Noise Wall Overhang Design

***Prepared by*:**

Benjamin R. Sperry
Blake Staley
Issam Khoury
Karel Cubick
Bill Ruggles
Jonathan Hren

***Prepared for*:**

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16. Abstract

The purpose of this research study was to determine if a roadway-side overhang component could provide meaningful noise reduction and air quality benefits for ODOT's noise walls in a manner that is cost-effective and meets all of ODOT’s structural design requirements. A comprehensive review of literature was conducted to identify past research on overhang impacts and the deployment of overhang designs in North America. Acoustical testing using a full-scale noise wall section was also conducted to determine the combination of overhang length and angle toward the roadway that provides the greatest noise reduction. The results of the acoustical testing were consistent with expectations based on previous studies, indicating that a perceptible noise reduction could be achieved with the overhang fixture. However, a preliminary analysis of the structural requirements and resulting construction costs found that the cost to retrofit an existing noise wall with an overhang was approximately twice as expensive as raising the height of the wall in the vertical direction to achieve a similar noise reduction. Consequently, deployment of overhang designs is not cost-effective for ODOT except in locations where it is not feasible to raise the height of the wall in the vertical direction.

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Prepared by:

Benjamin R. Sperry, Ph.D., P.E.
Blake Staley
Issam Khoury, Ph.D., P.E.
Ohio Research Institute for Transportation and the Environment
Ohio University

Karel Cubick
Bill Ruggles, P.E.
Jonathan Hren, P.E.
ms consultants, inc.

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EXECUTIVE SUMMARY

Research Problem

The ODOT noise program is continually seeking opportunities to deploy new and innovative options to accomplish FHWA-required abatement of highway traffic noise in a manner that is both cost-effective and within the structural design practices of the Department. One potential option to achieve noise reduction at a lower cost is to add a roadway-side overhang component to the top of an existing or proposed noise wall. Evaluations of the acoustical performance of overhang designs has been shown to be a benefit compared to a traditional wall of the same height [e.g., May and Osman, 1980a; Hajek and Blaney, 1984; Hothersall, et al., 1991; Watts, et al., 1994; Ishizuka and Fujiwara, 2004, Lodico, 2010; Diez, et al., 2012; Donovan, et al., 2018]. Deployment of noise wall overhang components in North America has been limited to two locations in Ontario [May and Osman, 1980b; Hajek and Blaney, 1984], the Ohio Turnpike [TranSystems, 2009], and Colorado [Lodico and Goldberg, 2010]. Given that the older overhang designs were constructed primarily using concrete materials, there were concerns about the cost, structural integrity, and motorist safety associated with such designs. With the emergence of new, relatively inexpensive, lighter-weight materials used to construct noise walls, the question of whether overhang designs can be deployed in a cost-effective manner should be re-examined. Additionally, while the air quality impacts of traditional noise walls have been examined in recent years [e.g., Bowker, et al., 2007; Baldauf, et al., 2008; Ning, et al., 2010; Baldauf, et al., 2016], the impacts of overhang designs on air quality are not completely understood. Consequently, this research was initiated to determine if a roadway side overhang component would provide meaningful noise reduction and air quality benefits for ODOT noise walls in a manner that is cost-effective and meets all of ODOT's structural design requirements.

Research Approach

Researchers from the Ohio Research Institute for Transportation and the Environment (ORITE) at Ohio University, with assistance from ms consultants, inc., approached the research problem with three key activities, described as follows:

- Comprehensive review of existing literature and research studies related to noise wall overhang design options and the impacts of different designs on factors including (but not limited to) acoustical performance, air quality impacts, life cycle cost requirements, constructability, durability, maintenance, safety, and aesthetics;
- Acoustical testing of various noise wall overhang design options using a full-scale noise wall section to determine the overhang length and angle combination that provides the greatest noise reduction relative to a plain-top noise wall design; and
- Preliminary structural analysis of up to four noise wall overhang design options to assess the compatibility of different overhang design options with AASHTO and ODOT design loads for noise walls, considering both new construction and "retro-fit" of existing walls.

Research Findings

The research team identified four examples of in-service deployment of noise wall overhangs in North America: two in the Toronto, Ontario region; one in Colorado; and one in Ohio. The ORITE research team reached out to individuals who had been involved or associated with the design, construction, and operation of these overhangs to obtain more detailed information about the in-service experience of these installations. Feedback provided to the research team related to the in-service performance of the overhangs was generally positive and no issues related to maintenance, traffic safety, or community viewpoints were mentioned.

The acoustic effectiveness of the different noise wall overhang design configurations was evaluated based on the insertion loss (IL) for each configuration relative to the "Base Condition" of the 12-foot tall plain-top wall. The results of the acoustical testing indicate that, on average, an additional insertion loss of 1.5 dBA can be realized for each additional 1-foot of overhang length toward the source. These results compare favorably with the results of other acoustical testing of noise wall overhang designs as identified in the literature review. The 90-degree or "Inverted L" overhang configuration provided an additional IL of 3.0 dBA in addition to the IL attributed to the length of the fixture. The results also demonstrate that the T-shape is not as effective as the "Inverted L" shape. With respect to the Y-Top design, the results of the current study indicate that very little acoustical benefit can be gained from the use of an angled design when compared to increasing the wall by the same height. The results suggest that ODOT could achieve a perceptible reduction in traffic noise (i.e., greater than 3.0 dBA reduction) with the deployment of a two-foot 90-degree overhang on an existing noise barrier.

The preliminary structural analysis found that the 'T-Top" design produces the lowest additional bending moment of the various design options evaluated due to the weight of the panel material being evenly distributed on both sides of the wall. However, for all the designs examined, the additional loading due to proposed overhangs on the existing noise wall concrete posts and foundations is a very small percentage of the total structural capacity of the existing posts and foundations. Assuming a two-foot wide overhang length and the use of an ODOT-approved lightweight material, the cost per square foot ranges from $89.50 to $117.50 depending on material used, with the 45-degree overhang being higher cost than the 90-degree option. Additional details of the cost estimate are presented in Appendix C of the full report. A matrix comparing the various attributes of three different noise wall overhang design options (Y-Top, Inverted L, and T-Top) is presented in Table 2 of the report.

Recommendations

Based on the findings and conclusions of this research project, the ORITE research team presents the following recommendations related to noise wall overhang designs:

- Recommendation #1: ODOT should consider the use of the 90-degree overhang options (either the "Inverted L" or "T-Top" shape) for deployment on its traffic noise walls.
- Recommendation #2: ODOT should not consider the use of the "Y-Top" overhang shape.
- Recommendation #3: ODOT should examine the 90-degree overhang options in more detail to determine which option may be best for its needs.

Additional details on these recommendations and a detailed implementation plan can be found in the main body and appendices of this report. The findings of this research study indicate that the 90-degree or "Inverted L" overhang shape has the greatest potential for deployment on existing ODOT noise walls. Barrier locations where the wall height cannot be increased due to utility conflicts, foundation issues, aesthetics, or community feedback are the ideal locations where an overhang could be of the greatest benefit. The ODOT Office of Environmental Services, in conjunction with the Office of Structural Engineering, is responsible for implementing the recommendations of this study, including any changes to ODOT's standard specifications for noise wall construction.

PROJECT BACKGROUND

Research Problem

In accordance with 23 CFR Part 772, State DOTs maintain primary responsibility for mitigating the adverse impacts of traffic noise associated with major highways. ODOT policies and practices for analysis and abatement of traffic noise impacts are described in the ODOT *Highway Traffic Noise Analysis Manual* [ODOT OES, 2015]. As of December 31, 2016, approximately 150 noise walls have been constructed along Ohio's roadways at an average cost of approximately $2.0 million per mile, accounting for more than 230 linear miles of wall structures with an average height between 12 and 16 feet [FHWA, 2017]. Noise walls constructed in Ohio must meet ODOT criteria for acoustical performance, cost-reasonableness, and structural design requirements based on standard drawings (NBS-1-09).

The ODOT noise program is continually seeking opportunities to deploy new and innovative options to accomplish FHWA-required abatement of highway traffic noise in a manner that is both cost-effective and within the structural design practices of the Department. One potential option to achieve noise reduction at a lower cost is to add a roadway-side overhang component to the top of an existing or proposed noise wall. Laboratory-scale evaluations of the acoustical performance of overhang designs has been shown to be a benefit compared to a traditional wall of the same height [e.g., May and Osman, 1980a; Hajek and Blaney, 1984; Hothersall, et al., 1991; Watts, et al., 1994; Ishizuka and Fujiwara, 2004, Lodico, 2010; Diez, et al., 2012; Donovan, et al., 2018]. Deployment of noise wall overhang components in North America has been limited to two locations in Ontario [May and Osman, 1980b; Hajek and Blaney, 1984], the Ohio Turnpike [TranSystems, 2009], and Colorado [Lodico and Goldberg, 2010]. Given that the older overhang designs were constructed primarily using concrete materials, there were concerns about the cost, structural integrity, and motorist safety associated with such designs. With the emergence of new, relatively inexpensive, lighter-weight materials used by State DOTs to construct noise walls, the question of whether overhang designs can be deployed in a cost-effective manner should be re-examined. Additionally, while the air quality impacts of traditional noise walls have been examined in recent years [e.g., Bowker, et al., 2007; Baldauf, et al., 2008; Ning, et al., 2010; Baldauf, et al., 2016], the impacts of overhang designs on community air quality are not completely understood. Consequently, research is needed to determine if a roadway side overhang component would provide meaningful noise reduction and air quality benefits for ODOT noise walls in a manner that is cost-effective and meets all of ODOT's structural design requirements.

Research Approach

Researchers from the Ohio Research Institute for Transportation and the Environment (ORITE) at Ohio University, with assistance from ms consultants, inc., approached the research problem with three key activities, described as follows:

- Comprehensive review of existing literature and research studies related to noise wall overhang design options and the impacts of different designs on factors including (but not limited to) acoustical performance, air quality impacts, life cycle cost requirements, constructability, durability, maintenance, safety, and aesthetics;
- Acoustical testing of various noise wall overhang design options using a full-scale noise wall section to determine the overhang length and angle combination that provides the greatest noise reduction relative to a plain-top noise wall design; and

- Preliminary structural analysis of up to four noise wall overhang design options to assess the compatibility of different overhang design options with AASHTO and ODOT design loads for noise walls, considering both new construction and "retro-fit" of existing walls.

RESEARCH CONTEXT

Research Objectives and Tasks

The goal of this research project was to determine if the addition of a roadway side overhang component to ODOT's noise walls would provide noise reduction and air pollutant reduction to communities behind the wall in a cost-effective manner relative to current practices. To accomplish this goal, ODOT implemented this project using a two-phase approach: Phase 1, including a comprehensive review of overhang design options and identification of a suitable design; and Phase 2, to include construction and field testing of the recommended overhang design if justified based on the Phase 1 findings. To accomplish the scope of Phase 1, the ORITE research team completed the following specific objectives:

1) Complete an extensive and comprehensive literature review on noise wall overhang design options, including (but not limited to) acoustical performance, life cycle cost requirements, constructability, durability, maintenance, safety, and aesthetics;
2) Using a full-scale wall section, perform acoustical testing of a range of proposed noise wall overhang design configurations to identify the overhang length and angle combination that provides the greatest noise reduction relative to a plain-top design;
3) Perform preliminary structural analysis of up to four overhang design options to assess compatibility of designs with AASHTO and ODOT design loads for noise walls;
4) Review existing ODOT noise analysis and abatement practices to identify situations where a noise wall overhang component could provide a cost-reasonable benefit (considering both new noise wall construction and "retro-fit" of existing walls);
5) Develop a matrix comparing potential overhang design options with existing ODOT noise wall design and construction practices, accounting for acoustical performance, life cycle cost requirements, constructability, structural integrity, and other factors; and
6) Develop an Interim Report documenting all Phase 1 activities and findings to include recommended overhang design(s) and a recommendation on Phase 2 deployment/scope.

To accomplish the research objectives, the ORITE research team completed the following eight tasks over a duration of eight months:

- Task 1: Project Start-Up Meeting;
- Task 2: Literature Review;
- Task 3: Performance Assessment of Overhang Designs;
- Task 4: Comparison of Overhang Design Alternatives;
- Task 5: Phase 1 Interim Report;
- Task 6: Phase 1 Progress Meeting;
- Task 7: Phase 1 Final Report; and
- Task 8: Project Management.

Task 3 was divided in to two sub-tasks: Task 3.1: Acoustical Testing of Overhang Designs, and Task 3.2: Structural Analysis of Overhang Designs.

Literature Review

Broadly, a noise wall "overhang" modification can be characterized as an additional structural element or fixture attached along the top edge of a traditional or "plain-top" noise wall. The acoustical premise behind adding an overhang modification in this manner is that the modification will function to increase the length of the diffracted path that the sound signal travels between the source and receiver (relative to the traditional plain-top noise wall) therefore providing greater attenuation. Evaluations of the acoustical performance of overhang designs have been undertaken based on scale-model testing [e.g., May and Osman, 1980a; Hajek and Blaney, 1984; Donovan, et al., 2018], full-scale noise wall models [e.g., Watts, et al., 1994; Lodico, 2010; Diez, et al., 2012], and computer-based modeling [e.g., Hothersall, et al., 1991; Ishizuka and Fujiwara, 2004]. Deployment of noise wall overhangs in North America has been limited to two locations in Ontario [May and Osman, 1980b; Hajek and Blaney, 1984], the Ohio Turnpike [TranSystems, 2009], and Colorado [Lodico and Goldberg, 2010]. Noise wall overhang designs have also been examined by several State DOTs as part of a more comprehensive evaluation of innovative noise wall applications [e.g., Cohn, et al., 1993; Romick-Allen, et al., 1999; Watson, 2006]. Based on previous research on noise wall overhangs, the following conclusions or observations are noted:

- Acoustical Performance: As noted in Appendix A (Table 3), previous research has indicated that for every 1-foot of increase in overhang length toward the roadway, an additional 0.5 to 1.0 dBA of insertion loss can be achieved. Most testing is based on the "T" overhang shape with limited testing of the "Y" or "90 Degree" shape in literature. In-service experience from Ontario and the Ohio Turnpike found an increase of insertion loss of approximately 1.5 dBA for a "T" shape with a length toward the source between 15 and 36 inches used, while the application in Colorado had field-measured noise reduction that was similar to what was modeled without the overhang attachment.
- Constructability: Overhang designs may to achieve an equivalent noise reduction with a shorter height wall, thereby reducing the wind loading and decreasing the foundation requirements; however, these benefits may be offset by the costs of the additional weight of the overhang material and the cantilevered nature of the design. Reduced height may also be beneficial where utility conflicts exist.
- Maintenance: Overhang designs have the potential for drainage issues (ponding along the top) and the collection of debris along the top edge of the overhang. Absorptive material, if used, may have a reduced effectiveness over time due to damage from weather.
- Safety: Proposed overhang designs should meet all necessary crash-testing requirements.
- Aesthetics: By allowing for an equivalent noise reduction with a shorter height wall, noise wall overhang designs may be a benefit in locations where a taller wall is undesirable for roadway views or shadows onto properties behind the wall.
- Cost: Overhang components have been found to be generally more expensive than increasing the height of a traditional plain-top wall to achieve the same noise reduction.
- Air Quality: While there have been several major studies to evaluate the air quality impacts of noise walls [e.g., Bowker, et al., 2007; Baldauf, et al., 2008; Ning, et al, 2010; Baldauf, et al., 2016], no studies examining the effects of overhangs were identified.

Complete details of the literature review are presented in Appendix A of this report.

RESEARCH APPROACH

The research approach for this project consisted of three main elements: a detailed literature review of noise wall overhang design research studies; acoustical testing of noise wall overhang design options; and preliminary structural analysis of selected noise wall overhang design options. Findings of the literature review, summarized in the previous section, are presented in more detail in Appendix A of this report. More details on the acoustical testing and preliminary structural analysis tasks are presented in this section.

The purpose of the acoustical testing was to determine the potential noise reduction that could be achieved with different combinations of overhang length and angle toward the source (i.e., the roadway). The research team utilized an acoustical testing setup featuring a specially-constructed full-scale test wall built at the ORITE Accelerated Pavement Load Facility (APLF) located at the Ohio University Lancaster (OUL) campus. The test wall was 12 feet tall and 56 feet long and constructed as a wooden frame wall utilizing plywood attached to a stud frame similar to the construction of a wall on a typical residential home. The test wall was designed to reduce flanking noise around the ends and also with materials that had a sufficient unit weight to ensure that noise does not pass through the wall. Overhang lengths of 1 foot, 2 feet, and 4 feet and angles of Zero (i.e., traditional wall), 45 degrees, 90 degrees, and “T-top” configuration were tested. Figure 1 [a] shows a photo of the test wall with the four-foot “T” configuration attached.

The acoustical performance of the various overhang design configurations was evaluated using a fixed speaker located 15 feet from the base of the wall as the noise source and measurements of the sound levels at three receiver locations (5, 25, and 50 feet at a height of 5 feet above the ground) behind the test wall. Three source heights were used (0, 5, and 12 feet) to represent the different source heights used for traffic noise modeling. Each test consisted of the test tone being played through the speaker system and observation of the 5-minute A-weighted equivalent sound level (Leq dBA) at each SLM location. Three replications of the test measurement were completed for each combination of overhang configuration and source height tested. The final sound level for each test consisted of the average five-minute Leq from the three replications with adjustment for calibration drift per FHWA guidelines [FHWA, 2018]. A total of 288 unique observations of the five-minute Leq were obtained for 96 different configurations, including the “base case” configuration. Figure 1 [b] shows the acoustical testing being carried out and the location of the three microphone positions behind the test wall.

Additional details of the acoustical testing are presented in Appendix B.

For the preliminary structural analysis, the ORITE research team analyzed the noise wall overhang designs to determine if that proposed design can be retro-fitted onto existing noise walls. Four specific overhang designs were analyzed: extension of a plain-top noise wall (i.e., 0 degrees), inverted L-top (90 degrees), Y-top (45 degrees), and T-top (90 degrees) for three lengths toward the highway (1, 2, and 4 feet). It was assumed the noise wall overhang designs would need to meet the design loads and construction requirements included in ODOT’s Ground Mounted Noise Barrier Specifications (NBS-1-09). The research team prepared calculations to determine the additional bending moment induced on existing standard (NBS-1-09) concrete posts and foundations due to wind, snow/ice and self-weight of the proposed panels and bracket materials assuming a lightweight panel material between 3.5 and 6.1 pounds per square foot.

Additional details of the structural analysis are presented in Appendix C.

[a] Test Wall with Four-Foot “T” Overhang Configuration Installed (11/2/2018)

[b] Acoustical Testing (10/5/2018)

Figure 1: Images of Task 3.1 Acoustical Testing

RESEARCH FINDINGS AND CONCLUSIONS

The acoustic effectiveness of the different noise wall overhang design configurations was evaluated based on the insertion loss (IL) for each configuration relative to the "Base Condition" of the 12-foot tall plain-top wall. The average relative IL for different overhang configurations based on the acoustical testing performed in this study is presented in Table 1.

Table 1: Task 3.1 Acoustical Testing Results – Summary

	"Plain Top" Angle = 0°	"Y-Top" Angle = 45°	"Inverted L" Angle = 90°	"T-Top" Angle = "T"	Average
Length = 1 Foot	+6.4	+6.9	+9.2	+6.2	+7.2
Length = 2 Feet	+7.8	+8.4	+10.7	+8.1	+8.8
Average	+7.1	+7.6	+10.0	+7.2	+8.0
Note: Data shown as insertion loss (dBA) for each overhang design configuration relative to insertion loss measured for 12-foot height plain-top wall at a source height of zero feet.					

The results of the acoustical testing indicate that, on average, an additional insertion loss of 1.5 dBA can be realized for each additional 1-foot of overhang length toward the source. These results compare favorably with the results of other acoustical testing of noise wall overhang designs. The 90-degree or "Inverted L" overhang configuration provides an additional IL of 3.0 dBA in addition to the IL attributed to the length of the fixture. This increase in insertion loss is likely attributed to the "double diffraction" nature of the 90 degree overhang design, requiring sound waves to diffract two different times between the source and receiver. Consequently, it is concluded that the 90 degree overhang angle could provide approximately double the noise reduction benefits as compared to increasing the wall height in the vertical direction by the same length. The results also demonstrate that the T-shape is not as effective as the "Inverted L" shape. With respect to the Y-Top design, the results of the current study indicate that very little acoustical benefit can be gained from the use of an angled design when compared to increasing the wall by the same height in the vertical direction. This result can be attributed to the fact that noise passes over the top edge of the 45 degree overhang in the same manner as the "Zero Degree" or plain top configuration (i.e., single diffraction). The most promising noise wall overhang design from an acoustical perspective only is the two-foot 90-degree design, with an insertion loss of approximately 10.7 dBA relative to the 12-foot tall plain top noise wall. However, it is unlikely that this level of IL could be achieved on an in-service noise barrier due to the difference in the nature of the source (i.e., point source versus moving source). Nevertheless, the results suggest that ODOT could achieve a perceptible reduction in traffic noise (i.e., greater than 3.0 dBA additional reduction) with the deployment of a two-foot 90-degree overhang on an existing noise barrier.

The results of the preliminary structural analysis (see Table 9) indicate that the 'T-Top" design produces the lowest additional bending moment of the various design options evaluated, based on the assumptions as outlined in Appendix C. This is due to the weight of the panel material being evenly distributed on both sides of the wall. The highest additional bending moment was produced by the four-foot "Inverted L" or 90 degree design. However, for all the designs examined, the additional loading due to proposed overhangs on the existing noise wall concrete posts and foundations is a very small percentage of the total structural capacity of the existing posts and foundations. Nevertheless, because each noise wall design is unique, it cannot be implied that the all existing noise wall posts have adequate capacity to resist the additional loading due to the self-weight of the proposed overhang brackets and panels and any applied wind, snow/ice loading. Consequently, it is concluded that each site and each individual wall must be evaluated on a case-by-case basis to determine the structural adequacy of the existing concrete posts and foundations.

Based on the structural analysis findings, the research team developed a preliminary cost estimate to retrofit a two-foot long overhang on an existing noise wall 1,200 feet in length. The results of the cost analysis are presented in Table 10. The cost estimate assumes an ODOT-approved lightweight material is used for the overhang. Assuming a two-foot wide overhang length, the cost per square foot ranges from \$89.50 to \$117.50 depending on material used, with the 45-degree overhang being higher cost than the 90-degree option. For reference, it is assumed that a traditional concrete noise wall is approximately \$25 per square foot; even if this cost is doubled to \$50 per square foot to allow a more reasonable comparison with the cost estimates generated in this project, the overhang costs are still approximately double the costs to increase the height of the noise wall in the vertical direction. The cost analysis also assumes a retrofit case, which is assumed to be more expensive than new construction on a unit-cost basis.

A matrix comparing the various attributes of three different noise wall overhang design options (Y-Top, Inverted L, and T-Top) is presented in Table 2.

Table 2: Comparison Matrix of Various Noise Wall Overhang Design Options

	"Y-Top" Angle = 45°	**"Inverted L" Angle = 90°**	**"T-Top" Angle = "T"**
Acoustical Performance (Impact of Overhang Length)	Similar to Plain Top; ≈ 1.5 dBA of Add'l IL for each 1 Ft. Length		
Acoustical Performance (Impact of Overhang Angle)	Similar to Plain Top	≈ 3.0 dBA Additional IL	Similar to Plain Top
Structural Loading (Additional Bending Moment on Posts)	Double	Double	Half
Construction Costs	Double; \$110 per SF	Double; \$98 per SF	Not Estimated; Likely Double
Air Quality Benefits (Potential for Pollutant Reduction)	Unknown based on literature review; however, some pollutant reduction may be realized with overhang fixture.		
Constructability	Likely more complex than traditional wall as contractors do not have experience in overhang construction. Overhangs could reduce potential utility conflicts if any exist.		
Drainage/Debris Collection Concerns	None/Limited Issues Expected	Drainage or debris collection issues may occur unless panels are angled slightly.	
Aesthetics	Some views may be blocked.	Existing views from residential properties will be retained.	
Note: Assessment of the performance of various noise wall overhang design options as determined by the ORITE research team and presented relative to plain top wall of similar length.			

RECOMMENDATIONS AND IMPLEMENTATION PLAN

Recommendations

Based on the findings and conclusions of this research project, the ORITE research team presents the following recommendations related to noise wall overhang designs:

- Recommendation #1: ODOT should consider the use of the 90-degree overhang options (either the "Inverted L" or "T-Top" shape) for deployment on its traffic noise walls. Based on the evaluations and analyses conducted for this research, the two 90-degree design options are the most promising to provide a perceptible acoustical benefit for approximately the same cost that would be required to increase the height of a plain-top noise wall to achieve the same noise reduction. For example, a two-foot "Inverted L" shape and a four-foot extension of the plain-top noise wall have approximately similar costs and approximately similar noise reduction levels.
- Recommendation #2: ODOT should not consider the use of the "Y-Top" overhang shape. Considering all relevant performance-related factors, the cost of implementing the "Y-top" design does not appear to offer any substantial benefits when compared to either the 90-degree designs or simply increasing the height of the plain-top wall.
- Recommendation #3: ODOT should examine the 90-degree overhang options in more detail to determine which option may be best for its needs.
  This study has demonstrated that the "Inverted L" shape holds the most promise for providing additional noise reduction in a cost-effective manner without raising the height of the existing noise wall. However, the structural considerations for the "T-Top" option may outweigh the relative decrease in acoustical performance. It is also possible that the acoustical performance of the "T-Top" may be consistent with the "Inverted L" shape when an equal length of overhang is provided toward the source. More detailed acoustical modeling and in-service testing should be undertaken to validate the acoustical performance and constructability of these overhang designs on an in-service noise wall.

Implementation Plan

For this Phase 1 report, the ORITE research team presents a two-part plan for implementation. The first element is a general strategy for the deployment of noise wall overhang designs on existing or future ODOT traffic noise walls. The second element is an outline of expected work activities for Phase 2 of the research study.

Deployment of Noise Wall Overhangs on ODOT Noise Walls

The findings of Phase 1 of this research study indicate that the 90-degree "Inverted L" overhang shape has the greatest potential for deployment on existing ODOT noise walls. It is evident from the findings of this study that the greatest potential benefit of the noise wall overhang fixture is that it can be used to increase the insertion loss of a noise barrier without raising the height of the noise barrier. Barrier locations where the wall height cannot be increased due to utility conflicts, foundation issues, aesthetics, or community feedback are the ideal locations where an overhang could be of the greatest benefit. If ODOT wishes to utilize overhang fixtures on its noise walls, revisions should be made to the NBS-1-09 standard drawing to provide details of how the overhang will be attached to the posts used on the noise wall structure. ODOT OES, in conjunction with the Office of Structural Engineering, is responsible for implementing changes to NBS-1-09 for new barrier construction. Appendix C provides a brief outline of the different factors that should be considered for retrofitting overhang fixtures on an existing ODOT noise wall. This outline can be used by ODOT and its consultants to determine if an overhang is feasible as a retrofit option. As with all roadside structures, there are unforeseen risks associated with deployment. For example, no crash testing was conducted as part of this study. If a noise barrier with an overhang is located within the clear zone of the highway (i.e., near the edge of the pavement), a guardrail or concrete crash barrier should be installed to minimize the possibility of vehicular impact. The design of the impact protection should address the overhang component to ensure that the overhang component itself does not become a safety hazard. A rigorous multidisciplinary review and approval process for any changes to the NBS-1-09 should help mitigate potential risks.

Phase 2 Implementation

The ORITE research team recommends that ODOT pursue Phase 2 of this study. Per the RFP, Phase 2 includes design and construction of the recommended overhang design on an existing ODOT noise wall and testing of noise reduction and air pollutant (CO and PM 2.5 only) reduction before and after overhang construction. Per the RFP, responsibility for Phase 2 site selection rests with ODOT. The research team recommends that a site be selected with the noise barrier reasonably close to the edge of the pavement, which would provide the greatest consistency with the acoustical testing conducted in Phase 1. The Phase 2 site should be of sufficient length (at least 500 feet) in order to make a reasonable conclusion about the performance of the overhang. Finally, the site should have sufficient space on the residential side for measurement of traffic noise per FHWA [2018] guidelines as well as for air quality measurements. An ideal location would also have a nearby site where an equivalent “No Barrier” condition could be analyzed.

In terms of overhang implementation, the ORITE research team proposes two alternatives for Phase 2. The first option is to construct the overhang fixtures based on the preliminary designs provided in this study (see Appendix C) to include the lightweight material and support brackets attached to the posts. This option would require the use of a detailed design plan and installation by a specialty contractor. The costs would be similar to what is estimated in this study and the installation would be permanent and suitable for long-term use. The second option would be to utilize sturdy plywood (similar to what was used in the Phase 1 acoustical testing) to construct a temporary overhang by attaching the plywood sheeting directly to the top edge of the Phase 2 wall location. The plywood sheeting would be easier to work with for a temporary structure and could be installed by ODOT’s in-house forces. By using this option, it would be understood that the installation is temporary and only for the measurement of acoustical and air quality performance attributed to the geometry of the overhang. This option was suggested by Donovan, et al. [2018] as a next step for testing overhang designs in Arizona. The long-term performance of the overhang would not be able to be assessed using this option. However, if ODOT is contemplating a more widespread deployment of overhangs on its noise walls, the lower costs and easier implementation of this option may be more attractive to demonstrate the proof of concept on an in-service noise barrier.

BIBLIOGRAPHY

Baldauf, R.W., Thoma, E., Khlystov, A., Isakov, V., Bowker, G., Long, T. and R. Snow (2008). Impacts of Noise Barriers on Near-Road Air Quality. *Atmospheric Environment*, Vol. 42, pp. 7502-7507. https://doi.org/10.1016/j.atmosenv.2008.05.051.

Baldauf, R.W., Isakov, V., Deshmukh, P., Venkatram, A., Yang, B., and K.M. Zhang (2016). Influence of Solid Noise Barriers on Near-Road and On-Road Air Quality. *Atmospheric Environment*, Vol. 129, pp. 265-276. http://dx.doi.org/10.1016/j.atmosenv.2016.01.025.

Bowker, G.E., Baldauf, R., Isakov, V., Khlystov, A., and W. Peterson (2007). The Effects of Roadside Structures on the Transport and Dispersion of Ultrafine Particles from Highways. *Atmospheric Environment*, Vol. 41, pp. 8128-8139. https://doi.org/10.1016/j.atmosenv.2007.06.064

Cohn, L.F., Harris, R.A., Rolfer, R.L., Duncan, D.L., and R.L. Woosley (1993). Special Noise Barrier Applications. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1416, pp. 69-74.

Diez, I., Fernandez, P., and I. Aspuru (2012). Analysis of Efficiency and Usefulness of Top Devices in Sound Barriers. *Proceedings of Internoise 2012*, New York City, New York.

Donovan, P., Janello, C., Lodico, D., Shaffer, S., Voropayev, S., Fernando, H. and N. Ovenden (2018). *Materials, Properties, and Optimum Geometries of the Design of Noise Walls*. Report No. FHWA-AZ-18-699, Arizona Department of Transportation, February 2018.

Fleming, G.G., Knauer, H.S., Lee, C.S.Y, and S. Pederson (2000). *Noise Barrier Design Handbook*. U.S. DOT FHWA, August 2000. URL: https://www.fhwa.dot.gov/environment/noise/noise_barriers/design_construction/design/index.cfm.

Foreman, J.E.K. (1990). *Sound Analysis and Noise Control*. Van Nostrand Reinhold, New York.

Hajek, J.J. and C.T. Blaney (1984). Evaluation of T-Profile Highway Noise Barriers. *Transportation Research Record: Journal of the Transportation Research Board*, No. 983, pp. 8-17.

Hothersall, D.C., Crombie, D.H., and S.N. Chandler-Wilde (1991). The Performance of T-Profile and Associated Noise Barriers. *Applied Acoustics*, Vol. 32, pp. 269-287. https://doi.org/10.1016/0003-682X(91)90075-P.

Ishizuka, T. and K. Fujiwara (2004). Performance of Noise barriers with Various Edge Shapes and Acoustical Conditions. *Applied Acoustics*, Vol. 65, pp. 125-141. https://doi.org/10.1016/j.apacoust.2003.08.006.

Lidman, J.K. (1985). Effect of a Noise Wall on Snow Accumulation and Air Quality. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1033, pp. 79-88. http://onlinepubs.trb.org/Onlinepubs/trr/1985/1033/1033-012.pdf

Lodico, D. and H. Goldberg (2010). “Acoustical Performance of T-Top Barrier Design on CO 93” Presented at the TRB ADC 40 Summer Meeting, Denver, Colorado. http://www.adc40.org/presentations/summer2010/Lodico%20TRB10.pdf

May, D.N. and M.M. Osman (1980a). Highway Noise Barriers: New Shapes. *Journal of Sound and Vibration*, Vol. 71, No. 1, pp. 65-71. https://doi.org/10.1016/0022-460X(80)90410-1.

May, D.N. and M.M. Osman (1980b). The Performance of Sound Absorptive, Reflective, and T-Profile Noise Barrier in Toronto. *Journal of Sound and Vibration*, Vol. 71, No. 1, pp. 73-101. https://doi.org/10.1016/0022-460X(80)90409-5.

Ning, Z., Hudda, N., Daher, N., Kam, W., Herner, J., Kozawa, K., Mara, S., and C. Sioutas (2010). Impact of Roadside Noise barriers on Particle Size Distributions and Pollutants Concentrations near Freeways. *Atmospheric Environment*, Vol. 44, pp. 3118-3127. http://dx.doi.org/10.1016/j.atmosenv.2010.05.033.

Nokes, W.A. and P.E. Benson (1984). *Carbon Monoxide Concentrations Adjacent to Sound Barriers*. Report No. FHWA/CE/TL-84/04, California Department of Transportation.

ODOT Office of Environmental Services (OES) (2015). *ODOT Highway Traffic Noise Analysis Manual*. ODOT OES, April 2015. URL: http://www.dot.state.oh.us/Divisions/Planning/Environment/NEPA_policy_issues/NOISE/Pages/NoiseManual.aspx.

Romick-Allen, R.K., Morgan, S.M., Lin, C. and R. Pierce (1999). *Acoustics of Sound Transmission over Noise Barrier Walls*. Report No. ITRC FR 97-4, Illinois Transportation Research Center.

TranSystems (2009). *Noise Mitigation Study Pilot Program Summary Report*. Prepared for the Ohio Turnpike Commission, Contract No. 71-08-02, November 2009.

U.S. Federal Highway Administration (FHWA) (2017). *Summary of Noise Barriers Constructed by December 31, 2016*. URL: https://www.fhwa.dot.gov/environment/noise/noise_barriers/inventory/. Accessed February 20, 2018.

U.S. Federal Highway Administration (FHWA) (2018). *Noise Measurement Handbook*. Report No. FHWA-HEP-18-065, June 2018.

Watson, D. (2006). *Evaluation of Benefits and Opportunities for Innovative Noise Barrier Designs*. Final Report 572, Arizona Department of Transportation, November 2006.

Watts, G.R., Crombie, D.H., and D.C. Hothersall (1994). Acoustic Performance of New Designs of Traffic Noise Barriers: Full Scale Tests. *Journal of Sound and Vibration*, Vol. 177, No. 3, pp. 289-305. https://doi.org/10.1006/jsvi.1994.1435.

APPENDIX A: LITERATURE REVIEW

Overview of Noise Wall Overhang Designs

In accordance with the *Federal-Aid Highway Act of 1970* and associated regulations described in 23 CFR Part 772, the U.S. Federal Highway Administration (FHWA) is primarily responsible for the regulation of highway traffic noise in the U.S. While FHWA's role focuses on the establishment and enforcement of Federal highway traffic noise regulations, state highway agencies (SHAs) (i.e., State DOTs) maintain primarily responsibility for implementing these regulations on highway projects within their jurisdictions. SHAs play a significant role in mitigating the adverse impacts of traffic noise associated with highway construction projects. Within the framework of 23 CFR Part 772, SHAs are required to develop highway traffic noise policies and programs that reflect the interests and concerns of their respective states. SHA traffic noise policies must address parameters for the analysis and reporting of traffic noise impacts of their projects; if a project is expected to have adverse impacts, SHAs can use Federal-aid highway funds for noise mitigation activities. Ohio Department of Transportation (ODOT) policies for analysis and abatement of traffic noise impacts are described in the *ODOT Highway Traffic Noise Analysis Manual* [ODOT OES, 2015]. The most common approach used in Ohio for the abatement of highway traffic noise is a noise barrier wall, which blocks the path of traffic noise between roadway sources and adjacent communities. As of December 31, 2016, approximately 150 noise walls have been constructed along Ohio's roadways at an average cost of more than $2.8 million per project, accounting for more than 230 linear miles of wall structures with an average height between 12 and 16 feet [FHWA, 2017].

Broadly, a noise wall "overhang" modification can be characterized as an additional structural element or fixture attached along the top edge of a traditional or "plain-top" noise wall. The application of overhang modifications along the top edge of a noise wall can be traced to the foundational work of May and Osman [1980a], who analyzed various top edge designs in a scale-model environment. The acoustical premise behind adding an overhang modification in this manner is that the modification will function to increase the length of the diffracted path that the sound signal travels between the source and receiver (relative to the traditional plain-top noise wall) therefore providing greater attenuation. In terms of nomenclature, most applications of noise wall overhang designs are characterized by the shape that is assumed by the wall's cross-section after the modification is deployed. An overhang design in which the overhang is at a 90° angle with respect to the vertical wall face is known as a "T-Top" noise barrier while any overhang with an angle between 0° and 90° is termed a "Y-Top" noise barrier. It should be noted that the "T-Top" option implies that there is some portion of the overhang fixture extending over the top edge of the wall on both the source and receiver sides of the barrier. An overhang design with a 90° angle relative to the vertical wall face but with no component on the receiver side does not appear to have a common parlance in the literature. As noted by Fleming, et al. [2000], a wide variety of shapes have been proposed as top edge modifications to try and improve the acoustical performance of traffic noise walls. For the current research project, the research team was charged with identifying the ideal overhang design configuration (i.e., combination of length toward the roadway and angle toward the roadway) for potential deployment on existing or future ODOT traffic noise walls. Therefore, only "T-Top" and "Y-Top" style overhang designs were examined as part of the literature review task of this study.

As noted previously, the first significant research work on the topic of noise wall overhang designs is attributed to the seminal work of May and Osman [1980a]. The initial motivation behind this work was that increasing the height of a plain top noise wall was not cost-effective above a height of approximately 13 feet and as such, modifications along the top edge could provide additional noise reduction without a significant cost burden. This work occurred at a time when the field of traffic noise analysis and abatement research was experiencing significant growth and there was substantial interest in how to make traffic noise barriers more efficient in their acoustical performance through top edge modifications, using absorptive materials, or other innovations. Following the work of May and Osman [1980a], further research has been undertaken to evaluate the performance of noise wall overhang designs with specific interest in the acoustical capabilities of these designs. These studies, which are presented in more detail in the next section, have been based on a mix of laboratory testing, computer modeling, and limited in-service evaluation. In general, these studies have concluded that the T-Top or Y-Top designs offer at least some acoustical benefits relative to a traditional plain-top wall of the same height.

Given the potential for acoustical benefits to be achieved in a more efficient manner, several State DOTs, including Arizona [Watson, 2006], Illinois [Romick-Allen, et al., 1999], and Washington [Cohn, et al., 1993], have undertaken a more comprehensive evaluation of overhang designs beyond the potential for noise reduction. Watson [2006] developed an evaluation matrix for the Arizona DOT comparing 12 different innovative noise barrier designs on various performance aspects, including acoustics, economics, constructability, maintenance, and aesthetics. That comparison indicated that the T-Top design with absorptive material was the highest-ranked design out of the 12 examined, while the T-Top with no absorptive material was 5^{th} ranked and the Y-Top was tied for 8^{th} (see Figure 2 and Figure 3) Romick-Allen, et al. [1999] concluded that a T-Top design was worth considering for the Illinois DOT as an option for increasing the insertion loss of a noise barrier without introducing additional design or maintenance complications. Finally, Cohn, et al. [1993] evaluated five special noise barrier designs for the Washington DOT, concluding that the T-Top and Y-Top both offered significant advantages over other designs (see Figure 4). Pertaining to the overall performance of noise wall overhang designs, the following general conclusions were noted from these three studies:

- Constructability: Overhang designs introduce the possibility of being able to achieve an equivalent noise reduction with a shorter height wall, thereby reducing the wind loading and decreasing the structural foundation requirements; however, these benefits may be offset by the costs of the additional weight of the overhang material and the cantilevered nature of the design. Reduced height may also be beneficial where utility conflicts exist.
- Maintenance: Overhang designs have the potential for drainage issues (ponding along the top) and the collection of debris along the top edge of the overhang. Absorptive material, if used, may have a reduced effectiveness over time due to damage from weather.
- Safety: Proposed overhang designs should meet all necessary crash-testing requirements.
- Aesthetics: By allowing for an equivalent noise reduction with a shorter height wall, noise wall overhang designs may be a benefit in locations where a taller wall is undesirable for roadway views or shadows onto properties behind the wall.
- Cost: Considering all of the above factors, the general consensus from the research is that overhang designs will be more expensive than a traditional plain-top wall of a height necessary to achieve the same noise reduction and therefore are only economical in instances where an increase in the plain top wall height cannot be accommodated. However, these conclusions are based on the use of heavier materials for the overhang

component and have not yet accounted for the evolution of noise wall design practices that incorporate lightweight materials currently in use by many State DOTs.

	Acoustic Performance			Availability / Economic Considerations		Constructability Considerations		
Barrier Type	Added IL * (dBA)	Potential reduced height (Range)	Potential reduced height (Average)	Special or proprietary material?	Additional cost	Foundation requirements	Structural issues	Drainage issues
T-top barrier design	1 - 1.5	2 - 3	2.5	no	3	3	3	3
T-top design with absorptive material	2 - 3	4 - 6	5	no / yes	4	3	3	3
Y-top barrier design	0.5 - 1	1 - 2	1.5	no	4	3	3	4
Jagged-top barrier design	0 - 6	0 - 3	1.5	no	3	3	3	3
Cylindrical top treatment	2 - 3	3 - 4	3.5	yes	5	3	4	3
Mushroom-shaped top treatment	0.5 - 1	1 - 2	1.5	yes	4	3	4	3
Multiple-edge top treatments	1.9 - 4	3 - 5	4	no / yes	4	3	4	4
Active noise control top treatment	2 - 4	4 - 6	5	yes	5	3	3	3
Angled barrier design	0	0	0	no	4	5	5	4
Absorptive barrier material	1 - 3	2 - 5	3.5	yes	4	3	3	3
Transparent barrier material	0	0	0	no / yes	3	3	3	3
Woven metal barrier material	0	0	0	yes	5	4	3	3

Source: Watson [2006]

Figure 2: Arizona DOT Noise Barrier Design Evaluation Matrix (Part 1 of 2)

	Maintenance Consideration			Aesthetic Considerations					
Barrier Type	Added maintenance	Debris collection	Durability	General appearance	Elimination of shadows	Increased visibility / views	**Average Score ****	**Average Score Weighted for Potential Reduced Height ****	**Rank ****
T-top barrier design	3	4	3	2	2	2	**2.8**	3.5	5
T-top design with absorptive material	4	4	4	2	1	1	**2.9**	**2.6**	**1**
Y-top barrier design	4	5	3	3	2	2	3.3	5.4	8 (tie)
Jagged-top barrier design	3	3	3	4	3	3	3.1	5.1	7
Cylindrical top treatment	4	3	4	4	2	2	3.4	3.6	6
Mushroom-shaped top treatment	4	3	4	4	2	2	3.3	5.4	8 (tie)
Multiple-edge top treatments	4	5	3	3	2	2	3.4	3.4	4
Active noise control top treatment	5	4	5	3	1	1	3.3	**3.0**	**2**
Angled barrier design	3	4	3	2	2	2	3.4	9.7	11
Absorptive barrier material	4	3	4	3	2	2	3.1	**3.3**	**3**
Transparent barrier material	5	3	4	2	1	1	**2.8**	8.0	10
Woven metal barrier material	5	4	4	2	3	3	3.6	10.3	12

Source: Watson [2006]

Figure 3: Arizona DOT Noise Barrier Design Evaluation Matrix (Part 2 of 2)

TABLE 1 Design Matrix for Special Noise Barrier Applications

Barrier Type	T-Top	Y-Top	Slanted Top	Absorptive Single	Absorptive Parallel
Height	> 13'	> 13'	> 13'	All	> 10'
Approx. Increased I.L. (dB)	1.5-2.0	1.0-1.5	0.0-0.5	0.0-2.0	2.0-3.0
Approx. Increased Cost (%)	10%	10-20%	10%	25%	20%
ADVANTAGES					
Reduced Height	✓	✓		✓	✓
Reduced Windloads	✓	✓		✓	
Smaller Foundation Requirements	✓	✓		✓	
Aesthetic Appearance	✓		✓		
DISADVANTAGES					
Debris Accumulation	✓	✓			
Drainage Problems	✓	✓			
Increased Foundation Requirements			✓		
Questionable Durability of Material				✓	
Periodic Maintenance	✓	✓		✓	✓

Source: Cohn, et al. [1993]

Figure 4: Washington DOT Design Matrix for Special Noise Barrier Applications

Acoustical Modeling

As noted previously, there has been significant interest in the acoustical performance of various overhang and other top edge treatments for noise walls since the early 1980s. A majority of these studies have been based on scale-model environments, full-scale noise wall layouts, or computer models incorporating Boundary Element Modeling (BEM). This section discusses the literature associated with acoustical modeling of overhang designs. It should be noted that only research findings focusing on T-Top and/or Y-Top style overhang designs is presented here as these designs were the only designs considered in this research study.

May and Osman [1980a] examined a wide range of barrier shapes in a 1:16 scale-model environment, including T-Top, Y-Top, cylinder, arrow-profile, and Thnadner-profile designs with and without absorptive material added. With respect to the T-Top barrier, they found that a 1.33-foot length overhang could provide an additional 2.0 dB(A) of noise reduction compared to a plain-top wall with no overhang fixture. The additional noise reduction was found to be 2.5 dB(A) for a 2-foot length, 4.0 dB(A) for an 8-foot length, and 6.5 dB(A) for a 16-foot length. A Y-Top design that was angled at 76° toward the source was found to have an insertion loss of 3.5 dB(A) when compared to the plain-top wall. Hajek and Blaney [1984] utilized a 1:16 acoustical scale model to analyze the impacts of T-Top overhangs and found that the addition of a 3.28-foot wide T-Top resulted in an increased insertion loss of approximately 1.0 dB(A) over several receiver points behind a 16.4-foot tall plain top barrier. Increasing the T-Top width to 6.56 feet resulted in an increased insertion loss of approximately 2.0 dB(A), which was the same approximate increase that was achieved by increasing the height of the barrier in the vertical direction by the exact same length. Additional work by these authors related to in-service deployments of noise wall overhang components is discussed in the next section. More recently, Donovan, et al. [2018] utilized a 1:10 scale model and found that a 3.28-foot "T-Top" had an insertion loss of approximately 5.0 dB(A) compared to the insertion loss realized by increasing the plain-top noise wall by that same length. Donovan, et al. [2018] also appears to be the only study from the literature examining the acoustical performance of an "Inverted L" overhang (i.e., 90° toward the source only), finding that the relative insertion loss of this design was approximately 3.3 dB(A) compared to the plain-top wall design.

Watts, et al. [1994] deployed the first use of a full-scale testing layout to examine the acoustical performance of noise wall overhang designs. They found that the addition of a 3.28-foot "T-Top" configuration on a 6.5-foot tall test wall (65.6 feet in length) resulted in a 1.4 dB(A) noise reduction versus a wall of the same height with no overhang component. Lodico [2010] analyzed the addition of a 3.0-foot long "T-Top" on a 5.5-foot tall concrete wall test section (40 feet in length) and calculated an average insertion loss of 4.3 dB(A) with no absorptive material added to the test. Diez, et al. [2012] used a 13.1-foot tall test wall section (26.2 feet in length) and found that a 3.28-foot "T-Top" overhang addition resulted in a noise reduction of 2.7 dB(A).

The emergence of improved computer modeling capabilities for noise analysis (notably, the use of BEM), has resulted in computer modeling studies examining noise barrier performance, including overhang designs. An early example of computer-based modeling is the work of Hothersall, et al. [1991], who used numerical modeling to conclude that the insertion loss of T-profile barriers is relatively constant with respect to the length of the overhang component when controlling for the relative path-length difference resulting from the change in barrier geometry. They also concluded that the Y-profile barriers were not as efficient as the T-profile barriers, but both designs were enhanced with the addition of absorptive material. A more comprehensive computer model study by Ishizuka and Fukiwara [2004] examined several different innovative top edge shapes, including the T-Top and Y-Top designs. They found that a 3.28-foot T-Top design could achieve an insertion loss of 1.9 dB(A) while a Y-Top design of the same length achieved an insertion loss of 3.1 dB(A) relative to the plain-top wall.

Table 3 presents details of acoustical modeling studies of noise wall overhang designs discussed in this section.

Table 3: Acoustical Performance of Noise Wall Overhang Designs from Literature

Study Reference	Design	Height	Length	Angle	Average IL	Relative IL
May and Osman [1980a]	Plain Top	16.0′	N/A	N/A	14.8	N/A
May and Osman [1980a]	1.3′ “T”	16.0′	0.65′	90° “T”	17.0	2.2
May and Osman [1980a]	2.0′ “T”	16.0′	1.0′	90° “T”	17.4	2.6
May and Osman [1980a]	8.0′ “T”	16.0′	4.0′	90° “T”	19.0	4.2
May and Osman [1980a]	16.0′ “T”	16.0′	8.0′	90° “T”	21.2	6.4
May and Osman [1980a]	8.0′ “Y”	16.0′	4.13′	76°	18.3	3.5
Hajek and Blaney [1984]	Plain Top	16.4′	N/A	N/A	N/A	N/A
Hajek and Blaney [1984]	3.28′ “T”	16.4′	1.64′	90° “T”	N/A	≈ 1.0
Hajek and Blaney [1984]	6.56′ “T”	16.4′	3.28′	90° “T”	N/A	≈ 2.0
Watts, et al. [1994]	Plain Top	6.5′	N/A	N/A	64.8	N/A
Watts, et al. [1994]	3.28′ “T”	6.5′	1.64′	90° “T”	63.4	1.4
Ishizuka and Fujiwara [2004]	Plain Top	9.8′	N/A	N/A	15.2	N/A
Ishizuka and Fujiwara [2004]	3.28′ “T”	9.8′	1.64′	90° “T”	17.1	1.9
Ishizuka and Fujiwara [2004]	3.28′ “Y”	9.8′	2.32′	45°	18.3	3.1
Lodico [2010]	Plain Top	5.5′	N/A	N/A	N/A	N/A
Lodico [2010]	3.0′ “T”	5.5′	3.0′	90° “T”	N/A	4.3
Diez, et al. [2012]	Plain Top	13.1′	N/A	N/A	N/A	N/A
Diez, et al. [2012]	3.28′ “T”	13.1′	1.64′	90° “T”	N/A	2.7
Donovan, et al. [2018]	Plain Top	N/A	3.28′	N/A	≈ 18.0	N/A
Donovan, et al. [2018]	“T-Top”	N/A	1.64′	90° “T”	≈ 23.0	≈ 5.0
Donovan, et al. [2018]	“LU-Top”	N/A	3.28′	90°	≈ 21.3	≈ 3.3
Note: Length presented as length of overhang component toward the source. For “T” designs it is assumed that approximately one-half of the length is on the source side. Angle reported with respect to plain top wall.						

In-Service Experience

The research team identified four examples of in-service deployment of noise wall overhangs in North America: two in the Toronto, Ontario region; one in Colorado; and one in Ohio. The performance of these in-service deployments is described in technical publications, journal articles, or other material associated with each. Additionally, the ORITE research team reached out to individuals who had been involved or associated with the design, construction, and operation of these overhangs to obtain more detailed information about the in-service experience with respect to maintenance, safety, community viewpoints, and other factors.

The two earliest examples of noise wall overhangs on in-service noise barriers were constructed on freeways in the Toronto, Ontario region. The first was a 30-inch “T-Top” component added to a 500-foot long segment of noise barrier located on one side of Highway 401 in 1978 [May and Osman, 1980b]. The traditional barrier was 13.3 feet in height and approximately 12 feet from the edge of the shoulder on the 12-lane freeway. Sound level measurements taken behind the barrier showed that the T-Top resulted in an increased insertion loss of 1.0 to 1.5 dB(A) compared with the insertion loss of the same barrier prior to the T-Top fixture addition. The addition of absorptive material on the T-Top did not have a statistically-significant impact on insertion loss. It appears that this installation was temporary for the purposes of initial testing of the acoustical performance and feasibility of the overhang design option. The second noise wall overhang constructed in the Toronto region, as described by Hajek and Blaney [1984], was a "T-Top" fixture 3.28 feet in length attached to the top of a 13.1-foot tall noise barrier along Queen Elizabeth Way (QEW) in 1981. The original motivation for adding a T-Top fixture at this location was that the foundation of the traditional noise wall could not support additional height in the vertical direction (due to wind loading) yet additional noise reduction was desired. Additionally, a pedestrian overpass was present on this section preventing additional increases in wall height. The fixture was constructed using lightweight sound-absorptive concrete material. Field measurements of the insertion loss of the T-Top fixture indicated an additional noise reduction of 1.0 dB(A) attributed to the T-Top. Outreach to one of the authors of this paper supplied additional information about how the T-Top fixture had performed since the initial acoustical analysis. Specifically, it was revealed that the fixture was removed in approximately 2005 due to structural failure of the overhang panels after more than 20 years of service and that the panels were never really meant for the T-Top application. It was also noted that after the removal, the top of the wall had to be power washed to remove dirt and accumulated soot because the area underneath the T-Top was partly-screened from the rain and it looked different than the adjacent plain top wall.

There have been two deployments of noise wall overhang components on U.S. highways, both of which were "T-Top" overhangs. Both applications were constructed around 2009 and still in place as of this writing. The first was constructed on Colorado Route 93 in Golden, Colorado, consisting of a 3.0-foot "T" shape attached to the top of a 15-foot tall traditional wall structure. Noise measurements reported by Lodico [2010] indicated that the day-night average noise level was approximately 72 dB(A) prior to wall construction and 57 dB(A) after construction (insertion loss of 15 dB(A)). Although there was no opportunity to measure the noise with and without the overhang component, it was noted that the noise reduction was comparable to levels obtained from traffic noise modeling without the T-Top component considered. The proposed addition of absorptive material at the top of the overhang structure was expected to further reduce the noise behind the barrier to 55 dB(A). The ORITE research team contacted the Deputy Director of Public Works for the City of Golden who had been involved with the initial construction and subsequent management of the noise wall. It was revealed that the project cost was $550,000 total, including the main wall and the overhang structure as well as a smaller wall that did not have a T-Top. The absorptive material was never added since the post-construction noise measurements met all the noise reduction goals for the project. It was also reported that there were no issues with driver safety or maintenance of the overhang component. Finally, in terms of community viewpoints on the design, there was positive feedback initially from local residents on the noise wall construction but very little has been provided in recent years.

The second U.S.-based in-service deployment of a noise wall overhang component was on the Ohio Turnpike near Berea, Ohio as part of the Turnpike's noise impact mitigation measures pilot study. A more detailed description of the deployment and analysis is presented in the technical report of the pilot study project [TransSystems, 2009]. A "T-Top" component 27 ½ inches in length was added to the top of a new 8-foot tall traditional noise barrier wall, of which 12 inches would be on the side facing traffic and 15 ½ inches would be on the residential side. The construction sequence used for the new wall allowed for noise measurements to be obtained for pre-construction, post-construction without overhang, and post-construction with overhang scenarios. Post-construction measurement indicated that the overhang provided an additional noise reduction of 1.2 dB(A) compared to the traditional plain-top noise wall measurements. Using this information and a validated TNM model, it was concluded that the traditional plain-top wall would need to be approximately 10.25 feet tall, or 2.25 feet taller, to achieve that same noise reduction. It was also noted that the cost of the wall with the T-Top component was an average of $29 per square foot (higher than the typical cost of $25 per square foot); however, by building a shorter wall overall a cost savings of approximately $25 per linear foot was realized. The ORITE research team reached out to the Ohio Turnpike and Infrastructure Commission to obtain additional information about how this overhang deployment has performed over time; however, no response was received to multiple inquiries.

Air Quality Impacts

One topic that has received some interest in the literature on highway traffic noise barriers is the impact of barriers on air quality in the areas on or near the highway. Early studies included the work of Nokes and Benson [1984] and Lidman [1985], who found that air pollution levels are generally lower immediately downwind of a highway with a traffic noise barrier present. These studies also showed that a noise barrier has the effect of creating an airborne emissions plume in the region directly above the highway and that this plume is carried to downwind locations (i.e., an elevated "stack" effect is created). More recently, a study of the air quality impacts of traffic noise barriers on Interstate 440 in Raleigh, North Carolina, found that the concentrations of carbon dioxide (CO) and particulate matter (PM) were 15 to 50 percent lower behind the noise barrier versus a nearby location with no barrier present [Bowker, et al., 2007; Baldauf, et al., 2008]. Ning, et al. [2010] conducted a comprehensive study of the air quality impacts of roadside noise barriers on two freeway locations in Southern California (Interstate 5 and Interstate 710) and found similar results, with concentrations of CO, PM, and Nitrogen Dioxide (NO_2) being 45 to 50 percent lower at locations behind the noise barrier. However, they also found that the noise barriers can result in an increase of the concentration of pollutants at distances further from the roadway versus locations without the barrier. For example, they noted that at approximately 150 to 200 meters downwind from the barrier, the distribution of particle size and concentration was between 1.5 and 2.5 times that observed at the same distances with no barrier present. They also found that the pollutant concentrations reached the background levels at a distance of 250 to 400 meters behind the barrier, as compared to 150 to 200 meters in locations with no barrier. Baldauf, et al. [2016] conducted a study of the impacts of noise barriers on air quality along Interstate 17 in Phoenix, Arizona and found that the noise barrier reduced pollutant concentrations by 50 percent at a distance of 50 meters and 30 percent at a distance of 300 meters behind the noise barrier.

These more recent studies have validated earlier work with several important findings. First, because the noise barrier creates an elevated plume of pollutants above the roadway, the pollutant concentrations are generally lower in the areas immediately behind the barrier (50 percent reduction within approximately 50 meters of the wall). This area of pollutant deficiency, known as the recirculation zone, is thought to be approximately 3 to 20 times the barrier height in length. Second, because the elevated plume is carried over the recirculation zone, higher pollutant concentration levels are expected at locations further downwind from the freeway with the barrier present, thereby potentially expanding the area that could be impacted by freeway-related air pollution.

It should be noted that the research team could not find any literature related to the air quality impacts of noise wall overhang modifications. One potential indication of how overhangs may perform to impact pollutant reduction is the experience of the QEW overhang in Toronto having accumulated soot on the vertical face of the barrier immediately underneath the overhang component. The presence of this soot may be due in part to the overhang trapping some air pollutant particles that would have otherwise escaped over the barrier. Therefore, it is reasonable to assume that overhang components could provide some air quality benefits by trapping at least some pollutants in the area underneath the overhang on the roadway side.

APPENDIX B: ACOUSTICAL TESTING

Purpose and Objectives

Task 3 of the research project consisted of a comprehensive performance assessment of different overhang design. Task 3 was divided into two sub-tasks: Task 3.1, focusing on the acoustical performance of different overhang designs; and Task 3.2, focusing on the structural feasibility of different designs. In Task 3.1 of this project, the ORITE research team conducted acoustical testing of various overhang design configurations. The purpose of the Task 3.1 acoustical testing was to determine the potential noise reduction that could be achieved with different combinations of overhang length and angle toward the source (i.e., the roadway). This appendix describes the details of the Task 3.1 acoustical testing, including the specific methodology used, analysis results, and acoustical modeling.

Acoustical Testing Methodology

To accomplish the Task 3.1 objectives, the research team utilized an acoustical testing setup featuring a specially-constructed full-scale test wall built at the ORITE Accelerated Pavement Load Facility (APLF) located at the Ohio University Lancaster (OUL) campus. The wall was constructed in a large open area immediately south of the main APLF office building. The test wall was 12 feet tall and 56 feet long. The length of the test wall included 40 feet of straight wall section with 8 foot long "wings" turned at a 45 degree angle back toward the source to reduce flanking noise around the ends of the wall. Using this "base" configuration, different overhang designs (combination of length and angle toward the source) would be attached and acoustical testing performed. A detailed plan view of the complete Task 3.1 testing setup showing the location of the test wall relative to the APLF office building and other site features can be viewed in Figure 5. The open space where the wall was constructed was relatively level (verified using topographic survey), free of reflective surfaces, and had a ground cover consisting primarily of grass (please see Figure 6 for more details). The dimensions of the test wall used in the Task 3.1 acoustical testing are comparable to the dimensions used in other full-scale tests of noise wall overhang designs [Watts, et al., 1994; Lodico, 2010; Diez, et al., 2012].

The test wall was constructed as a wooden frame wall utilizing plywood attached to a stud frame similar to the construction of a wall on a typical residential home (please see Figure 7 for additional details). The test wall used two layers of ¾-inch thick plywood as the primary wall material. Each sheet of plywood used had an approximate weight of 65 pounds per sheet, thus allowing the wall to have an average material weight of approximately 4 pounds per square foot, the minimum unit weight necessary to ensure that noise does not pass through the wall material [Fleming, et al., 2000]. To ensure no leakage of sound through the main wall, gaps between the plywood sheets were covered with the frame material, filled with silicone caulk, or covered with acoustical fence material leftover from a previous project. The entire wall structure was supported by diagonal bracing attached to the rear of the wall structure and anchored firmly into the ground with a wooden stake. The overhang components of the Task 3.1 test wall were also built using the same plywood as the main wall structure and were attached to the top edge of the main wall structure using custom-fabricated wooden brackets. Construction of the Task 3.1 test wall took place over a two-week period in early September 2018. An orange snow fence was installed around the test wall structure to deter trespassing and mischief. Images showing the completed "base" test wall can be viewed in Figure 8, Figure 9, and Figure 10.

Figure 5: Plan View of Task 3.1 Acoustical Testing Setup

The acoustical performance of the various overhang design configurations was evaluated using a fixed speaker as the noise source and corresponding measurements of the sound levels at three receiver locations behind the test wall. The noise source consisted of an Eastern Acoustics Model FR122e speaker connected to a 1000 Watt Pioneer GM-A5702 amplifier powered by a Optima brand deep-cycle battery. A test tone consisting of a recording of a 1000 Hz calibration tone from a Larson-Davis Model CAL150 hand-held calibrator was played back through the speaker system using a TASCAM Model DR-40 digital audio player that was connected to the amplifier. The speaker was located in the middle of the wall set back at a distance of 15 feet from the main test wall structure on a line perpendicular to the wall. This setup was designed to mimic the source distance from a noise barrier constructed on the edge of the roadway pavement. Three source heights were used (0, 5, and 12 feet) to represent the different source heights used for traffic noise modeling. To ensure consistency in the placement of the speaker at the appropriate height during testing, a "tower" was constructed (please see Figure 11 for additional details). Sound level measurements were obtained using a microphone assembly consisting of a Larson-Davis Model 2560 microphone, a Larson-Davis Model PRM 828 pre-amplifier, and a Larson-Davis Model 812 sound level meter (SLM). The microphone assembly was attached to sturdy tripods at a height of 5 feet above the base of the test wall and positioned at 5, 25, and 50 feet behind the test wall along a line perpendicular to the wall. Images showing the setup of the microphone array behind the test wall can be viewed in Figure 12 and Figure 13.

Each test consisted of the test tone being played through the speaker system and observation of the 5-minute A-weighted equivalent sound level (Leq dBA) at each SLM location. The playback volume of the TASCAM audio player and all other settings were consistent throughout the entirety of the Task 3.1 acoustical testing work. Use of the 5-minute Leq for this application allowed for minor variations in background noise to have a minimal impact on the final results. Three replications of the test measurement were completed for each combination of overhang configuration and source height tested. The calibration level of each SLM was checked before and after each overhang configuration was tested (approximately once per hour, consistent with FHWA guidelines) using a Larson-Davis Model CAL150 hand-held acoustic calibrator. The final sound level for each test consisted of the average five-minute Leq from the three replications with adjustment for calibration drift per FHWA guidelines. The temperature and humidity for each test period were recorded and observations of cloud cover and wind speed were also recorded based on FHWA guidelines [FHWA, 2018].

Acoustical testing for Task 3.1 was carried out over several months during late summer and fall 2018. Testing occurred on days when there was no precipitation or heavy winds expected in the forecast. Overhang lengths of 1 foot, 2 feet, and 4 feet and angles of Zero (i.e., traditional wall), 45 degrees, 90 degrees, and "T-top" configuration were tested. The "T-Top" configuration consisted of half of the overhang length on the source side and the remaining half on the receiver side. Additional details of selected overhang configurations are presented in Figure 14, Figure 15, Figure 16, and Figure 17. The original testing plan had called for angles of 30 and 60 degrees to also be tested, but these angles were removed based on the initial testing results. Additionally, problems with the 4 foot overhang length were encountered requiring the research team to further reduce the number of tests. A total of 288 unique observations of the five-minute Leq were obtained for 96 different configurations, including the "base case" configuration. All Task 3.1 acoustical testing work, including tear down of the test wall and restoration of the affected ground cover, was completed prior to the OUL winter break closure.

Acoustical Testing Results

The acoustic effectiveness of the different noise wall overhang design configurations was evaluated based on the insertion loss (IL) for each configuration. Two separate measures of IL were calculated. First, the Baseline IL was calculated by subtracting the average Leq for each configuration (including the "Base Condition") from the "No Barrier" average Leq levels for each of the three source heights and distance behind the wall. Second, the "Relative IL" was calculated by subtracting the average Leq for each configuration from the "Base Condition" average Leq for each combination of source height and distance behind the wall. Table 4 presents a summary of the insertion loss measurements comparing the “No Barrier” condition with the “Base Condition” consisting of the 12-foot tall plain top wall with no overhang fixtures attached. As noted in Table 4, the insertion loss for Source Height = 0 Feet was approximately 20 dBA for all three measurement locations. This result indicates that the test wall was well-constructed and was effective at reducing the noise emanating from the source to the receiver locations. A more pronounced decrease in the insertion loss with increasing distance was observed for the 5-foot source height while minimal insertion loss was realized for the 12-foot source height at both the 25-foot and 50-foot receiver locations. Given the path length geometries associated with each source height, these results were expected.

Table 4: Task 3.1 Acoustical Testing Results – “Base Case” Insertion Loss

	Distance	Leq (No Barrier)	Leq (Base Condition)	IL (Base Condition)
Height = 0 Feet	5 Feet	86.7	64.8	21.9
	25 Feet	81.3	60.6	20.7
	50 Feet	77.3	57.6	19.7
Height = 5 Feet	5 Feet	91.4	60.1	31.3
	25 Feet	87.7	61.9	25.8
	50 Feet	77.7	59.8	17.9
Height = 12 Feet	5 Feet	81.9	70.8	11.1
	25 Feet	73.5	72.2	1.3
	50 Feet	73.5	71.7	1.8
Note: All values shown in units of dBA.				

Details of the Task 3.1 acoustical testing results are reported in Table 6 (Source Height = 0 Feet); Table 7 (Source Height = 5 Feet); and Table 8 (Source Height = 12 Feet). Each table presents the average 5-minute Leq and the Relative IL for each configuration and measurement position behind the wall. The “Base Condition” average 5-minute Leq is also shown in each table for reference. The results presented in these tables indicate that the Relative IL was the highest and more consistent for zero-foot source height as compared with the other two source heights. One issue encountered with the 12-foot source height was that there were minor variations in the top edge of the test wall with the overhang configuration attached relative to the exact location of the speaker positioned at the 12-foot height. As a result, some 12-foot height measurements actually realized in an increase in average Leq relative to the base condition (see Table 8). An increase in the average Leq was also noted among some overhang configurations in the 5-foot source height tests (see Table 7). The research team encountered some difficulty working with some of the four-foot overhang length configurations; as a result, some of these configurations were not tested.

The primary objective of Task 3.1 was to determine the implications for different noise wall overhang length and angle combinations in terms of acoustical performance. Table 5 presents the average Relative IL for two overhang lengths (1 foot and 2 foot) and four angles toward the source (Zero, 45, 90 and “T” shape) as well as the marginal averages based on the average Relative IL of all receiver distances for zero-foot source height measurements only. It should be noted that the results from the overhang length of four feet are omitted from Table 5 because not all angles were tested for this length.

Table 5: Task 3.1 Acoustical Testing Results – Summary

	"Plain Top" Angle = 0°	"Y-Top" Angle = 45°	"Inverted L" Angle = 90°	"T-Top" Angle = "T"	Average
Length = 1 Foot	+6.4	+6.9	+9.2	+6.2	+7.2
Length = 2 Feet	+7.8	+8.4	+10.7	+8.1	+8.8
Average	+7.1	+7.6	+10.0	+7.2	+8.0
Note: Data shown as insertion loss (dBA) for each overhang design configuration relative to insertion loss measured for 12-foot height traditional wall at a source height of zero feet.					

Based on the results presented in Table 5, the following conclusions are noted:

- Increasing the length of the overhang by one foot increased the average insertion loss by approximately 1.5 dBA across all angle configurations tested.
- The average insertion loss for the "Zero Degree" and 45 degree overhang configurations were approximately equal (0.5 dBA difference on average). This result can be attributed to the fact that noise passes over the top edge of the 45 degree overhang in the same manner as the "Zero Degree" or plain top configuration (i.e., single diffraction). Consequently, it is concluded that the 45 degree overhang offers limited acoustical benefits as compared to increasing the wall in the vertical direction by the same length.
- The average insertion loss for the 90 degree overhang configurations was approximately 3.0 dBA higher than the average insertion loss for the plain top configuration. This increase in insertion loss is likely attributed to the "double diffraction" nature of the 90 degree overhang design, requiring sound waves to diffract two different times between the source and receiver. This 3.0 dBA increase in IL is in addition to the 1.5 dBA increase in IL that is attributed to the length of the fixture. Consequently, it is concluded that the 90 degree overhang could provide a noise reduction of double the reduction provided by increasing the wall height in the vertical direction by the same length.
- The average insertion loss for the "T" overhang configuration was lower than the corresponding average insertion loss for the 90 degree configuration. This difference is attributed to the length of the "T" configuration being divided evenly between the source side of the wall and the receiver side of the wall. It should be noted that the two-foot "T" configuration had a similar, but slightly lower, average insertion loss as the one-foot 90 degree configuration. This was because each configuration had an equivalent amount of overhang length toward the source. A similar pattern was noted comparing the four-foot "T" (see Table 6) with the two-foot 90 degree configuration. Consequently, it is concluded that the 90 degree configuration is more efficient than the "T" configuration, even when accounting for similar lengths of overhang on the source side of the wall.
- Among the length and angle combinations reported in Table 5, the best performance was achieved by the two-foot 90-degree overhang with a relative insertion loss of approximately 10.7 dBA across all three receiver locations. The research team conducted additional testing of this configuration to validate this result. Specifically, the acoustical testing sequence was performed with a microphone was attached to the top edge of the wall with and without this configuration attached. The result of this test indicated that the noise passing over the top edge of the wall was reduced by 8.7 dBA with the overhang present, validating the potential noise reduction of this design.

Discussion of Results

The results of the Task 3.1 testing (as reported in Table 5) indicate that, on average, an additional insertion loss of 1.5 dBA can be realized for each 1-foot of overhang length toward the source. These results compare favorably with the results of other acoustical testing of noise wall overhang designs (as reported in Table 3), which indicate that every 1-foot increase in overhang length toward the source results in an increase of approximately 0.5 to 1.0 dBA. However, the results of previous studies are based primarily on the "T" shape with only one 90° non-T shape analysis located in the literature. The testing performed in this study found that the "Inverted L" shape provided an additional 3.0 dBA of noise reduction (due to double diffraction) in addition to the 1.5 dBA increase in IL that is attributed to the length of the fixture. The results of the Task 3.1 testing demonstrate that the T-shape is not as effective as the "Inverted L" shape, which is not consistent with the results of the other study where both shapes were tested [Donovan, et al., 2018], although it is unclear from that study if the length of the overhang fixture toward the source was the same under both scenarios. With respect to the Y-Top design, the results of the current study indicate that very little acoustical benefit can be gained from the use of an angled design when compared to increasing the wall by the same height in the vertical direction. This result is not consistent with the two examples presented in Table 3 which indicated a greater insertion loss for the Y-Top, although it should be noted that the examples from literature had a greater length of the "Y" shape toward the source and the second angled component toward the receiver side of the barrier.

The acoustical testing undertaken as part of this study is subject to some limitations which may affect how this overhang design could perform on an in-service highway traffic noise barrier. First, while the testing undertaken in Task 3.1 is consistent with similar testing for both the nature of the source and the length of the test wall [e.g., Watts, et al., 1994; Lodico, 2010; Diez, et al., 2012], it is possible that the IL could be higher with an infinitely-long wall (i.e., a standard traffic noise barrier). However, because the noise source for an in-service application is a moving source rather than a fixed or point source, it is more likely that the IL will be lower than what was measured in this project since barrier effectiveness tends to be lower for moving sources [e.g., Foreman, 1990]. Second, the results of this testing are also limited in that only one height was examined for the base condition wall (12 feet), although this height is a fairly common height for new noise barrier construction in Ohio. Finally, the results of the Task 3.1 testing are also limited in that the distance between the speaker source and the test wall (15 feet) was designed to replicate a traffic noise barrier built on the edge of the pavement. While it is estimated that approximately one-third of ODOT's noise barriers are at or near the edge of the pavement, it is unclear how the overhang designs might perform for noise barriers that are greater distances away from the roadway or those with a different path length difference geometry condition. Based on the results of the Task 3.1 acoustical testing, the most promising noise wall overhang design from an acoustical perspective only is the two-foot 90-degree design. The Task 3.1 testing found that this design had an insertion loss of approximately 10.7 dBA relative to the 12-foot tall plain top noise wall. However, given the caveats discussed above, it is unlikely that this level of IL could be achieved on an in-service noise barrier. Nevertheless, the results of the Task 3.1 testing suggest that ODOT could achieve a perceptible reduction in traffic noise (i.e., greater than 3.0 dBA additional reduction) with the deployment of a two-foot 90-degree overhang on an existing noise barrier.

Table 6: Task 3.1 Acoustical Testing Results, Source Height = 0 Feet

	Distance	"Plain Top" Angle = 0°	"Y-Top" Angle = 45°	"Inverted L" Angle = 90°	"T-Top" Angle = "T"	Average
Length = 0 Feet (Base Condition)	5 Feet	64.8	N/A	N/A	N/A	N/A
	25 Feet	60.6	N/A	N/A	N/A	N/A
	50 Feet	57.6	N/A	N/A	N/A	N/A
	Average	61.0	N/A	N/A	N/A	N/A
Length = 1 Foot	5 Feet	56.3 (+8.5)	50.1 (+14.7)	51.5 (+13.3)	57.1 (+7.7)	**53.8 (+11.1)**
	25 Feet	56.3 (+4.3)	57.8 (+2.8)	52.6 (+8)	58.2 (+2.4)	**56.2 (+4.4)**
	50 Feet	51.1 (+6.5)	54.5 (+3.1)	51.4 (+6.2)	49.0 (+8.6)	**51.5 (+6.1)**
	Average	54.6 (+6.4)	54.1 (+6.9)	51.8 (+9.2)	54.8 (+6.2)	**53.8 (+7.2)**
Length = 2 Feet	5 Feet	49.5 (+15.3)	51.6 (+13.2)	49.8 (+15.0)	53.9 (+10.9)	**51.2 (+13.6)**
	25 Feet	56.8 (+3.8)	53.6 (+7.0)	49.8 (+10.8)	53.4 (+7.2)	**53.4 (+7.2)**
	50 Feet	53.2 (+4.4)	52.7 (+4.9)	51.2 (+6.4)	51.5 (+6.1)	**52.2 (+5.5)**
	Average	53.2 (+7.8)	52.6 (+8.4)	50.3 (+10.7)	52.9 (+8.1)	**52.3 (+8.8)**
Length = 4 Feet	5 Feet	60.4 (+4.4)	N/A	56.0 (+8.8)	53.2 (+11.6)	**56.5 (+8.3)**
	25 Feet	63.3 (-2.7)	N/A	57.3 (+3.3)	51.7 (+8.9)	**57.4 (+3.2)**
	50 Feet	59.4 (-1.8)	N/A	50.4 (+7.2)	52.6 (+5.0)	**54.1 (+3.5)**
	Average	61.0 (0.0)	N/A	54.6 (+6.4)	52.5 (+8.5)	**56.0 (+5.0)**
Average (Excluding 4 Foot Overhang Length)	5 Feet	52.9 (+11.9)	50.9 (+14.0)	50.7 (+14.2)	55.5 (+9.3)	**52.5 (+12.3)**
	25 Feet	56.6 (+4.1)	55.7 (+4.9)	51.2 (+9.4)	55.8 (+4.8)	**54.8 (+5.8)**
	50 Feet	52.2 (+5.5)	53.6 (+4.0)	51.3 (+6.3)	50.3 (+7.4)	**51.8 (+5.8)**
	All	**53.9 (+7.1)**	**53.4 (+7.6)**	**51.1 (+10.0)**	**53.9 (+7.2)**	**53.0 (+8.0)**
Note: Data shown as average five-minute Leq and relative insertion loss for each configuration shown in parenthesis in units of dBA. N/A indicates configurations not tested or data not collected.						

Table 7: Task 3.1 Acoustical Testing Results, Source Height = 5 Feet

	Distance	**"Plain Top" Angle = 0°**	**"Y-Top" Angle = 45°**	**"Inverted L" Angle = 90°**	**"T-Top" Angle = "T"**	**Average**
Length = 0 Feet (Base Condition)	5 Feet	60.1	N/A	N/A	N/A	N/A
	25 Feet	61.9	N/A	N/A	N/A	N/A
	50 Feet	59.8	N/A	N/A	N/A	N/A
	Average	60.6	N/A	N/A	N/A	N/A
Length = 1 Foot	5 Feet	57.4 (+2.7)	65.3 (-5.2)	60.6 (-0.5)	55.4 (+4.7)	**59.7 (+0.4)**
	25 Feet	64.7 (-2.8)	59.4 (+2.5)	59.8 (+2.1)	64.5 (-2.6)	**62.1 (-0.2)**
	50 Feet	57.2 (+2.6)	57.3 (+2.5)	57.3 (+2.5)	59.8 (+0.0)	**57.9 (+1.9)**
	Average	59.8 (+0.8)	60.7 (-0.1)	59.2 (+1.4)	59.9 (+0.7)	**59.9 (+0.7)**
Length = 2 Feet	5 Feet	61.1 (-1.0)	59.1 (+1.0)	63.3 (-3.2)	53.8 (+6.3)	**59.3 (+0.8)**
	25 Feet	55.2 (+6.7)	64.8 (-2.9)	58.4 (+3.5)	59.9 (+2.0)	**59.6 (+2.3)**
	50 Feet	58.0 (+1.8)	64.8 (-5.0)	61.9 (-2.1)	54.7 (+5.1)	**59.9 (0.0)**
	Average	58.1 (+2.5)	62.9 (-2.3)	61.2 (-0.6)	56.1 (+4.5)	**59.6 (+1.0)**
Length = 4 Feet	5 Feet	N/A	N/A	N/A	58.5 (+1.6)	**58.5 (+1.6)**
	25 Feet	N/A	N/A	N/A	56.8 (+5.1)	**56.8 (+5.1)**
	50 Feet	N/A	N/A	N/A	54.4 (+5.4)	**54.4 (+5.4)**
	Average	N/A	N/A	N/A	56.6 (+4.0)	**56.6 (+4.0)**
Average (Excluding 4 Foot Overhang Length)	5 Feet	59.3 (+0.9)	62.2 (-2.1)	62.0 (-1.9)	54.6 (+5.5)	**59.5 (+0.6)**
	25 Feet	60.0 (+2.0)	62.1 (-0.2)	59.1 (+2.8)	62.2 (-0.3)	**60.8 (+1.1)**
	50 Feet	57.6 (+2.2)	61.1 (-1.3)	59.6 (+0.2)	57.3 (+2.6)	**58.9 (+0.9)**
	All	**58.9 (+1.7)**	**61.8 (-1.2)**	**60.2 (+0.4)**	**58.0 (+2.6)**	59.7 (+0.9)
Note: Data shown as average five-minute Leq and relative insertion loss for each configuration shown in parenthesis in units of dBA. N/A indicates configurations not tested or data not collected.						

Table 8: Task 3.1 Acoustical Testing Results, Source Height = 12 Feet

	Distance	**"Plain Top" Angle = 0°**	**"Y-Top" Angle = 45°**	**"Inverted L" Angle = 90°**	**"T-Top" Angle = "T"**	**Average**
Length = 0 Feet (Base Condition)	5 Feet	70.8	N/A	N/A	N/A	N/A
	25 Feet	72.2	N/A	N/A	N/A	N/A
	50 Feet	71.7	N/A	N/A	N/A	N/A
	Average	71.6	N/A	N/A	N/A	N/A
Length = 1 Foot	5 Feet	57.1 (+13.7)	67.3 (+3.5)	69.6 (+1.2)	68.4 (+2.4)	**65.6 (+5.2)**
	25 Feet	69.7 (+2.5)	68.6 (+3.6)	70.1 (+2.1)	73.3 (-1.1)	**70.4 (+1.8)**
	50 Feet	63.2 (+8.5)	69.4 (+2.3)	69.9 (+1.8)	69.9 (+1.8)	**68.1 (+3.6)**
	Average	63.3 (+8.2)	68.4 (+3.1)	69.9 (+1.7)	70.5 (+1.0)	**68 (+3.5)**
Length = 2 Feet	5 Feet	64.3 (+6.5)	67.4 (+3.4)	63.4 (+7.4)	70.8 (0.0)	**66.5 (+4.3)**
	25 Feet	60.8 (+11.4)	69.1 (+3.1)	68.1 (+4.1)	71 (+1.2)	**67.3 (+5.0)**
	50 Feet	59.1 (+12.6)	68.1 (+3.6)	68.1 (+3.6)	65.7 (+6.0)	**65.3 (+6.5)**
	Average	61.4 (+10.2)	68.2 (+3.4)	66.5 (+5.0)	69.2 (+2.4)	**66.3 (+5.2)**
Length = 4 Feet	5 Feet	N/A	N/A	N/A	64.6 (+6.2)	**64.6 (+6.2)**
	25 Feet	N/A	N/A	N/A	65.7 (+6.5)	**65.7 (+6.5)**
	50 Feet	N/A	N/A	N/A	58.8 (+12.9)	**58.8 (+12.9)**
	Average	N/A	N/A	N/A	63.0 (+8.5)	**63.0 (+8.5)**
Average (Excluding 4 Foot Overhang Length)	5 Feet	60.7 (+10.1)	67.4 (+3.5)	66.5 (+4.3)	69.6 (+1.2)	**66.0 (+4.8)**
	25 Feet	65.3 (+7.0)	68.9 (+3.4)	69.1 (+3.1)	72.2 (+0.1)	**68.8 (+3.4)**
	50 Feet	61.2 (+10.6)	68.8 (+3.0)	69.0 (+2.7)	67.8 (+3.9)	**66.7 (+5.0)**
	All	**62.4 (+9.2)**	**68.3 (+3.3)**	**68.2 (+3.4)**	**69.9 (+1.7)**	**67.2 (+4.4)**
Note: Data shown as average five-minute Leq and relative insertion loss for each configuration shown in parenthesis in units of dBA. N/A indicates configurations not tested or data not collected.						

Photos of Acoustical Testing

This section presents images obtained by the ORITE research team during the acoustical testing activities undertaken as part of Task 3.1 of the project.

- Figure 6: Location of Test Wall Location Prior to Construction
- Figure 7: Construction of Test Wall
- Figure 8: Completed Test Wall (Source Side Elevation View)
- Figure 9: Completed Test Wall (Receiver Side Elevation View)
- Figure 10: Completed Test Wall (Additional View)
- Figure 11: Setup of Acoustical Testing Noise Source
- Figure 12: Setup of Microphone Array Behind Test Wall (Image 1 of 2)
- Figure 13: Setup of Microphone Array Behind Test Wall (Image 1 of 2)
- Figure 14: Detail of Test Wall Overhang Configuration (Image 1 of 4)
- Figure 15: Detail of Test Wall Overhang Configuration (Image 2 of 4)
- Figure 16: Detail of Test Wall Overhang Configuration (Image 3 of 4)
- Figure 17: Detail of Test Wall Overhang Configuration (Image 4 of 4)

Description: Approximately 15 feet behind noise source location looking straight along line connecting source location with receiver array.
Photo Credit: Ben Sperry (8/29/2018)
Figure 6: Location of Test Wall Location Prior to Construction

Photo Credit: Ben Sperry (9/7/2018)
Figure 7: Construction of Test Wall

Photo Credit: Ben Sperry (9/7/2018)
Figure 8: Completed Test Wall (Source Side Elevation View)

Photo Credit: Blake Staley (9/7/2018)
Figure 9: Completed Test Wall (Receiver Side Elevation View)

Photo Credit: Blake Staley (9/7/2018)
Figure 10: Completed Test Wall (Additional View)

Description: “Tower” constructed for Task 3.1 acoustical testing to ensure consistency in the placement of the speaker at Zero, 5, and 12 feet above the ground.
Photo Credit: Ben Sperry (10/5/2018)
Figure 11: Setup of Acoustical Testing Noise Source

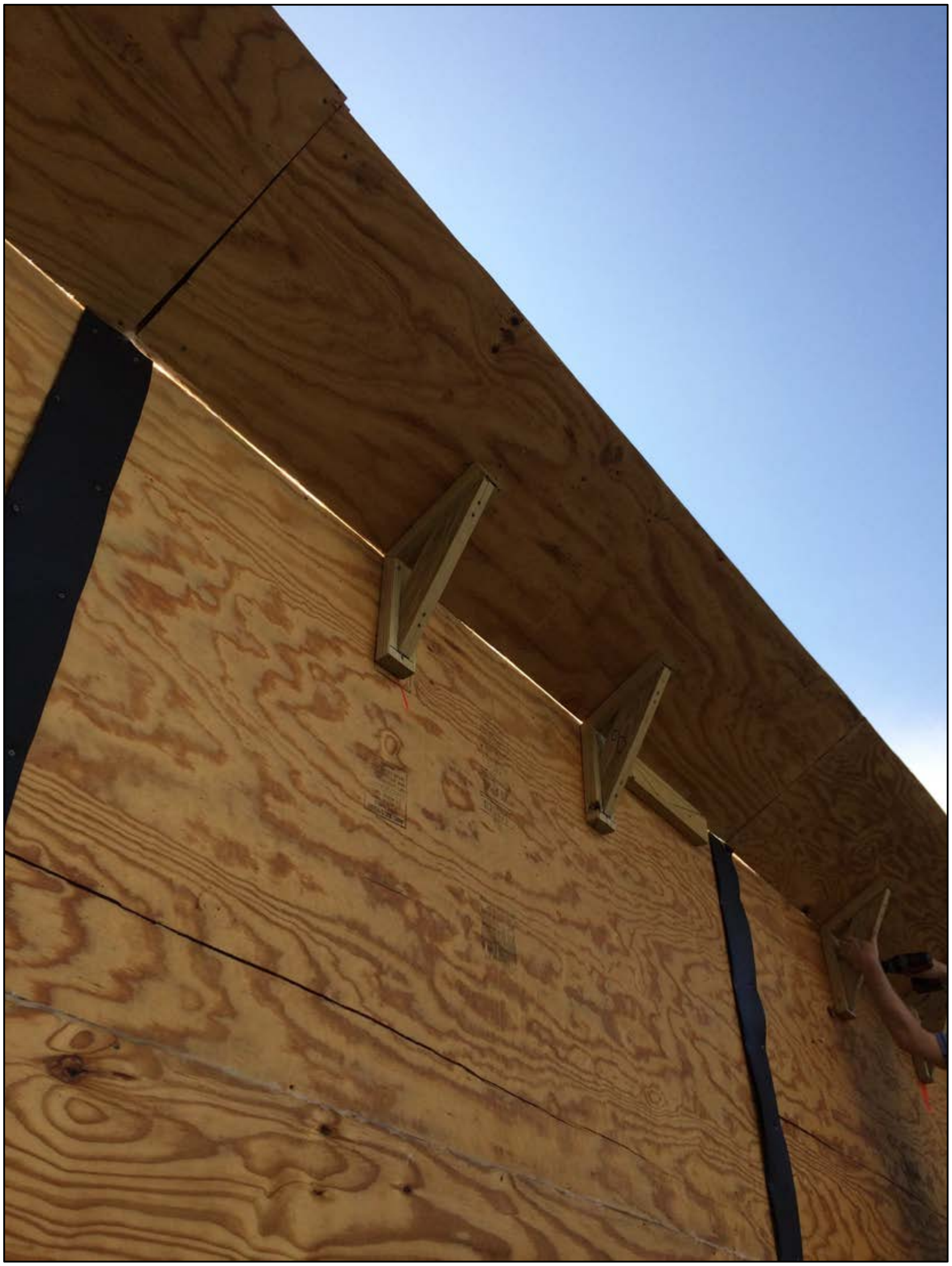
Photo Credit: Ben Sperry (10/5/2018)
Figure 12: Setup of Microphone Array behind Test Wall (Image 1 of 2)

Photo Credit: Ben Sperry (11/12/2018)

Figure 13: Setup of Microphone Array behind Test Wall (Image 2 of 2)

Description: Four-foot “T” configuration installed on test wall.
Photo Credit: Roger Green (11/2/2018)
Figure 14: Detail of Test Wall Overhang Configuration (Image 1 of 4)

Description: Two-foot 90-degree configuration installed on test wall.
Photo Credit: Ben Sperry (10/5/2018)
Figure 15: Detail of Test Wall Overhang Configuration (Image 2 of 4)



Description: Two-foot 45-degree configuration installed on test wall.
Photo Credit: Ben Sperry (10/5/2018)
Figure 16: Detail of Test Wall Overhang Configuration (Image 3 of 4)

Description: Four-foot 90-degree configuration installed on test wall.
Photo Credit: Ben Sperry (11/8/2018)
Figure 17: Detail of Test Wall Overhang Configuration (Image 4 of 4)

APPENDIX C: STRUCTURAL ANALYSIS AND COST ESTIMATE

In Task 3.2 of the research project, the ORITE research team analyzed the structural feasibility of adding an overhang fixture on an existing ODOT noise wall. Based on the Task 3.2 analysis, a cost estimate was developed for overhang installation assuming a lightweight noise wall material would be used for the overhang. For both the structural analysis and the cost estimate, it was assumed that the overhang would be “retrofitted” onto an existing ODOT noise wall, providing a conservative approach for both analyses. This work was undertaken by the research team subcontractor, ms consultants, inc. This appendix describes the activities and findings of the Task 3.2 structural analysis and associated cost estimate.

Structural Analysis

ms consultants, inc. structural engineers analyzed the noise wall overhang designs to confirm that proposed design can be retro-fitted onto existing noise walls. It was assumed the noise wall overhang designs would need to meet the design loads and construction requirements included in ODOT’s Ground Mounted Noise Barrier Specifications (NBS-1-09). ms prepared calculations to determine the additional bending moment induced on existing standard (NBS-1-09) concrete posts and foundations due to wind, snow/ice and self-weight of the proposed panels and bracket materials. Details of the post cross-sections are provided in Figure 18. Calculations were also performed to determine the approximate capacity of the ODOT Standard 16” and 20” thick concrete posts. Assumptions included:

- ODOT’s Standard Drawing NBS-1-09 (Noise Barrier Specifications for Ground Mounted Applications) was utilized as basis for structural analysis;
- The self-weight of lightweight panels was obtained from manufacturer data;
- Transparent Panel (Acrylite®) = 3.66 pounds per square foot to 6.1 pounds per square foot (depending on 15mm, 20mm or 25mm thickness);
- Fiberglas Panel (Carsonite®) = 3.5 to 4.0 pounds per square foot;
- A wind loading of 25 pounds per square foot (acting perpendicular to panel) was utilized for calculations. This loading is the recommended design loading per Table 1-2.1.2C of the AASHTO Guide *Specifications for Structural Design of Sound Barriers* as noted on ODOT NBS-1-09 drawing;
- A snow/ice loading of 20 pounds per square foot (acting downward) was utilized;
- Loads provided in table below are factored based upon Load Combinations shown in ASCE-7; and
- Tabulated loadings assume 24’ post spacing.

Based on these assumptions, loading calculations were prepared for four overhang alternatives, each having 1 foot, 2 foot and 4 foot overhangs:

- “Plain Top” vertical wall extension (0 degrees);
- “Y-Top” (45 degrees);
- “Inverted L” (90 degrees); and
- T-top (90 degrees).

The results of this analysis are presented in Table 9. The results indicate that the ‘T-Top” design produces the lowest additional bending moment of the various design options evaluated. This is due to the weight of the panel material being evenly distributed on both sides of the wall. The highest additional bending moment was produced by the four-foot “Inverted L” or 90 degree design. However, for all the designs examined, the additional loading due to proposed overhangs on the existing noise wall concrete posts and foundations is a very small percentage of the total structural capacity of the existing posts and foundations. Nevertheless, because each noise wall design is unique, it cannot be implied that the all existing noise wall posts have adequate capacity to resist the additional loading due to the self-weight of the proposed overhang brackets and panels and any applied wind, snow/ice loading. Consequently, it is concluded that each site and each individual wall must be evaluated on a case-by-case basis to determine the structural adequacy of the existing concrete posts, anchor rods, and foundations.

Table 9: Additional Bending Moment Applied to Top of Posts

Panel Length	"Plain Top" Angle = 0°	"Y-Top" Angle = 45°	"Inverted L" Angle = 90°	"T-Top" Angle = "T"
Length = 1 Foot	300	503	622	155
Length = 2 Feet	1,200	2,011	2,487	622
Length = 4 Feet	4,800	8,044	9,949	2,487
Note: Bending moment shown in units of torque (foot-pounds).				

One structural element not examined in the preliminary structural analysis was the anchor rods used to connect the concrete posts to the foundations. However, ODOT noted that it is common practice for the noise wall supplier to change the size of the post anchors from the standard drawings (NBS-1-09) to more efficiently build the walls (i.e., the anchors are optimized for wall height and length). It is possible, therefore, that existing anchors may have a lower capacity than what it shown in NBS-1-09 and therefore could make an overhang retrofit infeasible. As noted above, the capacity and adequacy of all structural components should be verified on a case-by-case basis prior to implementing a retrofitted overhang on an existing wall.

The following outline may be used as a guide to identify appropriate design parameters and constraints for the purpose of determining the structural adequacy of existing noise wall posts and foundations:

- Examine record (as-built) plans to determine:
  - Post spacing
  - Post size
  - If post caps or other constraints are present
- Perform structural calculations to determine the structural capacity of existing concrete noise wall posts.
- Perform structural calculations to determine the additional loading on existing posts due to the proposed overhang bracket and panels.
- Determine if existing posts have adequate "reserve" capacity for addition loading due to proposed bracket and panel.
- Examine record soil borings to determine foundation analysis parameters.
- Perform structural calculations to determine structural capacity of existing foundations.
- Determine if existing foundations have adequate capacity for additional loading due to proposed overhang bracket and panel.

Cost Analysis

ms consultants, inc. developed a preliminary cost estimate of multiple noise barrier overhang scenarios. For this task ms prepared a conceptual sketch of the inverted L-top (90 degrees) (see Figure 19) and obtained material and installation costs from light weight panel manufacturers and an experienced Ohio contractor. Assumptions included:

- Slotted holes will be required on one end of each panel to allow for thermal expansion of the overhang bracket independent of existing concrete posts and noise panels.
- It is assumed that steel brackets will be shop welded and panels will be attached to the brackets in the field and then the entire overhang assembly will be bolted to the existing concrete posts by a contractor.
- Assumes 24’ maximum post spacing.
- Pricing and total cost is based upon a 1,200 foot long section of existing noise wall that is readily accessible from the highway side of the wall.
- Cost estimate includes: dowel holes in existing concrete posts and epoxy adhesive bolts, steel frame, light-weight panels, shop welding, field bolting and other materials and labor required to furnish and install the overhang brackets with panels.
- Cost is based upon preliminary conceptual sketches.
- Any additional costs required for clearing of brush and trees is not included.
- Cost estimate assumes that all structural steel for bracket is to be galvanized.
- Cost includes minor costs for reseeding and mulching of ground adjacent to the wall.
- Cost estimate does not include maintenance of traffic (MOT); it is assumed that the existing wall is far enough away from any traveled pavement that MOT is not required.
- Sales tax on material is not included with the estimate.
- Cost of 15 mm thick light weight Acrylite® panels (uninstalled, cut to size and delivered) is $18/SF plus $14/LF for the F bracket + protective gasket (provided by Durisol).
- Cost of 3 inch thick light weight Carsonite® panels (uninstalled, made to size and delivered) is $17/LF for the (provided by Valmont).

Based upon ms’ analysis and conversations with the material manufacturers, either material will meet the design loads and construction requirements included in ODOT’s Ground Mounted Noise Barrier Specifications (NBS-1-09). The differences between the two materials are basically aesthetic. Given these assumptions, Table 10 presents the preliminary cost estimate for four different noise wall overhang designs. Estimated costs range from $179 per linear foot to $235 per linear foot depending upon the material type (Acrylite® or Carsonite®). Assuming a two-foot overhang length for all four cases, the cost per square foot ranges from $89.50 to $117.50 depending on material used, with the 45-degree overhang being higher cost than the 90-degree. These costs are approximately four times more expensive than the per square foot costs used by ODOT to analyze the reasonableness of a proposed noise wall ($25 to $30 per square foot). This higher cost is attributed to several factors, as follows:

- The lightweight materials used in the overhang are more expensive on a per square foot basis than concrete, which is used by ODOT for a vast majority of its new noise walls. As the research project was tasked with identifying overhang options using lightweight materials, no consideration was given to concrete options. It is likely that concrete would be less expensive but would require greater structural considerations which were not analyzed in this project. For reference, the two overhang projects in the U.S. utilized concrete material at a cost of $29 per square foot for the Ohio Turnpike location (length 1,200 feet) and $79 per square foot for the Colorado location (length 480 feet).

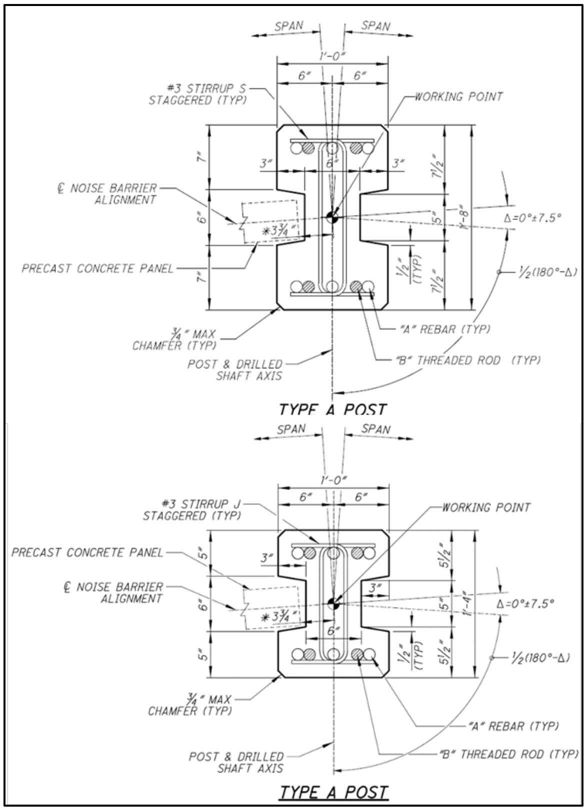
- For all four design options, the steel support elements are assumed to be galvanized for durability, which is more expensive than plain steel.
- The Acrylite® panels require additional support in the form of an F-channel and gasket element attached along the top edge of the vertical noise wall panel, resulting in increased material cost for this panel material type.
- The cost estimate in Table 10 assumes a retrofit of an overhang element onto an existing plain top noise wall. Construction of a new noise wall with an overhang element integrated into the design would most likely be less expensive.
- The cost estimate in Table 10 assumes complete custom fabrication of all necessary fixtures and structural support components. Greater adoption of the overhang design by ODOT will result in noise wall suppliers being able to gain greater efficiency in the fabrication of the necessary components with the unit costs decreasing over time.
- The cost estimate in Table 10 is developed for a sample wall of 1,200 foot length. The typical ODOT noise wall is approximately 7 times that length. As the material quantities increase as the length of the wall increases, the unit costs for various components (in particular, the steel) will decrease.

For the purposes of this research, it is difficult to quantify the effects of the various factors noted above on the cost estimate presented in Table 10. However, given the above factors, the cost estimate presented in Table 10 likely reflects a conservative or "worst-case" estimate of the costs associated with the construction of the overhang fixture.

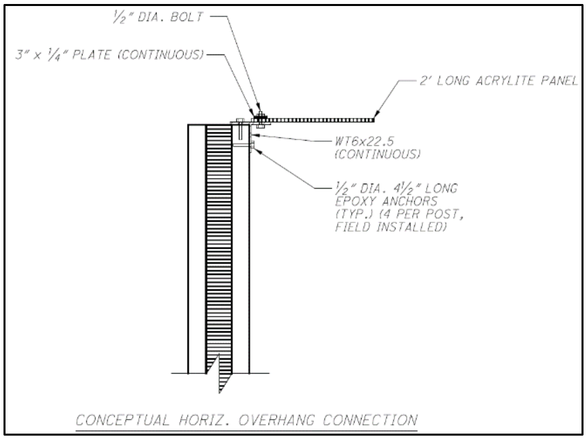
Table 10: Preliminary Cost Estimate for Noise Wall Overhang Designs

	2 Foot Wide Horizontal Overhang Acrylite® (L-Top 90 degrees)	**2 Foot Wide Inclined Overhang Acrylite® (Y-Top 45 degrees)**	**2 Foot Wide Horizontal Overhang Carsonite® (L-Top 90 degrees)**	**2 Foot Side Inclined Overhang Carsonite® (Y-Top 45 degrees)**
Material Cost (excluding panels):	$108,000	$120,000	$108,000	$120,000
Material Cost (Panels):	$60,200	$60,200	$20,400	$20,400
Installation Cost:	$86,400	$102,000	$86,400	$102,000
Total Cost (1,200' Long wall):	$254,600	$282,200	$214,800	$242,400
Cost per LF of Wall:	$212/LF	$235/LF	$179/LF	$202/LF

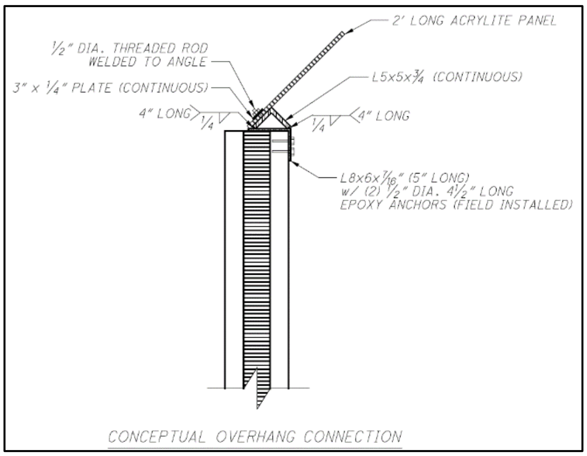
Appendix C Images



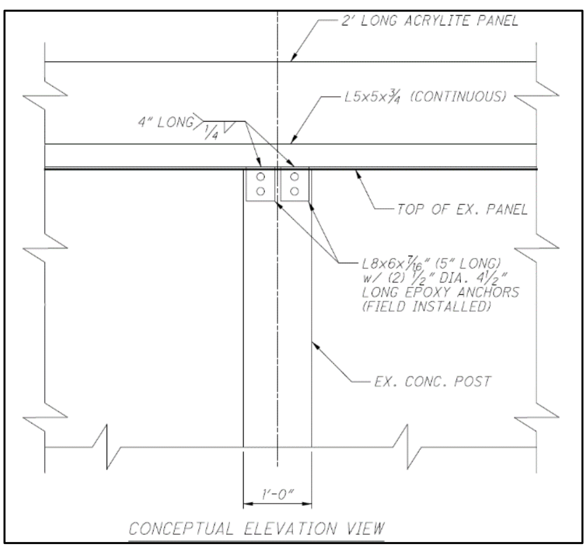
Source: ODOT Ground-Mounted Noise Barrier Specifications (NBS-1-09)
Figure 18: Type A Post Cross-Sections



[a] Conceptual Horizontal Overhang Connection



[b] Conceptual Overhang Connection



[c] Conceptual Elevation View

Source: ms consultants, inc.

Figure 19: Conceptual Drawings of Noise Wall Overhang Design