costs for berms are expected to be less than for noise walls.	berm bases (up to 11m (36 ft) for a 1.8 m (6 ft) high berm) Low-height berms will be most effective when the berm can be placed close to the source or receiver, and the elevation of the receiver is lower than the source.
Engineered low-height berms with steeper slopes	These berms could reach taller heights closer to the noise source, improving noise reduction compared to standard low-height berms.	In 2011, costs were estimated to be $25 to $50 per sq. ft.[86] If an irrigation system is needed to maintain vegetation, the costs would increase.	Engineered low-height berms could be implemented where there are ROW constraints for a standard berm.
Low-height berms with absorptive ground	A more absorptive ground type could increase the noise reduction by up to 5 dB compared to packed dirt.[87,88]	Costs would be geographically dependent based on the absorptive ground type selected.	Highways with ROWs that can accommodate acoustically softer ground surfaces.
Unusually shaped low-height berms	For a 1 m (3.3 ft) high berm next to an arterial road, unusually shaped berms did not provide a noise benefit compared to a traditional wall or berm.[89]	Unusually shaped berms have not been implemented; they were considered in a numerical model	Have yet to be implemented; considered in models only

[83] Lawhon and Associates, “Acoustical Performance of Small Height Earthen Berms,” Prepared for: The Ohio Department of Transportation, June 2018.

[84] Van Renterghem, T., D. Botteldooren, M. Hornikx, P Jean, J Defrance, Y. Smyrnova, and J. Kang, "Road traffic noise reduction by vegetated low noise barriers in urban streets," Euronoise Prague, Conference Paper, June 2012.

[85] Burton, K., E. Pinckney, J. Miles, J. Kubitza, J. Miller, and M. Burns, "Earthen Berm Noise Reduction Analysis", Sponsored by Ohio DOT, Report no. FHWA/OH-2016/17; October 2016.

[86] Abbas, A., R. Y. Liang, A. Frankhouser, J. Cardina, and K. L. Cubick, "Green Noise Wall Construction and Evaluation," Sponsored by Ohio Department of Transportation Contract No 134556, September 2011.

[87] BC Highways, “Noise Control Earth Berms: Guidelines for the Use of Earth Berms to Control Highway Noise”, British Columbia Ministry of Transportation and Highways, January 1997.

[88] Busch, T., M. Hodgson, and C. Wakefield. "Scale-model study of the effectiveness of highway noise barriers," Journal of the Acoustical Society of America, 114 pp. 1947-1954. 2003.

[89] Defrance, J., S. Lallement, P. Jean, and F. Koussa, “Acoustical performance of complex-shaped earth berms,” Proceedings of the Acoustics Conference, Nantes, France, April 2012.

4.1.1 Standard Low-Height Noise Berms

Most of the literature related to the acoustical performance of berms looks at full height berms, considered to be berms taller than 1.8 m (6 ft). Conversations with State DOT noise coordinators anecdotally revealed that low-height berms may be implemented by using project waste material (dirt), where such berms could eliminate noise impacts and save costs on hauling off the material; it was cautioned that if a future project requires removal of the berm (e.g., for drainage improvements), this may result in re-analysis of the noise.[90] It was also cautioned that berms low enough to block just the tire-pavement noise may make noise sources higher on a vehicle (e.g., heavy trucks exhaust stack) more prominent and potentially more annoying to nearby communities.[91] Low berms could also be implemented as visual screens in areas that do not qualify for noise barriers or may be put in by developments. Low berms are infrequently implemented as a noise abatement measure by State DOTs.

As part of the Arizona DOT project SR 202L HOV Lanes Gilbert Road to I-10, a 3.7 to 4.9 m (12 to 16 ft) high sound wall was recommended as noise abatement in a location with an existing low berm.[92] The community rejected the sound wall, preferring to keep the low berm unmodified.[93] These anecdotal examples of low-berms preferred to sound walls, or implemented as visual screens, illustrates their acceptance in communities and the need to better understand their potential for reducing noise.

Van Renterghem et al.[94] numerically modeled low berms that were 0.96 m (3.1 ft) in height in an urban environment. The model considered berms placed between a walkway and lanes of a four-lane roadway. The model found that noise reduction ranged from 2 to 5 dB with roadside and/or median berms. Insertion loss was greatest in the 500 to 1000 Hz frequency range, and that absorption at the surface of the low-height berm was important to see positive effects.

A study in Sweden considered the before-and-after noise reduction and reported annoyance from a 2.4 m (7.9 ft) tall low-earth berm and a quieter asphalt.[95] The site with quieter asphalt and no berm reduced noise by about 5.5 dB and reduced annoyance from 31% before treatment to 28% after treatment. The site with quiet asphalt plus a low-height berm reduced noise by about 6.5 dB, with up to 10 dB of reduction in the low-frequency range between 100 to 250 Hz. The quiet asphalt plus low-height berm reduced annoyance from 41% to 19%. The study suggests low-earth berms may be more effective at reducing annoyance than quiet asphalt because they are more effective at reducing low-frequency noise.

Ohio DOT created a low-height earth berm master database that includes noise measurements at 83 berms.[96] In the study, noise reduction is measured as noise on top of the berm minus noise behind the berm. This measured difference is not an insertion loss of the berm, because it does not capture the difference in noise level with and without the berm at a consistent location. Noise reduction as calculated

[90] Communication with Miles Kemp, Georgia DOT, November 2019.

[91] Communication with William McColl, retired NY DOT, November 2019.

[92] D'Onofrio Monh Environmental, LLC, "Final Noise Analysis Technical Report for SR 202L HOV Lanes, Gilbert Road to I-10 (MP 16.6- MP 55.0)," Prepared for Arizona Department of Transportation, Federal Project No. NH-202-B(BCC), ADOT Project Number 202 MA 016 H7457 01L, December 2009.

[93] Communication with A. Newton, Newton Environmental Consulting, October 2019.

[94] Van Renterghem, T., D. Botteldooren, M. Hornikx, P Jean, J Defrance, Y. Smyrnova, and J. Kang, "Road traffic noise reduction by vegetated low noise barriers in urban streets," Euronoise Prague, Conference Paper, June 2012.

[95] Gidlof-Gunnarson and E. Ohrstrom, "The effectiveness of quiet asphalt and earth berm in reducing annoyances due to road traffic noise in a residential area," 9th International Congress on Noise as a Public Health Problem (ICBEN), Foxwoods, Conn, 2008.

[96] Lawhon and Associates, "Acoustical Performance of Small Height Earthen Berms," Prepared for: The Ohio Department of Transportation, June 2018.

by the study ranged from 2.6 dB to 17.4 dB. The study found the variables that help berms of any size achieve substantial noise reduction are the relative location of the berm (the berm should be near to either the source or receiver) and the site-specific elevations between the roadway, berm, and receiver. Receivers situated at a substantially lower elevation than the roadway receive the highest sound level reduction. The berms studied were not implemented by Ohio DOT as a noise abatement measure, they were berms found in the community and likely put in by developers. An example of a community berm is shown in Figure 4-1.

Figure 4-1: Indiana berm adjacent to housing development.

Additional noise data were gathered and traffic noise modeling was completed at five of the low-berm sites included in the Ohio DOT database to confirm the original results.[97] The additional measurements at two of the five sites were within 2 dB of the original measurements; however, the other three sites showed a difference of about 5 dB from the original measurements. The study concludes that the difference in results is likely due to a difference in the placement of the sound level meter behind the berm. The TNM v2.5 results were within 2 dB of the updated measurements at three of the five locations. At the other two locations, the difference between the modeled and measured noise reduction was greater than 5 dB.

Iowa DOT[98] has been working with design engineers early in the design phase to utilize fill material strategically, especially on projects where noise barriers are found to be not "feasible and reasonable." The photos shown in Figure 4-2 are an example of this strategically placed fill. An approximate 2.4 m (8 ft) high berm built from extra material was used for visual shielding (and retention basins) between a highway and golf course. It was observed that the berm provided qualitatively lower noise, with an estimated reduction value of 6 dB.

[97] Lawhon and Associates, "Acoustical Performance of Small Height Earthen Berms," Prepared for: The Ohio Department of Transportation, June 2018.

[98] Communication with C. Bernhard, Iowa DOT, October 2019.

Figure 4-2: Berm protecting golf course in Iowa, built for visual shielding, providing noise reduction.[99]

The TNM validation study completed in 2002 and updated for TNM v2.5 in 2004 included one 4.9 m (16 ft) high berm site and found that TNM overpredicted the noise level behind the berm by less than 2 dB.[100] The Ohio DOT low-height earth berm and TNM validation study results show that TNM can predict noise reduction from earth berms to within 2 dB of measured data; however, large discrepancies between measured and modeled results are possible in sites with varying terrain conditions and careful consideration needs to be given to the placement of microphones and receivers during measurements and modeling, respectively.

The Ohio DOT also sponsored a life-cycle cost comparison study between earthen berms and concrete noise walls.[101] The study found that earthen berms are more cost-effective compared to concrete noise walls if right-of-way is available. By their calculations, in opening year a concrete noise wall is about 2.6 times more expensive than an earthen berm. By year ten, that factor increases to 3.0 and by year 20 it is 3.4 times more costly. The study assumed no maintenance costs for berms and used historical data from Ohio DOT on maintenance costs for concrete noise walls. The estimating department of Ohio DOT came up with an estimate of $345 per linear foot for a 4.8 m (15 ft) high noise wall versus $115 per linear foot for an earthen berm which includes embankment placement, four inch underdrains, topsoil, and Class 1 seeding.[102] However, the guidance in the Ohio DOT review of noise abatement alternatives[103] cautions that costs of earth berms must be calculated on a case-by-case basis due to the great variation in costs depending on the availability of the fill material and the engineering and earth moving requirements.

The Ohio Department of Commerce and Ohio Real Estate commission funded a research project that considered if property values were higher for residences behind earthen mounds compared to traditional

[99] Communication with C. Bernhard, Iowa DOT, October 2019.

[100] Rochat, J. and G. Fleming, "Validation of FHWA's Traffic Noise Model (TNM): Phase 1," Report No. U.S. Department of Transportation, Volpe National Transportation Systems Center, 2002 (2004 addendum).

[101] Burton, K., E. Pinckney, J. Miles, J. Kubitza, J. Miller, and M. Burns, "Earthen Berm Noise Reduction Analysis", Sponsored by Ohio DOT, Report no. FHWA/OH-2016/17; October 2016.

[102] Email communication, From: David Kauffman, To: Noel Alcala, Subject: RE: Noise Barriers Update (Historical Bid Data), May 16, 2018.

[103] McCormick Taylor and Burgess & Niple, "Statewide Investigation of Noise Abatement Alternatives," Prepared for: Ohio Department of Transportation, June 2006.

noise walls.[104] The study showed mixed results depending on which study area was considered and how many variables were included in the analysis. However, when analyzing the data set for the minimum three variables of building square footage, earth berm, or sound wall, the hypothesis that residences behind earthen berms had higher property values than residences behind structural walls or non-mitigated residences was true.

The Texas DOT noise policy includes specific guidance on how to assess berms for cost reasonableness.[105] For Texas DOT berms, a centerline length and height would be used to determine if the equivalent square footage is cost reasonable. The standard barrier cost does not include the costs of any additional right-of-way, utility adjustments directly associated with the construction of a noise barrier, or costs for additional design elements necessary to accommodate unusual topographic or drainage features directly associated with the construction of a noise barrier. North Carolina DOT takes a different approach, defining an allowable noise barrier base quantity of 3,211 meters cubed (4,200 yards cubed) per benefited receptor.[106] Some DOTs, such as Minnesota, do not include specific guidance relative to berms in their noise policy.[107]

4.1.2 Engineered Low-Height Berms with Steeper Slopes

Engineered berms with steeper slopes may also be called living sound walls, green noise walls, or noise bunds. Steeper slopes are possible using an engineered structure of soil and vegetation. In 2011, Ohio DOT sponsored a study to review existing green wall designs, survey state DOTs about their experience with green noise walls, and to develop a prototype of a green noise wall in Ohio.[108] The study identified and reviewed the following different green wall designs:

1. Willow trees in wood frames: Once the willow trees have been established, the wood frame is not visible; however, the willow trees require a high moisture environment. Another disadvantage is that the construction is labor intensive. Examples of products are The Living Wall and PileByg. www.thelivingwall.net, www.pilebyg.dk
2. Grid members tacked together with soil and rock backfilled: These designs have mostly been used as retaining walls, but could be used as sound walls. As free-standing walls the structures may need regular soil replenishment. The grid members could be concrete, wood, or recycled materials. Examples of products are Criblock, Timbergrid, Evergreen, or Recywall. www.retainingwallsnw.com, www.timbergrid.com, www.evergreenwall.com
3. Supported earth embankments: The most common form is a berm that uses steel mesh or net with steel or concrete supports to retain soil and vegetation for slopes steeper than a traditional embankment. There are also proprietary geo-grid systems that are made from more sustainable products, such as the Deltalok system or the Greenloxx system. These systems provide the advantages of earth berms, in that they use natural materials and can incorporate different types of vegetation, while allowing for steeper slopes. Some disadvantages of the systems are that they may require irrigation to sustain vegetation and there is likely to be some settlement in the soil

[104] Burton, K. and J. Kubitza, "Property Valuation Comparison of Noise-Mitigated Residences," Ohio Department of Commerce, August 2017.

[105] Texas Department of Transportation, “Noise Policy: Roadway Traffic and Construction Noise,” Document 730.01.POL; December 2019.

[106] North Carolina Department of Transportation, “Traffic Noise Policy,” October 2016.

[107] Minnesota Department of Transportation, “Noise Requirement for MnDOT and other Type I Federal-aid Projects,” July 2017.

[108] Abbas, A., R. Y. Liang, A. Frankhouser, J. Cardina, and K. L. Cubick, "Green Noise Wall Construction and Evaluation," Sponsored by Ohio Department of Transportation Contract No 134556, September 2011.

that will result in loss of height.
www.Deltalok.com, www.filtrexx.com/en/products/greenloxx

As part of their investigation, Ohio DOT built a prototype of the Deltalok supported earth embankment that was 3.7 m (12 ft) high and 2.7 m (9 ft) wide. However, a full-scale implementation of the green noise wall in a community was never implemented because it was determined that the relatively small footprint of the barrier did not allow enough rain water to infiltrate into the barrier to sustain vegetation. An irrigation system could have been incorporated into the barrier, but it would have increased the cost.

In addition to Ohio DOT, New Hampshire DOT, Colorado DOT, and Wisconsin DOT found that it was difficult to maintain vegetation in a living barrier with a steep slope with no irrigation system. Without vegetation, many of the barriers faced erosion issues. The Ontario Ministry of Transportation did successfully implement the Living Willow Walls along arterial roads with irrigation systems in Ontario. However, the green noise barriers were never implemented near major highways because of height limitation of the Living Willow Wall, additional maintenance requirements (weeding, trimming), and potential issues from de-icing salt.

In a presentation on living sound walls, Ohio DOT noise coordinator notes that the potential benefits for living sound walls are many, such as potential for better acoustical performance, lower maintenance, lower construction costs, and improved aesthetics. However, the challenges include drainage concerns, appropriate vegetative choices, space limitations, underground utilities, and landscaping/mowing issues.[109]

The costs of engineered low-height berms are greater than a traditional low-height berm due to the added cost of the grid-members used to support the soil. Additionally, many of these systems require irrigation to maintain vegetation which is both an added construction and maintenance cost. The type of vegetation may also add cost relative to a grassy berm. In the Ohio DOT proto-type project using the DeltaLok system, the barrier was about twice the cost of a traditional barrier. Part of the added cost was due to the fact that a DeltaLok barrier had not been used before. The literature review from that same study estimated that the cost of a traditional noise wall is about $25 to $35 per ft^2 and an engineered, living sound wall would be $50 to $70 per ft^2.

4.1.3 Low-Height Berms with Absorptive Ground

Several scale models of berms have shown that acoustically absorptive surfaces can improve the noise reduction of the berm. The British Columbia Ministry of Highways found that a berm with a highly absorptive surface can perform up to 5 dB better than a berm with a normal surface using 1/31.5 scale model.[110] In the scale model, the absorptive surface was modeled with felt which may be more absorptive than could be practically applied in the field.

In a study by Busch et al.,[111] their 1/31.5 scale model showed that a traditional wall outperformed a berm by 1 to 2 dB if the surface of the berm resembled that of packed earth. However, when the berm was modeled to be acoustically soft, the insertion loss increased sufficiently to favor berms by about 2 dB. When the slopes of the berm were made shallower, the effectiveness of the acoustically soft berm increased.

[109] Alcala, Noel, "Living Sound Walls," Presentation at Ohio Transportation Engineering Conference, 2015.

[110] BC Highways, “Noise Control Earth Berms: Guidelines for the Use of Earth Berms to Control Highway Noise,” British Columbia Ministry of Transportation and Highways. January 1997.

[111] Busch, T., M. Hodgson, and C. Wakefield. "Scale-model study of the effectiveness of highway noise barriers," Journal of the Acoustical Society of America, 114 pp. 1947-1954. 2003.

Hajek's scale-model study also found that an earth berm with a sound-absorptive top could improve noise reduction.[112] In Hajek's model, a sound-absorptive top with a noise-reduction coefficient of 0.75 improved performance of the berm by 2 dB compared to a grass top. He considered this level of absorption to be difficult to duplicate in the field, but the application of the material only on the top of the berm may make some materials more viable.

Van Renterghem used a numerical model to consider 4 m (13 ft) high berms with varying slopes and ground cover. The numerical model results matched those found with the scale model studies.[113] The numerical model showed that grass-covered berms are not as effective as forest-floor berms, which are acoustically softer. The numerical model also showed that the effect of the soil cover depends on the slope of the berm – steeper berms do not show as great an improvement in noise reduction with the application of a forest-floor type covering. The model considered berms with slopes of 1:1, 1:2 and 1:3.

Costs associated with adding absorptive material would depend on the geographic location and the type of material being applied. No practical implementation of a low-height berm with a specifically chosen absorptive ground type has been identified. Refer to Section 4.4 for details on absorptive ground.

4.1.4 Unusually Shaped Low-Height Berms

Defrance et al. [114] used numerical modeling (a 2D boundary element method, calculations for frequencies 100 to 2500 Hz) to consider berms with six different shapes, shown in Figure 4-3. Modeling results were generated for the six shapes at 1 m (3.3 ft) tall, to simulate a city center context, and at 4 m (13 ft) high, to simulate a major highway context. The effectiveness of the different berm shapes were compared to a reference sound wall of the same height, with the wall located at the front toe of the berm closest to the noise source. For cars with the 1 m (3.3 ft) high berm, only the rectangular berm and the triangle berm with a straight façade facing traffic showed comparable noise reduction to the reference wall. Neither of these configurations would be feasible to implement. For trams, the berm showed improved performance relative to the wall for all configurations, which may be explained by the difference in source height and placement for the two modes.

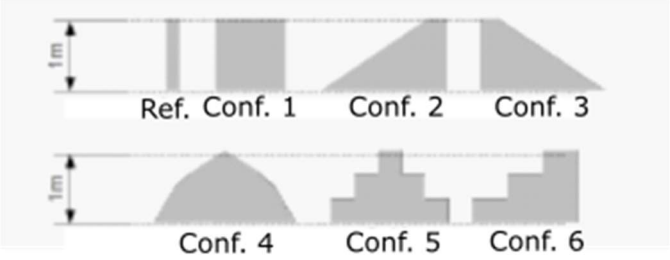

Figure 4-3: Geometry of low-height berm configurations included in numerical model.
Source: Defrance, 2012

[112] Hajek, J.J., "Are Earth Berms Acoustically Better than Thin-Wall Barriers," Transportation Research Record No. 896, Hydrology and Hydraulics: Water, Noise, and Air Quality, pp. 60-67, 1983.

[113] Van Renterghem, T. and D. Botteldooren, "On the choice between walls and berms for road traffic noise shielding including wind effects," Landscape and Urban Planning Volume 105, Issue 3, April 2012.

[114] Defrance, J., S. Lallement, P. Jean, and F. Koussa, "Acoustical performance of complex-shaped earth berms," Proceedings of the Acoustics Conference, Nantes, France, April 2012.

As part of the European Holistic and Sustainable Abatement of Noise by Optimized Combinations of Natural and Artificial Means (HOSANNA) project,[115] a summary of noise abatement strategies discussed the effects of grass-covered low berms with stair-step shapes (similar to "Conf. 5" in Figure 4-3) were predicted. For a 1 m (3.3 ft) high berm, 1 m (3.3 ft) wide, with slopes containing large irregularities (25 cm or 9.8 in depth) the noise reduction is 7 dB (up to 50 m or 164 ft behind the berm and 2-5 m (6.6-16.4 ft) above the ground) compared to an untreated situation for a highway, provided the infrastructure is significantly embanked (4 m or 13 ft high embankment). Without the embankment, the reduction appears to be about the same but not as high above the ground.

4.2 Vegetated Screens

Vegetative screens reduce noise levels at low frequencies primarily by absorption from the ground. Plants help to keep the soil loose through the action of their roots exploring the soil, by the fall of leaf litter to form a soft humus layer, and because of the shading of trees which prevents the soils becoming baked hard in hot, dry summers. At high-frequencies, vegetative screens reduce noise by reflection and scattering from the surfaces of leaves, branches and trunks.[116]

The HOSANNA project[117] describes that with trees, shrubs, and bushes, sound levels are reduced by interacting with plant material in two main ways: sound can be redirected by means of reflection, diffraction, or scattering, or sound can be effectively absorbed by plant material. Part of the absorption is caused by the damped vibrations of leaves. A single row of trees along a road beside an open field will not significantly affect traffic noise levels, though positive effects can be expected when there are multiple rows. Important design parameters in vegetation belts are tree spacing, trunk diameter, length and depth of the belt, the choice of planting scheme, and shrub biomass density. It's mentioned that, above 2 m (6.6 ft), tree height is usually not a relevant parameter in typical traffic noise situations.

The FHWA does not consider the planting of vegetation to be a highway traffic noise abatement measure because a substantial noise reduction does not occur until vegetation matures.[118] However, vegetative screens can affect the propagation of sound. TNM does allow the user to model "tree zones" if the trees are sufficiently dense enough to completely block the view along the propagation path, as required by the ISO 9613-2 standard that includes tree attenuation.[119]

Anecdotally, communities commonly perceive noise reduction with the implementation of a vegetative visual screen even if it is not dense enough or thick enough to provide much, if any, noise reduction. Ohio DOT allows neighborhoods to choose vegetative screening as an alternative to a noise barrier if they wish but does not consider the vegetative screens as noise abatement. A recommended layout for vegetative

[115] Chalmers University of Technology, CSTB, Canevaflor, IBBT Gent University, Muller BBM, Open University, City of Stockholm, TOI, University of Sheffield, University of Bradford, Stockholm University, Acoucite, and Hangyang University, "Novel solutions for quieter and greener cities, Brochure summarizing HOSANNA Project, 2013.

[116] Dobson, M., and J. Ryan, "Trees and shrubs for noise control," Arboricultural Advisory and Information Service, January 2000.

[117] Chalmers University of Technology, CSTB, Canevaflor, IBBT Gent University, Muller BBM, Open University, City of Stockholm, TOI, University of Sheffield, University of Bradford, Stockholm University, Acoucite, and Hangyang University, "Novel solutions for quieter and greener cities, Brochure summarizing HOSANNA Project, 2013.

[118] Federal Highway Administration, "Highway Traffic Noise: Analysis and Abatement Guidance," Document No FHWA-HEP-10-025, December 2011.

[119] Federal Highway Administration, "Traffic Noise Model: Frequently Asked Questions," https://www.fhwa.dot.gov/environment/noise/traffic_noise_model/tnm_faqs/, April 2004.

screening is shown in Figure 4-4.[120,121] Because vegetative screens are commonly used near roadways and may be requested by communities, it is useful to understand the properties of an effective vegetative screen for noise reduction, how much noise reduction can be expected, and what the perception effect is for narrow vegetative screens.

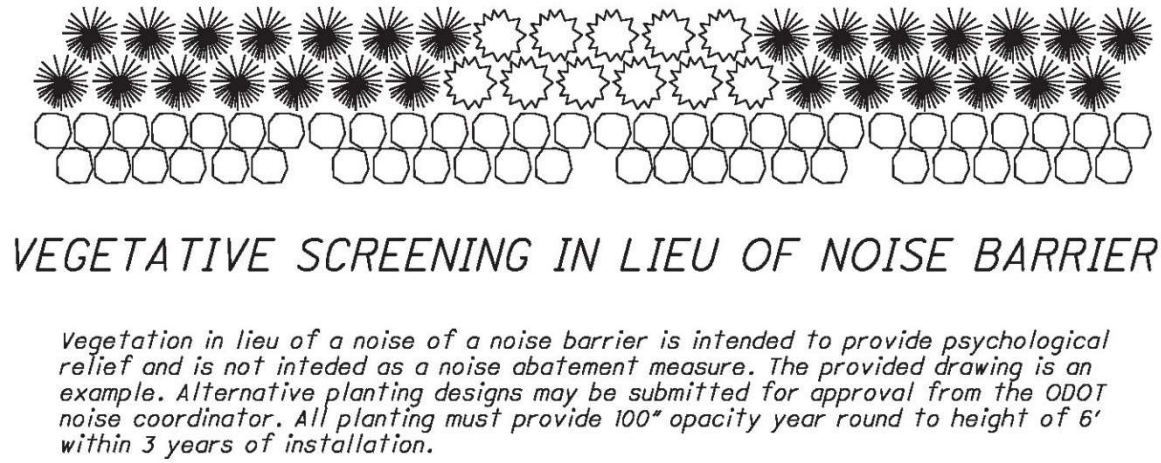

Figure 4-4: Ohio DOT recommended vegetative screening in lieu of noise barrier.[122]

Table 4-2 summarizes the results from the literature survey for three different approaches to vegetative screens: thick and dense vegetation belts that are greater than 20 m (65.6 ft) thick, moderate-to-low thickness vegetation screens implemented for noise reduction, and narrow vegetative screens implemented for improved perception of noise.

Table 4-2. Summary of strategy: vegetative screens

Strategy	Noise Benefit	Costs	Context Appropriateness
Thick vegetation belts (> 20 m (65.6 ft))	Measured noise reduction of 3-9 dB; up to 10 dB noise reduction in computational model with optimized planting.[123,124,125]	Geographically dependent on type of vegetation used (example cost of $100 to $300 per tree, installed)	Highways with significant ROW available; areas that can support sufficiently dense vegetation

[120] Cramer, J., R. Kolmansberger, and J. Wilson, *Statewide Investigation of Noise Abetment Alternatives*, Ohio DOT, June 2006.

[121] Ohio Department of Transportation, *Location and Design Manual – Volume One*, Roadway Design, "Vegetative Screening," 904-1, October 2019.

[122] Ohio Department of Transportation, *Location and Design Manual – Volume One*, Roadway Design, "Vegetative Screening," 904-1, October 2019.

[123] Huddart, L., "The use of vegetation for traffic noise screening," Transport and Road Research Laboratory Research, Report 238, 1990.

		and the need for upkeep; ROW cost could be significant.	
Moderate-to-low thickness vegetation screens (< 20 m (65.6 ft))	Measured noise reduction of 1-3 dB[126,127]; up to 6 dB noise reduction in computational model with optimized planting.[128]	Geographically dependent on type of vegetation used (example cost for two rows planted 10 ft apart would be $0.5-1.5 million/mile) and the need for upkeep; may be ROW cost for moderately thick vegetative belts of 10-20 m (33-66 ft)	Areas that need relatively minor noise reduction; areas that can support sufficiently dense vegetation
Vegetation to improve adverse sound propagation effects	A row of trees behind a noise barrier can reduce negative downwind noise effects A vegetated belt can reduce the likelihood of a temperature inversion layer which can bend sound downwards	Geographically dependent on type of vegetation used and the need for upkeep; may be additional ROW cost	Sites with a wall noise barrier, especially ones with prevalent downwind conditions Sites that can support vegetation, especially ones with frequent temperature inversion conditions
Vegetation to improve perception of noise with narrow vegetation screens	No noise benefit - subjective reports of decrease in annoyance when more vegetation is present; however, the relationship is difficult to show in subjective studies with test subjects at multiple vegetated or non-vegetated sites[129]	Geographically dependent on type of vegetation used and the need for upkeep	Areas that do not qualify for noise abatement, but report high levels of traffic noise annoyance

[124] Peng, J., R. Bullen, and S. Kean, "The effects of vegetation on road traffic noise," Proceedings of Internoise, 2014.

[125] Chalmers University of Technology, CSTB, Canevaflor, IBBT Gent University, Muller BBM, Open University, City of Stockholm, TOI, University of Sheffield, University of Bradford, Stockholm University, Acoucite, and Hangyang University, "Novel solutions for quieter and greener cities, Brochure summarizing HOSANNA Project, 2013.

[126] Fang, C. F., "Guidance for noise reduction provided by tree belts," Landscape and Urban Planning, 71 pp. 29-34, 2005.

[127] Hendriks, R., "Traffic Noise Attenuation as a Function of Ground and Vegetation (Interim Report)," Report No. FHWA/CA/TL-89/09, California Department of Transportation, September 1989.

[128] Van Renterghem, T., D Bottoeldooren, and K. Verheyen, "Road traffic noise shielding by vegetation belts of limited depth," Journal of Sound and Vibration, Volume 3310 Issue 10, May 2012.

[129] Van Renterghem, T., D. Botteldooren, "View on outdoor vegetation reduces noise annoyance for dwellers near busy roads," Landscape and Urban Planning, 148 pp. 203–215, 2016.

4.2.1 Noise Reduction from Thick Vegetation Belts

For the purpose of this study, a thick vegetative belt is considered to be at least 20 m (65.6 ft) thick with vegetation sufficiently dense to completely block the view along the sound propagation path. Noise reduction from thick vegetation belts has been examined primarily through measurements, as opposed to computational or scale models.

Huddart[130] found that density of the plantings is likely more important than the thickness of the belt. Vegetation can grow very densely over narrower belts, but over greater widths the undergrowth becomes less dense due to lower light penetration, reducing the effectiveness for noise attenuation. Huddart also posits that while soft ground attenuates low frequencies and vegetation attenuates high frequencies, there is an "acoustic window" in the mid-frequencies of 1000 to 2000 Hz where vegetative screens are not very effective and highway traffic noise is greatest. However, the change in frequency could affect the perception of noise at sensitive receptors. A field study with measurements confirmed the frequency change described in the literature review.

In Huddart's field study, the maximum attenuation was 6 dBA L_{10} through a 30 m (98.4 ft) dense spruce plantation. However, the effectiveness of the vegetation was greatest closest to the road, and a noise reduction of 5 dBA L_{10} was measured from 10 m (33 ft) of vegetation which is only 1 dB of improvement from a 20 m (65.6 ft) increase in vegetative belt depth.

Fang[131] looked at 35 evergreen tree belts and investigated the results to look at the effectiveness of belt width and density, as measured by visibility. One of the belts had a thickness of 15 meters (49 ft), the remaining belts ranged in thickness from 20 m (65.6 ft) to 300 m (984 ft). Tree belts that provided attenuation relative to open ground greater than 6 dBA were comprised of large shrubs with a visibility of less than 5 m (16.4 ft). Belts with sparsely distributed trees and shrubs with visibility greater than 20 m (65.6 ft) provided relative noise attenuation less than 3 dB. An intermediate range of relative noise reduction (3-5.9 dB) was measured in belts with visibility ranging between 6 and 9 m (19.7 and 29.5 ft). Fang used this information to create a map of the relationship between attenuation to both visibility and width to aid in the design of tree belts, shown in Figure 4-5. The noise measurements in the study were made with an amplified point source; the attenuation results may be different for a line source.

[130] Huddart, L., "The use of vegetation for traffic noise screening," Transport and Road Research Laboratory Research, Report 238, 1990.

[131] Fang, C.F., Ling, D.L., "Investigation of the noise reduction provided by tree belts," Landscape and Urban Planning, 63 pp. 187-195, 2003.

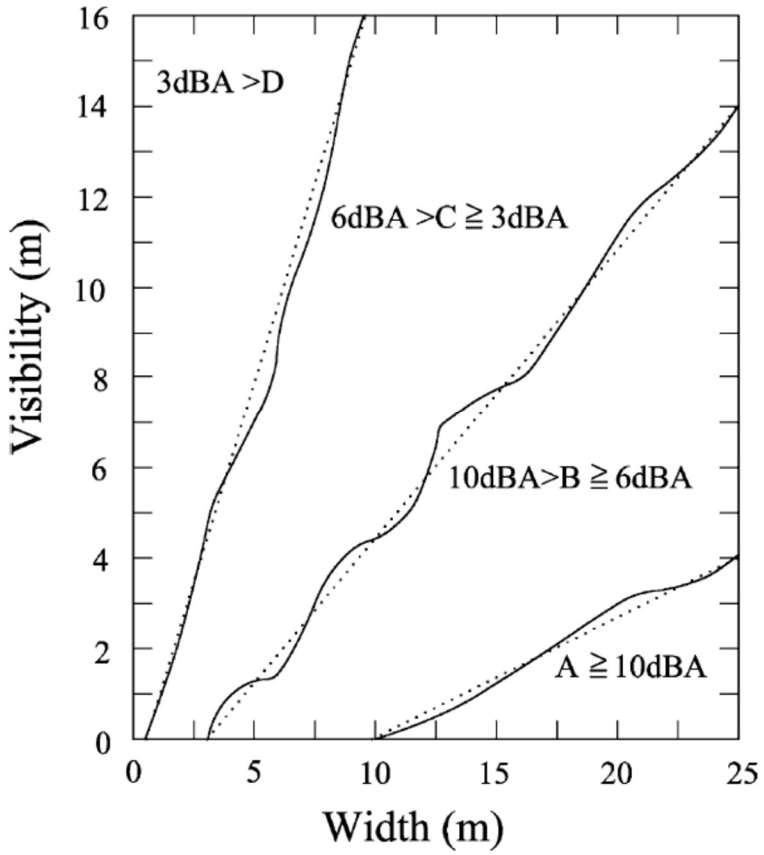

Figure 4-5: Relative noise reduction expected as a function of width and visibility in a vegetative belt.
Source: Fang 2003

In 2008, Virginia DOT[132] sponsored a study that collected data at 15 tree belts with the following selection criteria for the belts: tree width of at least 20 m (65.6 ft), coniferous dominant species, accessibility and safety for noise measurements, and the absence of leafed out deciduous trees. Their measurement results showed no excess attenuation relative to open ground. Many of the species of pine trees examined had lost their lower branches as the trees matured, which confirms the finding in Huddart's literature review that over greater widths the undergrowth may become less dense limiting noise reduction.

Peng[133] gathered measured data to examine whether there is additional noise reduction from vegetative belts compared to what is predicted by the Calculation of Road Traffic Noise (CRTN) model, the traffic noise model used in Australia. Measurements were completed at two control sites, four vegetated sites with tree belt depths greater than 100 m (328 ft), and two sites with limited tree belt depths less than 20 m (65.6 ft). The excess attenuation for the thick tree belts was between 3-7 dB. The excess attenuation of the

[132] Lee, S. E., S. Velasquez, G. Flintsch, and J. Peterson, "Road Noise Attenuation Study: Traffic Noise, Trees, and Quiet Pavement: A Report in Response to Item 442C. Of Chapter 847 of the Acts of Assembly of 2007, Virginia Department of Transportation, December 2008.

[133] Peng, J., R. Bullen, and S. Kean, "The effects of vegetation on road traffic noise," Proceedings of Internoise, 2014.

moderately thick tree belts of 10 to 20 m (32.8 to 65.6 ft) was found to be 2 to 3 dB. The data show that the thick tree belts do provide excess attenuation, but significantly increasing the thickness of the tree belt is likely to provide diminishing returns.

The HOSANNA project[134] used numerical calculations to determine the effects of many parameters on highway noise propagation, including vegetative screens. They report that a 30 m (98 ft) thick tree belt can provide up to 10 dB of noise reduction and that tree spacing should be as close as practically possible in a pseudo-random grid. The 10 dB of noise reduction estimated by the numerical model is greater than the measured noise reduction levels found in Huddart, Fang, Lee, or Peng, and may be the result of their computation model assuming more dense vegetation than is practically implementable over a thick tree belt on a repeatable basis.

The HOSANNA project also reported that, for a 25 m (82 ft) wide tree belt, the sound level at a 40 m (131 ft) distance from a two-lane road (5% heavy and 95% light vehicles traveling at 50 km/h or 31 mph), for a 1.5 m (5 ft) high receiver, the predicted insertion loss is 7 dBA. There is a reduction in sound from 125 Hz and up, the most being in the 500-1600 Hz range. Attenborough 2017 reports results from a study with similar parameters, except measured at a distance of 15 m (49 ft); the reported effect of the trees is 8 dB. The HOSANNA project also includes some recommendations in addition to proximity to the road and pseudo-random planting: the report recommends variations in trunk diameter to reduce road traffic noise level and that tree species should be selected that can develop high stand densities and large trunk diameters. Calculations reveal that a narrow (approximately 15 m or 49 ft wide) but optimized vegetation belt along a road is equivalent to the shielding of a 1-1.5 m (3.3-5 ft) high conventional concrete noise wall placed directly near the road, about 5-6 dBA.

Ohio DOT is currently conducting a Noise Model-to-Monitor Case Study to improve their noise analysis process. As part of the study, noise measurements are being taken in a neighborhood adjacent to a multi-lane highway, currently with a tree belt between the highway and homes. Measurements have been taken behind deciduous tree belts with two different widths, and measurements are planned for Fall 2019 (when the leaves have fallen off) and Spring 2020 (when the trees will be removed in preparation for noise barrier construction). It is anticipated that results will show the effect of the two different-width tree belts with and without leaves.

4.2.2 Noise Reduction form Moderate-to-Low Thickness Vegetation Screens

Moderate-to-low thickness vegetation screens are considered to be less than 20 m (65.6 ft) thick. This type of vegetation belt is often implemented as a visual screen as opposed to a noise abatement measure, but there is utility in understanding their potential for noise reduction; however, understanding their potential for noise reduction can help to maximize community benefit.

FHWA sponsored a study completed by Caltrans in 1989[135] that looked at the noise benefit for three types of existing landscaping: 1) oleander shrubs, 2) combination of oleander and redwoods, and 3) pine trees. The study found that a continuous strip of oleander or equivalent shrubs along the highway shoulder that is at least 2.4 m (7.9 ft) high and 4.5 to 6 m (14.8 to 19.7 ft) wide may provide noise reduction of 1 to 3 dB. The average noise reduction at the site with oleander and redwoods was only 0.5 dB, and the oleander was 4 m (13.1 ft) wide and 2.7 m (8.8 ft) high, and the redwoods were spaced 9.1 m (30 ft) on center. (It's unclear why the combination would provide less reduction; this illustrates how it can be

[134] Chalmers University of Technology, CSTB, Canevaflor, IBBT Gent University, Muller BBM, Open University, City of Stockholm, TOI, University of Sheffield, University of Bradford, Stockholm University, Acoucite, and Hangyang University, "Novel solutions for quieter and greener cities, Brochure summarizing HOSANNA Project, 2013.

[135] Hendriks, R., "Traffic Noise Attenuation as a Function of Ground and Vegetation (Interim Report)," Report No. FHWA/CA/TL-89/09, California Department of Transportation, September 1989.

difficult to achieve consistent noise reduction from vegetated screens.) The site with pine trees was 9.1 m (30 ft) deep, but with low density, also showed a noise reduction of only 0.5 dB.

Fang[136] looked at six narrow vegetative screens composed of hedges common in Taiwan, with thickness ranging from 1.2 to 3 m (3.9 to 9.8 ft). The measured attenuation at the hedges relative to flat ground was between 2 and 5 dB at a height of 1.5 m (4.9 ft) off the ground. The study found that a vegetative screen is effective in noise reduction when both receiver and noise source height are low, visibility is low, the screen is high and wide, and the distance between the noise source and receiver was less than eight times that of the vegetative screen height.

Van Renterghem et al.[137] also looked at noise reduction of hedges. The study comprised of measurements at eight sites with dense hedges with thickness ranging from 1.3 to 2.5 m (4.3 to 8.2 ft) and heights from 1.6 to 4 m (5.2 to 13.1 ft). Measured insertion losses ranged from 1.1 dBA to 3.6 dBA. Spectral analysis showed an improved ground effect due to the presence of the hedge in the frequency range between 250 and 1000 Hz; the noise reductions were found to be associated with an increased ground effect.

Peng[138] looked at moderately thick tree belts of 10 to 20 m (32.8 to 65.6 ft) comprised of shrubs and eucalyptus and pine trees planted very densely together. The relative attenuation compared to flat ground at these sites was found to be 2 to 3 dB.

Van Renterghem et al.[139] numerically modeled moderately thick tree belts of 15 m (49.2 ft) in width. In the model, the trees were periodically arranged for computation efficiency. The noise reducing effect of the forest floor and the optimized tree belt arrangement are found to be of similar importance in the calculations performed. Significant noise reduction is predicted to occur for a tree spacing of less than 3 m (9.8 ft) and a tree stem diameter of more than 0.11 m (0.36 ft). The model suggests that the optimized tree belt can compete with the noise reducing performance of a 1 to 1.5 m (3.3 to 5 ft) high barrier with noise reduction of 5 to 6 dB. The effect of shrubs with typically above-ground biomass is estimated to be a maximum of 2 dB.

A study from the University of Sheffield[140] focuses more on tree characteristics. Quantifying scattered sound energy from a tree, numerical predictions for a single tree with different conditions (crown size and shape, foliage condition, ground condition, receiver height, and source-receiver angle and distance) showed that reverberation time (RT) is proportional to tree size, the most determining factor. The presence of leaves increased the RT for highway frequencies, 0.08 seconds at 4 kHz. The source-receiver distance, ground condition, and receiver height affect the decay curves. The overall results indicate that trees can play an important role in outdoor sound propagation in urban spaces, especially at highway frequencies and with large trees.

[136] Fang, C. F., "Guidance for noise reduction provided by tree belts," Landscape and Urban Planning, 71 pp. 29-34, 2005.

[137] Van Renterghem, T., K. Attenborough, M. Maennel, et al, “Measured light vehicle noise reduction by hedges,” Applied Acoustics, 78 pp. 19-27. 2014.

[138] Peng, J., R. Bullen, and S. Kean, “The effects of vegetation on road traffic noise,” Proceedings of Internoise, 2014.

[139] Van Renterghem, T., D Bottoeldooren, and K. Verheyen, "Road traffic noise shielding by vegetation belts of limited depth," Journal of Sound and Vibration, Volume 3310 Issue 10, May 2012.

[140] Yang, Hong-Seok, Outdoor noise control by natural/sustainable material sin urban areas, Doctoral Thesis, The University of Sheffield, September 2013.

Van Renterghem[141] describes that rows of trees behind noise walls acts as a wind break; canopies of the trees can be effective in reducing wind speed. Measurements showed that at a wind speed of 12 m/s (27 mph) at a height of 10 m (33 ft), 3.5-4 dBA of noise shielding that was lost by the action of the wind was recovered by the trees. The effect was not restricted to the downwind direction. The specific distribution of biomass with height in the canopy is important; the most efficient seems to be a rectangular shape, where most biomass is located near the bottom of the canopy, resulting in a smooth transition near its top to limit the occurrence of wind speed gradients there. This means that conifers are most suited, not only because of their typical canopy shape, but also for their larger needle-area densities, larger drag coefficients, and since they do not drop leaves during winter. (A row of trees in front of a barrier was not discussed, however, it's likely the same effect would not apply. Van Renterghem describes that the positive action by a row a trees behind a barrier is caused by the removal of momentum of the wind flow as it moves over the barrier. Trees in front of the barrier are situated before the barrier effect on the wind, and should therefore have a different effect than is described for trees behind the barrier.)

Van Renterghem further describes that the start of the canopy below, at, or above the top of a noise wall affects what receiver ranges the largest wall efficiency improvement takes place. The absence of gaps between the top of the wall and canopy mainly improves shielding close behind the barrier in wind. With increasing downwind distance, the positive action of the wind-breaking trees become smaller and the canopies might even give rise to a slightly negative effect. With a gap present, the wind effect is not recovered at a close distance. However, the positive action of the trees remains up to a larger distance downwind relative to the absence of a gap in the canopy. An overall stronger improvement is therefore predicted. Note that gaps between the top of the barrier and tree canopy should be avoided if there are reflecting walls on both sides of the road.

The HOSANNA project[142] further describes how vegetation can improve noise barrier performance. Placing a row of trees behind a wall noise barrier will help to reduce negative downwind noise effects, where the tree canopy provides wind shelter that can help reduce the refraction effect of the wind. It is discussed that the improvement due to trees does not apply to a berm noise barrier. Also, because vegetation influences local micro-meteorology, a vegetated belt can reduce the likelihood of a temperature inversion layer which can bend sound downwards.

The benefit in windy conditions of a vegetative screen combined with a sound wall were established using a scale model[143] and with a numerical model.[144] In the 1:20 scale model a woven windscreen made of polyester was used in place of trees, and data was collected in a wind tunnel. The results showed the net effect of vegetative screens behind a sound wall may be up to 4 dB, but the magnitude will depend on the configuration used. In a practical implementation, it may be difficult to obtain an optimal porosity of the canopy throughout the year. In the 2008 numerical model study, three typical canopy shapes were simulated. The best canopy shape for reducing the wind effects was a triangular crown shape, where the

[141] Van Renterghem, T., J. Forssen, K. Attenborough, J. Philippe, J. Defrance, M. Harnikx, and J. Kang, "Using natural means to reduce surface transport noise during propagation outdoors," Applied Acoustics, 99 pp. 86-101, 2015.

[142] Chalmers University of Technology, CSTB, Canevaflor, IBBT Gent University, Muller BBM, Open University, City of Stockholm, TOI, University of Sheffield, University of Bradford, Stockholm University, Acoucite, and Hangyang University, "Novel solutions for quieter and greener cities", Brochure summarizing HOSANNA Project, 2013.

[143] Van Renterghem, T., D. Botteldooren, W. Cornelis, and D. Gabriels, "Reducing screen-induced refraction of noise barriers in wind by vegetative screens.," Acta Acustica united with Acustica, 88 pp. 231-238, 2002.

[144] Van Renterghem, T., and D. Botteldooren, "Numerical evaluation of tree canopy shape near noise barriers to improve downwind shielding," Journal of the Acoustical Society of America, 123 pp. 648-657, 2008.

pressure drop is maximum at the bottom of the canopy and which decreases linearly towards the top. Coniferous trees are more suited than deciduous trees to increase the downwind noise barrier efficiency.

4.2.3 Perception of Noise with Vegetated Screens

Anecdotal experience is that vegetative screens that are too narrow to provide noise benefit, but act as a visual screen, can reduce the perceived loudness of traffic noise in some communities. Several studies have tried to investigate this effect to determine why it may be true and what the optimal screen to exploit this effect may be.

Aylor and Marks[145] asked listeners to assess the loudness of a loudspeaker source under four different visual conditions. The noise source was white noise limited by filters to a one-third octave band centered at 100 Hz and the noise level varied from about 40 to 100 dB. The study found that sensitivity to noise was less when there was no visual screen at all or when the source was visible through an open slat fence. When the source was completely obscured behind a conifer hedge or a louvered barrier with gaps that obscured view, the sensitivity to noise was higher. The authors conclude that sounds coming from behind barriers are perceived as surprisingly loud because one expects the loudness to be diminished when the sound source cannot be seen.

Anderson[146] tested the perceived intensity or loudness of pure tones on 100 college students at different locations around Athens, Georgia. They found that the perceived loudness of sounds tends to increase as the amount of vegetation visible in the sites increased – the opposite of what they set out to show. They concluded that the visual influence of vegetation on loudness may be due to experience. People learn to expect reduced sound levels in more vegetated settings, at least compared with highly developed urban settings.

Watts[147] gathered subjective assessments of traffic noise at locations within three roadside sites with varying degrees of visual screening by vegetation at the Transport Research Laboratory's Noise Barrier Test Facility NBTF) using an artificial sound source. The study arranged for the noise exposure to vary as widely as possible and a relatively large number of listeners in an effort to accurately define the dose-response trend. The study found that the mean effect of vegetation on the perception of sound, if present, was probably relatively small compared with the variability of individual responses to a given noise exposure condition, but the study did find that listeners tended to give higher noisiness ratings under the same noise exposure when the source was obscured by vegetation which agrees with previous findings in Aylor and Marks and Anderson.

Joynt[148] attempted to determine if an aesthetically pleasing barrier can be used to increase the perception of noise reduction using a virtual reality setting of five different noise barriers. The study found that there was an inverse correlation between aesthetics and perception of how a noise barrier would perform. The transparent and deciduous vegetation barriers were judged most aesthetically pleasing, but least effective at attenuating noise. The respondents preconceptions influenced actual perception of the barrier's effectiveness at attenuating noise – they perceived greater noise reduction from the barriers they thought would be most effective.

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[145] Aylor, D.E., and Marks, L.E., "Perception of noise transmitted through barriers", Journal of Acoustical Society of America, vol 59 pp 397-400, 1976.

[146] Anderson, L.M., B.E. Mulligan, and L.S. Goodman, "Effects of Vegetation on Human Response to Sound," Journal of Arboriculture, 10(2), 1984.

[147] Watts, G., L. Chinn, and N. Godfrey, "The effects of vegetation on the perception of traffic noise," Applied Acoustics 56, 1999.

[148] Joynt, J.L.R., and J. Kang, "The influence of preconceptions on perceived sound reduction by environmental noise barriers," Science of the Total Environment, 408 (20) pp. 4368-4375, 2010.

Yang[149] also used a virtual reality setting and a loudspeaker to simulate traffic noise in two settings: on the sidewalk near a road and in an adjacent park behind vegetation. In addition to data from a qualitative survey, the quantitative emotional response was measured using an electroencephalogram (EEG). The survey found that most respondents believed landscape plants could contribute to noise reduction and the EEG results showed that there is significant difference in human physiological responses to vegetation and traffic views; the subject's frame of mind is significantly calmer in vegetation scenes than traffic scenes.

Van Renterghem[150] interviewed 105 respondents whose homes were all highly exposed to dominant road traffic noise. The interview data revealed the self-reported degree of vegetation as seen through the living room window was a strong and statistically significant predictor of self-reported noise annoyance. The complete absence of vegetation resulted in a 34% chance of at least being moderately annoyed by noise, while this chance reduced to 8% for respondents answering to having an extremely green visual, despite a median L_{den} level of 73 dBA at the street-facing facade of the residence.

For a case in Arizona with direct line-of-sight to a major arterial road, a community was looking for a solution to reduce road noise. With a privacy wall being too expensive, vegetation was planted to block the line-of-sight. The residents in the community expressed that the vegetation really helped with the noise.[151] It is unlikely that the vegetation actually reduced noise levels, and perhaps the help was in relation to a calming effect and/or reduction in annoyance.

The early surveys conducted by Aylor and Marks, Anderson, and Watts show that people generally expect reduced sound levels in vegetated spaces and are therefore more sensitive to the noise coming from behind vegetative screens, which is the opposite of the anecdotal evidence that annoyance to traffic noise will decrease if a vegetative screen is present. In the more recent studies, Yang and Van Renterghem show that vegetation may have a calming effect, and this calming effect may lead to lower annoyance in one's own home. However, it is very difficult to design a study that involves subjective perceptions, and the relationship between a visual vegetative screen and noise annoyance is still not well understood.

4.3 Vegetated Swales and Retention Basins

Vegetated swales/ditches or retention basins are constructed to reduce or store storm water run-off. It is possible for these features to provide some reduction in highway traffic noise for adjacent communities. The geometry and placement of the ditch or basin and any material in the ditch or ground type can all affect the noise propagation. However, the research team found no existing literature or studies looking at the noise reducing potential of these features.

To help estimate noise reduction due to vegetated swales and retention basins, the research team conducted a brief FHWA Traffic Noise Model (TNM v2.5) [152] study of a vegetated biofilter, applying a range of design parameters to estimate effects. A vegetated biofilter is a swale that allows runoff to spread out and move slowly through a shallow, flat, and grassed conveyance. It filters storm water through vegetation and potential infiltration. A vegetated biofilter consists of a grassed portion of the graded

[149] Yang, G. Z. Bao, Z. Zhu, "An assessment of psychological noise reduction by landscape plants," International Journal of Environmental Research and Public Health, 8(4) pp. 1032-1048, 2011.

[150] Van Renterghem, T., D. Botteldooren, "View on outdoor vegetation reduces noise annoyance for dwellers near busy roads," Landscape and Urban Planning, 148 pp. 203–215, 2016.

[151] Communication with A. Newton, Newton Environmental Consulting, October 2019.

[152] Menge, C., C. Rossano, G. Anderson, and C. Bajdek, *FHWA Traffic Noise Model, Version 1.0: Technical Manual*, Report No. FHWA-PD-96-010, 1998. TNM v2.5 update sheets: https://www.fhwa.dot.gov/environment/noise/traffic_noise_model/tnm_v25/tech_manual/index.cfm, 2004.

shoulder, grassed foreslope, and flat grassed ditch. Figure 4-6 shows photographs of vegetated basins. The results of the TNM modeling are summarized in Table 4-3.

Figure 4-6: Examples of vegetated biofilter basins (Ohio DOT,[153] used with permission).

Table 4-3. Summary of strategy: vegetated biofilter basin.

Strategy	Noise Benefit	Costs	Context Appropriateness
Vegetated biofilter basin	Less than 1 dB effect on noise adjacent to a 6-lane highway; For a two lane highway, there is less than 1 dB effect out to 91.4 m (300 ft) and up to 2.4 dB out to 152.4 m (500 ft)	No additional cost if the vegetated swale is already planned	Highways or roads where a vegetated swale is needed

For vegetated biofilters, the bottom width of the ditch typically ranges from 1.2 to 3.0 m (4 to 10 ft). Slopes are typically not steeper than 3:1, to ensure that maintenance is feasible. A vegetated filter strip is measured from the top of the foreslope to the edge of the ditch bottom. With a pavement width of 14.6 m (48 ft), it is recommended to have a 6:1 slope and 7.6 m (25 ft) width strip. For narrower pavement, 3:1 or narrower slopes are recommended, with a width reduced to 5.2 m (17 ft) for 7.3 m (24 ft) of pavement.[154]

Real traffic data was used in the TNM runs, with 5% heavy trucks and speeds ranging from 100-127 km/h (62-79 mph, lane-dependent). Both six- and two-lane scenarios were examined. The general ground type chosen was hard soil (mostly reflective). Results with a completely flat ground were compared to scenarios with basins adjacent to the highway, with insertion loss being calculated as basin minus flat ground. (Note that the insertion loss was calculated with hard soil rather than pavement, to represent more realistic scenarios; insertion loss values would be larger if comparing to pavement.) Figure 4-7 shows the cross-sections of the four basin geometries examined; the figure caption shows parameters applied. The vegetation is represented in TNM by simply adding a ground zone of softer ground type (refer to Section 4.4.1 for more information on acoustically soft ground). Note that TNM does not account for any

[153] Ohio Department of Transportation, photos from ODOT 1/18/2109 PCSW BMP presentation by Jon Prier, 2019.

[154] Ohio Department of Transportation, Location and Design Manual – Volume Two, Drainage Design, July 2019.

scattering that may occur from vegetation. The ground zone extends from the top of the foreslope to the top of the backslope. Two softer ground types are applied: field grass (sound absorptive) and also a very soft ground equivalent to the absorption of powdered snow.

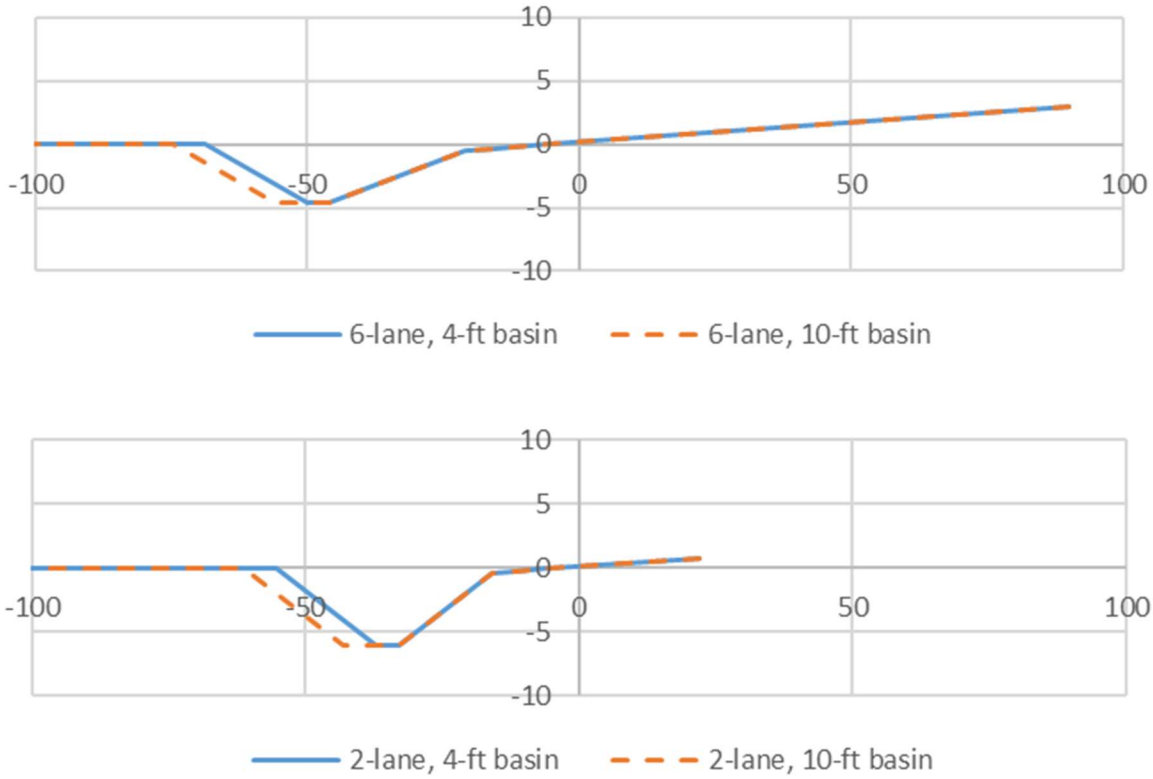


Figure 4-7: Road/vegetated basin cross-sections.

Top: 6-lane highway, 10 ft paved shoulder, 5 ft graded shoulder, 6:1 slope, 4 or 10 ft basin bottom, 4:1 slope.
Bottom: 2-lane highway, 6 ft paved shoulder, 5 ft graded shoulder, 3:1 slope, 4 or 10 ft basin bottom, 3:1 slope.

Figure 4-8 and Figure 4-9 show the predicted insertion loss due to each of the scenarios for a six-lane and two-lane highway, respectively. For a six-lane highway, Figure 4-8 shows a vegetated basin has less than 1 dB effect on noise adjacent to the highway. For a two-lane highway, Figure 4-9 shows that a vegetated basin has less than 1 dB influence out to 91.4 m (300 ft) and up to 2.4 dB out to 152.4 m (500 ft). Near the road (≤ 30.5 m or 100 ft), 250-300 Hz are reduced at least 2 dB; these frequencies have minimal effect on the broadband A-weighted sound level. Farther from the road (≥ 106.7 m or 350 ft), 400 and 800-1250 are reduced at least 2 dB; these frequencies have a meaningful effect on the broadband A-weighted sound level. For both highways, there is negligible influence from a very highly absorptive surface compared to field grass and also from widening the basin.

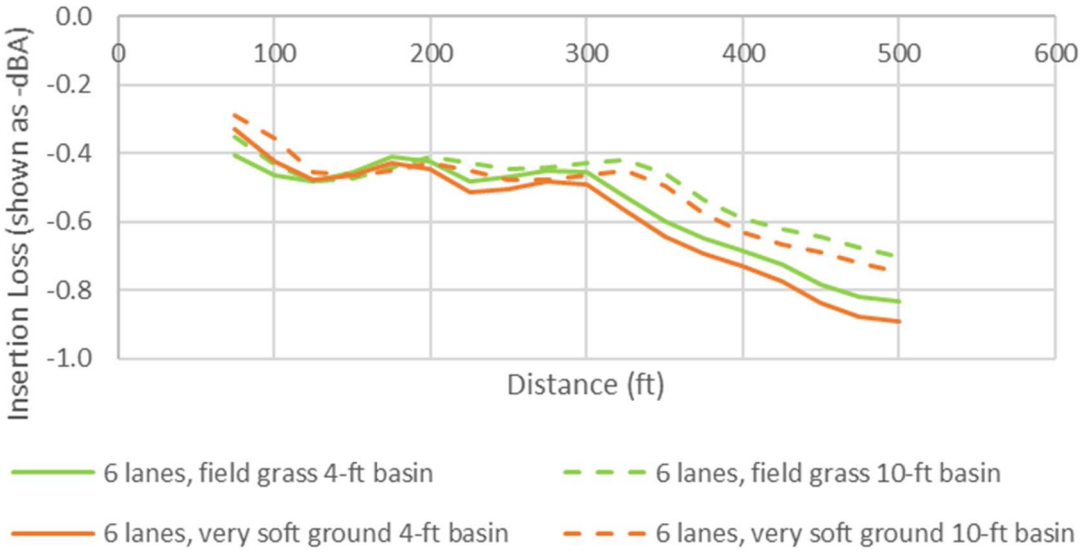


Figure 4-8: Predicted effects of vegetated basins, 6-lane highway.

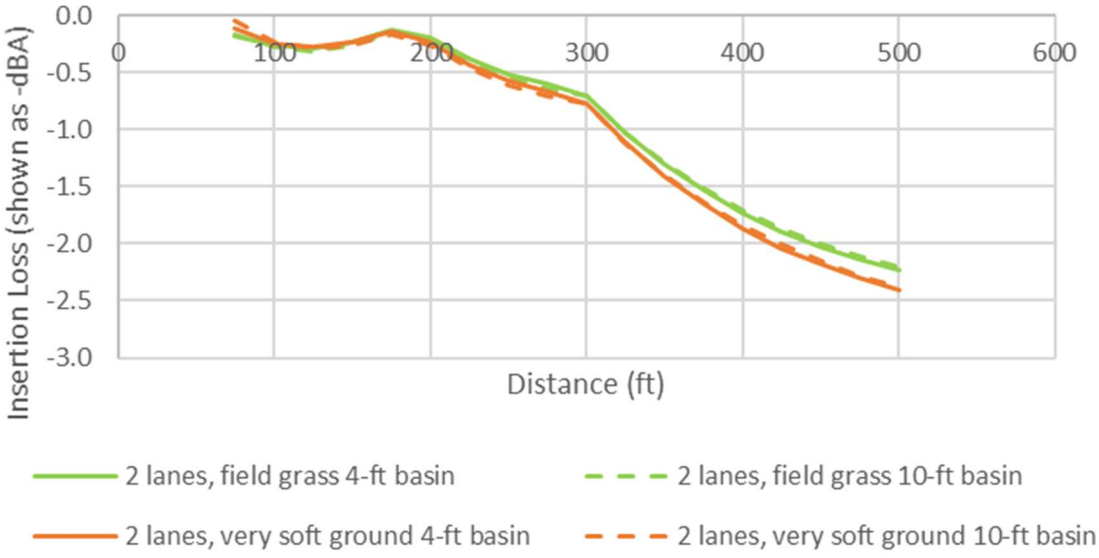


Figure 4-9: Predicted effects of vegetated basins, 2-lane highway.

4.4 Sound-Absorbing Ground Surfaces and Ground Treatments Adjacent to a Highway

Changing the ground adjacent to highways can affect received sound levels. Sound-absorbing ground surfaces or ground treatments can be applied. These strategies are detailed further in the following sections, with ground treatments being divided into two categories: in-ground and above-ground. The placement and extent of the surface can affect noise-reducing capabilities in adjacent communities. In general, the closer the surface or treatment is placed to the sound source, the more effective it is at nearby communities.

Table 4-4 shows a summary of the strategy *sound-absorbing ground surfaces and ground treatments adjacent to a highway*. The summary is based on information extracted from the references described in this subsection.

Table 4-4. Summary of strategy: sound-absorbing ground surfaces and ground treatments adjacent to a highway

Strategy	Noise Benefit	Costs	Context Appropriateness
Acoustically soft ground	TNM[155] predictions show 1-2 dB for placement in ROW or median, however, more may be realized with gravel surfaces (multi-lane highway) CRTN[156] predictions show 3-12 dB for placement 2.5 m (8.2 ft) from the edge of the near travel lane, largest decrease for gravel and low flow resistivity grassland (2-lane road); soft surface extended 25 m (82 ft) or more from road Soft ground treatments are less effective as the receiver height increases As source-receiver distance is increased, the insertion losses due to the near-source ground treatments do not decrease as they would with a traditional noise barrier	Geographically dependent – may need to maintain grass or gravel	Highways with ROWs or medians that can accommodate acoustically softer ground surfaces
In-ground treatments	Testing of WHISstone shows 2.4 and 4 dB reduction for a recessed lattice structure 0.95 and 1.9 m (3 and 6 ft) wide and 0.2 m (0.7 ft) deep, respectively, measured 12 m (39 ft) from a single vehicle pass-by source Calculations show 2-8 dB reduction for a recessed lattice structure 0.3 m (1 ft) deep placed 2.5 m (8 ft) from the nearest source; range of insertion loss depends on the width of the structure, ranging from 1.5-24 m (5-79 ft, widest being most effective) In-ground resonators may be tuned to reduce a specific frequency, although their effectiveness would likely be less than 2-3 dB (shoulder placement)	WHISstone is ~$170 USD per 1 meter or 3.3 feet length along road (single row, 0.95 m or 3 ft wide)	Highways with ROWs that can accommodate embedded structures close to the near travel lane (narrow shoulders, likely 2-lane road)
Above-ground treatments	Boundary Element Method predictions show the following:	Unknown – would need to	Highways with ROWs that

[155] Menge, C., C. Rossano, G. Anderson, and C. Bajdek, *FHWA Traffic Noise Model, Version 1.0: Technical Manual*, Report No. FHWA-PD-96-010, 1998. TNM v2.5 update sheets: https://www.fhwa.dot.gov/environment/noise/traffic_noise_model/tnm_v25/tech_manual/index.cfm, 2004.

[156] UK DOT, *Calculation of Road Traffic Noise*, ISBN 0 11 550847 3, Department of Transport, United Kingdom, 1988.

	- Low (< 0.3 m or 1 ft) parallel walls (12 m or 30 ft wide) can provide up to 9 dB reduction at 50 m or 164 ft - A low (< 0.3 m or 1 ft) lattice wall structure (12 m or 30 ft wide) can provide up to 11 dB reduction at 50 m or 164 ft Related notes: - Wider structures provide greater reduction - Comparative soft ground for half the source-receiver distance provides 9 dB reduction - Effectiveness is not affected by receiver height or distance	construct and maintain low parallel or lattice walls	can accommodate above-ground low structures close to the near travel lane (narrow shoulders, likely 2-lane road)

4.4.1 Acoustically Soft Ground

Sound waves interact with the ground, and both direct and reflected sound can reach communities adjacent to a highway. Direct and reflected sound waves interact, however, causing both constructive interference (increasing the sound) and destructive interference (decreasing the sound), depending on site-specific geometries, ground type, and frequency. Acoustically hard ground (e.g., pavement, water) reflects the sound, and for tire-pavement noise, destructive interference occurs at higher frequencies that have little effect on overall sound level, so constructive interference dominates. Acoustically soft ground (e.g., grass, gravel) alters the sound; in addition to reduction in magnitude, due to a phase change upon reflection, destructive interference occurs at a lower frequency that affects highway traffic noise. As a result of sound being able to penetrate a soft, porous surface, some of its energy is converted to heat. Porosity is not the only factor: sound is affected most by the ease with which air can move in and out of the ground surface. This is indicated by the flow resistivity (high values make it difficult for the air to flow, and low values allow easy flow; acoustically soft ground has lower values than hard).[157]

In presentations to the Transportation Research Board (TRB) and APTA Rail Conference noise and vibration participants, Rochat[158,159] and Layman[160] described how ground adjacent to transportation systems can help to reduce noise in nearby communities. Two elements were discussed in determining at what distances from a transportation system the noise reduction could be realized and how much the noise can be reduced. To estimate the area of greatest influence of a strip of soft ground, a simple Excel tool was developed that estimates the distances at which reflections off the soft ground could have the greatest effect on the received sound level. The tool uses a source height of 0.1 m (0.3 ft) for the tire-pavement noise source, a receiver height of 1.5 m (5 ft), and strips ranging in width from 1.5 to 9.1 m (5 to 30 ft). The ground strips are placed 4.9 m (16 ft) from the center of the near travel lane, and it is assumed that the full lane width is 3.7 m (12 ft) and the shoulder is 3.0 m (10 ft). The estimates are calculated based on sound reflecting at the nearest and farthest edges of the soft ground strip, and the calculations assume no other interference (e.g., shielding from rows of houses). The area of greatest influence is calculated to be:

- Ground strip width 5 ft, area of greatest influence 79.2-99.1 m (260-325 ft)
- Ground strip width 10 ft, area of greatest influence 79.2-123.7 m (260-406 ft)
- Ground strip width 20 ft, area of greatest influence 79.2-173.4 m (260-569 ft)
- Ground strip width 30 ft, area of greatest influence 79.2-222.8 m (260-731 ft)

The influencing ground would need to be placed closer to the source in order to affect receptors closer to the road. The shoulder placement, for example, has the area of greatest influence from 29.6 to 77.4 m (97 to 254 ft); this may be more ideal considering the first row of homes. Since the above calculations assume the nearest travel lane, it should be pointed out that regions of influence would expand for more travel lanes. In addition, higher traffic noise sub-sources would have closer regions of influence [e.g. for

[157] Van Renterghem, T., J. Forssen, K. Attenborough, J. Philippe, J. Defrance, M. Harnikx, and J. Kang, “Using natural means to reduce surface transport noise during propagation outdoors,” Applied Acoustics, 99 pp. 86-101, 2015.

[158] Rochat, J., "Using the ground to reduce transportation noise," presentation at Transportation Research Board Noise and Vibration Committee Summer Meeting, 2014.

[159] Rochat, J., "Using the ground to reduce sound," presentation at Transportation Research Board Noise and Vibration Committee Winter Meeting, 2016.

[160] Layman, C., McKenna, S., and Rochat, J., "Non-traditional noise and vibration mitigation strategies," presentation at APTA Rail Conference, 2016.

the engine height of 1.5 m (5 ft), and a 3.0 m (10 ft) strip next to the road, the region of influence is estimated as 9.6-11.0 (32-36 ft) and out to 23.2 m (76 ft) for a 9.1 m (30 ft) strip].

The Federal Highway Administration (FHWA) Traffic Noise Model (TNM) v2.5 was used to calculate the noise reduction in the region of influence. With ground strips up to 12.2 m (40 ft) in width placed adjacent to the shoulder, compared to hard ground (pavement), the influence of soft ground (effective flow resistivity of 490 cgs rayls, slightly less absorptive than lawn) was only up to 1.2 dB. For a very soft ground (effective flow resistivity of 10 cgs rayls, lowest number in TNM and less absorptive than gravel), the influence was only up to 1.3 dB. Both of the calculations were done for receivers ranging from 75 to 500 ft from the nearest travel lane. The conclusions were that soft ground placed in a highway right-of-way (ROW) provided only a small benefit for the geometry tested (including all flat ground). Also presented at TRB, Staiano[161] described the effect of placing acoustically soft ground in the median of a six-lane highway. Predicted with TNM v2.5, a 6.1 m (20 ft) soft ground median compared to acoustically hard ground provided about 2 dB reduction from 106.7-182.9 m (350-600 ft) from the road. Also, predictions showed that wider medians with acoustically soft ground provide more reduction over greater distances.

Predictions done with rail geometries/parameters and applying the very soft surface[162,163,164] showed that at a distance up to 45.7 m (150 ft), ballast/gravel provided up to 8 dB reduction for a strip width of 6.1 m (20 ft) (and slightly less with narrow strips). The presentations also referenced a study that showed ballast/gravel combined with a very low berm (0.4 m or 15 in) could provide up to 10 dB reduction. A different geometry tested with TNM with an elevated receiver showed influences up to 2 dB up to 30.5 m (100 ft) from the rails and with a strip up to 3.0 m (10 ft) wide. Since some of the rail scenario predictions are quite promising, the results emphasize the dependence on the source-strip-receiver geometry. Placing a very absorptive surface as a highway shoulder could lead to the most promising results, particularly when combined with quieter pavement. Also, it could be examined how use of gravel in highway ROWs could be optimized. TNM does not currently allow effective flow resistivity (EFR) values below 10 cgs rayls to be included in the calculations; the values for gravel can be well below 10 cgs rayls, with frequencies of influence being dependent on depth.

The FHWA TNM validation report on ground and pavement effects includes a table of ground types and associated EFR values. Additional values are shown in Rochat 2013[165] and Attenborough 2007.[166] A summary of various types is shown in Table 4-5. Figure 4-10 shows extremely sound absorptive surface, ballast (large gravel). It should be added that loose leaves change the sound absorption characteristics. An experiment and predictions for normal incidence showed that leaves on top of a soft surface do not affect

[161] Staiano, M., "Possible noise control benefits of highway cross-section selection," presentation at Transportation Research Board Noise and Vibration Committee Summer Meeting, 2009.

[162] Rochat, J., "Using the ground to reduce transportation noise," presentation at Transportation Research Board Noise and Vibration Committee Summer Meeting, 2014.

[163] Rochat, J., "Using the ground to reduce sound," presentation at Transportation Research Board Noise and Vibration Committee Winter Meeting, 2016.

[164] Layman, C., McKenna, S., and Rochat, J., "Non-traditional noise and vibration mitigation strategies," presentation at APTA Rail Conference, 2016.

[165] Rochat, J. and D. Read, “Effective flow resistivity of highway pavements,” J. Acoust. Soc. Am., 134 (6), Pt. 2, December 2013.

[166] Attenborough, K., K. Li, and K. Horoshenkov, *Predicting Outdoor Sound*, Taylor & Franscis, New York, NY, 2007.

the low-frequency range (< 250 Hz), increase absorption in the mid-frequency range (500-2,000 Hz), and decrease absorption in the higher frequency range (> 2000 Hz).[167]

Table 4-5. Ground types and associated EFR values.

Ground type	Additional Detail	EFR range (cgs rayls)[a]
Gravel	Various depths and rock dimensions, with larger stones and greater depth having lowest values	0.2-58
Snow	Newly fallen dry snow having lowest values	10-50
Forest floor	Pine or hemlock	20-80
Grass	Root layer in loamy sand and pastures having lowest values, large ratio of dirt/vegetation having highest	100-600
Soil	Various types	106-450
Sand	Various types	40-906
Roadside dirt	With ill-defined small rocks up to 100 mm (4 in) sieve size	300-800
Sandy silt	Hard packed by vehicles	800-2,500
Limestone chips	13-25 mm (0.5-1 in) sieve size	1,500-4,000
Exposed dirt	Rain-packed	4,000-8,000
Asphalt	Open-graded and porous having lowest values, old dense-graded highest	5,000-30,000
Concrete	Depends on finish, painted being highest	20,000-200,000
Upper limit	Set by thermal-conduction and viscous boundary layer	20,000-1,000,000

[a]1 cgs rayl = 1000 Pa s/m^2

[167] Ding, L., T. Van Renterghem, D. Botteldooren, K. Horoshenkov, and A. Khan, "Sound absorption of porous substrates covered by foliage: Experimental results and numerical predictions," J. Acoust. Soc. Am., 134 (6), Pt. 2, December 2013.

Figure 4-10: Extremely sound-absorptive surface, large gravel.[168]

The European Holistic and Sustainable Abatement of Noise by Optimized Combinations of Natural and Artificial Means (HOSANNA) project[169] aimed to develop a toolbox for reducing road and rail traffic noise in outdoor environments by the optimal use of vegetation, soil, other natural materials and recycled material in combination with artificial elements. The project utilized numerical calculations to determine the effects of various parameters on highway noise propagation. For acoustically soft ground investigations, it was found that introducing a single strip or multiple strips of an acoustically soft material such as gravel can reduce traffic noise in cases where there is otherwise hard ground. Predictions suggest a reduction potential of 3-9 dBA at a height of 1.5 m (5 ft), 50 m (164 ft) from a two-lane urban road (with single wide strip or several narrow strips). Attenborough 2016[170] and 2017[171] describe calculations further. Predictions were done with Calculation of Road Traffic Noise (CRTN, United Kingdom). It is stated that up to 300 m (984 ft) from a source, the presence of ground or other surfaces influences the sound level significantly. Compacted grassland (appears as lawn) compared to hard ground provides the most reduction between about 500 and 2,500 Hz, and non-compacted grassland (meadow) provides the most reduction between 200 and 2,500 Hz, with more reduction than compacted grassland between about 125 and 1,600 Hz. It is predicted that softening the ground between the source and receiver (e.g., using grass instead of pavement) can reduce the noise 5-9 dBA.

[168] Rochat, J., "Using the ground to reduce sound," presentation at Transportation Research Board Noise and Vibration Committee Winter Meeting, 2016.

[169] Chalmers University of Technology, CSTB, Canevaflor, IBBT Gent University, Muller BBM, Open University, City of Stockholm, TOI, University of Sheffield, University of Bradford, Stockholm University, Acoucite, and Hangyang University, "Novel solutions for quieter and greener cities, Brochure summarizing HOSANNA Project, 2013.

[170] Attenborough, K., I. Bashir, and S. Taherzadeh, "Exploiting ground effects for surface transport noise abatement," De Gruyter Open, Noise Mapp. 2016; 3:1-25, 2016.

[171] Attenborough, "Experimental methods for reducing surface transport noise," Northern Ireland Assembly, Knowledge Exchange Seminar Series, 2017.

From the Attenborough 2016 document,[172] at a distance of 50 m (164 ft) from a two-lane urban road containing 95% light vehicles, 5% heavy vehicles, traveling at 50 km/h (31 mph), the noise reduction ranges from 5.5 to 9.1 dB at a 1.5 m (5 ft) high receiver, with soft ground starting 2.5 m (8.2 ft) from sound source. At 50 m (164 ft), the greatest reduction is for application of 25 m (82 ft) of gravel next to the road. Please refer to Figure 4-11 for more information and other results. Note that at a distance of 100 m (328 ft) and a height of 1.5 m (5 ft), 7-12 dB reduction is predicted. Applying ISO 9613-2 (Standard: Acoustics – Attenuation of Sound During Propagation Outdoors – Part 2: General Method of Calculation), the predicted insertion loss decreases, showing the noise-reducing strategies to be somewhat less effective. The study also points out that soft ground treatments are less effective as the receiver height increases and that as the source-receiver distance is increased, the insertion losses due to the near-source ground treatments do not decrease as they would with a traditional noise barrier.

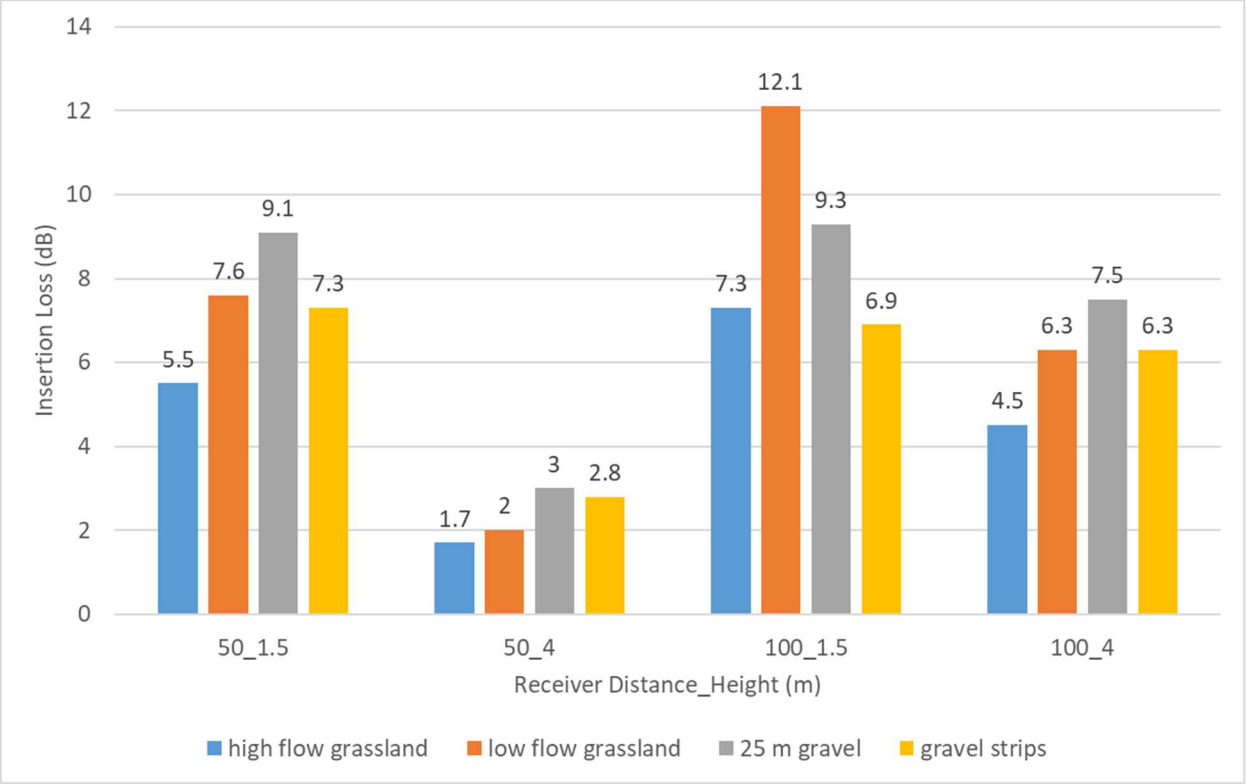


Figure 4-11: Softer ground study results at two receiver distances and heights, Attenborough 2016.

Data series:
45.7 or 97.5 m wide strips high flow resistivity grassland starting 2.5 m from nearest lane;
45.7 or 97.5 m wide strips low flow resistivity grassland starting 2.5 m from nearest lane;
25 m gravel (EFR 10 cgs rayls, at least 0.1 m deep);
25 m alternating 1 m wide strips of hard ground and gravel (EFR 10 cgs rayls, at least 0.1 m deep).

[172] Attenborough, K., I. Bashir, and S. Taherzadeh, "Exploiting ground effects for surface transport noise abatement," De Gruyter Open, Noise Mapp. 2016; 3:1-25, 2016.

The NCHRP Project 1-44[173] researchers conducted car pass-by testing for evaluating tire-pavement noise for various pavement types and test parameters. As part of the testing, sound propagation tests were conducted to evaluate ground effects. At a site with a two-lane PCC road with no shoulder, they measured the effect of propagation over part of the pavement and over adjacent ground. The ground adjacent to the shoulder was acoustically soft (appears as mowed field grass, not lawn), and the road was slightly depressed below grade (appears to be a few inches). Results showed that the effect of the acoustically soft ground and/or roadway depression was 2-4 dB. This is a case where the soft ground is very near the sound source and thus can have an effect that is not insubstantial when measuring sound adjacent to the road.

To elaborate on the influence of ground, Arizona DOT policy[174] emphasizes the importance by requiring, where possible, to do noise highway traffic noise measurements at two distances simultaneously (the second distance doubling the first) in order to determine the sound drop-off rate and validate the ground type used in TNM. In discussions with ADOT staff, [175] it was mentioned that measurements have shown typical ground in the Arizona to be acoustically softer than one would expect when examining the desert landscape. Using the proper ground type can help to minimize error in predicted sound levels. It was also mentioned that ground type near the road can influence the micro-climate and affect sound propagation. As is described in Section 4.2.2 for the effect of vegetation on the micro-climate, the ground can influence the air temperature profile, potentially reducing the likelihood of a temperature inversion layer which can bend sound downwards.

4.4.2 In-Ground Treatments

In-ground treatments are strategies with structures embedded in the ground (not raised above the surface). Grooves or pits add ground roughness to help reduce sound. As with propagation over acoustically soft ground, reflected sound is modified, affecting the sound that is received adjacent to a highway.

As discussed in Section 2.3 with quieter pavements, resonant cavities can be buried in the ROW ground (not just in travel lanes or shoulders).[176] A buried resonator (like a bottle) can be tuned to reduce noise at a desired frequency. With ROW placement, however, the effect of reducing sound may not reach 2-3 dBA, as predicted for shoulders.

Another example of an in-ground treatment product is WHISstone.[177,178] This and other 4Silence products were developed to reduce traffic noise by applying diffraction, where the sound is diverted upward in order to obtain horizontal noise reduction. WHISstone consists of concrete resonators placed horizontally on the ground next to a road. The product provides a flat surface that can be driven on, with a "grid" pattern in the concrete, with openings allowing drainage and for reflected sound to enter then be diverted back up, interacting with direct sound. This drivable surface it is most effective close to the source, so it is not necessarily suitable for a multi-lane highway with standard shoulders (the effect would

[173] Donavan, P. and D. Lodico, Measuring Tire-Pavement Noise at the Source, NCHRP Report 630 (Project 1-44), National Cooperative Highway Research Program, 2009.

[174] Arizona Department of Transportation, Noise Abatement Requirements, May 2017.

[175] Communication with Ivan Racic, Arizona Department of Transportation, 2019.

[176] Chalmers University of Technology, CSTB, Canevaflor, IBBT Gent University, Muller BBM, Open University, City of Stockholm, TOI, University of Sheffield, University of Bradford, Stockholm University, Acoucite, and Hangyang University, "Novel solutions for quieter and greener cities, Brochure summarizing HOSANNA Project, 2013.

[177] Willems, B., "Changing the landscape of noise reduction measures," Demonstration at Noise-Con 2019, August, 2019.

[178] 4Silence, "Changing the landscape of noise reduction matters," Product introduction sheet, 2019.

likely be small placed in the ROW or median). It could be considered for an extension of narrow shoulders. An example installation of a single row of WHISstone is in shown in Figure 4-12. WHISstone provides 2.5 dB reduction for a single row (0.95 m or 3 ft wide) and 4 dB for a double row (1.9 m or 6 ft wide), based on single vehicle pass-by testing. The structure is 0.2 m (0.7 ft) deep. At a distance of 12 m (39.4 ft), the reduction is about the same at heights of 1.2, 2, and 3 m (3.9, 6.5, and 9.8 ft). WHISstone has the greatest reduction from 630 to 1,600 Hz. Based on Dutch prices and some volume, the estimated cost for WHISwall completely installed (so including installation, foundation, etc.) is ± € 150 per meter or about $167 USD per 1 meter or 3.3 feet (~$267K/mi) (10/28/2019). The structure can be vacuumed if openings fill with debris. Consideration of noise reduction longevity would need to be considered for U.S. applications.

Figure 4-12: Example in-ground treatment adjacent to road (©4Silence, used by permission).

Numerical calculations discussed in Jean 2014[179] show 2-8 dB reduction for a recessed lattice structure 0.3 m (1 ft) deep placed 2.5 m (8 ft) from the nearest source. The range of insertion loss depends on the width of the structure, ranging from 1.5-24 m (5-79 ft, widest being most effective). The calculations assume a two-lane urban road (95% cars, 5% heavy trucks traveling 50 km/h), at a distance of 50 m (164 ft) and 1.5 m (5 ft) high, with calculations accounting for both lanes, The effect is 3-4 dB less than with a raised lattice structure, with less attenuation above 450 Hz for the recessed structure (discussed in next section). Recessed systems may be preferred, however, where there are restrictions on above ground construction close to roads or where they might be combined usefully with drainage arrangements. It's possible to make the recessed systems more effective by making them deeper than 0.3 m (1 ft).

4.4.3 Above-Ground Treatments

Above-ground treatments are structures above ground level, which create ground roughness to help reduce sound by interfering with ground reflections. The presence of small scale roughness makes a

[179] Jean, P., *Noise Reduction for Surface Roughness*, Chapter 6 of *Environmental Methods for Transport Noise Reduction*, CRC Press, Editors: Mats E. Nillson, Jörgen Bengtsson, Ronny Klaeboe, pp.119-152, 2014.

surface that appears acoustically hard at normal incidence and acoustically soft near grazing angles. If a surface is artificially or naturally rough, incident sound is not reflected perfectly but is scattered by the roughness. The distribution of the scattered sound depends on the roughness topology, the ratio of the roughness dimensions to the incident wavelength, and the relative locations of the source and receiver. Ground roughness can take the form of short parallel walls or walls in lattice patterns. As long as the height of the elements is 0.3 m (1 ft), which is approximately the wavelength of the sound in air at 1 kHz, or less, they can be considered as a form of artificial ground roughness.[180] Application of above-ground treatments to U.S. projects would need to consider safety and other restrictions.

HOSANNA[181] describes how the acoustical effects of roughness elements depend on their mean height, mean spacing, cross-sectional shape, total array width, and whether the configuration is random or periodic. One can design a roughness configuration 0.3 m (1 ft) high and 2 m (6.6 ft) wide that can help reduce traffic noise by at least 3 dB, compared with smooth, acoustically hard ground, at 10 m (33 ft) from the road. A 3 m (10 ft) wide configuration 0.3 m (1 ft) high reduces the noise by at least 7 dBA at 50 m (164 ft) from the road. Regular spacing can help focus the reduction to certain frequencies, and roughness elements distributed randomly results in reduction over a broad range of frequencies. Lattice configurations half the width of parallel-wall arrays of the same height are predicted to produce comparable noise reduction. Looking at a wider array, for a four-lane highway with 15% heavy and 85% light vehicles traveling at 70 km/h (44 mph), the noise reduction at 45 m (148 ft) from the edge of the road for a 16 m (52 ft) wide 26 wall array, with 0.247 m (0.8 ft) high parallel walls (wedge cross-sections) is predicted to be 8.5 dBA for receivers at the height of 1.5 m (5 ft) and 3 dBA for receivers at 4 m (13 ft). The sections between the roughness elements can be filled with small amounts (up to 10 cm or 4 in) of gravel, sand, soil, and plants in the gaps without affecting the noise reduction. Also, creating a 0.5 m (1.6 ft) path through the roughness configuration would not significantly reduce its noise reduction performance.

Attenborough 2016[182] and 2017[183] describe ground roughness results for a two-lane road with 5% heavy trucks. At 50 m (164 ft) from the road, a 3 m (10 ft) wide 16 wall array, with 0.3 m (1 ft) high parallel walls is predicted to reduce the noise by 7 dB compared to hard ground without the walls. For reducing noise from traffic, there is no advantage for placing low parallel walls regularly rather than randomly, but the appearance of uniform arrangements may be preferred. (Depending on how "advantage" is defined, this could contradict the HOSANNA reference, since they indicate that regular spacing can help focus the reduction to certain frequencies, and random spacing reduces sound over a broad range of frequencies.) Like the HOSANNA reference, the two Attenborough references also mention that, in contrast to a conventional noise barrier, the reduction is not much affected by creating a path through them. Attenborough agrees that, to improve their appearance, plants can be placed in low walls or lattice cells without affecting the noise reduction significantly as long as the depth of the gaps between the walls or lattice cells are not filled by more than about 30%. Also, it's stated that since the cells in the lattice structures are significantly larger than the pores in porous asphalt, they will not become

[180] Attenborough, K., I. Bashir, and S. Taherzadeh, "Exploiting ground effects for surface transport noise abatement," De Gruyter Open, Noise Mapp. 2016; 3:1-25, 2016.

[181] Chalmers University of Technology, CSTB, Canevaflor, IBBT Gent University, Muller BBM, Open University, City of Stockholm, TOI, University of Sheffield, University of Bradford, Stockholm University, Acoucite, and Hangyang University, "Novel solutions for quieter and greener cities, Brochure summarizing HOSANNA Project, 2013.

[182] Attenborough, K., I. Bashir, and S. Taherzadeh, "Exploiting ground effects for surface transport noise abatement," De Gruyter Open, Noise Mapp. 2016; 3:1-25, 2016.

[183] Attenborough, "Experimental methods for reducing surface transport noise," Northern Ireland Assembly, Knowledge Exchange Seminar Series, 2017.

clogged. However, to prevent accumulation of debris, they could be protected by acoustically transparent meshes or be used for planting without reducing their performance substantially. A cost-benefit analysis suggests that lattices places alongside a four-lane road could be a useful alternative to traditional noise barriers, particularly when used in combination with low noise road surfaces.

Figure 4-13 shows calculations of road noise reduction by ground treatment.[184] Noise was examined at receivers 1.5 and 4 m (5 and 13 ft) high at distances of 50 and 100 m (164 and 328 ft) from the nearest edge of a two-lane urban road containing 95% cars, 5% trucks traveling at 50 km/h (31 mph). The calculations used point source arrays to represent the vehicles, and HAMONOISE[185] methodology was used for sources characterization, assuming source heights of 0.01 m (0.03 ft) for tire-road noise (all vehicles) and either 0.3 m (1 ft) (light and medium vehicles) or 0.75 m (2.5 ft) (heavy vehicles) for engine noise. The spectrum of the noise sources is specified by vehicle type. A 2D Boundary Element Method (BEM) was used to predict insertion losses caused by ground treatments parallel to the road. (Attenborough mentions that standard prediction software/methods (CRTN, ISO 9613-2) have limited consideration of ground effect and under-predict insertion loss.) Insertion loss was calculated with respect to a smooth acoustically hard surface. The treatments start 2.5 m (8 ft) from the nearest travel lane (edge of road). The parallel wall configurations provide about 5-8.5 dB insertion loss at a height of 1.5 m (5 ft), greatest insertion loss for widest configuration (12 m or 39 ft). Lattice configurations are predicted to give higher insertion losses than parallel wall arrays of the same width and height, about 5-10.5 dB at a height of 1.5 m (5 ft), greatest insertion loss for widest configuration (12 m or 39 ft). The predicted reduction due to the proposed ground treatments is lower if the proportion of heavy vehicles is greater and if there are traffic lanes farther from the treatment.

Comparing soft ground and ground roughness at 50 m (164 ft), it's predicted that approximately the same insertion loss is found by either replacing 47.5 m (156 ft) of hard ground with low flow resistivity soft ground (-9.1 dB) or by constructing a 12 m (39 ft) wide array of 0.3 m (1 ft) high parallel walls on it (-8.6 dB). A 12 m (39 ft) lattice provides an additional 2 dB reduction (-10.5 dB). In contrast to soft ground, the insertion losses predicted for lattice and parallel wall configurations are not much affected if the receiver height is increased from 1.5 m to 4 m (5 to 13 ft) or if the receiver is farther from the road.

[184] Attenborough, K., I. Bashir, and S. Taherzadeh, "Exploiting ground effects for surface transport noise abatement," De Gruyter Open, Noise Mapp. 2016; 3:1-25, 2016.

[185] Salomons, E., D. van Maercke, J. Defrance, and F. de Roo, "The Harmonoise sound propagation model," Acustica, Vol 97, 62-74, 2011.

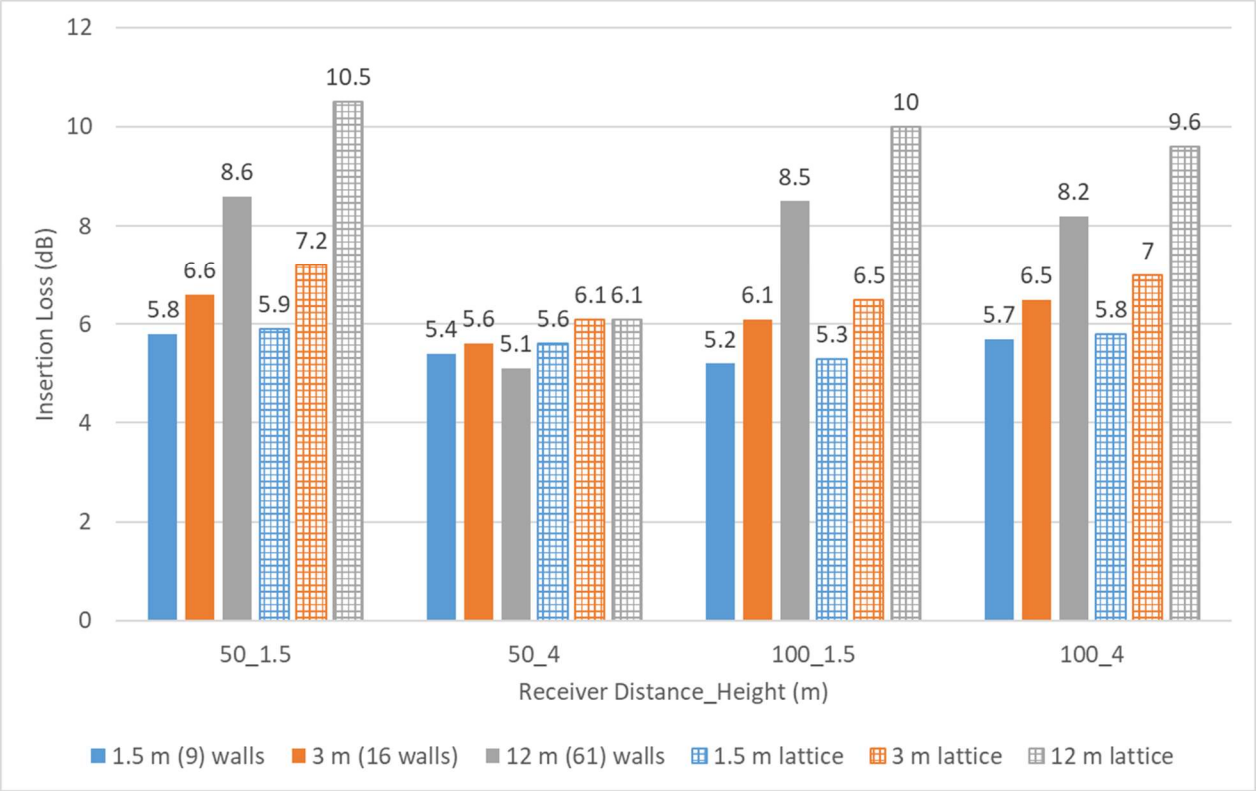


Figure 4-13: Above-ground treatment study results at two receiver distances and heights, Attenborough 2016.

Data series:
1.65 m wide array of 9 parallel walls, 0.3 m high, 0.05 m thick, 0.2 m center-to-center spacing;
3.05 m wide array of 16 parallel walls, 0.3 m high, 0.05 m thick, 0.2 m center-to-center spacing;
12.05 m wide array of 61 parallel walls, 0.3 m high, 0.05 m thick, 0.2 m center-to-center spacing;
1.53 m wide, 0.3 m high, 0.2 m square cell lattice;
3.05 m wide, 0.3 m high, 0.2 m square cell lattice;
12.05 m wide, 0.3 m high, 0.2 m square cell lattice.

Attenborough[186] and van Renterghem[187] also summarize a 1982 experiment that showed a 16-wall array of 0.21 m (0.7 ft) high parallel brick walls with edge to edge spacings of about 20 cm (7.9 in) placed on compacted grass showed a broadband insertion loss of about 4 dBA (100 to 12,500 Hz) and up to 20 dBA in the 1/3-octave bands between 400 and 1000 Hz. Another experiment showed an insertion loss of about 10 dB for a 14-wall, 3.25 m (10.7 ft) wide array with height and spacing of 0.25 m (0.8 ft). The array was placed halfway between the source and receiver, both at height 0.4 m (1.3 ft) and spaced 10 m (33 ft) apart.

Going beyond ground roughness/treatment, slightly taller ground mounted elements can also be used or potentially used to reduce noise. Such strategies are discussed in Section 8.

[186] Attenborough, K., I. Bashir, and S. Taherzadeh, "Exploiting ground effects for surface transport noise abatement," De Gruyter Open, Noise Mapp. 2016; 3:1-25, 2016.

[187] Van Renterghem, T., J. Forssen, K. Attenborough, J. Philippe, J. Defrance, M. Harnikx, and J. Kang, "Using natural means to reduce surface transport noise during propagation outdoors," Applied Acoustics, 99 pp. 86-101, 2015.

5. STRATEGY CATEGORY: OPERATIONS MANAGEMENT STRATEGIES

As an alternative or in addition to infrastructure improvements, traffic noise levels may be reduced by using operations management strategies. This section of the report considers two operations management strategies to reduce noise levels: speed restrictions and truck restrictions. Although these are primarily operations management strategies, both may be implemented along with infrastructure improvements. Table 5-1 shows a summary of the strategies. The summary is based on information extracted from the references described in the subsection below.

Table 5-1. Summary of strategies: operations management strategies

Strategy	Noise Benefit	Costs	Context Appropriateness
Speed restrictions	For combined traffic flows of automobiles and heavy vehicles, an overall noise reduction of approximately 2 dB (L_{Aeq}) may be expected with a reduction in speed of 16 km/h (10 mph).	Generally low; may impose costs of increased travel times. Other costs may include public education, enhanced enforcement, and related infrastructure improvements such as traffic calming measures.	Applicable either to limited-access highways or local road networks.
Truck restrictions	Reductions in maximum pass-by levels (L_{Amax}) of 10 dB or more. Overall L_{Aeq} noise reduction dependent on many factors, ranging from approximately 1 to 6 dB.	Generally low; may impose indirect costs on truck operators and general public. Other costs may include public education, enhanced enforcement, and increased maintenance on designated alternative truck routes.	Most commonly implemented on local road networks; also may be used on limited-access roads.

5.1 Speed Restrictions

Reducing vehicle speed reduces tire-pavement noise, and thereby reduces overall traffic noise levels under most conditions.[188] The following sections of the report describe the benefits of speed restrictions, discuss methods of implementation, describe the costs, and provide examples of implemented measures.

5.1.1 Benefits

The source noise level curves for the FHWA Traffic Noise Model (TNM)[189] shown in Figure 5-1 demonstrate the relationship between noise emission level and vehicle speed for traffic under cruise conditions on average pavement.

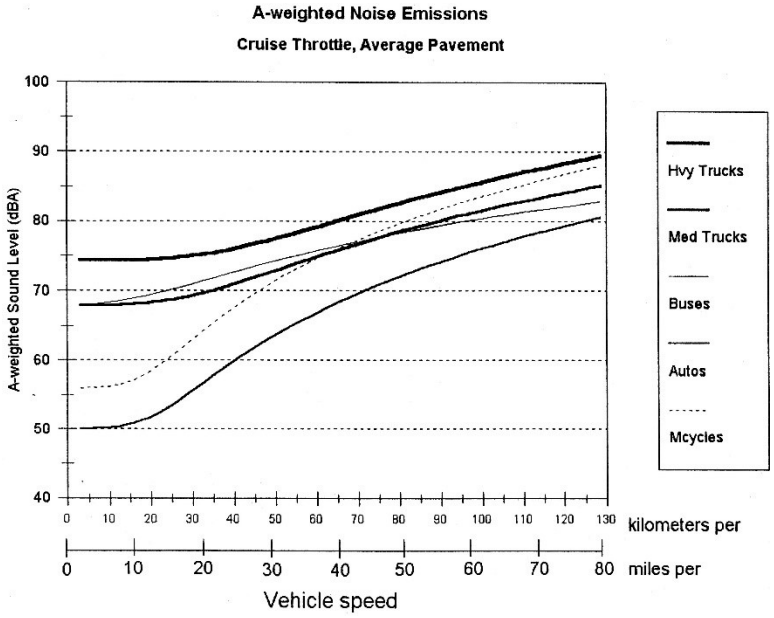
- The graph indicates that for all vehicle types, the noise emission level decreases at a relatively constant rate for typical highway speeds between about 105 and 72 km/h (65 and 45 mph). For automobiles in this speed range, a noise level reduction of slightly greater than 2 dB is associated

[188] In some situations, such as at very low speeds, during acceleration, or while climbing steep grades, engine and exhaust noise may dominate traffic noise levels.

[189] Menge, C., C. Rossano, G. Anderson, and C. Bajdek, *FHWA Traffic Noise Model, Version 1.0: Technical Manual*, Report No. FHWA-PD-96-010, Appendix A, Figure 6, 1998.

with a reduction in speed of 16 km/h (10 mph). For heavy trucks, the noise level reduction is slightly less than 2 dB for the same reduction in speed.

- At lower speeds between about 64 and 32 km/h (40 and 20 mph), as may be typical on local roads, the slopes of the emission level curves for trucks are somewhat less steep than at highway speeds, while for automobiles, the opposite is true. For automobiles at these lower speeds, a noise level reduction between 3 and 4 dB is associated with a reduction in speed of 16 km/h (10 mph). For heavy trucks, the noise level reduction is slightly more than 1 dB for the same reduction in speed.
- Together, these results indicate that for combined traffic flows of automobiles and heavy vehicles, as a first approximation, an overall reduction of about 2 dB (L_{Aeq}) may be expected with a reduction in speed of 16 km/h (10 mph).



- ***Source: FHWA Traffic Noise Model, Version 1.0 Technical Manual, Appendix A, Figure 6, p. 31.***

Figure 5-1: TNM 2.5 A-weighted vehicle noise emission levels under cruise conditions.

Numerous studies, involving traffic noise measurements, traffic noise modeling, or both, are generally consistent with the above findings. In addition to the amount speeds are reduced, other factors influencing the noise benefit may include the type and condition of pavement, the range of operating speeds (i.e., the actual speeds as opposed to the amount of the reduction), the level of compliance, and the mix of vehicle types.

- A comprehensive 2007 report on traffic noise reduction in Europe, including health effects, social costs, and technical and policy options,[190] provided estimates of noise reduction given by speed reductions, as obtained from a 2004 Danish study.[191] As shown in Table 5-2, for a traffic mix

[190] den Boer, L.C. (Eelco) and A. (Arno) Schroten, *Traffic noise reduction in Europe: Health effects, social costs and technical and policy options to reduce road and rail traffic noise*, CE Delft, Publication Code 07.4451.27, March 2007.

[191] Danish Road Institute, Ministry of Transport and Energy, *Traffic management and noise reducing pavements: Recommendations on additional noise reducing measures,* Copenhagen, 2004.

including 10% heavy vehicles, speed reductions of 10 km/h (6 mph) provided noise reductions ranging from under 1 dB to approximately 2 dB (L_{Aeq}), with the greatest reductions occurring in the range between 80 km/h (50 mph) and 50 km/h (31 mph).[192] Notably, a reduction of 20 km/h (12 mph), from 70 km/h (43 mph) to 50 km/h (31 mph), would reduce noise levels by nearly 4 dB (L_{Aeq}), approximately equivalent to a reduction in traffic volume of 60%.

Table 5-2. Noise reduction per 10 km/h (6 mph) reduction in speed (10% heavy vehicles).

Speed reduction	Noise Benefit (dB, LAeq)
110 to 100 km/h (68 to 62 mph)	0.7
100 to 90 km/h (62 to 56 mph)	0.7
90 to 80 km/h (56 to 50 mph)	1.3
80 to 70 km/h (50 to 43 mph)	1.7
70 to 60 km/h (43 to 37 mph)	1.8
60 to 50 km/h (37 to 31 mph)	2.1
50 to 40 km/h (31 to 25 mph)	1.4
40 to 30 km/h (25 to 19 mph)	0.0

Source: Danish Road Institute, Ministry of Transport and Energy, Traffic management and noise reducing pavements: Recommendations on additional noise reducing measures.

- Because of non-compliance with EU air quality regulations, speed limits on various motorway sections close to city dwellings in the Netherlands were reduced from 100 to 80 km/h (62 to 50 mph) and enforced with speed cameras that calculated average speeds. A 2006 study found that in addition to improving air quality, noise emissions were reduced by up to 1.5 dB (L_{Aeq}). People living close to the road sections in question also perceived the "absence of noise peaks by individual cars passing at high speed during the night."[193]
- A 2002 study included a speed restriction of 30 km/h (19 mph) on an urban thoroughfare in central Berlin from the beginning of July through mid-August accompanied by "extensive measurements of air quality and noise pollution." Measurements indicated that the noise reduction due to the speed restriction was approximately 2 dB (L_{Aeq}). It was estimated that had

[192] den Boer, L.C. (Eelco) and A. (Arno) Schroten, *Traffic noise reduction in Europe: Health effects, social costs and technical and policy options to reduce road and rail traffic noise*, CE Delft, Publication Code 07.4451.27, March 2007, p. 37.

[193] Dutch Minister of Transport, letter to the Dutch Parliament, "Evaluatie 80 km zones (Evaluation of 80-km zones), DGP/WV/u.06.02308, 2006. http://www.vananaarbeter.nl/Images/Evaluatie%2080%20km%20zone_tcm220-171282.pdf, as cited in den Boer and Schroten, p. 37.

100% compliance with the speed restriction been achieved, the noise reduction would have been 3 dB.[194]

- As part of a research initiative sponsored by the Ohio Department of Transportation (ODOT) to evaluate and analyze "the effectiveness of currently available proven and innovative methods for the abatement of highway traffic noise," TNM 2.5 was used to estimate the potential noise reduction benefits of speed restrictions. The analysis estimated the "reduction of highway noise associated with reducing speeds from [105 to 89 km/h] (65 to 55 mph) . . . at approximately 2 dBA," while noting that such measures would be effective only if "speed limits are enforced by local/state police departments."[195]
- A literature review by the Hong Kong government found that traffic noise may be reduced by up to 1 dB if the speed limit is reduced from 70 to 50 km/h (43 to 31 mph).[196]
- Using the standardized Nordic noise prediction method together with traffic flow measurements and population statistics, a Swedish study investigated how different noise reduction measures would influence the noise exposure on a city-wide scale in Gothenburg, a city with approximately 550,000 inhabitants. The study found that "reducing the speed limit for most roads by 10 km/h (6 mph)" would provide "an immediate reduction of approximately 20% in the number of exposed inhabitants."[197]

5.1.2 Methods of Implementation

Speed restrictions to reduce traffic noise may be implemented with measures similar to those used to implement speed reductions for other purposes, such as pedestrian safety. These measures include public information, enforcement, roadway design elements, and vehicle technology.[198] Each of these is discussed below:

- Public information: While the most obvious and direct form of public information is signage posting reduced speed limits, "the importance of well-structured traffic education policies and effective and constant publicity should not be underestimated."[199] Consistent with this, a broad implementation of noise-reducing speed restrictions in Lausanne, Switzerland in early 2020 will

[194] Lehmin, Bernard, *Outcomes of the HEAVEN (Healthier Environment through Abatement of Vehicle Emissions and Noise) pilot trial in Beusselstrasse and conclusions to be drawn for air quality management and noise abatement planning*, The SMILE Consortium, "Guidelines for Road Traffic Noise Abatement," SMILE (Sustainable Mobility Initiatives for Local Environment) Workshop, Berlin, Germany, October 20-21, 2003, p. 33.

[195] Ohio Department of Transportation, *Statewide Investigation of Noise Abatement Alternatives, Final Report*, Prepared by McCormick Taylor in association with Burgess and Niple, June 2006, p. 24. Assumes 1,000 vph, 6% heavy trucks, 4% medium trucks, approximately 150 feet from travel lanes.

[196] Wu, Jackie, *Mitigation Measured against Road Traffic Noise in Selected Places*, Hong Kong Research and Library Services Division, Legislative Council Secretariat, June 6, 2006, p. 82.

[197] Ögren, Mikael; Peter Molnár; and Lars Barregard, "Road traffic noise abatement scenarios in Gothenburg 2015 – 2035," *Environmental Research* Volume 164, July 2018, Pages 516-521, (https://www.sciencedirect.com/science/article/pii/S0013935117313245). Noise exposure defined as 55 dBA at the most exposed façade.

[198] Wijers, Philip, "Speed reduction methods to promote road safety and save lives," September 3, 2017. (https://making-traffic-safer.com/speed-reduction-methods-promote-road-safety-save-lives/)

[199] Wijers, Philip, "Speed reduction methods to promote road safety and save lives," September 3, 2017. (https://making-traffic-safer.com/speed-reduction-methods-promote-road-safety-save-lives/)

include a major communication campaign.[200] As an example of public information for a more targeted audience, The U.S. National Park Service has produced informational materials for park visitors on ways to protect natural soundscape within the national parks, including driving more slowly to reduce traffic noise levels.[201]

- Enforcement: As stated in the ODOT study of noise abatement alternatives, attempts to lower speeds by reducing speed limits "are only effective if speed limits are enforced by local/state police departments" and, therefore, "reducing posted speed to reduce traffic noise should be considered in conjunction with both manual and automated speed monitoring and enforcement."[202] During the multi-week speed-reduction trial conducted in Berlin, it was found that speeds dropped by 10 km/h (6 mph) during periods of visible police enforcement, but by only 5 km/h (3 mph) when no police enforcement was visible.[203] While manual enforcement is effective, it also is labor intensive. As an alternative, automated camera enforcement technology is available to send tickets or warnings directly to the vehicle owner's address.[204]
- Roadway design elements: Roadway design elements such as speed humps or raised platforms, gateway infrastructure treatments, pavement narrowings or optical treatments (such as pavement markings to imply a narrowing), and roundabouts all can be used to reduce traffic speeds.[205] The ODOT study cites speed bumps, rumble strips, narrow shoulders, or winding roadways as possible design elements to reduce speeds, while also observing that "many of these techniques are limited to local roadways or roadways with posted speeds well below highway travel speeds."[206] A Danish report, while noting the efficacy of speed reduction measures, cautions against locating such features where they may cause vehicles to accelerate, rattle, or otherwise increase noise levels near residences or other noise-sensitive receptors, and points out the importance of designing roadways "in order that the physical layout matches the intended speed" and helps to "minimize uneven driving patterns."[207] Regarding roundabouts, a measurement study conducted in Italy found that roundabouts may decrease noise levels (both L_{Amax} and L_{Aeq}) by about 3-4 dB compared to intersections. The study noted that roundabouts "already

[200] "Speed limit measure to curb noise pollution pushes ahead," SWI swissinfo.ch, August 31, 2019. (https://www.swissinfo.ch/eng/sweet-dreams_speed-limit-measure-to-curb-noise-pollution-pushes-ahead/45197896)

[201] National Park Service, Natural Sounds Program, "A National Park Guide: Protecting and Enhancing Soundscapes."

[202] Ohio Department of Transportation, *Statewide Investigation of Noise Abatement Alternatives, Final Report*, Prepared by McCormick Taylor in association with Burgess and Niple, June 2006, p. 24.

[203] Lehmin, Bernard, *Outcomes of the HEAVEN (Healthier Environment through Abatement of Vehicle Emissions and Noise) pilot trial in Beusselstrasse and conclusions to be drawn for air quality management and noise abatement planning*, The SMILE Consortium, "Guidelines for Road Traffic Noise Abatement," SMILE (Sustainable Mobility Initiatives for Local Environment) Workshop, Berlin, Germany, October 20-21, 2003, p. 33.

[204] Wijers, Philip, "Speed reduction methods to promote road safety and save lives," September 3, 2017. (https://making-traffic-safer.com/speed-reduction-methods-promote-road-safety-save-lives/)

[205] Wijers, Philip, "Speed reduction methods to promote road safety and save lives," September 3, 2017. (https://making-traffic-safer.com/speed-reduction-methods-promote-road-safety-save-lives/)

[206] Ohio Department of Transportation, *Statewide Investigation of Noise Abatement Alternatives, Final Report*, Prepared by McCormick Taylor in association with Burgess and Niple, June 2006, p. 24. It should also be noted that care should be taken in the design and implementation of rumble strips to avoid introducing a new noise source.

[207] Bendtsen, Hans, Jurgen Haberl, Ulf Sandberg, Greg Watts, "Traffic Management and Noise Reductions," *Nordic Road and Transport Research*, Vol. 17, No. 1, June 2005, p. 16.

appreciated for their safety advantages" may also be "strategically important for noise reduction policies."[208]

- Vehicle technology: Emerging vehicle technologies provide new opportunities for implementing speed reductions. Intelligent Speed Adaptation (ISA) involves any system that ensures the speed of a vehicle does not exceed a safe and/or legally enforced speed. The information on potential speeding may be derived from sources such as GPS location, road maps, radio beacons, or optical recognition (e.g. speed signs). In case of speeding and depending on the type of system, either the driver can be alerted, or the speed can be reduced automatically.[209]

5.1.3 Costs of Implementation

A broad survey report of traffic noise reduction measures throughout Europe concluded that "although traffic management measures [including speed restrictions] have relatively limited potential compared to the long-term potential of other measures, they involve only limited investments and have a direct effect, because of their implementation time." The report also noted, however, that "the costs associated with travel time losses may be significant."[210] Travel time losses may be diminished significantly with nighttime-only speed restrictions, under which substantially fewer vehicles are affected. Other costs associated with speed restrictions may include public education efforts and enhanced enforcement, whether through additional human resources or through the cost of installing and maintaining automated systems such as radar or speed cameras. When speed restrictions are implemented through infrastructure improvements such as speed humps, roundabouts, or other traffic calming measures, the costs include the initial infrastructure investment and any required ongoing maintenance.

In addition to noise reduction, speed restrictions may provide other benefits including improved air quality, enhanced safety through reducing the impact and likelihood of crashes, decreased greenhouse gas emissions, and improved average fuel economy.[211, 212] These additional benefits may be considered as negative costs, and in some case, may provide additional means to justify or secure funding to implement the measure.

5.1.4 Examples of Implemented Measures

Speed restrictions for the purpose of noise reduction have been implemented both on a project-specific basis and on a broader level. Examples of several implemented measures follow:

- In an example of a speed restriction implemented on a project-specific basis, the Missouri Department of Transportation (MoDOT) reduced the posted speed limit on a section of an expressway as part of roadway improvement project. The Business US 65/Glenstone Avenue

[208] Distefano, Natalia and Salvatore Leonardi, "Experimental investigation of the effect of roundabouts on noise emission level from motor vehicles," *Noise Control Engineering Journal* 67 (4), July-August 2019.

[209] Wijers, Philip, "Speed reduction methods to promote road safety and save lives," September 3, 2017. (https://making-traffic-safer.com/speed-reduction-methods-promote-road-safety-save-lives/)

[210] den Boer, L.C. (Eelco) and A. (Arno) Schroten, *Traffic noise reduction in Europe: Health effects, social costs and technical and policy options to reduce road and rail traffic noise*, CE Delft, Publication Code 07.4451.27, March 2007, p. 36.

[211] Wijers, Philip, "Speed reduction methods to promote road safety and save lives," September 3, 2017. (https://making-traffic-safer.com/speed-reduction-methods-promote-road-safety-save-lives/)

[212] The additional benefits of improved air quality, decreased greenhouse gas emissions, and improved average fuel economy are most likely to be realized when speed reductions occur on roads with speeds above approximately 80 km/h (50 mph). Speed reductions below approximately 80 km/h (50 mph) may result in lower average fuel economy, worsened air quality, and increased greenhouse gas emissions.

Project involved lane additions and intersection improvements to this multi-lane, divided roadway in South Springfield. Although sections of the roadway to the north and south had posted speed limits of 64 km/h (40 mph), the posted speed limit near a mobile home park was 72 km/h (45 mph). Noise measurements of existing conditions and traffic noise modeling conducted with TNM 2.5 indicated that constructing the project with the existing speed limit would result in traffic noise impacts at the mobile home park. Implementing a uniform posted speed limit of 64 km/h (40 mph), however, would reduce future sound levels below MoDOT's noise abatement criteria (NAC).[213] The project's noise study report concluded that "The results indicate that with the 8 km/h (5 mph) reduction in speed limit, the additional lane, increased traffic volume, and closer proximity of the receivers to the roadway result in only a slight increase (0.2 to 0.7 dBA) of traffic noise levels. Additionally, the noise levels remain below the NAC of 66 dBA. Therefore, the roadway improvements result in no impacted receptors within the study area."[214] Based on this analysis, MoDOT determined that the "reduction in speed limit compensates for the addition in traffic and added lanes" and because the future condition "predicted noise levels were determined to be below the NAC, noise mitigation alternatives were not considered."[215]

- In an example of a broader implementation of speed reductions, authorities in Lausanne, Switzerland announced in August 2019 that, barring any final opposition, the City would be implementing a plan to reduce the speed limit from 50 km/h (31 mph) down to 30 km/h (19 mph) at night (10 pm to 6 am) on major road networks starting in early 2020. The implementation of this measure will come after a two-year pilot test of the measure showed that the speed reduction could reduce average noise levels by two to three dB. Due to the nighttime hours, the speed reductions would impact only 10% of vehicles traveling on the major roads included under the program. "In addition to the speed limit measure, the city is also proposing additional sound-absorbing buffers, informational radars and a major communication campaign, which it estimates will cost CHF4.5 million." The measure is expected to affect 33,000 residents and is "considered a pioneering move on such a large stretch of roads in Switzerland."[216]
- In an example of incorporating speed restrictions for the purpose of noise reduction into general planning documents, Pasadena, California included speed reductions in the Noise Element of the City's General Plan. While noting that "noise is a normal part of the urban environment," the document states that "controlling noise sources can make a substantial improvement in the quality of life for City residents." Under the General Plan, the City will consider the use of traffic calming devices to reduce traffic speed in residential zones.[217] While not setting specific speed limit restrictions, the policy is noteworthy in that it allows for consideration of infrastructure improvements to reduce traffic speeds primarily as a noise reduction measure.

[213] Communication with Matthew Burcham, Missouri Department of Transportation, 2019.

[214] "Noise Technical Memorandum: Business US 65/Glenstone Avenue Improvements," Missouri Department of Transportation Project J8P3013, Prepared for Missouri Department of Transportation, Prepared by Jacobs, January 2015, p. 8.

[215] "Noise Technical Memorandum: Business US 65/Glenstone Avenue Improvements," Missouri Department of Transportation Project J8P3013, Prepared for Missouri Department of Transportation, Prepared by Jacobs, January 2015, p. 9.

[216] SWI swissinfo.ch, "Speed limit measure to curb noise pollution pushes ahead," August 31, 2019. (https://www.swissinfo.ch/eng/sweet-dreams_speed-limit-measure-to-curb-noise-pollution-pushes-ahead/45197896)

[217] "Revised Noise Element of the General Plan," City of Pasadena, CA, December 2002.

5.2 Truck Restrictions

Because one heavy truck is as loud as approximately 10 automobiles at highway speeds, truck restrictions have the potential to provide substantial reductions in noise levels. In some cases however, practical obstacles exist to implementing truck restrictions. The following sections of the report describe the benefits of truck restrictions, discuss methods of implementation, describe the costs, and provide examples of implemented measures.

5.2.1 Benefits

Truck restrictions provide noise reduction benefits both in terms of maximum sound levels (L_{Amax}) and overall noise exposure (L_{Aeq}). The TNM source level curves shown in Figure 5-1 demonstrate the differences in noise emission levels for automobiles and heavy vehicles at different cruise speeds (i.e. not under acceleration).

- The graph indicates that at typical highway speeds between about 105 and 89 km/h (65 and 55 mph), the emission levels for heavy trucks are about 9 to 10 dB higher than for automobiles. A truck restriction, therefore, would reduce maximum pass-by sound levels (L_{Amax}) by about 9 to 10 dB for traffic in this speed range.
- At lower speeds between about 64 and 48 km/h (40 and 30 mph), as may be typical on local roads, the emission levels for heavy trucks are about 11 to 14 dB higher than for automobiles. A truck restriction, therefore, would reduce maximum pass-by sound levels by about 11 to 14 dB (L_{Amax}) for traffic in this speed range.
- Based on these emission levels, for a traffic mix including 10% heavy trucks at 97 km/h (60 mph), a complete ban of heavy trucks may reduce L_{Aeq} noise levels by approximately 3 dB. For the same traffic mix at 48 km/h (30 mph), a complete ban of heavy trucks may provide up to approximately a 6 dB reduction in L_{Aeq}.

While the above examples from the TNM emission levels indicate reductions that may be achievable, real-world results also are dependent on a variety of other factors including: percentage of heavy trucks present prior to the restriction, types of other vehicles other than automobiles *not* included in the restriction (i.e., medium trucks, pick-up trucks, busses, and motorcycles), operating speeds, locations where acceleration occurs, and pavement type and condition. With these variables in mind, examples of expected noise reductions from truck restrictions are generally consistent with the range of benefits implied by the TNM emission levels:

- A literature review found that in Hong Kong "depending on the percentage of heavy vehicles in the flow and the total volume of traffic, noise reduction of up to 3 dBA may be achieved for banning heavy vehicles."[218]
- A research project using the Nordic Noise Prediction method concluded that "on a road with 10% heavy vehicles the noise will be reduced by 1 to 2 dB if all the heavy vehicles are removed."[219]
- The same report, however, also attributed a reduction of "up to 7 dBA (L_{Aeq}) at nighttime" for nighttime restrictions on heavy vehicles.[220]

[218] Wu, Jackie, *Mitigation Measured against Road Traffic Noise in Selected Places*, Hong Kong Research and Library Services Division, Legislative Council Secretariat, June 6, 2006, p. 82.

[219] Bendtsen, Hans, Jurgen Haberl, Ulf Sandberg, Greg Watts, "Traffic Management and Noise Reductions," *Nordic Road and Transport Research*, Vol. 17, No. 1, June 2005, p. 15.

[220] Bendtsen, Hans, Jurgen Haberl, Ulf Sandberg, Greg Watts, "Traffic Management and Noise Reductions," *Nordic Road and Transport Research*, Vol. 17, No. 1, June 2005, p. 16.

- On a project in Maricopa County, Arizona, TNM v2.5 modeling indicated that a truck restriction on a local arterial would provide the required 5 dB of noise reduction to be considered a mitigation measure.[221]

It is important to note that in addition to the reductions in L_{Aeq} cited above, truck restrictions can have the additional benefit of reducing maximum noise levels by roughly 10 to 15 dBA, thereby reducing the potential for annoyance, speech interference, and sleep disturbance.

5.2.2 Methods of Implementation

Truck restrictions may be implemented either full-time or during only certain periods, such as nighttime or weekends. Although nighttime curfews would appear to provide the most noise reduction benefit while affecting the fewest vehicles, some jurisdictions have considered daytime-only truck restrictions to reduce traffic congestion.[222] Because daytime-only truck restrictions are designed to promote nighttime truck traffic, they are not discussed here as a noise-reduction strategy. Nonetheless, proponents of nighttime truck restrictions should be aware of the possible disruption of nighttime delivery schedules and the possibility of daytime-only restrictions. (Section 5.2.4 provides further information on daytime-only truck restrictions.)

Because of the necessity of transporting goods on the Interstate system, truck restrictions may be most practical on local roadway networks.[223] In some cases, however, truck restrictions have been implemented successfully or have existed since the facility's construction on limited-access roads. Examples include parkways or commuter expressways (Merritt Parkway in Connecticut, Taconic State Parkway in New York, Storrow Drive in Boston, Massachusetts) and portions of the Interstate system with alternative truck routes (I-375 in St. Petersburg, Florida[224] and I-66 in Fairfax County, Virginia[225]).

5.2.3 Costs of Implementation

Similar to the speed restrictions discussed above, truck restrictions involve only limited investments and can have a direct and immediate effect, with a short implementation time. Direct costs associated with truck restrictions include public education efforts and enhanced enforcement, whether through additional human enforcement or through automated systems. Additional costs related to truck restrictions may include maintenance on designated alternative truck routes due to an increase in concentrated heavy vehicle traffic.

Other costs are primarily externalities that may accrue not to jurisdictions or agencies implementing the restriction, but to truck operators and the general public. Opponents to such measures have claimed that truck restrictions would result in longer truck routes, increased number of accidents, more roadway wear

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[221] Communication with Angela Newton, Newton Environmental Consulting, 2019.

[222] "Solutions Factsheet 3.5, Vehicle and operation restrictions," www.urban-mobility-solutions.eu, (http://www.uemi.net/uploads/4/8/9/5/48950199/solutions-factsheet-3-5-vehicle_and_operation_restrictions_041216.pdf).

[223] Ohio Department of Transportation, *Statewide Investigation of Noise Abatement Alternatives, Final Report*, Prepared by McCormick Taylor in association with Burgess and Niple, June 2006, p. 25.

[224] "Traffic Noise in Montana: Community Awareness and Recommendations for a Rural State," Report No. FHWA/MT-04-007/8172 , Reiter, Darlene, Ph.D., P.E., William Bowlby, Ph.D., P.E., Lloyd Herman, Ph.D., P.E., and Jim Boyer, Prepared for the Montana Department of Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration, July 2004, p. 37.

[225] Reiter, Darlene, Ph.D., P.E., William Bowlby, Ph.D., P.E., Lloyd Herman, Ph.D., P.E., and Jim Boyer, "Traffic Noise in Montana: Community Awareness and Recommendations for a Rural State," Report No. FHWA/MT-04-007/8172, Prepared for the Montana Department of Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration, July 2004, p. 39.

and tear, and increased prices of goods delivered by trucks.[226] Additional opposition to truck restrictions has come from neighboring communities concerned over truck traffic diverted into their neighborhoods.[227] Nighttime delivery restrictions also may incur additional operating costs or limitations on haulers.

In some cases, truck restrictions may result in negative costs or cost savings. In St. Petersburg, Florida, two parallel interstate highway spurs (I-375 and I-175) were constructed from I-75. By designating I-175 as a truck route, and restricting trucks from I-375, noise barriers on I-375 were able to be constructed at a height of only two meters (six feet), resulting in reduced mitigation costs.[228] Similarly, on a project in Baltimore County, Maryland, trucks were restricted from the relocated state highway (MD-702) due to the availability of parallel routes. The restriction allowed lower height noise barriers to be constructed at a reduced cost.[229]

5.2.4 Examples of Implemented Measures

Truck restrictions have been implemented on a nighttime-only, 24-hour, and daytime-only basis. The following examples include each type:

- The London Lorry Control Scheme (LLCS), enacted in 1985, controls the movement of heavy goods vehicles over 18 tons maximum gross weight at night and on weekends on specific roads to help minimize noise pollution. If haulers need to gain access via a restricted road, each vehicle is required permission to carry out deliveries/collections within the hours of control using a compliant route. The scheme's primary aim is to assist with minimizing noise pollution in residential areas in London during the prescribed hours of Monday to Friday: 9 pm – 7 am (including 9 pm Friday night to 7 am Saturday morning) and Saturday: 1 pm – 7 am Monday morning.[230]
- A truck restriction in Cambridge, Massachusetts bans, on a number of streets, all commercially plated trucks over 2268 kg (2.5 tons) gross vehicle weight 24-hours a day unless they have a delivery on that street or a nearby street. In addition to the ban on certain streets, other measures include: "Management of construction truck activity and routing in the City through the coordinated efforts of the Traffic Department and the Public Works Department; Restricting the operation of through-trucks from sensitive residential streets through coordination between the Traffic Department and the Massachusetts Department of Transportation; Controlling deliveries

[226] "City Council approves new truck route system to reduce traffic in residential neighborhoods," *The Resident*, Jacksonville, FL, March 5, 2019, (https://residentnews.net/2019/03/05/city-council-approve-s-new-truck-route-system-to-reduce-traffic-in-residential-neighborhoods/).

[227] Reiter, Darlene, Ph.D., P.E., William Bowlby, Ph.D., P.E., Lloyd Herman, Ph.D., P.E., and Jim Boyer, "Traffic Noise in Montana: Community Awareness and Recommendations for a Rural State," Report No. FHWA/MT-04-007/8172, Prepared for the Montana Department of Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration, July 2004, p. 37-38.

[228] Reiter, Darlene, Ph.D., P.E., William Bowlby, Ph.D., P.E., Lloyd Herman, Ph.D., P.E., and Jim Boyer, "Traffic Noise in Montana: Community Awareness and Recommendations for a Rural State," Report No. FHWA/MT-04-007/8172, Prepared for the Montana Department of Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration, July 2004, p. 37.

[229] Reiter, Darlene, Ph.D., P.E., William Bowlby, Ph.D., P.E., Lloyd Herman, Ph.D., P.E., and Jim Boyer, "Traffic Noise in Montana: Community Awareness and Recommendations for a Rural State," Report No. FHWA/MT-04-007/8172, Prepared for the Montana Department of Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration, July 2004, p. 37.

[230] "About the London Lorry Control Scheme," London Councils, (https://www.londoncouncils.gov.uk/services/london-lorry-control/about-llcs).

to new development through the coordinated efforts of the Traffic Department, the Community Development Department, and the Inspectional Services Department; and Enforcing truck safety and operations on restricted streets through the Truck Enforcement Unit of the Cambridge Police Department."[231] When originally proposed, the ordinance "was met with strong opposition from neighboring communities and trucking organizations," including legal challenges.[232] The City states that it "is committed to reducing the adverse impacts of truck noise and vibrations on residents while ensuring the continued delivery of goods and services to businesses and residences in the City." [233]

- In Pasadena, California, similar to the speed reductions discussed above, provisions for truck restrictions are included in the Noise Element of the City's General Plan. Under the General Plan, "the City will periodically review major roadways and designated truck routes to reduce traffic in residential zones [and] the City will encourage commercial and/or industrial uses abutting residential zones to limit deliveries and trash pick-ups from 7:00 A.M. to 9:00 P.M. Monday through Saturday, unless there are substantial transportation or other benefits for different times."[234]
- In August 2015, nighttime truck curfews from 10 pm to 6 am were introduced on key arterial routes in Melbourne, Australia as part of a 12-month trial.[235] A noise measurement survey, with monitoring conducted during the "shoulder hours" of the curfew (8 to 10 pm and 6 to 8 am) was completed in 2016 with the primary objective of identifying "which classes of heavy vehicles are most likely to contribute to sleep disturbance and amenity impacts for nearby residents associated with pass-by, braking, acceleration, and turning events." The study found that maximum sound levels for all 250 heavy vehicle pass-bys measured in the survey would exceed the study's criteria for sleep disturbance.[236] In March 2017, following completion of the assessment, it was announced that the curfews would remain in place.[237]
- In Jacksonville, Florida, an ordinance was enacted in January 2019 restricting routes in residential neighborhoods. The ordinance reduces the use of regulated trucks (those exceeding 26,001 pounds in gross vehicle weight designed for the specific purpose of transporting freight) "traveling on restricted roads except for delivery and pickup, with the intention of protecting residential neighborhoods from excessive truck traffic that would create greater hazards to pedestrians, bicyclists and children; increase congestion and noise pollution; and distress pavement conditions." The proposed ordinance met with "significant pushback" in 2017 from the Florida Department of Transportation, North Florida Transportation Planning Organization and

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[231] "Truck Restricted Streets List, City of Cambridge, MA," (https://www.cambridgema.gov/traffic/sustainabletransportation/Trucks/truckrestrictedstreetslist)

[232] "Traffic Noise in Montana: Community Awareness and Recommendations for a Rural State," Report No. FHWA/MT-04-007/8172 , Reiter, Darlene, Ph.D., P.E., William Bowlby, Ph.D., P.E., Lloyd Herman, Ph.D., P.E., and Jim Boyer, Prepared for the Montana Department of Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration, July 2004, p. 37-38.

[233] "Truck Restricted Streets List, City of Cambridge, MA."

[234] "Revised Noise Element of the General Plan," City of Pasadena, CA, December 2002.

[235] "Northeast truck curfew trial," VicRoads (website of State of Victoria, Australia, Department of Transport), (https://www.vicroads.vic.gov.au/planning-and-projects/melbourne-road-projects/north-east-truck-curfew-trial)

[236] "Rosanna Road-Greensborough Highway -- Heavy Vehicle Noise Assessment," Prepared for: VicRoads, Prepared by: Renzo Tonin & Associates, April 7, 2016, p. 5.

[237] "Northeast truck curfew trial."

the trucking industry and was reworked by a group including industry representatives and City officials before being implemented in 2019.[238]

- On a locally funded roadway widening project in Maricopa County, Arizona, noise impacts were predicted, but mitigation in the form of noise barriers was not feasible due to driveway openings. Truck restrictions were proposed as a mitigation measure and modeled using TNM v2.5. The TNM modeling indicated that restrictions would provide sufficient noise reduction to be included in the project as a mitigation measure under Maricopa County Department of Transportation (MCDOT) policy.[239] Subsequently, Maricopa County established "policy guidelines to allow or prohibit truck traffic on County roads." Under the policy, the MCDOT may make recommendations to the Board of Supervisors for the control of truck traffic on County roads.[240]
- While not a noise-reduction measure, some jurisdictions have prohibited trucks from making daytime deliveries to reduce traffic congestion. "Inner-city Night Delivery is the delivery to retailers and shops in the inner-city area during the night hours when the city is usually quiet and inactive." The goal is to replace a higher number of vehicles operating during daytime by a fewer number of vehicles operating during nighttime. Various forms of such restrictions are in place in Paris, Seoul, Hanoi, Manila, and Rome.[241] In Barcelona, the city conducted a pilot test of a silent night delivery program with trucks equipped with anti-noise systems. Instead of going to a regional distribution center, larger trucks serving grocery stores made nighttime deliveries directly to the stores. During the trial, it was determined that approximately seven daytime truck trips could be replaced by two nighttime truck trips utilizing larger vehicles. Noise levels were controlled through use of low-noise trucks, modified infrastructure such as loading docks, doors, and pavement, and training of personnel. The trial was found to be "successful both in terms of noise intrusion and from the commercial point of view."[242]

[238] "City Council approves new truck route system to reduce traffic in residential neighborhoods," *The Resident*, Jacksonville, FL, March 5, 2019, (https://residentnews.net/2019/03/05/city-council-approve-s-new-truck-route-system-to-reduce-traffic-in-residential-neighborhoods/).

[239] Communication with Angela Newton, Newton Environmental Consulting, 2019.

[240] Maricopa County (AZ) Department of Transportation, "Policy # T8601, Trucks on County Roads," June 30, 2014.

[241] "Solutions Factsheet 3.5, Vehicle and operation restrictions."

[242] "Innovative Approaches in City Logistics: Inner-city Night Delivery," NICHES, (https://www.eltis.org/sites/default/files/case-studies/documents/14683_pn7_night_delivery_ok_low_9.pdf).

6. STRATEGY CATEGORY: IMPLEMENTATIONS BY RECEPTORS OR LOCAL GOVERNMENTS

Table 6-1 shows a summary of the strategy: implementations by receptors or local governments. The summary is based on information extracted from the references described in the subsection below.

Table 6-1. Summary of strategy: implementation by receptors of local governments

Strategy	Noise Benefit	Costs	Context Appropriateness
Site Planning	Up to 3 dB when distance to the roadway is doubled. 10 dB or more when non-sensitive buildings are used to shield sensitive sites or areas	Minimal when considered early	New development
Building Design	Up to 13 dB when noise sensitive rooms are placed farthest away from the highway.	Minimal when considered early	New development or redevelopment
Construction Methods	Up to 35 dB (exterior to interior)	Expensive due to materials required	New development or redevelopment

The United States Department of Transportation Federal Highway Administration's (FHWA) Title 23 Code of Federal Regulations, Part 772 Section 17 (23 CFR 772.17) requires highway agencies to inform local officials of noise compatible planning concepts so that communities can protect future land development from becoming incompatible with anticipated highway noise. Because local government, not State government, is responsible for land development control, property owners, land developers, and other concerned parties depend upon local government agencies to provide guidance on traffic noise related concerns at specific locations. Based upon a review of available noise regulations and local ordinances from many cities, counties, and other local governments in the United States, these agencies are challenged with noise related issues from numerous noise sources in addition to highway traffic.[243]

6.1 Federal Guidance

Information on approaches that can be implemented by those outside the highway right-of-way can be found in FHWA's *The Audible Landscape: A Manual for Highway Noise and Land Use*.[244] This publication includes information on site planning, building design, and construction methods that can be employed by architects, developers, and builders, such as:

- Site planning: reducing noise impacts by utilizing natural terrain, open space, and building placement on a parcel to shield residential or noise-sensitive areas from highway noise. Simply increasing the distance between the noise source and the sensitive area can decrease noise by 6 dB for point sources and 3 dB for line sources such as roadways.[245] Furthermore, buildings that are not

[243] Noise Pollution Clearinghouse, https://nonoise.org/lawlib/cities/cities.htm, October 2019.

[244] Federal Highway Administration, *The Audible Landscape: A Manual for Highway Noise and Land Use*, November 1974.

[245] Federal Highway Administration, *The Audible Landscape: A Manual for Highway Noise and Land Use*, November 1974.

noise sensitive, such as garages, act like noise barriers providing 10 dB or more of noise reduction at some sites.

- Building design: considering existing and future highway noise when developing room layout, window placement, and balcony or courtyard/open space locations. *The Audible Landscape* explains the difference in noise levels between the side of a two-story building facing the highway and the side away from the highway can be as much as 13 dB.[246]
- Construction methods: considering potential noise transmission through building materials such as walls, windows, doors, ceilings, and floors in material selection.

The Audible Landscape: A Manual for Highway Noise and Land Use also describes administrative techniques and physical methods which require or encourage improved noise compatibility at locations near highways. Administrative techniques include:

- Zoning – to exclude incompatible uses (i.e., residences) from noise-impacted areas, regulating specific development details such as limits on building height or requirements for buffer strips or noise barriers, and permitting planned unit development.
- Other Legal Restrictions – to require subdivision standards such as acoustical site planning, building codes such as building insulation or sealed windows, health codes which can limit noise levels for habitable buildings, local laws to require occupancy permits showing all zoning and health codes are met before issuance, and environmental impact statements containing a noise impact section requiring a site-specific acoustical analysis.
- Municipal ownership/other control of the land – to keep land vacant or control development.
- Financial incentives – including reduced rate assessments for undeveloped/underdeveloped land, or the relaxation of municipal regulation enforcement.
- Educational and advisory municipal services – such as an architectural review board, municipal design services, an acoustical information library, or public information efforts.

Physical methods mentioned in *The Audible Landscape* include:

- Acoustical site planning – which involves arranging buildings on a tract to minimize noise impacts such as placing distance between a noise source and a noise-sensitive activity, locating noise-compatible activities between the noise and the sensitive activity, using buildings as barriers, and orienting noise-sensitive buildings/rooms to face away from the noise source.
- Acoustical construction – which includes the use of building components (walls, windows, doors ceilings/floors) treated to reduce interior noise impacts.
- Noise barriers – which can be berms, walls, fences, thick plantings of trees/shrubs, or some combination of these placed between noise sources and noise-sensitive areas.

Texas Southern University prepared a document for FHWA titled *Entering the Quiet Zone – Noise Compatible Land Use Planning.*[247] This document defines noise compatible land use planning as planning that eliminates or reduces the undesirable effects of highway traffic noise by:

- Encouraging the location of less noise-sensitive land uses next to highways.

[246] Federal Highway Administration, *The Audible Landscape: A Manual for Highway Noise and Land Use*, November 1974.

[247] Texas Southern University's Center for Transportation Training and Research, "*Entering the Quiet Zone – Noise Compatible Land Use Planning*" May 2002.

- Promoting the use of open space or special building construction techniques to minimize noise impacts.

Entering the Quiet Zone also explains that the first step in this process is to identify land uses that are suited for areas near highways, i.e., uses that are less sensitive to or are not disrupted by highway noise such as retail stores, warehouses, industrial operations, agriculture, and mining. Often these uses also benefit from being near the roadway in that easy access to buildings like shopping malls or office space make them good choices for locations near highways. Where practicable, maintaining open space or buffer zones next to a highway provides room for noise to dissipate before it reaches noise-sensitive areas, and can make commercial business properties more visible from the highway (refer to Figure 6-1: Buffer zone illustration from *Entering the Quiet Zone* (FHWA website). for an illustration of a buffer zone).

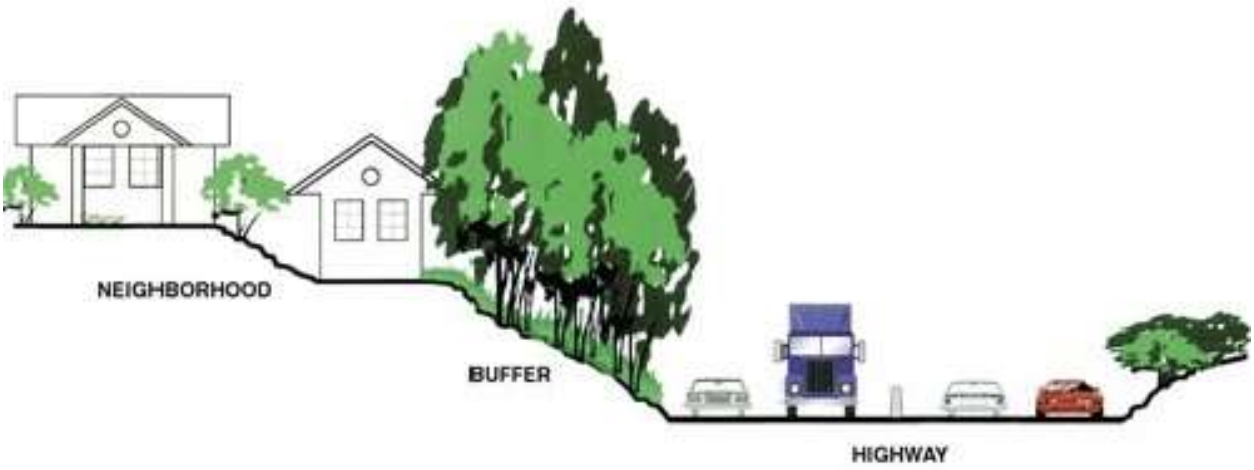

Figure 6-1: Buffer zone illustration from *Entering the Quiet Zone* (FHWA website).

In the section-by-section discussion of comments on the Notice of Proposed Rulemaking (NPRM) relative to 23 CFR 772 *Federal regulations on the Procedures for Abatement of Highway Traffic Noise and Construction Noise*, FHWA explained that few highway agencies properly fulfill the requirement to inform local officials about future noise impacts on undeveloped lands. FHWA recognized that State governments often have little control over local planning; however, FHWA has also promoted noise compatible planning strategies for more than 30 years with little active involvement by States on the issue. It is incumbent on State highway agencies, therefore, to demonstrate that they have educated local officials on noise issues if date of development may preclude some locations from receiving noise abatement.[248]

Based upon responses to the online survey and interviews conducted for this project, it appears that many State DOTs are sharing noise analysis reports with local government agencies. For example, Wisconsin DOT shares noise information with local units of government in areas that are currently not planned or platted to assist the municipality with good land use planning.[249] During the telephone interviews conducted for this project, Miles Kemp (Sr. Environmental Transportation Planning Manager

[248] Federal Regulations, *Procedures for Abatement of Highway Traffic Noise and Construction Noise*, 23 CFR Part 772, Fed. Reg. Vol. 75, No. 133, July 13, 2010..

[249] Online survey response, J. Waldschmidt, Wisconsin DOT, September 2019.

at Georgia DOT) explained that GDOT predicts noise levels on vacant land near highway and shares info with local agencies and developers.[250]

An example of State highway agency guidance to local officials is Montana DOT's *Growing Neighborhoods in Growing Corridors: Land Use Planning for Highway Noise.*[251] This document identifies noise compatible land uses, noise sensitive land uses, and provides an extensive list of noise compatible land use measures, both administrative and physical, including information on the practicality of implementation and the pros/cons of each measure. The document also demonstrates how to use noise contours to create noise overlay zones to help differentiate locations for noise compatible and noise sensitive land uses. An example of State regulation relative to noise compatible planning is California Government Code, Section 65302(f). It stipulates that a community's General Plan contain a noise element to analyze noise levels for highways/freeways, primary arterial streets, airports, and other ground sources which contribute to noise. The code requires that noise contours (prepared following generally accepted noise modeling techniques) be shown for all sources and be stated in terms of community noise equivalent level (CNEL) or day-night average sound level (L_{dn}). The contours are used as a guide for establishing a pattern of land uses that minimizes exposure to excessive noise. The noise element should also include implementation measures and possible solutions to address existing and foreseeable noise issues.[252]

During the telephone interviews conducted for this project, Jessica Goza-Tyner (Traffic Noise Analyst at Nevada DOT) explained that in several Nevada local jurisdictions, in order to get accompanying local permits, developers must show that noise levels will be below residential impact criteria. These traffic noise reductions are usually accomplished by moving back from the highway or building privacy walls.[253]

[250] Communication with J. Goza-Tyner, Nevada DOT, October 2019.

[251] Montana DOT, *Growing Neighborhoods in Growing Corridors: Land Use Planning for Highway Noise,* March 2008.

[252] California Government Code, Title 7, Division 1, Chapter 3, Article 5 -- Authority for and Scope of General Plans, Statutes 1965, Chapter 880. (http://leginfo.legislature.ca.gov/faces/codes_displaySection.xhtml?lawCode=GOV&sectionNum=65302)

[253] Communication with J. Goza-Tyner, Nevada DOT, October 2019.

Figure 6-2: Example of home with privacy wall (Newton Environmental Consulting, used with permission).

The Building Department of Clark County Nevada publishes 'How To Guides' detailing 25 dB, 30 dB, and 35 dB noise level reduction standards per the Clark County Code, Section 22.22. The noise level reduction is from exterior to interior of the building. These standards include performance or prescriptive standards for building components, or acceptance of the total building system by a recognized acoustical designer.[254] Furthermore, the Clark County Site Development Standards (Chapter 30.56.040.c) establishes requirements regarding lot development standards including setbacks related to some roadways. This document states in part that residential buildings cannot be erected within 15.2 m (50 ft) of the ROW of a non-depressed freeway but this setback can be reduced when a landscape buffer with a noise attenuating wall is constructed, or a 25 dB noise level reduction is incorporated into the dwelling construction.[255]

Clark County's 25 Decibel Noise Level Reduction Standard Building Permit Guide includes both a performance standard and a prescriptive standard. The performance standard is the sound transmission class (STC) rating, which is a numeric score indicating how well a specific item (window, door, etc.) reduces sound transmission. A higher number indicates more sound reduction than a lower number. Prescriptive standards are available at www.clarkcountynv.gov/building/HowToGuides/aspx and performance standards are as follows:

- Exterior walls shall have a laboratory STC rating of at least 30.
- Windows shall have a laboratory STC rating of at least 28.
- Doors shall have a laboratory STC rating of at least 26.
- Combined roof and ceiling shall have a laboratory STC rating of at least 39.
- Skylights shall conform to an STC rating of at least 28

[254] Clark County Nevada, Clark County, Code of Ordinances, Title 22, Chapter 22.22. Noise Attenuation Construction Standards (http://clarkcounty-nv.elaws.us/code/coor_title22_ch22.22)

[255] https://library.municode.com/nv/clark_county/codes/code_of_ordinances?nodeId=TIT30UNDECO_30.56SIDEST_PTGALST_30.56.140ALSIDEST

(Note: Another noise reduction rating, Outdoor-Indoor Transmission Class (OITC),[256] emphasizes low frequencies more than the STC rating. If a highway has or will have heavy truck traffic, which contains higher levels of low-frequency content, the OITC rating should be considered.)

In summary, FHWA's *The Audible Landscape: A Manual for Highway Noise and Land Use,*[257] Montana DOT's *Growing Neighborhoods in Growing Corridors: Land Use Planning for Highway Noise,*[258] and Clark County Nevada Code, Section 22.22[259] can provide local government agencies pertinent information about noise compatible land use planning.

[256] ASTM E1332, *Standard Classification of Outdoor-Indoor Transmission Class*, ASTM International, 2016.

[257] Federal Highway Administration, *The Audible Landscape: A Manual for Highway Noise and Land Use*, November 1974.

[258] Montana DOT, *Growing Neighborhoods in Growing Corridors: Land Use Planning for Highway Noise,* March 2008.

[259] http://clarkcounty-nv.elaws.us/code/coor_title22_ch22.22

7. STRATEGY CATEGORY: SOUND ABSORPTIVE TREATMENT ON STRUCTURES

Since 2010, FHWA has required State agencies to include provisions in their policies for use of absorptive treatment on roadside structures, including noise barriers, retaining walls, bridges, and any other structure the highway agency may consider for application of a sound-absorptive material.[260] For noise barriers, NCHRP Project 25-44[261] provides a literature review stating that the success of efforts to reduce noise reflected from barriers has varied across the United States. Some States have long-standing practices of installing noise barriers with absorptive surfaces where there is a noise-sensitive land use on the opposite side of the highway. Also, some States address concerns by adding sound-absorptive materials after construction. Whether formal or informal policy, here are some key considerations when adding sound absorptive treatment (from the NCHRP Project 25-44 report):

- Always install sound absorptive walls or treatment if there are noise-sensitive receptors opposite a noise wall or retaining wall. (There is also guidance as to when a receptor would qualify: if the distance from the barrier to the receptors is less than 20 times the barrier height.) Consider sound absorptive walls or treatment on the receptor side of the wall if other noise sources are present on the receptor side.
- The benefit of simply implementing absorptive treatments opposite residential areas outweighs the benefit of researching the issue or conducting detailed analyses to justify absorption, even if that use comes at a modest cost premium.
- An absorptive surface is defined as having a Noise Reduction Coefficient (NRC) of at least 0.8 on the road side and 0.7 on the residential side.
- For parallel walls, consider the ratio of wall height to separation distance. The ratio of 10:1 is considered large enough for sound absorptive treatment to not be required. Predictions can be done to determine degradation in parallel barrier effectiveness.

Sound absorptive treatment on the surface of a roadside structure can benefit noise-sensitive receptors on both sides of the road (refer to Figure 7-1 for example paths leading to receptors). The treatment can reduce reflections of noise back across the road or multiple reflections between parallel structures/vehicles, potentially affecting receptors on either side of the road. In some situations, the reflections can result in line-of-sight exposure to a reflected sound source and can cause more than a 3 dB increase in noise, particularly when the direct sound is blocked by a wall or terrain. Although in many situations, single reflections increase noise levels by no more than 1-2 dB, reflections can change the character of the sound. California guidance provides methods for calculating the contributions of reflections from structures, including retaining walls and bridge decks, for a broadband sound level.[262]

Sound absorptive treatment reduces the magnitude of reflected sound energy. As sound travels through a sound absorbing material, the sound waves change direction and follow a longer path. Every change in direction decreases the sound wave's energy, limiting the amount of sound reflected.

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

[261] Bowlby, W., R. Williamson, D. Reiter, C. Patton, K. Kaliski, J. Rochat, J. Meighan, K. Yoerg, A. El-Aassar, H. Knauer, K. Washburn, G. Sanchez, and D. Barrett, Field Evaluation of Reflected Noise from a Single Noise Barrier, Research Report 886, Project 25-44, National Cooperative Highway Research Program, Transportation Research Board, 2018.

[262] Hendriks, R., B. Rymer, D. Buehler, and J. Andrews, *Technical Noise Supplement to the Caltrans Traffic Noise Analysis Protocol - A Guide for the Measuring Modeling, and Abating Highway Operation and Construction Noise Impacts*, Report No. CT-HWANP-RT-13-069.25.2, California Department of Transportation, September 2013.

In this section, applications of sound absorptive treatment include retaining walls, the understructure of bridges, tunnels, and safety barriers. In addition, innovative sound absorbing measures and modification of reflected sound paths are discussed.

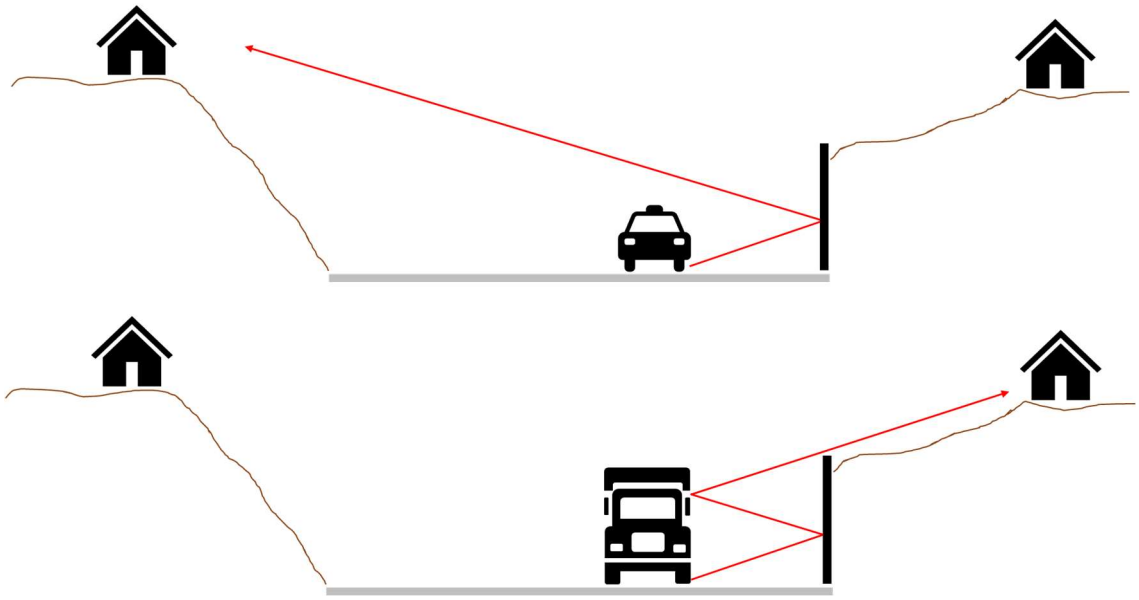

Figure 7-1: Example of tire-pavement sound paths with reflections off retaining wall.

Table 7-1. Summary of strategy: sound absorptive treatment on structures.

Strategy	Noise Benefit	Costs	Context Appropriateness
Treatment on retaining walls	Opposite side reflection: 1-2 dB with changes in spectral content potentially reducing adverse reflected noise effect Parallel barriers: predicted up to 2.5 dB Truck/barrier wall reflections: predicted up to 4 dB	Varies by treatment/project (one example was \$18-22/ft^2)	Locations where retaining walls can reflect noise to sensitive receptors
Treatment on bridge understructures	Highway measurements showed up to 6 dB, lab measurements up to 11 dB, and predictions up to 5 dB with sound absorptive treatment Low frequency vibration dampers can help to reduce noise from steel bridge structure	Cost of material, installation, maintenance	Elevated highway bridge structures or those over depressed highways where reflections can affect sensitive receptors
Treatment in tunnels	Measurements showed 5-10 dB reduction for sound absorptive treatment Surface roughening predicted to reduce noise by 4 dB	Cost of material, installation, maintenance	Highway tunnels where reflections can affect sensitive receptors
Other structure	Sound absorption using Helmholtz	Example: for a green	Locations where

applications	resonators or metamaterials; engineered products that can be tuned to optimize traffic noise reduction Curvature of a wall should be considered to avoid focusing sound Application of absorptive material to ramp and median safety barriers can reduce reflections Green wall systems on walls and rooftops can reduce reflections	area of 369 m^2 (3,972 ft^2) - investment 20,999 Euro ($23,236), maintenance 9,225 Euro ($10,208)	structure surfaces can reflect noise

7.1 Retaining Walls

Sound absorptive treatment on retaining walls can help to reduce highway traffic noise in cases with multiple reflections for a depressed highway or single reflections to noise sensitive receptors opposite a single retaining wall. The sound absorptive properties as well as placement can influence the effectiveness.

A 2010 special report on retaining wall noise reflections[263] describes a study that analyzed highway traffic noise reflections from retaining walls for a 6.1-9.1 m (20-30 ft) depressed highway. Applying FHWA's TNM v2.5, both image roadways and the parallel barrier module were used to predict the sound level increase attributed to the reflections, as well as the effect of absorptive treatment on a wall (please refer to Figure 7-2). Using the parallel barrier module provided a more accurate estimate of reflected noise and the effectiveness of sound absorptive material. Traffic noise reflected from untreated retaining walls was predicted to increase noise levels at the closest receivers up to 3.5 dBA. Covering the retaining walls with sound-absorptive material was found to be the most effective way to reduce the increase in traffic noise due to reflections. Examination included covering the full height (8.5 m or 28 ft), which resulted in a noise reduction of 2.5 dBA (resulting in only a 1 dBA increase due to reflections). Applying absorptive treatment to the middle and top (6.1 m or 20 ft), the noise was reduced 1.5 dBA. With the treatment only on the top 3 m (10 ft), there was no reduction in noise. Applying a Noise Reduction Coefficient of 0.80 to the absorptive material was mentioned as an example and is assumed to be the coefficient applied to the results stated.

[263] ms conslutants, Retaining Wall Noise Reflection Analysis, special report for I-70/I-71 South Innerbelt, FRA-70-8.93 PID 77369, February 2010.

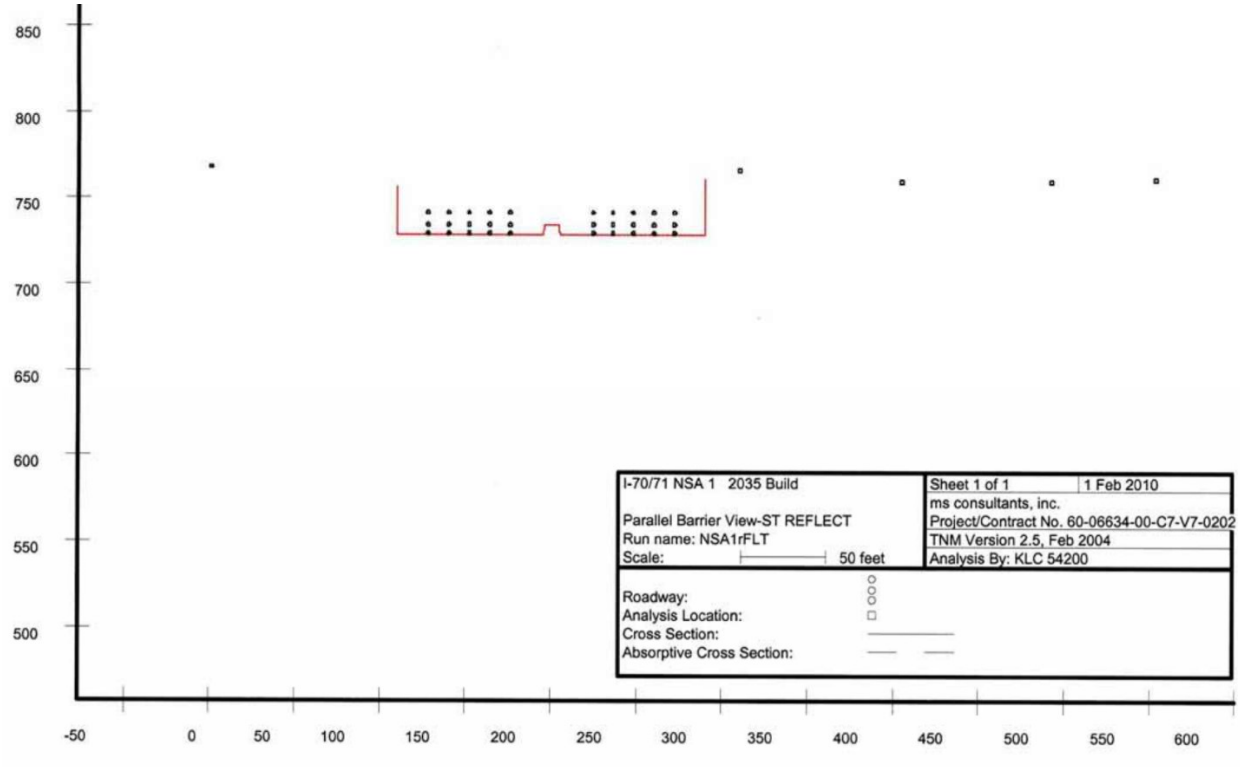

Figure 7-2: Example study applying the TNM parallel barrier module.[264]

Several other references discuss placement or percentage of sound absorptive treatment. One study focuses on the surface area of noise-absorbing material applied to noise barriers on viaducts (bridges), for a rail application.[265] Using measurements, the study examines the relationship between area of applied noise-absorbing material and noise reduction. The measurements were taken on one track with the microphone on the opposite-direction track, with high-speed trains passing. Sound walls with 56.9% and 74.3% coverage of sound absorbing material were tested. The noise reduction compared to the wall without sound absorbing material was about 1 dB for less coverage and 1.6 dB for more coverage. Increasing the surface area of the sound absorbing material increased the effectiveness.

Using ray theory with a specific site geometry, calculations can help to determine proper placement of absorptive treatment to allow maximum effect with minimal coverage of a reflecting surface. For a typical Arizona geometry, the bottom 1.8 m (6 ft) contributes most, and applying absorptive treatment to that portion will most effectively reduce reflected noise.[266] Applying treatment higher on a barrier may have little to no extra benefit.

[264] ms conslutants, Retaining Wall Noise Reflection Analysis, special report for I-70/I-71 South Innerbelt, FRA-70-8.93 PID 77369, February 2010.

[265] Matsunuma, M. and K. Kuribayashi, "Using on-site measurement to test the efficacy of increasing area of noise-absorbing material on sound proofing walls on viaducts high-speed rail lines," Proceedings in Inter-Noise 2017, 2017.

[266] Communication with Ivan Racic, Arizona Department of Transportation, 2019.

An Institute of Noise Control Engineering publication[267] states that, for a noise barrier, the full effect of absorptive treatment on the diffracted path can be achieved by a strip at the top or sides of a barrier that has a width of one wavelength. For a broadband spectrum, this may require the whole surface for normal height barriers (e.g., a 3.4 m or 11 ft width would be required to affect 100 Hz).

Applying ray theory to retaining walls will allow determination of where reflections occur that reach nearby noise sensitive receptors. These reflections may be more than 1st order (i.e.. the ray may reflect more than once) in a depressed highway situation, where higher order reflection points will be farther up the walls. Also consider that non-flat geometries may need very different material placement compared to flat. All noise source locations need to be considered when applying ray theory. In the case of multiple reflections between a wall and vehicle or opposing wall, noise sources can be the original source or a reflected source.

Further considering the noise reducing effect of absorptive treatment, an NCHRP noise barrier reflections project[268] researched the possible change in sound levels and sound characteristics caused by sound reflections off a noise barrier on the opposite side of a highway. Both sound-reflective and sound-absorptive barriers were examined. Data were collected at multiple sites, each with equivalent sub-sites with and without a noise barrier, to determine the increase due to reflections and the potential benefit of absorptive treatment. Data were analyzed in terms of both time-averaged sound levels (L_{Aeq}) and single vehicle pass-by events. Sound levels with a sound-reflective noise barrier on the opposite side of the highway increase by 0.5 to 4 dB L_{Aeq} (compared with no barrier present), with greater increases farther from the road. The greatest effect was shown in frequencies from 250 to 500 Hz and 1 to 3.15 kHz, with some site-dependent variation. The increased sound levels include frequencies that dominate highway traffic noise. Percentile metrics were used to determine that the background noise increased in the presence of a noise barrier. In addition, the presence of the barrier appears to generate a comb-filtering effect created by the combination of direct and reflected sound waves, resulting in harmonically related peaks in the spectral content, which can cause an adverse effect and be perceived as the sound being buzzy or raspy. Compared to a sound-reflective noise barrier, increases in noise levels are less apparent for sound-absorptive noise barriers. Spectral increases show more variation and are lower in magnitude as compared to sound-reflective barriers. Unlike sound-reflective barriers, the L_{90} and L_{99} statistical descriptors show that the background levels are not elevated due to the barrier. In addition, results show evidence that sound-absorptive barriers may reduce the comb-filtering effect, which could potentially reduce the adverse effect of reflections. Figure 7-3 shows vehicle pass-by events and the difference between barrier and no barrier sound levels, for both reflective wall barrier sites and absorptive wall barrier sites. The variation in frequencies that are emphasized due to reflections varies based on site parameters, including different distances from the road. For events at reflective barrier sites, the peaks are pronounced and show a strong harmonic relationship for lower frequencies (500 Hz and lower), as compared to results for absorptive barriers. In addition, the sound absorptive barrier peaks are generally lower in amplitude.[269]

[267] Institute of Noise Control Engineering, Technical Assessment of the Effectiveness of Noise Walls, I-INCE publication 99-1, 1999.

[268] Bowlby, W., R. Williamson, D. Reiter, C. Patton, K. Kaliski, J. Rochat, J. Meighan, K. Yoerg, A. El-Aassar, H. Knauer, K. Washburn, G. Sanchez, and D. Barrett, Field Evaluation of Reflected Noise from a Single Noise Barrier, Research Report 886, Project 25-44, National Cooperative Highway Research Program, Transportation Research Board, 2018.

[269] Rochat, J., "Changes in sound due to highway noise barrier reflections," Proceedings of Inter-Noise 2018, 2018.

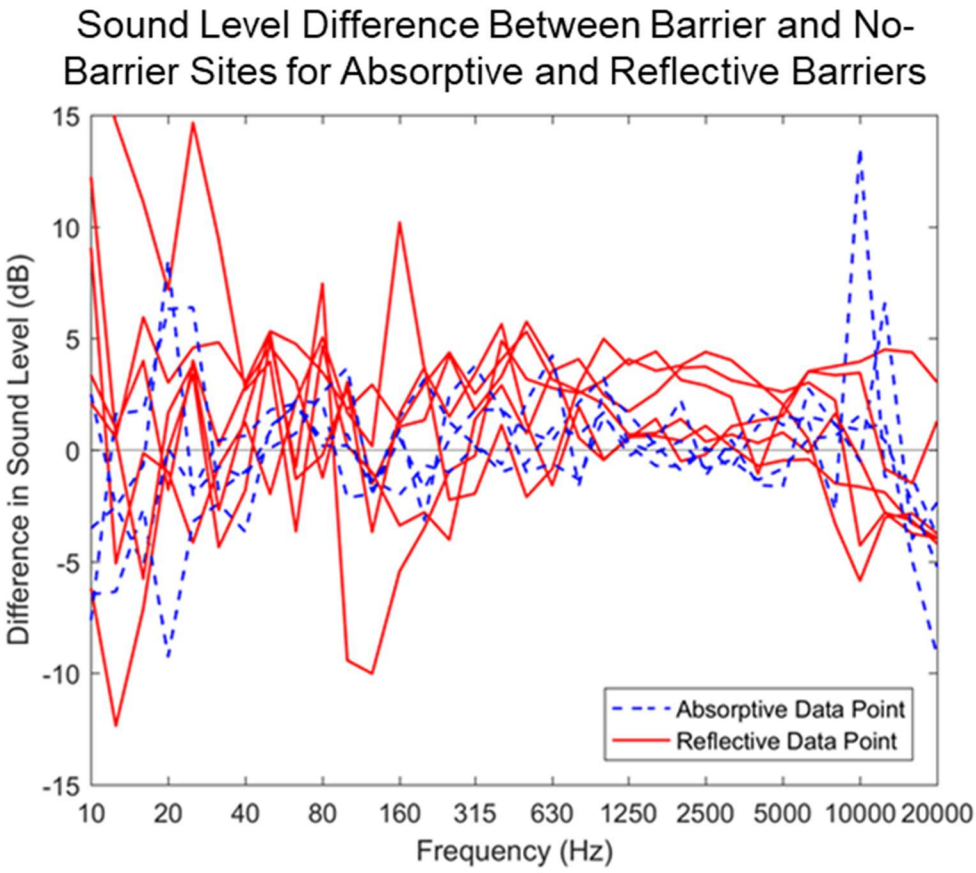

Figure 7-3: Difference in reflection effect for a reflective and absorptive wall surfaces. [270]

As part of the NCHRP barrier reflections project, the literature review provided a summary of information on the success of efforts to reduce reflected noise. In addition to discussion of various State policies related to absorptive treatment, noise reduction values from various studies were summarized. A California study for a freeway with terrain elevation changes (with super-elevated lanes with the eastbound lanes being 1-4 m or 3-14 ft higher than westbound) showed only a 3-4 dB barrier insertion loss for a case where there was a median barrier on a retaining wall; applying sound absorption to the median barrier and retaining wall, the insertion loss increased to 5 dB. This is a case where a 1-2 dB change makes the difference between an ineffective and effective noise barrier. Another California study predicted absorptive influence on parallel barriers to be 1-2.5 dB at close receptors and up to 3-5 dB at far receptors (> 152 m or 500 ft from the road), with some cases having direct line-of-sight blocked, but the receptor was in direct line-of-sight to the reflections sound source.

A Minnesota study focuses on application of noise-absorbing material to a highway noise barrier.[271] In this case a new barrier was constructed opposite an existing barrier, and it was shown, through use of an acoustic camera, that elevated receptors on the existing barrier side were affected by noise reflected off the new barrier. The existing barrier blocked the line-of-sight to the highway, but the new barrier created

[270] Rochat, J., "Changes in sound due to highway noise barrier reflections," Proceedings of Inter-Noise 2018, 2018.

[271] Burge, P., J. Crawford, and P. Wasko, "Use of advanced tools and techniques to resolve an atypical parallel noise barrier case," Proceedings of Noise-Con 2013, 2013.

a new sound source with direct line-of-sight to the second row receptors. The new barrier also created an additional noise source to the first row receptors, although that noise was also diffracted by the existing barrier. Using measurements and modeling, it was determined that the reflections caused a 4.5 dB increase in noise for the second row and 2.6 dB for the first row. Due to the increase Minnesota DOT evaluated several options for mitigation, including increasing the existing barrier height, removing the new barrier, covering the entire roadway, and adding sound absorption to the new barrier. Considering safety, cost, engineering, and politics, some options were removed. Of the remaining, it was determined that the most effective and cost efficient option was to add sound absorption to the new wall. Among several products investigated, a "backless" acoustical panel was selected (Empire Acoustical Products), which included a lightweight perforated front panel with sound absorptive material behind, but no solid back panel. The backless panel provides sound absorption without the added cost and weight of one with a solid back panel. It was calculated that the sound absorptive treatment reduced the reflected noise to a "less than noticeable" level increase. The neighbors were pleased with the results.

A study applying sound propagation simulations using Olive Tree Lab-Terrain (OTL-Terrain)[272] shows results for a case where there are reflections between a truck and a wall, with reflected sound reaching receivers behind the wall. Parameters include an absorptive surface placed on a noise barrier 4.9 m (16 ft) in height and 3 m (10 ft) from the source (heavy truck tire-pavement noise). The receivers are placed 24 m (80 ft) behind the barrier at a height of 1.8 m (6 ft). Results showed that the sound absorptive barrier provides better noise reduction, since it reduces repeated sound reflections between the truck and barrier. The noise was reduced approximately 4 dBA with the absorption applied, compared to a reflective surface. Although applicable to noise barriers only, examination of lower height barriers showed that shorter barriers with absorption can provide the same noise reduction as taller reflective barriers.

Examples of absorptive treatments applicable to retaining walls can be seen in Figure 7-4. An example is the Empire Acoustical product applied to the Minnesota study previously described. This product is the Empire M-90 panels shown in the figure. Another example is the Sound Fighter Systems product RetroSorb. These non-corrosive perforated aluminum panels are applicable to any outdoor structure and have an NRC rating of 1.05 (an NRC value > 1 does not indicate more than 100% sound absorption – it's a result of the material's shape/area and the test procedure) and cost based on square footage (typically $18-22). Durisol makes precast acoustics facings that can be attached to any flat surface, with highways listed as one of the applications for which this product is effective at reducing reflected noise. Durisol also makes sound absorptive retaining walls that can be integrated with their noise barriers. AIL Soundwalls makes Silent Protector absorptive barrier walls that are perforated PVC panels filled with acoustical mineral wool with an NRC of 0.95. Another product, Concrete Solution's SoundSorb, is wetcast concrete (a low cost solution), with an NRC rating of 0.7 to 1.0 (highest for 8+ cm or 3+ in); this product was considered in the OTL-Terrain study described above. Also applied in a rail noise study,[273] SoundSorb panels installed in between and beside rails along the track provided 2 dBA reduction in noise. The product was also added to noise barriers on the same project, but the effect of the absorption is not isolated from shielding. The total noise reduction with a combination of the panels, barriers, and rail dampers resulted in 9 dBA reduction. When deciding on a product or strategy, it is suggested to contact these and other companies to obtain more specifics. Note that guidance in California[274] suggests that a

[272] Economou, P., "Absorptive noise barrier acoustical modeling," by P.E. Mediterranean Acoustics Research & Development for Concrete Solutions, 2014.

[273] Vanhonacker, P. and K. Vogiatzis, "High railway rolling noise reduction by combining existing track based solutions," EU QUIET-TRACK FP 7 research project, 2015.

[274] Hendriks, R., B. Rymer, D. Buehler, and J. Andrews, *Technical Noise Supplement to the Caltrans Traffic Noise Analysis Protocol - A Guide for the Measuring Modeling, and Abating Highway Operation and Construction Noise Impacts*, Report No. CT-HWANP-RT-13-069.25.2, California Department of Transportation, September 2013.

minimum NRC of 0.85 should be used, where 85% of the incident energy is absorbed and 15% reflected. This guidance also points out that NRC values are based on the average absorption over four octave bands: 250, 500, 1,000, and 2,000 Hz.

Figure 7-4: Example sound absorptive wall treatments (clockwise starting left top: Empire M-90 Panels, Sound Fighter RetroSorb, AIL Silent Protector, Concrete Solutions SoundSorb, Durisol precast acoustic facings).

7.2 Understructure of Bridges

The understructure of bridges provides another surface off which sound can reflect, whether it's elevated and reflecting sound directly to noise sensitive receptors or over a depressed road causing multiple reflections among surfaces. This subsection describes experiences and products in relation to reflections from bridge understructures.

A Taiwanese university study[275] examined the effects of noise reflected from the overpass bottom under various conditions using onsite measurements and model simulation. Sites included highways with noise barriers, where the underside of the overpass reflected noise over the barriers and into the community. Sites varied, with the noise source roadway being both parallel and perpendicular to the overpass. The study used CadnaA to model traffic noise. The researchers compared measurements to predictions and validated the model. It was determined that reflections caused an increase in noise of 1 to 8 dB, with the largest effect being closest to the ground. They also determined that, as the height of the overpass increased, the level of reflected noise decreased. Also, an overpass parallel with the road influenced a larger area than perpendicular to the road, and when the distance between the overpass side and a receiver exceeded 30 m (98 ft), the level of reflected noise reduced significantly. The researchers

[275] Lin, C., Y. Peng, Y. Tsai, Y. Chang, and K. Chen, "Impact and control of reflected noise from an overpass bottom," Applied Sciences 2018, 8, 1908, 2018.

then used the model to predict the effect of adding absorptive treatment to the underside of the overpasses. The absorptive coefficients used were 0.36, 0.60, and 0.85. Closest to the ground (first floor), which was at the same level as the roadway, the absorptive material with a rating of 0.60 provided a decrease in sound up to 3 dB (1 hour L_{Aeq}). The benefit was greater with more absorption and dependent on geometry. With an absorption coefficient of 0.85, the first floor effect was predicted to be about 5.5 dB. Recommendations are that a minimum rating to use is 0.60, but higher is preferred. It is also recommended to increase the distance between a residential area and overpass to create a buffer zone and combine that with installation of sound absorbing material on the overpass bottom.

Express lanes of I-5 were generating noise that reflects from the underside of the I-5 mainline, causing adverse effects for the nearby residents. As part of a Noise Pilot Project,[276] WSDOT installed 700 quilted noise-absorptive ceiling panels on the underside of the bridge deck. The panels were hung vertically on the outer edges over the distance of the 152 m (500 ft) test section. WSDOT monitored this test section for one year to evaluate its effectiveness at reducing noise and its durability in this environment. Several measurements were taken at each site for each quarter. Noise was also monitored for two quarters prior to panel installation. Measurements were conducted at 18 locations. Modeling of the vertically hung absorptive panels predicted 4 to 5 dB noise reduction. First year results showed that the panels provided 0-4 dB (L_{Aeq}) reduction to nearby residents (farther away saw more reduction because the panels block more of the view to the ceiling). Statistics showed that post-construction measurements were not significantly quieter than pre-construction measurements. Reasons for test panels not performing as predicted included: 1) the predictions did not account for diffracted or direct path noise (implies these sources are dominant); 2) hard edges of panels were possibly diffracting and/or reflecting noise; 3) receivers in direct line-of-sight to exposed ceiling (in between panels) do not benefit from the absorptive panels. The panels were projected to perform consistent with the first year into the second and third year, so measurements/analysis were discontinued after the first year. Note that sound absorption measurements in the field showed the sound absorption coefficients to be 0.22 at 500 Hz and 0.27 at 800 Hz. These values were lower than those listed for the product, which were 0.74 at 500 Hz and 0.72 at 1,000 Hz.

Kobayasi Institute of Physical Research conducted a study[277] to determine the effect of attaching absorptive panels to the underside of a bridge deck to try to reduce reflected noise. The panels had two different facings and were filled with fiberglass off different thicknesses: 100, 150, and 200 mm (3.9, 5.9, and 7.9 in). The facing was either perforated aluminum sheet with an open area ratio of 35% or expanded metal with an open area ratio of 68%. The measurements applied a pulse signal with sound waves at oblique incidence to a sample surface in a semi-anechoic chamber. The researchers measured the absorption coefficient at various angles. The best selection for noise reduction was the absorptive panel of 150 mm (5.9 in) thickness with expanded metal with an open area ratio of 68%. The absorption coefficient was greater than 90% at predominant frequencies of road traffic noise (500 to 2000 Hz). Based on the laboratory measurements, the noise reduction at 6 m (20 ft) from the edge of the freeway bridge with a double deck structure was estimated to be about 11 dB when the panel is used. The resulting noise reduction was fairly consistent across frequencies of 500 to 3150 Hz and across different incidence angles.

[276] Washington DOT, I-5 Ship Canal Bridge: Noise Pilot Project - Measurement Results, Washington State Department of Transportation, Seattle, WA, 2012.

[277] Kimura, K. and S. Saiki, "A study on acoustical characteristics of absorptive panels attached to the underside of an elevated freeway bridge," Proceedings of Inter-Noise 1992, 1992.

Another study from the Kobayasi Institute of Physical Research[278] performed measurements and calculations to determine the contributions of bridge understructure reflections of noise from a road under the structure to areas at the road level in the vicinity of the bridge. The noise metric applied was L_{50} (sound exceeded 50% of the time) measured for 10 minutes every hour of a day. The road structures were constructed with steel plate girders, with four lanes, two with ramps. Calculations were done to estimate the effect of installing sound absorbing panels on the underside of the upper deck. Two materials were investigated, with sound absorption coefficients of 0.8 and 0.9 at the dominant frequency range of road traffic noise. The increase in sound levels due to reflected sounds varied according to the structure of the elevated road from 2 to 7 dB. The increase can be reduced to approximately 1 dB using sound absorbing panels with a sound absorption coefficient greater than 0.9.

An Ohio DOT study[279] examined reflections and absorptive treatment (NRC 1.0) for a highway underpass, in response to residential complaints and theorizing that multiple reflections from this location may be contributing to their annoyance. The researchers conducted before and after measurements and modeling to study the reflections and effects of absorption. They also conducted reverberation measurement and modeling tests. This was done to find the noise decay rate, an indicator of the amount of reflected rays present for the whole underpass as a single system. The researchers determined that traffic noise within the underpass represented a source with a sound level at least 5 dB above the source levels for typical sections of the highway. Results showed that applying absorptive treatment to the vertical retaining walls resulted in only a minor noise reduction (average 0.3 dB within ROW and 1.4 dB 300 m or 984 ft away) and a decay rate reduction of only 0.09 seconds. The researchers determined that reflections from the pavement and bridge understructure made a more significant contribution to the sound levels for a typical receptor located outside the underpass than reflections from the walls. They determined that making the pavement and understructure more sound absorptive in the highway underpass area would help to reduce noise from multiple reflections. It was predicted that noise reduction from an absorptive understructure was 1.2 dB.

One study explored practical and cost-effective aesthetic and acoustical upgrades for an existing bus stop located under a wide (ten lane) freeway overpass.[280] The study focuses on noise under the overpass at a bus stop. The bus stop was extremely loud and reverberant, with sound generated from both street level and overhead traffic. Noise measurements were conducted to quantify the existing sound, determine relative contributions from the different noise sources, and estimate the reverberation time in the space under the overpass. Broadband sound pressure level and 1/3-octave band data were collected during peak and off-peak periods. Based on observations, the team quantified overhead noise as the L_{90} value (sound exceeded 90% of the time), the combined level as the L_{eq} value (average), and the street traffic as the L_{eq} minus L_{90} value. The acoustical treatments considered were: 1) spray-on acoustically absorptive treatment on vertical surfaces and under the bridge deck; 2) replacing the roadway surface and sidewalk with "something better"; and 3) installing acoustical panels on vertical surfaces or underside of the bridge. Analysis was conducted for a rigid acoustical panel, which could be easily mounted on the underside of the bridge, that could provide both transmission loss and acoustical absorption. The effect of the panel was applied to the reverberation time (RT) and noise sources to determine the noise reduction with the panels installed. Measurements under the underpass were quite loud with 1-minute L_{eq} values typically ranging from 75 to 80 dBA, and occasionally as high as 95 dBA. The overhead bridge deck noise was

[278] Kimura, K., J. Kaku, and M. Hiroe, "Determination of reflected sounds from elevated road structures using a signal compression method," Proceedings of Inter-Noise 1995, 1995.

[279] Herman, L., S. Seshadri, and E. Pinckney, "Placement of sound-absorbing materials to control traffic noise reflections at a highway underpass," Transportation Research Record, Paper No. 99-0557, 1999.

[280] Burge, P., "Trolling for better acoustics under a highway overpass," presentation at Transportation Research Board Noise and Vibration Committee Meeting, June 2018.

found to be about 5 dBA lower than the local street noise. Reverberation time (RT) should be under 1 second for speech intelligibility, and results showed times of 0.2 to 2.9 seconds, depending on the frequency, averaging 1.6 seconds. Results of the acoustical treatments analysis showed high values for both transmission loss and acoustical absorption for the panels; the RT was reduced to an average of 0.7 seconds, and the noise reduction for the combined noise was 3.6 dB. It was also stated that there was substantial low frequency noise coming from the bridge, which would be difficult to effectively reduce.

An example of bridge understructure absorptive treatment can be seen in Figure 7-5. The figure shows one product from IHI Infrastructure Systems;[281] another example product is Nippon Steel Silent Road (not shown).[282] The example products and strategies provided for retaining walls in the previous section, may also be applicable. The appropriate product/strategy to choose should be researched for a specific application.

Figure 7-5: Example bridge understructure absorptive treatment (IHI INRP-E-6).

Another study focuses on noise radiated from steel bridge structures.[283] The research presents approaches to reduce noise from a railway on a steel bridge. One of the strategies applies to any steel bridge, not just for railways. Targeting low frequencies radiating from the bridge, vibration dampers are added to the body of the bridge. Mid-frequency reduction is also discussed. Results of measurements on 30 bridges are provided. The paper references studies that state that coating flat areas of the bridge structure with plastic foil or with magnetic constraint layers can reduce mid-frequency noise radiation; it is mentioned that bridges that mainly consist of lattice bars cannot be treated by this technique. For low frequencies, vibration absorbers are attached to the structure by bolts. The two absorbers discussed reduce vibration in the 80-315 Hz range and 30-125 Hz range. Measured data showed a substantial increase in the damping ratio in the 80 to 160 Hz range with the low-frequency absorbers attached compared to without. Low-frequency absorbers combined with top-of-bridge mitigation for trains resulted in 6 to 10 dBA reduction in noise. Examples of low-frequency absorbers can be found here: https://www.railway-technology.com/contractors/noise/schrey/, under vibration dampers for steel bridges. With a vibration damper application, each bridge needs to be analyzed to determine the most beneficial damper characteristic and installation position.

[281] https://www.ihi.co.jp/iis/en/products/other/sound_absorbing_board/index.html

[282] https://www.ns-kenzai.co.jp/english/041silent_road.html

[283] Venghaus, H., "Noise reduction of steel bridges in urban areas," Proceedings of Inter-Noise 2012, 2012.

7.3 Tunnels

Sound absorptive treatment can also be applied to tunnel surfaces. The example products and strategies provided for retaining walls and bridge understructures in the previous two sections may be applicable. The appropriate product/strategy to choose should be researched for a specific application.

Noise from a tunnel opening propagates in the vicinity of the area, often causing noise problems. A study in Japan focused on application of acoustic treatment inside a road tunnel.[284] The noise sources were automobiles and ventilation fans. Testing was done with sound absorptive porous ceramic boards placed near the ends of the tunnel. At the tunnel exits, the measured noise reduction from a small truck was 5-10 dBA, with 30 to 50 m (98 to 164 ft) length of absorptive treatment. Also, reverberation times were reduced, with greater reductions for lower frequencies.

Another study from Japan examined application of absorptive treatment to a tunnel structure that allows waste trucks access to a waste processing plant.[285] Noise radiation was measured from a semi-circular road tunnel opening before and after absorptive treatment was applied. Two materials were applied: 1) porous board material backed with 200 mm (7.9 in) air space, and 2) and porous concrete without backing air space. Measurements to show the effectiveness of the acoustic treatment were done outside the tunnel with a swept-sine noise source placed at different locations inside the tunnel. (Please refer to Figure 7-6 for the source and measurement positions. It should also be noted that at the end of the tunnel, there are walls extending outward and tapering off, so it appears in the figure as if M1 and M2 are inside the tunnel, but they are actually outside). With application of the absorptive treatment to the tunnel surface, a 5-10 dBA reduction was measured in the middle and high frequency ranges (not specified by material, although sound absorption coefficients show the board/air to have more of a consistent absorption across frequencies, and the porous concrete to absorb most in the 630-1,000 Hz range and 1,600 Hz). Also, reverberation times were greatly reduced.

[284] Kobayashi, Y., S. Seki, T. Kitamura, K. Mitsui, and S. Yamada, "Study on the characteristics of noise-propagation in tunnel and noise control with absorbing material of ceramics," Proceedings of Inter-Noise 1999, 1999.

[285] Yano, H., S. Yokoyama, H. Tachibana, and M. Owaki, "The effect of reducing noise radiation from a tunnel mouth by sound absorption treatment," Proceedings of Inter-Noise 2007, 2007.

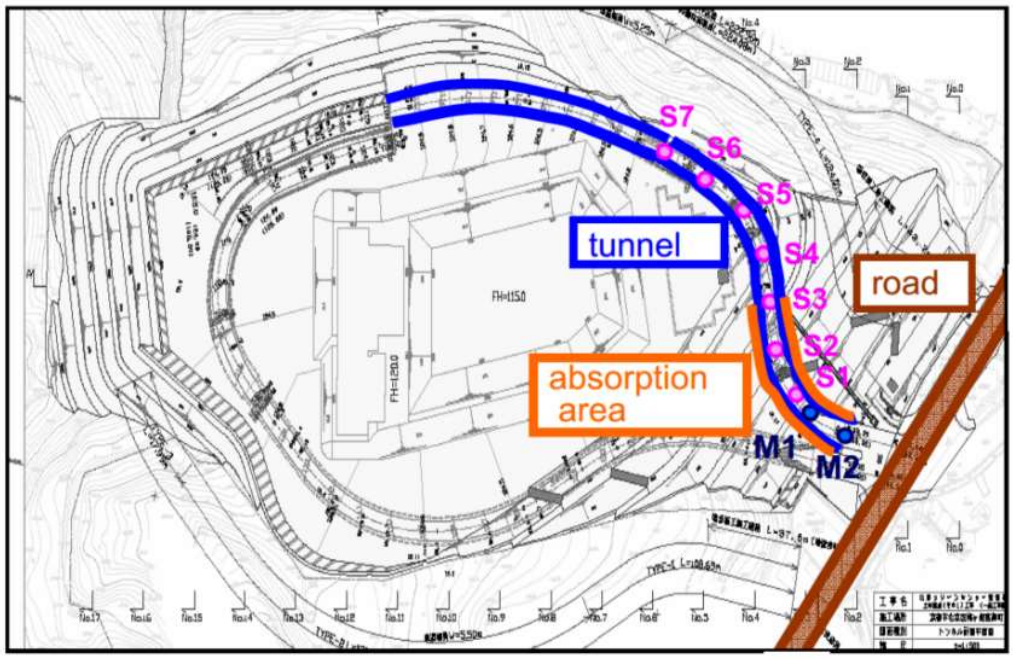

Figure 7-6: Schematic plan for tunnel and source (S) and measurement (M) positions.[286]

Measurements and simulations were included in an Austrian study of sound radiation from roadway tunnel openings, and results were used to investigate various parameters.[287] The amount of sound energy which is radiated from a tunnel portal is closely related to the noise emission of the traffic in the tunnel and the acoustical damping factor of the tunnel. The damping factor depends on the position of the receiver with respect to the tunnel portal as well as on several parameters of the tunnel (includes shape and size). The following results were stated:

- The size of the tunnel has only a minor effect (differences of about 1 dB) on sound radiation, with bigger cross sections having higher sound radiation;
- Skewing the opening (tilted backward) also has only about a 1 dBA effect;
- The end of the tunnel being a trumpet form has a strong influence on sound radiation, with most being radiated in the direction of the tunnel axis (which leads to a strong decrease in sound in other directions);
- Positioning sound absorptive material in a tunnel near the portal is reasonable. The effect of sound absorptive material depends on the angle of view to the tunnel opening. For small angles to the tunnel axis, the effect is small, but for greater angles, the effect can be significant. As an example, for a 30 degree angle from a round tunnel with several traffic lanes, adding 50 m (164 ft) of absorption (841 m^2 or 9052 ft^2 absorber in the 50 m or 164 ft section, 0.8 absorption coefficient) results in an 8 dBA decrease. In general, the greater the angle and greater length of absorptive material, the greater the noise reduction. In general, the greater the angle and greater

[286] Yano, H., S. Yokoyama, H. Tachibana, and M. Owaki, "The effect of reducing noise radiation from a tunnel mouth by sound absorption treatment," Proceedings of Inter-Noise 2007, 2007.

[287] Hoislbauer, H. and G. Strohamayer, "Noise emission from road tunnel openings," Proceedings of Inter-Noise 2013, 2013.

the length of absorptive material, the greater the noise reduction, although, beyond 70 m (230 ft) of material combined with angles 45 degrees and greater, the reduction does not increase.

The Alcazaba tunnel in Malaga, Spain is a tunnel built with a reinforced concrete curved wall, with a polished smooth surface. Inside, there are four lanes of traffic and two sidewalks. Because of the geometry and surfaces, pedestrians experience a very high noise level inside the tunnel. Calculations using EASE were applied to study different noise mitigation measures to reduce noise levels inside the tunnels. Model results were also compared to noise measured in the tunnel. Through measurements and modeling, it was determined that pedestrians were experiencing maximum sound levels of 101 dBA, averaging about 90 dBA. Independently, noise reductions were predicted to be 3 dB for sound absorptive asphalt, 7 dB for a sound-absorptive mortar wall surface, 1 dB for a barrier between the traffic and pedestrians, and 5 dB for sound absorptive panels on the wall surface. None of the independent measures, nor any combinations, were found to provide adequate noise reduction. The solution was to provide an enclosed, insulated pedestrian and bike path, which was predicted to provide a 41 dB noise reduction inside the tunnel.[288]

Another study[289] examines ways other than sound absorption to reduce noise in tunnels, since sound absorptive materials may become a health hazard (aging fiberglass), and tunnels are designed to reduce potential risks of fire hazards to minimize costs associated with cleaning and maintenance. The study investigated the effect of deliberate roughening on tunnel walls to explore the potential use for noise reduction. Modeling and scale-model testing were applied to the study, which focused on rectangular tunnels. A point source was placed at different heights and proximity to walls for the research. For the full scale simulations, the wall roughness simulated semi-cylindrical concrete blocks with a radius of 0.075 m (0.25 ft) constructed to form a two-dimensional hard rough surface. The blocks were spaced and distributed with an average separation of 0.3 m (1 ft). In the scale model studies, the introduction of surface roughness applied to one of the vertical walls resulted in a noise level reduction of about 3 dB (predicted and measured insertion loss) over a frequency range from 500 to 5,000 Hz, as measured in the tunnel center line at different distances from the source. Simulations showed that tunnel reflections without the roughness cause an 8 dB increase in noise for one point source and 16 dB increase for multiple sources. Simulations for a realistic tunnel with a 6 m × 8 m (20 ft × 26 ft) cross-sectional area showed that the introduction of a hard rough surface can lead to an average noise reduction of 4 dB over the frequency range of 300 to 3,000 Hz.

7.4 Other Applications

7.4.1 Engineered Treatments

Expanding the treatment beyond use of traditional sound absorptive materials, Helmholtz resonators can be integrated into a wall to help reduce reflected noise. In one study,[290] modeling was done to determine if Helmholtz resonators integrated into parallel barriers could reduce the parallel barrier insertion loss. Results showed that the noise reduction enhancement is sensitive to the location of the resonator. If the resonator is far from the sound source, the noise reduction attributed to the resonator around the target frequency is decreased (i.e., not as effective if wall is far from sound source). When two resonators at different frequencies (289 and 474 Hz) are integrated, the sound response peaks in the

[288] Araguiez del Corral, I. T. Kimenez, and E. Baro, "An innovative proposal to reduce noise level at Alcazaba Tunnel in Malaga (Spain)," EuroRegio2016, 2016.

[289] Law, M., K. Li, and C. Leung, "Noise reduction in tunnels by hard rough surfaces," J. Acoust. Soc. Am. 124 (2), August 2008.

[290] Wang, Z. and Y. Choy, "Environmental noise control by parallel barriers integrated with Helmholtz resonator," Proceedings of Inter-Noise 2017, 2017.

frequencies ranging from 200 to 1,000 Hz can be reduced, not just at the resonator frequencies. This study using Helmholtz resonators with a noise barrier can also apply to retaining walls, and again, specific geometries would need to be considered, as well as Helmholtz resonator designs.

Also on the innovative side of sound absorption, acoustic metamaterials can be used in highway applications. A Boston University study[291] showed the effectiveness of such materials. In a trial lab setting, the material was measured to reduce 94% of the noise. For a wall, the material would be a lightweight hexagonal shape, where elements would fit together in a honeycomb-like structure. The structure elements are mathematically designed and 3D-printed. They incorporate a helical pattern that interferes with the sound; even with an open center (air can flow through), these elements can block sound.

In addition to changing the sound upon reflection, changing the direction of reflections should be considered. Elements added to a wall surface can reflect the sound in scattered or focused directions. Curvature of the wall itself can focus or defocus sound. Racic[292] conducted a highway noise study to determine why specific residences were experiencing objectionable sound. Highway noise measurements and modeling, using TNM v2.5, were used to determine the effects of noise barrier curvature on resulting reflections to a community on the opposite side of the road. It was determined that a curved noise wall was reflecting noise from traffic, focusing into the area of homes where residences were adversely affected. The focused reflection potentially caused a 0.8-1.2 dB increase. Based on the analysis, the 2017 policy was updated. Arizona DOT policy[293] now includes an engineering feasibility criterion on barrier curvature: *When feasible, barrier should not be having an outline or surface that curves inward, like the interior of a circle or sphere, thus focusing the reflected noise to a single point, if there are noise sensitive Receptors in the area of the focus*. This could also apply to curvature of retaining walls. In addition to avoiding inward curvature that focuses the noise, it is interesting to consider outward curvature to reduce the noise at a specific point.

7.4.2 Safety Barriers

In Arizona, application of absorptive treatment to some safety barriers is practiced. Ramps are usually less than 6.1 m (20 ft) wide and can incorporate 1.2 m (4 ft) safety barriers on each side, reflecting sound and creating a parallel barrier situation. In these cases, sound absorptive treatment can help to reduce the reflections. For typical highways with median barriers above 0.9 m (3 ft) high, ADOT recommends sound absorption treatment. Each case should be examined to determine proper application. [294]

7.4.3 Green Systems on Walls and Roof Tops

Some studies include the effect of natural and sustainable materials including vegetation, green roof systems, and green walls on noise reduction and sound field control in urban spaces. One such study is from the University of Sheffield in England.[295] The work includes the examination of the acoustic properties of vegetation, which has two main components – growing media (soil) and plant (leaf, stem, root), which play different roles in absorbing and scattering sound. Green roof systems were examined for roadway noise applications, where such systems could be installed on low-profile structures, such as the

[291] Mcalpine, K., "Researchers develop acoustics metamaterial that cancels sound," Boston University, https://phys.org/news/2019-03-acoustic-metamaterial-cancels.html, 2019.

[292] Racic, I., "Noise analysis technical memorandum," Project TRACS 1628746737, response to noise inquiry, 2017.

[293] Arizona Department of Transportation, Noise Abatement Requirements, May 2017.

[294] Communication with Ivan Racic, Arizona Department of Transportation, 2019.

[295] Yang, Hong-Seok, Outdoor noise control by natural/sustainable material sin urban areas, Doctoral Thesis, The University of Sheffield, September 2013.

top level of underground parking structures or simply as a sustainable low barrier. Examining green roof systems, the systems in an experiment were comprised of 600 x 400 x 280 mm (24 x 16 x 11 in) plastic trays placed on top of a large fiberboard box, where sound transmission through and around the box was minimized (it appears that effects due to shielding from the box were subtracted out, although the work would need to be examined further to verify). The components in the trays were: a 30 mm (1 in) drainage layer on the bottom and plastic panels as wells, a geotextile membrane filter layer to prevent obstruction of the drainage layer by small particles of growing media, and growing media of Zinco (brand name) or limestone-based substrates. The Zinco substrate was a 1:1 mixture of Zinco sedum carpet substrate and Zinco roof garden substrate. Fresh leaves or polyester cotton were used to simulate a layer of vegetation. In examination of different soil depths, the work shows that even a thin soil layer with a depth of 50 mm (2 in) provided an absorption coefficient of about 0.9 at around 1 kHz, and there were only slight changes in the absorption coefficient with increases soil depth. Conclusions were based on measurements in a reverberation chamber. An increase in soil moisture content resulted in a decrease in absorption coefficient by about 0.6. With increasing vegetation coverage, the absorption coefficient increased by about 0.2 at low and mid frequencies. The stronger effect on sound absorption and scattering by above ground vegetation components was found at higher frequencies with increasing vegetation coverage; the maximum absorption scattering coefficients were 0.49 at 5 kHz and 0.43 at 2.5 kHz. It was also found that a green wall with highly porous substrate kept a relatively high absorption coefficient of about 0.6 even though it was nearly saturated (note: this seems to be somewhat contradictory to the above conclusion of a 0.6 coefficient reduction). Green roof systems were examined applying measurements in a semi-anechoic chamber using roof systems consisting of Zinco and limestone-based substrates; supplemental numerical simulations were also conducted. Study parameters included the area, depth, type and position of the green roof system and type of vegetation. Results show sound pressure level (SPL unspecified, dBA) attenuation gradually increases with increasing number of rows of green roof trays. The research found that attenuation could be up to 9.7 dB at a height of 5 feet (1.6 m). Frequencies greater than 315 Hz are affected by more than 5 dB, and up to 12-22 dB from 1,250 to 3,150 Hz. Vegetation on top of the trays could result in an additional 4 dB noise reduction for traffic noise.

Figure 7-7: Example of green wall and rooftop.[296]

[296] Yang, Hong-Seok, Outdoor noise control by natural/sustainable material sin urban areas, Doctoral Thesis, The University of Sheffield, September 2013.

In a study by Smyrnova et al.,[297] for the geometries of an urban street and square, energy-based and wave-based methods were applied to simulate the effect of vegetation on noise propagation from road traffic (assuming a line source). The simulations included a road with six-story buildings on each side, with windows included. Receivers were located along the building facades and on the ground adjacent to the road. Acoustic treatments were the application of vegetation on either the facades or on a low-height (0.96 m or 3.1 ft) barrier in the middle of the road. For brickwork, an absorption coefficient (normal incidence) of 0.33 was applied. For the vegetated wall, normal incidence absorption coefficients varied by frequency, ranging from 0.08 to 0.55 for lower frequencies (50-200 Hz) and from 0.7 to 0.91 for higher frequencies (250-1,600 Hz); these are based on dry conditions, and it is noted that the absorption coefficient of vegetation can drastically depend on water content. Insertion loss due to the absorptive treatment is calculated as an average of the various receiver positions. In the street case, when vegetation covers the lower half of the facades, the average insertion loss is 0.3 dBA, while results for the case of vegetation in the upper part average of 0.6 dBA. Results also reveal that a low height vegetated barrier in the road results in a decrease in SPL of 2 dBA.

Research in a public health article[298] presents approaches to the economic valuation of noise attenuation in quiet areas near roadways (as opposed to facades facing the roadway) and the inclusion of non-acoustic benefits (aesthetics, land price, etc.). Part of the study includes prediction of the noise benefits of green walls. For noise inside a courtyard of a six-story apartment building, where a tunnel type entrance has 3-meter (10-ft) high facades as green walls, the noise reduction was 4.5 dBA for apartments facing the courtyard. Where the entrance is instead the same width as the tunnel but open all the way up the building, green walls (19.2 m or 63 ft high) provided 4.1 dBA reduction for road noise. Using demonstration projects, it was shown that green walls can be economically promising as noise attenuation measures with additional amenity benefits. For investment and annual maintenance costs for green walls, the costs were stated as follows (with currency conversion from 11/21/2109): for an area of 58 m^2 (624 ft^2) - investment 3,301 Euro ($3,653), maintenance 1,450 Euro ($1,604); for an area of 369 m^2 (3,972 ft^2) - investment 20,999 Euro ($23,236), maintenance 9,225 Euro ($10,208).

[297] Smyrnova, Y., J. Kang, M. Hornikx, and J. Forssen, "Effect of vegetation on noise propagation in streets and squares," Proceedings of the Institute of Acoustics, Vol. 34 Pt. 1, 2012.

[298] Veisten, K., Y. Smyrnova, R. Klaeboe, M. Hornikx, M. Mosslemi, and J. Kang, "Valuation of green walls and green roofs as soundscape measures: including monetised amenity values together with noise-attenuation values in a cost-benefit analysis of a green wall affecting courtyards," Int. J. Environ. Res. Public Health 2012, 9, 3770-3788, 2012.

8. STRATEGY CATEGORY: OTHER

In the course of researching the 13 targeted strategies, two other strategies showing substantial promise were also examined and summaries reported in this section. These additional strategies can be labeled as right-of-way design choices, but are shown separately here, since they are outside the scope of the primary strategies to be examined.

Table 8-1: Summaries of other strategies.

Strategy	Noise Benefit	Costs	Context Appropriateness
Low barriers and diffractors	Up to 9 dB Most effective close to sound source	WHISwall is ~$777/ft or ~$1.2M/mi	May be limited to 2-lane road, although wider highway applications could be examined
Solar panels	If continuous panels assumed, then > 11 dB, however gaps between arrays and panel angles need to be considered	Cost for purchase, installation, and maintenance of panels	Highways with ROW space

8.1 Low Barriers and Diffractors

Getting beyond the height of the ground roughness strategy discussed in Section 4.4.3 but still low height, HOSANNA[299] describes a strategy that uses a 1 m (3 ft) high, 1 m (3 ft) wide gabion barrier (wire encased stones of 15-20 cm or 6-8 in in dimension), intended for a location where the mitigation measure can be placed close to the sound source. It is discussed that the noise was reduced 3-8 dB up to 50 m (164 ft) behind the barrier.

Another example of a low barrier is shown in Figure 8-1. This is another product by 4Silence, WHISwall.[300,301] In addition to blocking tire-pavement noise, WHISwall reduces traffic noise by applying diffraction. WHISwall has the following approximate dimensions: length (parallel to road) = 3 m (10 ft), depth (perpendicular to road) = 0.9 m (3 ft), and height = 1 m (3.3 ft). Based on Dutch prices and a reasonable volume, the estimated cost for WHISwall completely installed (including installation, foundation, etc.) is ± € 700 per meter or about $777 USD per 1 meter or 3.3 feet (~$1.2M/mi) (10/28/2019). Sample installations were tested to measure the noise reduction achieved by WHISwall. Results show WHISwall provides 7-9 dB noise reduction at a height of 1.2 m (4 ft), with less at greater heights (found for both roads and rail). The noise reduction is broadband, 100 Hz and up. A similar 4Silence product is WHIStop, with a top like WHISwall, but placed atop a noise wall. 4Silence is currently doing safety testing with WHIStop placed on a safety barrier, with very promising crash test

[299] Chalmers University of Technology, CSTB, Canevaflor, IBBT Gent University, Muller BBM, Open University, City of Stockholm, TOI, University of Sheffield, University of Bradford, Stockholm University, Acoucite, and Hangyang University, "Novel solutions for quieter and greener cities, Brochure summarizing HOSANNA Project, 2013.

[300] Willems, B., "Changing the landscape of noise reduction measures," Demonstration at Noise-Con 2019, August, 2019.

[301] 4Silence, "Changing the landscape of noise reduction matters," Product introduction sheet, 2019.

results. A safety barrier with WHIStop could be a very useful application for the U.S. (please refer back to Section 3.2, where noise reduction from a standard safety barrier would be increased due to WHIStop). For noise reduction, it is expected to perform as well as WHISwall. Based on Dutch prices and a reasonable volume, the estimated cost for WHIStop completely installed is ± € 550 per meter or about $611 USD per 1 meter or 3.3 feet (~$978K/mi) (10/28/2019).

Schwanen 2018[302] conducted measurements with WHISwall for a rail application. The highest noise reduction is realized at short distances and low heights. At a receiver height of 1.2 m (4 ft), the noise reduction is about 10, 6.5 and 6.5 dB for receivers at distances of 7.5, 15, and 25 m (25, 49, and 82 ft), respectively, and averaged for near and far tracks. As the distance from the source is increased, higher receiver positions realize reduction as well. All distances exhibit noise reduction at medium and high frequencies, dependent on the height but virtually independent of the frequency. For lower frequencies they observed a decrease in noise reduction as the measurement height goes up. At a 1.2 m (4 ft) height, the noise is clearly reduced at 250 and 315 Hz. At 5 m (16 ft), this reduction has moved to 80 Hz. The reference points out that, before WHISwall can be implemented as noise mitigation in practice, a calculation rule must be created and included in the Dutch noise measurement and calculation protocol.

Figure 8-1: Example above-ground/low barrier treatment adjacent to surface transportation (©4Silence, used by permission).

For a highway application, Goubert 2017[303] conducted measurements with plastic and metal diffractors on top of low walls, similar to WHISwall. The diffractor/wall height combined ranged from 45 cm (1.5 ft) to around 60 cm (2 ft). A diffractor in the ground (immediately adjacent to the road) was also measured in combination with the low barrier/diffractor. Controlled vehicle pass-by measurements were conducted and the maximum sound pressure level measured (A-weighted, fast time response). Data were collected at a height of 1.2 m (4 ft) and at distances of 12, 30, and 60 m (36, 98, and 197 ft) from the center of the travel lane. The vehicles tested were a passenger car traveling at 75 and 85 km/h (47 and 53 mph) and a

[302] Schwanen, W. and R. van der Heijeden, *Determining Whiswall Noise Reduction*, M+P report for ProRail, March 23, 2018.

[303] Goubert, L., *Measurements report from the test set-up in Losser (NL) using a diffractor*, Belgian Road Research Centre, May 31, 2017.

truck at 50 and 80 km/h (31 and 50 mph). Measurements with noise-reducing element results were averaged and compared to no element results along the same road.

For the passenger car, for the lane on the low barrier/diffractor side of the road, noise reduction was about 9 dB out to 30 m (98 ft) and 4-5 dB at a distance of 50 m (197 ft), and speed did not affect the reduction. With the car driving in the lane on the opposite side of the road, the reductions were about 6.5-7 dB out to 30 m (98 ft) and 2-4 dB at 50 m (197 ft), where varying weather possibly contributed to differences. For trucks in the lane on the low barrier/diffractor side of the road, noise reduction was about 5-6 dB out to 30 m (98 ft) and about 4 dB at 50 m (197 ft), independent of speed. With the truck driving on the opposite side of the road, the reductions were 6 dB out to 30 m (98 ft) and 2-3.5 dB at 50 m (197 ft). The low barrier/diffractor provides a broadband influence from 125 to 4,000 Hz.

Goubert mentioned that the low barrier/diffractor is a welcome addition to the arsenal of means to combat traffic noise. It is also pointed out that there are secondary benefits: the low barriers with diffractors on top are much less disruptive to the landscape, they do not block the motorist's field of view nor that of local residents, and they are less susceptible to graffiti. Further vehicle pass-by testing on low barriers/diffractors is being conducted in Belgium. The combined height of the barrier/diffractor is 1 m (3.3 ft). They are currently evaluating the results.

8.2 Solar Panels

Solar panels placed in highway ROWs have the potential to reduce noise in communities adjacent to the highway. FHWA provides guidance on and must approve use of renewable energy in a federally funded highway ROW.[304] Allowance of renewable energy use in a ROW depends on the State Utility Accommodation Policy and if the project serves the public. Renewable energy projects that are connected to the public electricity grid or provide electricity used by a public agency such as a State DOT would generally be considered as serving the public. Some states apply or are considering the use of solar panels in the ROW, as arrays of panels a single row of panels intended strictly as a renewable energy source and as photovoltaic noise barriers.

Intended for utility purposes, an example of an array is shown in Figure 8-2. These panels have the potential to provide noise reduction beyond that for ground roughness (Section 4.4.3, which discusses parallel wall arrays in a ROW), being more effective since the solar panel height above ground is greater than for ground roughness elements (effect up to 11 dB reduction for roughness elements), although gaps between solar arrays and panel angles need to be considered. An ideal angle of the panels is 33.3-36.5° from horizontal, considering both electricity production and noise reduction.[305] The angle at which the panels are set can affect the noise reduction, and that angle can change by season. At a 60° angle, the highest height is reached, 2.4 m (8 ft). FHWA Public Roads[306,307] shows examples of single-row solar panels installed for utility purposes in highway ROWs. Figure 8-3 shows an installation in Massachusetts, where MassDOT has guidelines for renewable energy technology use along their highways. Other States that have implemented solar technology along highways include Arizona, California, Colorado, Michigan, Ohio, and Oregon. Additional States are preparing for or considering the application. Both of

[304] Federal Highway Administration, "Quick Guide: Federal Highway Administration (FHWA) Requirements for Renewable Energy Projects in Highway Right-of-Way (ROW)," 2018.

[305] Communication with Ivan Racic, Arizona Department of Transportation, 2019.

[306] Filosa, G. and C. Poe, "An array of possibilities," Publication No. FHWA-HRT-15-006, Public Roads, Vol. 79 No. 2, 2015.

[307] Hodges, T. and A. Plovnick, "Renewable roadsides," Publication No. FHWA-HRT-19-002, Public Roads, Vol. 82 No. 4, 2019.

the utility use applications would need to be investigated further as to the noise benefits, cost, and context-appropriateness.

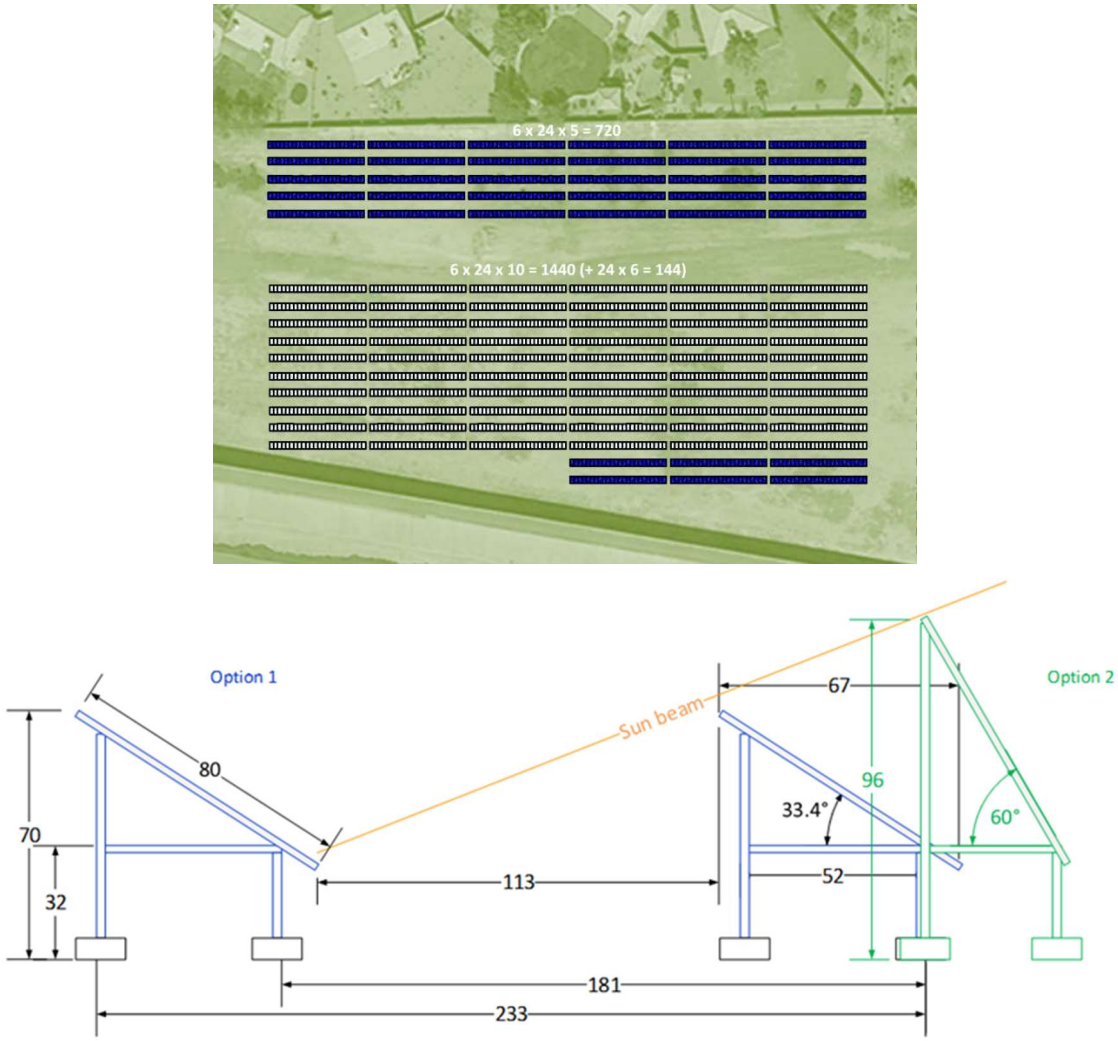

Figure 8-2: Example ROW solar panel array; top: plan view layout, bottom: row height/spacing (inches). [308]

Intended as noise barriers, a 2017 FHWA report[309] provides information on photovoltaic noise barriers, a combination of noise barriers and photovoltaic systems. The report shows several installations in Europe as well as designs of barrier/photovoltaic system configurations. Shown as Figure 1 in the FHWA report, Figure 8-4 in this report shows example configurations of photovoltaic noise barriers. It is discussed that noise abatement characteristics of noise barriers do not significantly change after being retrofit with photovoltaic modules, and new photovoltaic noise barriers can be designed to adhere to all

[308] Communication with Ivan Racic, Arizona Department of Transportation, 2019.

[309] Poe, C., A. Plovnick, T. Hodges, A. Hastings, and S. Dresley, *Highway Renewable Energy: Photovoltaic Noise Barriers*, FHWA-HEP-17-88, Federal Highway Administration, 2017.

relevant noise requirements. Regarding safety, it is mentioned that there is little to no evidence to date that photovoltaic barriers significantly affect driver safety; driver distraction and glare can be minimized. Also, existing installations have minimal maintenance needs. Thought should be given to noise reflecting from solar panels back across the highway. To minimize noise reflections that could affect opposing communities, a general suggestion is to avoid placing reflecting surfaces (in this case, solar panels) in the bottom 1.8 m (6 ft) of the barrier,[310] although each specific site geometry should be considered.

Figure 8-3: Example of right-of-way solar panels (Massachusetts, Route 44).

[310] Communication with Ivan Racic, Arizona Department of Transportation, 2019.

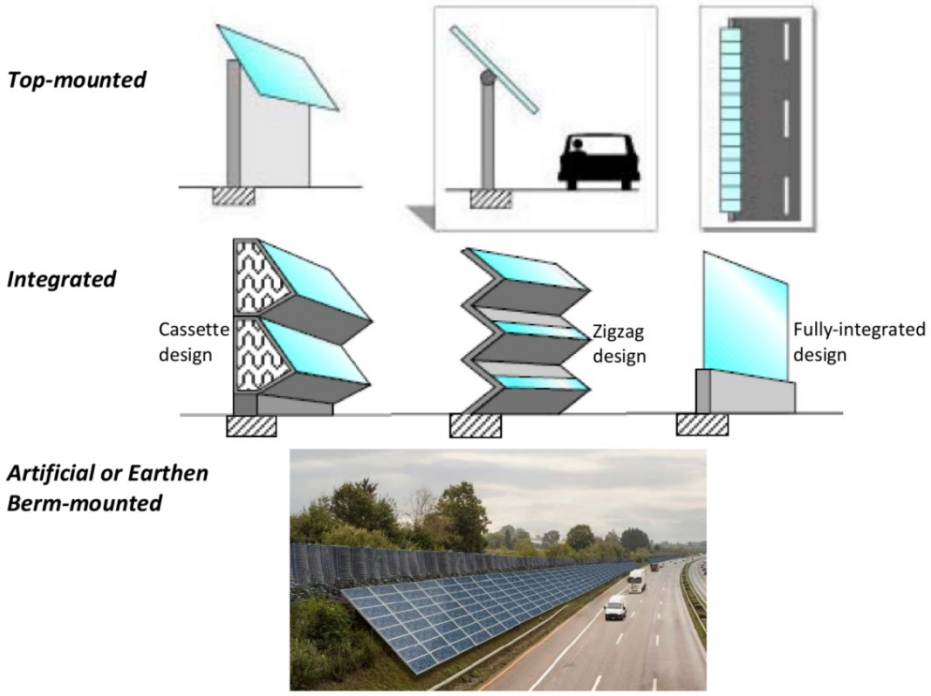

Figure 8-4: Example photovoltaic barrier configurations (FHWA[311]).

[311] Poe, C., A. Plovnick, T. Hodges, A. Hastings, and S. Dresley, *Highway Renewable Energy: Photovoltaic Noise Barriers*, FHWA-HEP-17-88, Federal Highway Administration, 2017.

9. CONCLUSIONS AND DISCUSSION

Table 9-1 in the conclusions section of this report shows the summarized results from all strategies examined as part of this research project. Highlights are presented below, including potential noise reduction values and key considerations, with relative cost estimates ($-$$$$$). Comments on strategy combinations follow the highlights.

On-road design choices:

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

Highway design choices:

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

Right-of-way design choices:

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

Operations management strategies:

- ($-$$) A reduction in speed of 16 km/h (10 mph) may result in a 2 dB noise reduction.
- ($-$$) Truck restrictions may reduce maximum noise levels up to 10 dB and L_{Aeq} values 1-6 dB, although effectiveness is based on multiple factors.

Strategies implemented by receptors or local governments:

- ($) Site planning strategies include creating a wider buffer zone (up to 3 dB reduction per doubling of distance) and shielding with privacy walls or other structures (up to about 10 dB reduction).
- ($) For building design, placing the sensitive rooms farthest from the highway may provide up to 13 dB reduction.
- ($$-$$$$) Construction methods/materials may provide up to 35 dB reduction for interior noise levels.

Sound absorptive treatment:

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

Other:

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

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

- Addressing multiple locations: at the source, in the propagation path, and at the receptor. The combination of addressing more than one of the locations can be additive. In general, most of the strategies can be combined with the on-road design choices. As an example, if quieter pavements are used in combination with above-ground ROW treatments/roughness, the combined noise reduction would likely be greater than either strategy alone. Other source location strategies are sound absorptive treatment (source being the reflection) and speed or truck restrictions.
- Addressing the same location: The combination of addressing the same location can also be additive. For example, sound absorptive pavement combined with sound absorptive treatment on structures can help to reduce multiple reflections for bridge and tunnel applications. Also, soft ground combined with low structures within the ROW can help further reduce the noise.
- Considering frequency content: the frequency range of reduction for a particular strategy may be the same as another strategy or in a different range. If the frequency range is the same, one needs to consider that the strategies may not be additive in terms of the broadband noise level,

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

Table 9-1: Summary of alternate highway traffic noise-reducing strategies.

Category	Strategy	Noise Benefit	Costs	Context Appropriateness
On-road design choices	Quieter bridge decks using diamond grinding or polyester overlays	5 to 10 dB	Polyester overlay \$10-\$30 per ft^2, geographically dependent; diamond grinding \$1-\$3 per ft^2, geographically dependent	Bridges or other structures
	Quieter bridge joints using patterned joint cover plates	6 to 9 dB	20% to 40% higher than conventional joints	Bridges or other structures with expansion joints, particularly designed seismic activity
	Quieter rumble strips with a sinusoidal pattern	3 to 7 dB	After minor equipment modifications, costs are similar to conventionally ground rumble strips; \$0.50 to \$2.00 per lineal meter (\$0.15 to \$0.60 per lineal ft)	Outside edges of travel lanes or centerline of undivided roadway
	Quieter pavement using diamond grinding	Up to 7 dB	\$2.50 to \$15.00 per m^2 (\$0.25 to \$1.50 per ft^2)	All pavement surfaces
	Quieter pavement using open-graded or rubberized asphalt	Up to 9 dB	\$5.00 to \$15.00 per m^2 (\$0.50 to \$1.50 per ft^2)	All pavement surfaces

	Quieter pavement using thin bonded asphalt overlays	Up to 6 dB	$5.00 to $15.00 per m^2 ($0.50 to $1.50 per ft^2)	All pavement surfaces
Highway design choices	Horizontal alignment shift	< 1 dB to 10+ dB depending on project specifics: extent of shift, site topography, and vehicle types	Very expensive due to additional right-of-way and construction costs	Highways or local roadways with vacant land opposite the sensitive sites
	Vertical alignment shift	< 1 dB to 10+ dB depending on project specifics: extent of shift, site topography, and vehicle types	May be less expensive than horizontal shift if right-of-way is sufficient	Highways or local roadways where right-of-way is sufficient
	Solid safety barrier in lieu of guardrail freeway	0.4 dB to 2.6 dB depending on project specifics: distance to receiver and site topography	Minor overall project cost increase	Limited-access highways if state standards allow
	Solid safety barrier in lieu of guardrail arterial	2.0 dB to 6.6 dB depending on project specifics: distance to receiver and site topography	Minor overall project cost increase	State or local roadways if state or local standards allow
	Adding a separation zone between roadway and side path to TNM	When the surface in the separation zone was very different from the default ground type (pavement vs. lawn), the separation zones can be modeled to accurately account for noise increases and decreases (although the decrease when switching from lawn to snow showed reductions only up to 0.3 dB). When the surface in the separation zone was similar to the default ground type, the addition of a Ground Zone for the separation zone made only a slight (0.1 dB or 0.2 dB) difference. Can increase accuracy up to 1.2 dB to 1.6 dB if separation zone is hard soil or pavement compared to lawn; for more absorptive surfaces than lawn, provides minimal noise	Minimal for modeling effort; construction and maintenance costs would vary by ground type and geographical area	Roadways with sidewalks or shared-use paths

		reduction benefit (up to 0.3 dB). The noise reduction would be greater if separation zone is highly sound absorptive and the default ground type is not.		
Right-of-way design choices	Standard low-height berms (up to 6ft high)	The noise benefit of low-height berms ranges from 2 dB to more than 10 dB. The noise benefit strongly depends on the relative elevation of the source, berm, and receiver with the greatest noise reduction for receivers situated at a lower elevation than the roadway. A model of a 0.96 m (3.1 ft) high berm showed a noise reduction of 2 to 5 dB with roadside and/or median berms.	In opening year, a concrete wall is about 2.6 to 3 times more expensive than an earthen berm. This assumes no right-of-way costs or fill costs for the berm. (Berms can be as or more expensive than a wall if material has to be brought in.) Maintenance costs for berms are expected to be less than for noise walls.	Highways or arterials with sufficient ROW space for berm bases (up to 11m (36 ft) for a 1.8 m (6 ft) high berm) Low-height berms will be most effective when the berm can be placed close to the source or receiver, and the elevation of the receiver is lower than the source.
	Engineered low-height berms with steeper slopes	These berms could reach taller heights closer to the noise source, improving noise reduction compared to standard low-height berms.	In 2011, costs were estimated to be $25 to $50 per sq. ft. If an irrigation system is needed to maintain vegetation, the costs would increase.	Engineered low-height berms could be implemented where there are ROW constraints for a standard berm.
	Low-height berms with absorptive ground	A more absorptive ground type could increase the noise reduction by up to 5 dB compared to packed dirt.	Costs would be geographically dependent based on the absorptive ground type selected.	Highways with ROWs that can accommodate acoustically softer ground surfaces.

	Unusually shaped low-height berms	For a 1 m (3.3 ft) high berm next to an arterial road, unusually shaped berms did not provide a noise benefit compared to a traditional wall or berm.	Unusually shaped berms have not been implemented; they were considered in a numerical model	Have yet to be implemented; considered in models only
	Thick vegetation belts (> 20 m (65.6 ft))	Measured noise reduction of 3-9 dB; up to 10 dB noise reduction in computational model with optimized planting.	Geographically dependent on type of vegetation used (example cost of $100 to $300 per tree, installed) and the need for upkeep; ROW cost could be significant.	Highways with significant ROW available; areas that can support sufficiently dense vegetation
	Moderate-to-low thickness vegetation screens (< 20 m (65.6 ft))	Measured noise reduction of 1-3 dB; up to 6 dB noise reduction in computational model with optimized planting.	Geographically dependent on type of vegetation used (example cost for two rows planted 10 ft apart would be $0.5-1.5 million/mile) and the need for upkeep; may be ROW cost for moderately thick vegetative belts of 10-20 m (33-66 ft)	Areas that need relatively minor noise reduction; areas that can support sufficiently dense vegetation
	Vegetation to improve adverse sound propagation effects	A row of trees behind a noise barrier can reduce negative downwind noise effects A vegetated belt can reduce the likelihood of a temperature inversion layer which can bend sound downwards	Geographically dependent on type of vegetation used and the need for upkeep; may be additional ROW cost	Sites with a wall noise barrier, especially ones with prevalent downwind conditions Sites that can support vegetation, especially ones with frequent

				temperature inversion conditions
	Vegetation to improve perception of noise with narrow vegetation screens	No noise benefit - subjective reports of decrease in annoyance when more vegetation is present; however, the relationship is difficult to show in subjective studies with test subjects at multiple vegetated or non-vegetated sites	Geographically dependent on type of vegetation used and the need for upkeep	Areas that do not qualify for noise abatement, but report high levels of traffic noise annoyance
	Vegetated biofilter basin	Less than 1 dB effect on noise adjacent to a 6-lane highway; For a two lane highway, there is less than 1 dB effect out to 91.4 m (300 ft) and up to 2.4 dB out to 152.4 m (500 ft)	No additional cost if the vegetated swale is already planned	Highways or roads where a vegetated swale is needed
	Acoustically soft ground	TNM predictions show 1-2 dB for placement in ROW or median, however, more may be realized with gravel surfaces (multi-lane highway) CRTN predictions show 3-12 dB for placement 2.5 m (8.2 ft) from the edge of the near travel lane, largest decrease for gravel and low flow resistivity grassland (2-lane road); soft surface extended 25 m (82 ft) or more from road Soft ground treatments are less effective as the receiver height increases As source-receiver distance is increased, the insertion losses due to the near-source ground treatments do not decrease as they would with a traditional noise barrier	Geographically dependent – may need to maintain grass or gravel	Highways with ROWs or medians that can accommodate acoustically softer ground surfaces
	In-ground treatments	Testing of WHISstone shows 2.4 and 4 dB reduction for a recessed lattice structure 0.95 and 1.9 m (3 and 6 ft) wide and 0.2 m (0.7 ft) deep, respectively, measured 12 m (39 ft) from a single vehicle pass-by source Calculations show 2-8 dB reduction for a recessed lattice structure 0.3 m (1 ft) deep placed 2.5 m (8 ft) from the nearest source; range of insertion loss depends on the width of the structure, ranging from 1.5-24 m (5-79 ft, widest being most effective)	WHISstone is ~$170 USD per 1 meter or 3.3 feet length along road (single row, 0.95 m or 3 ft wide)	Highways with ROWs that can accommodate embedded structures close to the near travel lane (narrow shoulders, likely 2-lane road)

		In-ground resonators may be tuned to reduce a specific frequency, although their effectiveness would likely be less than 2-3 dB (shoulder placement)		
	Above-ground treatments	Boundary Element Method predictions show the following: - Low (< 0.3 m or 1 ft) parallel walls (12 m or 30 ft wide) can provide up to 9 dB reduction at 50 m or 164 ft - A low (< 0.3 m or 1 ft) lattice wall structure (12 m or 30 ft wide) can provide up to 11 dB reduction at 50 m or 164 ft Related notes: - Wider structures provide greater reduction - Comparative soft ground for half the source-receiver distance provides 9 dB reduction Effectiveness is not affected by receiver height or distance	Unknown – would need to construct and maintain low parallel or lattice walls	Highways with ROWs that can accommodate above-ground low structures close to the near travel lane (narrow shoulders, likely 2-lane road)
Operations management strategies	Speed restrictions	For combined traffic flows of automobiles and heavy vehicles, an overall noise reduction of approximately 2 dB (L_{Aeq}) may be expected with a reduction in speed of 16 km/h (10 mph).	Generally low; may impose costs of increased travel times. Other costs may include public education, enhanced enforcement, and related infrastructure improvements such as traffic calming measures.	Applicable either to limited-access highways or local road networks.
	Truck restrictions	Reductions in maximum pass-by levels (L_{Amax}) of 10 dB or more. Overall L_{Aeq} noise reduction dependent on many factors, ranging from approximately 1 to 6 dB.	Generally low; may impose indirect costs on truck operators and general public. Other costs may include public education, enhanced	Most commonly implemented on local road networks; also may be used on limited-access roads.

			enforcement, and increased maintenance on designated alternative truck routes.	
Implementations by receptors or local governments	Site Planning	Up to 3 dB when distance to the roadway is doubled. 10 dB or more when non-sensitive buildings or privacy walls are used to shield sensitive sites or areas	Minimal when considered early	New development
	Building Design	Up to 13 dB when noise sensitive rooms are placed farthest away from the highway.	Minimal when considered early	New development or redevelopment
	Construction Methods	Up to 35 dB interior	Expensive due to materials required	New development or redevelopment
Sound absorptive treatment	Treatment on retaining walls	Opposite side reflection: 1-2 dB with changes in spectral content potentially reducing adverse reflected noise effect Parallel barriers: predicted up to 2.5 dB Truck/barrier wall reflections: predicted up to 4 dB	Varies by treatment/project (one example was \$18-22/ft^2)	Locations where retaining walls can reflect noise to sensitive receptors
	Treatment on bridge understructures	Highway measurements showed up to 6 dB, lab measurements up to 11 dB, and predictions up to 5 dB with sound absorptive treatment Low frequency vibration dampers can help to reduce noise from steel bridge structure	Cost of material, installation, maintenance	Elevated highway bridge structures or those over depressed highways where reflections can affect sensitive receptors
	Treatment in tunnels	Measurements showed 5-10 dB reduction for sound absorptive treatment Surface roughening predicted to reduce noise by 4 dB	Cost of material, installation, maintenance	Highway tunnels where reflections can affect sensitive receptors
	Other structure applications	Sound absorption using Helmholtz resonators or metamaterials; engineered products that can be tuned to optimize traffic noise reduction	Example: for a green area of 369 m^2 (3,972 ft^2) - investment 20,999 Euro	Locations where structure surfaces can reflect noise

		Curvature of a wall should be considered to avoid focusing sound Application of absorptive material to ramp and median safety barriers can reduce reflections Green wall systems on walls and rooftops can reduce reflections	($23,236), maintenance 9,225 Euro ($10,208)	
Other	Low barriers and diffractors	Up to 9 dB Most effective close to sound source	WHISwall is ~$777/ft or ~$1.2M/mi	May be limited to 2-lane road, although wider highway applications should be examined
	Solar panels	If continuous panels assumed, then > 11 dB, however gaps between arrays and panel angles need to be considered	Cost for purchase, installation, and maintenance of panels	Highways with ROW space

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APPENDIX A: TERMINOLOGY

Highway traffic noise terminology are shown below, extracted/modified (removed non-applicable terms and added C weighting) from the terminology list shown in the FHWA Noise Measurement Handbook (FHWA-HEP-18-065). The terminology includes sound level metrics and abbreviations.

A-Weighting

A-weighting is the weighting network used to account for changes in level sensitivity as a function of frequency. The A-weighting network de-emphasizes the high (6.3 kHz and above) and low (below 1 kHz) frequencies, and emphasizes the frequencies between 1 kHz and 6.3 kHz, to simulate the relative response of the human ear to environmental noise. An A-weighted sound level has the A-weighting applied and is reported in units of decibels, often with a designator of A on the abbreviation (dBA).

Absorption Coefficient

See Sound Absorption Coefficient.

Acoustic Energy

Acoustic energy, commonly referred to as "sound energy," or just "energy," is the total energy in a medium minus the energy that would exist at that same part of a medium with no sound waves. Unit, joule (J). Some practitioners refer to the unitless solution of pressure ratio = $10^{SPL/10}$, where SPL is the sound pressure level and is expressed in decibels re 20 μ Pa, as a quantity of energy, since sound pressure is related to acoustic energy through sound power.

C-Weighting

C-weighting is the weighting network represents the effect of low-frequency sounds on the human ear and differs most from A-weighting below 1 kHz. A C-weighted sound level has the C-weighting applied and is reported in units of decibels, often with a designator of C on the abbreviation (dBC).

Community Noise Equivalent Level (CNEL, denoted by the symbol L_{den})

CNEL is 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" for relaxation and conversation time) and addition of 10 dB to nighttime sound levels between the hours of 2200 (10:00 p.m.) and 0700 (7:00 a.m.) ("penalty" for sleep time). Unit, dBA (assumes A-weighting). The CNEL noise descriptor is used primarily in the state of California. Internationally, it is also known as the "day-evening-night level." CNEL is computed as follows based on hourly equivalent sound levels:

Equation 10-1: Formula for Community Noise Equivalent Level

$$L_{den} = 10log_{10}\left[\frac{1}{24}\sum_{i=1}^{24} 10^{\frac{L_{eq}(\mathrm{h})+W_i}{10}}\right] \quad (dB)$$

where:

L_{den} = Community Noise Equivalent Level in dB;

L_{eq}(h) = equivalent sound level (see definition) for the ith hour; and

W_i = 0 for day hours (7:00 a.m. to 7:00 p.m.)

= 5 for evening hours (7:00 p.m. to 10:00 p.m.)

= 10 for night hours (10:00 p.m. to 7:00 a.m.)

The equation can also be written as follows and can be applied when the equivalent sound level is known for each part of the day:

Equation 10-2: Alternative Formula for Community Noise Equivalent Level

$$L_{den} = 10log_{10}\left[\left(\frac{12}{24}\right)10^{\frac{L_{day}}{10}} + \left(\frac{3}{24}\right)10^{\frac{L_{eve}+5}{10}} + \left(\frac{9}{24}\right)10^{\frac{L_{night}+10}{10}}\right] \quad (dB)$$

where:

L_{den} = Community Noise Equivalent Sound Level in dB;

L_{day} = equivalent sound level for day hours (7:00 a.m. to 7:00 p.m.)—the day term in the equation can be divided by peak and off-peak traffic hours if desired, with the appropriate constant of elapsed time/24 hours applied;

L_{eve} = equivalent sound level for evening hours (7:00 p.m. to 10:00 p.m.); and

L_{night} = equivalent sound level for night hours (10:00 p.m. to 7:00 a.m.).

The CNEL can also be expressed in terms of SEL as follows:

Equation 10-3: Formula for Community Noise Equivalent Level based on SEL

$L_{den} = L_{AE} + 10\ log_{10}\ (N_{day} + 3.162\ N_{eve} + 10\ N_{night}) - 49.4\ dB$

where:

L_{AE} = SEL in dB (see definition);

N_{day} = Number of vehicle pass-bys between 7:00 a.m. to 7:00 p.m., local time;

N_{eve} = Number of vehicle pass-bys between 7:00 p.m. to 10:00 p.m., local time;

N_{night} = Number of vehicle pass-bys between 10:00 p.m. to 7:00 a.m., local time; and

49.4 = A normalization constant that spreads the acoustic energy associated with highway vehicle pass-bys over a 24-hour period [i.e., 10 $\log_{10}$ (86,400 seconds per day) = 49.4 dB].

Day-Night Average Sound Level (DNL, denoted by the symbol L_{dn})

DNL is a 24- hour A-weighted average sound level for a given day, after the addition of 10 dB to sound levels between the nighttime hours of 2200 (10:00 p.m.) and 0700 (7:00 a.m.) ("penalty" for sleep time). Unit, dBA (assumes A-weighting). L_{dn} is computed as follows based on hourly equivalent sound levels:

Equation 10-4: Formula for Day-Night Average Sound Level

$$L_{dn} = 10log_{10}\left[\frac{1}{24}\sum_{i=1}^{24} 10^{\frac{L_{eq}(\mathrm{h})+W_i}{10}}\right] \quad (dB)$$

where:

L_{dn} = Day-Night Average Sound Level in dB;

L_{eq}(h) = equivalent sound level (see definition) for the ith hour; and

W_i = 0 for day and evening hours (7:00 a.m. to 10:00 p.m.)

= 10 for night hours (10:00 p.m. to 7:00 a.m.)

The equation can also be written as follows and can be applied when the equivalent sound level is known for each part of the day:

Equation 10-5: Alternative Formula for Day-Night Average Sound Level

$$L_{dn} = 10log_{10}\left[\left(\frac{15}{24}\right)10^{\frac{L_{day}}{10}} + \left(\frac{9}{24}\right)10^{\frac{L_{night}+10}{10}}\right] \quad (dB)$$

where:

L_{dn} = Day-Night Average Sound Level in dB;

L_{day} = equivalent sound level for day hours (7:00 a.m. to 10:00 p.m.)—the day term in the equation can be divided by peak and off-peak traffic hours if desired, with the appropriate constant of elapsed time/24 hours applied; and

L_{night} = equivalent sound level for night hours (10:00 p.m. to 7:00 a.m.).

The day-night average sound level can also be expressed in terms of SEL as follows:

Equation 10-6: Formula for Day-Night Average Sound Level based on SEL

$L_{dn} = L_{AE} + 10\ log_{10}\ (N_{day} + 10N_{night}) - 49.4 \quad (dB)$

where:

L_{AE} = SEL in dB (see definition);

N_{day} = Number of vehicle pass-bys between 7:00 a.m. to 7:00 p.m., local time;

N_{night} = Number of vehicle pass-bys between 10:00 p.m. to 7:00 a.m., local time; and

49.4 = A normalization constant which spreads the acoustic energy associated with highway vehicle pass-bys over a 24-hour period [i.e., 10 $\log_{10}$ (86,400 seconds per day) = 49.4 dB].

Decibel (dB)

A decibel is a unit of level that denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the base 10 logarithm of this ratio. For the purpose of this document, the reference level of sound pressure or noise is 20 µPa (approximately the threshold of human hearing at 1 kHz). The reference level of vibration is 1 µ-inches/second.

Diffracted Wave

A diffracted wave is a sound wave whose front has been changed in direction by an obstacle or other non-homogeneity in the propagation medium, typically air for the purposes of this document, other than by reflection or refraction.

Divergence

Divergence is the spreading of sound waves from a source in a free-field environment. In the case of highway noise, two types of divergence are common: spherical and cylindrical. Spherical divergence occurs for sound emanating from a point source (e.g., a single vehicle pass-by). It is independent of frequency, and is computed using a 20 $\log_{10}(d_1/d_2)$ relationship. For example, if the sound level from a point source at 50 ft (15 m) was 90 dB, then at 100 ft (30 m) it would be 84 dB due to divergence [i.e., 90 + 20 $\log_{10}$ (50/100)]. Cylindrical divergence occurs for sound emanating from a line source, (e.g., continuous traffic on a highway). It is independent of frequency, and is computed using a 10 $\log_{10}$ (d_1/d_2) relationship. For example, if the sound level from a line source at 50 ft (15 m) was 90 dB, then at 100 ft (30 m) it would be 87 dB due to divergence [i.e., 90 + 10 $\log_{10}$ (50/100)].

Equivalent Sound Level or Equivalent Continuous Sound Level

The Equivalent Sound Level or Equivalent Continuous Sound Level (TEQ or L_{eq}, denoted by the symbol LAeqT, or generically, L_{eq}) is ten times the base-10 logarithm of the ratio of time-mean-squared instantaneous sound pressure, during a stated time interval, T (where $T=t_2-t_1$), to the square of the standard reference sound pressure. Unit, dBA (assumes A-weighting). For the purpose of this document, the reference sound pressure is 20 µPa. The equivalent sound level is a time-averaged sound level that has

the same acoustic energy as the time-varying sound level during the same time period. L_{AeqT} can be measured and reported for a specific time interval T or it can be calculated from multiple samples as follows:

Equation 10-7: Formula for Equivalent Sound Level

$$L_{AeqT} = 10Log_{10}\left[\frac{\left(10^{SPL_1/10} + 10^{SPL_2/10} + \cdots 10^{SPL_N/10}\right)}{N}\right]$$

where:

L_{AeqT} = A-weighted equivalent sound level in dB for time T;

$SPL_1, SPL_2, \ldots SPL_N$ = first, second, and N^{th} A-weighted sound pressure level;

N = number of sound level samples; and

T = total time interval constructed from N samples

[e.g., T = 1 hour for twelve 5-minute samples; in this case the sound descriptor can be written as L_{Aeq1h} or another common format, L_{eq}(h)].

The equivalent sound level can also be expressed in terms of SEL as follows:

$L_{AeqT} = L_{AE} - 10\ log_{10}(t_2 - t_1)$

where:

L_{AeqT} = equivalent sound level in dB;

L_{AE} = SEL in dB (see definition); and

t_1, t_2 = t_1 is the start time, and t_2 is the end time for the time interval.

Exponential Time-Weighted Sound Level

The exponential time-weighted sound level is 10 times the logarithm to the base 10 of the ratio of the running time average of the exponential-time-weighted and frequency-weighted squared sound pressure to the square of the reference pressure. Unit, decibel (dB). Exponential time weightings are most commonly fast-scale (τ = 0.125 seconds) and slow-scale (τ = 1.0 seconds), where τ is the exponential time constant, which is the time required to increase the time-varying quantity by (1 – 1/e), or decrease by (1/e). Sound level fluctuations are easier to read on a sound level meter with the slow setting compared to the fast setting; however, the fast setting gives better resolution of instantaneous response.

Frequency

Frequency is 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

Ground attenuation is the change in sound level—either positive or negative—due to intervening ground between source and receiver. Ground attenuation is a relatively complex acoustic phenomenon, which is a function of ground characteristics, source-to-receiver geometry, and the spectral characteristics of the source. A commonly used rule-of-thumb for propagation over soft ground (i.e., grass, terrain) is that ground effects will account for about 1.5 dB per doubling of distance (in addition to divergence). However, this relationship is quite empirical and tends to break down for distances greater than about 100 ft to 200 ft (30 m to 61 m). Specific methodologies have been developed to estimate ground attenuation, such as that utilized in FHWA's Traffic Noise Model.

Ground Impedance
Ground impedance is a complex function of frequency relating the sound transmission characteristics of a ground surface type. Measurements to determine ground impedance can be made in accordance with ANSI/ASA S1.18-2010.[312]

Hard Ground
Hard ground, also referred to as acoustically hard ground, is any highly acoustically reflective surface in which the phase of the sound energy is essentially preserved upon reflection. Examples include water, water-soaked earth, hard-packed earth, asphalt, and concrete. Although the effects of hard ground vary by frequency, the overall result is a net amplification in sound (reflected sound adds to direct sound).

Insertion Loss (IL)
Insertion loss is the difference in levels BEFORE and AFTER installation of a barrier (encompassing all causes of the difference), where the source, terrain, ground, and atmospheric conditions, in the BEFORE and AFTER cases, are equivalent.

kHz (Kilohertz)
kHz is an abbreviation for 1,000 hertz (Hz); hertz is a unit of frequency.

L_{AE}
See Sound Exposure Level (SEL, denoted by the symbol LAE).

L_{Aeq}
See Equivalent Sound Level or Equivalent Continuous Sound Level.

L_{AFmx}/L_{ASmx}
See Maximum Sound Level (MXFA or MXSA, denoted by the symbol LAFmx or LASmx, respectively).

L_{den}
See Community Noise Equivalent Level (CNEL, denoted by the symbol Lden).

L_{dn}
See Day-Night Average Sound Level (DNL, denoted by the symbol Ldn).

L_{90}
L_{90} is a statistical descriptor describing the sound level exceeded 90% of a measurement period. Unit, dBA (assumes A-weighting).

Line Source
A line source is multiple closely spaced or moving point sources collectively radiating sound cylindrically. (Sound levels measured from a line source decrease at a rate of 3 dB per doubling of distance in free-field conditions.)

Maximum Sound Level (MXFA or MXSA, denoted by the symbol L_{AFmx} or L_{ASmx}, respectively)
Maximum sound level is the maximum, A-weighted and exponential-time-weighted (fast or slow) sound level associated with a given event or during a time interval (Figure). Unit, dBA (assumes A-weighting).

Noise
Noise is any unwanted sound. Objectively, noise can be defined as erratic, intermittent, or statistically random oscillation (variation from reference).

[312] "Method for Determining the Acoustic Impedance of Ground Surfaces," ANSI/ASA S1.18-2010, Acoustical Society of America, Melville, New York, 2010.

Noise Barrier
A noise barrier is a wall or earth berm (or combination of the two) that interferes with sound propagation and minimizes excessive or intrusive noise for inhabitants of noise-sensitive land uses near a noise source (e.g., busy highway).

Noise Reduction Coefficient (NRC)
Noise reduction coefficient is the single-number rating of the sound absorption properties of a material; it is the arithmetic mean of the Sound Absorption Coefficient at 250 Hz, 500 Hz, 1,000 Hz, and 2,000 Hz, rounded to the nearest multiple of 0.05 metric sabins per square meter. Measurements to obtain the noise reduction coefficient value are performed in accordance with ASTM Standard C423.

Octave Band
Octave bands are sounds that can be represented by several frequency bands between two frequency limits (for human hearing the frequency limits are 20 Hz to 20,000 Hz). One customary bandwidth is one octave, where the upper frequency limit of the band is approximately twice ($2^{1/1}$) the lower limit. Octave bands are represented by their center frequencies (e.g., 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, and 1,000 Hz).

One-Third Octave Band
One-third octave band is the most customary bandwidth for a highway noise frequency analysis. One-third octave bands reveal more details in the spectral content than octave bands and are typically appropriate for highway traffic noise. The upper frequency limit for a one-third octave band is approximately 1.26 ($2^{1/3}$) times the lower limit. One-third octave bands are represented by their center frequencies (e.g., 20 Hz, 25 Hz, 31.5 Hz, 40 Hz, 50 Hz, 63 Hz, 80 Hz, 100 Hz, 125 Hz, 160 Hz, 200 Hz, 250 Hz, 315 Hz, 400 Hz, 500 Hz, 630 Hz, 800 Hz, and 1,000 Hz).

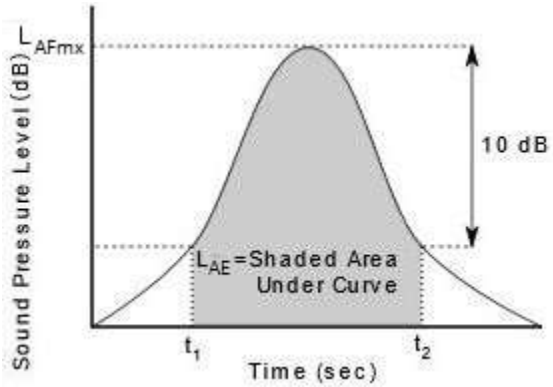
Point Source
Point source is a source that radiates sound spherically. (Sound levels measured from a point-source decrease at a rate of 6 dB per doubling of distance in free-field conditions.)

Soft Ground
Soft ground, which is also referred to as acoustically soft ground or porous ground, is any highly absorptive surface in which the phase of the sound energy is changed upon reflection, except at low frequencies. Examples include grassland, terrain covered with dense vegetation, plowed or aerated earth, or freshly fallen snow. Although the effects of soft ground vary by frequency, for sound propagation angles typically associated with highway traffic noise, the overall result is an attenuation in reflected noise as compared to hard ground. (At propagation angles greater than 20° from horizontal, which can occur at short ranges, or in the case of elevated sources or receivers, soft ground becomes a good reflector and can be considered hard ground.) See also Ground Attenuation and Hard Ground.

Sound Absorption Coefficient
Sound absorption coefficient is the ratio of the sound energy, as a function of frequency, absorbed by a surface, to the sound energy incident upon that surface.

Sound Exposure Level (SEL, denoted by the symbol L_{AE})
Sound exposure level is 10 times the logarithm to the base 10 of the ratio of a given time integral of squared instantaneous sound pressure to the squared reference sound pressure of 20 μ Pa. Unit, dBA (assumes A-weighting). The time interval must be long enough to include most of the sound source's acoustic energy. At a minimum, this interval should encompass the 10 dB down points.

Figure: Graphical Representation of L_{AE} and L_{AFmx} Noise Descriptors



In addition, L_{AE} is related to L_{AeqT} by the following equation:

$$L_{AE} = L_{AeqT} + 10\ log_{10}(t_2 - t_1) \quad (dB)$$

where:

L_{AE} = Sound exposure level;

L_{AeqT} = Equivalent sound level in dB (see definition above); and

t_1, t_2 = t_1 is the start time, and t_2 is the end time for the time interval.

Sound Intensity (I)

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. Unit, watt per square meter (power/area) [W/m^2= $N/(s*m)$]. Since sound intensity is sound power over an area, it is dependent on the shape of the sound wave. For example, for a spherical wave, area = $4\pi r^2$, where r is the distance from the sound source at which intensity is being evaluated. Sound intensity is directly proportional to the square of p_{rms} (RMS pressure) and is related by the density (ρ) and speed of sound (c) in a medium: $I = (p_{rms})^2/(\rho*c)$.

Sound Intensity Level (denoted by the symbol L_I)

Sound intensity level is 10 times the base-10 logarithm of the ratio of a time-average intensity of a given sound in a stated direction, to the reference value for sound intensity of 1 picowatt per square meter ($picoW/m^2$). Unit, dBA (assumes A-weighting). Sound intensity level values can apply to broadband levels or for a stated frequency band.

Sound Power (P)

Sound power, for a specified sound source, is the sound energy radiated per unit of time (rate of energy flow). Unit, watt (W = J/s = N*m/s).

Sound Pressure (p)

Sound pressure is the total instantaneous pressure at a point in a medium minus the static pressure at that point. Unit, pascal ($Pa = N/m^2$). Sound pressure (p_{rms}) squared is directly proportional to sound intensity and is related by the density (ρ) and speed of sound (c) in a medium: $(p_{rms})^2 = I*(\rho*c)$. Since sound intensity is related to sound power, sound pressure is also related to sound power.

Sound Pressure Level (SPL, denoted by the symbol L_p)

Sound pressure level is 10 times the base-10 logarithm of the ratio of the square of p_{rms} (RMS pressure) signal, to the square of the reference sound pressure of 20 μPa, the approximate threshold of human hearing at 1 kHz. Unit, dBA (assumes A-weighting). SPL values can apply to broadband levels or for a stated frequency band.

Sound Transmission Class (STC)

Sound transmission class is a single-number rating used to compare the sound insulation properties of barriers, including windows and doors in buildings.

Spectrum

Spectrum is a signal's resolution expressed in component frequencies or fractional octave bands.