



INVESTIGATION INTO EFFECTIVE TRAFFIC NOISE ABATEMENT DESIGN SOLUTIONS FOR MOUNTAIN CORRIDORS

Felsburg Holt & Ullevig
Dale Tischmak

July 2013

COLORADO DEPARTMENT OF TRANSPORTATION
DTD APPLIED RESEARCH AND INNOVATION BRANCH

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Technical Report Documentation Page

1. Report No. CDOT-2013-11		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle INVESTIGATION INTO EFFECTIVE TRAFFIC NOISE ABATEMENT DESIGN SOLUTIONS FOR MOUNTAIN CORRIDORS				5. Report Date July 2013	
				6. Performing Organization Code	
7. Author(s) Dale Tischmak				8. Performing Organization Report No. CDOT-2013-11	
9. Performing Organization Name and Address Felsburg, Holt and Ullevig 6300 S. Syracuse Way, Suite 600 Centennial, CO 80111				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No. 34.28	
12. Sponsoring Agency Name and Address Colorado Department of Transportation - Research 4201 E. Arkansas Ave. Denver, CO 80222				13. Type of Report and Period Covered	
				14. Sponsoring Agency Code	
15. Supplementary Notes Prepared in cooperation with the US Department of Transportation, Federal Highway Administration					
16. Abstract Traffic noise abatement in mountain corridors can be difficult because traditional roadside barriers may be ineffective due to topography or may not fit the setting. This study examined current best practices from around the world to gather concepts for mitigating traffic noise in mountain corridors in Colorado. A literature review of prospective noise abatement actions found that noise barriers are the most effective direct noise abatement measure, although quieter pavements could have an important supporting role. The literature review was followed by computerized traffic noise modeling of promising candidate barrier concepts. Several noise barriers were evaluated through modeling at two areas along the I-70 corridor using the Nord2000 Road prediction method. Each of the barriers was found to be effective in some or many situations; the largest, most imposing barrier (galleries) showed the most potential for reducing traffic noise at locations above the elevation of the highway. Continued use of noise barriers as a primary abatement mechanism was recommended. Consideration of quieter default pavement types was recommended to lower general traffic noise levels in support of environmental stewardship goals. Implementation Several implementation steps were suggested as potential future implementation steps. Update CDOT's noise technical guidance to include these findings. Build off previous CDOT efforts with context-sensitive solutions by beginning to define what it will mean in terms of noise abatement. Additional analysis tools may be needed beyond TNM. Noise barrier concepts and materials that are new to CDOT may need to be implemented for future projects. Build off previous CDOT research to investigate potential benefits from quieter standard pavement types. CDOT should continue to monitor new developments for improved noise abatement solutions.					
17. Keywords I-70 mountain corridor, traffic noise mitigation, noise barriers, noise walls, earth berms, context sensitive noise abatement, Traffic Noise Model (TNM), Nord2000 Road			18. Distribution Statement This document is available on CDOT's Research Report website http://www.coloradodot.info/programs/research/pdfs		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 118	
				22. Price	

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Report No. CDOT-2013-11

Dale Tischmak, Senior Environmental Scientist

Felsburg Holt & Ullevig

6300 S. Syracuse Way, Suite 600

Centennial, CO 80111

Sponsored by the

Colorado Department of Transportation

July 2013

Colorado Department of Transportation

Division of Transportation Development

Applied Research and Innovation Branch

4201 E. Arkansas Avenue

Denver, CO 80222

ACKNOWLEDGEMENTS

The project team would like to acknowledge the insight and assistance provided by the project technical panel, including study manager Bryan Roeder, CDOT Applied Research and Innovation Branch; Jill Schlaefter, CDOT Environmental Programs Branch; Richard Griffin, CDOT Applied Research and Innovation Branch; Chuck Attardo, CDOT Region 1 Environmental; Jordan Rudel, CDOT Region 1 Environmental; Bob Mero, CDOT Region 1 Materials; and Stephanie Gibson, FHWA.

The author would also like to recognize the modeling and other technical support provided by Hans Forschner of Navcon Engineering Network.

EXECUTIVE SUMMARY

The primary objective of this study was to identify the most effective traffic noise abatement option(s) for high-volume traffic corridors in mountain settings to support the Colorado Department of Transportation's (CDOT's) environmental stewardship efforts. The scope of the project was to assist CDOT with the review and evaluation of prospective traffic noise abatement actions for mountainous corridors where the traditional abatement actions (e.g., traditional roadside barriers) may be ineffective, due largely to topography. The project consisted of a literature review of relevant noise abatement actions reported from anywhere in the world, followed by computerized noise modeling of promising candidate abatement actions.

The findings of the literature review reiterated the three basic abatement approaches for traffic noise: reductions at the sound source; reduction measures in the sound propagation path; or, reductions at the receptor. The effectiveness of these approaches is, in order: affect the source; affect the propagation path; and, affect the environment at the receptor.

The general finding from the literature review was that the propagation path, or noise barrier, approach was the most effective of the three approaches and would be the focus of the noise modeling and abatement evaluation. The computerized noise modeling looked at six noise wall concepts in two representative locations along the I-70 corridor. Traffic noise modeling used both the TNM and Nord2000 Road calculation methods. Most of the results for this study were from Nord2000 Road calculations for several reasons, including the method for handling complex terrain data, the method of handling of vertical distances in calculations and the capability to model weather conditions other than neutral.

Each of the wall concepts was found to provide substantial noise reductions, although the benefits uphill/above the highway often were limited. Galleries and vertical walls with central median walls were found to provide greater noise reductions for larger areas, including for uphill areas. These walls would be among the largest, costliest and most visually intrusive of the walls analyzed; however, these may be the only effective abatement options in difficult cases. The other wall types examined also provided substantial traffic noise reductions—the size of the areas benefitting from each concept tended to be similar, but the amount of noise reduction close behind these walls varied.

The main conclusion was that noise barriers, such as walls and berms, were the best currently available option for mitigating traffic noise in the mountain corridors, and so barriers are recommended as primary tools in reducing traffic noise levels. Different barrier shapes and/or different barrier materials may perform better in specific situations and each situation could be different enough that a detailed local analysis will be needed. Quieter pavement types cannot be used as a traffic noise abatement action because of Federal Highway Administration policy, but could be chosen to minimize general traffic noise.

Implementation

Through the activities in this project, CDOT has data available on the relative effectiveness of various noise abatement methods and several specific noise wall concepts in mountainous settings. Barrier concepts that would be new for CDOT (e.g., galleries or T-tops) showed promise in reducing traffic noise in some difficult noise abatement situations. To implement these results, CDOT has several choices available:

- ▶ The project findings can be implemented through an appropriate revision in the CDOT Noise Analysis and Abatement Guidelines.
- ▶ Interest in developing context-sensitive traffic noise solutions can build on existing CDOT context-sensitivity resources. Noise abatement should be included in context-sensitive planning, but what this may mean on the ground is not well defined. There can be contentious social and technical issues involved, such as visual intrusions, physical separation of communities or impacts to wildlife; starting a conversation among the stakeholders may be a valuable implementation approach.
- ▶ Each site in the mountain corridors will be unique and will need a detailed noise analysis. TNM Version 2.5 may not be able to address all of the modeling needs, so supplemental analysis tools should be implemented as needed.
- ▶ CDOT can consider the implementation of different wall concepts and materials that may be needed to overcome noise abatement difficulties in the mountain corridors where pre-cast concrete panels may not be the ideal barrier choice.
- ▶ CDOT can implement a mechanism to capitalize on the knowledge about their quieter pavements gained from previous CDOT research studies to lower general traffic noise.

- ▶ CDOT should continue to monitor and explore new developments in best noise abatement practices.

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ABBREVIATIONS, ACRONYMS AND DEFINITIONS

CDOT	Colorado Department of Transportation
dB	decibel
Feasible barrier	Criteria defined by Colorado Department of Transportation are: barrier provides at least 5 decibels of noise reduction; causes no fatal flaw physical issues; and, not more than 20 feet tall
FHWA	Federal Highway Administration
I-70	Interstate 70
mm	millimeters
MPH	miles per hour
NAC	Noise Abatement Criteria of Colorado Department of Transportation
NEPA	National Environmental Policy Act
Nord2000	Nord2000 Road noise level prediction method
PEIS	Programmatic Environmental Impact Statement for Interstate 70
Reasonable barrier	Criteria defined by Colorado Department of Transportation are: barrier provides at least 7 decibels of noise reduction; cost/benefit index value is not more than \$6,800/receptor/decibel; and, at least 50 percent of benefitting receptors support the barrier
TNM	Traffic Noise Model of the Federal Highway Administration
US	U.S. Highway

1. INTRODUCTION

For more than 60 years, major transportation corridors have crossed the mountain regions of Colorado to facilitate personal travel, inter-regional and interstate freight, transit, and commercial use. As population and travel demands have grown over time, expansion of the mountain highways has led to the encroachment of transportation conditions typical of urban areas into historically rural and natural settings by adding traffic and noise. The urban road conditions have led to both near-road traffic noise impacts and elevated background noise levels (i.e., “nuisance noise”). Many mountain destinations are tourist or recreation attractions with an expectation by the visitors of relative quiet, so high traffic noise levels are detractions.

The Interstate 70 (I-70) corridor between Denver and Grand Junction is an example of this, with rugged terrain and small valley communities situated next to a high-volume, high-speed highway. Other mountain corridors with similar noise issues include US Highway (US) 285, US 50 and US 160.

When I-70 was constructed, it encroached on many small communities as the highway often was built near homes. The population growth in mountain communities in narrow canyons with limited buildable ground has also put homes near the highway. The I-70 Mountain Corridor Programmatic Environmental Impact Statement (PEIS) identified segments of the I-70 corridor in need of safety and capacity improvements and general areas with traffic noise concerns [1]. In some places, the PEIS found traffic noise levels in excess of the Colorado Noise Abatement Criteria (NAC) threshold [2]. Lower levels of audible traffic noise can contribute to the perception of impacts by residents, even when noise levels are below the NAC and at greater distances from the highway [1]. This has affected the quality of life for some residents, which can lead to tension over I-70 operations and improvements. Travel demand along I-70 is expected to increase into the future, which could worsen the situation.

1.1 Project Scope

The traffic noise concerns described above have led to this research project. The research was intended to examine the current best practices worldwide for noise abatement of high-volume traffic areas in difficult terrain (i.e., mountains) within sensitive noise environments such that CDOT may be able to utilize the findings effectively in future projects.

The scope of the project was to assist CDOT with the review and evaluation of prospective traffic noise abatement actions for mountainous corridors where the traditional abatement actions (e.g., roadside barriers) may be ineffective, due largely to topography. The scope consisted primarily of a literature review of relevant noise abatement actions reported from anywhere in the world, followed by computerized noise modeling of the most promising candidate abatement actions in a Colorado setting. The results were reviewed and recommendations made accordingly.

1.2 Project Objectives

The main objective of the study was to identify the most effective traffic noise abatement option(s) for the high-volume traffic corridors in difficult terrain settings to support CDOT's environmental stewardship efforts. Effectiveness was based on several parameters, including cost, durability, maintenance, constructability and noise reduction. These results may be combined with other traffic noise solution data collected by CDOT through other projects to develop more comprehensive and effective traffic noise reduction approaches.

To accomplish this objective, the research project was divided into two main components. The first was a review of recent published information on traffic noise abatement measures employed by transportation agencies worldwide, primarily focusing on measures in mountainous areas. The second was to evaluate the effectiveness of prospective abatement measures through computerized noise modeling.

2. LITERATURE REVIEW

A literature review was conducted of published and online resources for relevant and effective traffic noise reduction methods. This included methods commonly used today as well as emerging new concepts. The search centered on publications from transportation agencies and noise-control organizations as well as published research findings. Information from around the world was reviewed, but was limited to publications in English. The search targeted noise abatement actions that would be most relevant to mountainous terrain.

Reduction of transportation noise has been a topic of interest worldwide for many years. A sizeable body of work has been generated and it is an active area of ongoing research for better solutions. Some of the work on traffic noise abatement has been developed within the U.S. European nations have been prolific in implementing a broad range of traffic noise reduction actions currently and were valuable sources of information. For example, some European nations have hard noise level ceilings that must be met, are relatively restrictive and provide impetus for implementing multi-pronged traffic noise reduction actions. So generally, European transportation or environment agencies were rich sources for current best practices. Findings from the review are presented below.

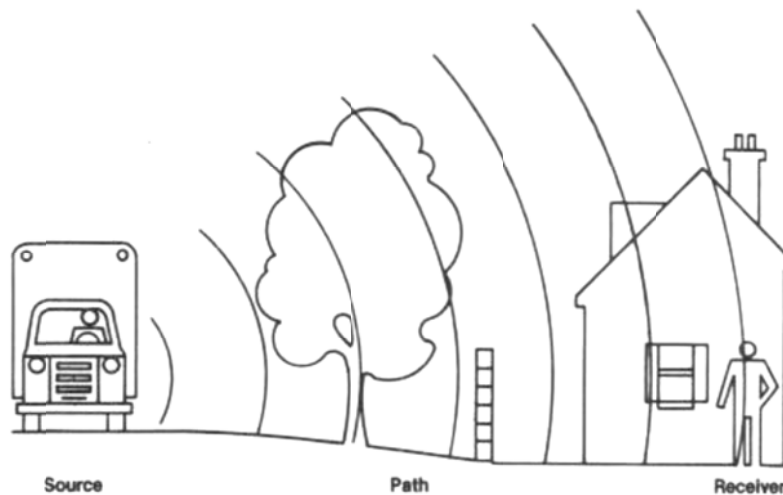
2.1 Traffic Noise Reduction Approaches

There are three basic approaches for reducing traffic noise: at the source; in the sound propagation path; or, at the receptor (Figure 1). This is also the order from most effective to least effective of the common solutions for reducing traffic noise levels. This is generally true for all geographic settings, although some of the solutions can be more difficult in mountainous areas.

2.1.1 Noise Source Abatement

The primary source of noise from vehicles at highway speeds is the tire/pavement interaction [3]. Even otherwise silent electric vehicles will produce tire noise at highway speeds. Other noise sources from vehicles that can be important in steep mountain corridors are drive train, engine brake and engine exhaust noise, primarily from heavy trucks.

Figure 1. Illustration of Noise Source, Propagation Path and Receptor/Receiver



From U.S. Department of Housing and Urban development [4]

The type of vehicle is an important noise source consideration. For example, passenger cars have different noise characteristics from heavy trucks and trains, and management of these differences could be part of an abatement solution. The types of vehicles passing by a location can be unpredictable and inconsistent, which affects the noise environment.

Reducing noise at the source is the most effective of the three approaches because it prevents the sound from entering the environment rather than attempting to manage the sound after it has been emitted. Abatement of a noise source on an individual vehicle may be relatively inexpensive, but the total costs for abating an entire vehicle population may be high. In terms of abatement for the road surface, quieter pavements have been found to be 10-25 percent more expensive than traditional surfaces [5].

2.1.2 Propagation Path Abatement

The next most effective noise reduction approach is to affect sound propagation and/or the path between the sound source and the receptor. This is commonly accomplished with a sound-blocking barrier such as a noise wall. More extreme examples of barriers are road galleries and tunnels (Figure 2). The conditions for reducing traffic noise via the propagation path can be more challenging in mountain areas due to the topography (e.g., receptors are at elevations above the road).

A barrier can be any physical object that is substantial enough to block the transmission of sound on the line of sight between the source and the receptor. Many materials can act as barriers [6]. For example, one inch of wood or its equivalent can be an effective barrier. Physical features of the road can act as barriers, such as the terrain (cuts/fills), the roadway elevation or ramp configurations. Other potential tools to affect the propagation path include sound-absorbing treatments and active noise control.

Figure 2. Example of noise barrier with gallery-style top



From Swiss Federal Roads Office [7]

Propagation path abatement actions typically attempt to manage the noise after it has been generated. Sometimes the action will redirect the noise, which can cause other impacts. These kinds of actions generally affect only some of the traffic noise emissions (i.e., those striking the barrier) and only reduce noise levels at locations close behind the barriers. Therefore, these actions generally only benefit those locations relatively close to the barrier and are less effective in the broader noise environment than abatement actions at the source. Note that fully encapsulating tunnels as noise barriers could overcome several of these limitations but would increase the complexity and cost of the abatement action. Barriers are expensive—typical noise walls can cost \$1-\$2 million per mile [5]. Galleries and tunnels would be more complex and considerably more expensive.

2.1.3 Receptor Abatement

Abatement at the receptor aims to reduce interior noise levels. An example would be installation of insulated windows and doors at a building. Note that the windows/doors will have to remain

closed for this abatement to be effective, unless units with special ventilation capabilities are used.

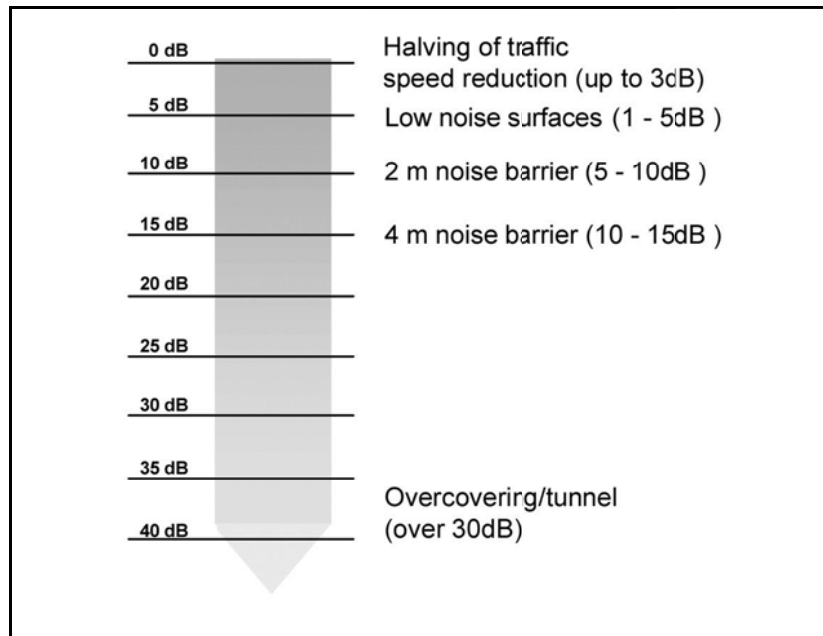
Generally, this approach is the least effective overall of the three noise reduction approaches as it provides a narrow noise benefit. Retrofitting windows and doors are examples, but the concept can take many forms and may include planning, zoning or site layout. A small number of receptors benefit from each action, but the benefits can be carefully targeted. The costs can be relatively inexpensive per building compared to noise walls, but overall abatement costs may be large, depending on the type and number of buildings needing abatement.

2.2 Review of Potential Noise Reduction Strategies

There are multiple ways to achieve noise reductions through each of the approaches described in Section 2.1. One effective noise impact avoidance strategy is appropriate land development through compatible land use planning, where noise sensitive land uses are not permitted near noisy roads, or optimized site layouts. This strategy could help at new developments, but generally does not address noise issues at established areas produced by past decisions with different land use priorities. Specific traffic noise reducing actions are generally needed for established areas and Figure 3 shows typical noise reductions that can be expected from typical traffic noise abatement actions.

Actions that eliminate or reduce noise at the source can provide the most comprehensive and effective noise abatement, so reducing tire/pavement noise could be an important step. But, the Federal Highway Administration (FHWA) does not allow “quiet” pavements as an abatement action because the benefits are viewed as temporary [2]. Furthermore, prospective noise abatement actions must meet the CDOT criteria for feasibility and reasonableness (from FHWA requirements) to be implemented as a primary abatement measure on CDOT projects [2]. The feasibility and reasonableness criteria most critical for the barriers examined for this review are: at least one receptor beside the road (“wayside”) must receive 7 decibels (dB) of noise reduction from the action; the benefit/cost value must not exceed \$6,800/dB/receptor; and, barrier height must not exceed 20 feet.

Figure 3. Approximate Noise Reductions Available from Various Abatement Methods



From Swiss Agency for the Environment, Forests and Landscape [8]

Each situation would be different and need to be analyzed to determine the feasibility and reasonableness of a specific abatement action. A combination of actions may be needed and the expected outcomes for the various traffic noise abatement actions are described below.

2.2.1 Noise Reduction Options at the Source

The tire/pavement contact interaction is the primary source of traffic noise at highway speeds. The details for the potential traffic noise abatement solutions at these sources can be complex and technical and an in-depth presentation of each topic was beyond the scope of this memorandum, so a summary by abatement approach is provided below.

2.2.1.1 Reducing Noise from Tires

Tires provide half of the tire/pavement contact interaction that is the greatest source of vehicle noise at highway speeds [3]. The noise produced by tires depends on many characteristics, including width, tread pattern, tread depth and rubber stiffness [9]. There is a diverse population of tires available. For example, it has been reported that approximately 16,000 tread patterns alone are in use [9]. Tire design also affects grip, which is an important driving safety feature especially during adverse weather. The diversity of tire types in the U.S. is extensive and the final choice is left to the consumer.

Some tire designs appear to be quieter than others and use of quieter tires could contribute to lower traffic noise levels. The differences in tire loudness can be substantial—as much as 10 dB measured at the tire [9] over a broad range of tire types—though the difference among the more common passenger car tires is 3-4 dB [10] measured at the tire. Some of the quieter tires may have less grip in wet conditions [11].

The noise levels from tires may change as they wear [9]. Studded tires can be an important safety feature in snowy/icy conditions but often are louder and more damaging to the driving surface [9]. This is also true for tire chains, which can be mandated for heavy trucks during icy driving conditions in the mountain corridors—but these are usually driven at slower vehicle speeds. The resulting pavement damage can also increase traffic noise levels from the rougher surface.

CDOT does not have authority to regulate tire usage for noise so it was not a feasible solution for this project. The State of Colorado could restrict use of studded tires, but currently allows their use year round.

2.2.1.2 Reducing Noise of Pavement

Pavement represents the other half of the tire/pavement contact interaction that is the greatest source of vehicle noise at highway speeds [3]. Quiet pavement was one of the two most widely reported traffic noise reduction actions in Europe (along with barriers) encountered during the literature review. Pavement selection is an area where transportation agencies such as CDOT have considerable control.

The body of data on quiet and quieter pavement is extensive and too complex to be repeated here, so major points have been summarized. Substantial research and testing has gone into quiet pavement by a number of agencies operating in a wide range of environments [3, 5, 12, 13, and 14]. CDOT has undertaken research to compare the loudness of different pavement types [15]. The findings support the conclusion that some pavement types are quieter than others and the noise difference can be substantial—up to 13 dB measured at the tire has been reported [10]. It should be noted that these results were from on-board sound intensity measurements near the tires and were not the same as a person would perceive at the wayside. The results from measurements at these positions may differ [16]. For example, wayside noise is affected by more sources than just the tire/pavement interaction, so a difference in noise levels between tires

measured at the pavement surface may be less when measured at the wayside. The actual possible noise reduction depends upon the nature of the existing pavement and the replacement pavement.

Colorado's mountain corridors frequently have challenging winter driving conditions that must be considered for potential solutions. Pavements must perform well under snowy and icy driving conditions and withstand snow plowing, liquid deicing and application of grit sand.

Another issue can be construction conditions—some materials require weather conditions for installation that are not common in Colorado's mountain areas. For example, rubberized asphalt requires a placement temperature of 65 degrees Fahrenheit and rising [17]. Many of these pavements are not feasible for economic and technical reasons.

To summarize, several groups of pavements have reliably been found to be among the quieter surfaces, including [5]:

- ▶ Thin-surfaced, negatively textured gap-graded asphalt—A basic feature of these pavements is a surface structure with indentations (voids) that reduce the noise from air pumping caused by rolling tires. The thin pavement surface layer (e.g., 25-50 mm or 1-2 inches) is usually applied as a wearing course (e.g., hot mix asphalt or stone matrix asphalt) on top of a base course that provides structural support (e.g., dense asphalt or concrete). The thin layer can be sacrificed and replaced by milling and overlaying with a new surface when the noise reduction has deteriorated [18].
- ▶ Single-layer porous asphalt (greater than 18 percent voids)—Often referred to as open graded friction course in the U.S., these pavements contain interconnecting voids that allow water to drain away and also absorb tire noise. Generally, a thicker and more porous layer means quieter pavement. The wearing course is typically 40 mm (1.5 inches) thick. Note that porous pavement tends to have lower thermal conductivity than dense pavement, meaning there is risk that the road surface would freeze quicker and be more prone to ice coverage in winter than dense asphalt. CDOT placed this type of pavement on I-70 near Evergreen approximately 10 years ago, but preferential icing made it an unsafe winter driving surface and the pavement was replaced with stone matrix asphalt. Porous pavement may also wear more quickly from tire studs and chains

[18]. Porous asphalts tend to be 50 percent more expensive than conventional pavements [11].

- ▶ Double-layer porous asphalt (greater than 18 percent voids)—Similar to the single-layer porous asphalt but consists of two layers: a fine-grained top layer and a coarser-grained bottom layer with larger voids. Typical course thicknesses are 25 mm and 45 mm (1 and 2 inches) for the top and bottom layers, respectively. The top layer protects the bottom layer, which provides more sound absorption [18]. The top layer is intended to be replaced more frequently to maintain noise reduction. This pavement has the same winter icing concerns as the single-layer porous asphalt.
- ▶ Rubberized asphalt—This pavement is hot mix asphalt that includes approximately 20 percent crumb rubber or rubber chips, often recycled from scrap tires, as some of the aggregate. It is applied in approximately 1-inch lifts. It has been found to be durable and skid resistant. Rubberized asphalt must be applied when the concrete base pavement surface is between 85 and 145 degrees Fahrenheit for the material to adhere properly, which can limit the construction season and applicability for this material [19]. CDOT has tested rubberized dense-graded asphalt in a separate study [20].
- ▶ Certain concrete pavement finishes—concrete pavement is one of the more durable driving surfaces and the surface texture has a profound effect on traffic loudness. Typically, longitudinal tining or grooving provides relatively quiet surfaces. Diamond grinding is one of the quietest options for concrete pavement and may be used to rehabilitate older road surfaces [5, 18, 21, and 22]. Under a separate research project, CDOT has assessed concrete pavement surface textures (including tire noise), which led CDOT to modify their specification for pavement texture [23].
- ▶ Porous concrete pavements—Portland cement concrete can also be made porous and provide noise reductions as with porous asphalt. Studies in Germany showed a noise reduction of 5 dB at the wayside compared with burlap-texture concrete and stone matrix asphalt; however, traction became unsatisfactory after about two years [18].
- ▶ Poro-elastic road surface—this is an experimental paving product comprised mainly of recycled tire rubber, other aggregate and polyurethane binder. It has a high void content and remains flexible. It is intended to be the top coat/driving surface of a road and has shown exceptional traffic noise reduction potential—on the order of 8-12 dB better at the

wayside than typical pavement. The material is expensive and not widely available. There are a number of technical challenges with installation. Some long-term performance aspects have been inadequate in test applications [18]. This does not appear to be a viable solution now but may be in the future.

It should be noted that the initial noise reductions from quieter pavements can change through time or by site application. The overall noise reduction depends on more variables than mixing a pavement recipe and paving a road. The pavement must be installed and maintained properly to maximize the noise reduction, so differences in construction and maintenance can lead to differences in loudness. Noise levels from the same kinds of pavement have been reported to differ by as much as 10 dB at the tire [24]. Pavements have been proven to get louder over time through wear [25], so installing quiet pavement once at a location is not a permanent noise solution.

Relatively good noise reduction has been reported for porous pavements; however, there may be other issues with this pavement type in Colorado's mountain areas such as described above for I-70 near Evergreen. Porous pavements generally allow the road to freeze faster and stay frozen longer than dense asphalt, which can contribute to icy roads and hazardous driving conditions [11]. Porous pavements typically need more de-icer (approximately 50 percent) and winter maintenance attention. They are also less resistant to damage from snow plowing, studded tires and tire chains. The pavement voids may become plugged from traction sand [18]. For these reasons, porous pavement may not be the best choice for snowy climates. Low noise varieties of dense asphalt and concrete pavements generally perform better in winter and do not typically need special winter maintenance [18]. Thin-surface, gap-graded pavement with fine aggregate, such as stone matrix asphalt, may be a better choice in wintery areas [5].

CDOT has conducted research on pavement loudness and has generated Colorado-specific data [15]. The results showed that the main CDOT pavement types (concrete, dense asphalt and stone matrix asphalt) have quieter versions, but that there is variability among each type in terms of loudness. No general pavement type was found to be consistently louder or quieter than the other types and each type got louder with age and wear. Careful selection of pavement type for a project could contribute to lower overall traffic noise levels for an area.

An important caveat with quiet pavements is that Federal policy prohibits the selection of pavement type as a noise abatement action. This is largely because of concerns that noise reductions will not be maintained at a specified level of noise reduction over the life of the highway project [26]; therefore, other abatement actions would still be needed to mitigate noise impacts.

2.2.1.3 Reducing Speed of Sources

Traffic noise increases with vehicle speed, so slower driving speeds would reduce traffic noise. To achieve a 5 dB wayside reduction (one that is noticeable) in traffic noise requires a speed reduction of approximately 20 miles per hour [2]. A 7-dB wayside reduction would require speed reductions of approximately 25 miles per hour [3]. This may sound like a relatively simple and inexpensive action for freeway sections near towns, but a drawback is that lowered vehicle speeds are generally not compatible with the function of an interstate highway. Lowered nighttime speed limits could reduce noise during typical sleeping periods. However, the noise reductions depend upon the behavior of drivers and/or law enforcement and are therefore uncertain, unlike most of the physical noise abatement measures.

2.2.1.4 Types of Vehicle Sources

The transportation noise environment can be greatly affected by the mode of travel. The primary travel mode in Colorado is by automobile, but there is interest in the I-70 corridor for other modes, such as rail transit [1]. Cars and trucks have different noise characteristics and both are different from trains. Different types of trains also have different noise characteristics. Switching travel to quieter vehicle types could lower overall transportation noise levels. However, none of these vehicle types are completely silent—modal shifts from one vehicle type to another would change the transportation noise challenges being faced, not eliminate them.

It is important to note some fundamental difficulties with this potential solution. For example, elimination of half of the highway vehicles through a switch to another mode (a large and unlikely mode shift) would result in a highway noise decrease to sensitive noise receptors of approximately 3 dB (barely noticeable to most people). Providing a new alternative travel mode may be expensive and challenging where a corridor is not already in place.

2.2.1.5 Timing of Vehicle Sources

Limiting the time of day certain sources are allowed to operate would eliminate noise from those sources during the prohibited times. An example would be prohibiting heavy truck traffic at night during the usual sleeping periods. The size of the noise reduction would depend upon the contribution from the sources being limited. This action is generally not compatible with the function of an interstate highway and there may be other factors that conflict with such timing restrictions that need to be considered.

2.2.1.6 Relocation of Vehicle Sources

Traffic noise sources (i.e., highways) could be relocated away from sensitive receptors (i.e., towns). This can be an effective but costly approach and is more feasible in locations with accessible vacant land and relatively flat ground, which is generally not the case in mountain corridors. As an example, Switzerland has rerouted several major highways away from town centers and/or through traffic tunnels through mountains which can lead to a substantial reduction of noise from highway traffic. This approach would create obligations to build, operate and maintain a more complex and expensive transportation system. This approach would not affect noise from the remaining local traffic.

2.2.1.7 Evaluation of Source Noise Reduction Options

Reduction of traffic noise at the source, before the noise is produced, is the best abatement approach. It would prevent the noise from entering the environment and remove any need for further noise management.

None of the options described above are practical today in reliably providing a 7-dB wayside noise reduction for the long term at a reasonable cost/benefit level for the sensitive receptors along a highway facility, so none of these are suggested as a primary noise abatement strategy for mountain corridors. For example, CDOT does not have regulatory authority needed for several of the options (e.g., tire types). Relocating roads can be effective, but would be a challenging and expensive choice. Reducing speed limits or managing traffic could be used to reduce traffic noise, but these actions conflict with typical interstate highway operations and would require compliance from each driver (which is unpredictable).

The best option for reducing traffic noise at the source may be for CDOT to use it as an informal or supplemental measure. Quiet pavement cannot be counted as a formal noise abatement action, so other abatement actions will still be needed. CDOT could prefer quieter versions of the standard road surfaces [15] to lower traffic noise generally. Quiet pavements provide a noise reduction in the early years after installation. The quietness benefit will decrease over time and may eventually disappear without regular maintenance [15].

2.2.2 Noise Reduction Options through the Propagation Path

FHWA's noise abatement policies [26] only allow for five types of noise abatement to be considered for new highway or highway expansion projects and receive federal funding:

- ▶ Traffic management
- ▶ Alteration of the highway alignment away from sensitive receptors
- ▶ Barriers in the form of sound walls or earthen berms
- ▶ Creation of buffer zones along the highway
- ▶ Sound insulation for some public buildings

Barriers are almost always the abatement action selected for traffic noise because the action must be permanent and the roads usually are in areas with mature land use developments [3]. Barriers act by affecting sound propagation on the path from source to receptor. Other propagation path options are also described below.

2.2.2.1 Barriers

Traffic noise barriers were the other of the two most widely reported traffic noise reduction actions (along with quiet pavements in Europe) encountered during the literature review. Barriers are used extensively and can be beneficial in many instances. For example, Switzerland has spent approximately 78 percent of their traffic noise abatement funds on barriers and tunnels [27].

Barriers are a broad category of action as they can come in many forms and often need to be customized to each location. A common form is a free-standing wall that can be constructed from a variety of materials, such as CDOT has done on many previous projects. Earth berms can be effective where space and terrain permit. More complex types of barriers include galleries (Figure 2) or highways with “walls” and “lids” (e.g., cut-and-cover or tunnels)—these tend to be

used in more difficult noise abatement situations and are expensive, but can provide substantial noise reductions in difficult terrain (Figure 3).

Typical noise barriers are reliably capable of providing 10-15 dB of noise reduction, which is more than would be expected from current quiet pavements [3]. Fully encapsulating tunnels can provide noise reduction in excess of 30 dB (Figure 3). Generally, taller barriers are needed to provide higher levels of noise reductions to minimize refraction of sound into the area behind the barrier. Barriers generally are the common noise abatement action that provides the greatest noise reduction to the receptors nearest to the road.

Noise barriers tend to provide noise relief for a relatively small number of receptors immediately behind the barrier. Noise barriers will provide little to no benefit for homes that overlook a road or buildings that rise above the barrier, unless the barrier can nearly encapsulate the road [3]; therefore, relatively tall barriers may be needed. Generally, a noise barrier provides effective noise reduction for approximately 200 feet behind the barrier [28]. Parallel reflective barriers can limit the overall barrier effectiveness by reflecting traffic noise back into the barrier shadow zones [29].

Barriers are expensive—precast panel noise walls can cost \$1-\$2 million per mile [5]. A wide variety of barrier materials are available. Some can absorb sound but many of the commonly used materials do not. Many proprietary commercial products are available, as are numerous non-proprietary designs and materials [29]. Many products can be effective barrier materials and a project-specific materials-selection process is often the best way to choose.

2.2.2.2 Road Elevations

Both elevated viaducts and sunken roadways can affect the sound propagation path by changing the geometry between noise source and receptor. Viaducts can raise traffic above the receptors so that the driving surface and road edge act as a noise barrier for the receptors below. Sunken roads can benefit from the road cuts acting as earthen barriers that block traffic noise. Raised or sunken roads generally are not effective when traffic is visible to receptors at or above the elevation of the road. These are not add-on actions and must be designed components of the road when it is built. The expected noise reduction would be similar to a barrier—approximately 10-15 dB.

2.2.2.3 Absorptive Treatments

An issue with many common wall materials is that they reflect sound. Natural rock surfaces that are exposed by steep or vertical cuts on the side of a mountain road are also reflective. These surfaces can reflect traffic noise and affect the noise environment. The increase is generally 2 dB or less at the wayside [29], but people may be annoyed from changes in the sound character. Higher frequency sounds are reflected more easily than lower frequency sounds, and the human ear is more sensitive to the higher frequencies. People may notice a change from sound reflections even if overall sound levels do not change. Absorptive materials can reduce noise reflections off both natural and man-made surfaces.

There are many materials that absorb much of the traffic sound that strikes it and would reduce reflections. Absorptive material is a better choice than a reflective material for barriers if other parameters (cost, strength, etc.) are acceptable. A typical absorptive material has a noise reduction coefficient of 0.6-0.9 (0.0 reflects all sound; 1.0 absorbs all sound) [29]; the CDOT standard specification is greater than or equal to 0.65.

Sound-absorbing products (e.g., sprays, mats or panels) can be attached or applied to reflective barriers or rock faces. These materials have varying levels of maintenance requirements beyond that of standard reflective materials (e.g., rock face or plain concrete), and some may be less weather resistant, requiring occasional replacement. The visual appearance of these materials is equally diverse and can be an aesthetics consideration. Some newer technologies include micro-perforated panels and porous metal foam.

2.2.2.4 Vegetation

Vegetation/trees along a road can act as a barrier, both acoustically and psychologically. In acoustical terms, the vegetation needs to be sufficiently tall, dense and wide to be an effective noise barrier [26], which is difficult to create or find along a highway. Colorado's dry climate and cold winters would present a challenge for growing the plants. Deciduous plants would not be effective barriers in wintertime.

Plants can alter the perception of sound, but in numeric terms, plants usually make poor noise barriers. Generally, the height and density achievable with vegetation does not create an acceptable noise barrier under CDOT/FHWA guidelines. However, plants can disproportionately

scatter (and reduce) higher frequency sounds that many people find annoying, and thereby affect the human perception of the noise more than the noise level values may suggest. This scattering may be a benefit to receptors beyond the vegetation, but one drawback may be that vegetation along a noise barrier scatters higher frequency sound into the shadow zone behind the barrier—a small effect but may diminish the overall effectiveness of the barrier.

2.2.2.5 Evaluation of Propagation Path Options

Reduction of traffic noise through the propagation path (e.g., barriers) is the most frequently used method to provide the greatest traffic noise level reductions. Although not as comprehensive as reducing noise at the source, barriers tend to provide the greatest decibel reductions available. The noise benefit achieved with barriers does not diminish over time as quiet pavement does. Absorptive barrier materials could reduce or eliminate concerns from reflected noise.

Barriers are an important tool for traffic noise abatement and appear to be the best option for the linear highway geometries for traffic noise abatement. The other propagation path options described above may be useful in certain situations, but would be difficult or ineffective as widespread abatement actions. Barriers are recommended for consideration in the mountain corridors.

2.2.3 *Noise Reduction Options at Receptors*

Solutions at the receptors usually are considered when neither of the approaches described above will be feasible/reasonable or effective. In broad terms, these actions are taken to increase the sound transmission loss provided by a building envelope—to increase the barrier effect provided by a building's walls. Each action typically applies to a single building.

A typical house wall will provide at least 20-25 dB of noise reduction for exterior sources [26], but this can be increased by various methods. The simplest approach is to improve the weakest links in the building envelope—typically by replacing windows or doors with higher quality units. Supplemental air conditioning may be needed if the windows are to be kept closed year-round. The rest of the building envelope must be adequate as well, so supplemental insulation may be needed in the walls and/or roof in some cases.

Replacement window and door vendors now have improved insulating materials available to augment standard practices. This may be a relatively inexpensive solution if a small number of buildings are affected and other abatement methods are not appropriate. Historic buildings may require special attention when being considered for retrofitting.

This approach is recommended as a last resort, when none of the options described above are implementable and traffic noise levels are so high that aggressive abatement is warranted. An important caveat with this approach is that use of Federal money for insulation abatement is limited to public and nonprofit buildings and excludes private residences [26].

2.2.4 Experimental Noise Reduction Approaches

The approaches described above are generally widely available and well established actions for traffic noise issues. There is ongoing research with experimental approaches to improve or expand the tools available. The concepts may not yet be fully field tested or developed into commercial products. Some of interest for this project include:

- ▶ Top treatments for noise walls—treatment of wall tops is a way to improve wall performance by inhibiting refraction of sound waves across the top of the wall into the shadow zone behind the wall. The top of the wall is finished with a shape other than the typical squared-edged flat top, thereby giving more noise reduction without adding wall height. These tops can be retrofitted onto existing walls to improve noise reduction. Various concepts have been forwarded as to the shapes of wall tops that perform well—T-tops seem to be among the more favored. Note that this action is supplemental to the benefit provided by the wall itself, and would only affect the sound that strikes the wall top. Relatively small gains in noise reduction would be expected from these (generally less than 2 dB) and would most affect the area close behind the wall. The added cost of constructing shaped barrier tops typically outweighs the cost of simply increasing the barrier height to achieve the same acoustic benefit [29].
- ▶ Green (vegetation) noise walls—there are several products available that combine various support structures with growing plants to create “green” noise walls. One example is essentially sand bags with plant seeds incorporated [30]. The sand bags are deployed into the environment and the seeds sprout and grow. In a noise wall application, the bags

would be stacked and fastened together, resembling an earth berm but potentially with a smaller footprint. Another product stacks precast concrete trays filled with soil and plants to form a wall [30]. The plants grow in the trays and transform the appearance of the wall. There are a number of other products available along similar lines. In these cases, the supporting structure usually is acting as the noise barrier and is effective. The plants are added usually to soften the appearance of the wall, provide a benefit regarding greenhouse gases, and/or reduce reflected noise. These options tend to be wider than standard walls to provide the plants with adequate soil for growth and there is a long term maintenance obligation in cultivating the plants. Colorado's mountain climate would be challenging for cultivating plants in this way.

- ▶ Sonic crystals—these “crystals” consist of regular spacing of cylindrical elements arrayed in a frame, e.g., a horizontal scaffold of PVC pipes [31]. The crystal is not solid like a typical noise wall as air can pass through the structure. The crystal can attenuate noise in a large frequency range (called the “stop band”) by interferences from scattered waves within the crystal canceling each other out to reduce noise levels. The crystals can also be “tuned” for certain frequencies by changing the crystal parameters (size, spacing, etc.). It may also be possible to redirect sound using crystals. This concept has not been developed into a commercial product, but conceptually crystals could be stacked and strung together to create traffic noise barriers. The materials may be light enough and made from standard enough materials that “lids” for highways could be constructed to address traffic noise travelling upward. This is not a mature solution at this time.
- ▶ Concrete resonators—these could be treatments built into the face of noise walls for sound absorption and are sometimes used in pavement (see modular pavement below) [32]. Simple resonators can be a hollow block with an open hole or neck and can be optimized for specific sound frequencies. Oscillation of the air mass in the resonator's neck causes energy dissipation and sound reduction. The resonators could be built into the face of a standard noise wall. This would be a variation of the absorptive wall applications, but presumably the absorbers could be made of durable material such as concrete and require relatively little maintenance. Construction of the barriers could be more complex, though.

- ▶ Modular pavement—a series of modular pavements have been tested in the Netherlands [18]. The modular surfaces consist of different layers, potentially prefabricated off-site, with each layer having a specific function. The predicted noise reductions for each pavement are listed below, but measured wayside noise reductions were on the order of 5-7 dB [18]:
 - Modieslab—prefabricated two-layer porous concrete slabs on piles, offering a predicted noise reduction of 7 dB relative to the Dutch dense asphalt concrete reference surface
 - The Rollable Road—resonators in concrete with two thin, rollable porous asphalt top layers, offering a predicted noise reduction of 10 dB relative to the Dutch dense asphalt concrete reference surface
 - The Very Silent Noise Module—resonators in concrete with a very thin, quiet asphalt top layer, offering a predicted noise reduction of 13 dB relative to the Dutch dense asphalt concrete reference surface
 - Rollpave—a rollable porous asphalt with an adhesive, geostatic support layer, offering a predicted noise reduction of 6 dB relative to the Dutch dense asphalt concrete reference surface.
- ▶ Active noise reduction—this consists of actively producing specific sounds to negate other undesirable sounds, generally by broadcasting same frequency anti-phase sounds [33]. An advantage of this approach is that noise could be eliminated rather than managed, though it is most effective close to the barrier. Sensory microphones and broadcast speakers need to be strategically placed in the environment and a control system operates the array. Current research seems most directed at controlling sound refraction over the top of barriers into the shadow zone, much as was described above for wall top treatments. Therefore, this action would be supplemental to the benefit provided by the barrier itself. Theoretically, the approach could be scaled up to address more of the traffic noise directly and without a wall. There would be a number of challenges in developing an efficiently operating active noise reduction system along a major highway, such as matching the highly variable noise coming from the highway or effective deployment and operation of the electronic equipment.

2.2.5 In-Depth Review: Switzerland

Switzerland was selected for closer review as a case study for highway noise abatement because of its relatively strict transportation noise reduction/control policies and its mountainous terrain.

At the Swiss federal level, primary controlling authority over noise pollution is through the Environmental Protection Act and the Noise Abatement Ordinance. The requirements for road noise are more rigorous than Colorado. Purely residential areas generally have a maximum rating sound level limit (the average sound level for the time period) of 60 dB during the day and 50 dB at night, although this does depend on the individual circumstances [34]. These levels have regulatory status and carry more enforcement weight than the guidelines here in the U.S.

Transportation is a major consideration in the Swiss noise environment. Swiss law operates on the “polluter pays” principle, so road and rail operators are responsible for noise abatement costs. The cost/benefit approach to noise abatement in Switzerland is very different from CDOT’s and allows higher overall costs to mitigate than CDOT typically would.

The evaluation of road noise abatement approaches generally addresses mitigation to the sources first, followed by mitigation in the sound propagation path(s), and finally at the receptors if needed [7]. The actions at the sources include quiet pavement, lowered speed limits and banning cargo trucks at night. Noise barriers (absorptive materials are common), road coverings and road tunnels are the primary propagation path abatement measures. The final actions occur at the receptor and generally consist of retrofitting windows/doors or supplementing insulation to protect interior spaces.

Between 1985 and 2009, Switzerland spent approximately \$1 billion on road noise abatement [27]. Approximately 78 percent of those funds went toward barriers and road coverings, illustrating that this has been the primary abatement action, with the remaining funds spent primarily on windows in buildings. Costs for quiet pavement were not provided. Over the upcoming several years, the Swiss Federal Roads Office expects to spend more than \$100 million per year for noise abatement for highways [7]. Interest in abatement at the source through quiet pavements and tires appears to be growing [35]. The preferred Swiss quiet pavement is a dense asphalt—MR8 [7].

2.3 Context Sensitive Noise Abatement

The I-70 PEIS embraced the concept of context sensitive solutions [1]. With this backdrop, traffic noise solutions different from those CDOT has traditionally built may be needed in mountain corridors. More integrated and multifaceted approaches, such as combinations of noise reduction actions, may be appropriate to realize the goals for context sensitivity because CDOT's typical noise walls may not suffice.

For example, a goal of lower overall traffic noise levels more fitting for rural and natural areas may suggest a quieter default pavement should be preferred, even though this action would not count as a formal noise abatement action with FHWA. Such pavements may not produce dramatic drops in noise levels—benefits may be 2-4 dB at the wayside—but this may be important within a multi-faceted noise abatement strategy. Maintaining a noise benefit from quieter pavements may mean more frequent pavement replacement. One approach that may reduce costs is use of relatively thin driving surface layers that are easier to replace. Furthermore, the highway design could incorporate as many noise-shielding structures as possible through creative layout and taking any advantage that can be provided by the topography (elevations, ramps, road cuts, etc.).

Currently, barriers are the single abatement action that provides the greatest localized reductions in traffic noise—often 10-15 dB at the wayside by themselves—and should not be excluded. Barriers with sound-absorbing surfaces could further reduce traffic noise by up to 3 dB and are an option. Transparent barriers could maintain views and relieve some of the shadowing from barriers that could be problematic during winter, but may introduce other maintenance concerns. Because of the terrain, taller or gallery-like (Figure 2) noise barriers may be needed to be effective in some locations. Barriers may pose challenges in some locations for winter highway maintenance such as snow plowing. Installation of noise barriers may conflict with other corridor resources, such as wildlife migration.

Particularly difficult situations are found where the highways bisect small towns. Strictly in terms of traffic noise, the best solution in these cases may be to remove the source by relocating the road either to another alignment or into a tunnel. But when considering more than just reducing noise levels, such as right-of-way needs or construction costs, relocating the highway would be a challenging choice.

2.4 Summary of Literature Review Findings

The purpose of this study was to examine traffic noise abatement options for high traffic volume areas with difficult terrain in sensitive noise environments. A primary goal was to identify abatement solutions that reduce community noise levels measurably over what conventional barriers provide. Note that CDOT's more common conventional barriers of late favor vertical precast (and reflective) concrete panels in post-and-panel walls.

A number of traffic noise abatement strategies that are in use around the world were reviewed. It was concluded that actions to reduce traffic noise at the source have the greatest efficacy, but there are several technical and policy challenges (Section 2.2.1) that preclude this approach from being a formal abatement strategy for CDOT.

The most widespread and seemingly effective current strategies are noise barriers, which have been in use for a number of years. Noise barriers in their many forms (walls, lids, tunnels, etc.) typically can provide the greatest noise reductions. Traffic tunnels/covers are essentially fully encapsulating noise barriers and are the single action reported to give the highest noise reduction levels (e.g., 30 dB at the wayside). Such tunnels are expensive but may be the best noise abatement solution in some difficult environments. More frequently, the noise barriers are "conventional" and do not differ markedly from what CDOT has traditionally done, but there are design variations for traditional noise barriers worth considering. Therefore, design variations on barriers are an abatement action that is recommended for supplemental modeling for use in mountain corridors (Section 3.0).

Quiet pavements are accepted outside the U.S.—both as a formal abatement measure and to minimize road noise generally at the source and limit disturbances. Under FHWA requirements, quiet pavements cannot be recommended as a stand-alone abatement action for defined project impacts, but combinations of abatement actions (e.g., barriers and quiet pavements) may be used together to provide a higher level of environmental stewardship. This could achieve greater overall levels of noise reduction and may be the most context sensitive solution, which is an important consideration in the I-70 corridor. The various options described above are summarized in Table 1.

Table 1. Summary of Traffic Noise Abatement Approaches

Abatement Approach	Abatement Technique	Advantages	Disadvantages	Conclusion for this Study
At the source	Quieter tires	▪ Reduces the noise level ▪ Benefits entire environment	▪ CDOT does not have authority ▪ Tires must meet safety thresholds ▪ Relatively small noise reductions	Not applicable. CDOT does not have authority.
	Quieter pavement	▪ Reduces the noise level ▪ Benefits entire environment ▪ CDOT has authority	▪ Must meet safety thresholds ▪ Benefits diminish over time ▪ Higher road maintenance costs ▪ Relatively small noise reductions	Supplemental. Not a primary abatement action but could lower general traffic noise for some time after initial placement.
	Lower vehicle speeds	▪ Reduces the noise level ▪ Benefits entire environment ▪ CDOT has authority ▪ Maybe fewer accidents ▪ Inexpensive to implement	▪ Depends on driver behavior & enforcement ▪ Counter to driver expectations ▪ Relatively small noise reductions	Supplemental. Not a primary abatement action but could lower general traffic noise.
	Limit types of vehicles allowed	▪ Eliminates noise from removed vehicles ▪ Benefits entire environment ▪ May reduce traffic volumes ▪ Inexpensive to implement	▪ May not be allowed on publicly funded highways ▪ Challenging enforcement ▪ Counter to highways' purposes	Not applicable for many road projects. May be relevant on large projects that affect regional traffic patterns.
	Shift travel modes	▪ Eliminates noise from removed vehicles ▪ May benefit entire environment ▪ May reduce traffic volumes ▪ Expands travel options	▪ Adds noise from other modes ▪ Requires substantial mode shift to produce a benefit ▪ Maybe expensive	Not applicable for most road projects. Beyond the scope of most highway noise abatement actions. May be relevant on large multi-modal projects.
	Limit timing of vehicles	▪ Eliminates noise from removed vehicles for certain periods ▪ Benefits entire environment for certain periods ▪ May reduce traffic volume for certain periods ▪ Inexpensive to implement	▪ May not be allowed on publicly funded highways ▪ Counter to highways' purposes ▪ Challenging enforcement ▪ May have economic effects	Not applicable for many road projects. May be relevant on large projects that affect regional traffic patterns.

Abatement Approach	Abatement Technique	Advantages	Disadvantages	Conclusion for this Study
	Relocate highway	▪ Eliminates nearby noise sources from sensitive areas ▪ May remove community divider	▪ Very expensive ▪ Other environmental factors ▪ May affect other receptors ▪ Does not affect local traffic noise	Supplemental. Not a primary abatement action but could be an option in some situations.
In the propagation path	Physical barriers (walls, galleries, tunnels, road cuts/fills, berms, etc.)	▪ Proven methods ▪ Benefits most-affected receptors ▪ Benefits are long lasting and can be more substantial ▪ Compatible with FHWA rules	▪ Benefits relatively few receptors ▪ Expensive ▪ Ongoing maintenance costs ▪ Right-of-way and terrain considerations	Primary. One of the most effective abatement strategies.
	Road design (elevated viaducts, ramps, etc.)	▪ Proven methods ▪ May benefit most-affected receptors ▪ Benefits are long lasting and can be more substantial	▪ May benefit relatively few receptors ▪ Maybe more expensive ▪ Right-of-way and terrain considerations	Primary. Should be used whenever feasible. Typically would have to be part of initial road design; not a common retrofit option.
	Absorptive treatments	▪ Removes noise from the environment ▪ Reduces reflected noise	▪ Typically has small added benefit to barrier ▪ Maintenance & durability concerns	Supplemental. Not a primary abatement action but could be an option in some situations.
	Vegetation	▪ Potential natural barrier ▪ Potential psychological benefits ▪ May be visually appealing	▪ Not effective in reducing noise levels ▪ Difficult to establish & maintain in Colorado climate ▪ May only be seasonal	Not applicable. Unlikely to be an effective noise abatement strategy.
At the receptor	Upgraded windows/doors	▪ May be relatively inexpensive ▪ Benefits are very targeted	▪ Only benefits interior spaces	Supplemental. Not a primary abatement action but could be a last resort option in some situations.
	Supplemental insulation	▪ May be relatively inexpensive ▪ Benefits are very targeted	▪ Only benefits interior spaces ▪ Maybe more intrusive than just replacing windows & doors	Supplemental. Not a primary abatement action but could be a last resort option in some situations.

3. COMPUTERIZED NOISE MODELING ACTIVITIES

As was described in Section 2.4, there are a number of options available to reduce traffic noise. The options are more limited when looking for formal mitigation of specific traffic noise impacts from a road project (Table 1). For example, an abatement technique at the noise source such as quiet pavement would not be available for the reasons discussed above. The propagation path and noise receptor abatement techniques generally would be available, as appropriate for a given situation.

An objective of this study was to evaluate the efficacy of various noise abatement strategies available. Of these strategies, noise barriers and road design were identified as the two primary traffic noise abatement strategies available to CDOT (Table 1). The most effective and widespread options identified from the literature review were noise barriers. The effectiveness of various barriers can be compared through computerized noise modeling, so a modeling regimen was developed to assess a range of representative noise wall concepts. The results from the noise wall modeling were used to develop the recommendations presented in Section 4.0.

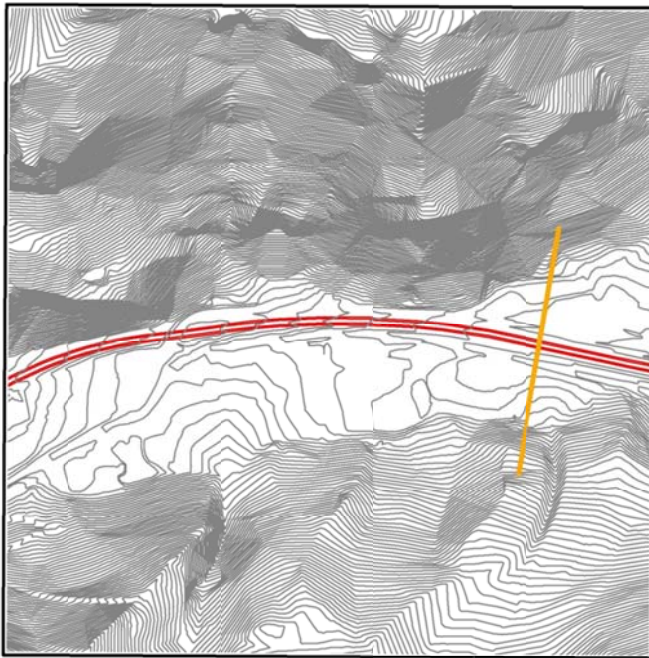
Road location and design can be important parts of a noise abatement strategy (Table 1), particularly for new roads. However, the opportunities to change road location or design to reduce traffic noise for existing roads tend to be limited because of land development that often happens near the roads. The opportunities often depend on unique conditions that may not be present elsewhere. Therefore, it was concluded that attempting to develop (and noise model) a general road design concept that would be both quiet and widely applicable would not be part of this project.

3.1 General Modeling Approach

The selected approach was to evaluate noise reduction benefits that may be provided by various noise wall concepts through review and comparison of noise modeling results. The model results with walls were compared to the model results without walls, and these results for the walls examined were compared to each other to assess and contrast the efficacy of the various wall concepts.

Figure 4. Overviews of Project Noise Modeling Areas and Terrain

Location 1



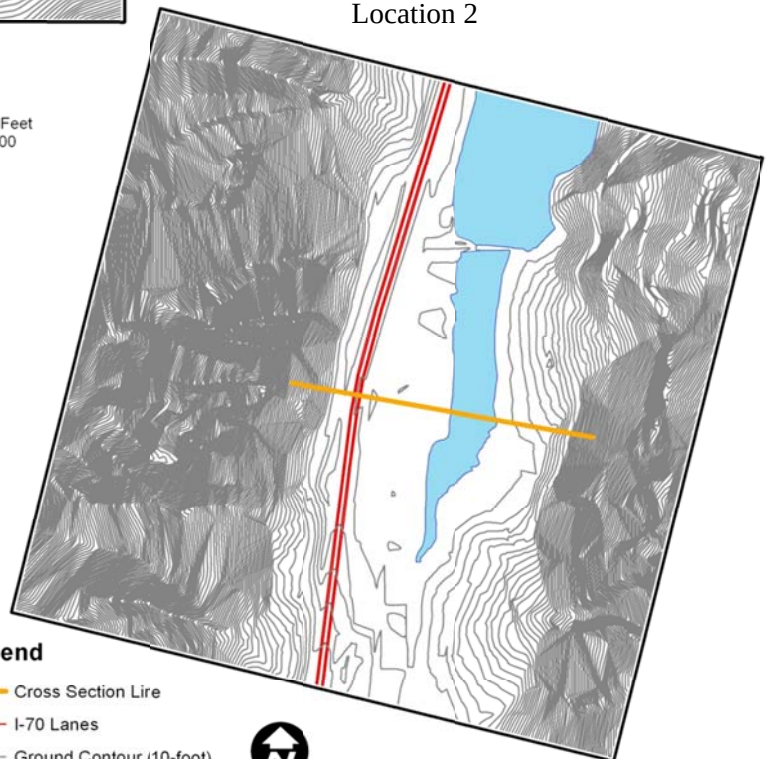
Legend

-  Cross Section Line
-  I-70 Lanes
-  Ground Contour (10-foot)
-  Location 1 Modeling Area



0 250 500 1,000 Feet

Location 2



Legend

-  Cross Section Line
-  I-70 Lanes
-  Ground Contour (10-foot)
-  Location 2 Modeling Area
-  Water



0 250 500 1,000 Feet

Two locations along I-70 were selected for modeling (Figure 4) to be representative of real-world settings as well as mountain settings in general. Each modeled location consisted of a 4,500 feet per side square area straddling I-70. For each location/wall combination, the 4,500-foot square was modeled for noise levels on 100-foot grid centers. Modeled noise levels become less reliable with increasing distance from the sources, but were still valuable in understanding noise patterns in the corridors.

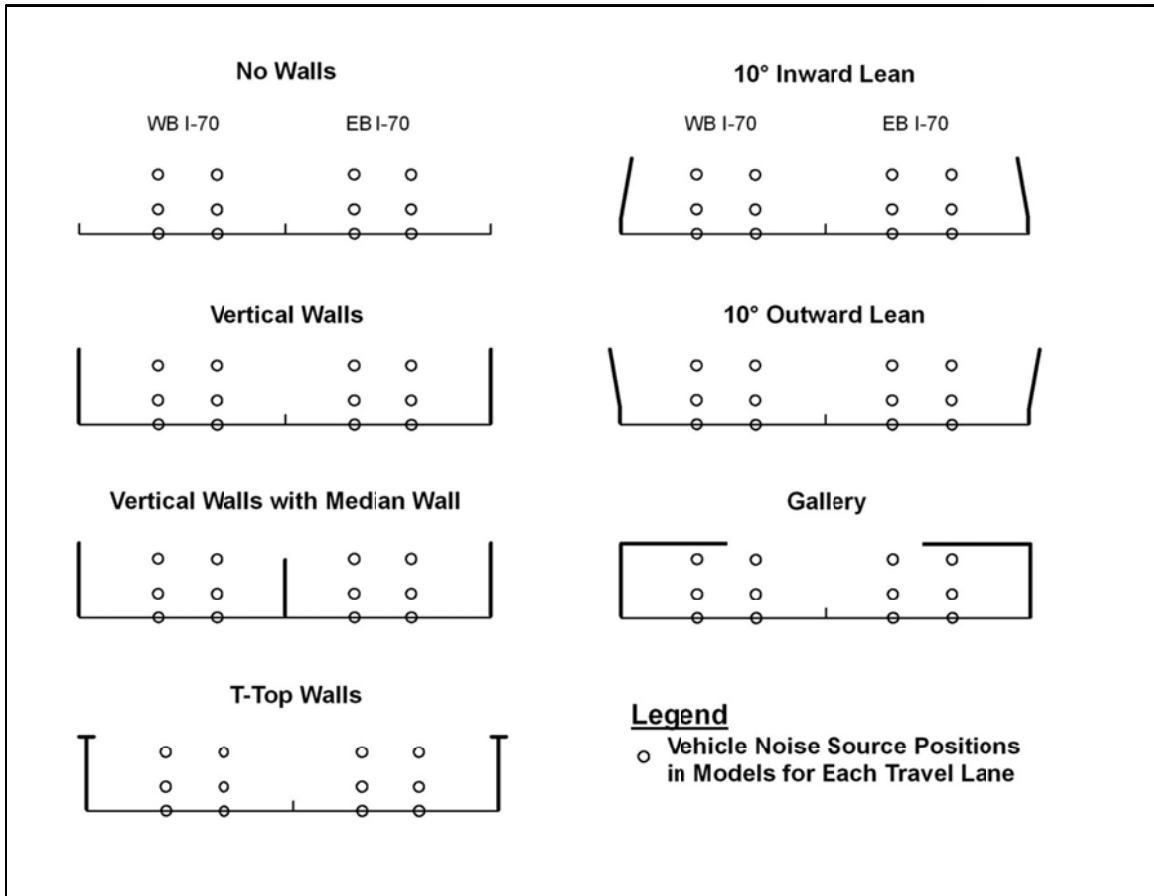
Within each of the squares, a cross section line through I-70 was chosen to evaluate the vertical characteristics of the traffic noise. For Location 1, the cross section line was chosen such that I-70 was approximately centered in the mountain valley. For Location 2, the cross section line was chosen such that I-70 was offset to one side of the valley. A cross-section grid approximately 200 feet high was modeled on 10-foot centers to illustrate noise levels in the vertical direction. These modeled noise levels within the grids are the primary results for this project.

A selection of prospective wall concepts was modeled for each location, along with an unmitigated, or no wall, base case condition. To keep the project data manageable and meaningful, the number of conceptual noise walls was limited to six of interest (Figure 5). Each wall concept was modeled for each location in three configurations: with a single wall on either side of the highway alone; and, with mirror-image walls on each side of the highway. The median wall was only modeled with the two associated vertical walls.

The main modeling results for the various wall types and configurations were difference grids calculated for each by subtracting the “with wall” grid results from the “no wall” grid results to emphasize the calculated changes in sound levels from each of the wall concepts. The difference grids were prepared as contour maps (Section 3.3) to facilitate interpretation. The results for the various wall concepts can be compared to assess effectiveness relative to each other, which formed the foundation of the findings for this project.

Techniques to abate noise at the receptor, such as supplemental windows or insulation, were not modeled for this project. Abatements using insulation have been infrequent by CDOT, are situation dependent, and are fairly straightforward building construction actions.

Figure 5. Cross Sections of Highway Road Profiles Examined by Noise Modeling



3.2 Modeling Methods

The current prescribed noise modeling software for traffic noise impacts and abatement analysis by both FHWA and CDOT is Traffic Noise Model (TNM) Version 2.5. However, the TNM package has several operational limitations that prevented it from being the best choice for this project. A few of these included limitations with grid-mapping/contouring large areas, handling complex terrain data effectively, calculating reflections off walls, handling of vertical distances in calculations and modeling weather conditions other than neutral.

The Nord2000 Road method (Nord2000) was chosen instead to perform the primary noise modeling and wall evaluations. Nord2000 is a noise modeling package developed for several Nordic countries and has several technical capabilities (such as accommodating different weather conditions) that were important for the success of this project [36, 37 and 38]. Note that FHWA and CDOT projects require the use of the TNM model for the official noise impact and

mitigation analysis, but Nord2000 allowed investigations of other sound propagation characteristics that TNM does not provide.

The model software package used was SoundPLAN® 7.1 as it can do calculations for both TNM and Nord2000. Base case (unmitigated condition) models for each of the two locations (Figure 4) using TNM and Nord2000 within SoundPLAN® were developed for reference and comparison with each other.

To keep the project data manageable and meaningful, many modeling choices had to be limited. Some of the more important project modeling settings are described below, but there are many other modeling parameters that had to be set that may affect model results if changed:

- ▶ Each wall was placed at the road's edge of pavement and assigned a height of 15 feet above the adjoining pavement.
- ▶ Neutral weather conditions were modeled in Nord2000 to emulate standard TNM conditions, except in the few special weather cases with Nord2000 that are noted later in this section.
- ▶ A single highway profile was selected to be the test case in all the models, including four travel lanes (Figure 5) and representative “worst case” hourly traffic volumes, i.e., 1,800 vehicles per lane.
- ▶ The highway profile represented relatively narrow road conditions: 85 feet of overall width with 42 feet of pavement for each travel direction and a 1-foot central median. A different road profile would be expected to give different model results, but the general trends and overall conclusions about the noise walls should be similar.
- ▶ The vehicle mix modeled was 89.0, 2.8 and 8.2 percent passenger cars, medium trucks and heavy trucks, respectively.
- ▶ Vehicles were assigned speeds of 65 miles per hour (MPH), except heavy trucks travelling uphill were set at 55 MPH; the uphill grade was approximately two percent.

Various configurations of noise walls (Figure 5) were considered with the modeling:

- ▶ Standard vertical noise walls
- ▶ Standard vertical noise walls with an added 12-foot center median wall
- ▶ Walls with 10 degrees of lean toward the highway

- ▶ Walls with 10 degrees of lean away from the highway
- ▶ Vertical walls with a 3-feet-wide “T” top
- ▶ Gallery-type walls with 22 feet of overhang over the highway (fully covered the outside travel lane)

The modeled walls were continuous across the entire grid zones (Figure 4) and were extended well beyond the grid zone edges to eliminate interpretation complications that may be caused by end effects at the wall termini (Appendix B). The standard vertical walls (Figure 5) were examined as both reflective and absorptive structures; none of the other walls were modeled as reflective. Reflective walls were set to lose 1 dB per reflection (absorption coefficient of 0.2) while absorptive vertical walls were set to lose 5 dB (absorption coefficient of 0.65). Note that the inclusion of sound reflections off of the standard vertical walls would account for effects from parallel reflective barriers. Also note that the modeling combination of the 85-foot-wide highway profile with 15-foot-high barriers provides a wall separation distance versus wall height of less than 10:1, so parallel barrier effects are a potential concern for the two-wall configurations.

Heavy truck traffic is an important consideration for traffic noise abatement because each vehicle is disproportionately loud and has the highest vehicle noise source (i.e., exhaust stack). This is important in the mountains because I-70 is an important national freight route. Truck traffic in the mountains may be high during daytime hours; in urban areas, truck traffic may be concentrated at night to avoid congested daytime traffic. Regardless, the CDOT noise analysis guidance is to examine the peak traffic noise hour and is not affected by the time of day that it occurs.

Nord2000 requires the input of weather data beyond just the temperature and humidity needed for TNM. Neutral weather data inputs were developed for Nord2000 that approximated TNM’s neutral weather conditions (i.e., no wind or inversion) for consistency with TNM results. In addition, three alternative weather conditions were examined using Nord2000 for a one wall condition to look at potential effects to wall performance: a temperature inversion gradient (10 Kelvin/100 meters); a 10 MPH perpendicular cross-wind; and, the combined inversion/cross-wind condition.

3.3 Modeling Results

The computerized modeling results are presented as a series of contour maps and associated cross section figures in Appendices A and B. Appendix A contains the base case model results without any noise abatement barriers for the two study areas (Figure 4) for both the TNM and Nord2000 methods. For these maps, hourly average traffic noise level contours are presented in plan view and cross section. Contour maps of the calculated noise level differences between the TNM and Nord2000 results are also included. Appendix B contains illustrations of the calculated noise reduction (or increase) amounts and locations with the various noise walls (Figure 5) in place. These were obtained by subtracting the gridded noise level values with a wall in place from the applicable base case noise levels for each grid node from the Nord2000 results (Appendix A).

The base case, unmitigated traffic noise levels using the TNM and Nord2000 calculation methods (Appendix A) for the two modeling areas (Figure 4) were intended to have similar model conditions. Note that TNM and Nord2000 use different vehicle emission levels, ground-smoothing algorithms, etc., so conditions and results would not be expected to be identical. However, similar results were produced by the two methods. Relatively similar noise levels and patterns were produced (generally within 3 dB of each other), which indicated that Nord2000 results could represent TNM results fairly well. The most noticeable differences in results occurred where there appeared to be relatively sharp terrain breaks. These are most likely due to differences in how each method handles ground smoothing and calculates ground effects. Typically the TNM results were higher. Also note the unusual contour lines shown directly above the highway in the TNM cross section figures; these contours are due to TNM's two-dimensional method for calculating distances. Also note that the Nord2000 base case figures in Appendix A represent the reference conditions against which the noise difference maps discussed below and in Appendix B are based.

The modeling results of the traffic noise reductions produced by the various wall configurations described in Section 3.2 are presented as contour maps and cross section figures of the differences in noise levels from the base case in Appendix B. That is, how much and where would noise levels change (reduce or increase) with the various noise wall configurations in place.

The organization of Appendix B is as follows: for each modeled area then wall type, the model results for a wall on both sides of the highway are followed by the results for a single wall on one side and a single wall on the other side. No noise sources other than the highway were included in the models. Note that the areas within the green shading in the figures were calculated to benefit according to CDOT noise abatement guidance, i.e., receive at least 5 dB of noise reduction to sensitive noise receptors.

For convenience, calculated noise levels for the Nord2000 models are listed in Table 2. These results are from grid points at three distances from the roadside barriers along the cross section lines shown in Figure 4. These results are intended to provide a quick comparison between noise levels for the different conditions modeled. Note that the model results are dependent upon the terrain, so the results shown in Table 2 will not be the same for all locations at those distances along the highway.

Table 2. Summary of Estimated Noise Levels for the Noise Barrier Concepts

Barrier type and position	Noise Level at Distance from Barrier (dBA)					
	250 ft	100 ft	50 ft	50 ft	100 ft	250 ft
Modeling Area 1	South side of road			North side of road		
No barrier	72	62	63	76	73	71
Vertical reflective barrier-both sides	65	65	62	64	63	66
Vertical reflective barrier-north side	74	63	64	61	60	60
Vertical reflective barrier-south side	60	62	60	78	75	74
Vertical reflective barrier-both sides and median	63	64	61	62	61	63
Vertical absorptive barrier-both sides	62	63	60	62	61	62
Vertical absorptive barrier-north side	73	62	63	61	60	60
Vertical absorptive barrier-south side	60	62	60	77	74	72
Vertical absorptive barrier-both sides and median	58	61	59	59	58	58
Lean-in absorptive barrier-both sides	59	61	59	60	59	59
Lean-in absorptive barrier-north side	72	62	63	60	59	59
Lean-in absorptive barrier-south side	59	61	59	76	73	71
Lean-out absorptive barrier-both sides	60	62	60	61	60	60
Lean-out absorptive barrier-north side	73	62	63	61	60	60
Lean-out absorptive barrier-south side	60	62	60	77	74	72
T-top absorptive barrier-both sides	58	59	55	57	55	57
T-top absorptive barrier-north side	72	62	63	57	55	56
T-top absorptive barrier-south side	57	58	55	77	74	71
Gallery absorptive barrier-both sides	54	51	49	49	50	53
Gallery absorptive barrier-north side	72	62	63	50	50	53
Gallery absorptive barrier-south side	54	51	49	76	73	71
Vertical reflective barrier-north side + south wind	71	61	62	63	62	63
Vertical reflective barrier-north side + inversion	75	67	67	64	63	63
Vertical reflective barrier + wind + inversion	72	66	67	66	65	66
Modeling Area 2	West side of road			East side of road		
No barrier	75	79	77	76	73	68
Vertical reflective barrier-both sides	75	68	65	62	64	61
Vertical reflective barrier-east side	77	81	79	60	61	57
Vertical reflective barrier-west side	72	64	63	76	73	69
Vertical reflective barrier-both sides and median	75	66	64	61	63	59
Vertical absorptive barrier-both sides	73	66	63	60	62	58
Vertical absorptive barrier-east side	76	80	77	60	61	57
Vertical absorptive barrier-west side	72	64	62	76	73	68
Vertical absorptive barrier-both sides and median	71	63	61	58	59	55
Lean-in absorptive barrier-both sides	72	64	62	59	60	56
Lean-in absorptive barrier-east side	75	79	77	59	60	56
Lean-in absorptive barrier-west side	72	64	62	75	72	68
Lean-out absorptive barrier-both sides	72	64	62	59	61	56
Lean-out absorptive barrier-east side	75	80	77	59	61	56
Lean-out absorptive barrier-west side	72	64	62	76	73	68
T-top absorptive barrier-both sides	72	60	58	55	57	53
T-top absorptive barrier-east side	76	79	77	55	56	52
T-top absorptive barrier-west side	72	59	58	76	73	68
Gallery absorptive barrier-both sides	66	55	52	48	50	47
Gallery absorptive barrier-east side	75	79	77	48	50	47
Gallery absorptive barrier-west side	66	55	51	75	73	68
Vertical reflective barrier-east side + west wind	77	76	75	62	63	59
Vertical reflective barrier-east side + inversion	77	81	80	63	64	61
Vertical reflective barrier + wind + inversion	77	77	76	64	65	62

4. CONCLUSIONS AND RECOMMENDATIONS

The conclusions from the literature review are summarized in Section 2.4 and are not repeated here. Other conclusions and overall recommendations from the noise modeling are provided below.

4.1 Conclusions from Noise Modeling

The potential comparisons that could be made among the noise modeling results (Appendix B) were too numerous and complex to be fully captured here. Several conclusions from the modeling results have been grouped together based on the type of result.

4.1.1 *Terrain Effects*

Several of the conclusions were due to the three-dimensional terrain that was included in the models. These included:

- ▶ The local terrain had a profound effect on the results. Mountain corridor terrain can be extreme and irregular and the noise level results reflected this. The initial noise levels and the reductions achievable by various walls were irregular due to the uneven ground. These effects are dependent on location-specific characteristics and are not readily transferable from other settings.
- ▶ The modeled terrain was based on 10-foot ground surface contours, which provided a general mountain valley setting but was not intended to examine specific effects from small local details like an exposed rock cliff face. Therefore, the modeled results do not include noise reflections off natural rock surfaces. Because the local terrain and geometries (in sound propagation) matter so much for the final results, the effects from such characteristics would be best examined through a detailed local analysis.
- ▶ Providing a substantial noise reduction for impacted receptors uphill from the highway may be difficult. The modeling indicated that the benefitting zone uphill from the road often is relatively small with several of the walls, so stronger measures may be necessary.
- ▶ When the highway is perched above a town and/or valley floor, conventional noise walls at the road level can have a sizeable benefitting zone for these lower elevations.

- ▶ In some cases, it appeared that addition of noise walls at the road edge may affect the local sound propagation geometry such that traffic noise was directed into otherwise sound-shadowed areas blocked by the natural terrain (Figure 7). These situations appeared to be behind a hump or break in the terrain where the ground slope moving away from the road transitioned from steeper to flatter. The results appeared to be due to how the model handles ground effects and/or sound refraction. The resulting noise levels were relatively low compared to the NAC, but could represent a relatively large increase. At a minimum, results such as these may indicate areas where unexpected noise changes could develop from changes to the highway. This situation may be an important consideration for elevating a road, for example, and would be influenced by local terrain.
- ▶ The alternate weather conditions modeled (cross wind, inversion and both) were found to reduce the noise barriers' effectiveness. If these types of weather conditions are common for an area, traffic noise barriers will be less effective.

4.1.2 Barrier Shape Effects

Several of the conclusions were due to the three-dimensional shapes of the noise barriers that were modeled. These included:

- ▶ The wall concepts that were evaluated all could provide the CDOT noise reduction goal (at least 7 dB) for near-road locations, which is required for feasibility [2]. Whether impacted receptors would be within this zone will depend on individual circumstances.
- ▶ Noise reductions of 15 dB were calculated for some locations with the 15-foot-tall walls.
- ▶ Several wall concepts showed promise in providing noise reductions in many situations. The largest and most comprehensive noise abatement structures were found to provide the greatest noise reductions. The galleries, which form enclosures similar to tunnels, naturally showed the greatest noise reductions. Vertical walls with center median walls also showed relatively large noise reductions. These concepts would also be among the most expensive and visually intrusive abatement options due to the size of the structures.
- ▶ The geographic areas that received a 5-dB noise reduction (the green areas in the Appendix B figures) were similar but not identical for several of the wall concepts (vertical, lean in, lean out and T-top). However, the predicted noise reductions within

these areas differed among the concepts. The leaning-in and T-top walls were found to have generally higher noise reductions in areas close behind the walls.

- ▶ Gallery barriers were found to have the best potential to provide benefits to receptors uphill from the highway. For most other wall types examined, the geographic differences in the benefitting zones observed for similarly sized walls were usually not large (particularly in uphill situations), so a simpler concept should be preferred among these.
- ▶ Complex or exotic noise barrier concepts are likely to be more expensive than the traditional vertical concepts CDOT has used in the past. True costs would be heavily influenced by the support structures needed for the local ground conditions, which can be highly variable. In the absence of a specific design or materials selections for a specific situation, CDOT's standard barrier cost (\$45 per square foot) could be used for a preliminary estimate of barrier reasonableness.
- ▶ An important consideration for any noise abatement measures that may overhang a road's driving surface is that a minimum 17.5-foot vertical clear zone may be required by CDOT specifications. This could affect the viability of galleries, leaning-in walls, T-top walls or similar wall concepts.

4.1.3 Barrier Material Effects

Several of the conclusions were due to the type of barrier material that was modeled. These included:

- ▶ Sound reflections from barriers may increase noise levels for some locations. The increases from reflections in single-wall situations were generally less than 2 dB. This finding was based on total sound levels and was not examined on a frequency-band basis where the changes among the frequency bands may differ.
- ▶ For single wall situations, sound-absorptive materials did not appear to provide any added benefit versus reflective materials for locations behind the wall. Unprotected sensitive receptors on the opposite side of the road may benefit, though.
- ▶ Absorptive barriers may be particularly important and provide noticeable noise reductions for parallel barrier situations (Figure 6).

Figure 6. Noise Benefit from Absorptive Instead of Reflective Wall Material (Parallel Walls at Location 1)

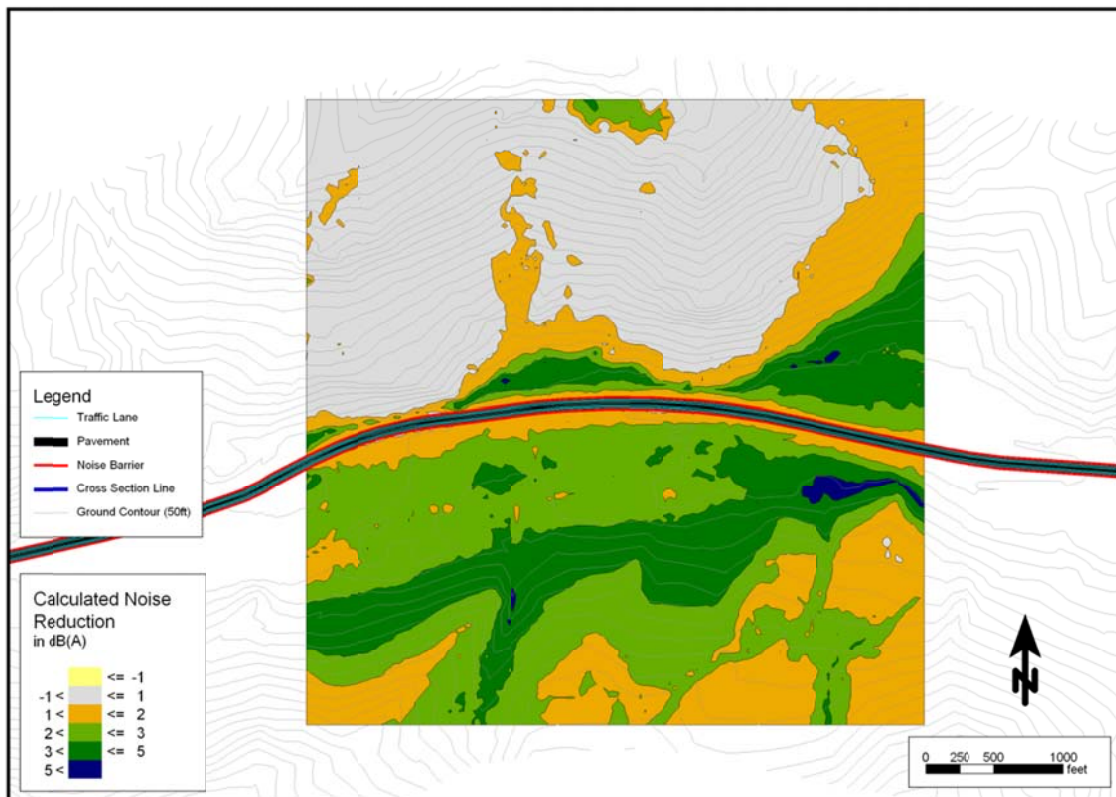
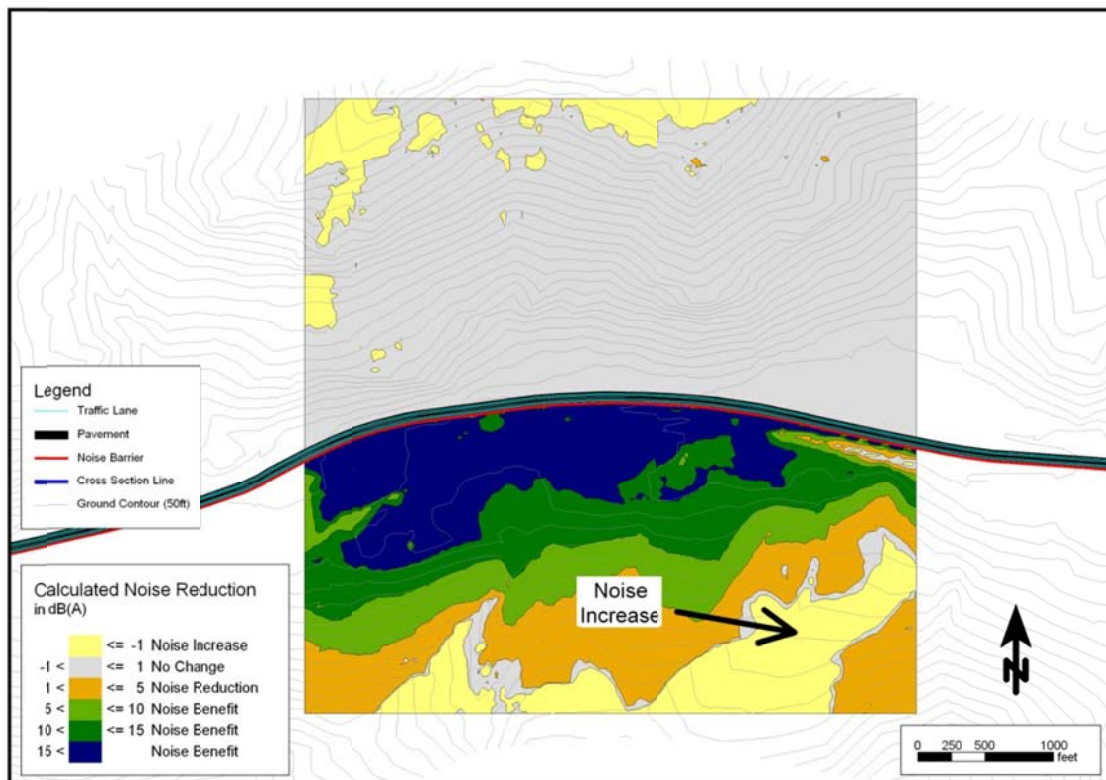


Figure 7. Example of Modeled Noise Increases at Distance from Highway with a Barrier



4.1.4 Maintenance Considerations

Winter road maintenance in mountain corridors with noise walls would be expected to be more challenging and expensive than areas without walls. To be effective, noise walls need to be free from gaps and often close to the source; therefore, traditional winter plowing that pushes snow onto or over the road shoulder would be hindered due to blockage by noise walls. Another maintenance method, such as snow collection and removal, may be required.

I-70 is predominantly an east/west route, so noise barriers on the south side of I-70 may lead to full or partial shadowing that would inhibit snow and ice melting from sunshine. Transparent barrier material could be used to reduce this and also preserve the natural vistas, but there may be higher maintenance costs if the material loses transparency as it ages. Alternatively, some barriers such as galleries may reduce the amount of snow that accumulates on the driving surface. Noise barrier designs would need to resist rock falls in susceptible areas.

When considering noise abatement actions in mountain corridors for feasibility and reasonableness according to CDOT's guidelines [2], there are several common factors that often work against finding that a barrier is reasonable. When evaluating noise barriers as abatement actions, the same unit costs for walls are used statewide. Homes are often more dispersed in mountain communities than in the larger urban areas, which will worsen the cost/benefit results regardless of other construction challenges. Walls may need to be larger to overcome topographic challenges, which would increase cost and affect the cost/benefit results.

4.1.5 Estimated Costs

Noise walls are expensive and a long-running challenge with noise wall materials has been identifying less expensive materials that are effective and durable yet still acceptable to local communities. Lowering the overall costs would increase the chances traffic noise abatement actions could be found to be reasonable and recommended within a project.

Accurate costs to mitigate can be difficult to determine without doing detailed analysis and design for an actual situation. A great deal of the cost will depend on materials selected and the foundation/support needed for the design selected. Wall foundations can be challenging in rocky areas so walls with simpler foundation designs may be advantageous, though each site would have unique characteristics that may affect the choices.

The cost/benefit effectiveness of the various wall design concepts (Section 3.1) was compared through the estimated relative cost to construct a wall versus the amount of noise benefit that could be realized from the wall (Table 3). Note that detailed wall designs were not prepared for this project and that unique conditions at a site will affect final design and the associated costs. Several simplifying assumptions about the walls were made for this evaluation, including:

- ▶ Below-ground elements (i.e., foundations) were similar for each wall type.
- ▶ The same wall materials were used for each wall type. Absorptive versus reflective wall materials were not considered.
- ▶ Lighter structure was used for the gallery roof. Galleries required more structure (e.g., trusses or frames) to support the roof, which added cost.
- ▶ No additional right-of-way needs or other environmental issues were considered.

The costs of the various wall configurations were estimated at a gross level from the professional opinion of a structural engineer. Each wall was assigned a numeric score relative to a standard 15-foot vertical wall based on the estimated cost—a score of 200 would represent twice the cost of the vertical wall (Table 3).

Table 3. Summary of Estimated Cost/Benefit Effectiveness of Noise Barrier Concepts

Wall Configuration	Relative Cost versus Vertical Wall (Percent)^a	Relative Noise Benefit versus Vertical Wall (Percent)^b	Relative Benefit/Cost versus Vertical Wall^c
Vertical wall	100	100	1.0
Vertical wall and median wall	140	190	1.4
Inward lean wall	120	160	1.3
Outward lean wall	120	150	1.2
T-top wall	120	180	1.5
Gallery	300	300	1.0

^a Higher number reflects higher overall cost.

^b Higher number reflects higher overall noise reduction.

^c Higher number reflects better overall effectiveness of the barrier concept.

The relative benefit (at least 5-dB noise reduction) provided by each wall concept was scored by multiplying the size of the area receiving a benefit (Appendix B) by the approximate benefit (in dB) provided in each area and comparing the results to those for the standard vertical wall (Table 3). Only the situation with walls on both sides of I-70 for both of the model areas was reviewed for this analysis. A score of 200 in this category equates to twice as much overall noise reduction in the modeled area (Appendix B) as the standard vertical wall. Note that the physical area

receiving a noise benefit was used as a proxy for actual sensitive receptors—individual circumstances will dictate whether any receptors are in the benefitting areas.

Finally, the benefit score was divided by the cost score to provide an overall estimate of the effectiveness of the modeled barriers. A higher score represents a more effective barrier (Table 3).

The estimates on barrier effectiveness show that the alternative wall concepts may perform at least as well as standard vertical walls; T-top walls and vertical/median wall combinations may be the best among these. The gallery walls showed approximately equal overall effectiveness as standard vertical walls, but recall that galleries may be most effective in benefitting receptors uphill from the highway. Even so, the alternative barrier concepts may not be appropriate in every situation.

To reiterate, the cost estimates in Table 3 are gross and could be greatly influenced by many factors, such as materials selection, roadside conditions or site structural support issues and may vary widely in the future.

4.2 Recommendations

The recommendations have been divided into design element considerations and abatement measure considerations.

4.2.1 Road Design Elements

Generally, many effective traffic noise minimization measures can be part of the initial design of a road and some of the measures may be available during subsequent road improvements. This is true for mountain corridors as well as other settings and includes such things as providing distance between the road and sensitive receptors (i.e., compatible land use planning or highway routing).

Moving the highway away from sensitive receptors may be an effective noise reduction strategy in theory, but it is often not realistic in developed areas. Still, it is recommended where applicable.

Road design should make maximum use of both the natural terrain and constructed highway elements by exploiting the sound shielding that can be provided from hills, cuts, ramps, safety barriers, etc. This would require early consultation between road designers and noise specialists on projects.

Pavement selection should include tire noise considerations. Pavement choice cannot be counted as a formal noise abatement action but can still be beneficial and selection of pavement through an informed process is recommended. CDOT research has demonstrated that quieter versions of the standard pavement types are available, so this knowledge could be used to lower overall traffic noise [15]. Pavement selection should be a consideration in context-sensitive decisions.

CDOT could enable quiet pavement to become a formal abatement action by establishing a Quiet Pavement Pilot Program with FHWA. However, this can be a difficult process and is not guaranteed to be successful. Several cautions on this subject were presented with previous CDOT research and are still valid [15]. Even if a program was implemented, ensuring that a 7-dB noise reduction from pavement is achieved and maintained may be difficult. CDOT likely would be obligated to more frequent pavement replacement than otherwise planned. This approach is not recommended, but the pilot programs in other states should be monitored for new developments.

4.2.2 Noise Abatement Measures

Although not a perfect solution, noise barriers were found to be the most effective and proven traffic noise abatement action. In cases where relatively modest road improvements are proposed for an existing highway, there may not be other viable options for noise abatement. Therefore, barriers are recommended for consideration as primary noise abatement actions in the mountain corridors.

The typical vertical noise wall can be effective in mountainous areas, but can also be limited in some situations. Each noise abatement situation will need to be examined in detail individually—blanket recommendations would not fit all situations in Colorado. The modeling results showed that some unconventional barrier concepts (e.g., galleries) may be effective in otherwise difficult situations or may provide more cost effective mitigation (Table 3). TNM Version 2.5 may not be

able to handle these types of analyses, so use of more capable noise modeling tools is recommended for consideration in these situations.

Absorptive barrier materials are recommended for consideration during the materials selection process. Absorptive barriers can reduce the negative indirect effects from sound reflections in single-wall situations that may affect unprotected receptors and could be important for context sensitivity. Absorptive barriers may be particularly effective in minimizing unfavorable reflections from parallel barriers (Figure 6).

Research and engineering feasibility evaluations into items for special noise wall types and treatments, such as foundation requirements, durability, cost and maintenance requirements, in Colorado mountain corridor conditions may be useful. This could include construction of prototype walls to assess effectiveness and performance.

Interest in developing context-sensitive traffic noise solutions was one motivation for this project. CDOT has some resources on context sensitivity, such as Policy Memo 26, the I-70 Mountain Corridor PEIS Context Sensitive Solutions guidance and the CDOT NEPA Manual. Noise abatement should be included in context-sensitive planning, but what this will translate into as on-the-ground actions is not well defined. Put another way, what tools will be in the toolbox when implementing context sensitivity? There are a number of constraints that affect deciding what noise abatement action will (or will not) go where. For context sensitivity, might any allowances be made for actions in the mountain corridors? There are a number of social and technical considerations involved; some can be contentious. Starting a conversation earlier among stakeholders may be a valuable outreach action and implementation approach. A continuing discussion and examination of what can or cannot be done may be warranted internally among CDOT staff and externally with affected communities to continue developing strategies and design guidelines for context sensitivity.

4.3 Summary of Conclusions and Recommendations

To summarize, major conclusions and recommendations from this research study include:

- ▶ Highway noise abatement is challenging in mountain environments, particularly for sensitive receptors located uphill from the highway.

- ▶ Even with inherent specific challenges in the mountains, noise barriers were found to be the most appropriate noise mitigation measures for mountain highway corridors. Earth berms can be effective barriers, but space constraints in mountain corridors often preclude their use.
- ▶ Special noise wall types and treatments, such as galleries, T-tops and absorptive surfaces, can increase barrier effectiveness in certain situations, and may be more important in mountain corridors than in other places with flatter terrain.
- ▶ Quieter pavement types may be useful as a supplemental measure, but cannot be a primary noise abatement measure.
- ▶ Noise abatement issues will need to be considered in detail during design of mountain corridor highways and take into account all available conditions and consider abatement options presented here. This should take into consideration the complex terrain and roadway parameters, geometric constraints, available mitigation options and context sensitivity. Detailed modeling using a tool such as Nord2000 may be useful for supporting effective barrier design in these environments.
- ▶ Additional research and engineering feasibility evaluations may be useful in evaluating factors such as foundation requirements, durability, cost and maintenance requirements for special noise wall types and treatments in Colorado mountain corridor conditions.

4.4 Future Research

Several options for further research are available. A goal in these efforts should be toward spotlighting noise abatement measures that will be effective, feasible and reasonable in the mountain corridors.

4.4.1 Abatement Barrier Materials and Designs

Research into engineering and maintenance feasibility for several wall concepts and materials may be useful in evaluating factors such as real-world noise reduction performance, wall foundation requirements, durability, cost and maintenance requirements in Colorado mountain corridor conditions. This may include building prototype wall segments for field testing. A location with an adjacent uphill slope may be preferable to assess performance in these difficult traffic noise conditions. Wall placement on the south side of I-70 would facilitate evaluation of

effects from sun shading, which would be primarily a winter maintenance concern. A possible location may be near Lawson, which is a relatively small area where homes are near I-70. However, Clear Creek is south of I-70 at this location, which means that uphill areas behind the prototype wall would be set back a distance. A review of I-70 in Clear Creek County indicated that a location west of the Continental Divide along I-70 may be needed to avoid this situation.

4.4.2 Noise Modeling

Further research into comparing results from TNM versus Nord2000 could help determine the value of Nord2000 as a supplemental noise evaluation and design tool for projects in mountain settings. Field verification through noise measurements may be needed.

4.4.3 Quiet Pavements

CDOT could continue efforts for identifying quieter types of pavements that also have good engineering performance. Even though pavement cannot be used as a mitigation action, deliberate use of quieter pavements would demonstrate support of CDOT's stewardship goals.

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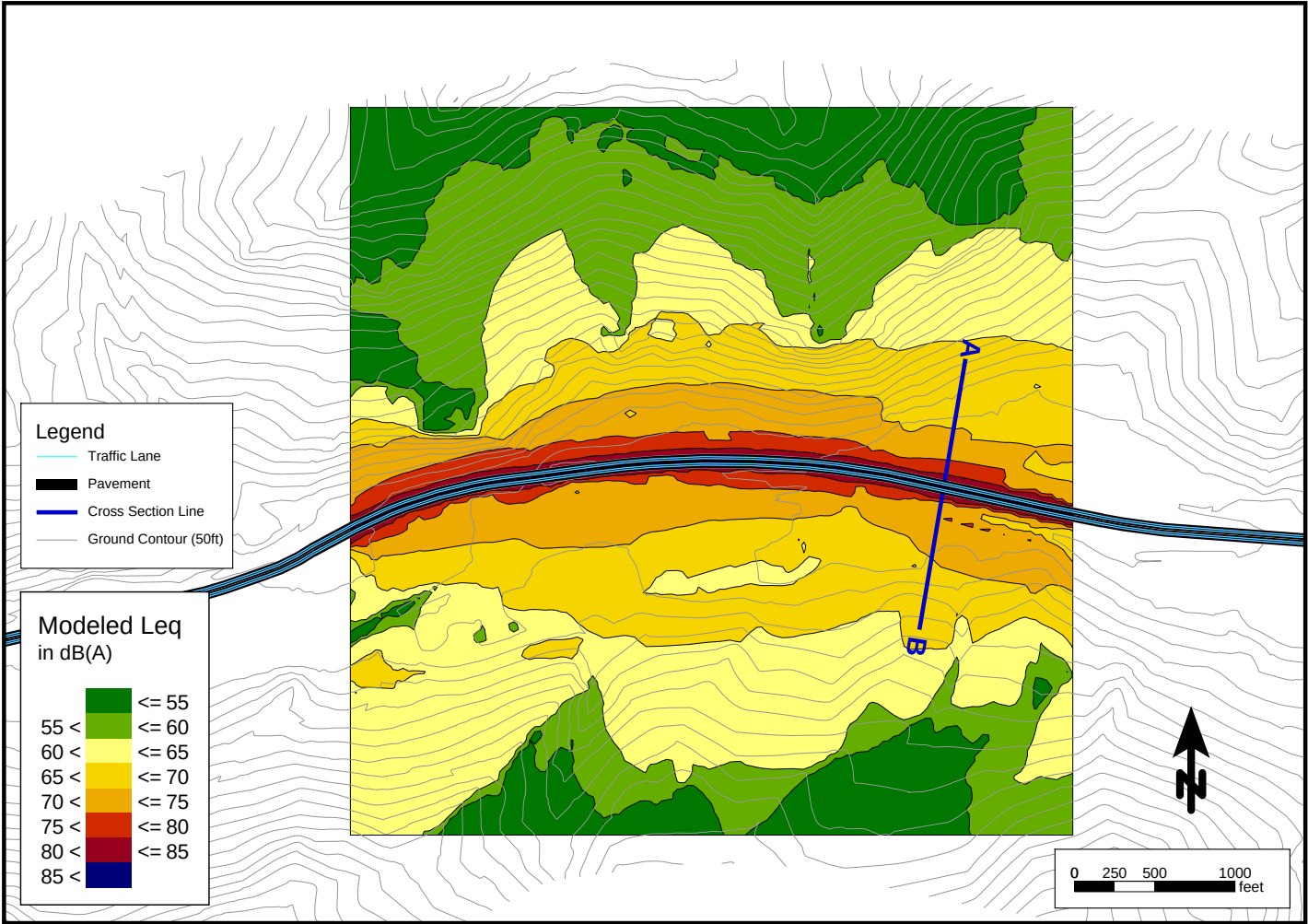
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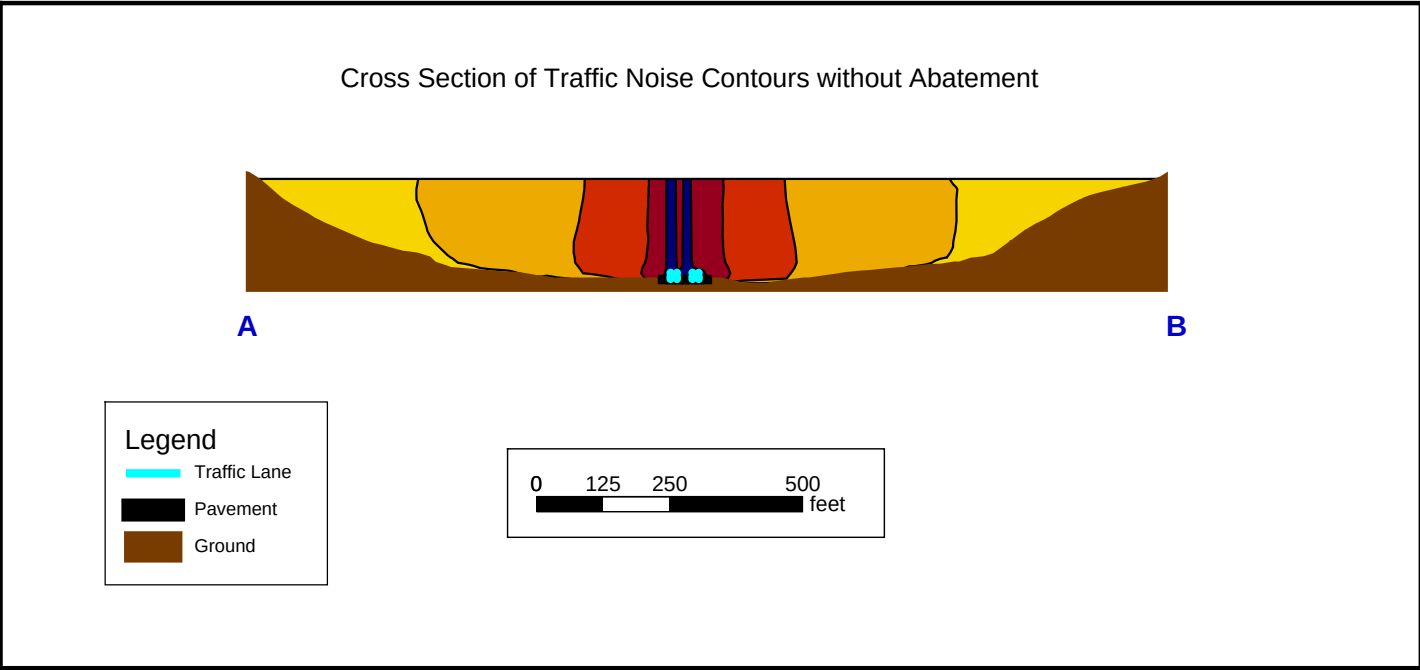
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APPENDIX A
Modeled Traffic Noise Levels Without Abatement
From TNM and Nord2000 Road

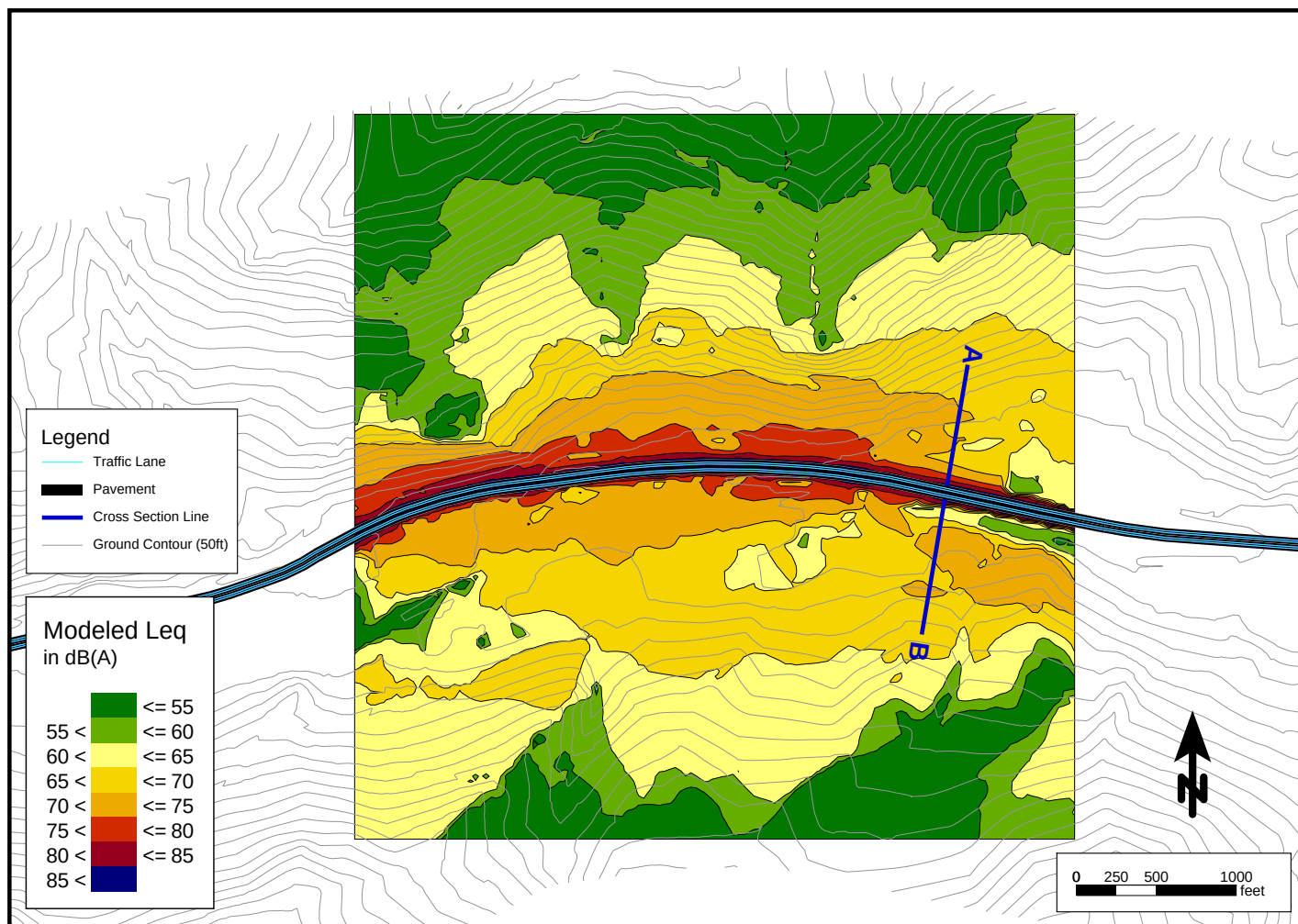
Area 1 Traffic Noise Levels Without Abatement--TNM



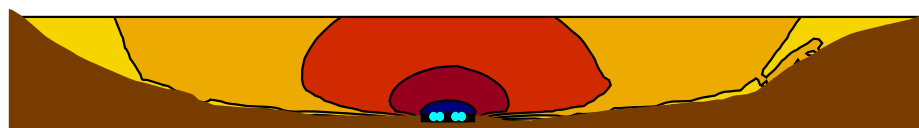
Cross Section of Traffic Noise Contours without Abatement



Area 1 Traffic Noise Levels Without Abatement--Nord2000

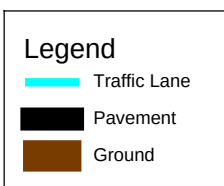


Cross Section of Traffic Noise Contours without Abatement

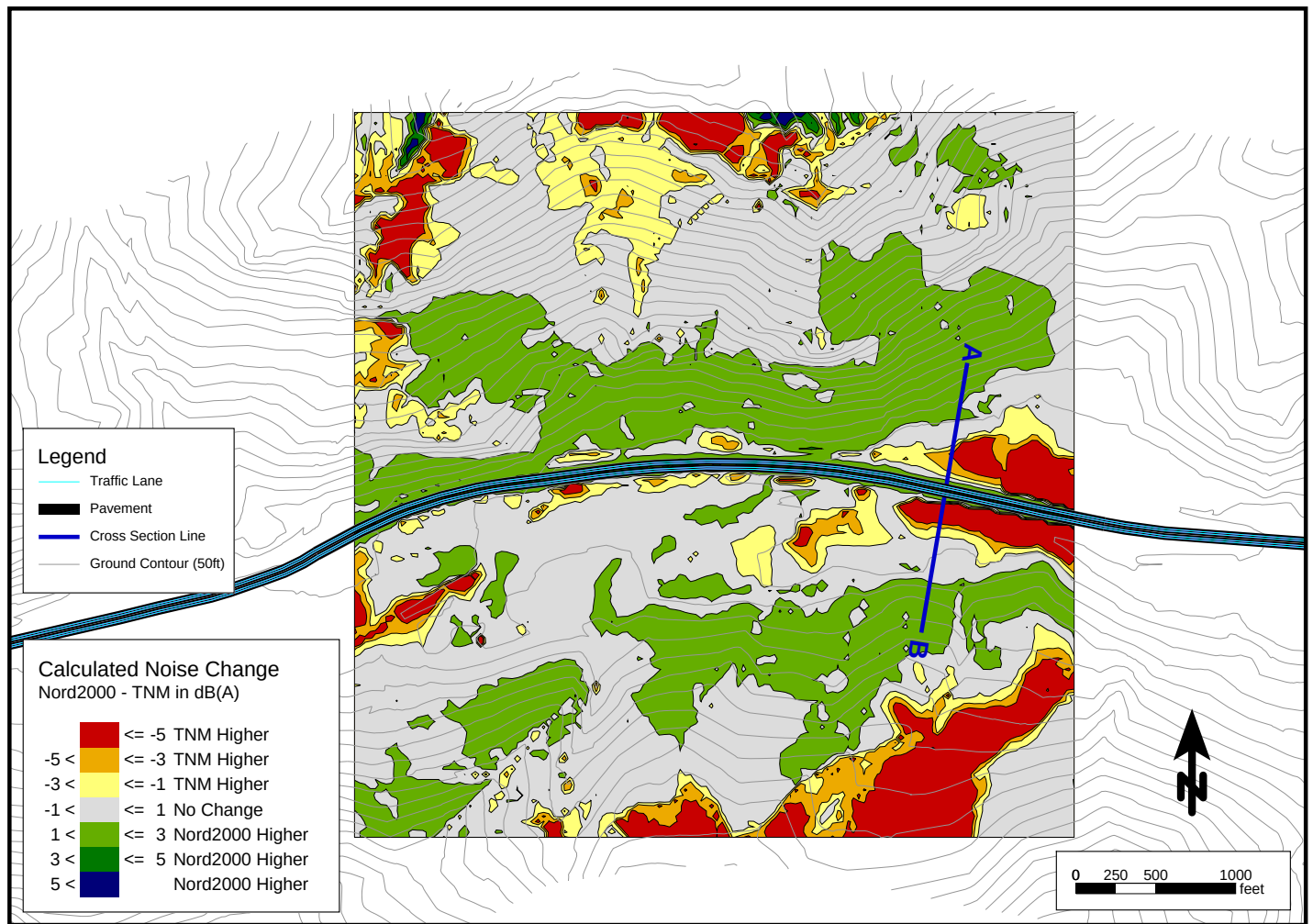


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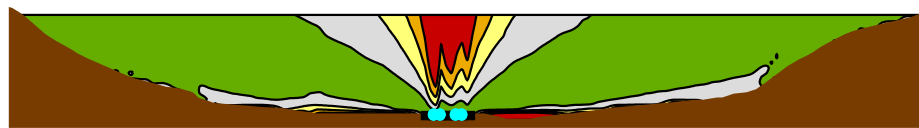
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Area 1 Modeled Noise Difference--Nord2000 Compared to TNM

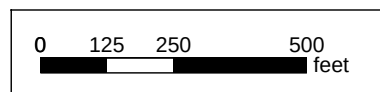
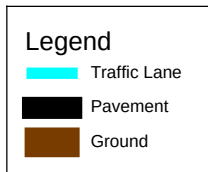


Cross Section of Noise Level Differences

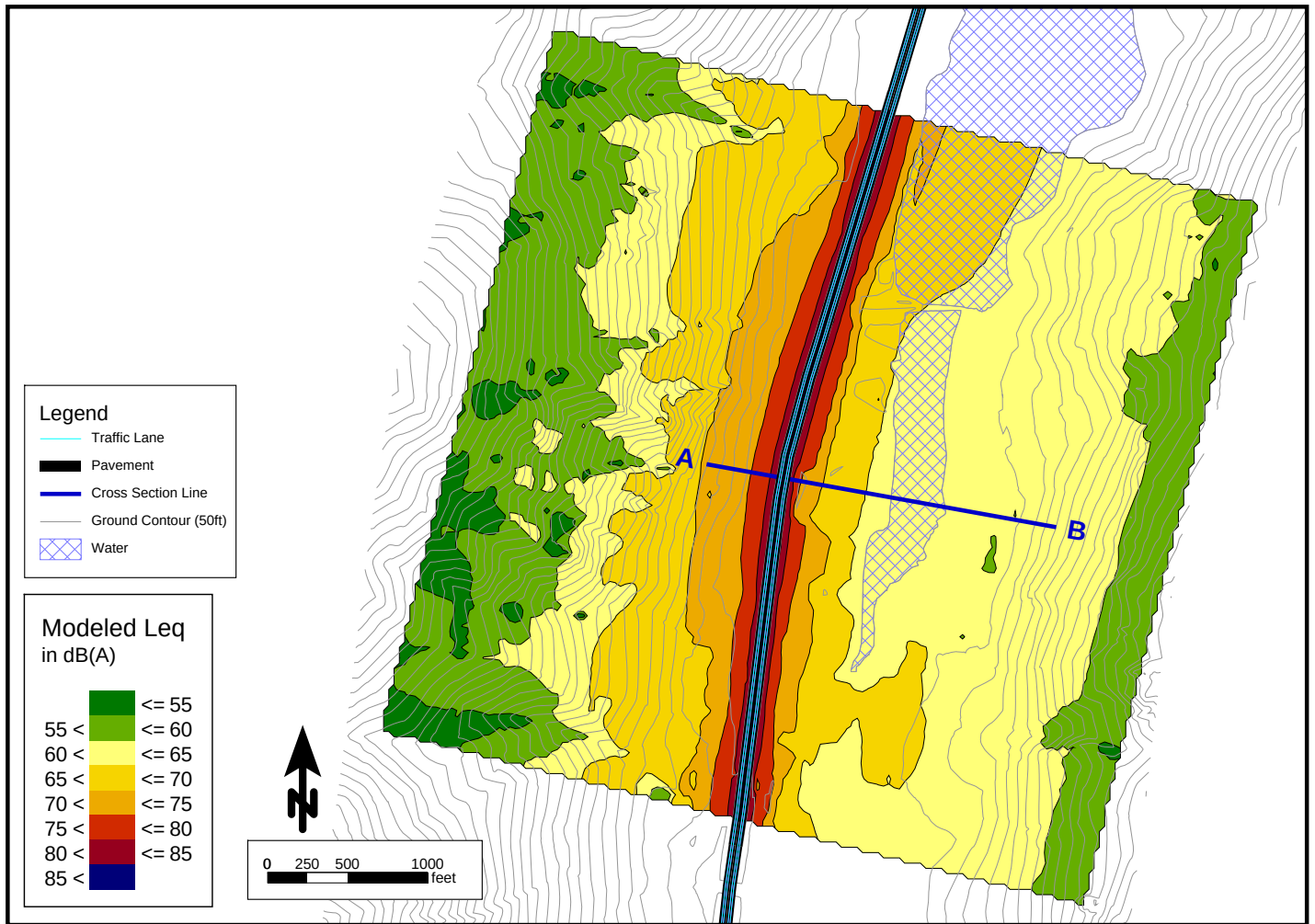


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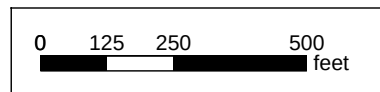
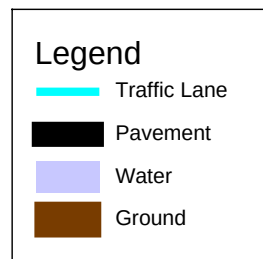
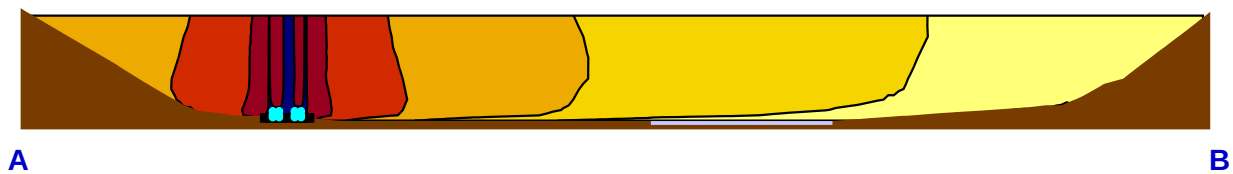
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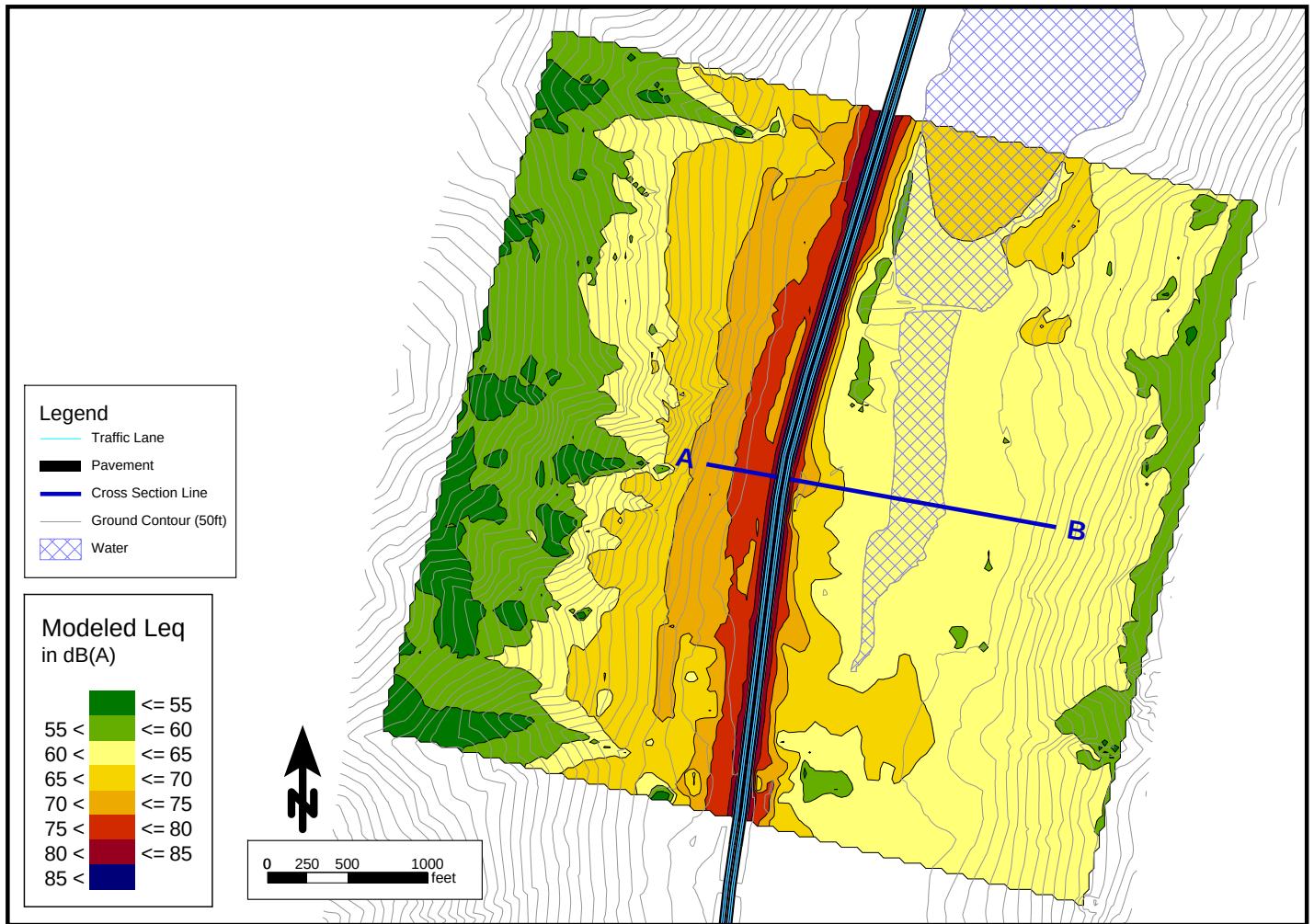
Area 2 Traffic Noise Levels Without Abatement--TNM



Cross Section of Traffic Noise Contours without Abatement



Area 2 Traffic Noise Levels Without Abatement--Nord2000



Cross Section of Traffic Noise Contours without Abatement



A

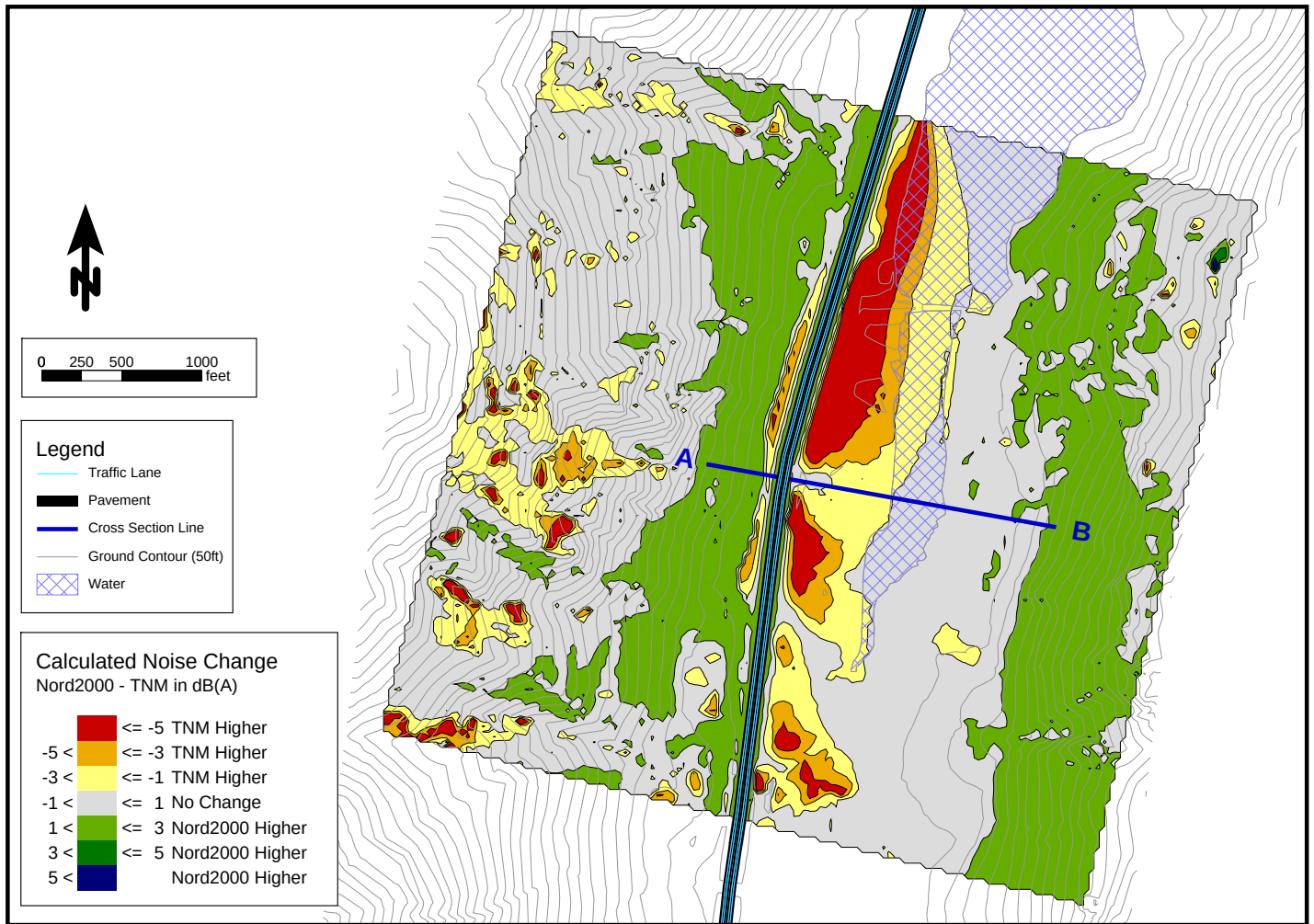
B

Legend

- Traffic Lane
- Pavement
- Water
- Ground

0 125 250 500 feet

Area 2 Modeled Noise Difference--Nord2000 Compared to TNM

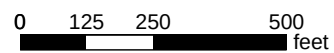


Cross Section of Noise Level Differences



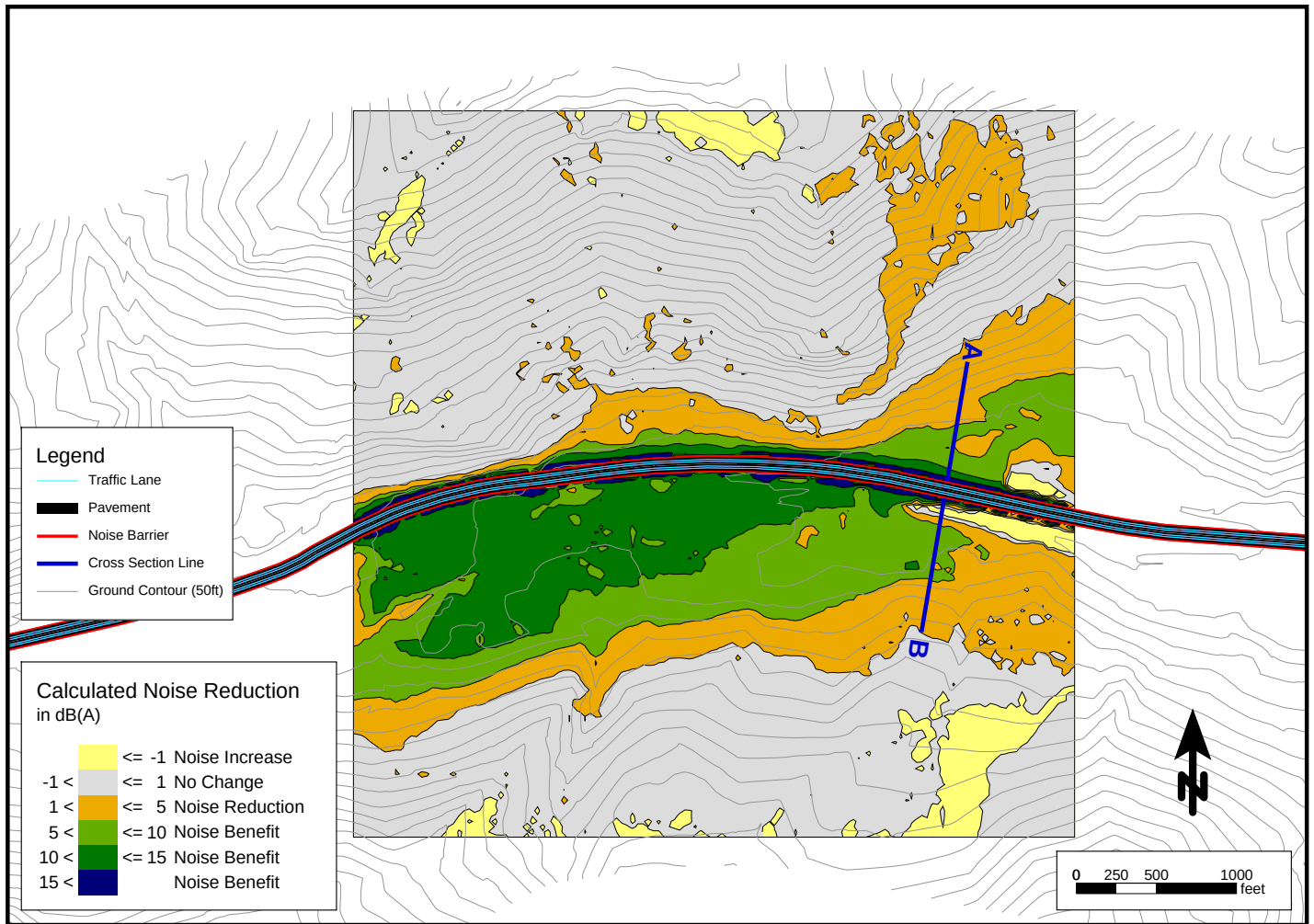
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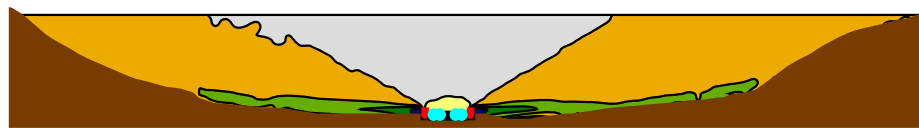


APPENDIX B
Calculated Differences In Noise Levels From Various Noise Walls
Using Nord2000 Road

Area 1 Modeled Noise Reductions From 2 Reflective Barriers

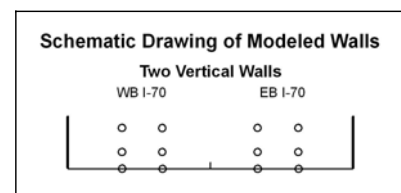
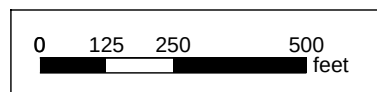


Cross Section of Noise Level Reductions with Abatement

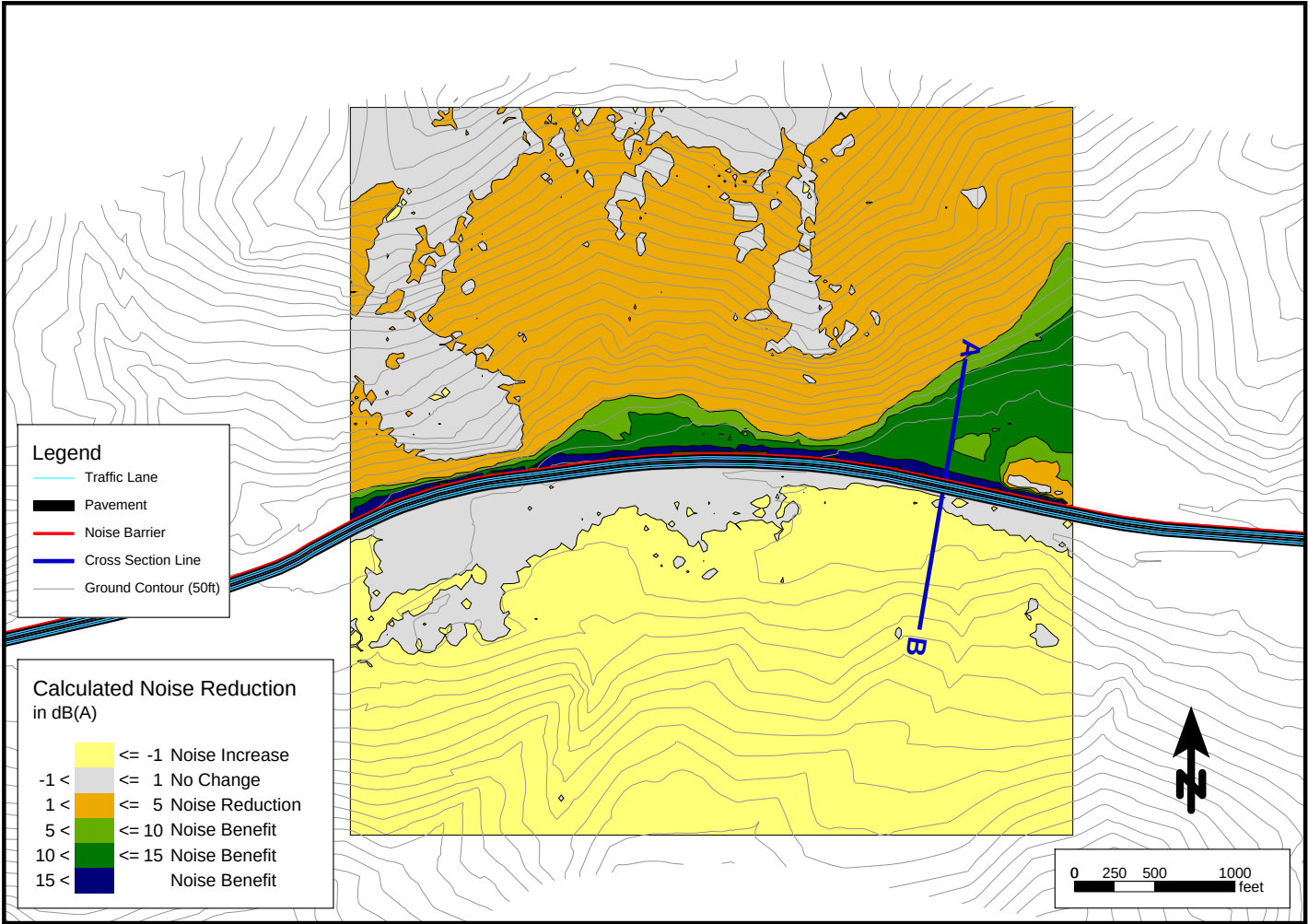


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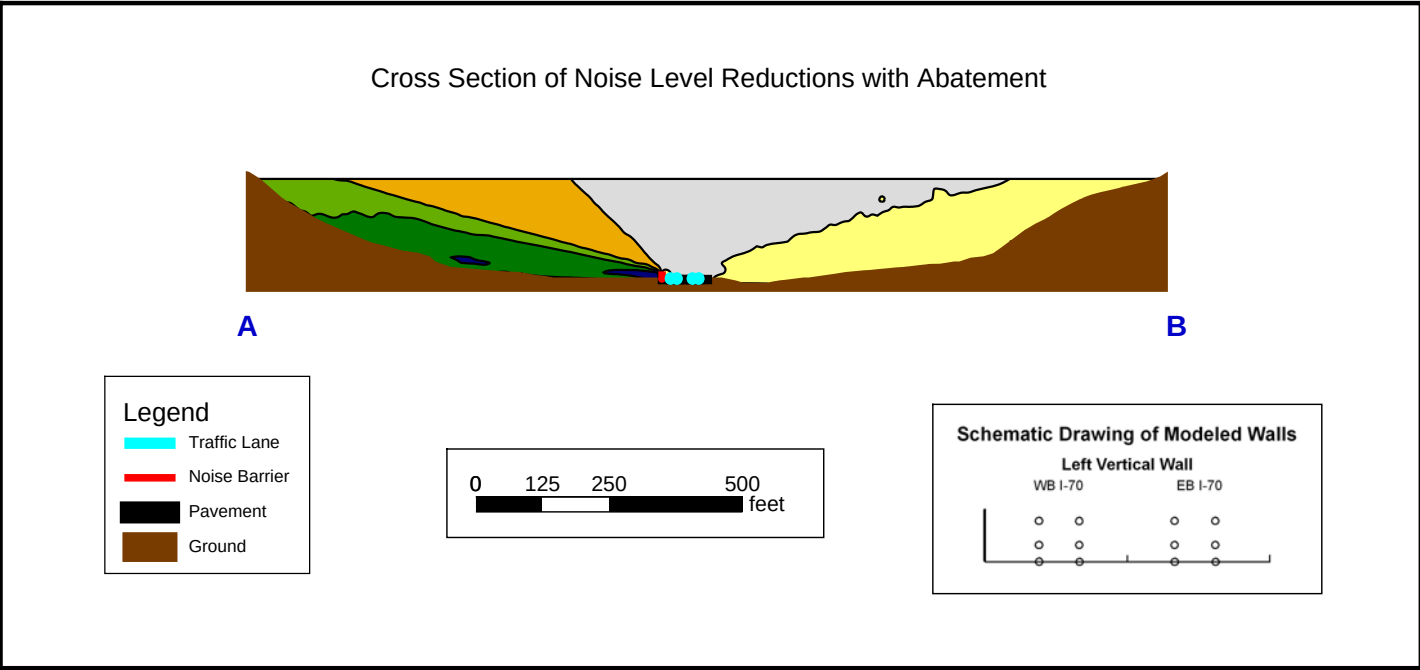
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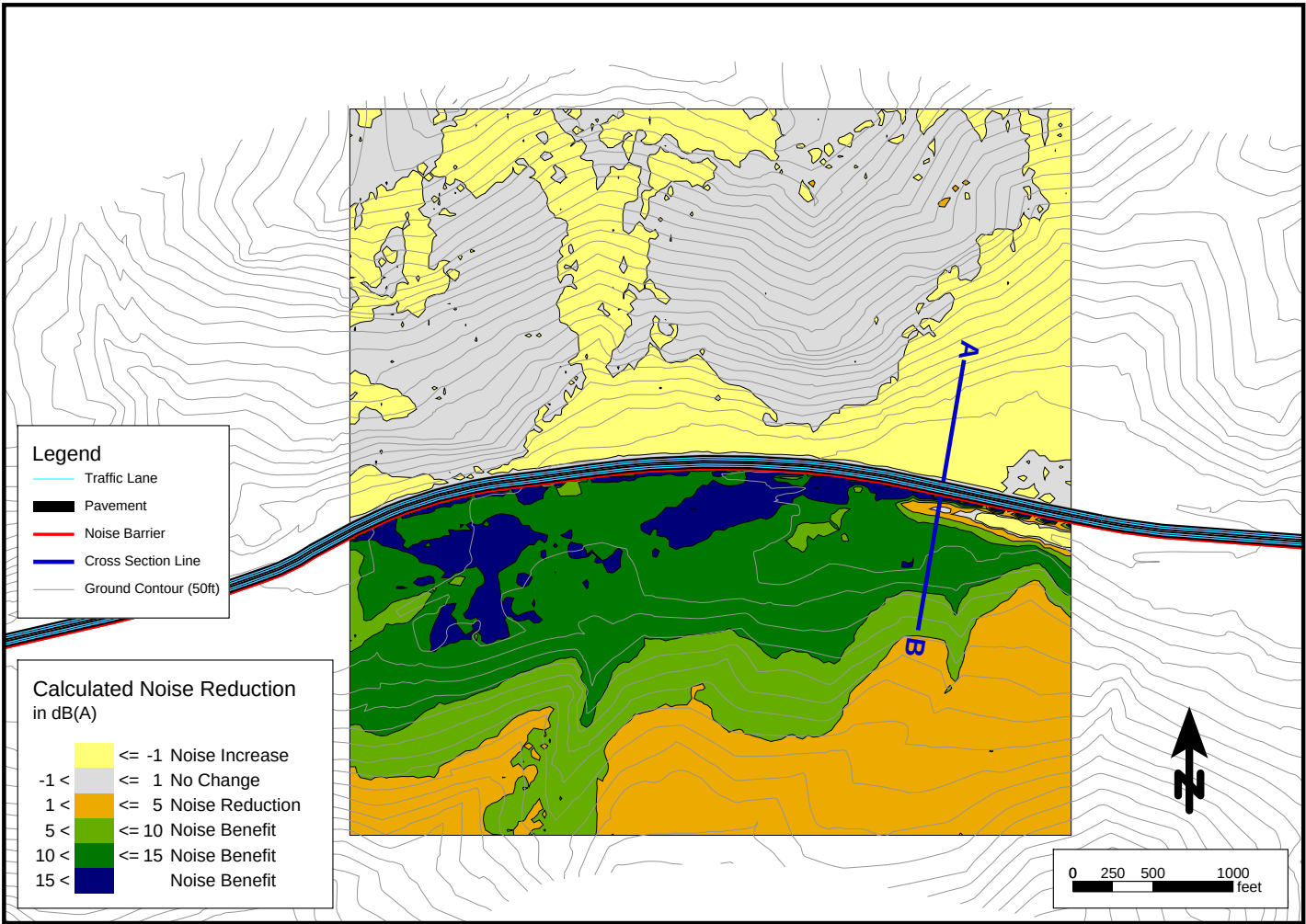
Area 1 Modeled Noise Reductions From North Reflective Barrier



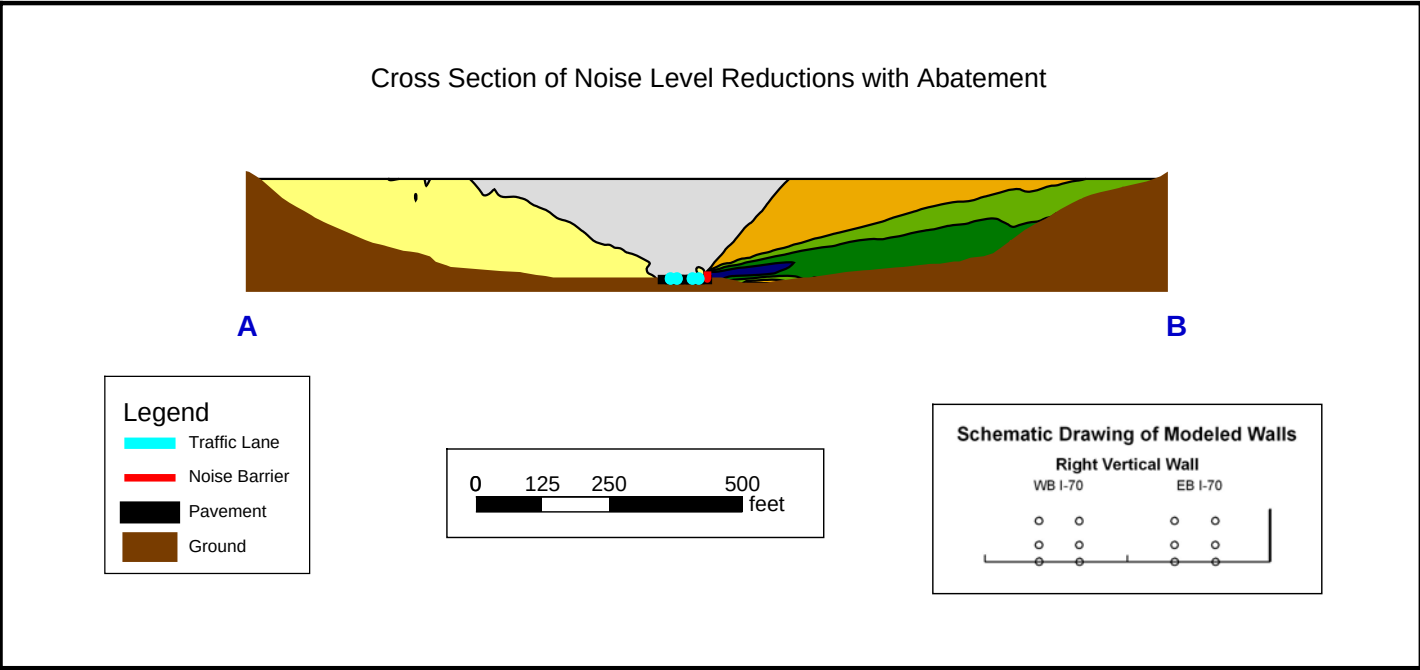
Cross Section of Noise Level Reductions with Abatement



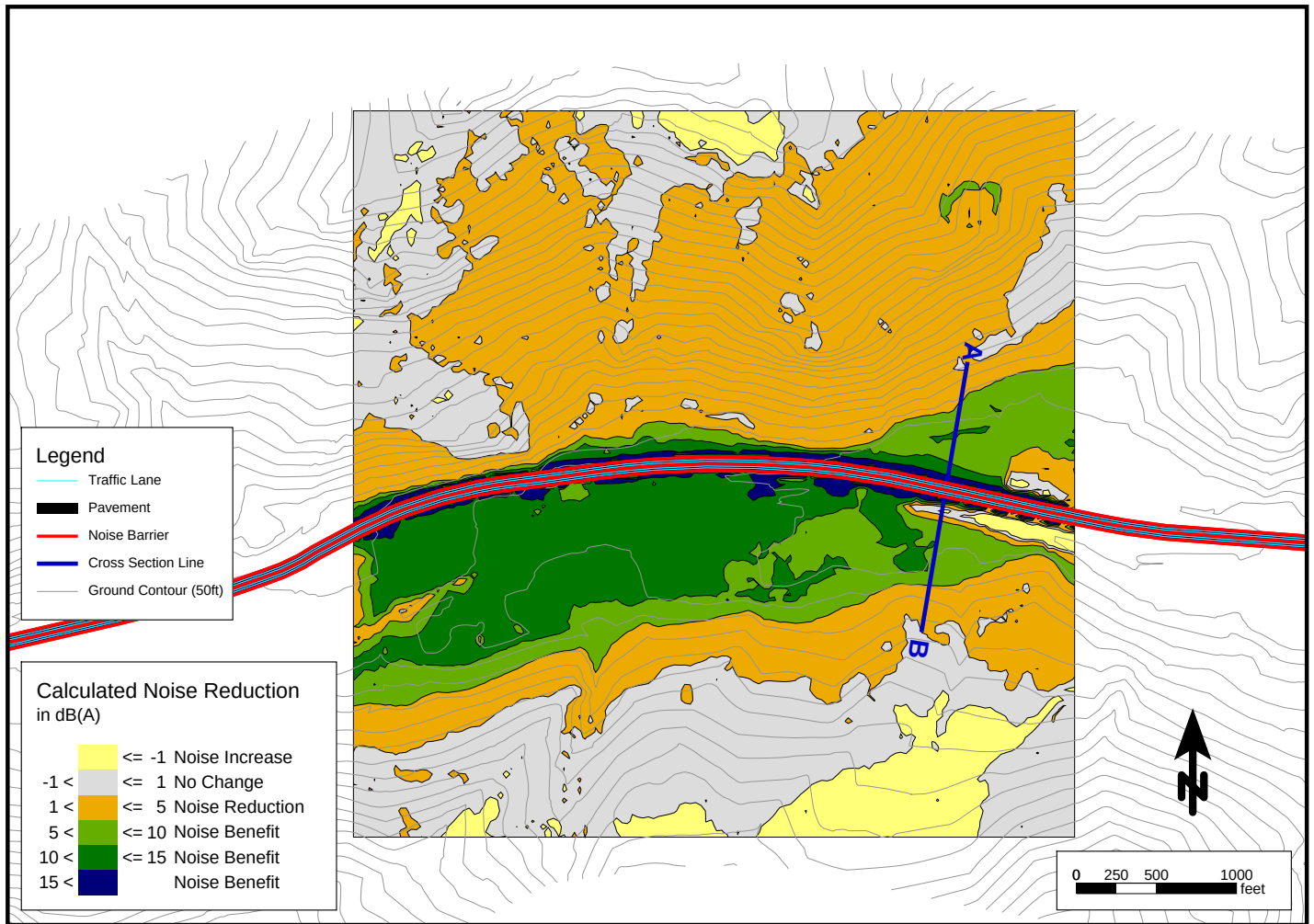
Area 1 Modeled Noise Reductions From South Reflective Barrier



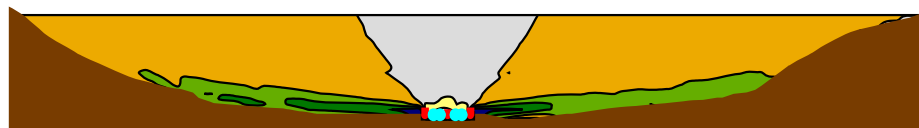
Cross Section of Noise Level Reductions with Abatement



Area 1 Modeled Noise Reductions From Reflective Median Barriers

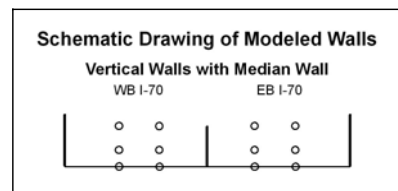
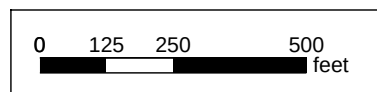


Cross Section of Noise Level Reductions with Abatement

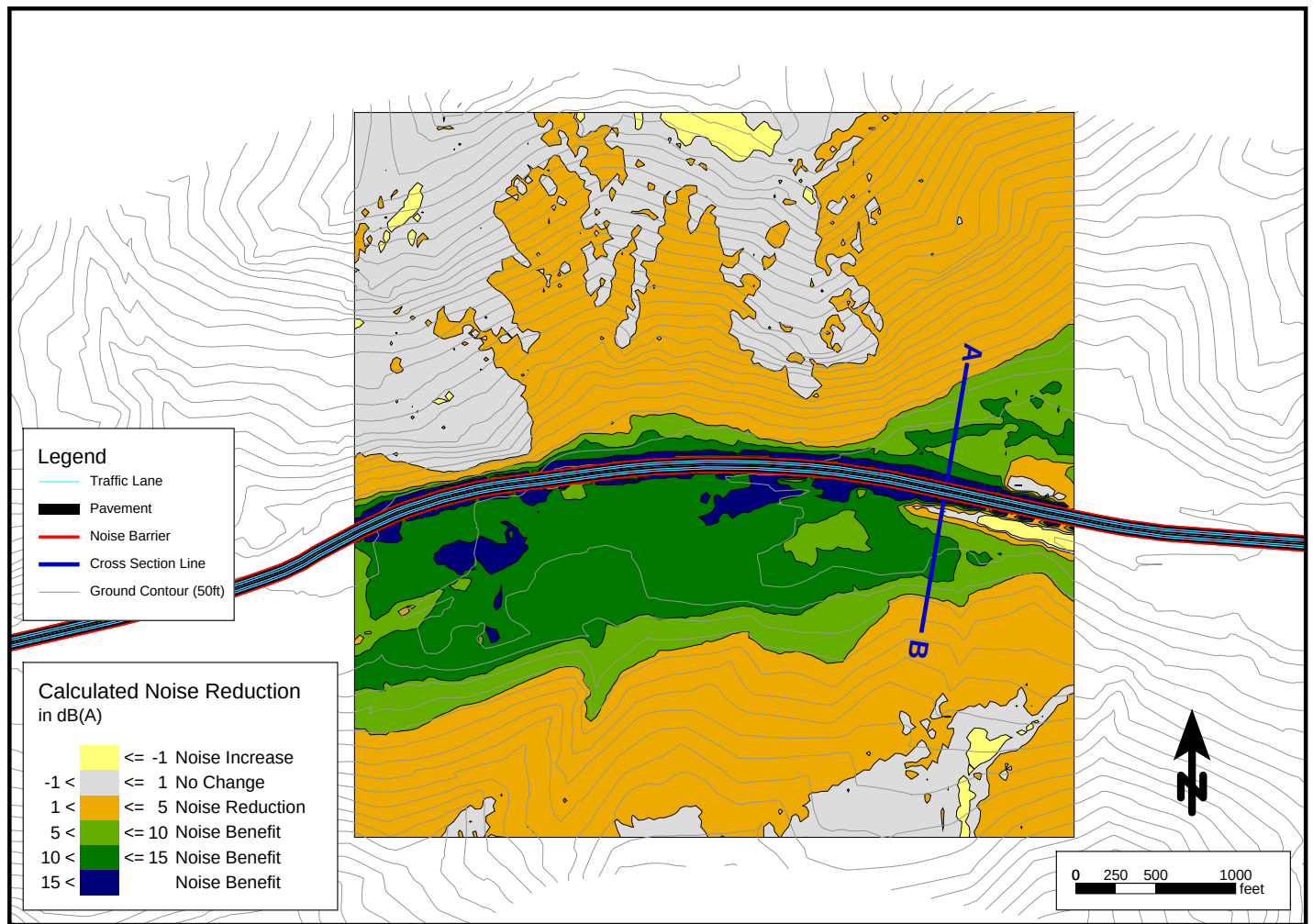


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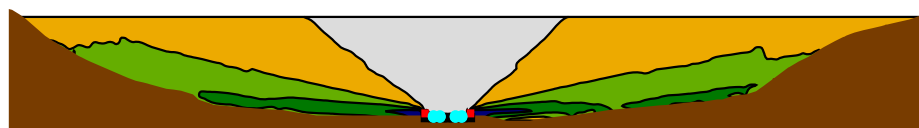
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Area 1 Modeled Noise Reductions From 2 Absorptive Barriers

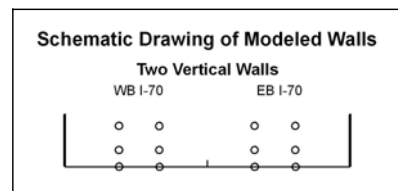
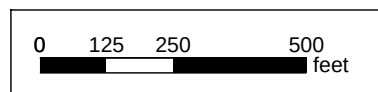
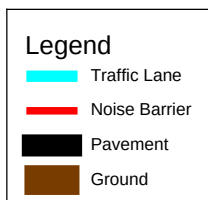


Cross Section of Noise Level Reductions with Abatement

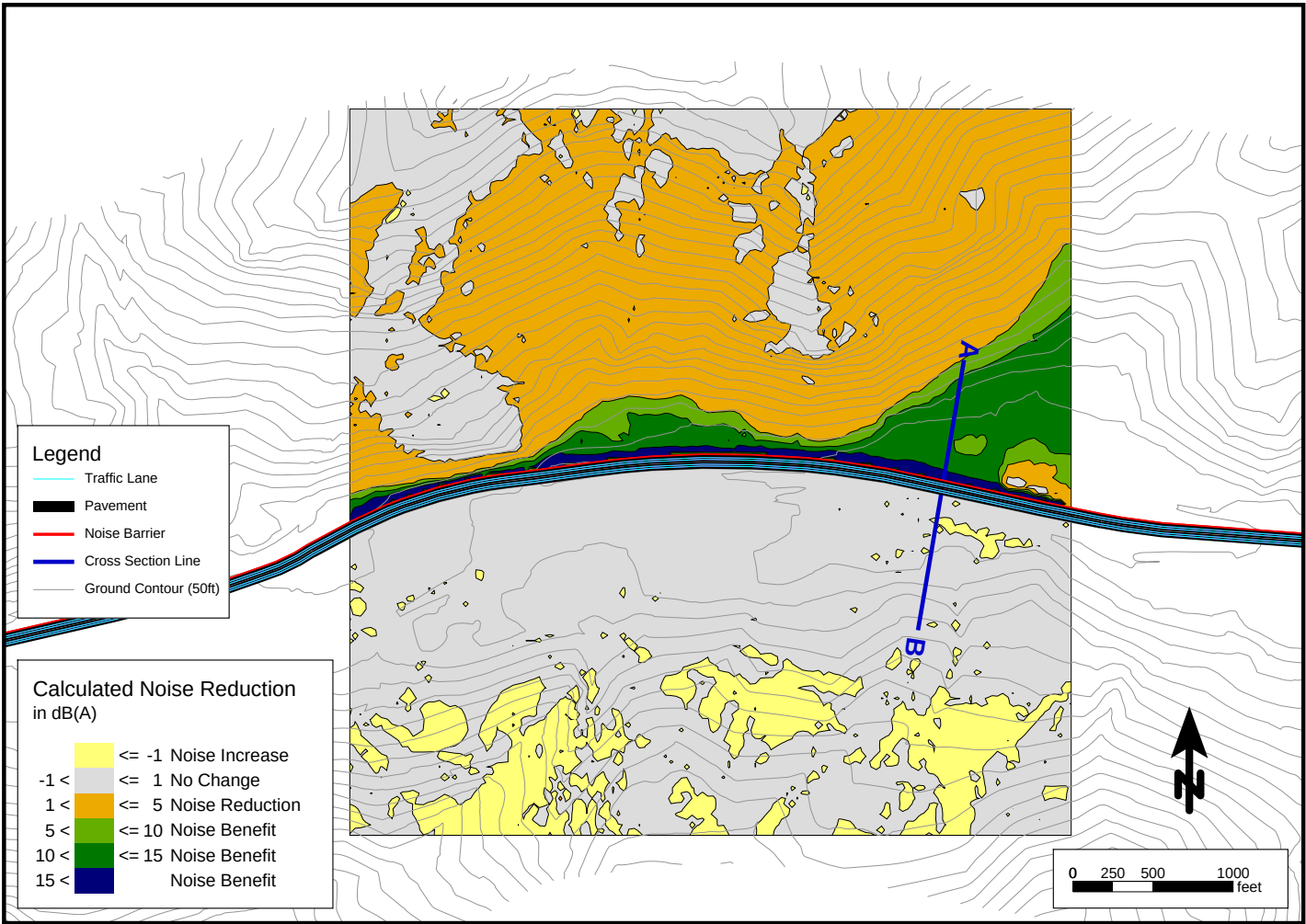


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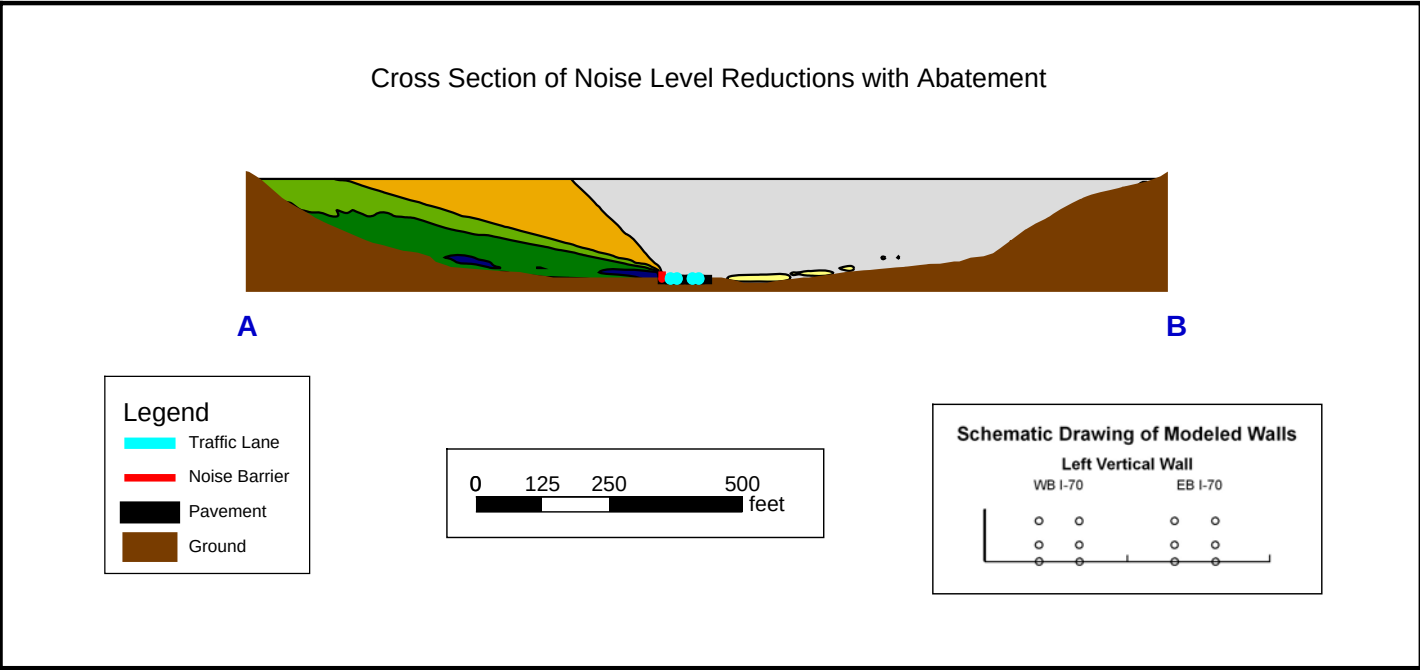
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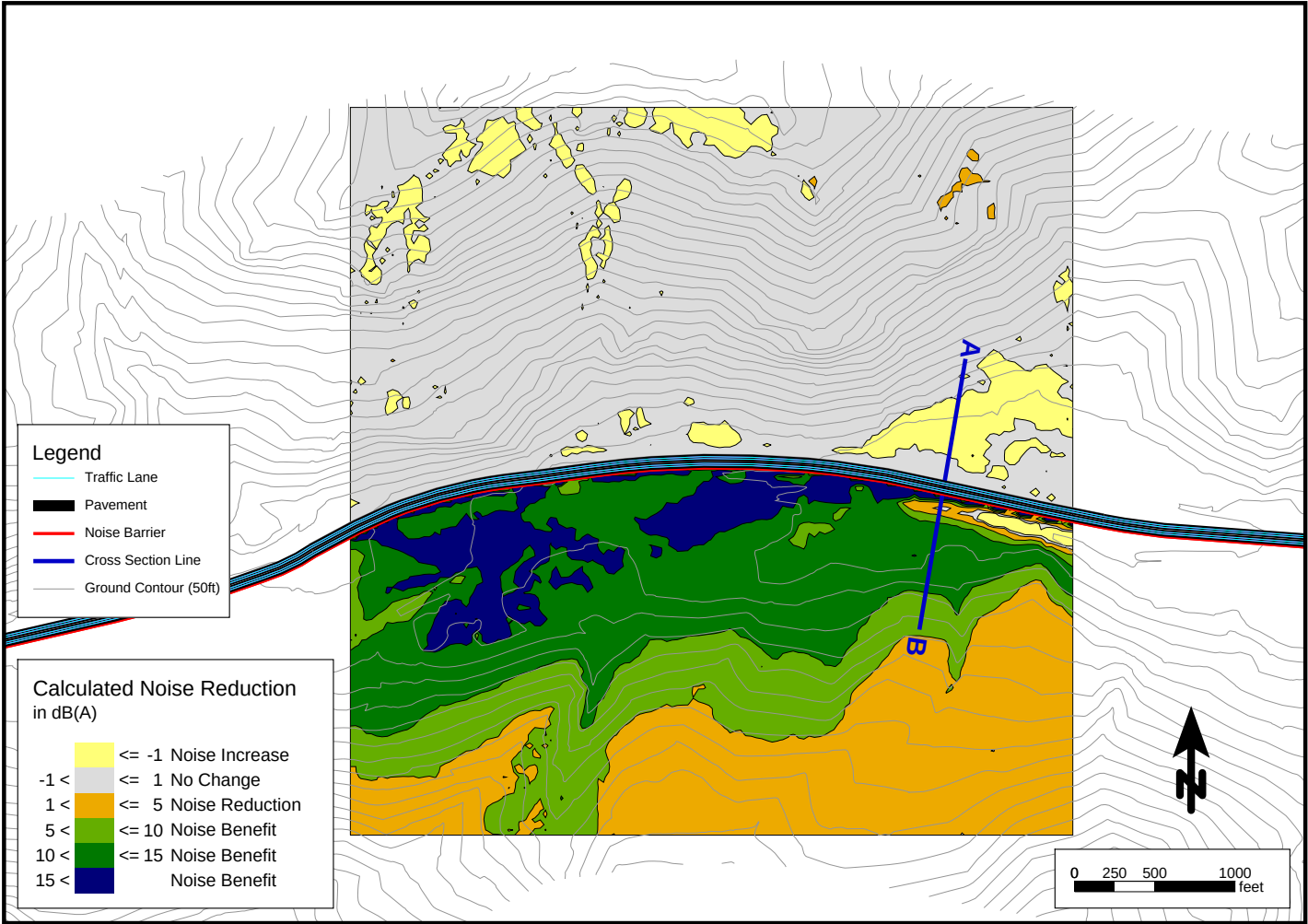
Area 1 Modeled Noise Reductions From North Absorptive Barrier



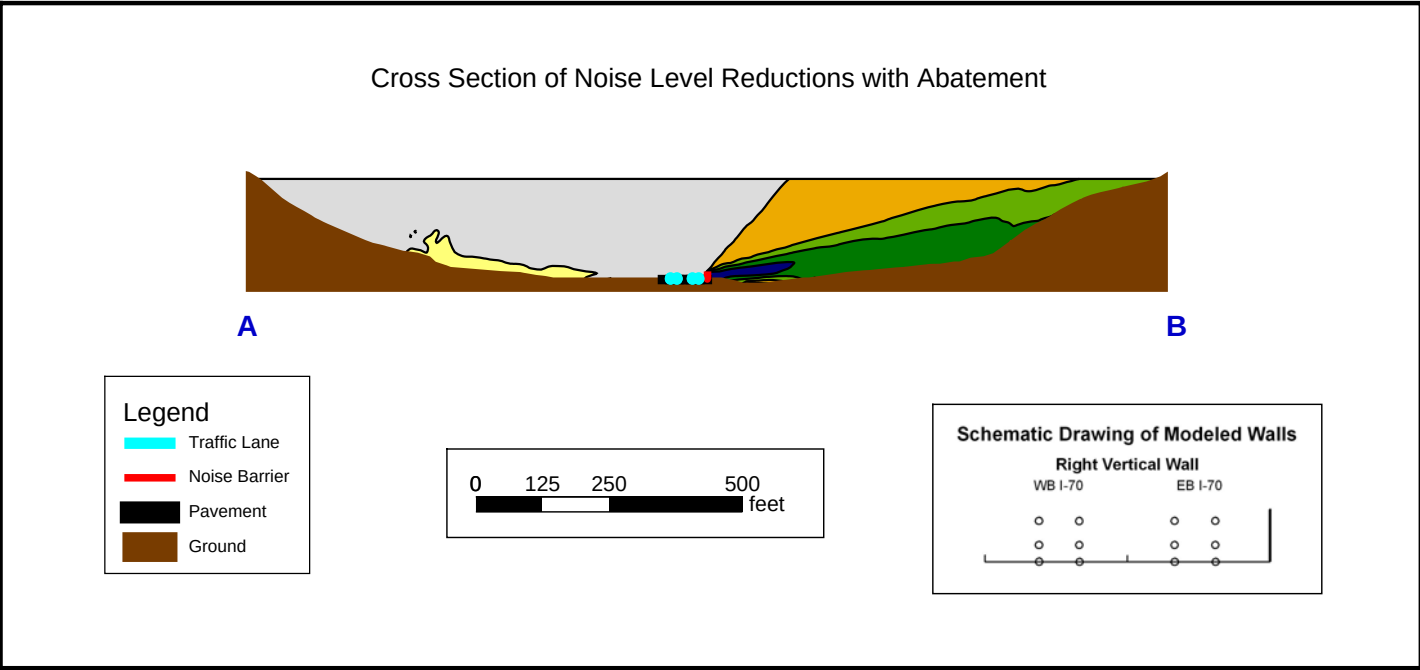
Cross Section of Noise Level Reductions with Abatement



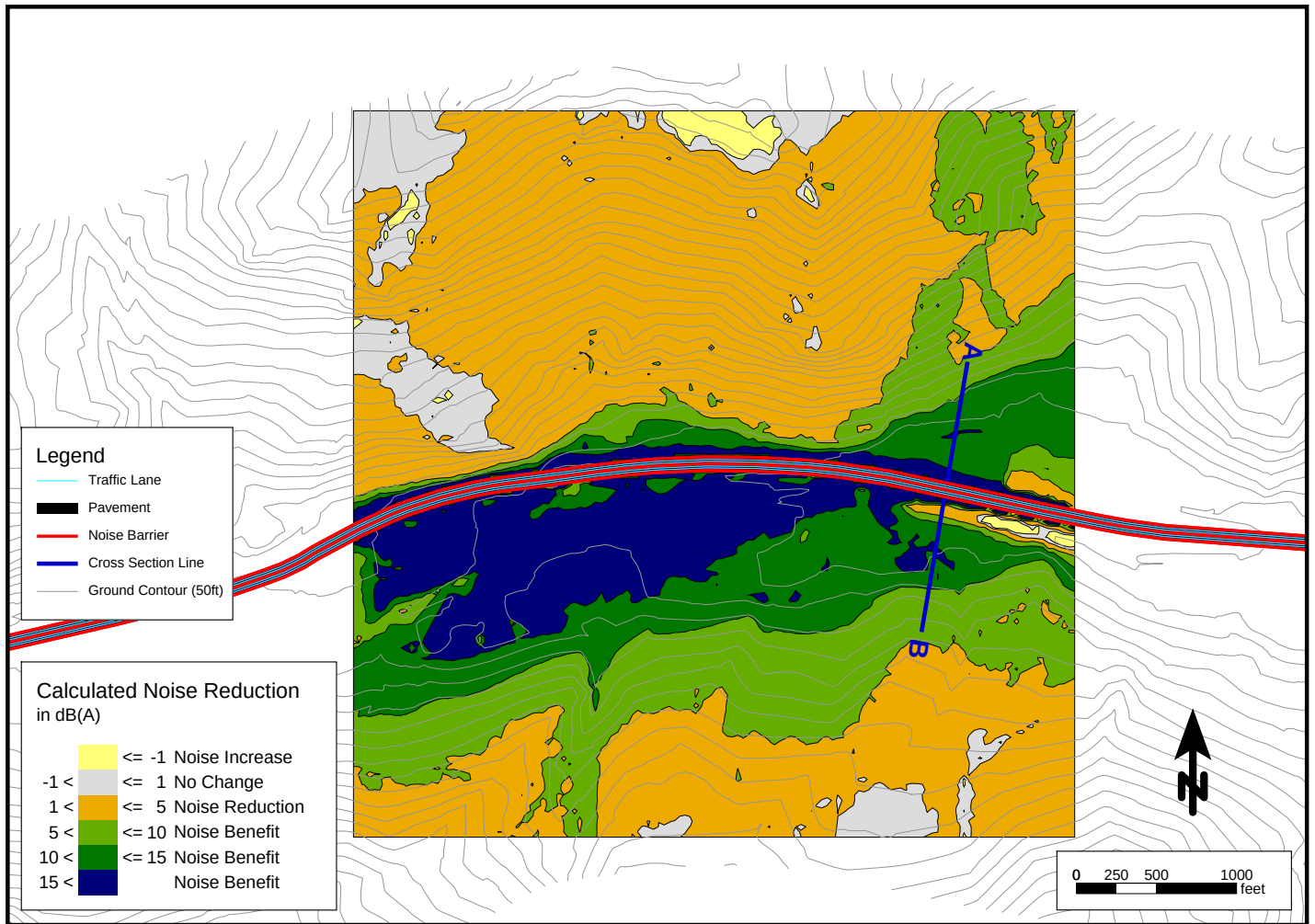
Area 1 Modeled Noise Reductions From South Absorptive Barrier



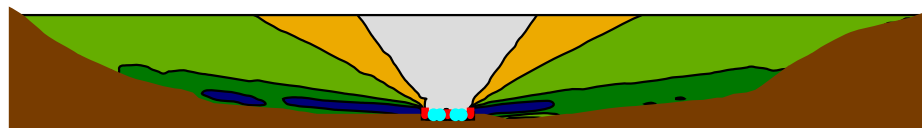
Cross Section of Noise Level Reductions with Abatement



Area 1 Modeled Noise Reductions From Absorptive Median Barriers

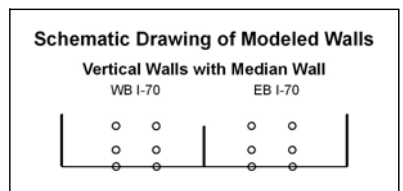
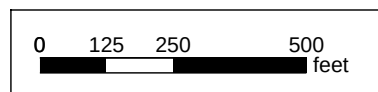


Cross Section of Noise Level Reductions with Abatement

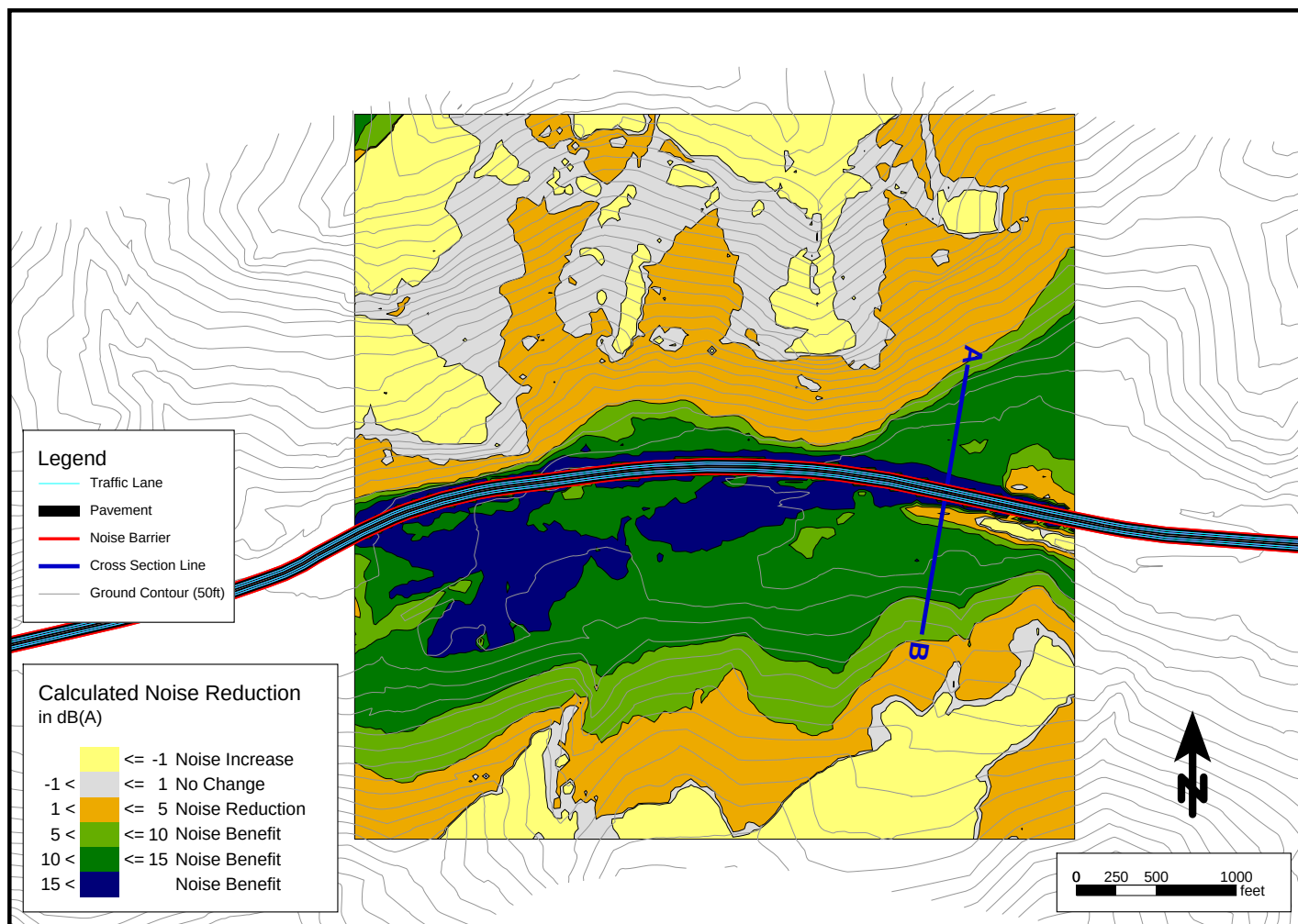


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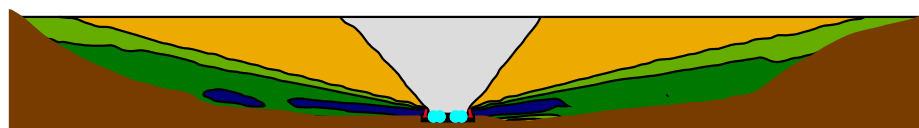
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Area 1 Modeled Noise Reductions From 2 Barriers Lean In 10°

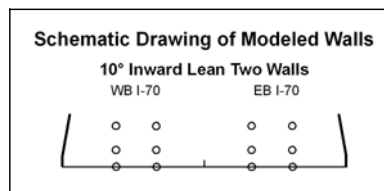
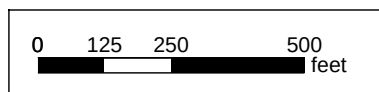


Cross Section of Noise Level Reductions with Abatement

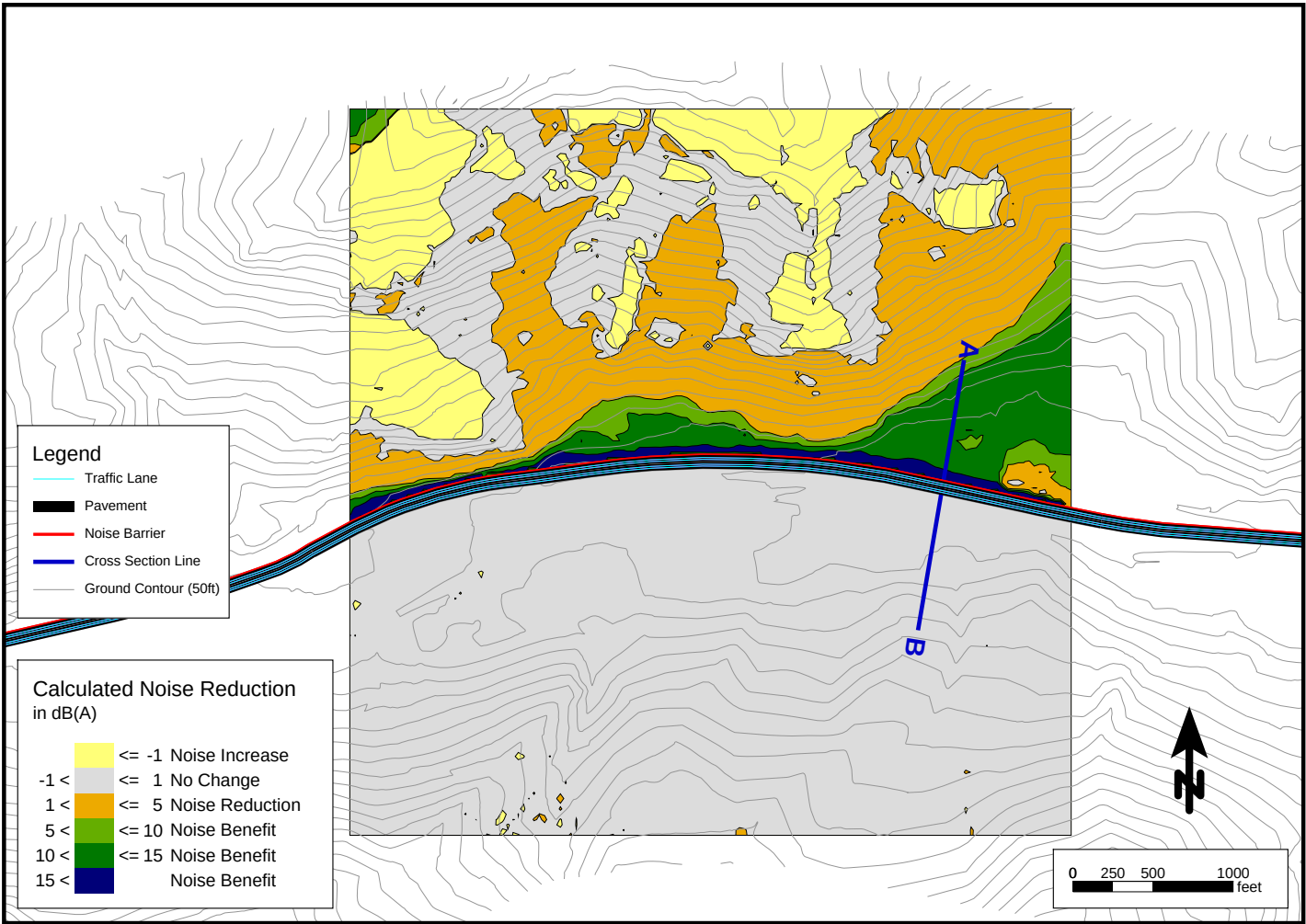


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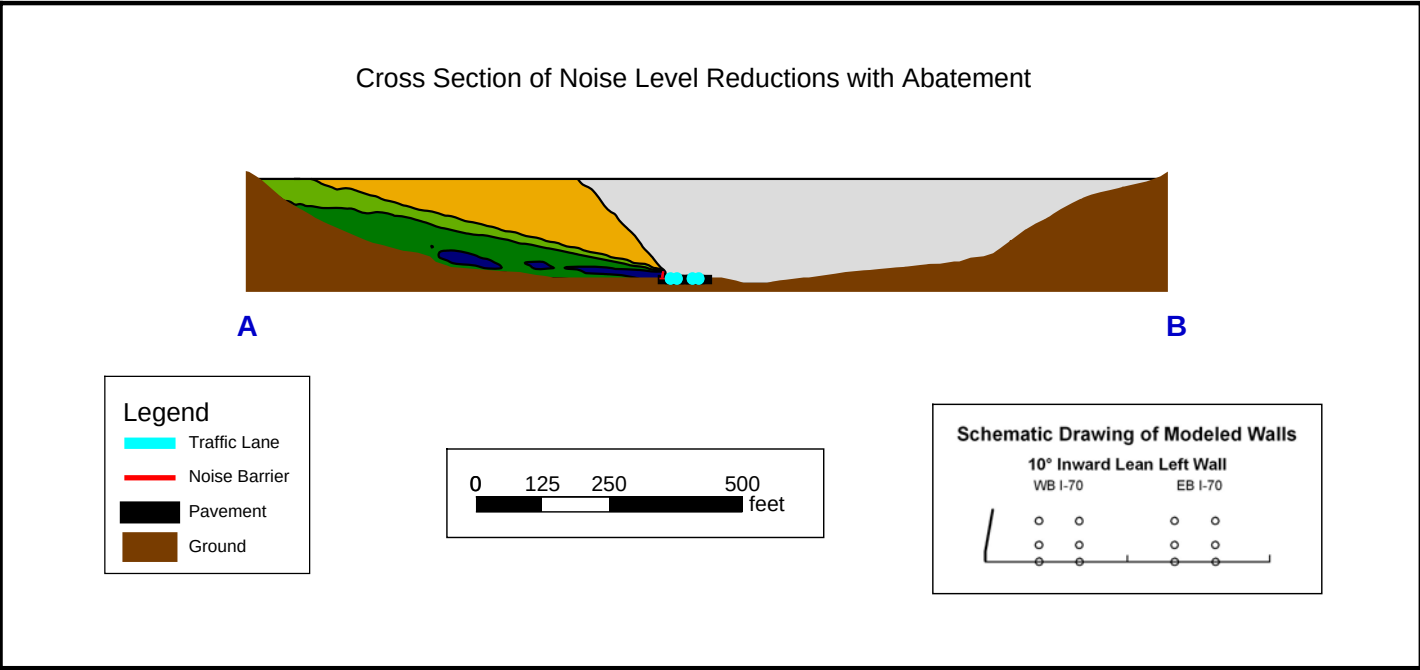
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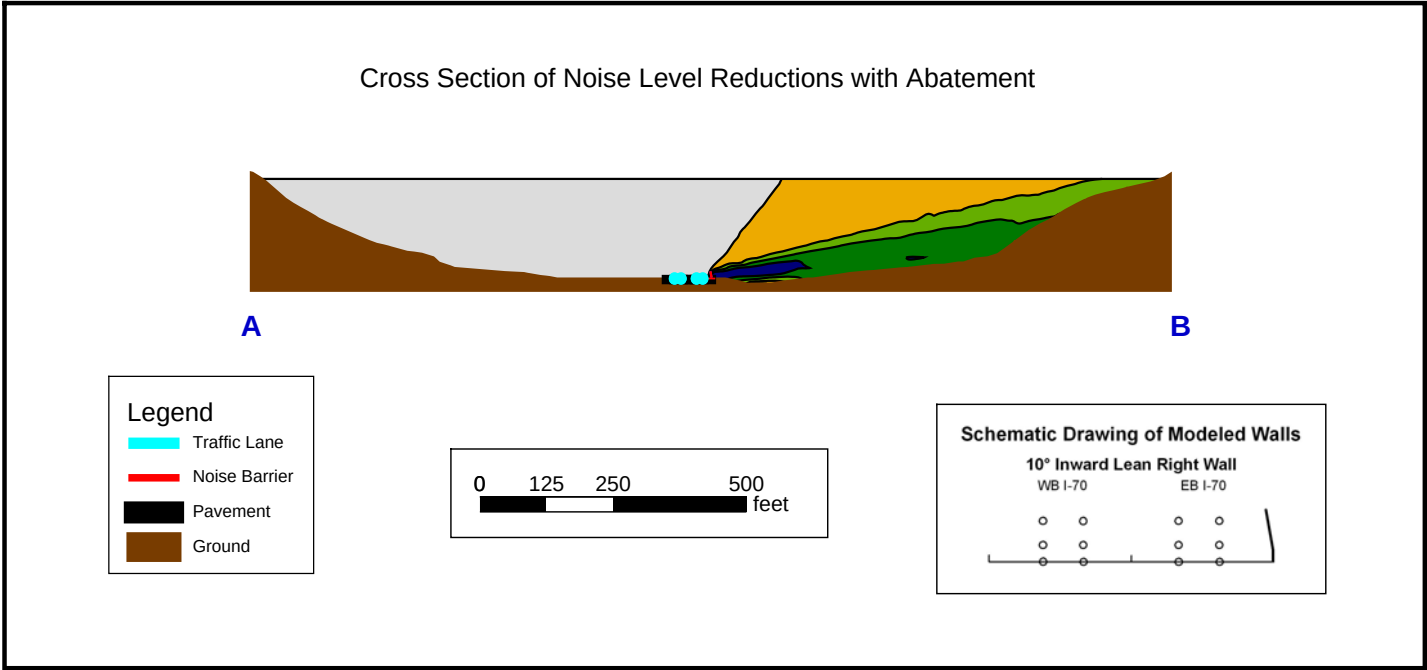
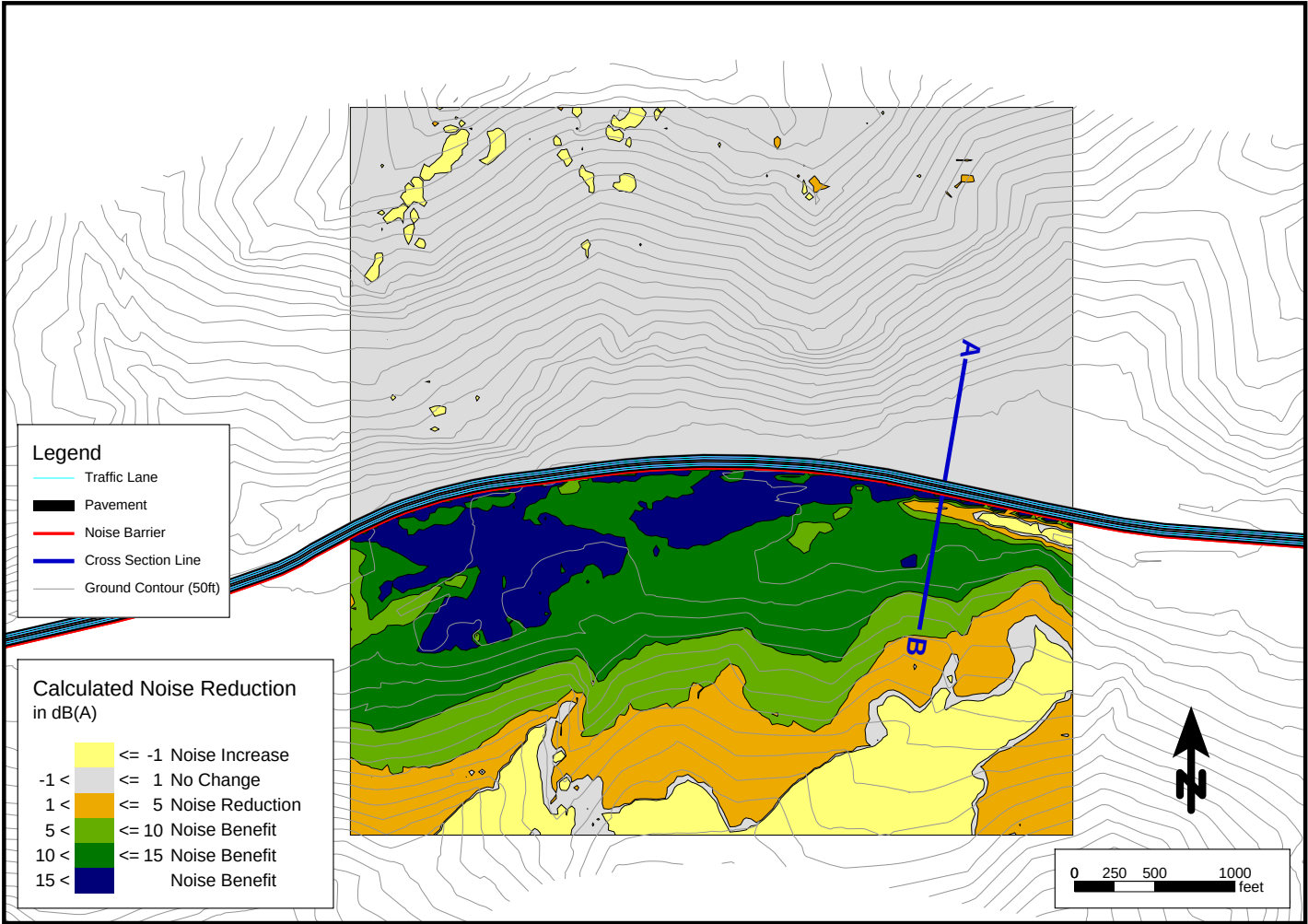
Area 1 Modeled Noise Reductions From North Barrier Lean In 10°



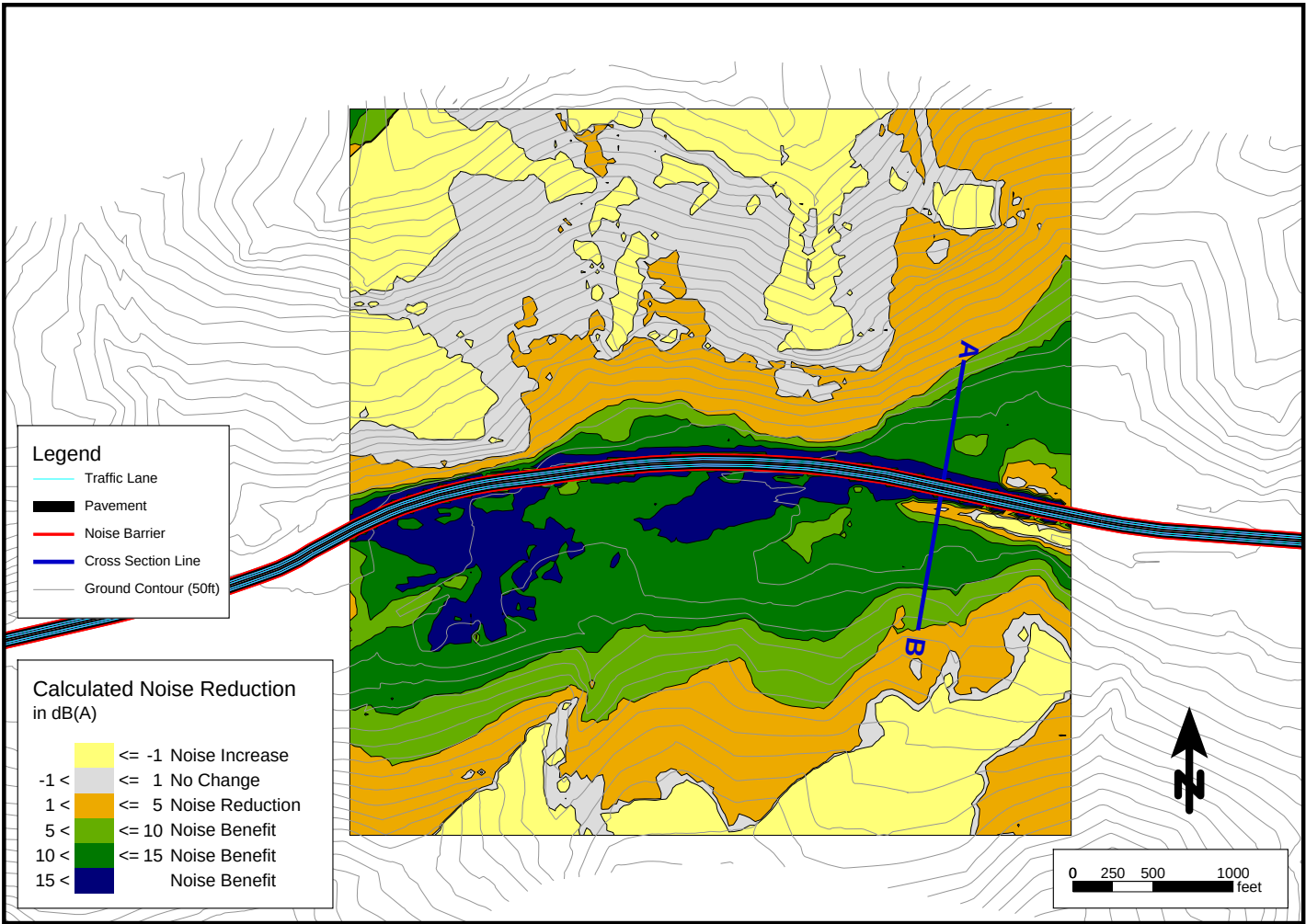
Cross Section of Noise Level Reductions with Abatement



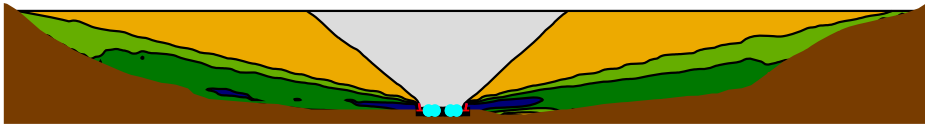
Area 1 Modeled Noise Reductions From South Barrier Lean In 10°



Area 1 Modeled Noise Reductions From 2 Barriers Lean Out 10°

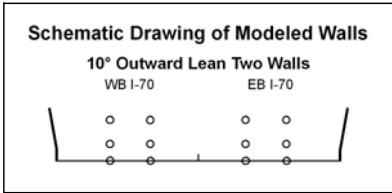
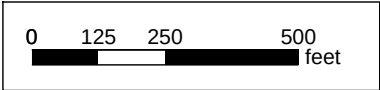


Cross Section of Noise Level Reductions with Abatement

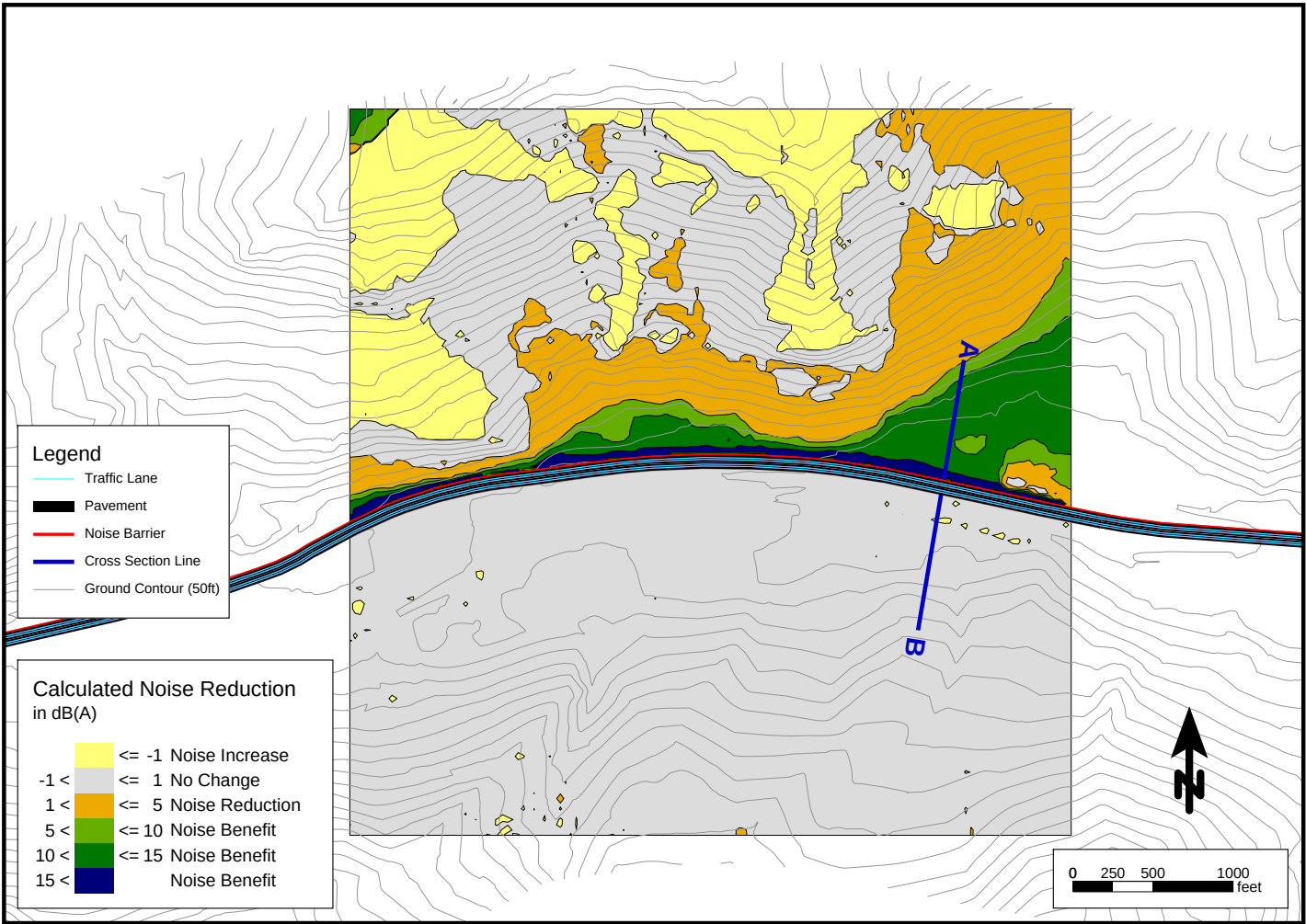


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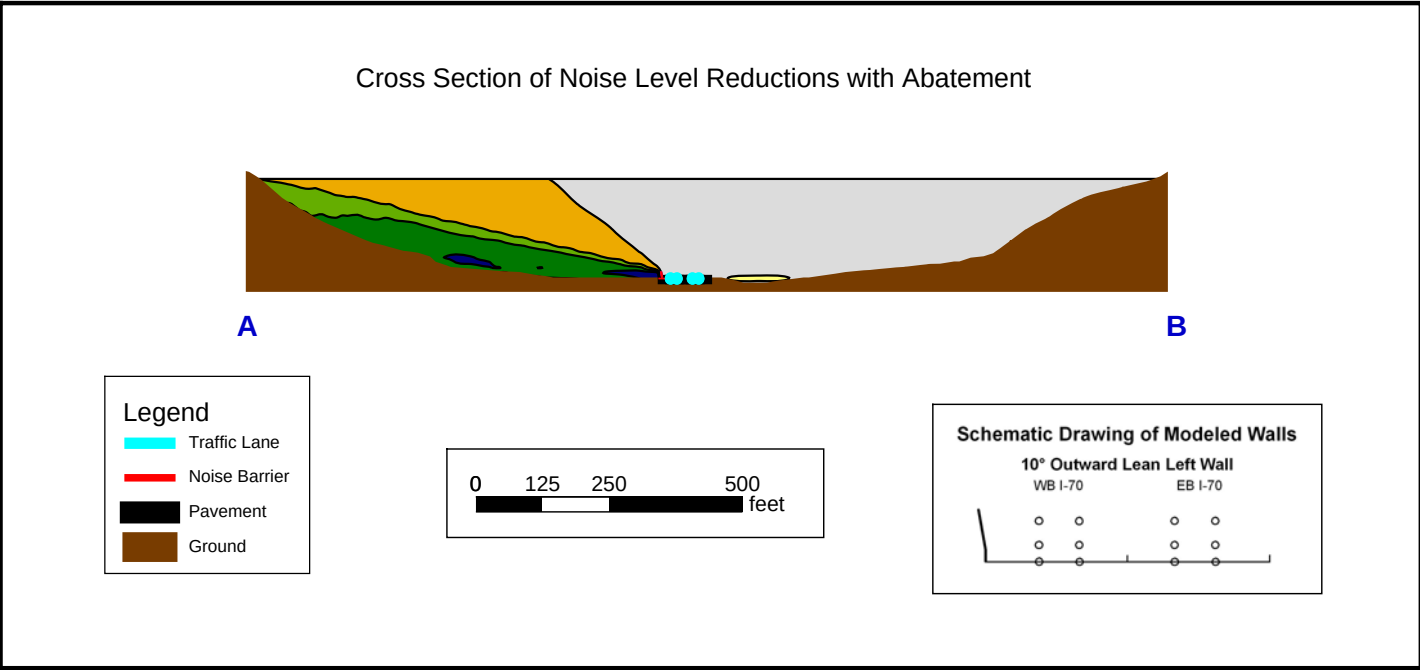
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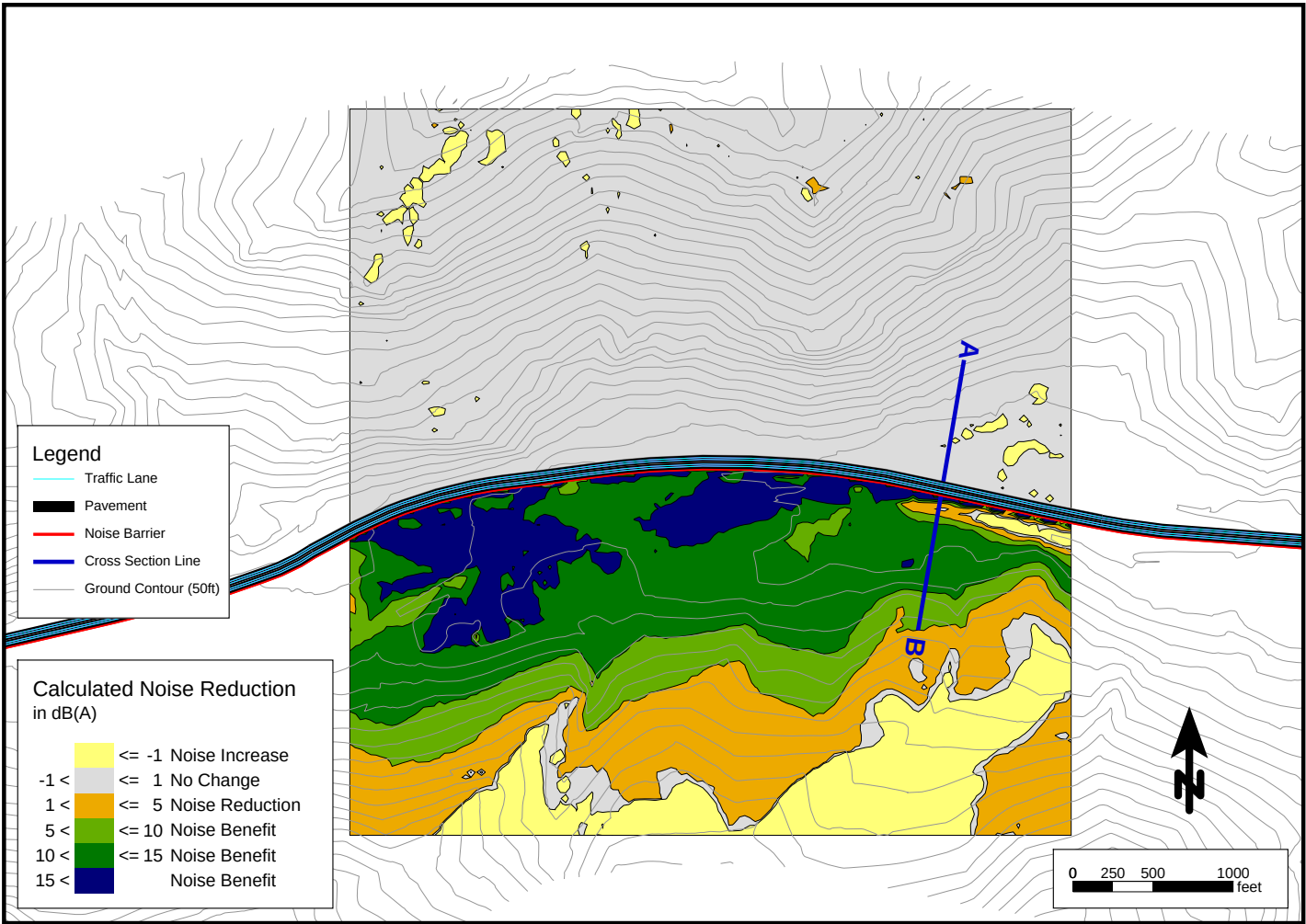
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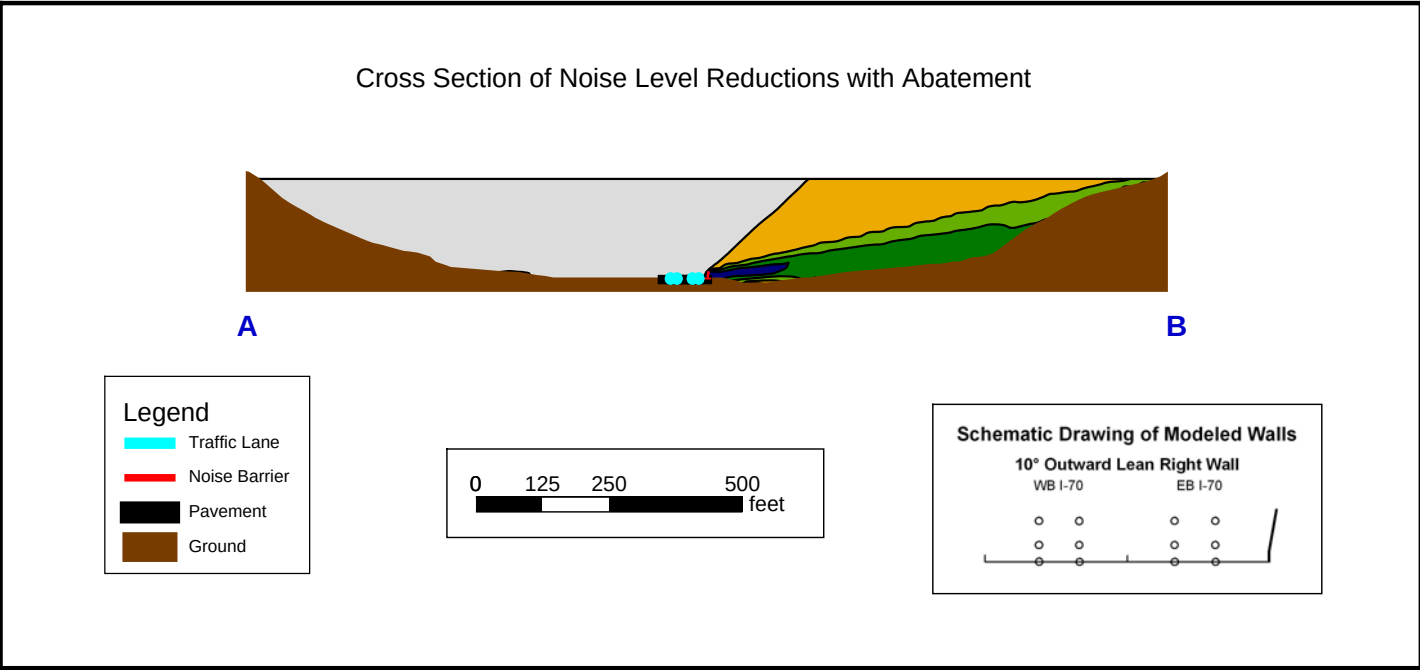
Cross Section of Noise Level Reductions with Abatement



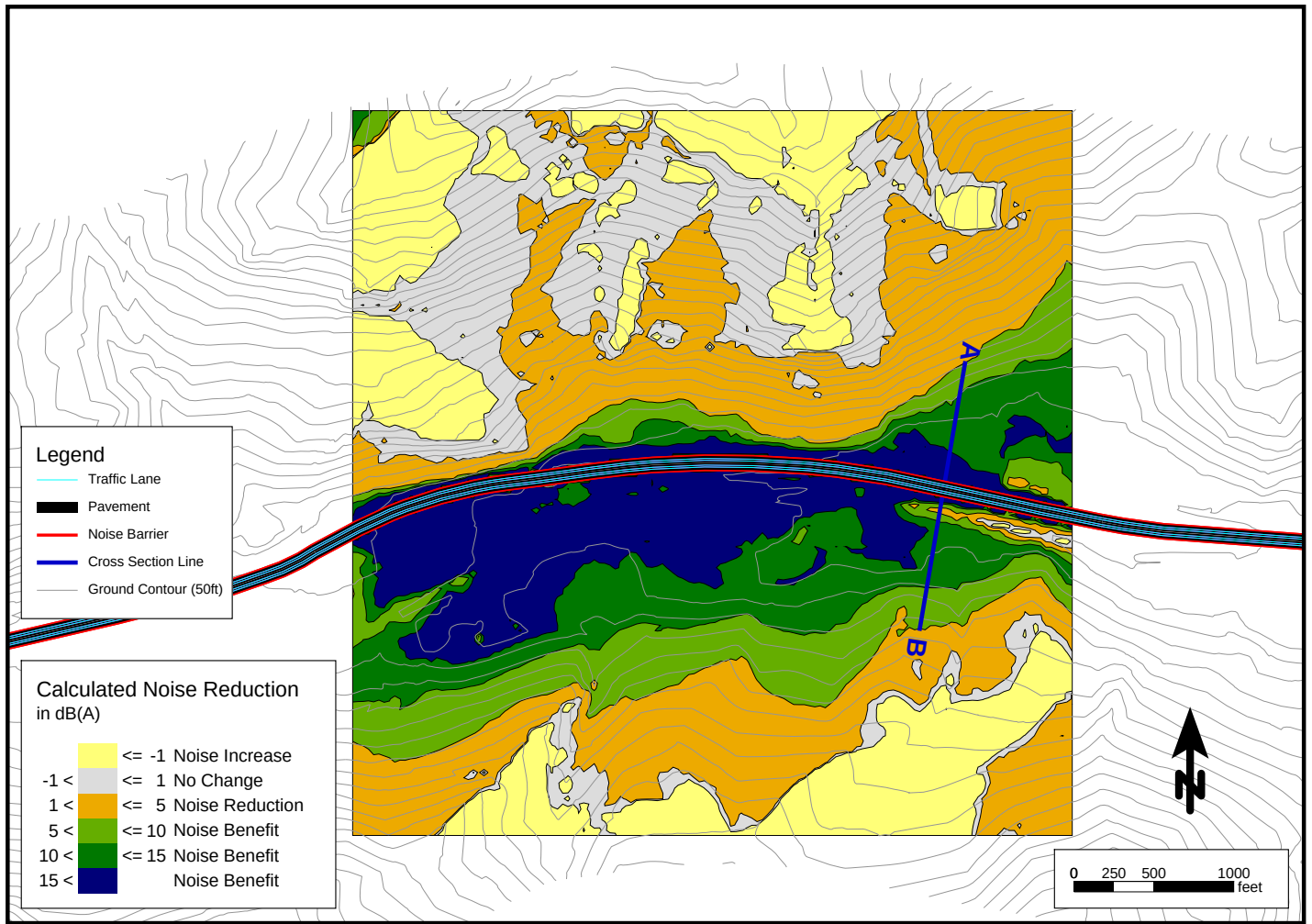
Area 1 Modeled Noise Reductions From South Barrier Lean Out 10°



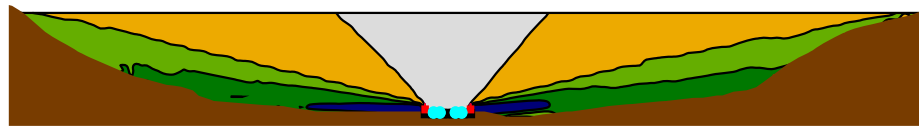
Cross Section of Noise Level Reductions with Abatement



Area 1 Modeled Noise Reductions From 2 T-top Barriers

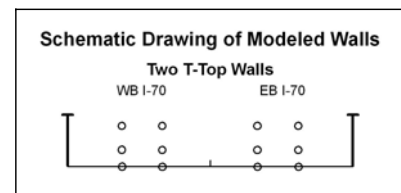
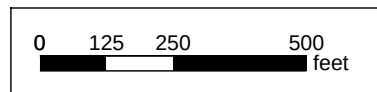


Cross Section of Noise Level Reductions with Abatement

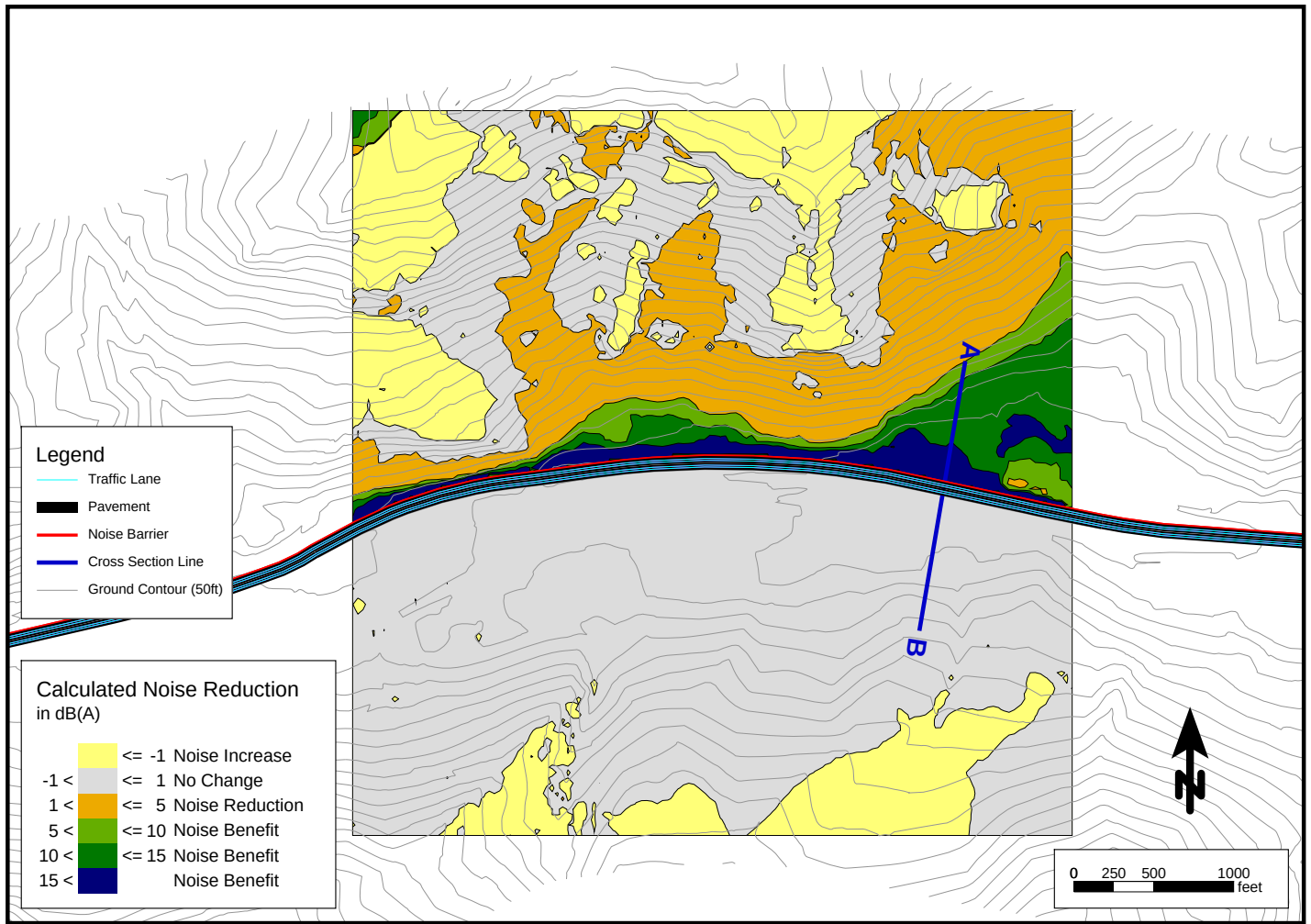


A

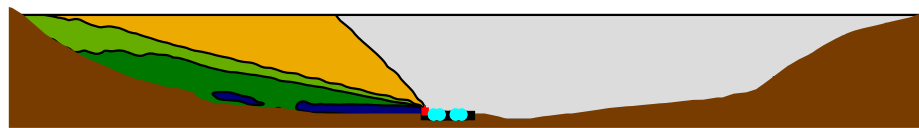
B



Area 1 Modeled Noise Reductions From North T-top Barrier

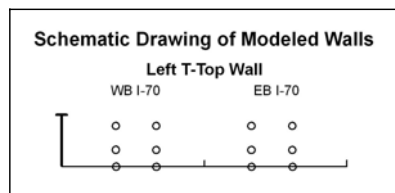
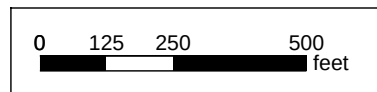


Cross Section of Noise Level Reductions with Abatement

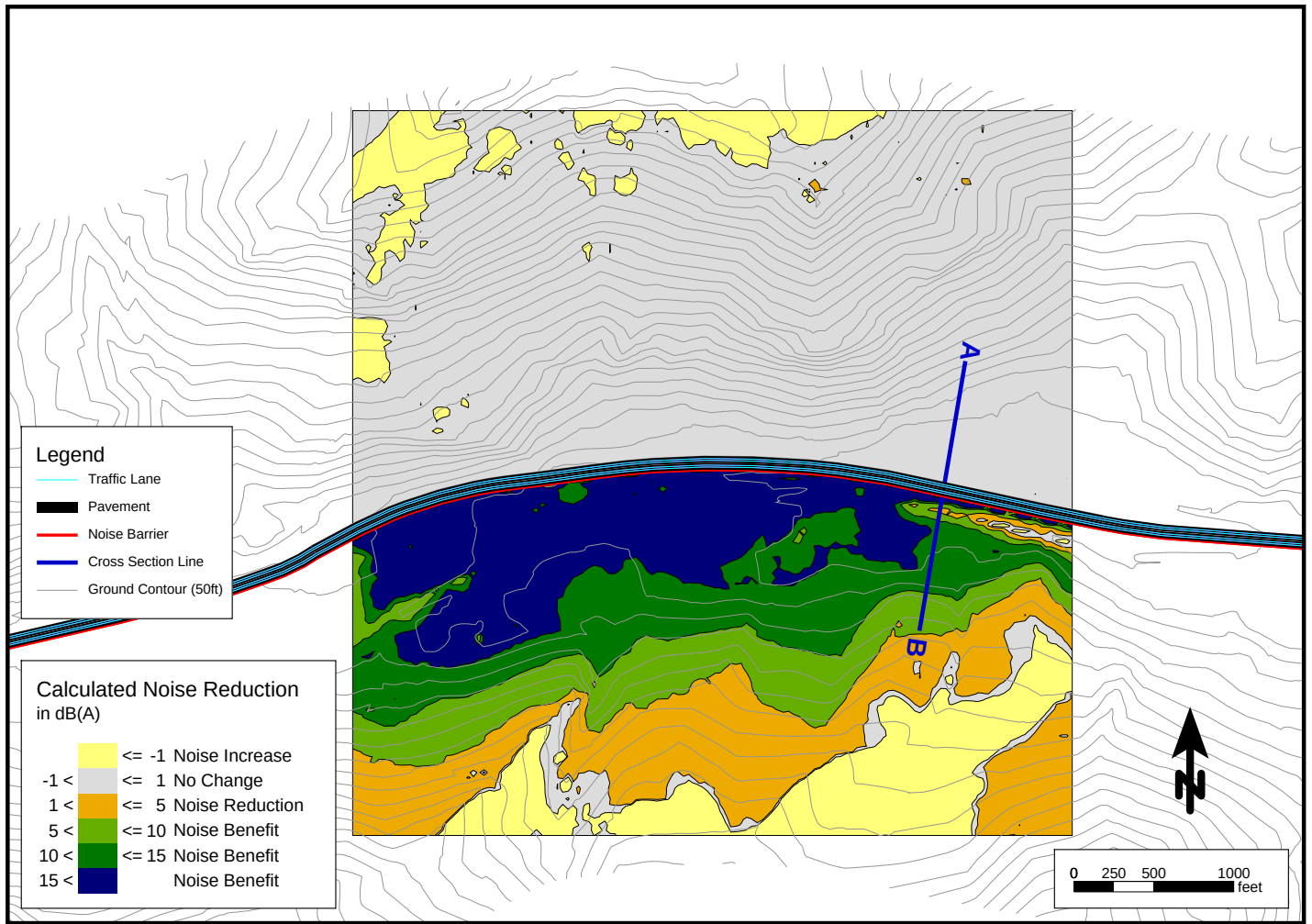


A

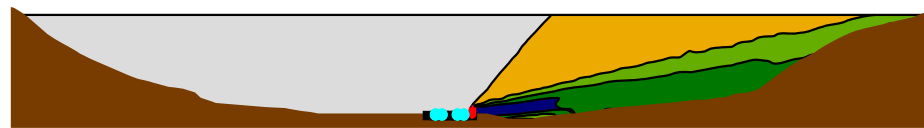
B



Area 1 Modeled Noise Reductions From South T-top Barrier

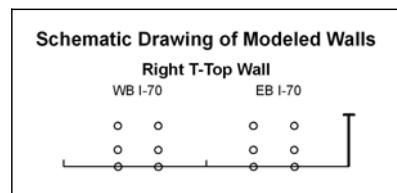
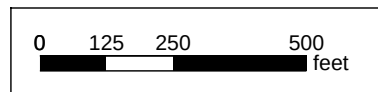


Cross Section of Noise Level Reductions with Abatement

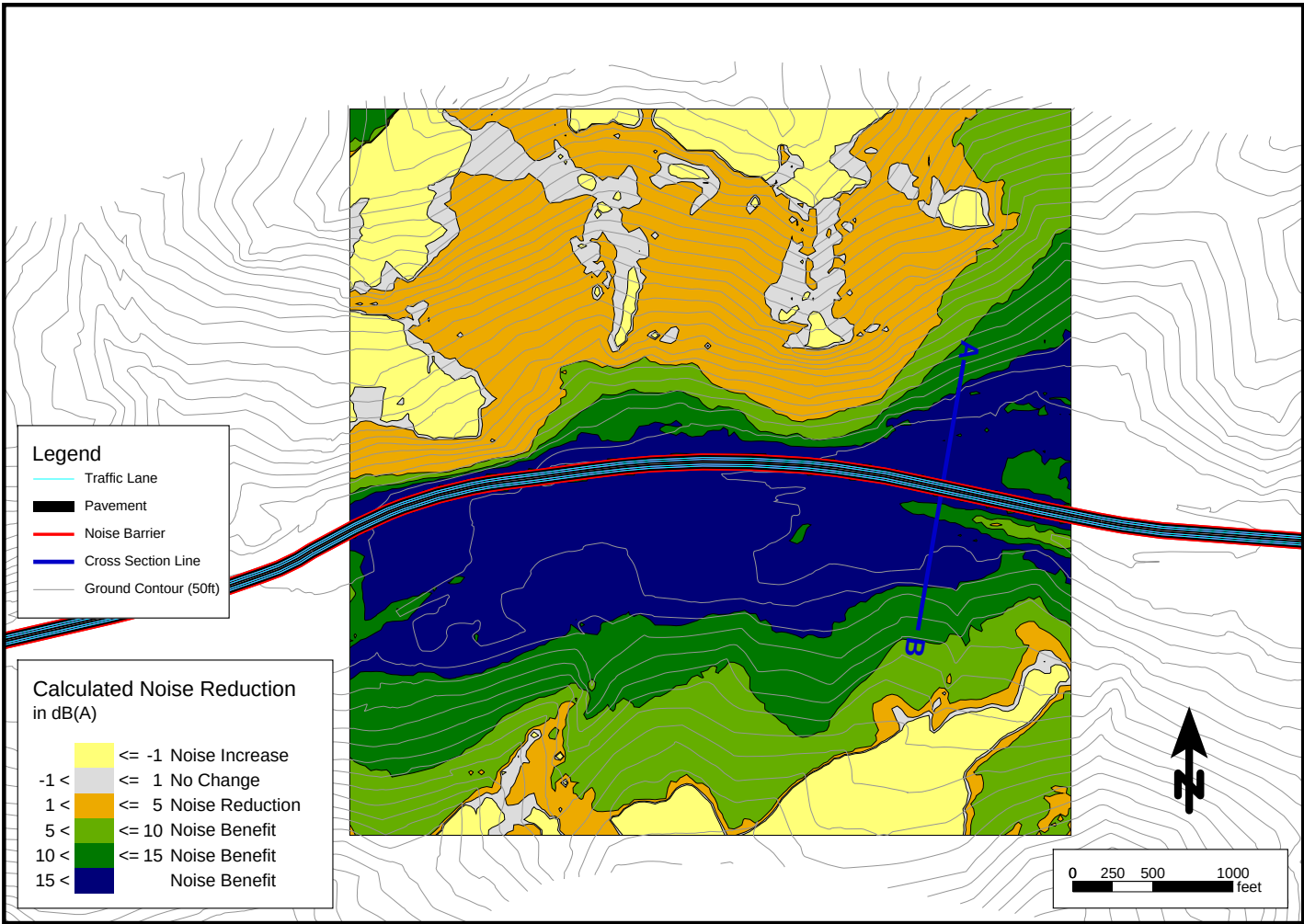


A

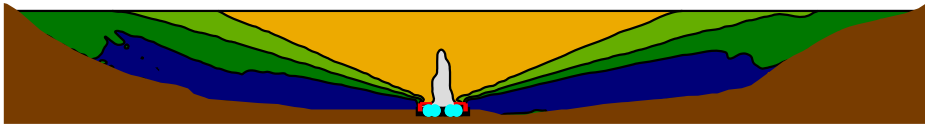
B



Area 1 Modeled Noise Reductions From 2 Gallery Barriers

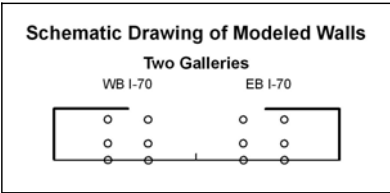
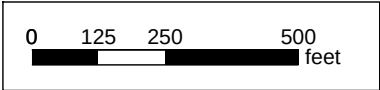


Cross Section of Noise Level Reductions with Abatement

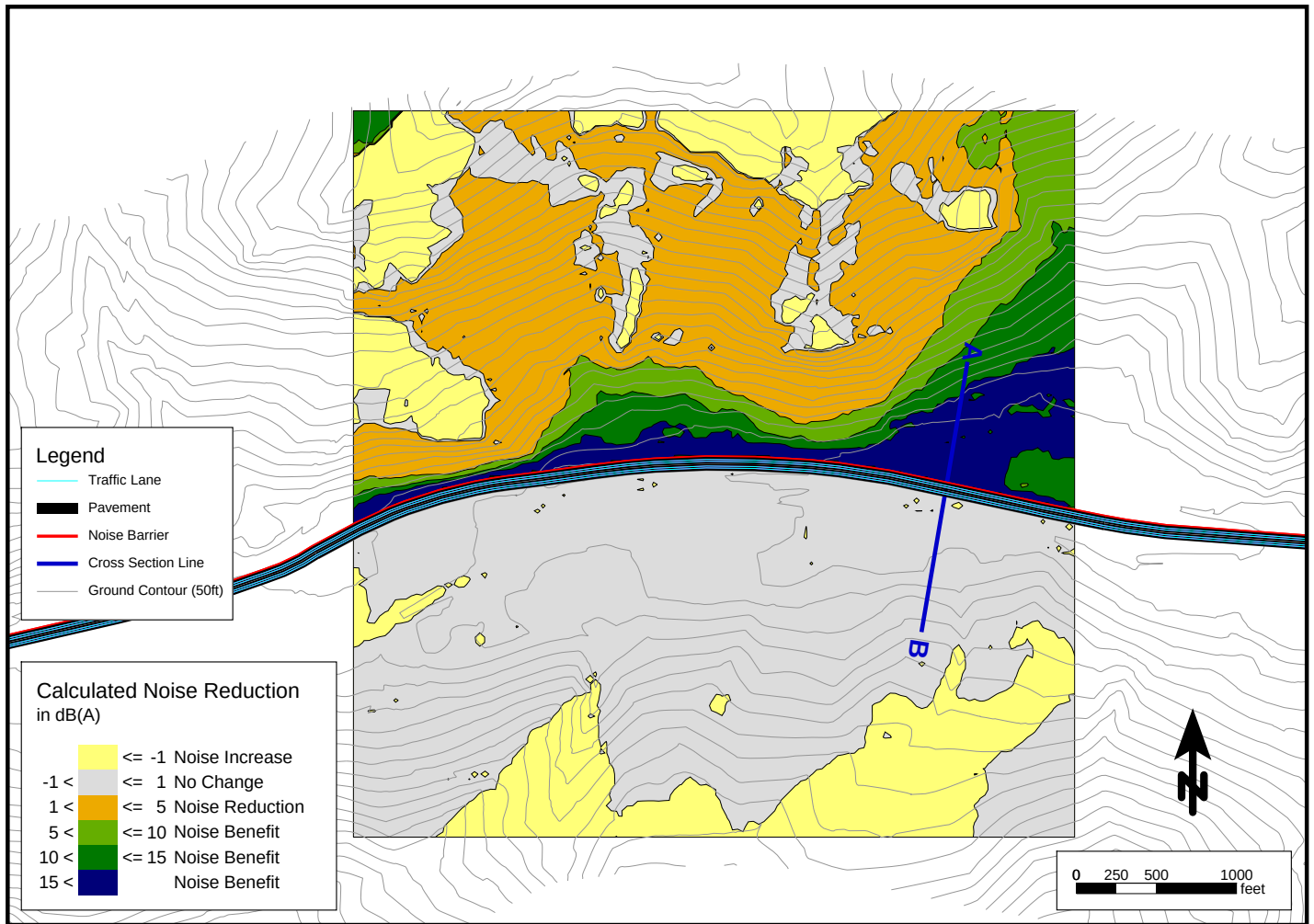


A

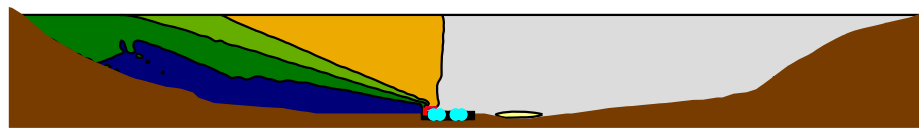
B



Area 1 Modeled Noise Reductions From North Gallery Barrier

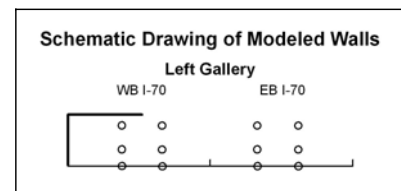
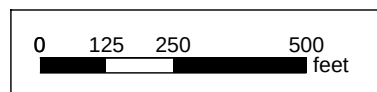


Cross Section of Noise Level Reductions with Abatement

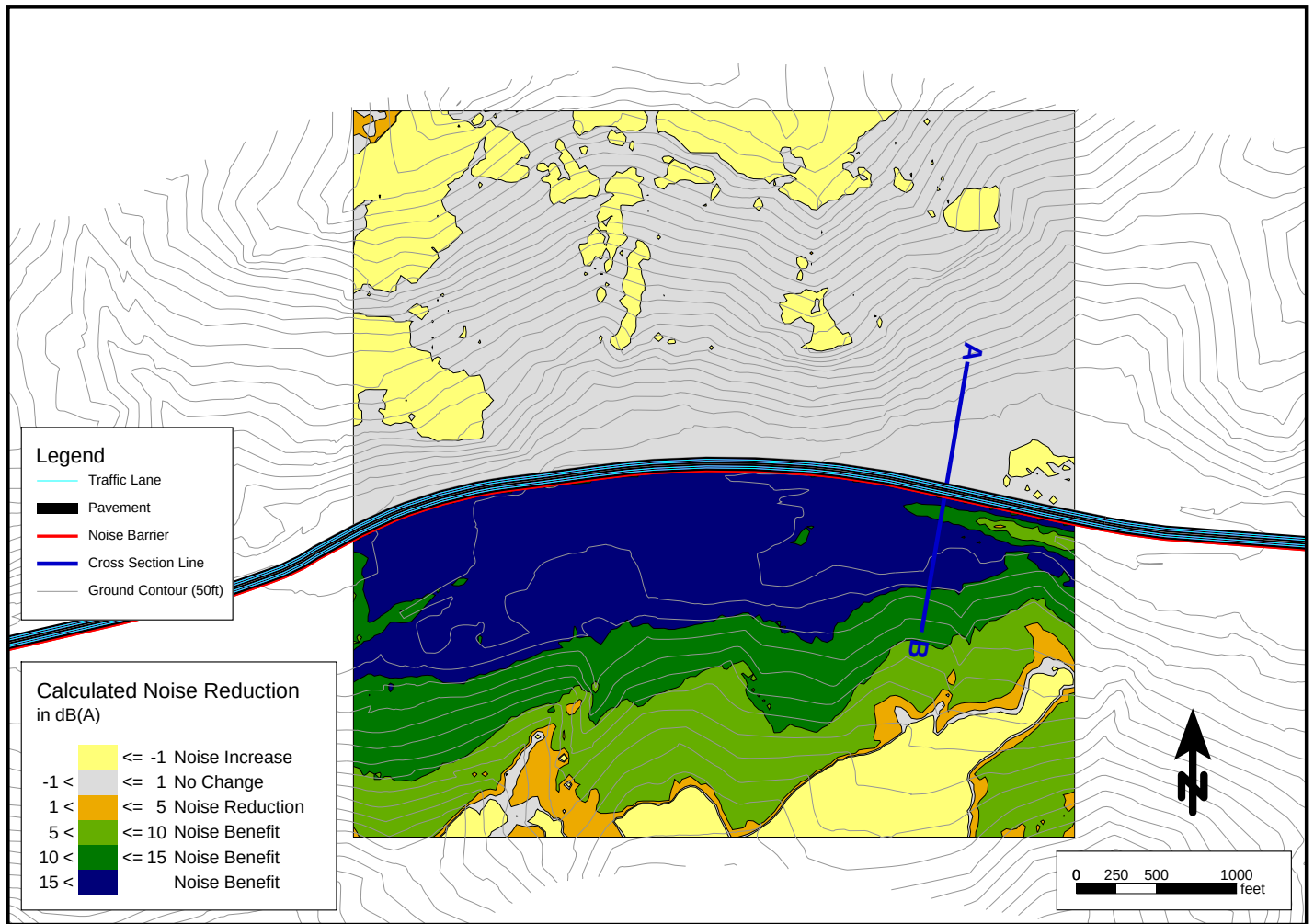


A

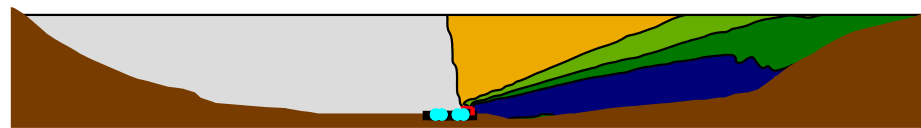
B



Area 1 Modeled Noise Reductions From South Gallery Barrier

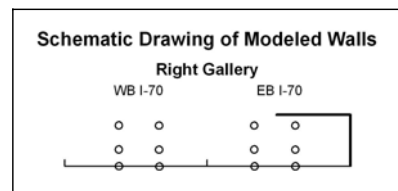
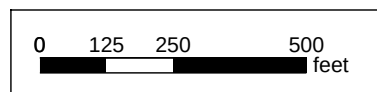


Cross Section of Noise Level Reductions with Abatement

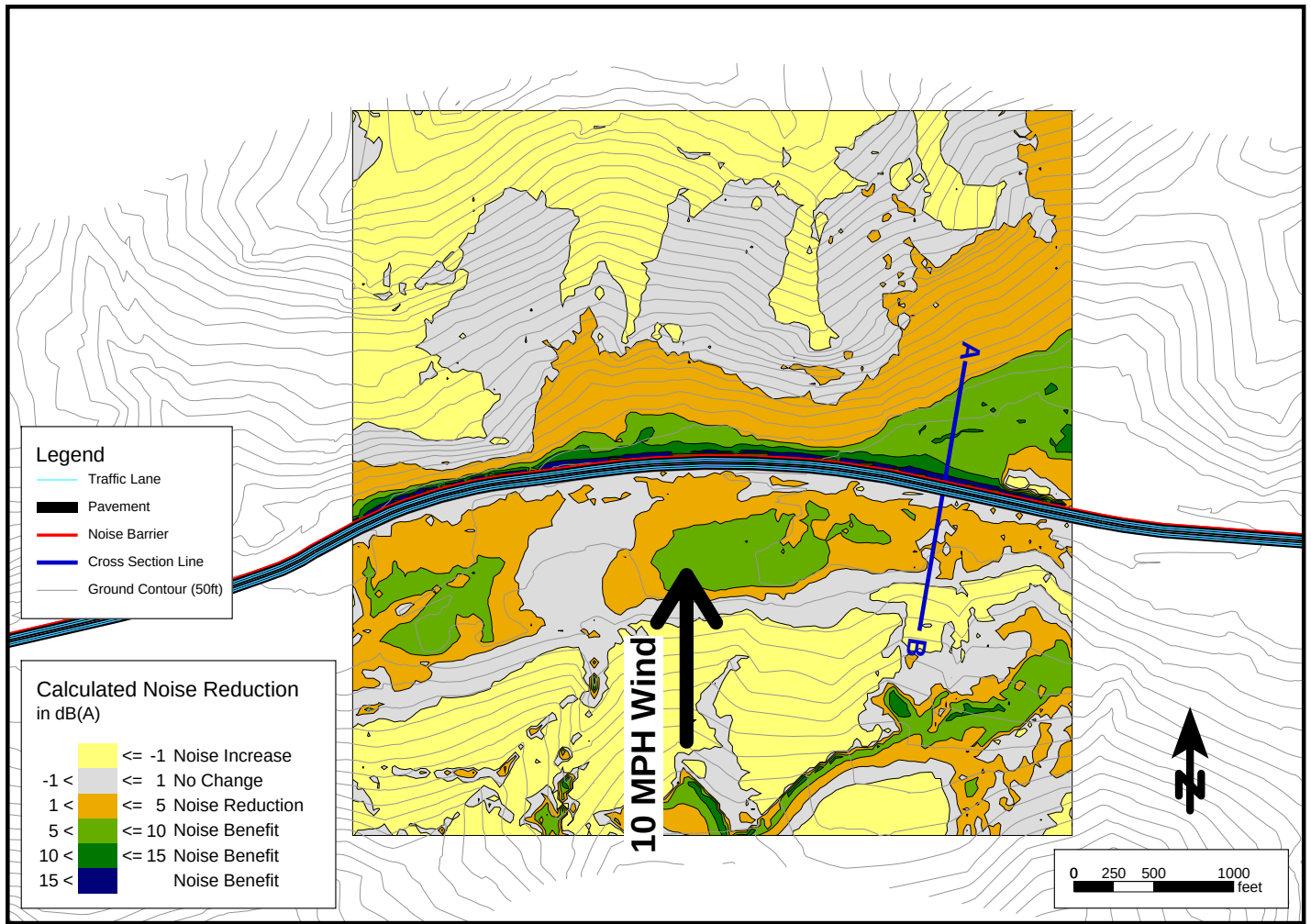


A

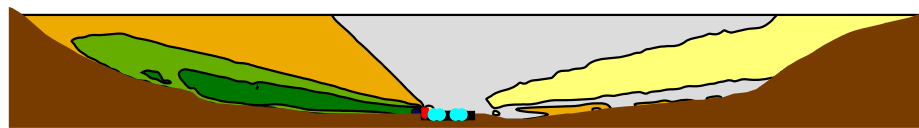
B



Area 1 Modeled Noise Reductions From North Reflective Barrier + South Wind

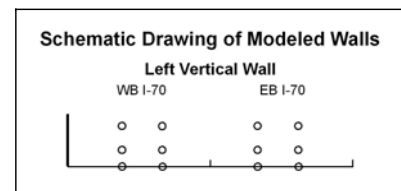
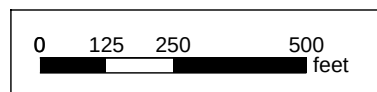


Cross Section of Noise Level Reductions with Abatement

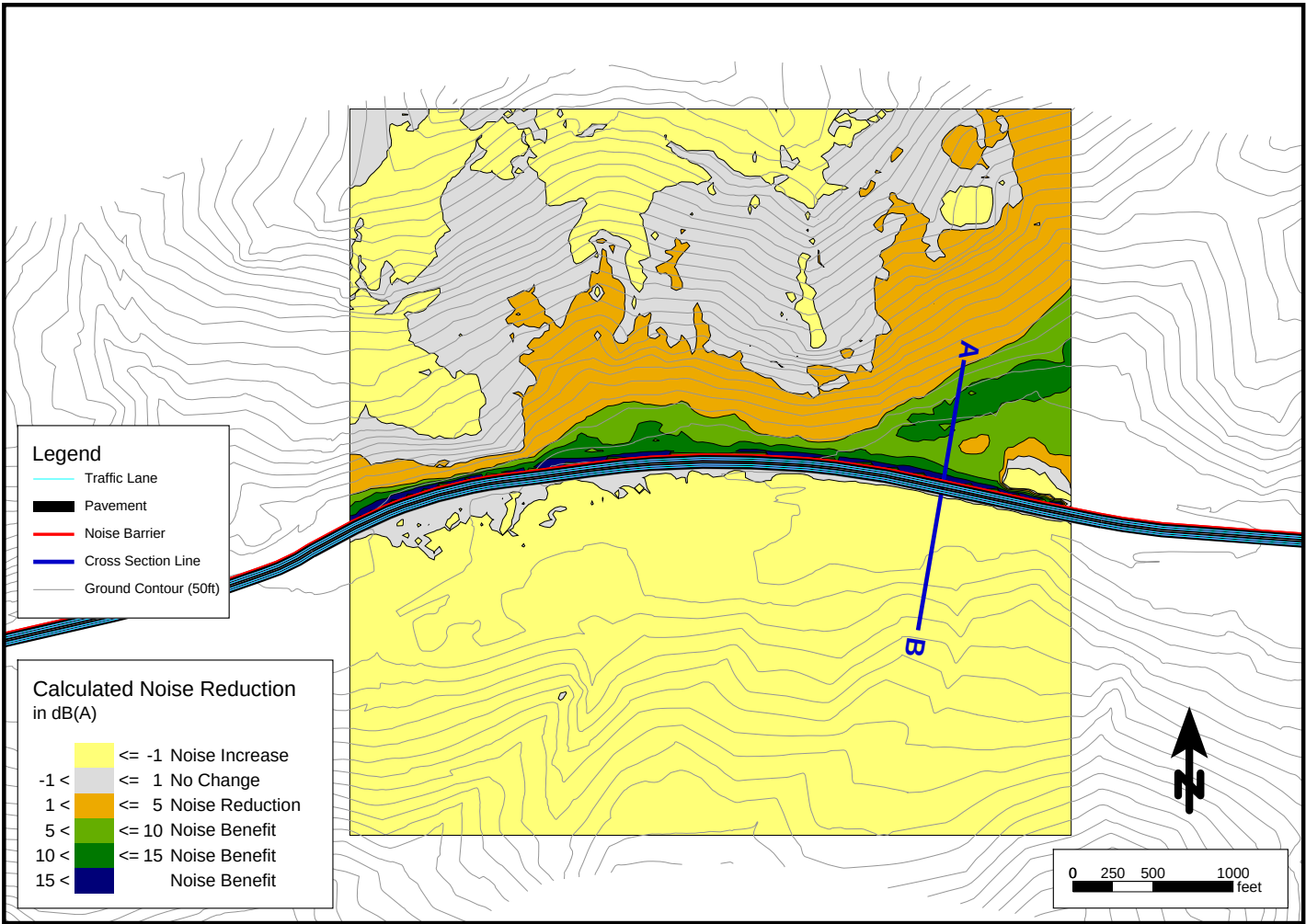


A

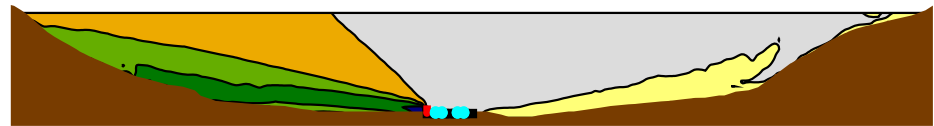
B



Area 1 Modeled Noise Reductions From North Reflective Barrier + Inversion

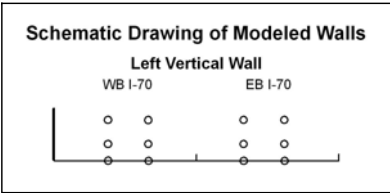
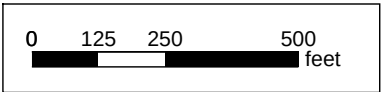


Cross Section of Noise Level Reductions with Abatement

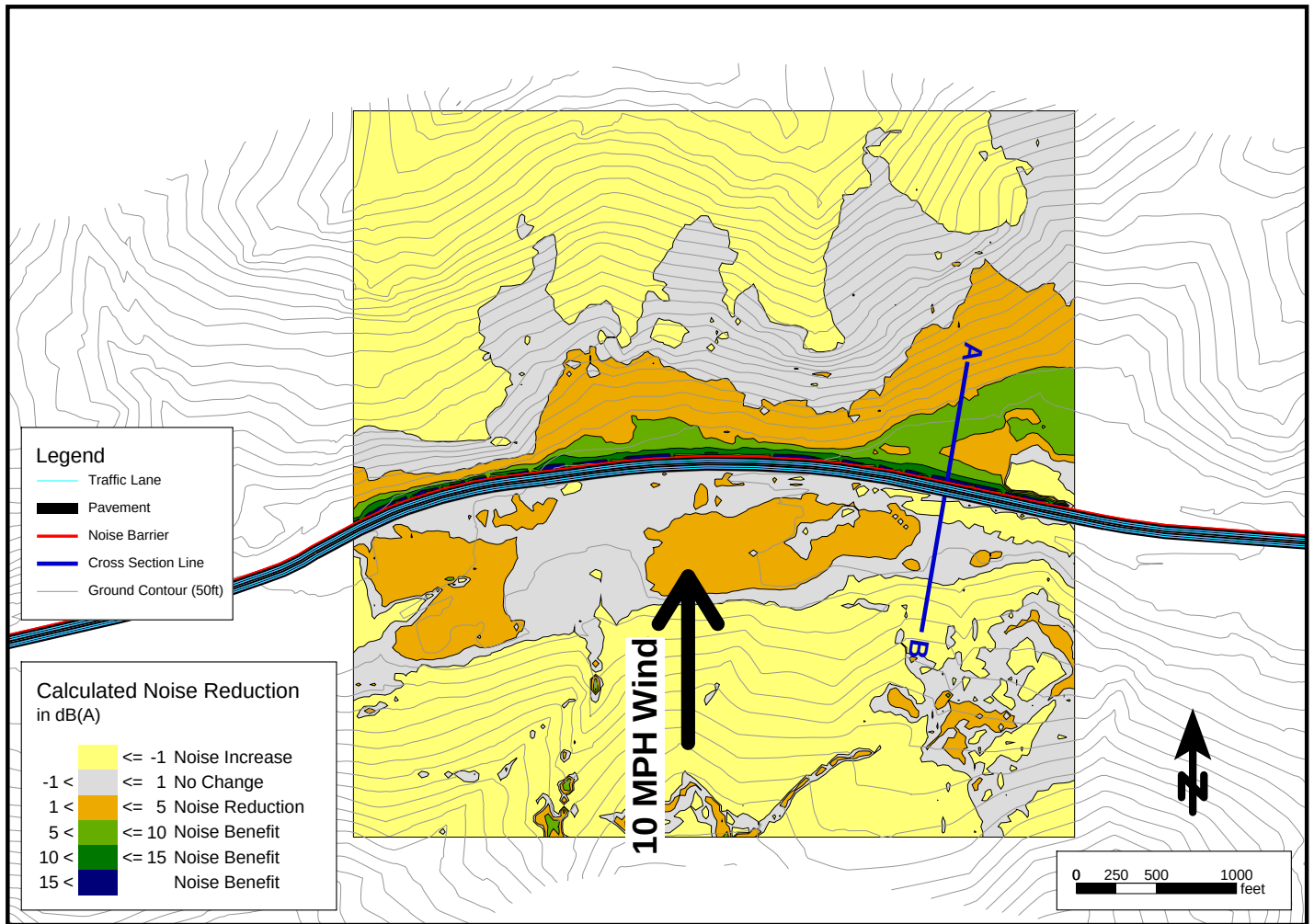


A

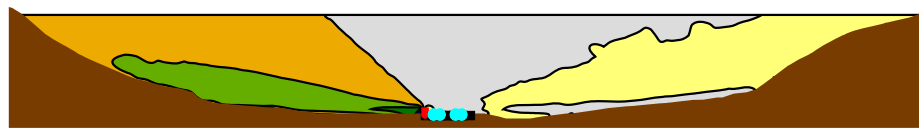
B



Area 1 Modeled Noise Reductions From North Reflective Barrier + Wind + Inversion

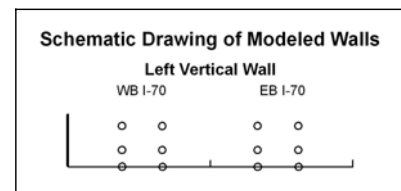
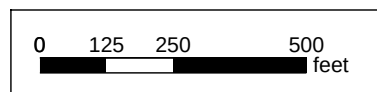


Cross Section of Noise Level Reductions with Abatement

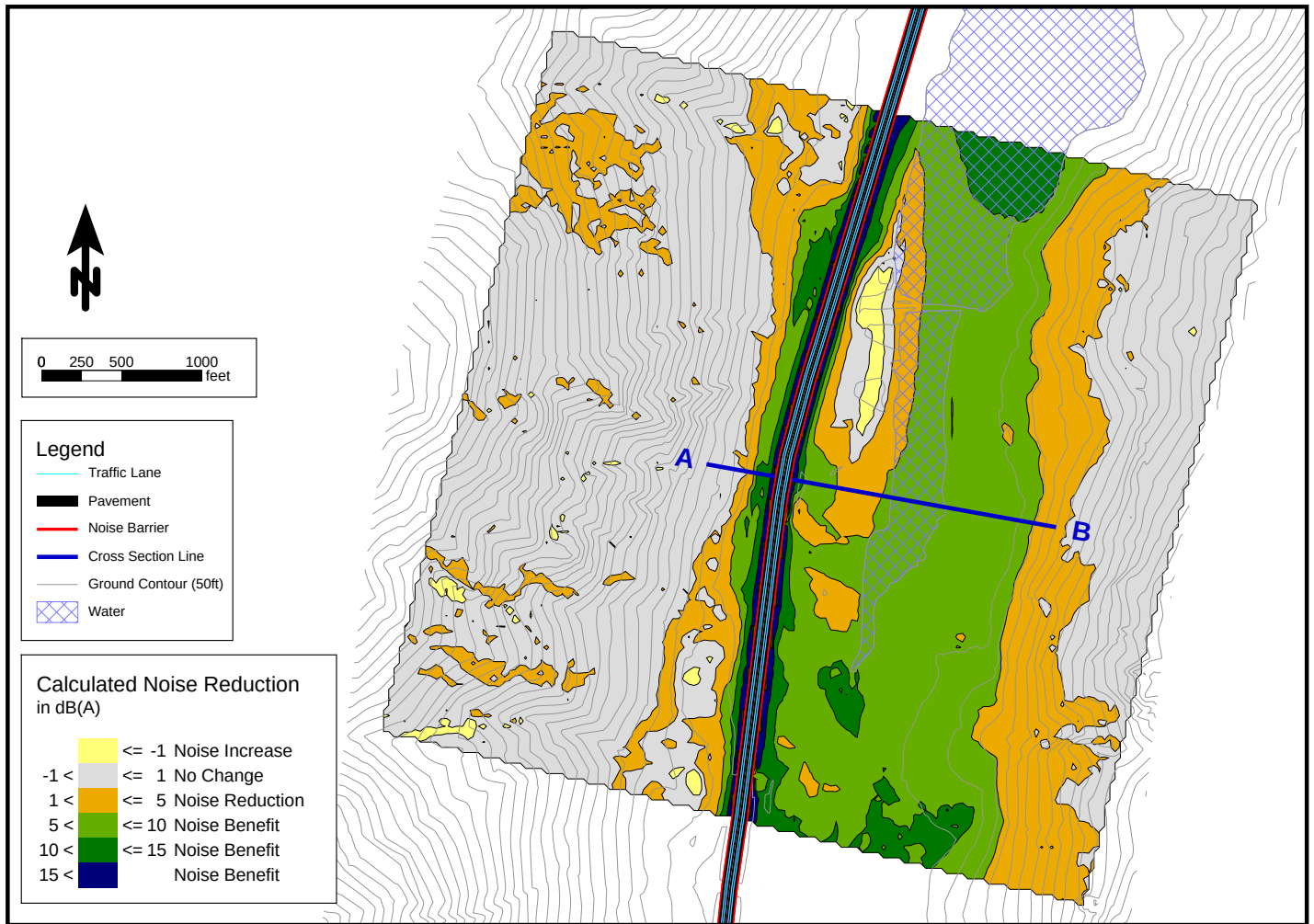


A

B



Area 2 Modeled Noise Reductions From 2 Reflective Barriers



Cross Section of Noise Level Reductions with Abatement



A

B

Legend

- Traffic Lane
- Noise Barrier
- Pavement
- Water
- Ground

0 125 250 500 feet

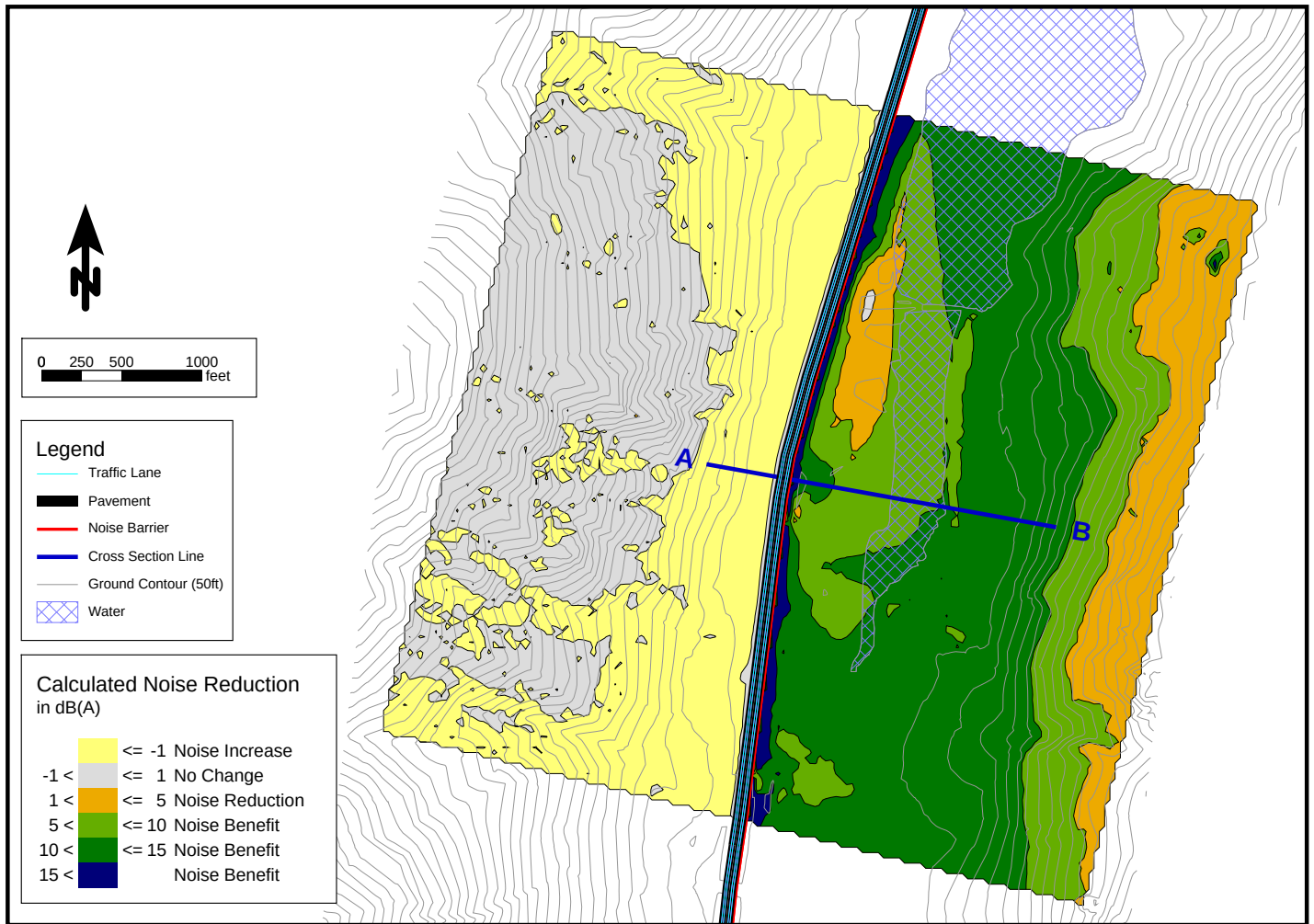
Schematic Drawing of Modeled Walls

Two Vertical Walls

WB I-70 EB I-70



Area 2 Modeled Noise Reductions From East Reflective Barrier



Cross Section of Noise Level Reductions with Abatement



A

B

Legend

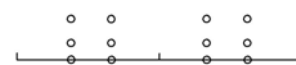
- Traffic Lane
- Noise Barrier
- Pavement
- Water
- Ground

0 125 250 500 feet

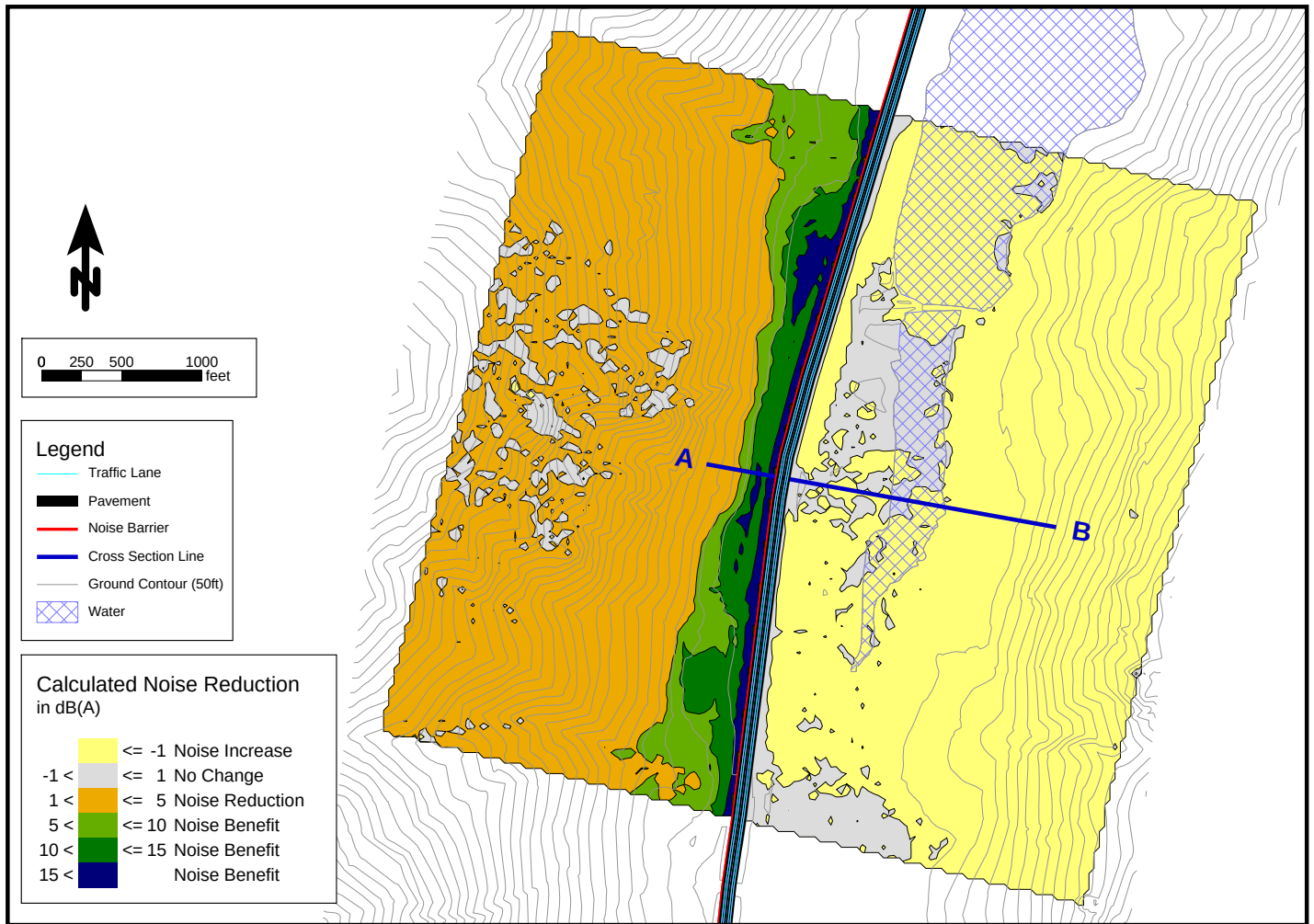
Schematic Drawing of Modeled Walls

Right Vertical Wall

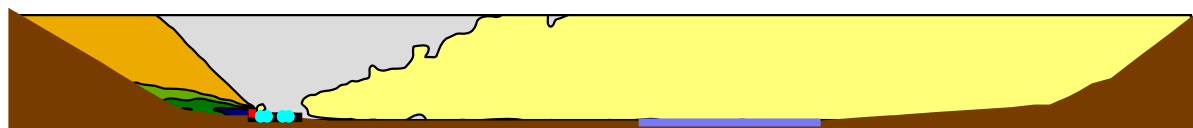
WB I-70 EB I-70



Area 2 Modeled Noise Reductions From West Reflective Barrier



Cross Section of Noise Level Reductions with Abatement



A

B

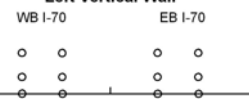
Legend

- Traffic Lane
- Noise Barrier
- Pavement
- Water
- Ground

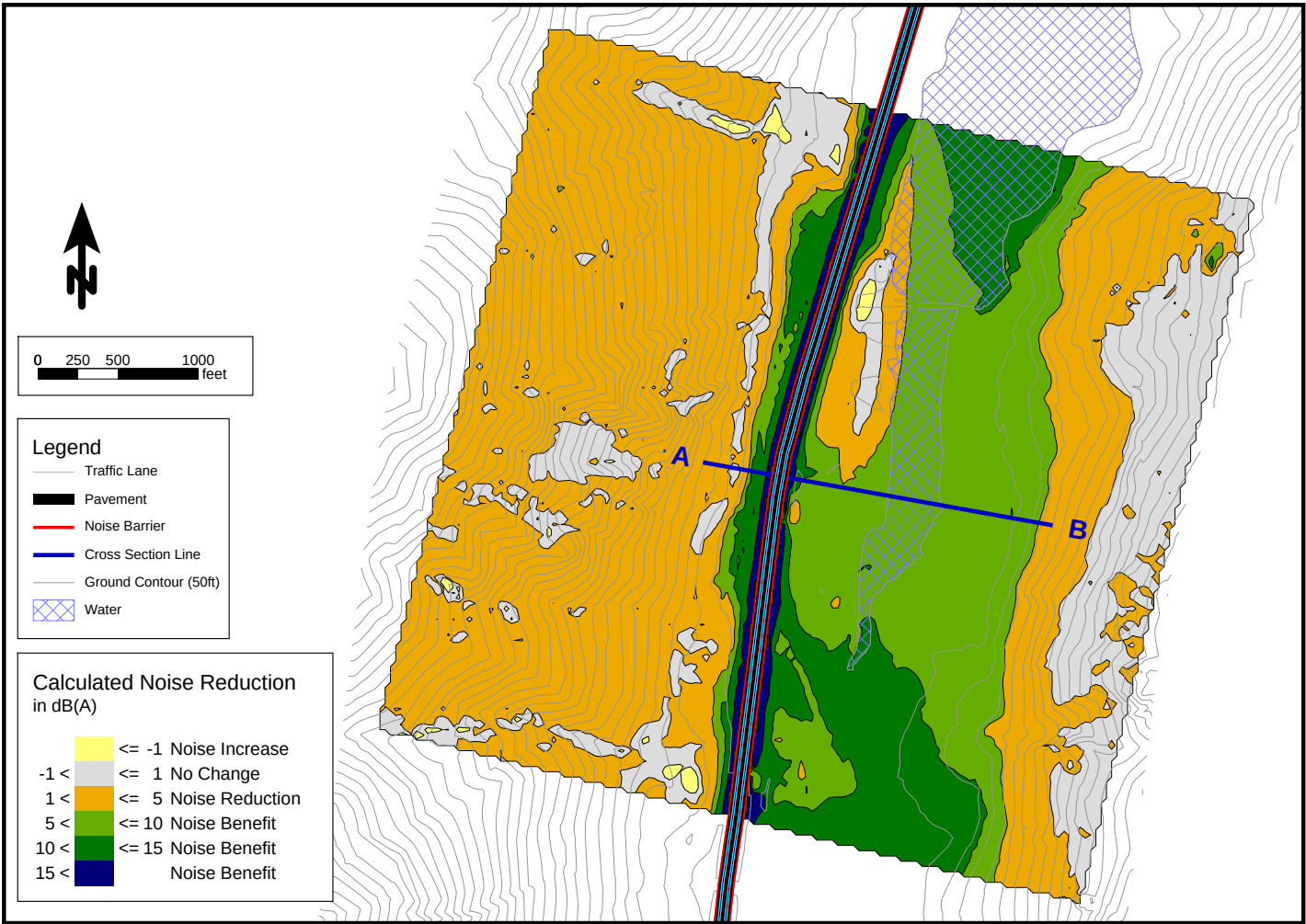
0 125 250 500 feet

Schematic Drawing of Modeled Walls

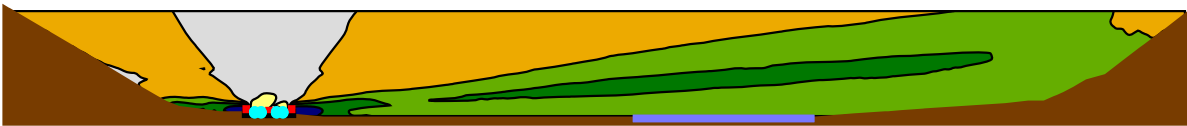
Left Vertical Wall



Area 2 Modeled Noise Reductions From Reflective Median Barrier

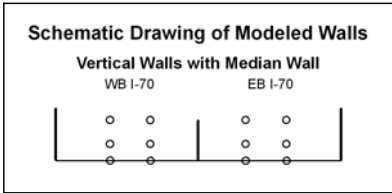
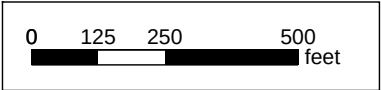


Cross Section of Noise Level Reductions with Abatement

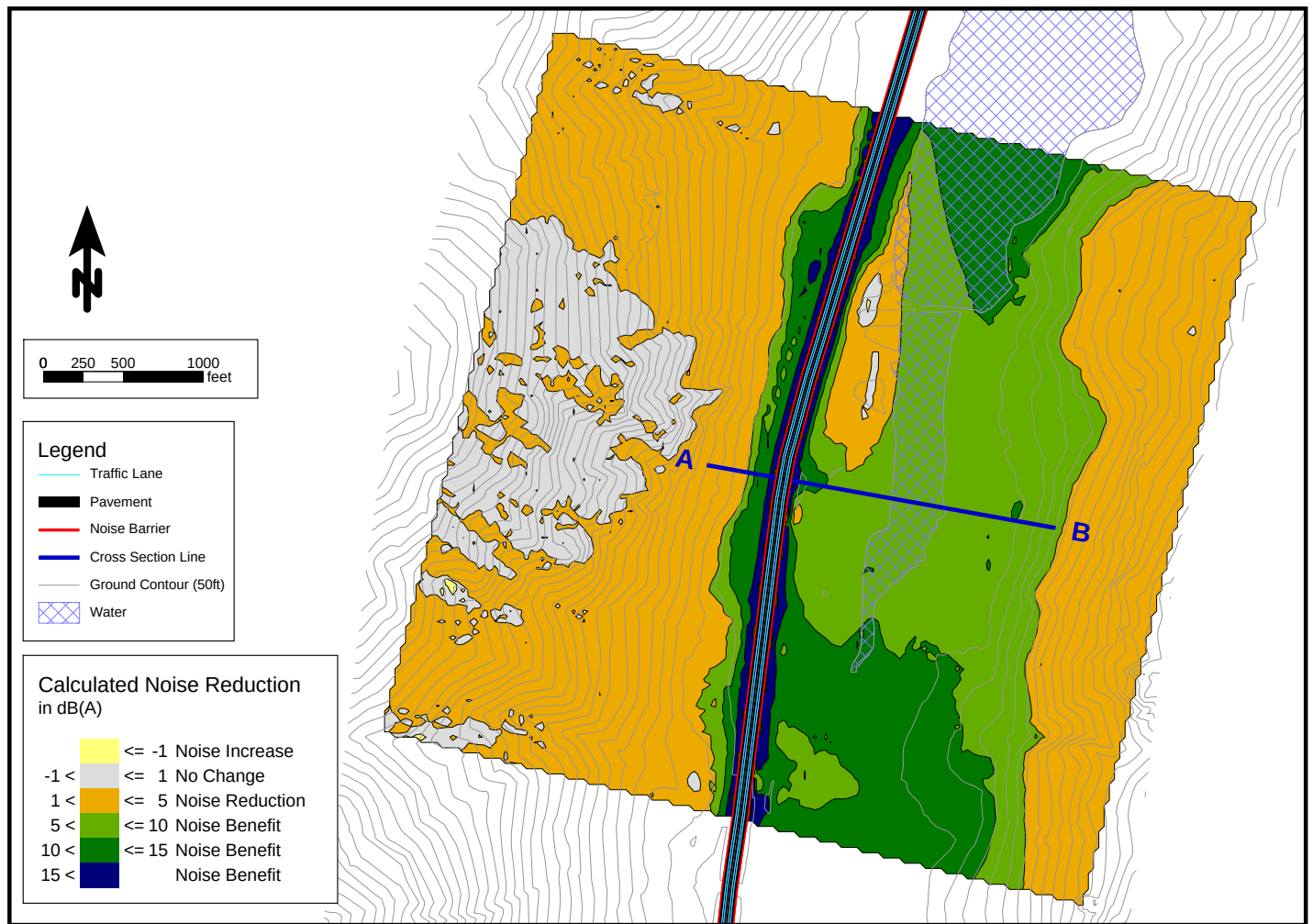


A

B



Area 2 Modeled Noise Reductions From 2 Absorptive Barriers



Cross Section of Noise Level Reductions with Abatement



A

B

Legend

- Traffic Lane
- Noise Barrier
- Pavement
- Water
- Ground

0 125 250 500 feet

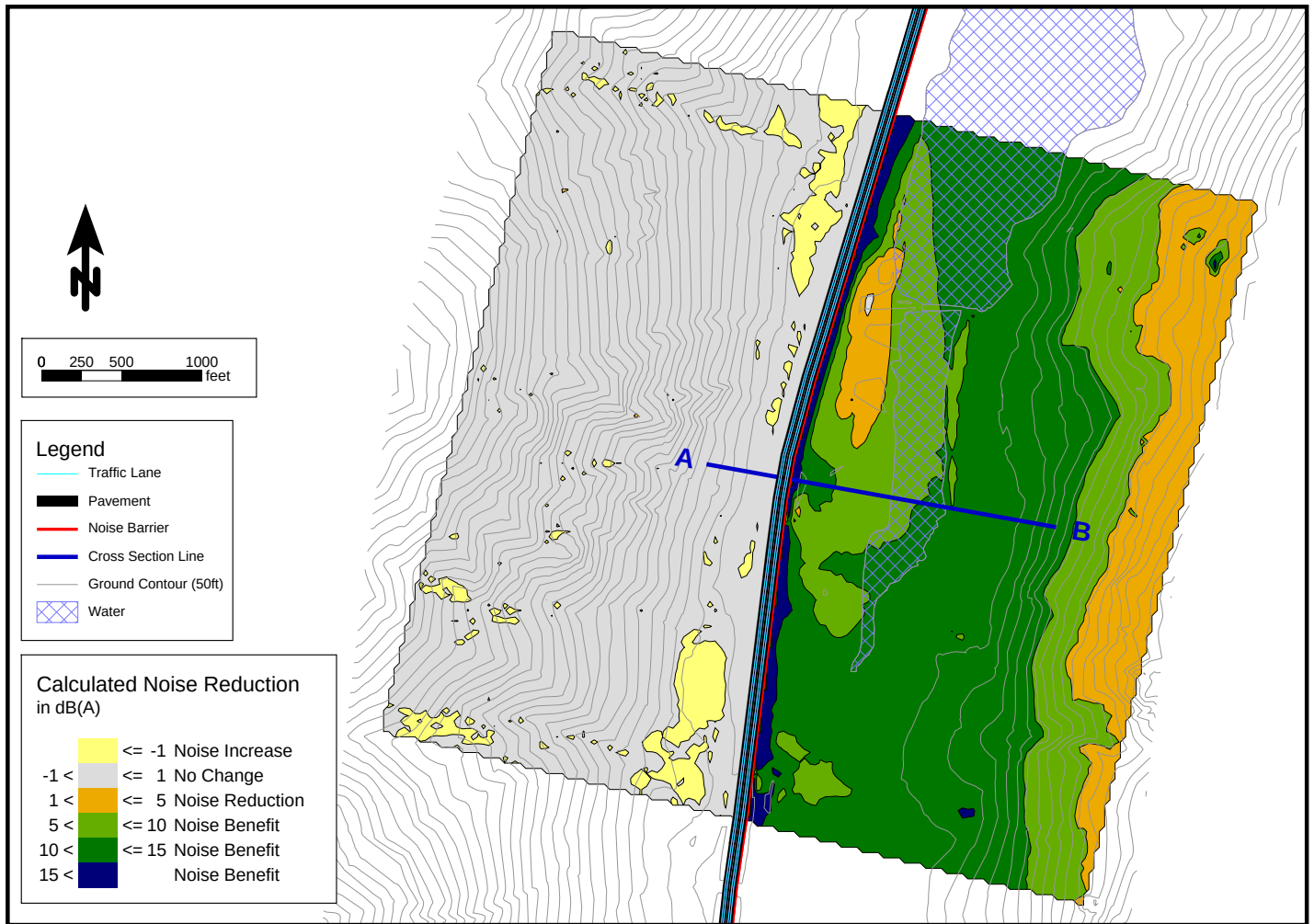
Schematic Drawing of Modeled Walls

Two Vertical Walls

WB I-70 EB I-70



Area 2 Modeled Noise Reductions From East Absorptive Barrier



Cross Section of Noise Level Reductions with Abatement



A

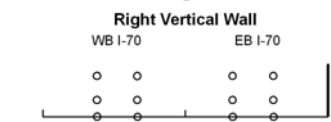
B

Legend

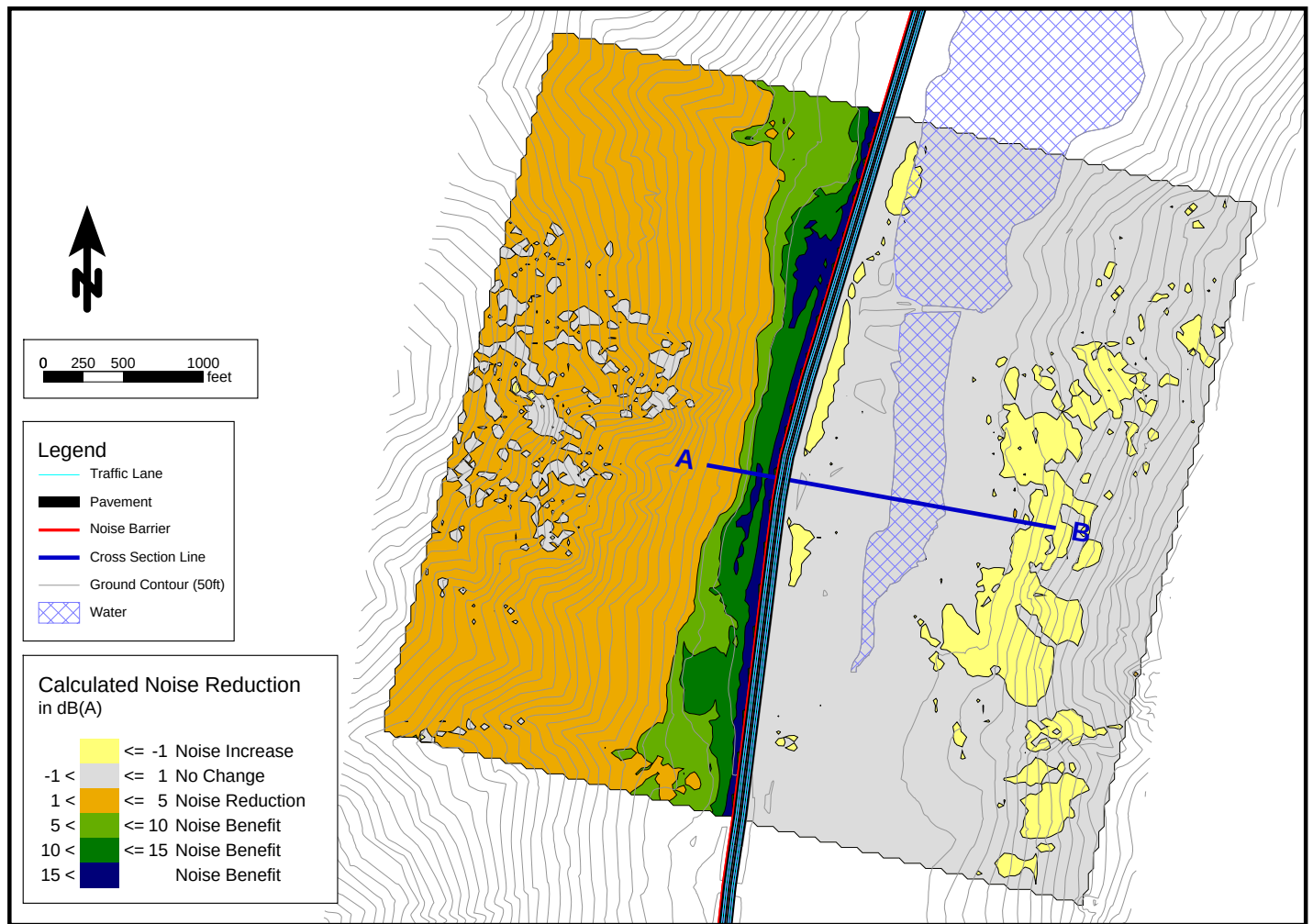
- Traffic Lane
- Noise Barrier
- Pavement
- Water
- Ground

0 125 250 500 feet

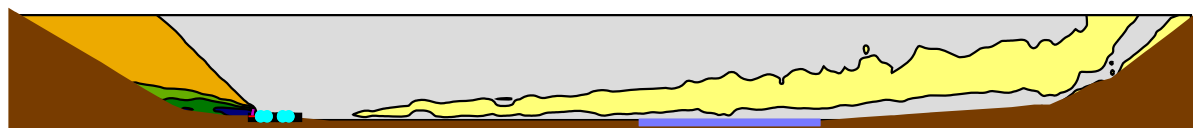
Schematic Drawing of Modeled Walls



Area 2 Modeled Noise Reductions From West Absorptive Barrier



Cross Section of Noise Level Reductions with Abatement



A

B

Legend

- Traffic Lane
- Noise Barrier
- Pavement
- Water
- Ground

0 125 250 500 feet

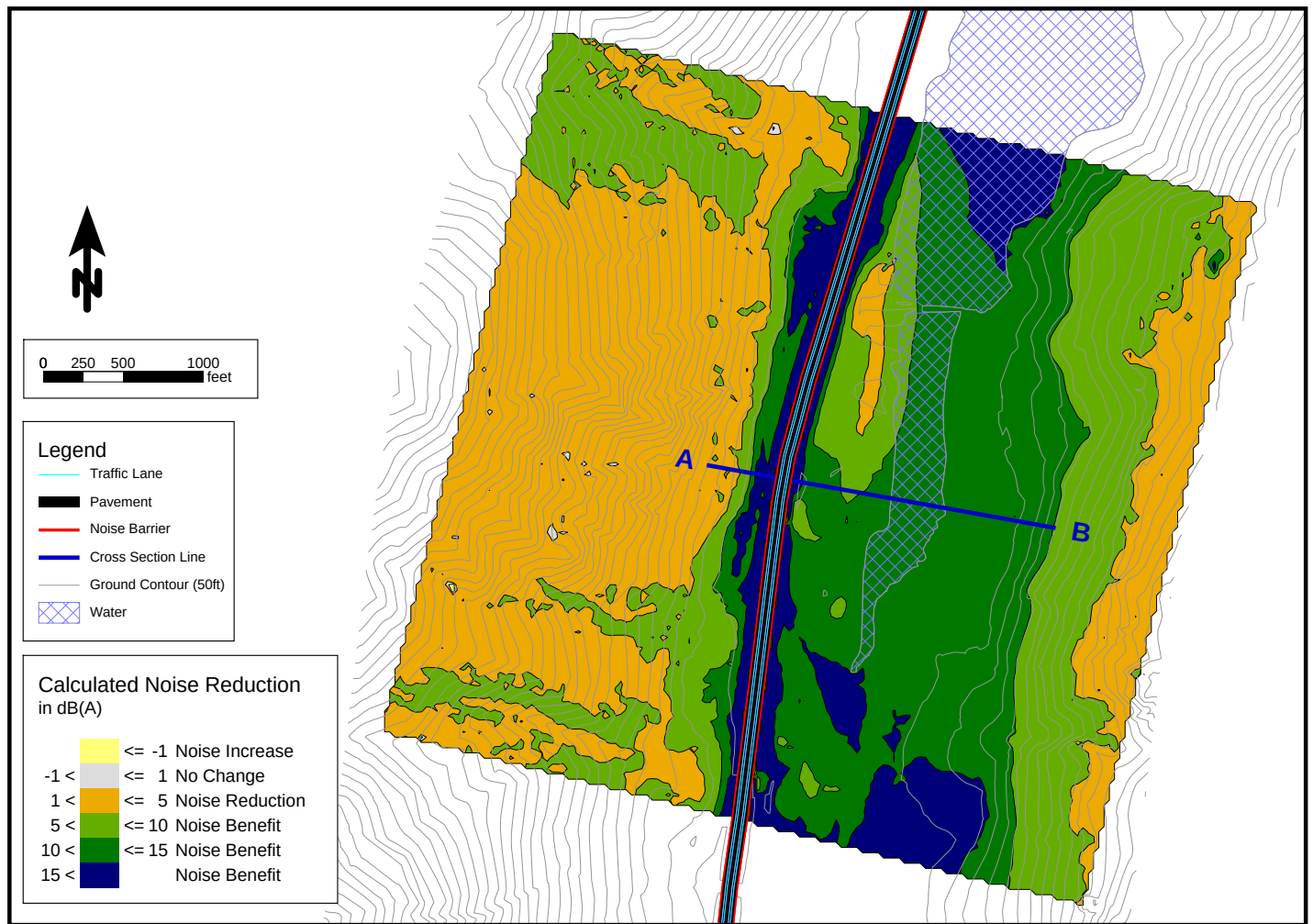
Schematic Drawing of Modeled Walls

Left Vertical Wall

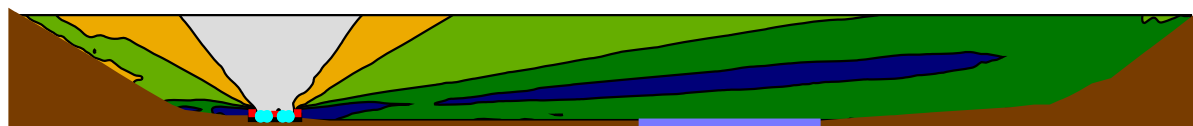
WB I-70 EB I-70



Area 2 Modeled Noise Reductions From Absorptive Median Barrier

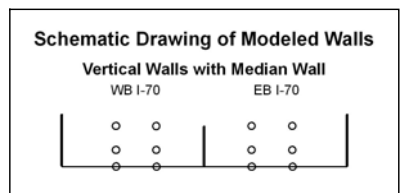
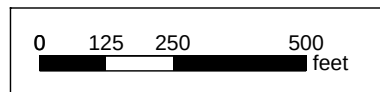


Cross Section of Noise Level Reductions with Abatement

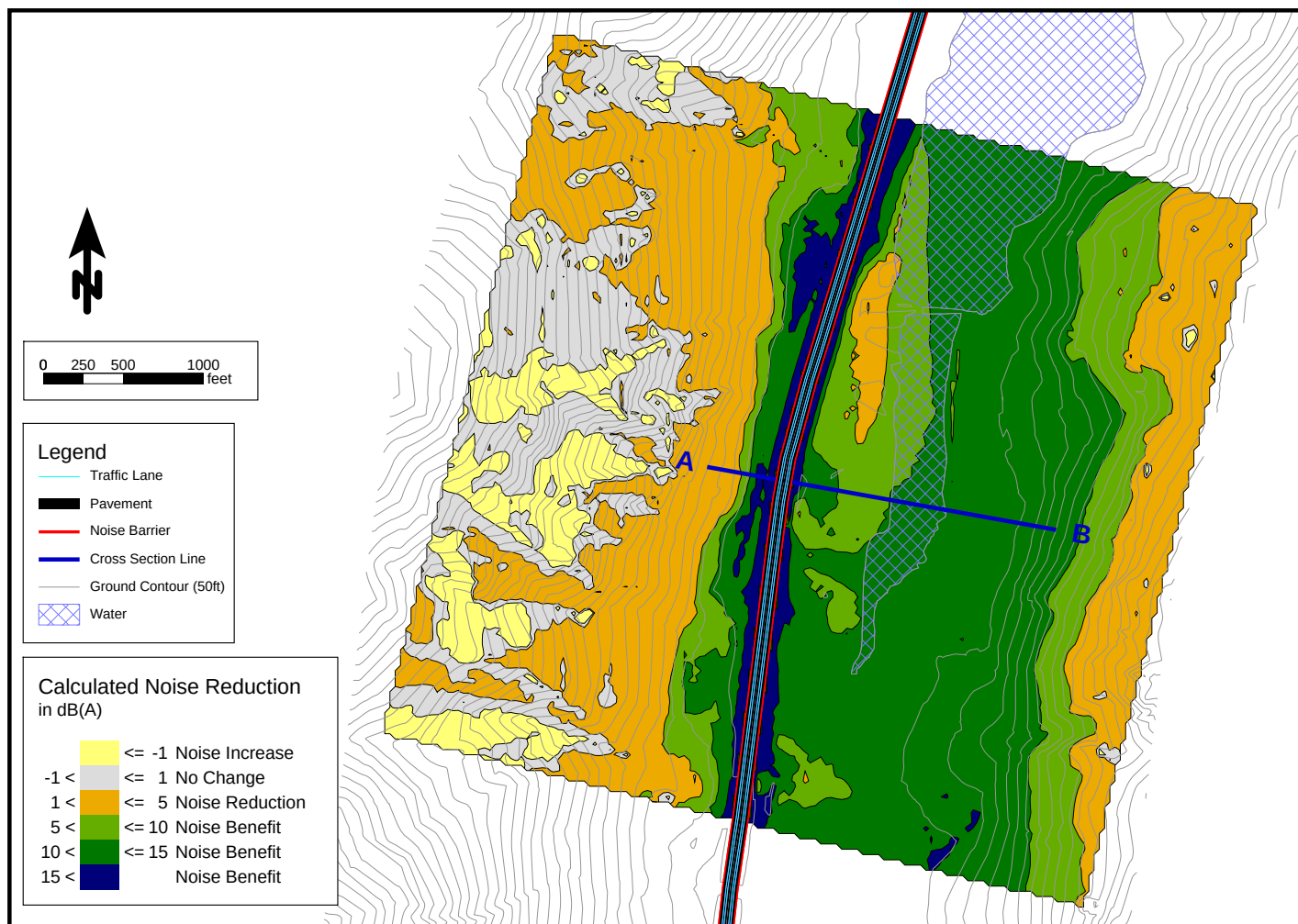


A

B



Area 2 Modeled Noise Reductions From 2 Barriers Lean In 10°



Cross Section of Noise Level Reductions with Abatement



A

B

Legend

- Traffic Lane
- Noise Barrier
- Pavement
- Water
- Ground

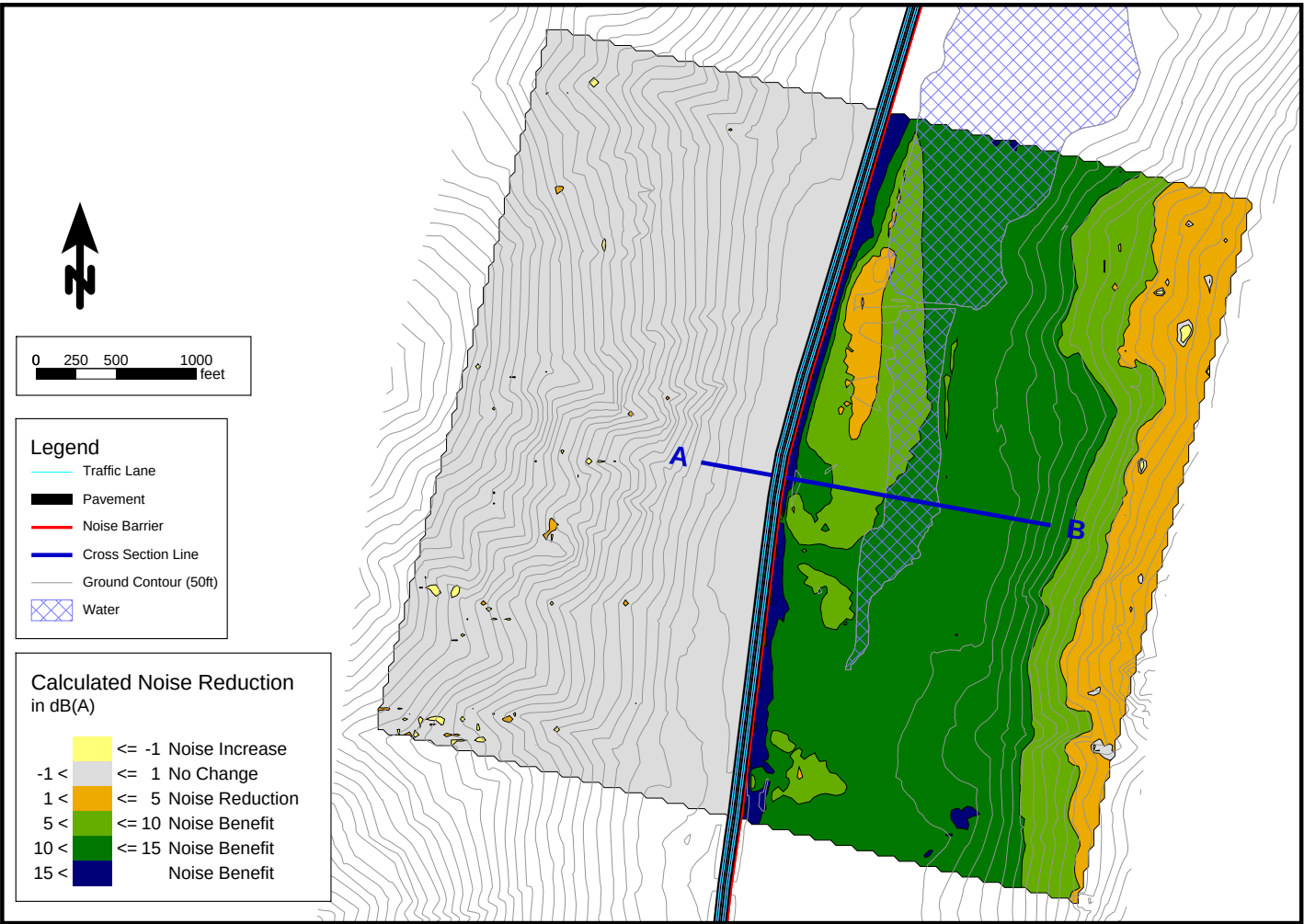
0 125 250 500 feet

Schematic Drawing of Modeled Walls

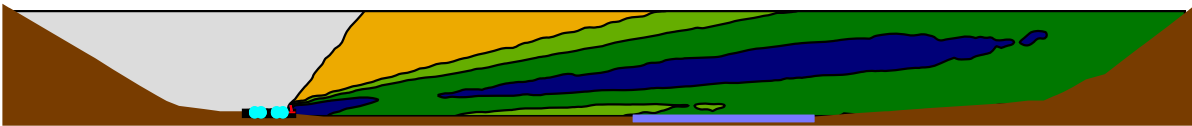
10° Inward Lean Two Walls
WB I-70 EB I-70



Area 2 Modeled Noise Reductions From East Barrier Lean In 10°

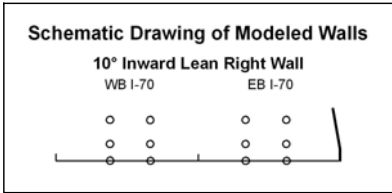
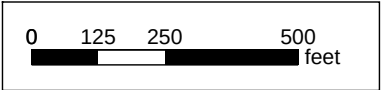
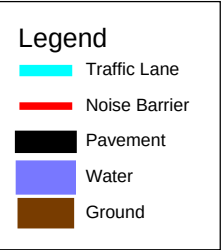


Cross Section of Noise Level Reductions with Abatement

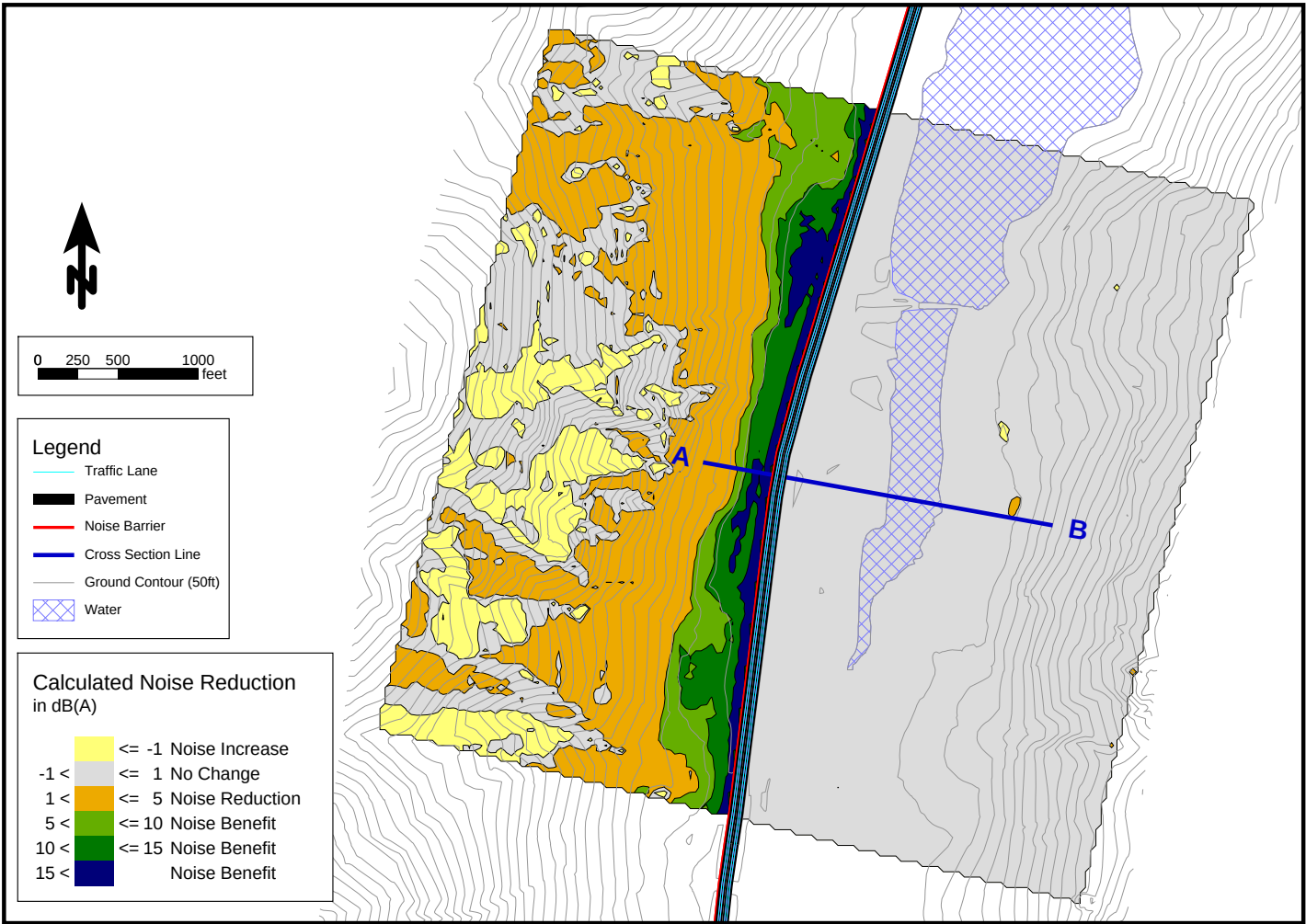


A

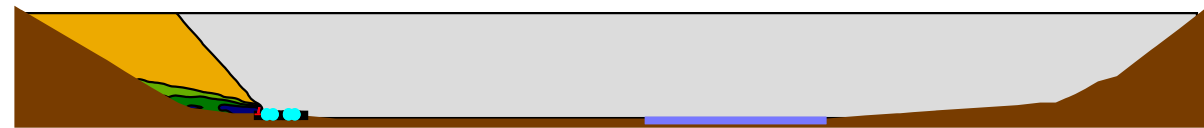
B



Area 2 Modeled Noise Reductions From West Barrier Lean In 10°

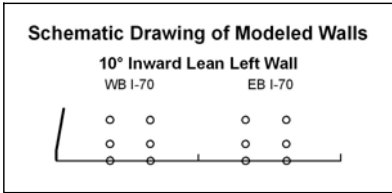
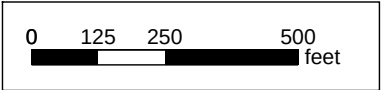


Cross Section of Noise Level Reductions with Abatement

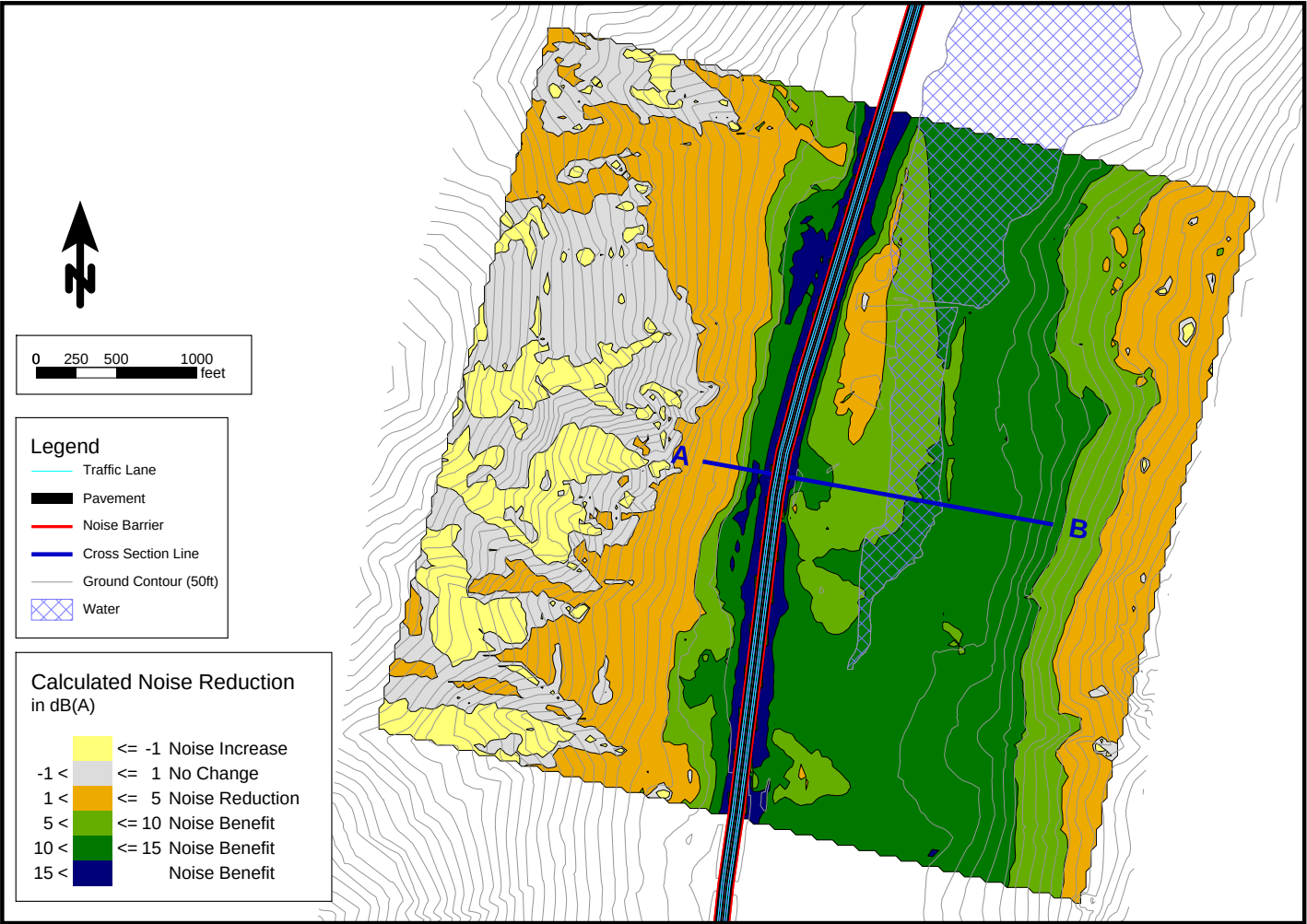


A

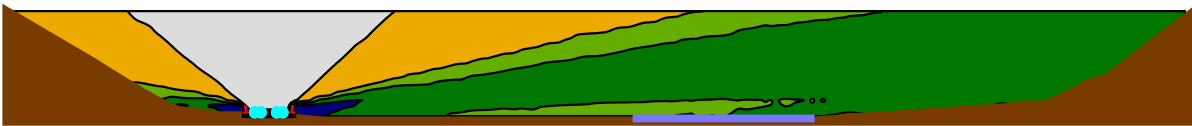
B



Area 2 Modeled Noise Reductions From 2 Barriers Lean Out 10°

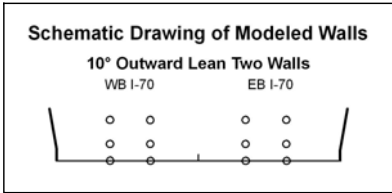
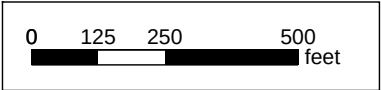
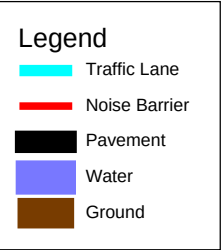


Cross Section of Noise Level Reductions with Abatement

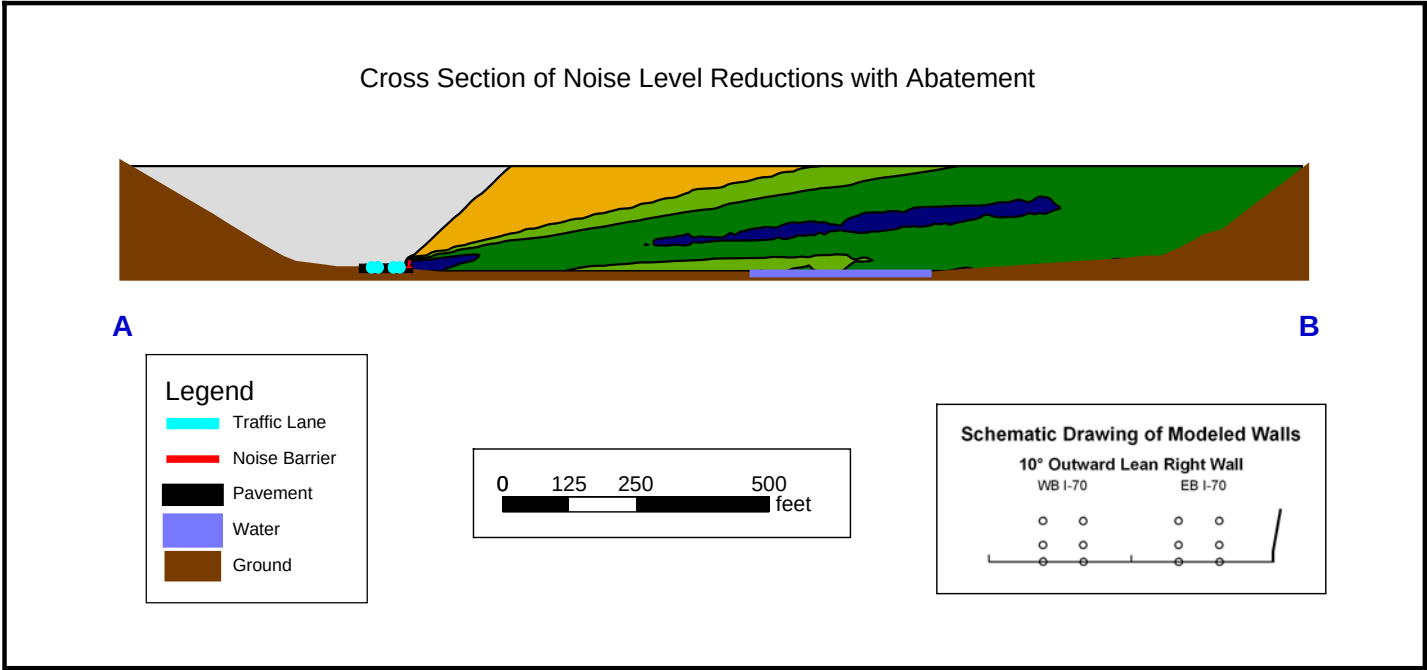
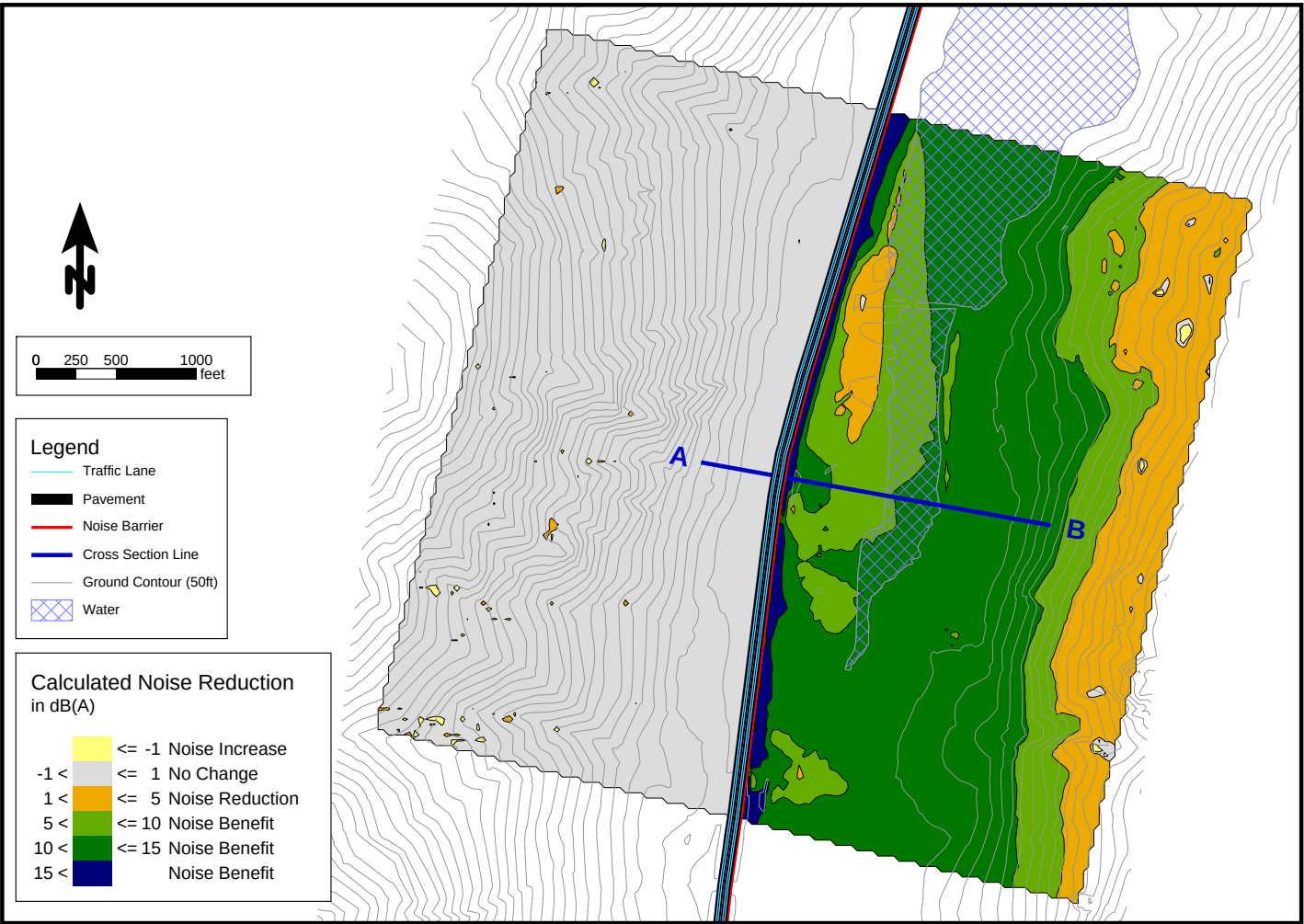


A

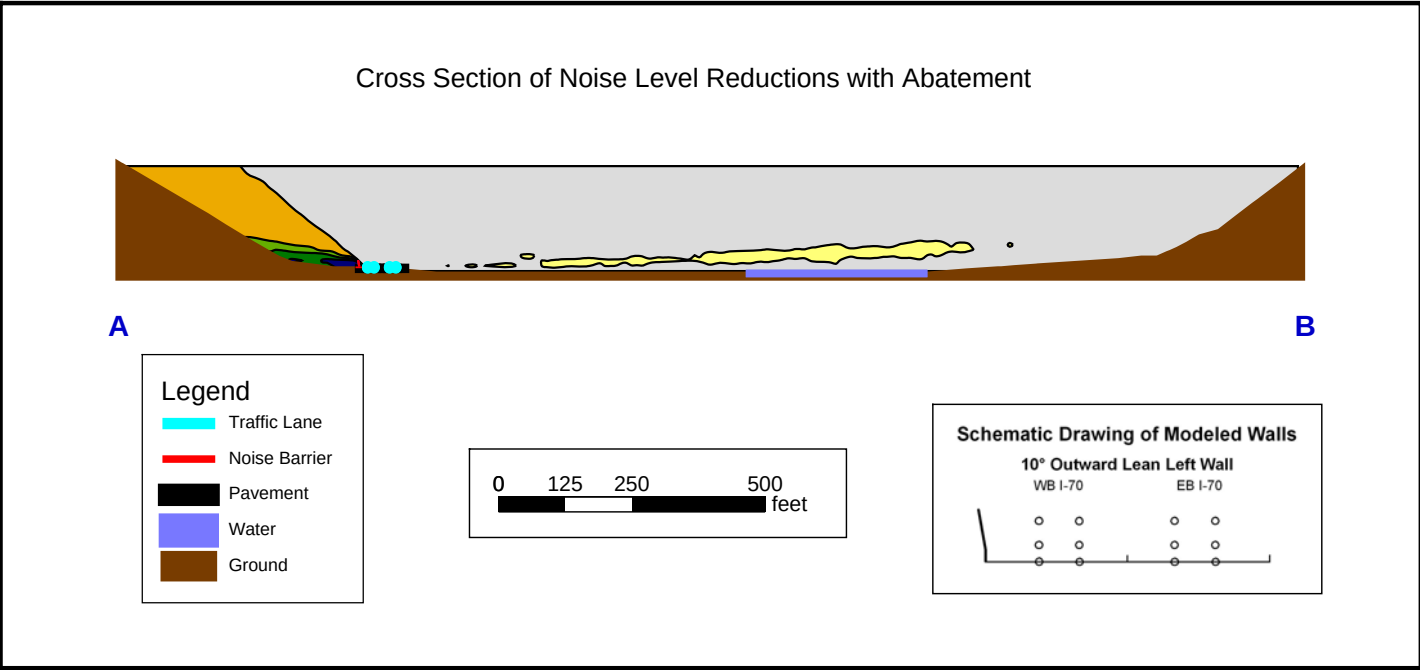
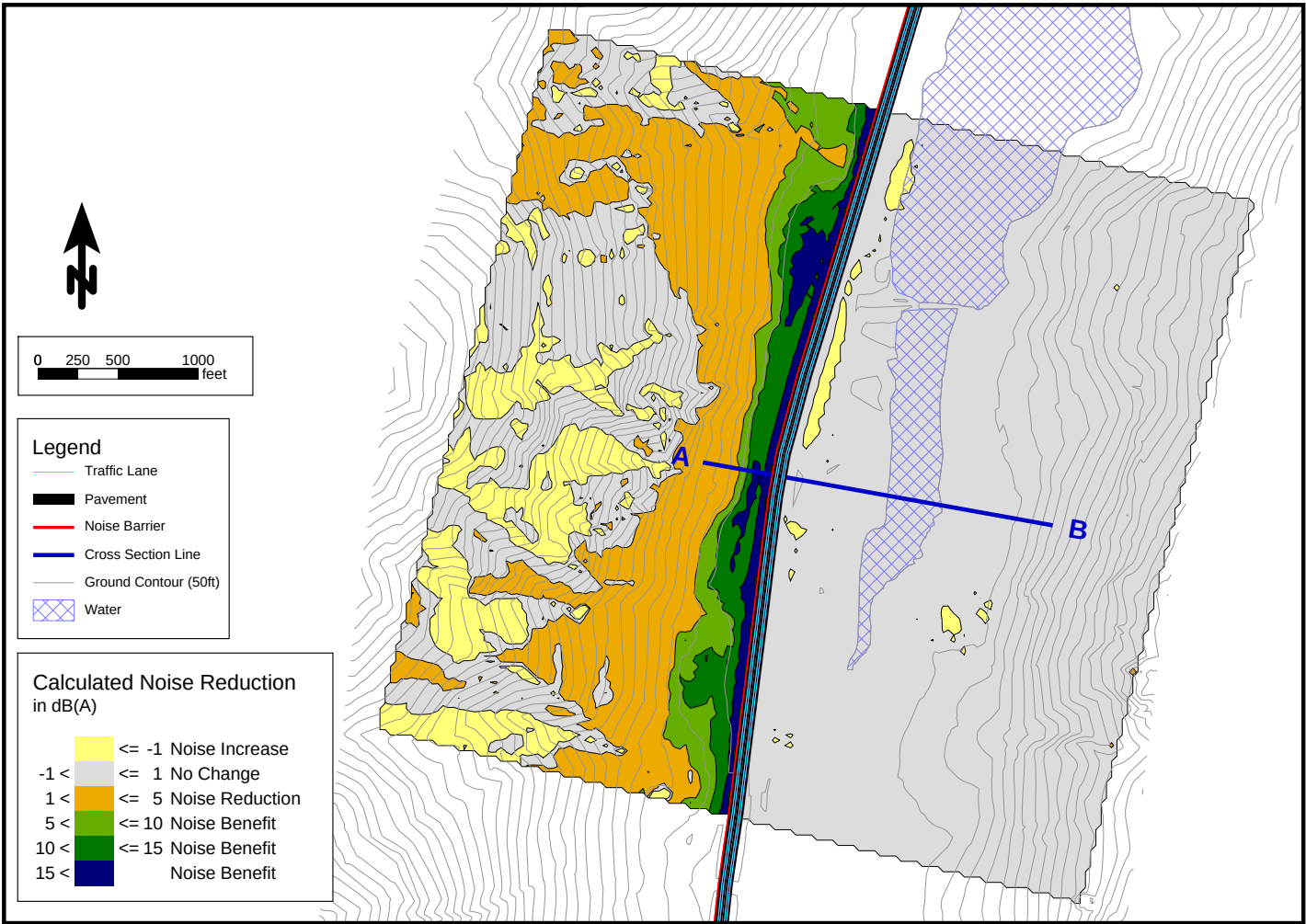
B



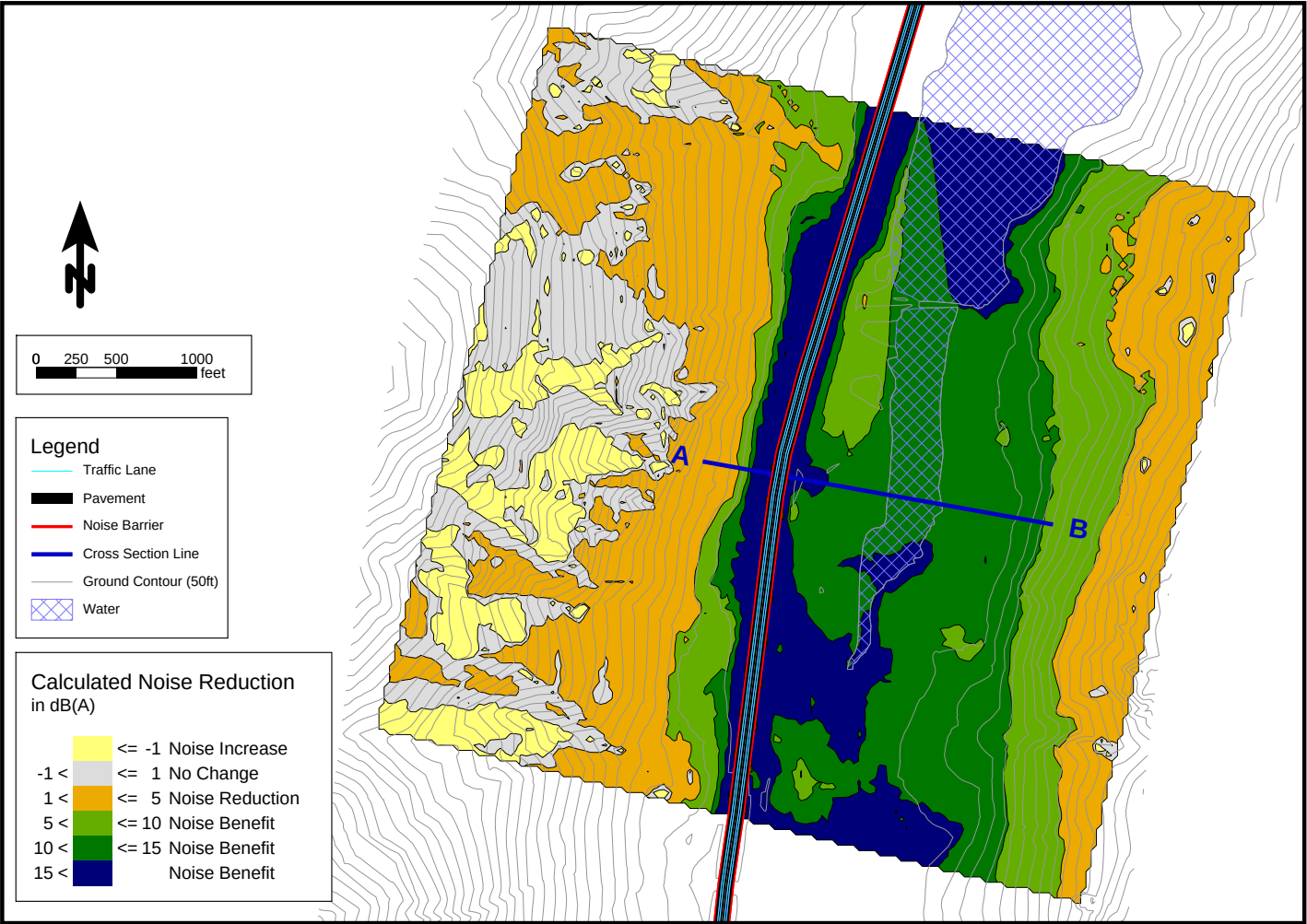
Area 2 Modeled Noise Reductions From East Barrier Lean Out 10°



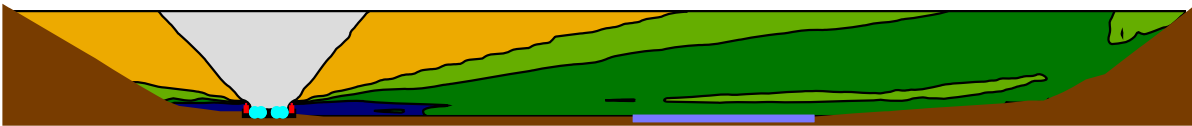
Area 2 Modeled Noise Reductions From West Barrier Lean Out 10°



Area 2 Modeled Noise Reductions From 2 T-top Barriers

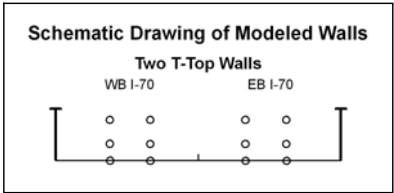
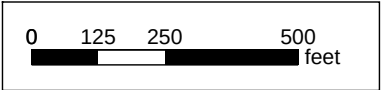


Cross Section of Noise Level Reductions with Abatement

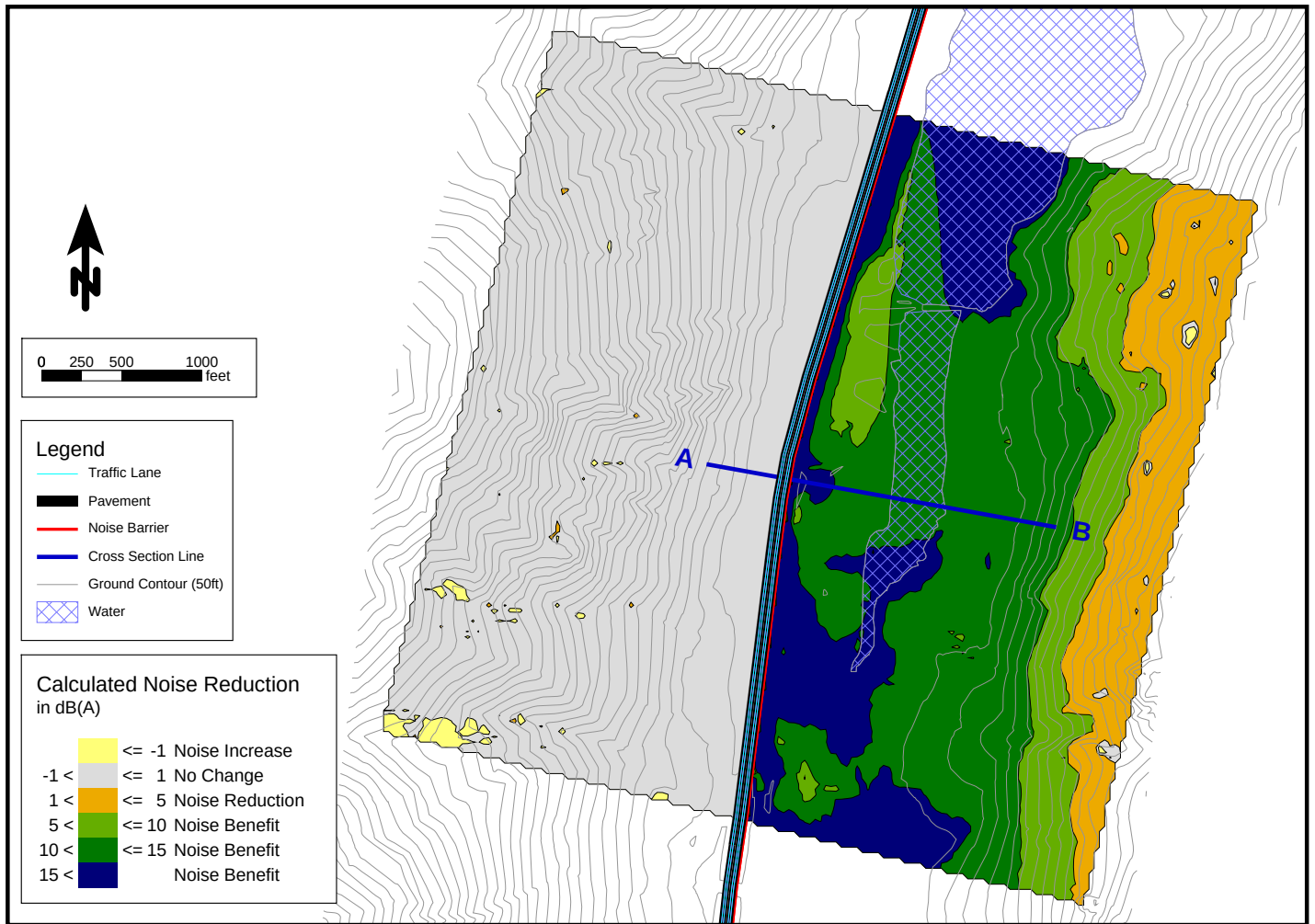


A

B



Area 2 Modeled Noise Reductions From East T-top Barrier



Cross Section of Noise Level Reductions with Abatement



A

B

Legend

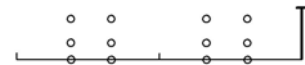
- Traffic Lane
- Noise Barrier
- Pavement
- Water
- Ground

0 125 250 500 feet

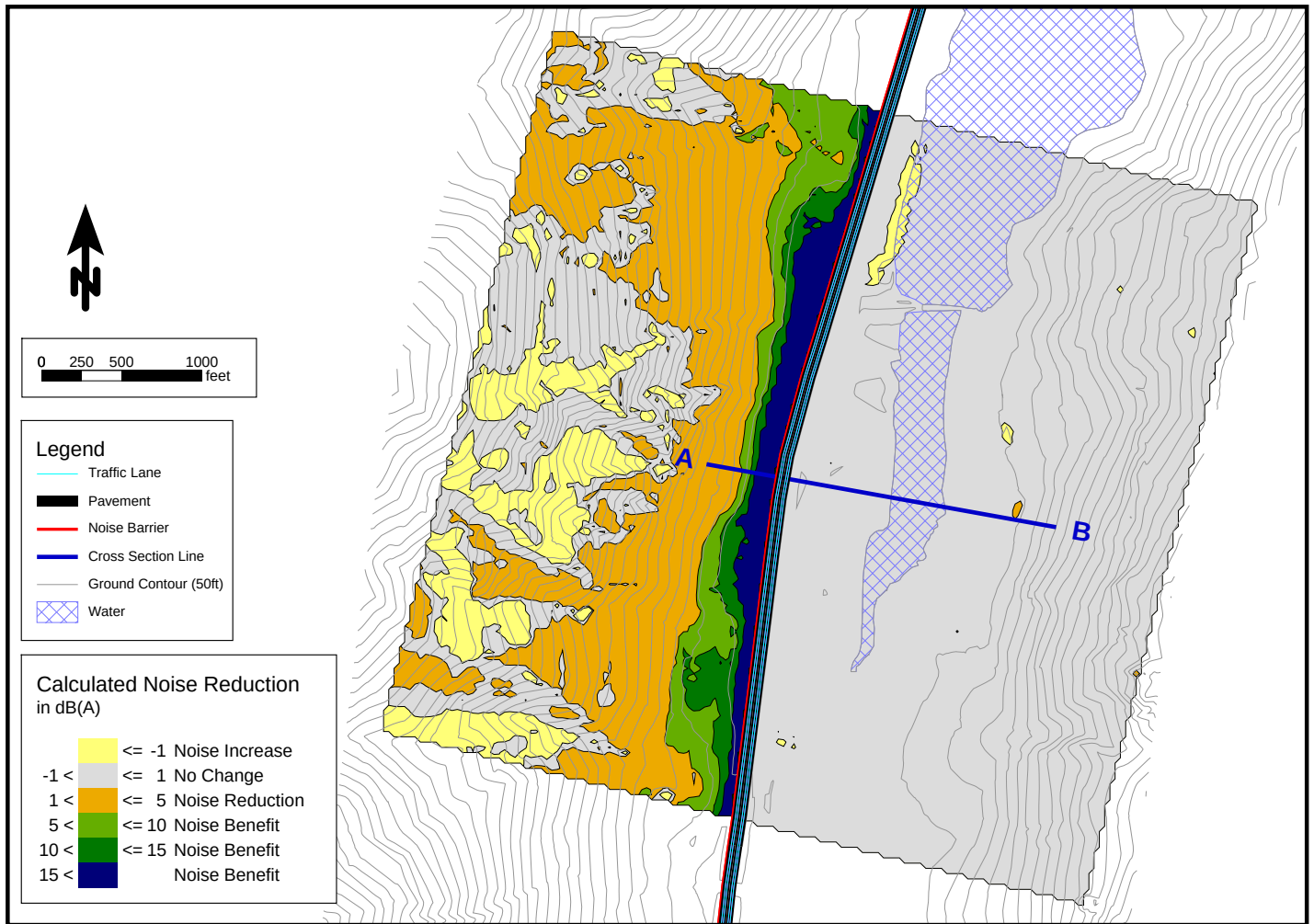
Schematic Drawing of Modeled Walls

Right T-Top Wall

WB I-70 EB I-70



Area 2 Modeled Noise Reductions From West T-top Barrier



Cross Section of Noise Level Reductions with Abatement



A

B

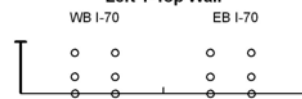
Legend

- Traffic Lane
- Noise Barrier
- Pavement
- Water
- Ground

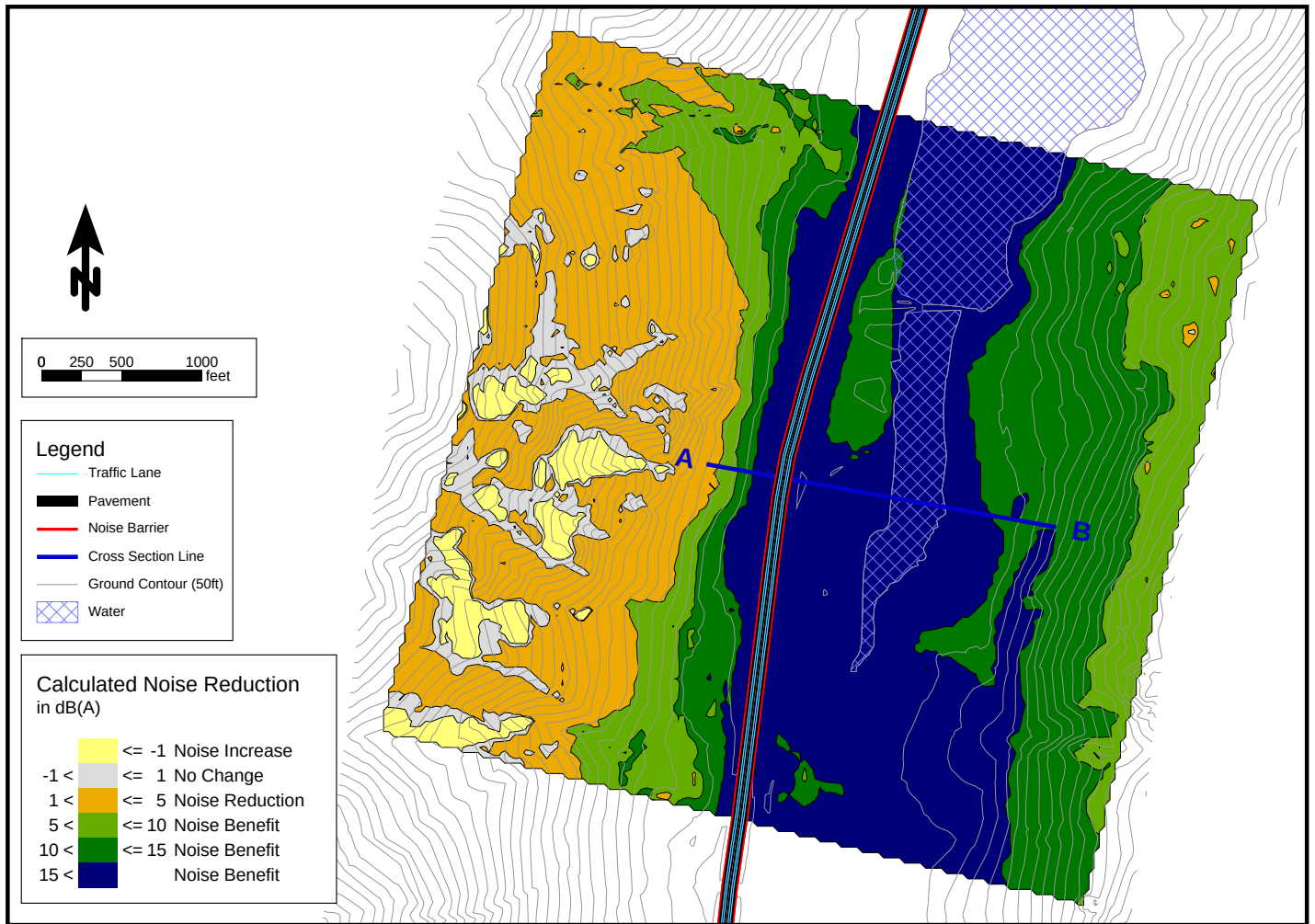
0 125 250 500 feet

Schematic Drawing of Modeled Walls

Left T-Top Wall



Area 2 Modeled Noise Reductions From 2 Gallery Barriers



Cross Section of Noise Level Reductions with Abatement



A

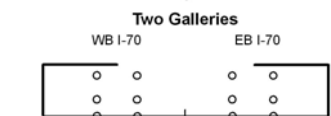
B

Legend

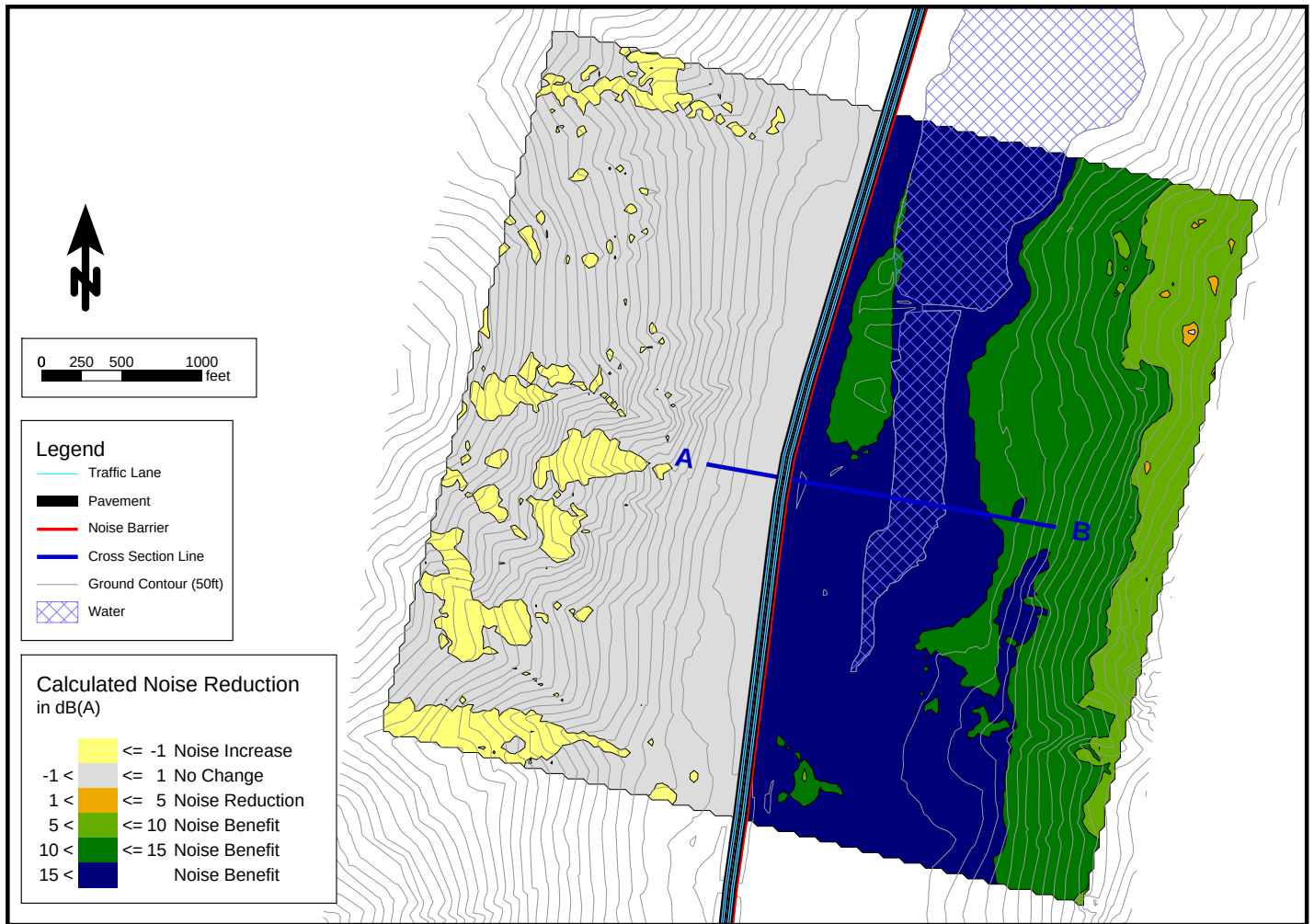
- Traffic Lane
- Noise Barrier
- Pavement
- Water
- Ground

0 125 250 500 feet

Schematic Drawing of Modeled Walls



Area 2 Modeled Noise Reductions From East Gallery Barrier



Cross Section of Noise Level Reductions with Abatement



A

B

Legend

- Traffic Lane
- Noise Barrier
- Pavement
- Water
- Ground

0 125 250 500 feet

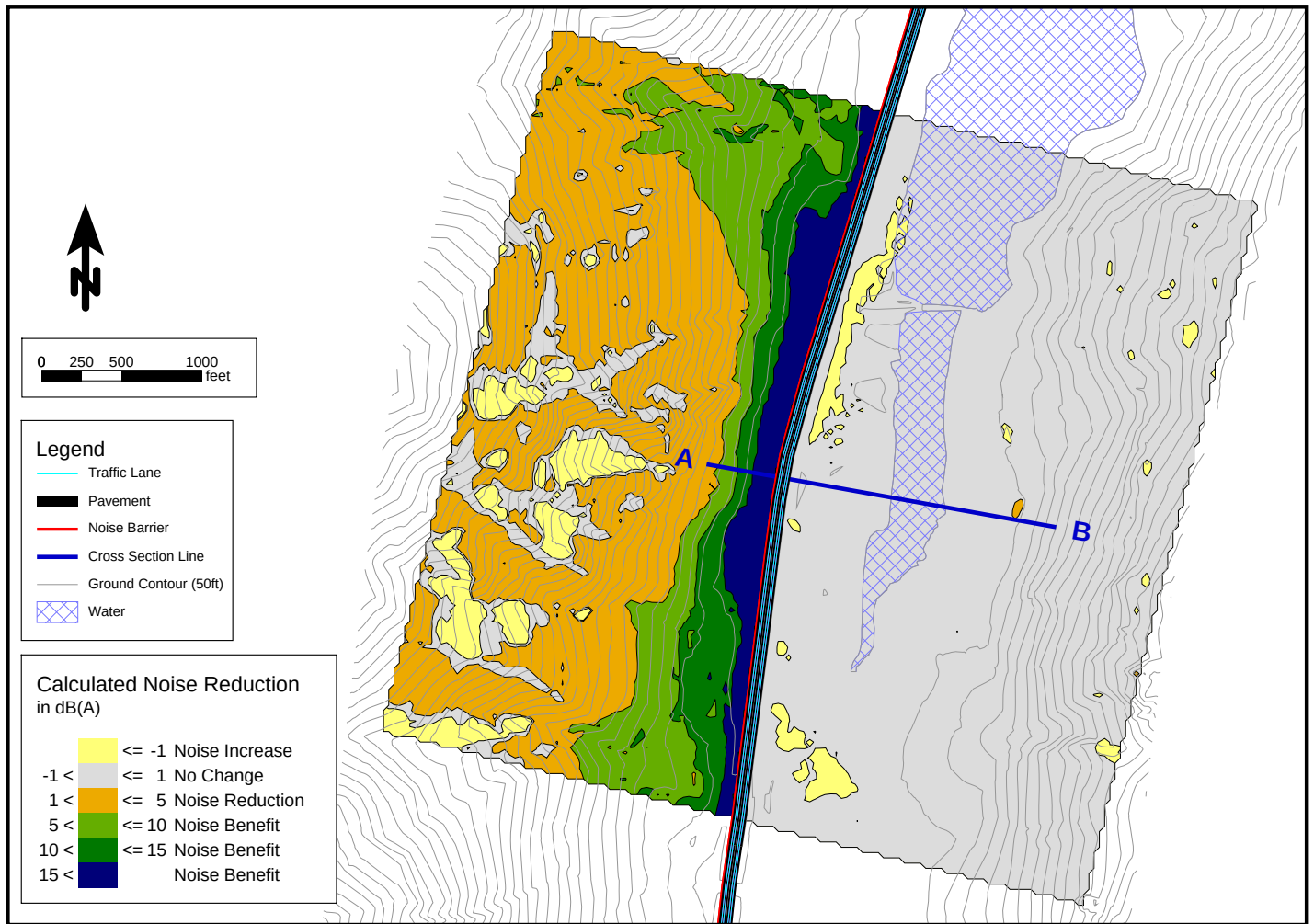
Schematic Drawing of Modeled Walls

Right Gallery

WB I-70 EB I-70



Area 2 Modeled Noise Reductions From West Gallery Barrier



Cross Section of Noise Level Reductions with Abatement



A

B

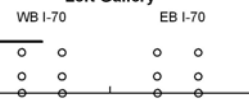
Legend

- Traffic Lane
- Noise Barrier
- Pavement
- Water
- Ground

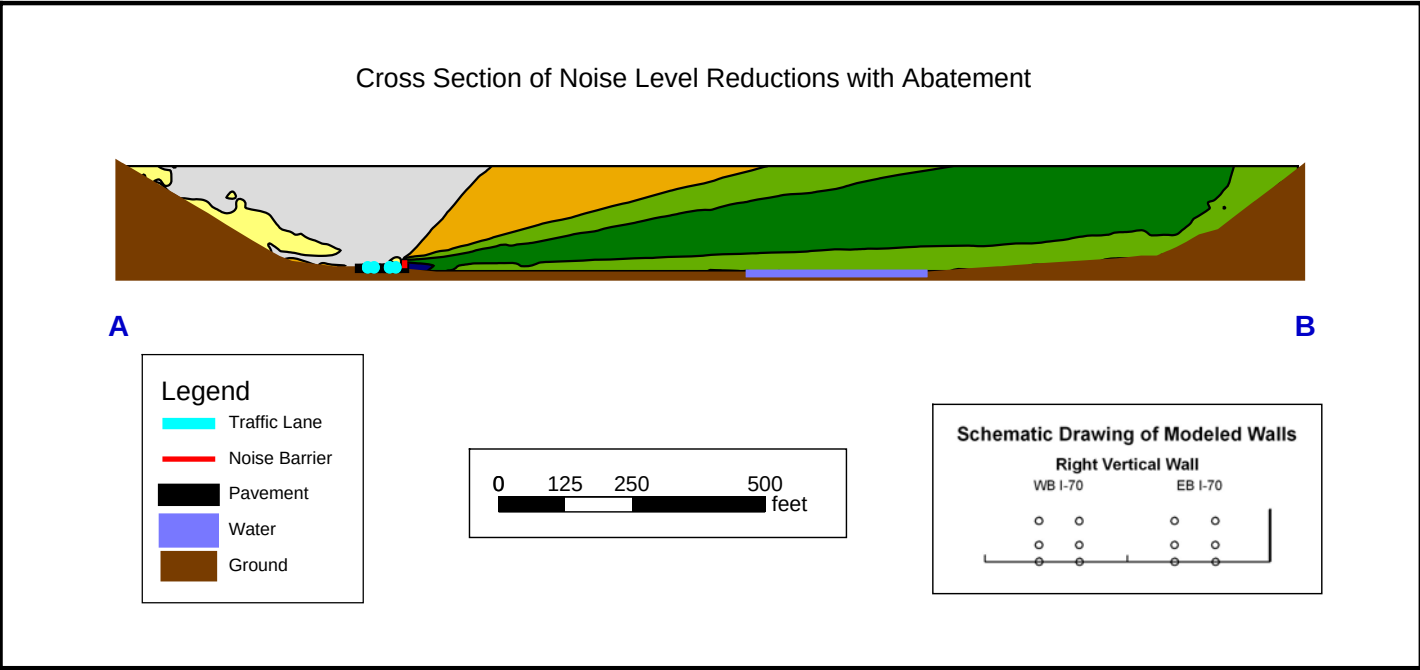
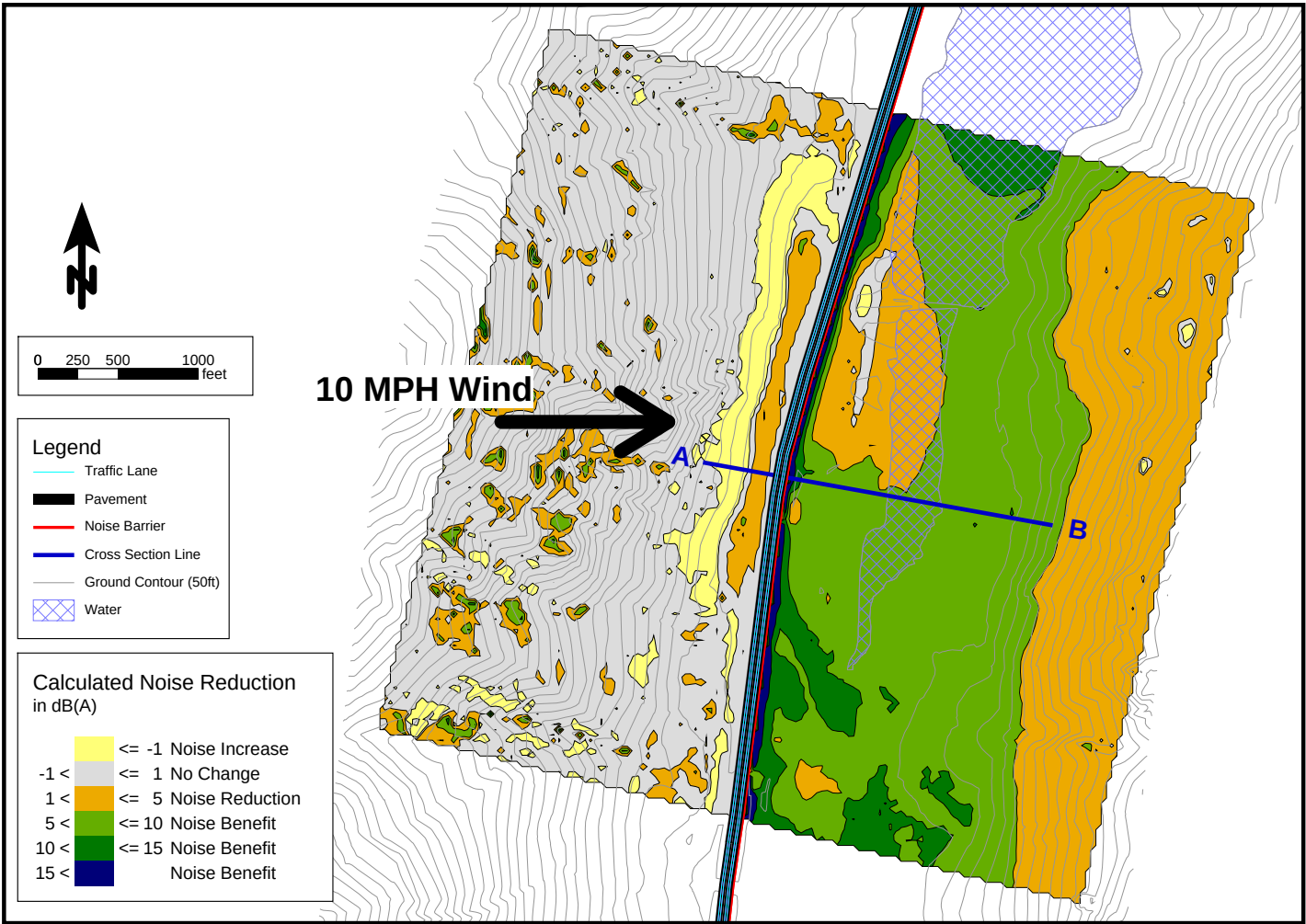
0 125 250 500 feet

Schematic Drawing of Modeled Walls

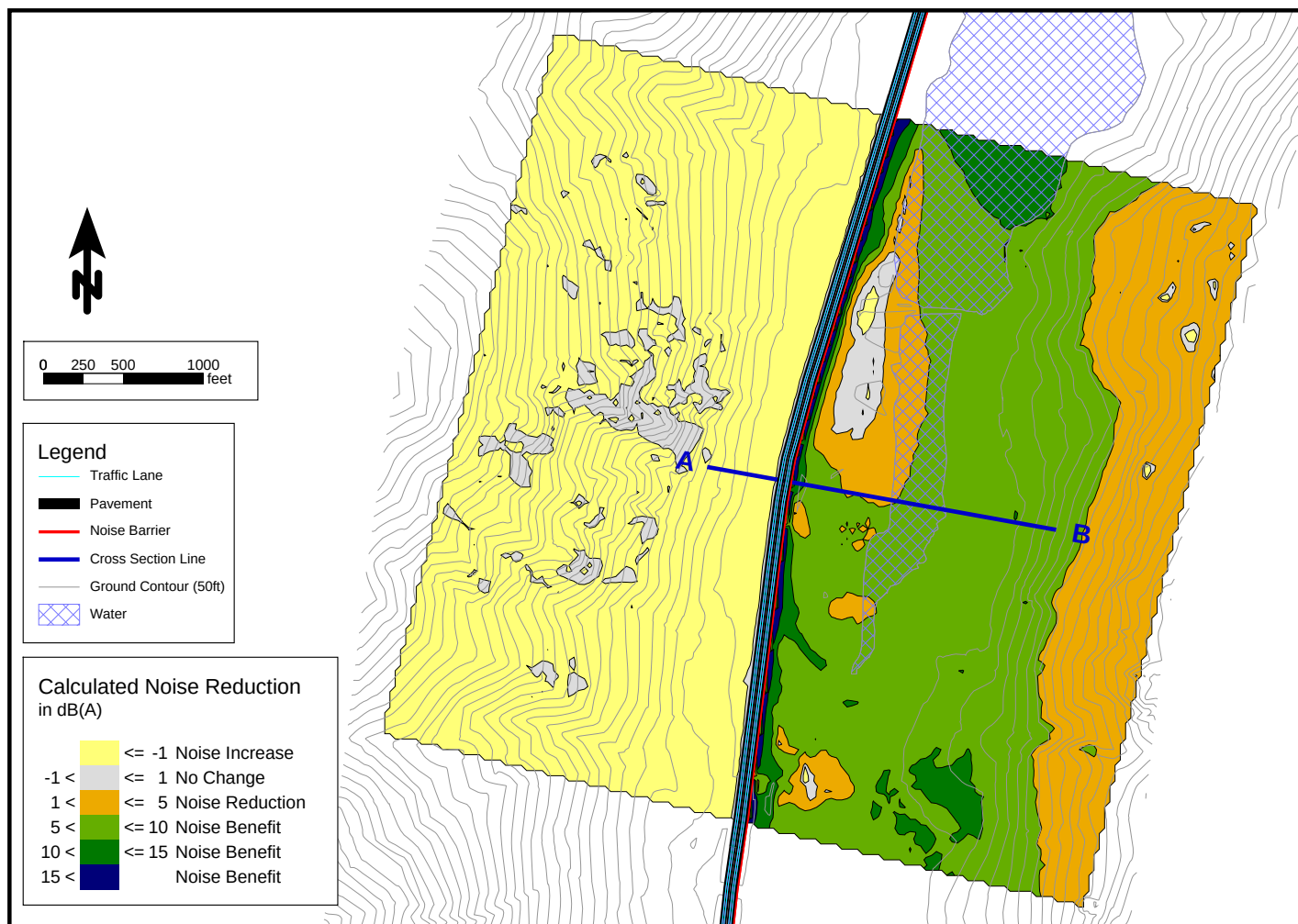
Left Gallery



Area 2 Modeled Noise Reductions From East Reflective Barrier + West Wind



Area 2 Modeled Noise Reductions From East Reflective Barrier + Inversion



Cross Section of Noise Level Reductions with Abatement



A

B

Legend

- Traffic Lane
- Noise Barrier
- Pavement
- Water
- Ground

0 125 250 500 feet

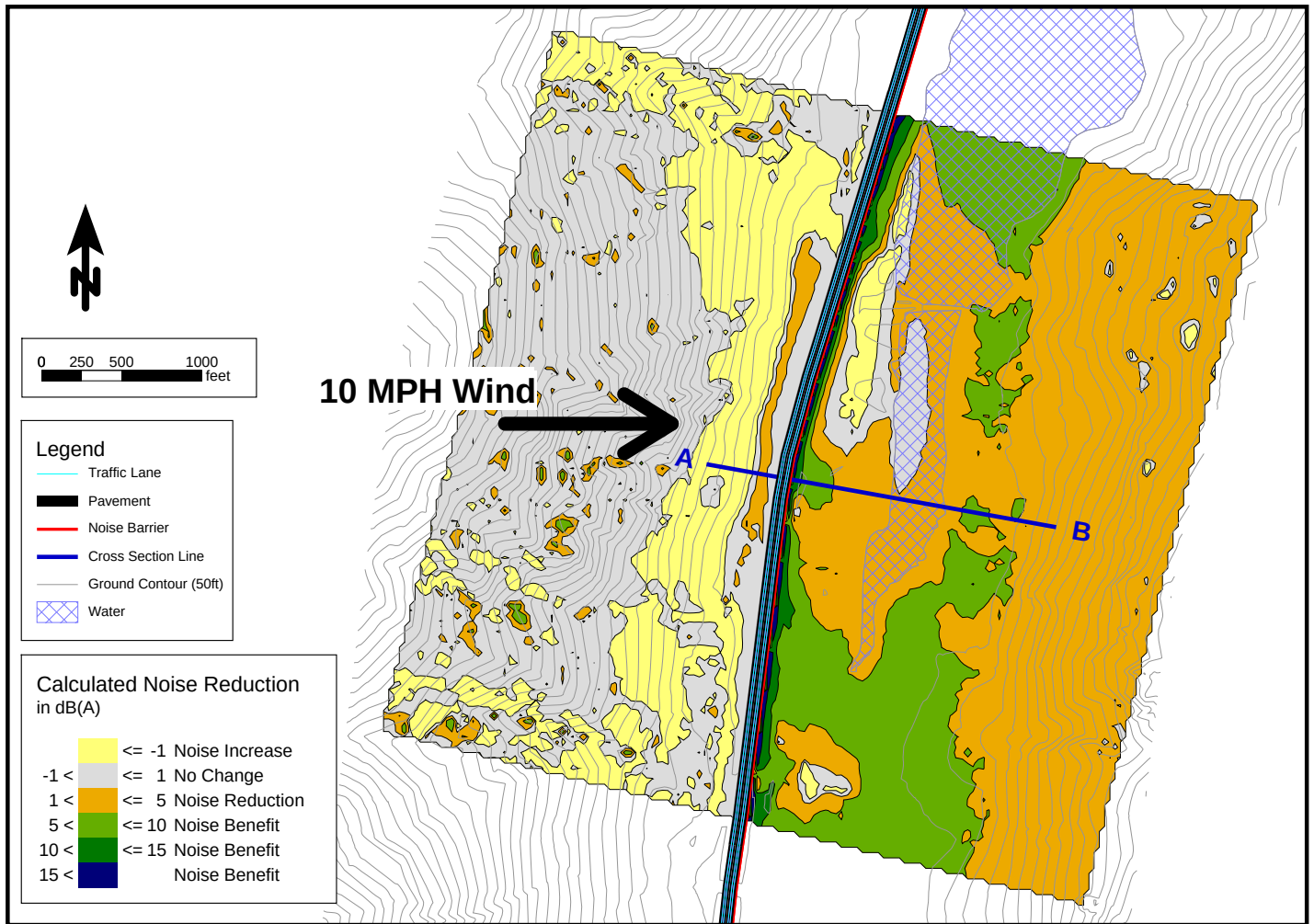
Schematic Drawing of Modeled Walls

Right Vertical Wall

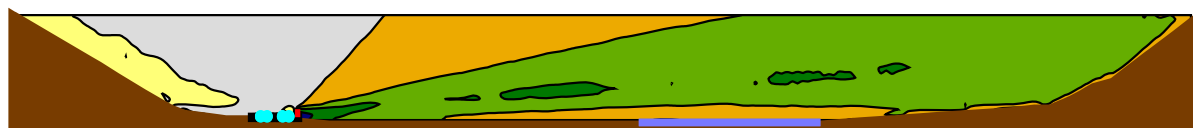
WB I-70 EB I-70



Area 2 Modeled Noise Reductions From East Reflective Barrier + Wind + Inversion



Cross Section of Noise Level Reductions with Abatement



A

B

Legend

- Traffic Lane
- Noise Barrier
- Pavement
- Water
- Ground

0 125 250 500 feet

Schematic Drawing of Modeled Walls

Right Vertical Wall

WB I-70 EB I-70

