5. NOISE MITIGATION OPTIONS

When considering traffic noise and noise mitigation options, there are three main components that should be recognized: the Noise Source, the Noise Path, and the Noise Receiver. These three components affect the type, tone, and volume of noise that originates from a given roadway and reaches a given receiver. Since these are the main components associated with the production and transmission of highway-related noise, each of these three components are discussed below.

For each component, a summary is given to the concepts affecting noise, as well as the options to mitigate noise. In addition to these three components (i.e., source, path and receiver), the report will also examine planning strategies that can be considered to avoid highway-noise conflicts. The use of planning strategies to avoid future noise impacts relies on logical development and site planning to reduce the influence of highway noise on adjacent land uses. Generally, this technique uses a number of tools to promote non noise-sensitive land uses adjacent to highway corridors, and the placement of noise-sensitive land uses away from transportation noise sources. The following section of the report will examine and discuss each of the three noise components (i.e., source, path and receiver), as well as planning initiatives to avoid the development of non-compatible land uses adjacent to highway corridors.

5.1. Noise Source

For the purposes of this report, the noise source is considered to represent an existing and/or planned highway corridor. As discussed in **Section 3 - Fundamentals of Highway Traffic Noise**, when considering highway projects the main source of noise is produced by the vehicles using a given roadway. As discussed previously, there are many factors associated with the vehicle/roadway interaction that can affect the type, tone, and volume of noise emanating from a specific roadway. This section of the report will examine the noise source in greater detail and address potential noise mitigation measures that could effectively reduce noise levels produced at the source. When examining the noise source, factors affecting noise emissions can generally be grouped into three categories: the vehicles themselves, vehicle operational characteristics, and roadway engineering considerations.

5.1.1 Vehicles

Again, the main noise sources of highway vehicles include the engine/power train, the exhaust system, and the tires. Mechanical and aerodynamic noise sources are also present. While some research suggests the use of additional noise components, including vehicle fans, intake, and transmission [6], these additional factors will be grouped into and generalized as engine/power train-related noise for the purposes of this report. As discussed in **Section 3.2 - Causes of Highway Traffic Noise**, when considering the total noise produced by vehicles, engine and exhaust noise usually dominate at vehicle speeds under 30 miles per hour (mph); while tire noise often becomes the dominant noise source from individual vehicles at highway speeds.

5.1.1.1 Engine/Power Train/Mechanical Noise

When considering highway-vehicle induced noise, an obvious component is the engine/power train-related noise component (including fan, intake, and transmission). The actual influence from this component can vary considerably, depending on the type, age, and condition of the vehicle under consideration. Smaller engines generally produce less noise, when compared to larger, higher horse-power engines. Also, the age and condition of a vehicles engine can also influence its noise emissions. Generally, newer vehicles and vehicles that are better maintained produce less noise than older or poorly maintained vehicles. Noise control on newer vehicles is generally a market driven requirement. Vehicle manufacturers have continued to reduce both interior and exterior vehicle noise levels due to consumer-driven demands for quieter vehicles. This has been accomplished through refined vehicle engineering/design and improved tolerances between moving engine/mechanical parts.

5.1.1.2 Exhaust Noise

Exhaust noise is another component that can vary considerably from vehicle to vehicle. Vehicles with poorly functioning or modified exhaust systems can significantly increase vehicle-induced noise levels; and exhaust noise from vehicles without mufflers can often dominate over all other components of vehicle noise [6]. Mufflers are standard equipment and provided by vehicle manufacturers on all road-legal vehicles. While mufflers are very effective at reducing exhaust-related noise, mufflers can also reduce vehicle performance by reducing horse-power and increasing fuel consumption. Muffler systems on most vehicles are in good working condition and unmodified. However, when factory mufflers are not maintained or are replaced with modified/high-performance exhaust systems, noise levels from these vehicles can increase significantly. Generally, standard factory-provided mufflers have reached their limit of effectiveness and maintain a practical balance of noise control while limiting loss of engine performance.

5.1.1.3 Tire Noise

Tire noise is the final component of the vehicle noise source. This component represents the complex interaction between a vehicles tires and the roadway surface. There is currently a significant amount of research underway related to this interaction, but unfortunately, many of the factors involved in this interaction are only qualitatively understood. Detailed studies necessary to quantitatively understand this interaction are still ongoing and incomplete [7].

The main factors affecting tire-related noise include the speed of the rotation of the tire, the tire tread-pattern, the tire material, and the type and texture of the roadway surface. It was once believed that changes in tire construction and tread pattern had less of an effect on rolling tire noise than changes in roadway surface material and texture; however, more recent research indicates that tire design and tread-pattern may play a greater role in the ultimate noise level produced by this interaction [7]. The following discussion on the tire/roadway interaction will focus specifically on the tire component. The pavement component of this interaction will be discussed in great detail in **Section 5.1.3.4** of this report.

As suggested above, we have only limited quantitative results related to tire noise, mainly due to the many factors that can influence this issue. Some of the factors that can influence noise levels from a given tire include tread width, sidewall height, tread design, tire composition, tire stiffness, and tread life/tire softness. Generally, high performance tires and tires with aggressive, off-road treads produce greater noise levels than all season and touring tires. Additional factors outside the control of tire manufacturers are tire wear and proper inflation. These factors can change noise levels from individual vehicles throughout the life of a set of tires. Tests on the same vehicle using tires of different manufacturers and design can produce a range in vehicle drive-by sound levels of 10 dBA [6].

5.1.1.4 Engine Brakes

As discussed in **Section 3.2 – Causes of Highway Traffic Noise**, the composition of vehicles in the vehicle fleet, and specifically the amount of heavy truck traffic, can also significantly affect the volume of noise produced by a roadway. As suggested in **Figure 2**, one heavy truck at 55 mph produces about the same acoustic energy as approximately 28 cars at that same speed. Heavy trucks can also introduce additional noise sources/components that are not associated with automobile traffic. Engine brakes (often referred to as Jake brakes) can produce spikes in diesel truck traffic exhaust noise when they are applied. Engine brakes are commonly used by diesel trucks on steep down-grades to slow the vehicles without using wheel brakes. This technology is used at the discretion of the driver, to shift the power producing engine into a power-absorbing air compressor. The more cylinders the driver chooses to apply, the greater the breaking power, and the greater the noise level.

Fortunately, complaints associated with engine brakes are often limited to specific locations where steep roadway grades or highway interchanges are adjacent to residential or other noise-sensitive locations. Noise associated with engine brakes can be controlled by changing driver behavior and/or by restricting the use of engine brakes in these areas. To combat this noise concern, many municipalities have chosen to restrict the use of engine brakes in those areas where this problem exists. This approach is effective at addressing the case-by-case nature of the problem.

5.1.1.5 Summary and Limitations

Noise production and control at the vehicle source is discussed above. Generally, much of the noise controls associated with individual vehicles are addressed by vehicle manufacturers and by owner maintenance. Poorly maintained and modified vehicles often dominate the noise spectrum, when compared to well maintained and factory-equipped vehicles. EPA noise level limitations and market-driven demands of vehicle manufacturers for quieter vehicles will continue to control noise produced by new vehicles. Much of the discussion above focuses on vehicle manufacturer and maintenance requirements to limit vehicle-induced noise, and many of these factors are beyond the control of FHWA and ODOT. Other operational factors such as engine brake noise are generally only concerns on a case-by-case basis, and local/municipal restrictions are often available to eliminate this concern. Considering these limitations, no further consideration will be given to controlling noise produced by individual motor-vehicles.

5.1.2 Operational Factors

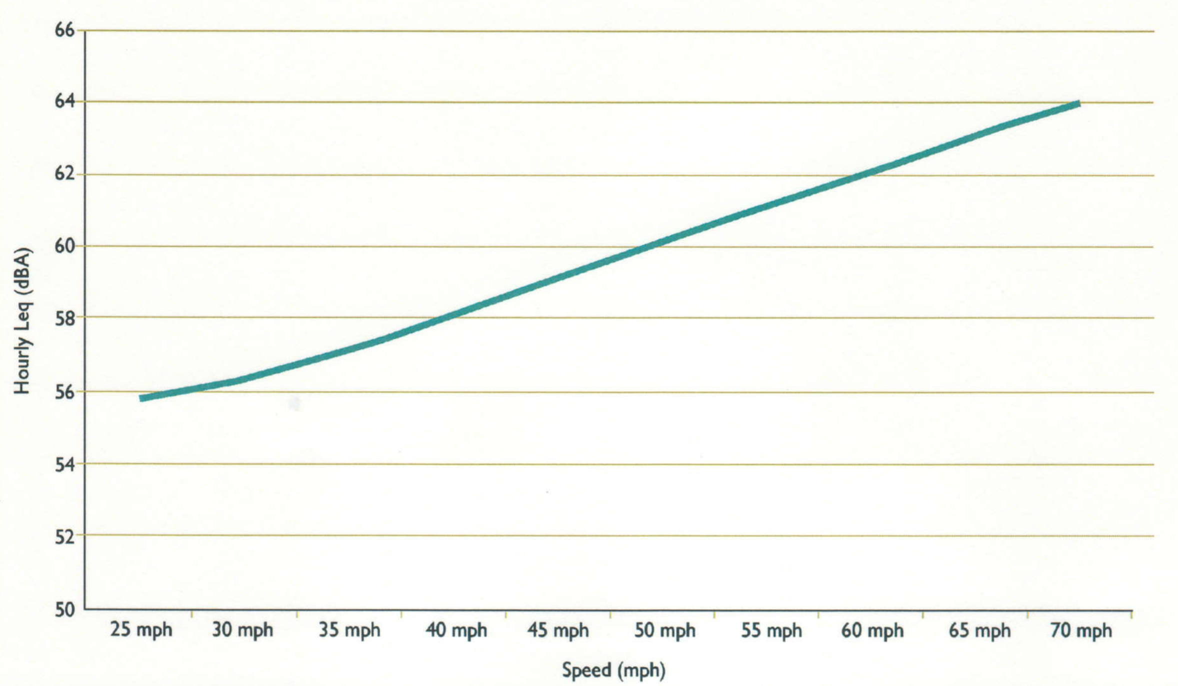
As discussed above, there are many factors (generally outside the control of FHWA and ODOT) that may vary the actual noise level produced by individual vehicles using the highway system. Assuming the mix of vehicles and noise sources using the system are a constant, we can then focus on operational factors that can be modified in an attempt to reduce noise levels. As discussed in **Section 3.2 - Causes of Highway Traffic Noise**, the overall noise level generated by a highway system also depends on operational factors, including speed of vehicles using the roadway, the volume of vehicles using the roadway, and the composition of the vehicles using the roadway, specifically the percentage of medium and heavy trucks in the fleet. System continuity and driver behavior can also affect total noise levels produced by the system and will be discussed below.

5.1.2.1 Speed Consideration

The effects of speed on vehicles noise is an obvious consideration for reducing highway-related noise. **Figure 3** provides a summary of the effects of speed on noise from roadway sources. This figure is based on a simple noise model using the FHWA Traffic Noise Model (TNM 2.5), and assumes 1000 vehicles per hour (with 10% truck traffic) and a receiver distance of approximately 150 feet from the roadway. As shown, noise levels can vary from approximately 56 dBA to approximately 64 dBA, based solely on speed changes, from 25 mph to 65 mph.

Based on this comparison, it is clear that reducing vehicle speeds can effectively reduce highway-related noise levels. At highway speeds, cutting average speeds in half could reduce associated noise levels by up to 6 dBA [7]. On roadways, the concept of reducing speeds is typically only considered for safety reasons; however, any reduction in vehicle speeds for safety reasons would also provide benefits by reducing noise at the source. While reducing travel speeds on roadways does have its challenges and consequences, there are several techniques available to ODOT to promote this form of noise mitigation.

Figure 3: EFFECTS OF SPEED ON TOTAL NOISE LEVELS



*Assumes receiver approximately 150' from travel lanes.
*Assumes 1,000 cars and 10% trucks (6% heavy trucks).
Source: McCormick Taylor, 2006

Perhaps the most obvious operational change to promote reduced speeds is to lower posted speed limits. The reduction of highway noise associated with reducing speeds from 65 to 55 mph is estimated at approximately 2 dBA. When compared to the benefits of cutting traffic speeds in half, the benefits gained by reducing travel speeds by 10 mph is minimal. Additionally, attempts to lower speeds by reducing speed limits are only effective if speed limits are enforced by local/state police departments. Therefore, reducing posted speeds to reduce traffic noise should be considered in conjunction with both manual and automated speed monitoring and enforcement.

Additional design elements can also promote reduced travel speeds and speed limits. Speed restraints can be incorporated into some roadway design to promote lower speeds. Examples of these design elements can include introducing "speed bumps", "rumble strips", narrow shoulders, or winding roadways. Unfortunately, many of these techniques are limited to local-roadways or roadways with posted speeds well below highway travel speeds.

5.1.2.2 Reductions in Vehicle Volume

Reducing vehicle volume is another obvious method to reduce roadway-induced noise levels, however, this concept often conflicts with the idea that most roadways are being built to address growing travel demands to move people and goods. One technique that can effectively reduce traffic volumes in specific locations is to concentrate vehicles in urban environments on a few main roadways, by-passes, or highways; thereby reducing vehicle volumes on the parallel collector or arterial routes in the transportation corridor. Unfortunately, the benefits derived by removing traffic from local, collector, or arterial roads may be offset by additional noise impacts on parallel routes. This situation may be absorbed better by limited-access highways that were designed to carry heavier traffic volumes and designed with mitigation components in place to reduce traffic impacts [7]. Traffic management measures often have limited application to provide noise benefits on limited-access highways, since these measures would directly conflict with the travel demands and purpose of these roadways; therefore this technique is generally limited to reducing traffic-induced noise on the local/collector roadway network.

5.1.2.3 Modifications to Vehicle Composition and Reduced Truck Volumes

Utilizing traffic management measures to reduce medium and heavy truck traffic volumes can provide another method to reduce noise levels from a given roadway. However, similar to the concepts of reducing vehicle volume, reductions in truck volumes may only truly be applicable to reducing traffic-induced noise on the local roadway network. Given the necessity of the interstate system to provide a method to move consumer goods, truck prohibitions and time-use restrictions do not appear applicable to limited access roadways. This technique does appear to have some benefits to local roadways by restricting heavy truck traffic on specific roadways (either entirely, or during certain time fames). Often traffic management and vehicle restrictions can be imposed by local government as a means of controlling noise impacts on the local roadway network, but again, this technique appears to have little application on the highway network, due to conflicts with the regional movement of people and goods.

5.1.2.4 Other Traffic Calming and Flow Improvement Measures

Traffic calming involves the concept of introducing measures to reduce vehicle speeds, typically for safety reasons, and often on local/collector roadways. Many of the measures discussed above could be defined as traffic calming measures. Additional examples of traffic calming measures include raised cross-walks and intersections, traffic-circles, center islands, median barriers, and similar design items intended to reduce vehicle speeds. Flow improvement measures such as the intentional synchronization or staggering of sequential traffic signals can also affect travel speeds and associated noise levels. However, as implied by the nature of these improvements, these measures are typically only effective at reducing noise levels on local/collector roadways, and have little application or benefit to limited-access highways.

5.1.2.5 Driver Behavior

The noise produced by an individual vehicle is not only a function of the vehicle speed, but also a function of the driving style in which the vehicle is driven. Aggressive drivers tend to drive in lower engine gears and at higher engine speeds (i.e., RPM's), producing more noise than similar vehicles, driven less aggressively. Those same drivers tend to accelerate and decelerate in an aggressive manner particularly on roadways with sequential traffic signals and other control devices. The influence of driving style on noise production can be considerable. Therefore, the variations in driver behavior can provide a potentially useful means of controlling noise.

Unfortunately, changes in automobile driver behavior have the greatest potential for implementation and benefit on local/arterial roadways, due the nature of conditions and travel speeds of these roads. Changes in driver behavior have less benefit of limited access highways, where more constant speeds are maintained. Additionally, the benefits of modifying driving style can only reduce noise levels from those drivers who currently drive in an aggressive manner and are willing to modify that to adopt a more passive driving style.

In general, driving styles which reduce noise also improve fuel efficiency, reduce fuel consumption, reduce exhaust emissions, and improve traffic safety. Therefore, educating drivers to be more aware of how driving styles can save fuel, reduce pollutants, and/or increase safety, can indirectly promote noise control. Passive driving styles can result in considerable fuel savings, less emissions and substantial noise reductions. The average reduction that can be achieved by changing from an aggressive to passive driving style can be approximately 5 dBA for cars, 7 dBA for motorcycles, and 5 dBA for commercial vehicles [7].

5.1.2.6 Summary and Limitations

As discussed above, there are various operational factors that can reduce traffic noise levels at the sources and are within the control of ODOT. Reduced speed limits and consideration of traffic calming measures can effectively reduce vehicle speeds and noise emission levels. Reduced speeds can reduce noise levels on both limited access and local/collector roadways. As indicated, traffic noise levels can be reduced by as much as 6 dBA by cutting traffic speeds in half. Unfortunately, reductions in posted speed limits are often ineffective at reducing travel speeds if these operational changes are not accompanied by active enforcement of speed limits by local and state police departments.

Attempts to reduce traffic noise levels using other operational factors can also provide noise reductions in specific situations. Reductions in vehicle volume, reductions in truck traffic, and traffic calming measures can effectively reduce traffic-induced noise levels adjacent local/collector roadways; however, these measures appear to have limited application and/or benefits on limited access roadways, mainly due to conflicts with travel demands on the highway system. Any reduction in traffic flow and travel speeds on limited access roadways can negatively impact the efficiency and continuity of the entire highway system. Unfortunately, the noise level benefits that can be achieved by reducing travel speeds often do not outweigh the operational impacts that can result from reduced speeds on these roadways. Regardless, there is some potential for reduced travel speeds to reduce noise levels in certain situations.

Promoting changes in driver behavior and educating drivers to be more aware of how passive driving styles can save fuel, reduce pollution, and increase safety can indirectly promote noise control. Significant noise reductions from individual vehicles, particularly on local/collector roadways, can be achieved by promoting passive driving styles over aggressive styles. Minimal benefits are anticipated for limited access highways as a result of changes in driver behavior, due to the more consistent driving styles that are typical on limited access roadways. Additionally, while ODOT and municipalities can educate and encourage this concept, any potential noise benefits associated with changes in driver behavior can only be achieved if drivers are willing to change to more passive driving styles.

5.1.3 Engineering Considerations

When considering options to reduce noise levels at the source, engineering considerations appear to have some of the greatest potential for both acoustical benefits and engineering implementation. Engineering considerations include specific options that are at the control and discretion of ODOT. These options are typically applied to the highway system as a whole, and not directly affected by individual vehicles or driving styles/behaviors. Rather, the potential benefits associated with engineering options will consider the vehicle fleet and mix (and the varying noise sources associated with that fleet) as constant factor. While **Section 5.1 – Noise Sources** discusses individual noise components of vehicle-induced noise and methods to control those levels, these factors are generally beyond the control and authority of ODOT. Alternatively, engineering considerations that affect roadway design features are well within the control of ODOT and FHWA; therefore, these options have potential for implementation to reduce noise impacts.

Some of these engineering considerations discussed below are very simple and obvious, while others are much more complex, variable, and difficult to quantify. The main concept of reducing noise levels with source-related engineering considerations is to introduce variables at the time of the highway design that can help to reduce noise levels produced by the highway corridor. As with most forms of noise mitigation, while options are available that can reduce ultimate noise levels, these options can be offset by increased design and construction costs, as well as impacts to other environmental, cultural, or socio-economic resources. Below is a summary of various engineering considerations that may be available to reduce noise at the source.

5.1.3.1 Alteration of Vertical/Horizontal Alignments

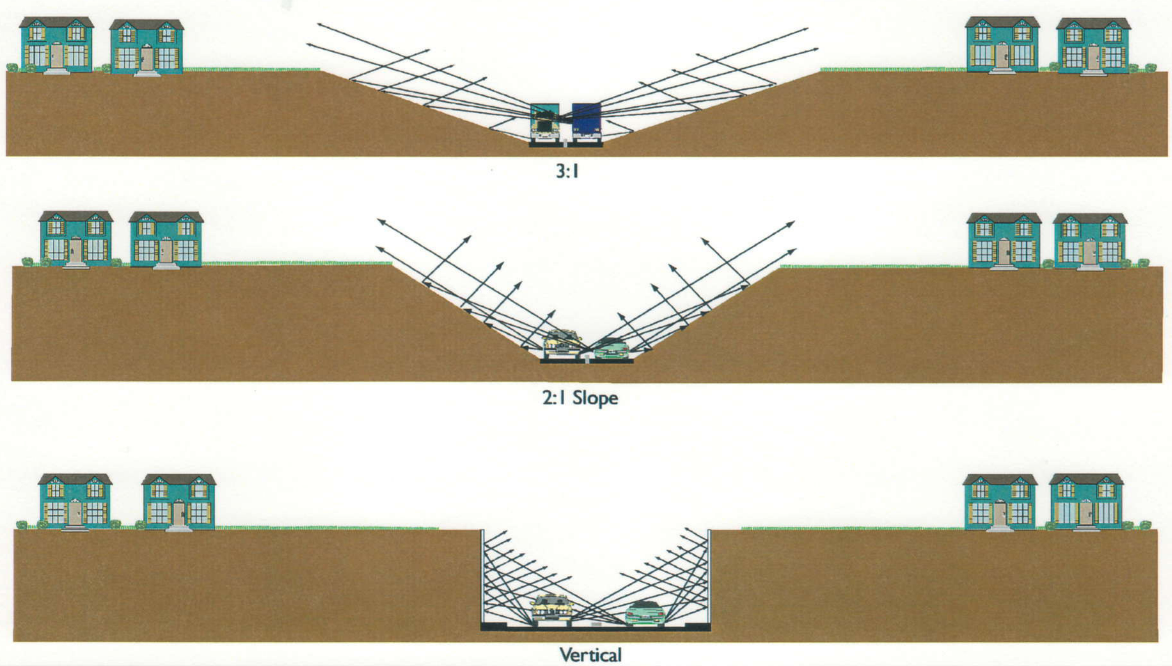
Perhaps the most obvious engineering consideration that can be applied is to move proposed roadways away from noise-sensitive land uses such as residences, schools, and park lands. Where possible it may be most practical to design new roadways adjacent to commercial and industrial areas, where traffic noise is generally less intrusive to the outdoor activities performed at these locations. This is an obvious solution for Type I highway projects proposed on new locations; however, this solution often has limited option for implementation on Type I projects that involve lane additions and or improvements to existing facilities.

While this planning tool is often considered throughout the NEPA process (i.e., the environmental evaluation and clearance phase of highway projects), modification of vertical alignments can have limited opportunities on certain projects, due to potential increase in construction costs and potential impacts to other environmental resources. Ultimately, the Environmental Impact Statement (or similar document) weighs the total impacts (including noise) of multiple highway alignments (to each other and to State and Federal requirements) to choose the appropriate location for a given highway. Achieving the balance of an efficient, cost-effective, environmentally-friendly highway design is not an easy process and often decisions, trade-offs, and compromises must be made to reach a constructible design. Feasible roadway designs often attempt to avoid residential and other noise-sensitive land uses thereby reducing/eliminating noise impacts to those properties. Unfortunately, due to the complexity and interrelation between numerous environmental and engineering factors affecting roadway design, avoidance of these areas is not always possible. Given the variables associated with relocating roadways (altering horizontal design), the benefits of this option can vary from minimal (where only minor roadway shifts are available), to significant (when options exist to totally avoid noise-sensitive properties).

When noise sensitive areas cannot be avoided by horizontal shifts of a given roadway option, often vertical shifts can be considered to depress the highway corridor below the grade of near-by noise-sensitive land uses. Depressing roadways into the natural landscape, by design, is almost always a benefit to both the noise environment adjacent to roadway corridors as well as to the view-shed from adjacent properties. The concepts of using vertical shifts to depress the roadway into the natural terrain are demonstrated in **Figure 4**. As shown in these examples, when roadways are lowered below the natural grade, roadway "cut-slopes" are created that can effectively shield the noise source from the receiver. In theory, this technique is actually more related to modifying the "noise path", rather than the noise source; however, since this concept involves significant engineering considerations and repercussions, it is typically considered early (and throughout) the highway design process, therefore it will be discussed here.

As shown in **Figure 4**, there are many different styles of "cut-slopes" that can be considered for depressed roadways. These options are typically a function of terrain, roadway grades, and geotechnical considerations; and the benefits associated with roadway "cut-slopes" can vary considerably depending on many engineering specifics, including the depth of the cut-section. As shown, "cut-slopes" can range from gradual slopes (3:1 or 4:1), to typical engineering design specifications (2:1), to very steep cuts (1:1 or vertical) where rock faces or retaining walls are planned. As suggested above, the specific engineering design and the depth of roadway cut can play significant factors in the ability of alterations in vertical alignments to reduce noise impacts. Generally, increases to the depth of the cut can provide further reductions in final noise levels; however, some limitations do exist. Often, improved shielding of the noise path provided by increased depth in cut can be offset by increases in reflective noise in areas where steep slopes (1:1) or retaining walls are used on the opposite side of the highway. **Figure 4** also provides an example of this concern. Regardless of the specifics, depressing roadways below the natural grade can supply significant benefits to noise-sensitive land uses adjacent to highway corridors.

Figure 4: EXAMPLE OF ROADWAY CUTS AND EFFECTS ON NOISE



Source: Trans-Lake Washington Project, Noise Mitigations and Design Options, 2001

The highway design process is a very dynamic process that evolves throughout the life of the design, from initial planning to final design and construction. During this process the line and grade of the roadway is continually developed and refined until the final balance is met between engineering design and environmental sensitivity. Engineering design goals include reducing roadway grades, and achieving a balance between roadway cut and fill requirements so that excess earthmoving is minimized and road construction materials do not need to be brought to or removed from the project corridor. Given this involved relationship to the design process, it is important for noise analyses to identify areas where depressed roadways may truly provide a benefit to the noise environment adjacent to the roadway corridor. Given the interrelationship between the highway design and noise mitigation, ODOT actively considers this option to reduce noise levels throughout the project development and design phases.

5.1.3.2 Reduced grades

Engineering design goals, including reducing roadway grades, and achieving a balance between roadway cut and fill requirements were mentioned above. Through the design process, attempts are typically made to reduce roadway grades which in turn, improve the efficiency of the roadway. Additionally, ODOT and FHWA maintain roadway design standards that limit allowable grades, based on specific roadway classifications. At freeway speeds, FHWA recommends that grades should not exceed 4% in level terrain, and 5% in rolling terrain.

Specific to noise levels associated with roadway design, the elimination of steep grades helps to reduce traffic noise levels, especially levels associated with truck traffic. Steep grades can cause truck noise to increase significantly as they accelerate up-grade and decelerate down-grade. Level roadways can avoid excess noise generation associated with roadway grades. As with the modification of vertical and horizontal alignments, consideration of roadway grades is given throughout the roadway design process, from initial planning through final design. Given the interrelationship between the highway design and noise mitigation, ODOT actively considers this option to improve highway efficiency and reduce noise levels throughout the project development and design phases.

5.1.3.3 Tunnels

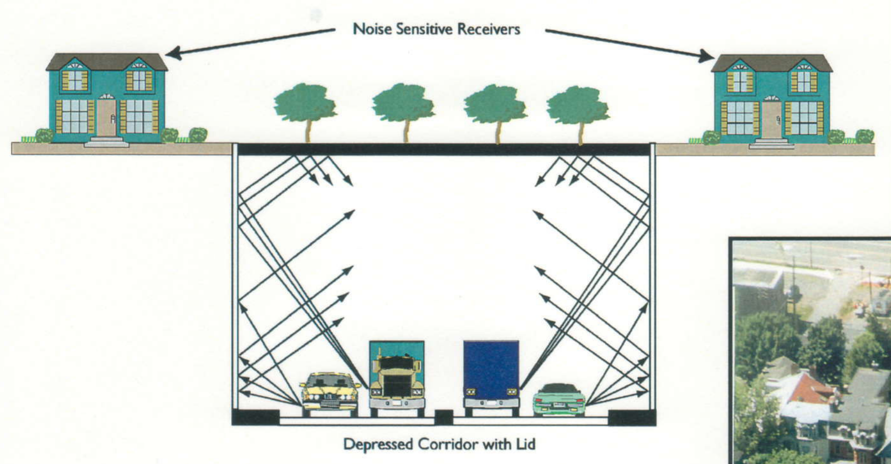
Roadway grades were mentioned in the previous sections of this report. Generally, the goals of engineering design include reducing roadway grades to acceptable design standards. When roadways are being constructed in areas with extreme topography, occasionally acceptable roadway grades cannot be achieved without significant modifications to horizontal alignments. Occasionally, in these cases the engineering solution is to implement a tunnel rather than traversing a significant geographic feature such as a mountain.

Tunnels are very effective at reducing noise emissions from highway sources, yet tunnels are very expensive to construct and maintain, and often introduce significant engineering issues associated with maintenance. For these reasons, tunnels are seldom constructed for the sole purpose of addressing noise abatement. One exception where "tunnels" are considered are in urban centers, where land is expensive and options exist to cover these roadways with buildings or other features [7]. In these situations, tunnels are often referred to as "cut-and-cover" sections of the roadway. **Figure 5** provides a photograph and graphic to better understand "cut-and-cover" designs and the noise reductions associated with this concept. As shown, this concept can effectively reduce (or eliminate) noise impacts, especially at noise-sensitive properties that are positioned away from the mouths of tunnel/cut-and-cover sections. While this option is available to ODOT, opportunities to consider and implement this option are very limited. Despite the potential acoustical benefits, given the unique opportunities to consider this option, it is not considered readily available for implementation on most projects.

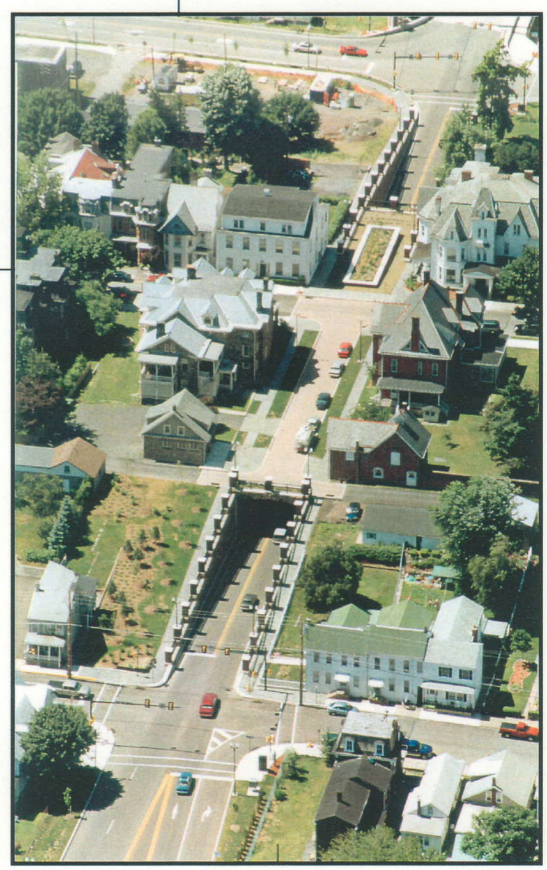
5.1.3.4 Pavement Considerations

As discussed in **Section 5.1.1.3 - Tire Noise**, the production of tire-noise involves a complex interaction between a vehicle's tires and the roadway surface. As identified, the main factors affecting tire-related noise include the speed of the rotation of the tire, the tire tread-pattern, the tire material, and the type and texture of the roadway surface. This section of the report will focus specifically on the pavement component of the tire/pavement interaction.

Figure 5: TYPICAL DEPRESSED ROADWAY WITH LID



Source: Trans-Lake Washington Project, Noise Mitigations and Design Options, 2001



There is currently a significant amount of ongoing and recently published research related to "quiet" pavement. Research indicates that pavement characteristics can play a significant role in the volume and tone of noise produced by the roadway surface. While the noise variations associated with different pavement types are of specific interest to this study, additional safety, maintenance, and durability factors are also of great concern to ODOT, and will be discussed.

5.1.3.4.1 Pavement Options and Characteristics

As discussed in previous sections of this report, there are many ways to reduce noise at the source. Some of these options are within the control of the Department, and some of these options are clearly voluntary and outside of ODOT's influence. As discussed, state agencies have very little authority and governing power over vehicle source noise or driving behaviors, assuming vehicles comply with EPA standards; and driving behavior and speeds are within legal limits. There is one component related to the noise source that ODOT and FHWA have complete jurisdiction over, that is, the type of pavement surface used for each highway improvement project.

Currently, state agencies have several general choices for roadway pavement surfaces including, Portland Cement Concrete (PCC), Porous PCC Pavement Surfaces, Densely-Graded Asphalt, Open-Graded Friction Course Pavements, and Rubberized Asphalts (or "Quiet Pavements"). Each pavement type has its own unique characteristics with respect to sound levels, maintenance and cost. There is considerable research ongoing, which evaluates the effectiveness of the newer "quieter" pavements, such as Open-Graded Friction Course (OGFC) and Rubberized Asphalt Pavements. These pavements have been in the developmental stages for well over 50 years, and have received significant study, development, and noise testing for the last two decades. This section will detail the sound reducing qualities of "quiet pavements" when compared to the other standard pavement types and will also outline other factors, such as maintenance and associated cost, which may affect a state agency's decision to use one of these quiet pavement treatments in place of a standard concrete pavement system.

5.1.3.4.1.1 Portland Cement Concrete (PCC)

Portland Cement Concrete (or PCC) roadway surfaces have long been the industry standard for new highway construction and is still currently the most widely used pavement type for highways with high vehicle volumes. PCC is nearly 100% impervious to water, which is why it is used in any climate region. These extremely durable characteristics of the PCC pavement minimize long-term costs, which makes PCC pavement a highly economical choice for state agencies. However, the extremely hard and impervious characteristics of PCC forms a highly reflective surface, which yields higher traffic noise levels when compared to other asphalt-based pavements.

Noise levels associated with a specific pavement type can also be affected by surface textures of the roadway. "Isotropic" textures are surface textures that are similar in all directions. The opposite is true of "anisotropic" textures, which have texture treatments that are orientated mostly in one direction. "Tining" is the concept of placing groves in PCC pavement, mainly to channel water runoff and to improve traction and safety characteristics. Transversely-tined PCC roadway surfaces are grooved perpendicular to the direction of traffic movement. This texture offers increased vehicle traction, but unfortunately the characteristics of uniformly textured transverse-tined PCC pavements tend to produce nearly 50% more high frequency noise when compared to longitudinally-tined (i.e., parallel to the flow of traffic) PCC pavements. The associated "whine" with transverse-tined pavements often makes them an undesirable option for highways in close proximity to residential developments because the high frequency noise component is a much more noticeable sound to the general public. Therefore, attempts are being made to eliminate transverse-tined PCC pavements on highways near residential developments. Studies have shown that a noise reduction of 2-3 dBA can be achieved by diamond-grinding transverse-tined pavements. Diamond-grinding provides these reductions by forming a smoother pavement surface which produces less tire friction and noise. Additionally, on newly constructed highways, longitudinally-tined PCC pavements can reduce noise by 4-7 dBA when compared to the transverse texture. Longitudinally-tined surface treatments can also reduce the undesirable "whine" that is commonly associated with transverse-tined surfaces.

The "brushing" of pavements, usually in a transverse direction, can also provide slight increases in noise and tonal changes when compared to untreated surfaces, however bushing surface treatments typically produce much less of an increase in noise than "tining" treatments. Studies show that regardless of surface treatments, noise levels can also change through the life of the pavement, as surface treatments wear and roadway surfaces become smooth. Regardless of surface treatments, PCC pavements still yield the highest noise levels during peak traffic periods when compared to other asphalt pavements.

Additionally, there are a few drawbacks that may increase noise levels even further on PCC roadway surfaces. Some old PCC pavement surfaces may have faulty transverse joints, which make a "clap" sound when the tires pass over them. Most noise studies do not report these annoying "peak" sounds at the joints, even though they are certainly important to the people nearby. One study in Japan (1998) reported the peak "clap" noise to be 5 dBA higher than the "constant" noise from the surrounding road surface [8]. For the drivers of the vehicles or the residents in proximity, these high noise levels at the joints are a major annoyance that should be considered when choosing PCC as a roadway surface.

5.1.3.4.1.2 Porous PCC Pavement Surfaces

European countries have been evaluating the effectiveness of porous PCC pavements for years. These pavement surfaces essentially combine the durability of normal PCC pavement with the noise reducing qualities of porous asphalt pavements (discussed in the following sections). This process involves treating a normal PCC roadway with a thin top overlay of a much coarser aggregate. The amount of void space in the top layer must be at least 25 percent. It was determined that the most promising noise emission reduction technique would be a porous top layer (approximately 25% porosity) using a finely grained epoxy surface dressing [9]. Field testing in Europe has indicated that porous concrete treatments yield noise levels that are comparable to open-graded asphalt pavements; in the range of 4 to 7 dBA quieter than standard PCC pavements. Additional benefits of porous PCC pavements are increased driver comfort and low spray, due to the positive drainage characteristics of porous pavements.

5.1.3.4.1.3 Densely-Graded Asphalt

Another option for roadway surfaces is Densely-Graded Asphalt pavements, or more commonly know as Hot Mix Asphalt (HMA). Conventional HMA pavements have an isotropic surface, that is, the texture is similar in all directions [8]. Additionally, HMA pavements are semi-porous in nature, due to the use of smaller pebbles and fine sand mixed in an asphalt matrix. The amount of void space in densely-graded HMA ranges from 7% to 8%, which is an important noise reducing quality of asphalt pavements, as compared to PCC pavements. For example when a tire rolls over a normal impervious pavement surface, the air within the tire treads is compressed and as the tire rolls on, is suddenly released in a pulse of noise, comparable to the action of a suction cup. The small voids (7 to 8% of the area) in HMA pavements allow some of the air to escape from the tire treads instead of causing the "suction cup" effect, which is characteristic of PCC pavements. Recent studies have shown that densely-graded asphalt pavements are 3-4 decibels quieter than PCC pavements at construction. Much of the focus of newer "quieter" pavements is the amount of void space in the asphalt matrix. The higher the percent of void space in the pavement, the more sound absorbing qualities it will exhibit.

5.1.3.4.1.4 Open Graded Friction Course Pavement (OGFC)

Open Graded Friction Course Pavement (OGFC) is similar to HMA; however, OGFC pavement is composed of a much smaller proportion of fine materials (e.g., sands or fine rock particles). In standard dense asphalt mixes, these fine materials fill most of the voids and form more of an impervious surface than OGFC. The increased size of air pockets in OGFC reduces its noise-producing characteristics. These air pockets form what is known as a negative texture that has sound-reducing qualities. As a tire rolls over an open graded asphalt surface, the air is forced into nearly 15% voided space in the asphalt mix and the result is a substantial reduction in noise levels when compared to other pavement types. Since tire noise is dominant at speeds greater than 30 mph, on most highways OGFC can have a significant positive affect on overall traffic noise levels. Actual noise reduction varies, but recent studies have shown that the noise reduction can be in the range of 4 to 7 decibels when compared to PCC pavements, and range from 1 to 5 dBA when compared to Densely-Graded Asphalt or HMA. Additionally, the higher frequency noise is reduced, which results in a less annoying sound [10]. This quiet pavement technology is being used effectively in Texas, Arizona and California with moderate results.

5.1.3.4.1.5 Rubberized Asphalts and Quiet Pavements

Rubberized Asphalt is a popular choice in southern climates as an option for quiet pavement technology. Rubberized asphalt consists of regular asphalt paving mixed with ground rubber from recycled tires. The extracted rubber from these tires is ground to the consistency of ground coffee. By using rubber as the binding agent, a smoother and softer roadway surface is created, which is a beneficial characteristic for quieter tire/pavement noise interactions. Preliminary studies on this type of pavement have shown that the rubberized asphalt generally reduces tire noise by an average of 4 decibels, when compared to densely-graded HMA, which are comparable noise reductions to OGFC pavements. Also, since the roadway surface is much softer, the noise generated by vehicles tends to be of a much lower frequency, which is less noticeable to the general public.

Rubberized asphalt has the benefit of being smoother and quieter and may last as long as conventional pavement surfaces; however it does have some negative issues associated with its implementation. While this type of pavement surface can offer supreme skid resistance in dry weather; there tends to be a slicker surface during periods of precipitation. Additionally, roadway surface temperatures must be between 85 and 145 degrees (Fahrenheit) before crews can pave a roadway with rubberized asphalts. This is due to the stiffness of the rubber binder that can occur in cooler conditions. Also, costs associated with rubberized pavements tend to be slightly higher when compared to conventional asphalt mixes. The Arizona DOT (ADOT) has been using these forms of rubberized asphalt since 1988 as resurfacing overlays for deteriorating PCC pavements.

5.1.3.4.1.6 Quiet Pavement Pilot Program (QPPP)

Recently, Arizona DOT (ADOT) has partnered with FHWA, as part of a QPPP (Quiet Pavement Pilot Program) to evaluate the effectiveness of this rubberized asphalt for sound reduction qualities. As part of this QPPP, ADOT has spent nearly $34 million to pave/overlay approximately 115 miles of its freeways with rubberized asphalt [11]. This pavement initiative involves paving concrete slabs that range from 12-14" thick with a thin, one-inch overlay of the rubberized asphalt (**Section 5.1.3.4.1.8** will further expand on the concepts of pavement overlays). The ADOT quiet pavement program has been very successful and preliminary studies have shown that noise reductions of at least 4 dBA are feasible, when compared to normal

PCC pavements. Additionally, this particular QPPP is earth-friendly, as nearly 1500 tires, per lane mile are recycled as a result of this pavement mixture. To date, ADOT states that nearly 15 million tires have been recycled, as part of this program, since 1988.

FHWA has a section of their website dedicated to state DOTs that want to initiate a QPPP of their own. A QPPP is a federally regulated program that state DOTs can participate in, which evaluates the effectiveness of quiet pavement initiatives. These programs are evaluated for a 5 to 10 year duration, upon which the FHWA will consider project-specific facts and will determine if changes to current policy are necessary. There is a set of requirements that must be adhered to if the state DOT wants guidance and backing from FHWA. FHWA requires that noise modeling be performed to determine the total effectiveness of quiet pavement by adjusting model input parameters directly associated with the reflectivity or absorptive qualities of different pavement types. Additionally, post-construction monitoring is required to document "actual versus modeled" noise levels associated with a QPPP. Proper discretion should be used when monitoring "pre-paved" conditions so that the true benefits of rubberized asphalt are realized. FHWA has attached a "Sample Data Acquisition Plan" to its website for these purposes. Finally, it is important to document the general public's reaction to this type of pavement, once it has been implemented.

5.1.3.4.1.7 Quiet Pavement Research

If state DOT's want to realize the benefit of quiet-pavement, but don't want to go through the expenditure of developing a QPPP, there is another option that is endorsed by FHWA. Quiet Pavement Research, is a highly technical research program that basically uses the exact same data that is used for the development of a QPPP. The difference between the two programs is that a state DOT, which sponsors a QPPP, has probably already completed Quiet Pavement Research. A state DOT that is performing a Quiet Pavement Research may not make adjustments to noise model pavement input parameters or use pavement types or surface textures as a noise abatement measure until FHWA is presented with sufficient documentation and testing. Additionally, a state DOT that has initiated a QPPP is committed to monitor noise levels and take appropriate actions if noise reduction levels decrease over the life of the pavement. State DOT's that initiate a Quiet Pavement Research do not have to guarantee noise level reductions for the pavement type. Often times, a state will initiate a Quiet Pavement Research as a concept, in order to determine if they want to put the effort and time into a QPPP.

5.1.3.4.1.8 Roadway Surface Treatments and Overlays

A roadway surface treatment that is gaining popularity with state DOT's is the concept of thin hot-mix asphalt overlays. Of the many pavement preservation techniques available, hot-mix asphalt overlays are probably the most versatile. They add structural capacity, seal cracks, improve ride, enhance skid resistance, reduce noise, and improve drainage.

Overlays can be placed in varying thicknesses. Thick overlays add substantial strength to a pavement when needed. Thin overlays (1.5 inches or less) also add structural capacity to pavement. Overlays can also be placed very thin, down to about 0.5-inch thick. The increase in structural value will vary depending on the thickness and condition of the existing pavement. Typically, thick overlays are reserved for maintenance to deteriorating PCC pavement surfaces, whereas thinner overlays are used on new highways to "deaden" or muffle sound produced by the highly reflective PCC pavements.

Thin pavement overlays can also be incorporated into new highway construction as a noise mitigation measure. The majority of the roadway surface would be a durable PCC pavement; however, once skim-coated with an asphalt overlay, the roadway would exhibit noise reduction qualities of densely-graded asphalt. While this thin pavement overlay may not be as durable as a thicker asphalt surface, the associated cost savings are substantial.

5.1.3.4.2 Maintenance and Wear Issues

As previously discussed, PCC pavements are the most durable and among the most popular roadway surfaces being used today. The conjunction of rebar and properly cured concrete forms a roadway surface that can be free of major maintenance for twenty-five years, or more. The same cannot be said for the more porous asphalt pavements. Due to the fact that water can infiltrate the pores of the pavement, the freeze/thaw cycles of the northern climates can literally break the roadway apart within 10 years. Constant resurfacing or patching of potholes is a common procedure related to older asphalt pavements, which can drastically increase maintenance costs. The OGFC pavements have more void space than Dense Graded Asphalts or HMA pavements, so they can typically trap and hold more water, and freeze thaw cycles can significantly reduce their lifespan.

Another maintenance consideration of quieter pavements is the increase or subsequent decrease of noise levels over the lifespan of the pavement. PCC pavements have been known to become 1-2 dBA quieter as the roadway surface wears. This is due to the wear of surface treatments that create a smoother roadway surface over time. A smoother roadway surface results in less tire/pavement friction and can reduce the annoying "whine" affect as well. Alternatively, asphalt pavements tend to get louder as they wear. The small pores of densely-graded HMA can clog within two years and can reduce the amount of voids to half of the amount at construction. As roadway dust clogs small pores in the asphalt matrix, noise levels increase and traction can be reduced. OGFC pavements are currently being designed to prevent clogging of the asphalt matrix voids; however, this is still a problem with porous pavements. The voids in OGFC are almost twice the size of those in HMA pavements; therefore they can be cleaned and maintained so that the void space in the pavement matrix experiences very little decrease in volume over time and thus, retains its sound reducing qualities. Currently, some European countries are experimenting with a cleaning mechanism for the porous pavements, but this technology has not been considered for use in the United States.

There are areas of the country where studded tires can be used during the winter season for increased traction. Studded tire usage is a major contributor to asphalt pavement damage. PCC pavements resist this type of wear relatively well, however both dense-graded HMA and OGFC pavements can rut considerably in the course of a few years. It is for this specific reason that OGFC pavements are typically not used in areas that experience harsh winter climates.

5.1.3.4.3 Costs

Implementation costs of pavement types vary, however upon review of the most recent roadway improvement projects and their associated construction costs, it was determined that flexible pavement (asphalt based pavements) are at least 10% cheaper to construct and maintain, than PCC, over the entire life cycle of the roadway surface. The initial cost of PCC pavement is nearly 50 % more than the cost of asphalt pavement, due to the manpower and materials required for a concrete surface. Also, projected maintenance costs are comparable, with asphalt-based pavements costing slightly more to maintain over a 30-year period. Therefore, asphalt-based pavements are the cheaper alternative when considering total life cycle costs. Due to a shorter lifespan and routine maintenance of OFGC pavements, the annualized costs can be nearly twice the costs of HMA or PCC roadway surfaces. This should be evaluated further when considering all the options of roadway surfaces for a highway re-surfacing project.

Costs associated with asphalt-based pavements and PCC roadway surfaces may vary based on physical location and actual site characteristics. Research performed on several of ODOT's recent highway improvement projects indicate that asphalt-based pavement construction costs about $1.2 million per linear mile for a 4-lane roadway, whereas PCC pavements cost, on average, about $1.5 million. When calculating the total life cycle cost of each pavement, which includes regularly scheduled maintenance, PCC pavements cost about $1.75 million per mile of four-lane highway, whereas asphalt-based pavements are about 10-20% less expensive. Total OGFC-porous asphalt pavements are a bit more expensive than standard asphalt based pavements when comparing the overall life cycle costs, due to the increase maintenance and cleaning associated with them, which is necessary in order to preserve the noise reducing qualities of the pavement surface.

5.1.4 Summary and Limitations

This section of the report focuses on the "noise source". Based on this discussion, it should be clear that there are many variables that can affect that amount of noise produced at the noise source. These variables can affect the amount of noise produced by individual vehicles and vehicle pass-bys; as well as by the vehicle fleet/stream, as a whole. Again, for the purposes of FHWA/ODOT highway noise analyses, all studies are conducted to evaluate "equivalent" (energy-averaged) sound levels (or Leq), representative of worst-case, one-hour average sound levels that occur during a typical 24-hour day.

The use of hourly-equivalent noise levels to measure traffic-induced noise impacts, places a greater influence on the vehicle fleet as a whole, and places less emphasis on noise anomalies associated with individual vehicles within the fleet. For example, a noise spike associated with the pass-by of a particularly loud vehicle produces only a minor influence to the hourly-average sound level at an adjacent property, when considering that 1500 vehicles may pass that point in the worst-case noise hour.

Therefore, the most effective mitigation measures that can be implemented at the source are those that can benefit the vehicle fleet, rather than individual vehicles. These options are summarized in **Section 5.1.2 - Operational Factors** and **Section 5.1.3 - Engineering Considerations.** Related to engineering considerations, there are many considerations that can be incorporated into the engineering design of a roadway to reduce noise impacts to adjacent noise-sensitive land uses. Many of these factors are situational, and the opportunity to consider the options discussed above should be considered on a case-by-case basis. Of these engineering factors, alternate pavement options may have the greatest potential for noise benefits on most projects. Compared to PCC pavements, alternate pavement types have the potential to reduce highway-induced noise levels in the range of 3 to 8 dBA, depending on the alternate pavement type available and/or selected. Unfortunately, the noise benefits associated with alternate pavements must be weighed against increased costs, durability, maintenance, and safety concerns.

5.2 Noise Path

The previous section of the report presents variables that can affect the volume of sound produced at the noise source. As discussed, there are many variables (within and outside) the control of ODOT that can change the strength of sound produced at the highway source. This section of the report will now discuss the second component of the highway/receiver noise interaction, the noise path.

As discussed in **Section 3 - Fundamentals of Highway Traffic Noise**, the propagation of traffic noise depends on several factors including; atmospheric effects (refraction), geometric spreading effects, ground effects (absorption), and shielding (created by natural and man-made objects). As with the noise source, some of these factors are within the control of ODOT and FHWA, while some are clearly beyond ODOT/FHWA control. Below is a summary of potential noise mitigation options that can be considered for implementation in the noise path.

5.2.1 Atmospheric Considerations

Currently, there is a significant amount of research ongoing related to atmospheric effects on transportation-related noise. Research indicates that atmospheric factors, including wind, temperature, and humidity can have significant influence on the amount of noise leaving the highway system and reaching nearby receivers. It is estimated that within 230 feet of a roadway, winds as low as 2.2 mph could shift noise levels by +/- 1 dBA [3]. To offset the variations associated with atmospheric effects to noise propagation, FHWA has issued noise monitoring guidelines, *FHWA Measurement of Highway Related Noise, 1996* that place limitations on acceptable conditions for which highway-induced (and ambient) noise levels can be measured. General limitations include wind speeds of less than 12 mph and dry roadways.

The goal of these limitations is to avoid those conditions that could significantly affect noise measurements adjacent to highway corridors. While there is a significant amount of documented research that quantifies these atmospheric effects, much of this detail is beyond the scope of this effort and beyond the control of the Department.

5.2.2 Geometric Spreading

As discussed previously, sound propagation is also affected by "spreading" effects, which diminish sound at a constant rate as the sound travels away from the source. Sound from a line-source (such as a highway) decreases at a rate of approximately 3 dBA per doubling of distance, when no other factors such as absorption are considered. Given this theory, noise levels of 65 dBA at 100 feet from the roadway would drop to 62 dBA at 200 feet, to 59 dBA at 400 feet, and to 56 dBA at 800 feet; representing a 3-dBA drop with each doubling of distance from the source. This drop in noise level is based solely on "spreading" effects, assuming a direct line-of-sight from source to receiver, and no other propagation effects. Given this concept, an obvious option to reduce noise levels is to lengthen the noise path between the source and the receiver. This form of mitigation is best achieved by modifying horizontal roadway alignments (as discussed in **Section 5.1.3.1**) to avoid (or increase the distance to) adjacent noise sensitive land uses. This option is typically available on Type I highway projects involving construction on new location, but often limited or not applicable to projects involving improvements to existing facilities (or Type II projects).

The option to lengthen the noise path between source and receiver can also be applied to the receiver in certain circumstances. By placing noise sensitive land uses as far away from existing transportation facilities as possible, land use planning and effective site design can be applied to reduce transportation-induced noise impacts in areas of future development. These concepts are explored further in **Section 5-4 – Planning Initiatives**.

5.2.3 Noise Barriers

Noise barriers are perhaps the most common form of noise mitigation implemented in response to traffic-noise impacts. Noise barriers are solid obstructions built between a highway and adjacent noise-sensitive land uses. Barriers are a popular solution because they have been proven effective at reducing noise impacts from both existing and planned transportation improvement projects and are typically available to the Department to provide noise mitigation for both Type I and Type II highway projects.

In theory, any natural or man-made feature located between the noise source and the receiver can be considered a noise barrier. However, for the purposes of this discussion, the term noise barrier refers specifically to a free-standing structure constructed to mitigate noise from a specific transportation facility. A noise berm is a very similar element, but is generally created from earth moved to a specific location during the highway construction process. Earth berms function similar to noise barriers; however, they have very different costs and engineering challenges and therefore, will be discussed separately in the following section of this report.

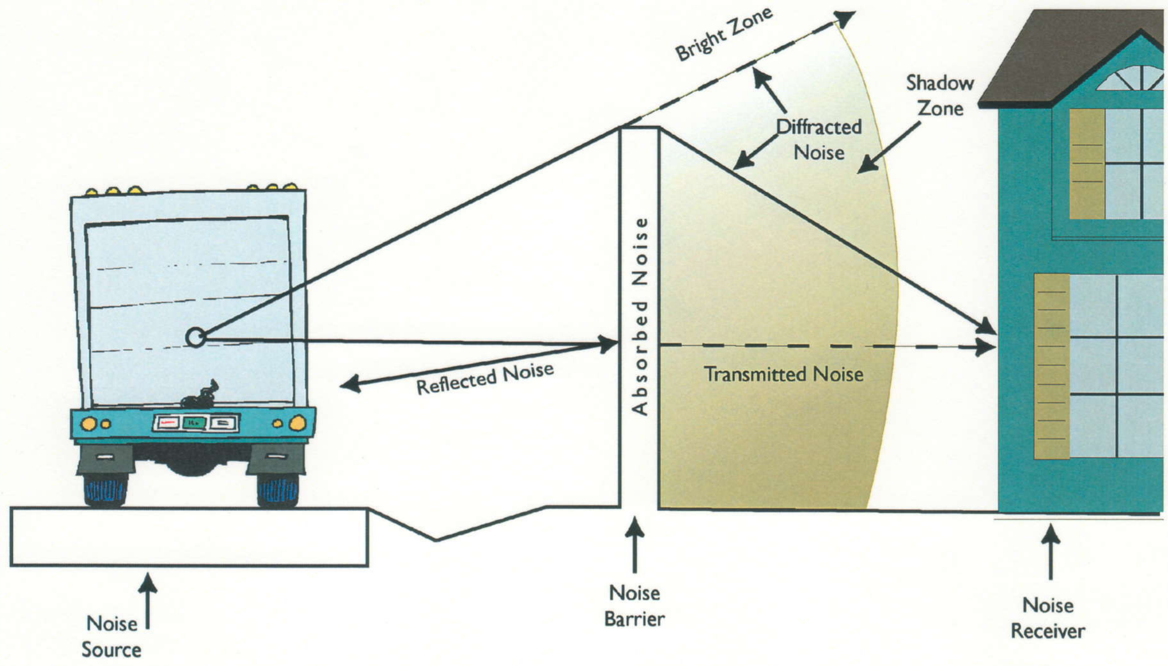
5.2.3.1 Quantified Prediction Techniques

Based on the effective and common use of noise barriers for highway applications, there is now considerable experience in the evaluation and design of noise barriers, and comprehensive prediction and design tools are available. Currently, the FHWA Traffic Noise Model® (FHWA TNM) is the accepted tool for predicting highway induced noise levels and evaluating/designing noise barriers (and earth berms) to effectively reduce noise impacts. Through years of model development and refinement, FHWA TNM has been established as a reliable tool to aid the noise barrier design process, and provides a measure to accurately quantify anticipated noise reductions associated with noise barriers. FHWA TNM allows noise barriers and other features that affect the noise path to be quantified and evaluated for cost/effectiveness. This tool allows a detailed level of analysis for noise barrier (and berm) concepts that generally exceeds the level of analysis/accuracy available for any other form of highway noise mitigation.

5.2.3.2 Noise Barrier Attenuation

As shown in **Figure 6**, noise barriers can reduce highway-induced noise levels by absorbing noise, reflecting noise back across the highway, and by shielding noise from the receiver (creating an area commonly referred to as the "shadow zone"). When considering noise barriers, the noise reaching the receiver is typically transmitted through the noise barrier or diffracted over or around the barrier. "Diffraction" is an acoustical phenomenon which describes the bending of sound waves around objects. The effects of diffraction explain why noise barriers can effectively reduce highway-induced noise levels, yet can not eliminate highway noise completely.

Figure 6: NOISE BARRIER ABSORPTION, REFLECTION, TRANSMISSION, AND DIFFRACTION

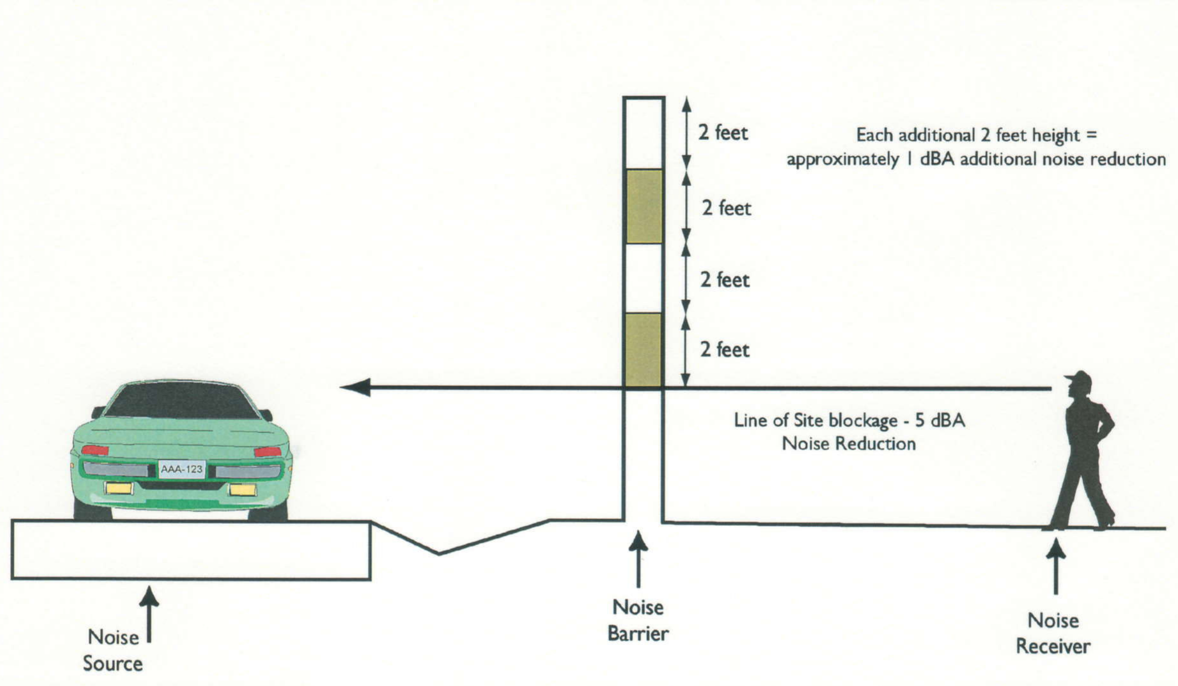


Source: CALTRANS Technical Noise Supplement, 1998

5.2.3.3 Barrier Height Considerations

Effective noise barriers are both tall enough and long enough to significantly eliminate the line-of-sight from the roadway to the receiver. **Figure 7** provides an example of how noise barrier height and line-of-sight considerations can affect noise barrier performance. Generally, noticeable noise reductions (in the range of 5 dBA) are not achieved until the line-of-sight between the source to the receiver is effectively broken. Once that point is reached, additional 1-dBA reductions can typically be achieved with each 2-foot step of additional barrier height. While the maximum theoretical limit of noise reduction associated with noise barriers is approximately 20 dBA, a more practical limit of noise reduction in real-world application is 10 to 15 dBA [4].

Figure 7: NOISE BARRIER LINE-OF-SITE CHARACTERISTICS

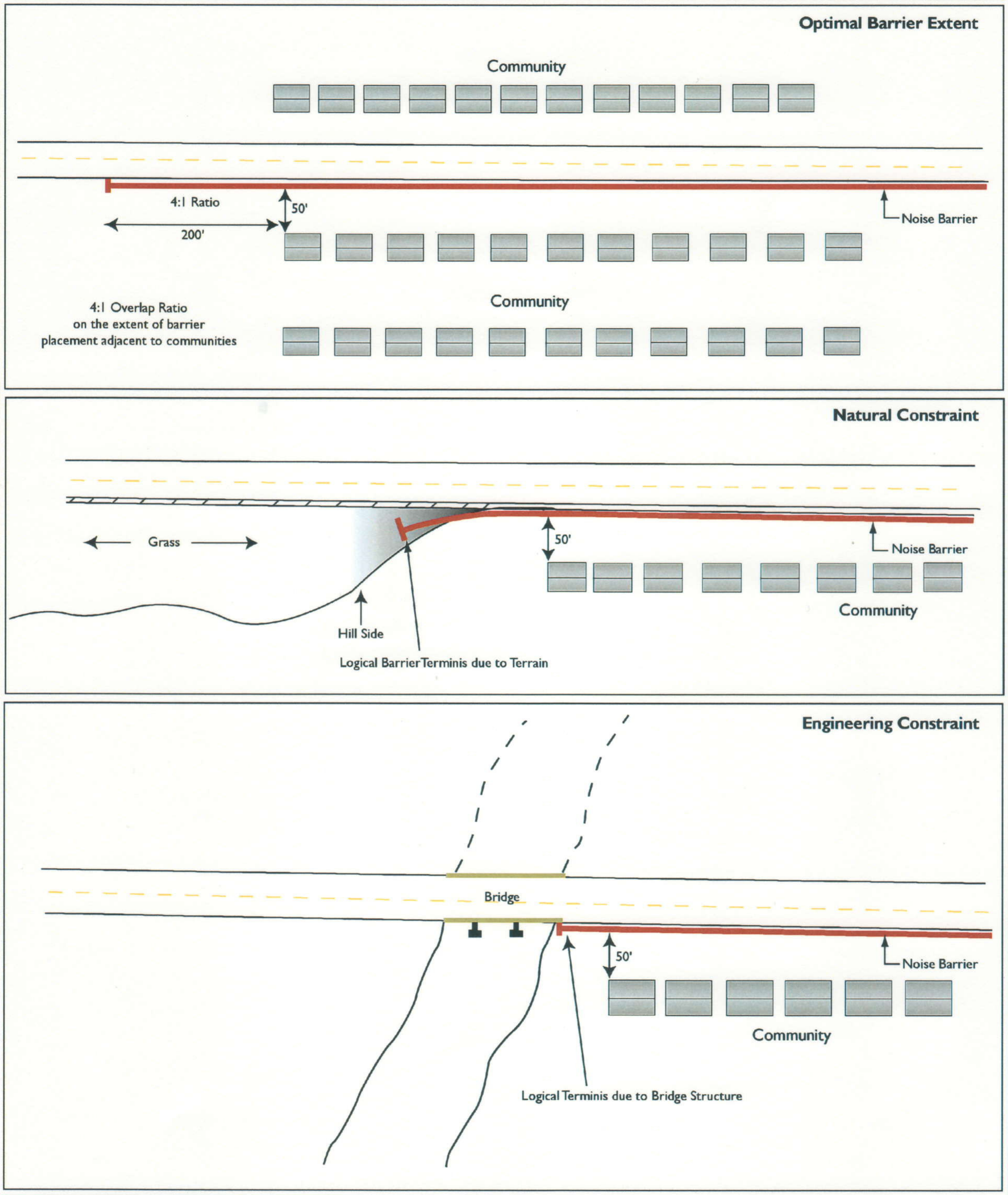


Source: FHWA Highway Noise Barrier Design Handbook, 2001

5.2.3.4 Barrier Length/ Flanking Noise Considerations

Flanking noise must also be considered to effectively mitigate for highway-noise with noise barriers. Flanking noise refers to the noise component that diffracts around the ends of a noise barrier, as compared to over the barrier. When considering the design of noise barriers to avoid flanking noise, barriers should extend well beyond the noise-sensitive land uses they are designed to protect. FHWA recommends barriers extend beyond impacted receivers by as much as four-times the distance from the road to the receiver to offset the effects of flanking noise [4]. Often physical features or logical-termini exist, such as hill sides or bridge structures that dictate the horizontal-limits and termini of noise barrier designs. **Figure 8** provides an example of flanking noise considerations and design requirements to address those considerations.

Figure 8: NOISE BARRIER FLANKING NOISE CONSIDERATIONS



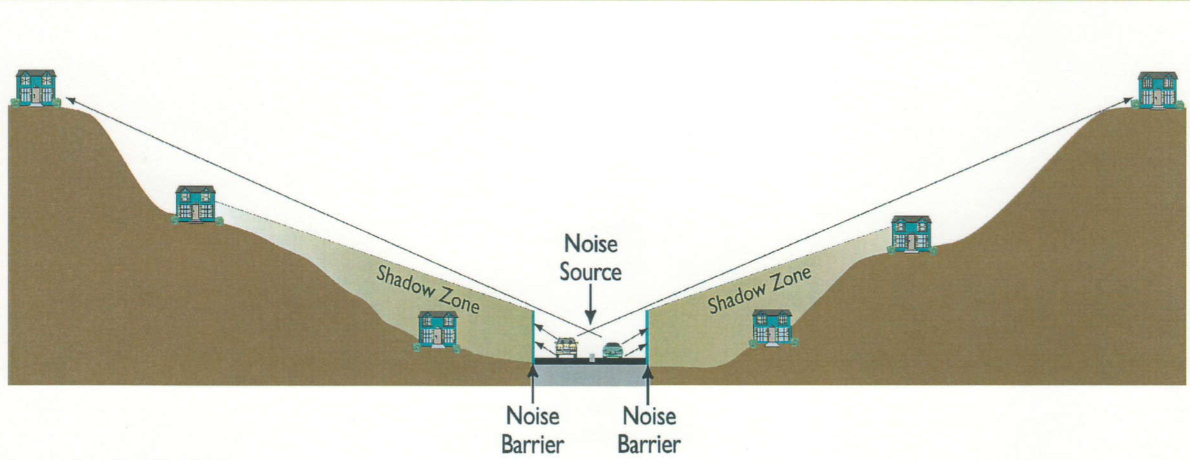
Source: McCormick Taylor, 2006

Another important component in noise barrier design is for noise barriers to consist of long stretches of continuous barrier without openings or gaps. Introducing openings into noise barriers to allow for driveways, intersecting streets, or pedestrian access can quickly compromise the effectiveness of a noise barrier, due to diffraction. For this reason, noise barriers are often reserved for limited-access roadways or roadways where barrier construction would not restrict vehicular or pedestrian access.

5.2.3.5 Horizontal Placement of Barriers

The horizontal placement of a noise barrier in relation to the source and the receiver can also impact the overall effectiveness of that barrier. In general, noise barriers are most effective when placed as close to the noise source or as close to the noise receiver as possible [12]. The relationship of roadway, barrier, and receiver elevations can also influence the effectiveness of noise barriers, and in certain situations can render a noise barrier ineffective. If noise-sensitive land uses adjacent to a roadway corridor are significantly above the roadway grade it may impossible to effectively block the line-of-sight (noise path) with a noise barrier. Receivers that are effectively shielded by a noise barrier are considered to be in the "shadow zone" of the barrier. **Figure 9** provides an example of noise barrier shadow zone effects and an example of situations where effective mitigation from a noise barrier is not feasible, due to terrain effects.

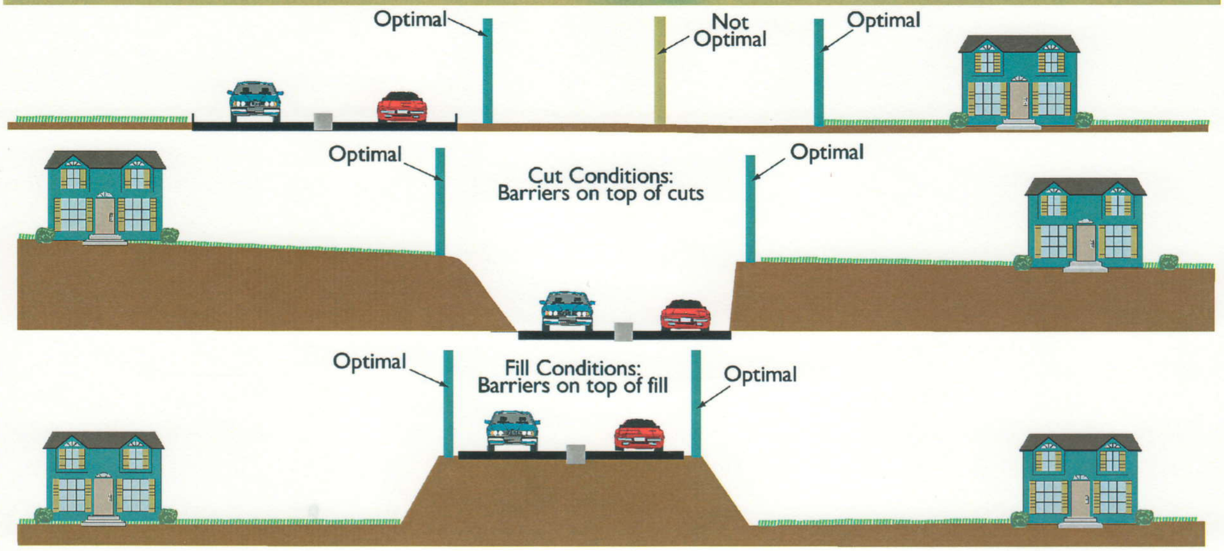
Figure 9: NOISE BARRIER SHADOW ZONE



Source: Adapted from Trans-Lake Washington Project, Noise Mitigations and Design Options, 2001

Roadway design features can also dictate noise barrier placement. In roadway cut conditions, noise barriers are typically placed atop the cut slope, near the roadway right-of-way to take advantage of natural terrain and increase barrier base elevations. In roadway fill conditions, noise barriers are typically placed along the roadway shoulder to achieve the maximum benefit from the barrier configuration. **Figure 10** demonstrates how barrier placement can affect potential effectiveness.

Figure 10: NOISE BARRIER PLACEMENT: OPTIMAL VS. NON-OPTIMAL



To reduce the chances of a noise barrier interfering with future widening projects, ODOT prefers to place noise barriers along highway right-of-way lines. As per ODOT Barrier Design Criteria, barriers should only be located adjacent to roadway shoulders in cases where roadways are constructed on fill or in cases where no other feasible barrier location is available. In all other conditions, noise barriers should be designed as close to the right-of-way as possible. This direction reduces safety considerations and possible conflicts with future expansion projects [5].

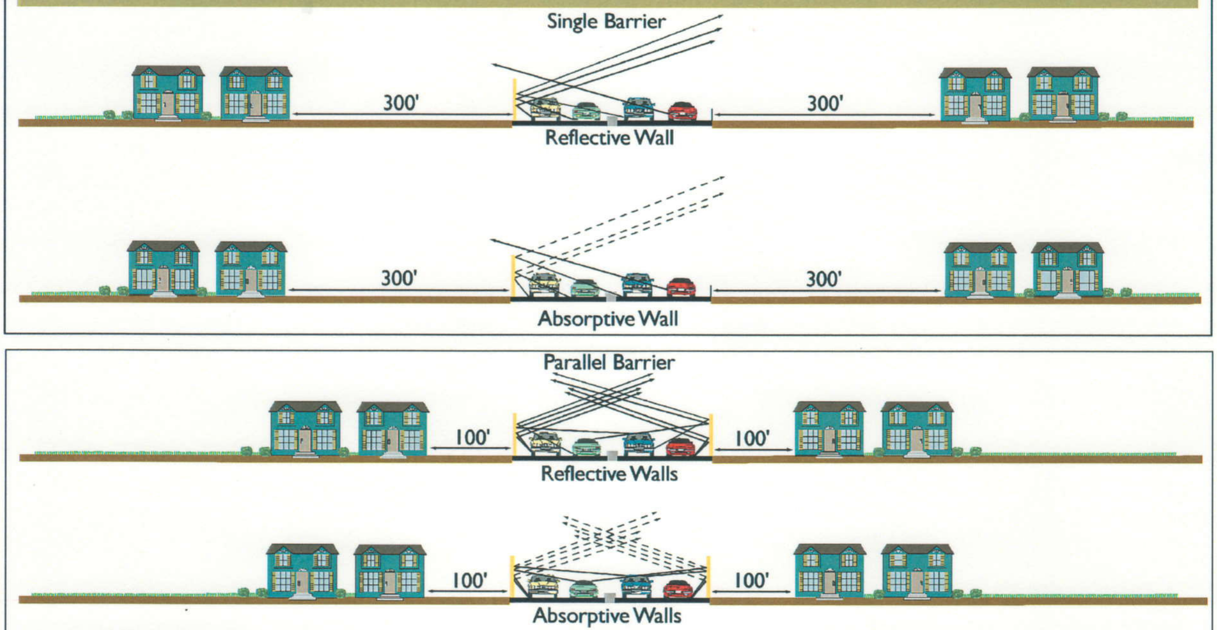
5.2.3.6 Absorptive Noise Barrier Considerations

As discussed above, and displayed in **Figure 6,** noise barriers reduce noise by shielding receivers from the noise source. Sound that reaches a noise barrier is either reflected or absorbed. In situations where noise-sensitive land uses exist on only one side of a roadway, barriers are designed to adequately shield those receivers. This situation can become more complex where noise sensitive land uses exist on both sides of the roadway. Attempts to provide barriers for both communities can create what is referred to as a "parallel barrier" condition. In those situations, reflective noise from a barrier on one side of the roadway can increase noise levels reaching the receivers on the opposite side of the roadway by as much as 3 dBA.

To combat this situation, noise barriers can be designed with greater sound-absorbing characteristics to offset the affects of reflective noise. Sound-absorbing noise barriers allow sound waves to enter the wall. As the sound travels through the sound absorbing material the sound waves change direction and follow a longer path. Every change in direction decreases the sound waves' energy, limiting the amount of sound that reenters the environment as reflective sound [13]. **Figure 11** provides examples of situations that can increase reflective noise and identifies how absorptive barriers can reduce this influence. Absorptive noise barriers can effectively offset the affects of reflective noise, often reducing reflective noise by 2 to 3 dBA at receivers on the opposite side of the road as a noise barrier.

ODOT requires the installation of absorptive noise barriers in all parallel barrier situations and in urban and suburban areas regardless of the land use opposite the barrier (except for industrial land uses). Absorptive noise barriers are also required in locations where future development may result in a noise sensitive land uses on the opposite side of a roadway being considered for noise barriers. Reflective noise barriers are appropriate in isolated areas where no noise sensitive land uses exist on the opposite side of the roadway, or where industrial land uses exist on the opposite side of the roadway.

Figure 11: REFLECTIVE AND ABSORPTIVE WALLS

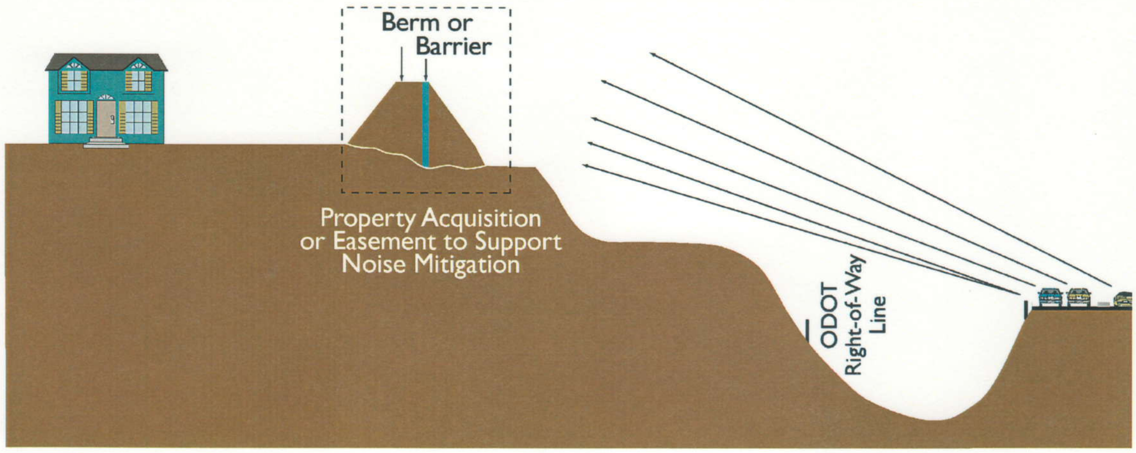


Source: McCormick Taylor, 2006

5.2.3.7 Land Acquisition for Construction of Noise Barriers

Noise barrier placement was discussed above and illustrated in **Figure 10**. As suggested above, the effectiveness of a noise barrier correlates to the ability to block the line-of-sight from the roadway to the receiver and effectively create a shadow-zone over adjacent noise receivers. Occasionally, situations exist where the geographic relationship of the roadway and the receivers prevents the interruption of the noise path by constructing a noise barrier within ODOT right-of-way. In these situations, it may be appropriate to purchase or establish construction/maintenance easements on adjacent property to construct noise mitigation beyond ODOT right-of way. **Figure 12** provides examples of geographic relationships that might warrant the acquisition of land to construct noise barriers. In these situations it is typically appropriate to include any costs associated with property acquisition (if for the sole purpose of noise mitigation) into the total costs of noise mitigation, when considering the reasonableness of noise mitigation.

Figure 12: LAND ACQUISITON FOR CONSTRUCTION OF NOISE BARRIER



Source: McCormick Taylor, 2006

5.2.3.8 ODOT Standard design/criteria

ODOT *Standard Procedures for Analysis and Abatement of Highway Traffic Noise* provides design criteria that should be incorporated into the design and construction of noise barriers. These criteria limit barrier height to a minimum of 8 feet and a maximum of 20 feet. These criteria also specify end treatment and barrier stepping requirements as well as aesthetic considerations (consistent with ODOT Aesthetic Guidelines). Landscaping is also considered for all noise barrier projects to "soften" the look and blend barriers into the surrounding landscape. Lateral clearance must also be considered and all mitigation designs must comply with ODOT safety design standards. Additionally, ODOT is clear that under no circumstances will structural noise abatement be considered for public or private golf courses, due to short-lived exposure times to active participants and the seasonal nature of these land uses.

Related to final decisions for noise mitigation, ODOT offers potential noise mitigation options to the affected public, but does not require the installation of mitigation measures. Prior to final design plan development, public meetings are held, as per the Ohio Revised Code (ORC) 5517.05, to solicit input from affected property owners, giving particular attention to front-row properties. Desires for or against noise mitigation, as well as potential noise barrier material, texture, and color are discussed with the public, and their preferences are documented and considered throughout the final design process.

Generally, noise barriers will be included in the project plans where they are warranted, feasible, reasonable, and wanted by impacted residents. Concerns of local officials will also be considered but will not be the sole determining factor regarding noise barrier construction.

5.2.3.9 Potential Benefits

As discussed above, the maximum theoretical limit of noise reduction associated with noise barriers is approximately 20 dBA, however, in real-world application a more practical limit of noise reduction is 10 to 15 dBA [4]. As per FHWA, Noise Barrier Design Handbook, a properly designed noise barrier should achieve noise reductions approaching 10 dBA at front-row receivers. This level of noise reduction is dependent upon appropriate barrier placement and adequate barrier length and height to effectively shield adjacent noise-sensitive land uses.

As per FHWA and ODOT requirements, noise mitigation must provide a minimum 5-dBA reduction in noise levels to be considered "feasible". ODOT stresses that while a minimum 5-dBA reduction is required, attempts should be made to achieve substantial reductions. A design goal of 8-dBA in average noise reduction is desired for front-row receivers to provide noticeable and effective noise reductions [5].

5.2.3.10 Anticipated Costs

As indicated above, noise barriers can provide effective noise mitigation on both Type I and Type II projects. Based on recent noise barrier construction cost estimates, noise barriers are estimated at $25.00 per square foot for both Type I and Type II projects. While there may be variations in actual costs of Type I and Type II noise barriers (due to additional construction costs associated with retrofitting noise barriers on existing highways, as compared to constructing noise barriers integrated into the highway design), recent estimates suggest an average cost of $25.00 per square foot is applicable to both Type I and Type II applications. Assuming average barrier heights of 16-feet above the ground line, noise barriers are estimated at approximately $400 per linear foot of barrier for both Type I and Type II projects. Using this cost as a basis, average noise barrier costs are approximate $2,112,000 per linear mile (assuming 16-foot high barriers). These costs are applicable to both absorptive and reflective noise barrier systems.

As per ODOT Noise Policy, to be considered reasonable, the cost of noise mitigation cannot exceed $35,000 per benefited residential unit. Benefited residential units are front-row receptors that receive 5-dBA or greater reductions and all other sensitive-receptors (i.e., second-row and beyond) that receive 3-dBA or greater reductions. Noise mitigation designs that exceed $35,000 per benefited residential unit are typically considered unreasonable. These cost comparisons should include the cost of noise barriers as well as the cost of any land acquisition that may be necessary to construct barriers (although not typically required). Noise mitigation designs that are not reasonable are typically not constructed.

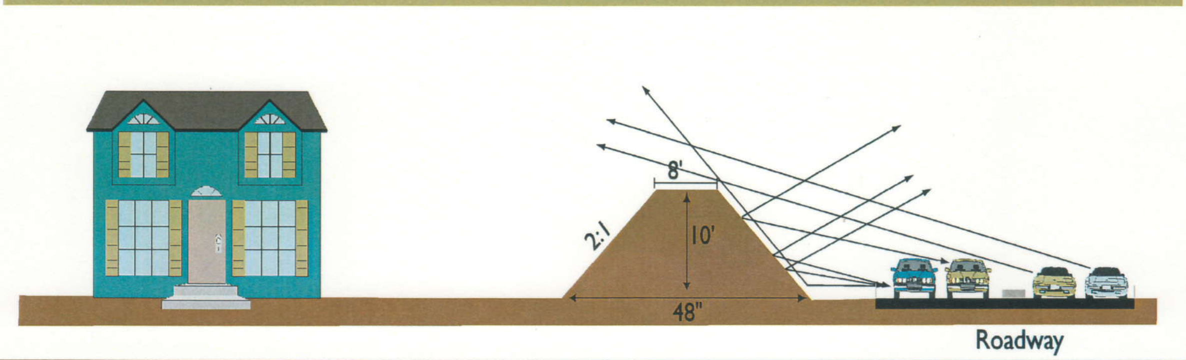
ODOT also considers noise barriers for Special Land Uses. Special Land Uses are nonprofit institutional noise-sensitive land uses such as churches, hospitals, libraries, parks, recreation areas, and schools. There is no cost reasonableness criterion for Special Land Uses. ODOT will consider noise abatement for these areas on a case-by-case basis, considering the nature of the activity performed at these locations, the degree of noise impact, the potential benefit associated with a barrier, and the cost of the mitigation measure.

5.2.4 Earth Berms

Earth berms are often used as a practical alternative to noise barriers. An earth berm is generally created from earthen-material that has been moved to a specific location during the highway construction process. Earth berms are often a preferred alternative to free-standing noise barriers since they can provide comparable (or greater) noise reductions, require less maintenance, provide a natural appearance, and can typically be constructed at much lower cost than typical post-and-panel noise barrier systems. However, earth berms require considerably more space than noise barriers, often precluding them from consideration.

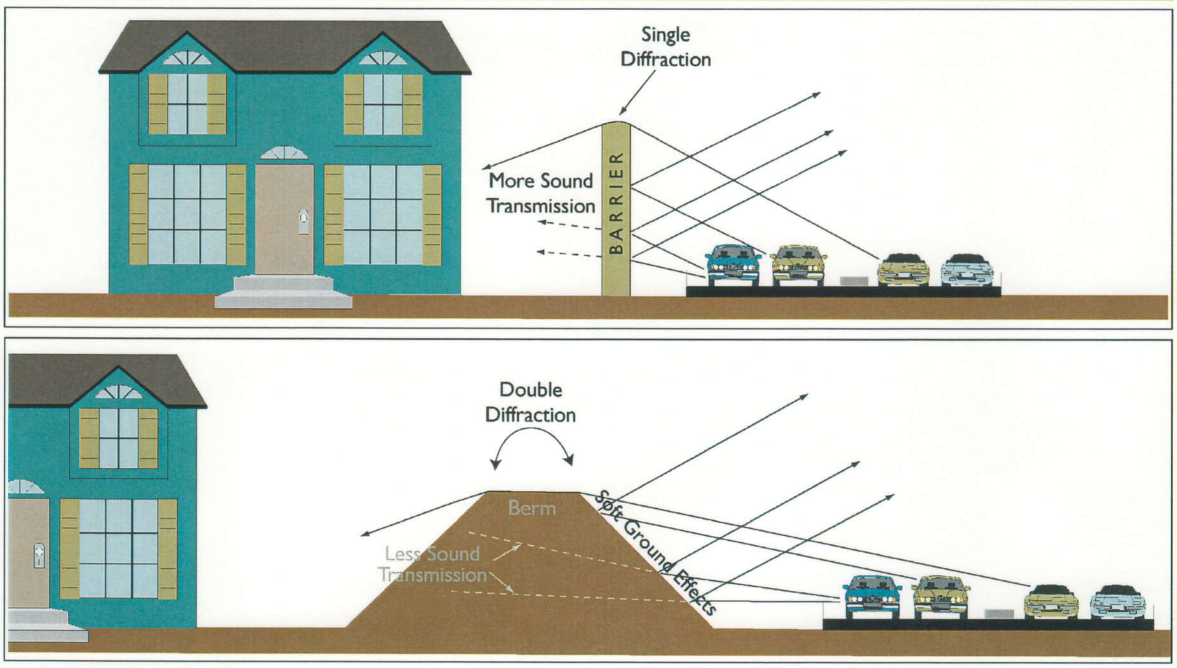
Figure 13 provides an example of design considerations and acoustical concepts associated with earth berms. Often, typical berm designs include 2:1 slopes on each side of the berm, with a level top (often in the range of 8-foot in width). Assuming this standard design cross-section, a berm with a total height of 10-feet above the roadway surface would require approximately 48-feet of horizontal width. Similarly, a berm with a total height of 20-feet above the roadway surface would require approximately 88-feet of horizontal width. These space requirements can often limit the use of berms, especially in developed corridors with limited space between the highway and adjacent noise-sensitive land uses. This space requirement becomes even more of a challenge on Type I highway improvement/expansion projects or on Type II projects, where the roadway right-of-way is already established.

Figure 13: EARTH BERM DESIGN



Related to the effectiveness of earth berms (in comparison to noise barriers), given the same cross-section, distance between source and receiver, and equivalent height, berms are assumed to reduce noise by up to an additional 3-dBA beyond barriers. As identified in **Figure 14**, there are several reasons for the additional reductions that can be achieved by earth berms. First, the shape of the berm (with level top-height) requires "double-diffraction", resulting in longer noise path than if the sound was traveling over a noise barrier (with a typical width of approximately 1-foot). Additionally, as sound travels over a berm, the noise path propagates over soft terrain and experiences more ground absorption, leading to less noise reaching adjacent receivers. Finally, due to the width and density of earth berms, less traffic noise is transmitted through a berm than through a noise barrier of comparable height. While FHWA assumes up to 3-additional dBA of attenuation due to the above factors, some studies suggest the additional attenuation may actually be somewhere in the range of 1 to 3 dBA [3].

Figure 14: ATTENUATION OF BERM Vs. BARRIER



Source: CALTRANS Technical Noise Supplement, 1998

Earth berms are also generally considered a much more aesthetically pleasing option than noise barriers, due to their natural look and ability to blend into the natural landscape. Berms are usually planted with grass or other vegetation which can greatly reduce the visual impact of a highway corridor to adjacent properties. Berms also have limited long-term maintenance issues and generally have a much greater life-cycle than noise barriers, making berms a more preferred option to both the public and the Department, where they are feasible to construct. As per the Ohio Revised Code § 5517.05, when considering noise barrier design options, when physically feasible, the Department should provide the public with at least one noise mitigation design option consisting of natural barriers such as trees, shrubs, mounds, and similar elements.

The cost of earth berms must be calculated on a case-by-case, project-by-project basis due to the great variation in costs associated with their construction. These costs can vary based on the availability of fill material, as well as the engineering and earth moving requirements to construct berms. In certain situations, the use of earth berms can actually save costs, if excess fill material is available from the highway project that would otherwise need to be transported off-site. Alternatively, berms can exceed typical noise barrier costs if no fill material is available on-site, and the construction of berms would require materials to be brought to the project site.

Also, as mentioned above earth berms require a much wider foot-print than noise barriers. The cost of acquiring additional right-of-way (if needed) can significantly increase the costs of constructing noise berms, as compared to noise barriers. Ultimately the costs, benefits, right-of-way impacts, and aesthetic issues must be considered when determining if earth berms are preferred over noise barriers.

5.2.5 Buildings and Other Man Made Objects

Buildings and other man-made objects can also effectively reduce noise levels that leave the highway corridor and reach adjacent noise-sensitive receivers. While front-row homes often have a direct line-of-sight to a highway facility, these front-row homes (and other features) can effectively shield noise reaching second-row homes and beyond. The amount of noise reduction that can be supplied varies with building size, spacing between buildings, and other geographic and geometric considerations. Some general rules-of-thumb assume approximately 3-dBA of noise reduction from the first row of homes or buildings, and an additional 1.5 dBA of noise reduction for each additional building row, up to a practical limit of about 10-dBA. These reductions can increase proportionally as size and length of buildings increase and/or the space between buildings in each row is reduced. Large scale buildings (with significant height/length) that front a highway corridor can function very similar to noise barriers and can effectively eliminate noise impacts to noise sensitive land uses beyond that point.

Generally, increasing building coverage is beyond the control of ODOT; however, this component is still worth discussing due to the significant shielding (and associated benefits) that can be provided by building rows. **Section 5.4 - Planning Initiatives** will discuss how the promotion of practical noise compatible land use planning and logical site planning can take advantage of natural shielding to ultimately reduce traffic-induced noise levels.

5.2.6 Vegetative Screening

Vegetation can also provide varying levels of noise reduction if it has adequate height, length, and density to eliminate a clear line-of-sight between the noise source and receiver. Generally, a 100-foot wide corridor of dense vegetation that effectively obstructs the line-of-sight may reduce noise levels by up to 5-dBA; and corridors of dense vegetation of 200-feet or greater may reduce noise levels by up to 10-dBA. This represents the practical limit of noise reduction associated with dense vegetation, due to atmospheric diffraction and the affects of wind and temperature gradients on sound transmission.

Vegetation type can also affect the achievable amount of noise reduction, and can cause seasonal differences in the total noise reduction available. Generally, the amount of noise reduction will increase as the density of the vegetation increases. Vegetation reduces noise levels by both absorbing noise (from leaf and other soft materials), as well as by scattering noise (from tree trunks and branches). Given these differences, the amount of noise reduction from deciduous vegetation can vary from summer-time to winter-time conditions. For this reason, ever-green and other coniferous trees/undergrowth are preferred vegetation types for the purposes of reducing noise levels.

Given the distance and density requirements, as well as the vegetation-type (i.e., non-deciduous/coniferous) requirements to achieve effective and consistent noise reductions, it is often impossible to plant enough vegetation along a roadside to achieve such reductions. Therefore, FHWA does not consider the planting of vegetation to be an effective noise abatement measure. However, if dense vegetation already exists adjacent to an existing or proposed roadway corridor, attempts should be made throughout the highway design process to save that vegetation.

FHWA does recognize the psychological benefit that can be achieved from vegetation, even if noticeable noise reductions are not provided. In situations with limited space available between the highway and adjacent receivers, roadside vegetation including trees and shrubs can provide psychological benefits by providing visual relief and an "out-of-sight, out-of-mind" response from adjacent property owners. Thin or sporadic plantings can also increase home-owner privacy and improve the overall aesthetics of the highway system. For this reason vegetation should be considered for its aesthetic qualities but has limited potential for implementation in response to an identified noise impact.

ODOT includes provisions for vegetative screening in its noise policy. As mentioned previously, if a neighborhood opposes construction of a given noise barrier, the neighborhood may choose vegetative screening as an alternative. ODOT is clear that vegetation is not considered noise abatement but can be offered to provide a visual screen to the roadway. Spending on vegetation in lieu of a noise barrier is limited to $125 per lineal foot. In no case will ODOT spend more to install vegetation in lieu of a noise barrier than the estimated cost for the noise barrier. As per the Ohio Revised Code § 5517.05, when considering noise mitigation design options, when physically feasible, the Department should provide the public with at least one noise mitigation design option consisting of natural barriers such as trees, shrubs, mounds, and similar elements.

In addition, ODOT and FHWA will consider landscaping to improve aesthetic qualities associated with noise barrier projects. As discussed above, landscaping is effective in softening the visual impact of highway improvement projects, and can help blend those improvements (including noise barriers and other elements) into the surrounding landscape. The landscaping design plan for all noise barrier projects shall be designed by ODOT or an approved ODOT design consultant.

5.2.7 Active Noise Cancellation

As discussed in **Section 3 - Fundamentals of Highway Traffic Noise,** sound is vibratory disturbance created by a moving or vibrating source. The movement of objects causes vibrations in air molecules that move the surrounding air in a manner similar to waves on water. When these vibrations reach our ears, we hear what we call sound. Sound also travels in waves (i.e., sound waves) and most environmental sounds are complex. The term "complex" means that sound from a given noise source is comprised of a combination of multiple frequencies (or sound waves), and the specific combination of frequencies give each sound source its unique sound signature. Sound at a given location becomes even more complex when you consider that every location has a unique set of sound sources influencing noise levels at that location; and as you move from location to location, the noise influence of each individual source can vary.

To combat these complexities and to generalize the tonal-differences of common noise sources highway noise assessments rely on the use of the A-weighted scale. As discussed previously, the A-weighted scale places an adjustment on high and low-pitched sounds to best approximate the way the average person hears sounds. For simplicity, sound pressure levels associated with highway noise assessments are measured on the A-weighted scale and are presented in A-weighted decibels, abbreviated dBA. The concept of complex noise sources is relevant to the following discussion, since active noise control relies on "modifying" the sound waves, rather than blocking, or extending the path of sound waves.

The theory of Active Noise Control (ANC), applies a different concept to controlling noise than traditional noise mitigation (and all other mitigation methods discussed in this report). Traditional noise mitigation methods are considered "passive" forms of noise mitigation. These techniques attempt to block, extend, absorb or dampen the noise path, ultimately dispersing and redirecting the sound energy over distance.

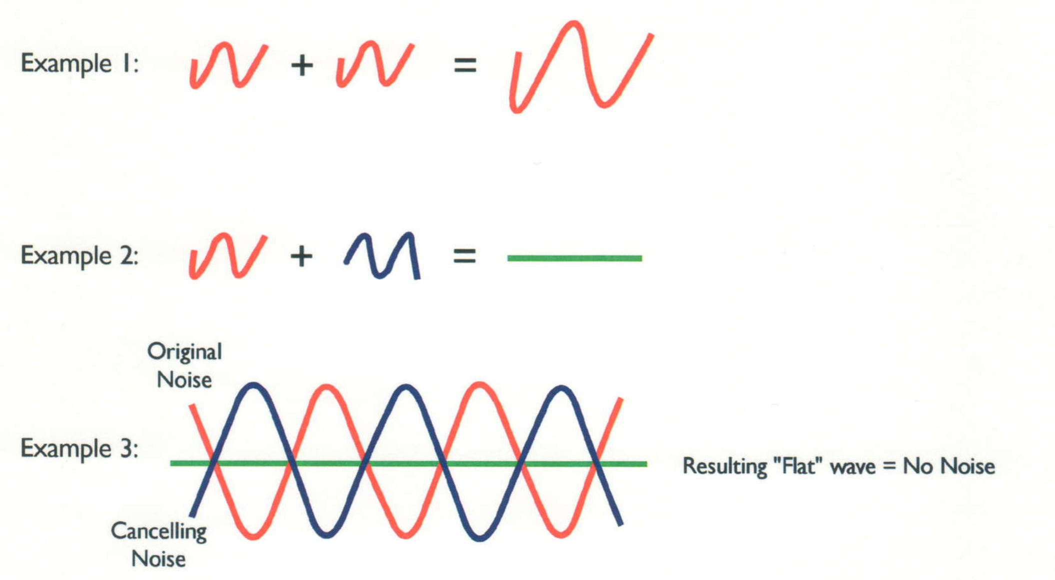
As an alternative, the concept of active noise control focuses specifically on characteristics of the sound wave, and attempts to eliminate the sound wave by introducing an exact but opposite wave to offset the vibrations of the first. A simple example of this concept is presented in **Figure 15**. In Example 1, two waves of equal amplitude and identical phase add together constructively, resulting in a doubling of overall amplitude. In Example 2, two waves of equal amplitude and opposite phase add together destructively, resulting in the cancelling of the overall amplitude. In Example 3, two waves (the original wave and the out-of-phase wave) are shown together. When these waves are identical and exactly out-of-phase (i.e., the "peak" of one wave exactly matches the "valley" of the other), then the amplitude of the waves cancel each other out. In Example 3, the addition of both waves would result in the "flat" wave in the middle, representing a situation were the combination of both waves create no sound.

The principals of destructive interference requires an active noise cancellation system, which would typically include physical space for the sound to propagate, microphones to sense the sound signal, sound processors which interpret and create an "inverse-wave", an amplifier to power speakers, and speakers to broadcast sound waves to interfere with the original sound wave. While this system is complex, its concepts are being applied successfully in some applications.

Perhaps the most successful forms of active noise cancellation being used today are noise cancelling headsets, such as those used in the aviation industry. Active noise cancellation headsets are effective because they work at the listeners ears, and function in very controlled conditions. In this example, headsets can monitor and produce "inverse" sound waves at the listener's ears, effectively canceling noise in a one-dimensional environment. There are many manufactures of personal active noise cancellation headsets, and prices vary significantly, depending on the quality and technology of the product.

Another successful form of one-dimensional active noise control has been applied to HVAC systems, specifically in duct work of these systems. In these systems, speakers are placed directly in ducts; matching the original sound wave (exactly out-of-phase) as the sound propagates one-dimensionally down the duct. While there are limitations, this concept has successfully been applied to HVAC systems.

Figure 15: CONCEPTS OF ACTIVE NOISE CONTROL



The concepts of active noise control in real-world, three-dimensional applications become much more complex and challenging. In three-dimensional applications, it is very difficult to monitor and replicate out-of-phase waves, given the multiple sources of noise in real-world environments, the various locations of those sources and a phenomenon know as the "Doppler Effect". In these situations it is very difficult for an active noise cancellation system to effectively cancel sound at more than one specific location (coordinate) in space. This is due to the difficulty of loud speakers of the system to match the exact pattern of divergence of the noise field, which would have been produced at a greater distance away than the cancellation system. With current systems, for widespread cancellation to occur, loudspeakers should be placed precisely at the center of the noise source, usually an impossible task [14].

This research project included the evaluation of *The Flatwave Project*, a sound screen apparatus (in development by Armstrong Interactive) that proposes the concept of three-dimensional noise control which applies both active and passive noise control methods in a single device. The project claims to have the potential to provide unique solutions to reproduce out-of-phase three-dimensional sounds that offset the Doppler Effect and effectively cancel highway-related noise. Armstrong Interactive claims that this proprietary system has demonstrated successful in-lab testing, but has not yet been applied to real-world setting [15]. To date no actual in-field testing results have been supplied or reviewed.

The theory of active noise cancellation has been around for a long time, yet the successful use of this concept has traditionally been limited to one-dimensional applications, such as headphones or in HVAC ducts. To date, the application of three-dimensional systems has been limited, due to the complexities of real-word noise propagation, the Doppler Effect, and the general inability to place noise-cancelling devices at the center of noise sources. For these reasons, active noise cancellation in the noise path is currently non-existent. While there may be some potential for future implementation, this concept is extremely complex and may be difficult to implement effectively in response to highway-related noise.

No cost-specific data is currently available related to *The Flatwave Project*, or other projects that could mitigate (or actively-cancel) highway related noise. Since the magnitude of the system, is unknown at this time, it is difficult to quantify an anticipated range of costs. However, if the system would be required to run parallel a given highway, it would be safe to assume this concept would require structural framing and foundation systems that would be required to meet ODOT Design Standards. Additionally, the technology would require microphones, sound processors, amplifiers and speakers to successfully implement this concept. Operating costs, maintenance requirements, and system longevity are also unknown but would need to be considered as well. Given the experimental nature to this technology, the unknown costs, and the undocumented effectiveness at this time, the cost-effectiveness is difficult to predict. Again ODOT standards limit allowable costs for noise mitigation to $25,000 per benefited residential unit. Therefore, this standard should be considered throughout the development of any highway-specific active noise cancellation concepts, to ensure these methods could be reasonable for implementation on highway projects.

5.2.8 Summary and Limitations

This section of the report focuses on the "noise path". As discussed, there are many factors that can affect the noise path and ultimately, the amount of noise that leaves the noise source and reaches the receiver. While atmospheric conditions can influence noise levels, they are generally beyond the control of the Department. Additionally, extreme conditions that can provide greater affects to noise levels, such as high winds, precipitation, and high humidity are avoided during noise monitoring activities to avoid erroneous results.

Another effective method to reduce noise levels is to increase the distance between the source and the receiver. As discussed, noise levels from highway sources decrease at a rate of approximately 3 dBA per doubling of distance. Given this concept, an effective form of noise mitigation is to modify the horizontal (or vertical) foot-print of a proposed highway to increase the distance from a proposed roadway to existing noise-sensitive land uses. This technique is actively applied to roadway projects on new location, but is often limited when addressing Type I improvements to existing roadways, or Type II noise mitigation projects.

Noise barriers and earth berms are the most common form of highway noise mitigation, nation-wide. Noise barriers and earth berms provide very effective noise reductions and have proven modeling techniques that allow for detailed and accurate predictions of their potential costs and benefits. Barriers and berms must provide a minimum of 5-dBA reductions to be considered feasible, with 8-dBA design goals in place by ODOT for front-row receptors. Some feasible/reasonable noise mitigation designs can provide 10 to 15 dBA noise reductions, when designed to adequately address flanking noise and block the line-of-sight from the receiver to the highway. Noise barriers are currently estimated at $400 per linear foot, or approximately $2.1 million per liner mile. The cost of earth berms varies significantly from project-to-project, depending on the availability of fill material. Berms are sometimes preferred over noise barriers due to aesthetic reasons; however, berms are not always an available option, due to the space requirements to construct berms of reasonable height. This issue becomes more complex for addressing noise mitigation on existing facilities (either Type I or Type II), where space is often limited adjacent to the roadway corridor.

Vegetative screening can only provide significant noise reductions if it has adequate height, length and density to effectively block the line-of-sight from the roadway to the receivers. Effective noise reductions typically require 100 to 200 feet of dense vegetation to provide significant noise reductions. Additionally, the noise reduction associated with deciduous vegetation can vary from season-to-season, with varying degrees of foliage. Evergreen and other coniferous vegetation can help to offset these variations. Given the distance and density requirements, FHWA does not consider the planting of vegetation to be an effective noise mitigation measure. ODOT and FHWA will support the use of vegetative screening and landscaping to soften the appearance of highway projects (and noise mitigation features), and therefore will incorporate landscaping into these designs, on a case-by-case basis. In lieu of noise barriers, ODOT would spend up to $125 per lineal foot to supply vegetative screening for transportation projects.

Active Noise Control was the final mitigation measure considered to mitigate in the noise "path". Active noise cancellation is a very complicated concept that involves using additional sound waves to offset (or cancel) the original sound wave. This concept has been successfully applied in one-dimensional applications, including ear-phone/headset as well as in HVAC ducts, when the path of sound wave is limited to the distance between the ear-phone and the ear, or within the walls of the HVAC duct work. To date, the concept of active noise cancellation in a real-world, three-dimensional environment has been limited, due to the complexities of real-word noise propagation, the Doppler Effect, and the general inability to place noise-cancelling devices at the center of noise sources. While the theory of active cancellation is being considered to reduce the impact of highway noise, to date there are currently no products available that have successfully been applied to reduce transportation noise along the noise path. In addition, no cost (or cost-benefit) data is currently available related to the potential cost of constructing and implementing such a system. Therefore, active noise cancellation is currently not considered a viable option to control highway-related traffic noise.

5.3 Noise Receivers

Previous sections of this report discussed the many variables associated with noise levels and mitigation options that can be considered at either the noise source or in the noise path. This section of the report will address noise concerns and mitigation options that are available at the noise receiver. For the purposes of highway noise analysis and mitigation design, noise receivers represent existing (or planned) exterior noise-sensitive areas where frequent human use occurs. These locations typically represent residential neighborhoods, parks, churches, schools, hospitals, libraries, or similar locations, and can also include commercial and industrial areas. Interior measurements, analyses and mitigation are typically reserved for nonprofit institutional structures such as churches, hospitals, and libraries, where no outdoor activity exists.

Depending on the land use and the presence of outdoor use areas at specific receivers, noise assessments are typically performed at one of three exterior locations: At or near the property boundary (or highway right-of-way) line; at or near buildings in residential or commercial areas; or at an area between the right-of-way line and the building where frequent human activity occurs, such as a patio or the yard of a home [4].

FHWA has defined a variety of "Activity Categories" and assigned a Noise Abatement Criteria (NAC) for each category. The NAC defines the appropriate maximum traffic-induced noise levels that are allowable before noise mitigation must be considered. **Table 3** provides a summary of the FHWA NAC for a variety of land uses. ODOT considers noise mitigation to be warranted if future design year noise levels approach (i.e., within 1 dBA) the noise levels shown in **Table 3**, or when design year noise levels exceed existing noise levels by 10 dBA or greater.

As shown, the majority of noise-sensitive land uses are classified under Activity Category B, including picnic areas, recreation areas, playgrounds, active sports areas, parks, residences, motels, hotels, schools, churches, libraries, and hospitals. Activity Category A Receivers represent lands in which serenity and quiet are of extraordinary significance, serve an important public need, and where the preservation of those qualities is essential to continue to serve its intended purpose. These land uses are few and far between, and must be approved by ODOT and FHWA before they are considered for analysis. Activity Category C represents developed lands properties, or activities not included in Categories A or B. Activity Category D represents undeveloped lands. Activity Category E provides interior noise level criteria for noise-sensitive land uses that have no exterior use areas where frequent outdoor human activity occurs. Interior noise level assessments must also be approved by the Department and by FHWA prior to initiating such studies.

When noise levels exceed the NAC, as defined in **Table 3**, the consideration of noise mitigation is "warranted". If warranted, noise mitigation is then considered for feasibility and reasonableness, as defined in **Section 4 - FHWA and ODOT Noise Analysis Procedures and Mitigation Requirements**.

The majority of noise mitigation options available to the Department typically involve noise control at either the noise source or in the noise path, as discussed above. However, there are a few additional mitigation methods that may be available in certain situations to protect the noise receiver. Protection at the receiver is often limited to protecting interior noise levels, in situations where there are no exterior areas of frequent human activity, or where mitigation options to protect exterior areas have been determined to be not feasible and/or reasonable. In these cases, it may be practical to examine noise mitigation options at the receiver.

5.3.1 Sound Insulation

Insulating buildings can greatly reduce highway traffic noise, especially when windows can be sealed and cracks and other openings can be filled. Significant interior noise level reductions can be achieved by installing central air conditioning, allowing windows in structures that front the highway corridor to remain closed during the summer months. Additional noise insulation options include replacing poorly designed/constructed windows and doors with double paned windows and solid-core doors. Sound absorbing materials including acoustical drapes and wall treatments can also be considered to increase sound insulation and absorption characteristics of noise-impacted facilities. Measures as simple as replacing weather stripping can help conserve energy as well as reduce noise levels in buildings adjacent to highway corridors. Sound insulation is not the preferred solution to traffic noise impacts because it typically leaves outdoor areas unprotected; however this option can provide effective noise mitigation in certain circumstances, or to certain land uses.

In Ohio, most sound insulation projects are limited to special land uses. Special land uses are defined as nonprofit institutional noise-sensitive land uses such as churches, hospitals, libraries, parks, recreational areas, and schools. Impacted structures such as churches, hospitals, libraries, and schools are eligible for consideration for insulation in lieu of noise barriers as a noise abatement measures. Again, this option is also applicable to situations where there are no outdoor use areas at the receiver, or where noise mitigation options to protect exterior areas were determined to be infeasible and/or unreasonable. In no case will the Department spend more to insulate a special land use then it would to cost to build a noise barrier to protect that same location.

Not all special land uses qualify for insulation as a noise abatement measure. A structure that already has central air conditioning, double-paned windows, and solid-core doors will benefit little from further insulation. In these cases the Department will not offer insulation as a noise abatement measure. To fulfill the eligibility test for building insulation, ODOT has developed a Noise Insulation Inspection Checklist that must be completed for each institutional structure where sound insulation is being considered. For churches, libraries, meeting rooms and schools, consideration is limited to classrooms, libraries, and auditoriums (sanctuaries) with exterior windows or exterior doors facing the roadway. For hospitals, consideration is limited to first-floor in-patient rooms with exterior windows or doors facing the roadway.

In addition to special land uses, ODOT will consider noise insulation as a noise abatement measure for residential land uses that are predicted to experience extraordinary increases in design year noise levels as a result of a transportation project. An extraordinary noise increase occurs when design year noise levels are predicted to increase by 30 dBA or more as a result of an improvement project. Noise insulation will only be offered for private residences when normal abatement measures are neither feasible nor cost reasonable. In these cases, the cost for noise insulation may not exceed $35,000 per dwelling unit.

ODOT has been required to participate in sound insulation projects for transportation improvement projects on a very limited basis. In 2006, approximately $11,000 was spent to provide new exterior doors and an insulated false wall to mitigate interior noise levels at Two Ridges Presbyterian Church, in Winterville, Ohio. Also in 2006, ODOT spent approximately $30,000 to provide new exterior doors, replace large windows with smaller windows, and install storm windows at the Temple Baptist Church in Forest Park, Ohio. In 2004, $221,200 was provided to replace exterior windows and doors at the Robert A. Taft Middle School in Canton, Ohio. In 2000, sound insulation of the Center Street Elementary School (in Mentor, Ohio) was estimated at $64,780 for exterior windows and doors; and sound insulation of the Temple Am Shalom (also in Mentor, Ohio) was estimated at $20,093 for exterior windows, entry doors, acoustical drapes, and an insulated wall. These previous projects can be used to gage the varying costs of ODOT's sound insulation program.

5.3.2 Noise Masking

Noise masking is technique that is aimed at reducing the "annoyance" of highway-related noise, rather than reducing the volume of that noise. Noise masking is a simple concept that generally involves the implementation of local noise sources at the receiver that produce more pleasant sounds than the distant noise source (such as a highway). Noise at the local source is produced at a slightly louder volume than the distant highway source, with the goal of "masking" the objectionable sounds with more pleasant sounds. Since noise masking involves raising the total volume at the receiver, it does have limited application in very loud areas. In these situations, the volume of the "masking-source" can become objectionable and interfere with activities, limiting the application of this technique to locations where traffic noise is audible, but not excessive.

Noise masking can be implemented in both interior and exterior conditions, and can include a wide variety of techniques. In exterior conditions, effective noise masking includes the construction of fountains, waterfalls, or other water features. To be effective, water features must produce as much noise as current background (or traffic-induced) noise levels at the location under consideration. Therefore the size and design of outside water features can vary significantly, depending on the degree of noise masking necessary. In some situations, such as outdoor restaurants/cafes and other commercial locations, background music can effectively reduce the annoyance of highway-related noise although this technique does not reduce volume. Additionally, the benefit of noise masking is lost as distance from the masking source is increased.

In situations where interior noise levels are influenced by traffic noise, interior noise masking techniques are also available. This situation may be true in communities within a few hundred feet of a highway; or in communities directly adjacent to a highway where noise barriers have been constructed, but highway-related noise is still audible with adjacent structures. In these conditions small water features and background music are very cost-effective forms of noise masking. In office settings, hotels, restaurants, and in other commercial settings often music or "white noise" is used to mask highway sources. White-noise is noise produced by speakers (or mechanical sources) that contain sounds in the full frequency spectrum of sound audible to the human ear. Introducing white noise to the audible environment at the right volume can effectively "mask" the sounds of traffic noise. White noise generators can vary significantly in complexity and cost, and can range from interactive office "speech-privacy" systems, to "sound-conditioners", to fans and air conditioners. The effectiveness of each system varies based on the complexity of the system and the needs of the user.

The potential to implement noise masking in response to noise impacts is limited, due to the nature of the mitigation method. Noise masking softens the noise impact but does not reduce noise levels at the receiver. Exterior noise masking such as the use of fountains could provide benefits in certain noise-sensitive situations, and may have the greatest potential for implementation if coupled with "enhancement projects" or as a community outreach to offset the environmental impact of a transportation project in an urban setting. Costs to construct these types of features can vary significantly, depending on size and design of the feature. Generally construction cost could range from a few hundred dollars to $100,000 or more. The opportunity and necessity for ODOT to construct fountains/water features or consider other noise masking needs is limited, and typically not supported in response transportation-related noise levels. Any exterior noise masking on private property, interior noise masking, and any costs associated with these options are the responsibility of the property owner. It may be practical for ODOT to make information available to concerned property owners related to this strategy for "masking" the noise affects of highways; however, this strategy is generally beyond the control and responsibility of ODOT.

5.3.3 Summary and limitations

Techniques to reduce highway traffic noise at nearby residential land uses, by addressing noise at the receiver are limited; however, for special land uses, such as libraries, churches and schools, sound insulation of the structure may be a beneficial option. ODOT has adopted criteria for the sound insulation of these structures and those that have no outdoor use area, strictly on a case-by-case basis. The structure must not have central air conditioning or double-paned windows because providing additional insulation to structures having these components would have no additional benefit. Also, the cost of insulating by these means must not exceed the cost of a noise barrier for the same property. While actual results may vary, the insulation of these structures can have a positive affect on interior noise levels.

ODOT, on a limited basis, will consider insulation for residential areas. For residences that have experienced a 30 dBA increase from existing to design year noise levels, sound insulation may be a viable option. However, sound insulation for residences is treated as a "last resort" measure, when all other noise abatement methods will not work. Finally, ODOT limits the cost of sound insulation for residences to $35,000 per residence.

Another non-traditional method to mitigate for highway traffic noise at the receiver is through noise masking. The concept of noise masking does not reduce noise levels at the receiver, similar to other mitigation methods such as a noise barrier or earth berm. Alternatively, noise masking involves the implementation of a much more pleasing sound at a similar noise level to lessen the annoyance of traffic noise. Noise masking techniques may actually increase the total amount of noise at the receiver, but the resident will experience a much more pleasing sound. For example, the construction of a water fountain could be designed to drown out the noise produced from a nearby highway, on the interior, or exterior of a home. While this is certainly a viable noise abatement option, the costs and maintenance issues associated with noise masking are highly variable.

5.4 Planning Initiatives

Many of the noise control and mitigation strategies discussed throughout this report focus on active or passive noise abatement in response to existing or anticipated highway-related noise impacts. In most situations, highway-related noise concerns stem from incompatible land uses competing for limited available open space. In these situations, often noise-sensitive land uses are developed in close proximity to highway corridors, leading to the need to consider noise abatement alternatives to lessen identified noise impacts. In many situations incompatible land uses already exist adjacent to highway corridors, and in these cases, the noise mitigation techniques discussed previously may be the only option to reduce impacts. However, there are several hundred thousand miles of existing highways throughout the country that are currently bordered by vacant lands which may some day be developed. Prudent land use controls and logical land use planning can help prevent many future noise problems in these areas. Such controls need not prohibit development, but rather require logical development plans and reasonable distances between noise-sensitive land uses and transportation corridors. Many local governments are currently working on land use controls to limit future noise impacts [16].

5.4.1 Noise Compatible Land Use Planning

Another effective strategy for mitigating traffic noise from highway sources is a planning initiative called Noise Compatible Land Use Planning. This planning technique can reduce or eliminate the undesirable effects of highway traffic noise by encouraging the development of less noise-sensitive land uses next to a highway or by promoting the use of open space to minimize noise impacts [17]. Noise compatible land use planning considers land use options in conjunction with existing and future noise environments to encourage practical development and the right kind of land uses adjacent to highway corridors.

This type of planning is initiated by identifying the land uses adjacent to highway systems that are less sensitive to traffic noise, such as commercial or industrial uses. Typically, these land uses benefit from their proximity to a highway and the accessibility that it provides. In general, office space and shopping malls are often great choices near highway corridors. Industrial land uses and warehousing are also practical land uses that benefit from the access of highway systems, yet activities at these locations are typically not affected by highway noise.

As discussed in **Chapter 5.2.2 - Geometric Spreading**, sound propagation is affected by spreading effects, which diminish sound at a constant rate as the sound travels away from the source. Sound from a line source such as a highway decreases at a rate of approximately 3 dBA per doubling of distance, when no other factors such as absorption are considered. Given this concept, another useful strategy is to develop open space adjacent to highways to allow noise to dissipate before it reaches noise sensitive areas. Local municipalities can implement the following approaches to encourage noise compatible land use planning within their local jurisdictions:

- Develop planning, zoning or other legal means (such as a subdivision or development standards, building codes, health codes, or occupancy permits);
- Municipal controls that include land or easement purchases or the acceptance of land donations;
- Community education programs to inform citizens, developers, and local planners of the options for structures and land uses that will be harmonious next to a highway; or

- Acoustical site planning, architectural design or acoustical construction [12].

There are many benefits to noise compatible land use planning. Not only can it save State DOT's money for roadway improvements and maintenance programs, but it can also promote positive effects on a community's finances, aesthetics, and overall quality-of-life. Additional benefits to the community can be achieved by developing quiet zones into passive or active recreational areas. All community members adjacent to a highway corridor can utilize these areas for activities that are less sensitive to highway noise.

Successful noise compatible land use planning requires a proactive approach and starts at the local government level. Federal and State governments should provide support and direction when utilizing this planning tool, while the local government should serve as the primary regulator and controlling authority. The degree of cooperation and collaboration between the partners determines the level of success [13].

Cost of implementation of noise compatible land use planning must also be considered before it is accepted as an early planning tool. Local governments may need to fund administrative costs for including noise compatible land use standards in their guidelines and ordinances. Additionally, developers may need to bear the cost for design alternatives that result in fewer homes due to set back requirements. Developers may also need to consider absorptive construction materials that are more sound absorbent than typical construction materials. However, these costs can be possibly offset by an increase in rental or sales rates due to the reduced effects of highway traffic noise.

There are several techniques, under the broad spectrum of Noise Compatible Land Use Planning that may reduce future traffic noise problems, that can usually be generalized under either small, or large scale mitigation strategies. These planning measures are categorized based on what level of detail is required for implementation of these procedures. Small scale mitigation strategies are those, which are implemented and governed at the local level. Since these strategies are governed by local townships and municipalities, they are strictly voluntary in nature. On the other hand, large scale mitigation strategies, which are a considerable effort to develop, are governed by the local municipality, but may involve increased coordination with State and Federal agencies and sometimes municipal planning organizations. These strategies are coordinated regardless of municipal boundaries, which can eventually lead to a consistent, regional planning approach [21].

5.4.1.1 Small Scale Noise Mitigation Strategies

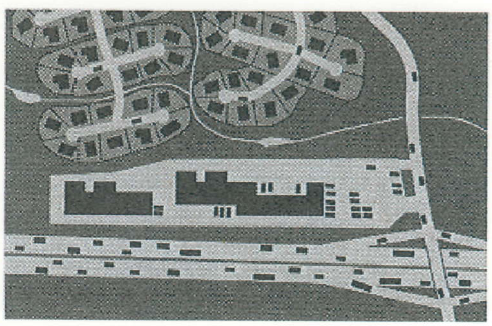
Small scale noise mitigation strategies are most often controlled by the local municipality. The implementation of noise barriers or earth berms, on a case-by-case basis, can help to alleviate traffic noise at noise-sensitive land uses. These methods are very effective at reducing highway traffic noise; however, current ODOT policy does not allow or fund the construction of noise barriers or earth berms on ODOT right-of-way, unless they are tied to a Type I or Type II highway improvement project. Occasionally, noise barriers or berms can be effective at or near the noise receiver (see **Figures 10 &**

12). Unfortunately, due to limitations it is often impractical for local municipalities to recommend the construction of noise barriers or earth berms as part of a noise compatible land use program. However, there are several methods that the municipality has control over, which can yield reduced noise levels at noise-sensitive land uses adjacent to highways, by taking a proactive approach to their planning doctrines.

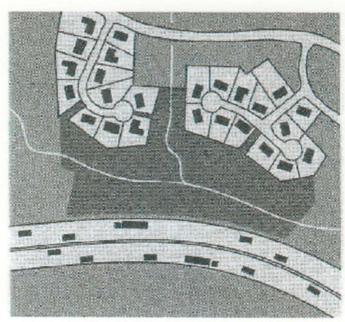
Two examples of small scale noise mitigation strategies, that the local municipality has control over, can be seen in **Figure 16**. By incorporating buffer areas and concentrating development in areas behind these buffers, a reduced noise exposure is achieved at the noise-sensitive land uses within the development. Given these concepts, the development of open space/buffers adjacent to highways is one of the most effective tools to control highway traffic noise at noise-sensitive land uses.

To develop these buffers in an efficient manner, often times a community noise study should be performed to determine the size of the buffer needed. By developing noise contours during a community noise study, noise impact lines can be determined and residential development can be prohibited in these areas. These impact areas can then remain undeveloped and used as recreation areas or strict open space or greenways. In these cases, the municipality must work with developers to develop a feasible solution to highway traffic noise and development within the community. These methods place most of the responsibility and cost on the developer, because they involve altering site development plans or site designs, and often require additional open space to front highway corridors.

Figure 16: NOISE - COMPATIBLE LAND USE CONSIDERATIONS



Zoning and land use initiatives should encourage commercial buildings to be placed next to a highway corridor, with residences farther away.



Open space can be left as a buffer zone between residences and high corridors.

Source: FHWA, Highway Traffic Noise, 2006

Another example of a small scale mitigation strategy is altering the building layout of a development, which can be used as a mitigation tool for residential areas if the developer uses common sense and good judgment. Once again, if developers are encouraged by the local municipality, through incentives, to place less noise-sensitive buildings (e.g, parking garages or maintenance sheds) adjacent to the highways, these buildings can be as effective as a noise barrier if arranged properly. This measure can significantly reduce noise exposure at the bordering residential areas by blocking the noise path and by increasing the distance from the highway to the residences.

Another small scale mitigation strategy that can be incorporated into local building or site development codes, involves altering the floor plan of the homes in such a manner that the living areas and bedrooms of the home do not front the highway. This planning measure can effectively reduce interior noise levels in the most frequented, or noise-sensitive rooms of the house. While typically there are no current criteria for the consideration and abatement of interior noise levels by developers (unless HUD funding is being provided), this is still an effective tool that developers can implement for a noise compatible development design.

Local governments can also require the use of different building materials as another option that developers may have to implement in order to reduce interior noise levels. By incorporating noise absorbing materials such as brick, wood, thicker drywall, more insulation, multi-paned windows and solid core doors, the developer can significantly reduce interior sound levels by 5 to 15 decibels when compared to standard construction materials [18]. All of these requirements can be documented in local sub-division ordinances, which are legally binding documents. Proper coordination should be made between the municipality and the developer to develop a plan that is a feasible alternative for both parties involved.

5.4.1.2 Large Scale Noise Mitigation Strategies

The majority of large scale noise compatible planning measures are controlled and implemented by local government with some guidance and direction from state and federal agencies and regional planning commissions. Large scale mitigation strategies are more complex and often require a great deal of trained personnel before implementation is possible. In most cases, state and federal agencies must offer assistance to local government for these methods to be successful. One of these large-scale strategies is for the municipality to try to acquire development rights from property owners. The purchase of development rights (PDR) essentially removes a property owner's right to develop a parcel; however, all other land rights remain intact. This is performed by amending the deed for the parcel and placing a permanent deed restriction on it. Due to the highly controversial nature of this program, PDRs are usually only possible in mostly undeveloped areas. Moreover, most property owners shy at the concept of giving up rights for their property. Therefore, the purchasing of PDRs for noise abatement measures is often a very difficult task.

Somewhat related to PDRs are Transfers of Development Rights (TDR). These land use controls are essentially a "trade-off" between the developer and the municipality. Basically, the municipality will grant denser development in the form of a variance, if the land adjacent to the highway remains as open space or a buffer area. This planning measure is also somewhat attractive to developers because they can usually recoup lost funds (stemming from implementing the buffer area) with a much more dense development, which can have additional benefits. Developers prefer more dense developments because they often require less utility and roadway infrastructure, which can save additional funds.

While TDR programs are a highly successful tool to mitigate roadway noise, there are some concerns related towards implementing a TDR program. TDR programs are a highly labor-intensive agenda and will require full-time staff, which most rural municipalities may not be able to support. Additionally, due to the "sprawl" affect in most of the rural United States, many areas are already at their developmental limits and would not be able to accommodate additional residential densities. Therefore, much like PDRs, TDR programs are most effective in areas that have not achieved their full "build out" potential.

The most utilized and most effective Large Scale mitigation method is that of "Proponent Mitigated Development". Proponent mitigated development (PMD) strategies are used in the planning stages of new development to bring about compatibility between noise sensitive land uses and transportation noise. Development can be a transportation project initiated by a transportation agency or it can be a residential community proposed by a private developer. In either case, the proponent of the development bears the responsibility for mitigation of transportation noise to make noise and land use compatible. In these cases, the developer should be required to perform a noise study of the area in question and also evaluate noise abatement options for the area. Studies have shown that proponent mitigated development strategies can be an effective complement to land use zoning in traffic noise and land use compatibility programs. Furthermore, administrators of existing programs report minimal maintenance costs to planning agencies, and suggest that these programs are easily managed by most local government agencies [19].

5.4.2 Roadway Noise Mitigation Programs

While the techniques associated with Noise Compatible Land Use Planning rely on the small scale and large scale mitigation strategies discussed above, the effective implementation of this concept often relies on thorough evaluations of the existing and future noise environments as well as effective communication with local municipalities. Often, it is the role of state transportation agencies to inventory areas of potential development and existing/future noise exposure. Similarly, it is often the role of local municipalities and planning commissions to implement the strategies discussed above to facilitate noise compatible planning and development practices, and encourage practical/compatible development trends at the local level.

This proactive noise compatible planning approach is typically initiated by categorizing each individual land use that is discussed in local zoning or planning laws. Each of these land use activity areas has a different sensitivity to noise and can be categorized from "highly-sensitive" to "less-sensitive" to highway traffic noise. Highly-sensitive areas tend to be residential in nature. Additional areas that may be highly-sensitive to noise are theatres, churches, parks, and recreational areas. Proper discretion should be taken when developing zoning laws to deter development of these areas in close proximity to highway corridors. On the other hand, by encouraging development of the less-sensitive land uses (e.g., industrial areas or large commercial areas) in closer proximity to highway corridors, the municipality can essentially alleviate a future domestic noise problem. Also, since highway corridors are often appealing to businesses, due to the increased visibility and access, practical zoning can effectively promote additional commercial and industrial development in the community.

Upon categorizing the land uses within the municipality, the next step is to perform an inventory of existing noise levels, which can lead to a community noise study. While it may be too late to mitigate noise levels for existing residential developments, this community noise study evaluates areas open to development. It is important to consider existing and potential future highway corridors in this analysis, which sets the framework for future residential development in the municipality. The development of noise contours for the municipality is an important step in this process. Developing these noise contours will allow the municipality to establish areas of that have the highest noise exposure based on the existing highway network. These areas can be defined as noise impact zones. By limiting noise-sensitive development in these areas, the local municipality can avoid future noise problems associated with potential noise-sensitive developments. Additionally, preferred noise abatement measures should be included in this program to act as guidance for potential developers.

The final component of a roadway noise mitigation plan is to have a post-construction review process. This step ensures harmonious interaction between the plan and the developer and will act as a check and balance for future developers. While there are concerns associated with the cost of developing a Roadway Noise Mitigation Program, the ongoing maintenance costs are minimal. By implementing one of these programs, more compatible development will result in the community, in addition to the development of open spaces for noise abatement and aesthetics along highway corridors.

5.4.3 ODOT Initiatives

Noise compatible land use planning measures have been successfully implemented around the country. ODOT is currently working on improving the coordination effort between local planning agencies across the state to identify potential noise impact zones along highways and to prevent incompatible development. With a proactive approach before the start of environmental studies, Ohio DOT is seeking the best opportunity to contribute to residential zoning and development decisions [20].

ODOT has initiated noise compatible land use planning and is currently working with the Miami Valley Regional Planning Commission (MVRPC) to promote these strategies. This effort was initiated in a two-phased approach along the I-675 corridor in Greene County, Ohio. Phase I of the project involved identifying the existing and proposed land uses and determining existing and future noise levels on vacant lands adjacent to I-675, where future noise-sensitive development was likely. ODOT participated in the "Phase I" pilot study along the I-675 corridor in Greene County and developed noise contours for existing and future 2025 conditions. By developing noise contours on these undeveloped parcels adjacent to I-675, future development can be modified to ensure that noise sensitive land uses are not developed within the noise impact zone. By educating local officials about traffic noise and arming them with noise contours, noise compatible land use planning can be a perfect solution to resolve noise issues, and can save millions of dollars on the design, construction and maintenance of noise barriers.

MVRPC was commissioned to conduct Phase II of the project. The objective of Phase II is to educate local jurisdictions about the finding of the Phase I study, and to assist them in implementing planning and/or legislative measures to address such impacts. During the preliminary stages of Phase II, MVRPC conducted a series of public outreach meetings with five local jurisdictions located along the I-675 corridor within Green County. The goal of this outreach program is to educate local planners and arm them with the tools needed to effectively plan, to avoid the development of noise-sensitive land uses adjacent to non-compatible land uses such as transportation facilities.

5.4.4 Other State Initiatives

Other State DOT's are also actively promoting and/or requiring noise compatible planning initiatives to avoid future noise impacts along existing highway corridors. Again, the success of implementing noise compatible land use planning varies from state to state and often depends on how proactive state and local governments are at promoting such techniques. Land use zoning and noise mitigated development are the two primary programs that local municipalities have implemented with the guidance of State DOT's. Below is a brief summary of some of the activities that are currently ongoing to promote the concepts of noise compatible land use planning [22].

The Arizona Department of Transportation (ADOT) has no requirements regarding the regulation of noise through planning techniques, but is very proactive in encouraging local governments to address the issue. ADOT has adopted roles and responsibilities for local agencies and developers to follow to limit noise impacts on communities adjacent to highway corridors. Recommendations to local governments have been documented encouraging the use of "set-backs", buffer zones, and other visual and noise improvement options in areas that do not qualify for mitigation by ADOT [23].

Illinois DOT participates in a 50/50 cost-sharing program for noise abatement retrofitting of state highways in urban areas. If an area is found to have an abatable noise problem, Illinois DOT will provide 50% of the mitigation cost to the local municipality. After the initial departmental funding, local governments are required to provide a land use ordinance assuring future land development will be noise compatible to avoid further government funding.

Delaware DOT requires developers to conduct a noise analysis based upon the forecasted traffic on the roadway adjacent to the proposed subdivision, for any road that is designated in whole or in part on the DelDOT Functional Classification Map as a principal arterial, a freeway or an interstate. Should it be determined that a proposed Land Development project will experience a traffic noise impact, the Department may require the Developer to redesign the site plan, changing impacted areas from sensitive land uses to non-sensitive land uses, thus potentially eliminating the need for a noise barrier. A DelDOT letter of approval to record the subdivision will be contingent upon a subdivision layout that has been designed to minimize noise impacts following development construction.

Although Maryland does not have statewide regulation to promote traffic noise compatible planning, areas adjacent to Washington D.C. have developed comprehensive noise compatible development plans. These plans follow a hierarchy of development strategies, with land use compatibility approaches being the most supported. Additional options include buffer zones, setbacks, and noise barriers or berms in areas where predicted impacts remain. Acoustic insulation of noise receivers is the last mitigation option. Land use compatible zoning is undertaken during the master planning stage of development projects.

The City of Livonia, Michigan requires a 30-foot buffer zone between any roadway (e.g. freeways, major and minor arterials, collectors) and the closest fringe of an adjacent residential neighborhood. Furthermore, a landscaped berm must be provided to increase the attenuation of traffic induced noise. These requirements limit the need for noise walls, which are largely considered "unsightly" to local residences.

Caltrans (California DOT) requires local government ordinances to address noise as an element of the planning process. Mitigation strategies include the use of buffers, setbacks, and building orientation options to limit noise impacts. Although the state requires traffic noise to be addressed, it is the prime responsibility of local governments to initiate action. These actions vary by communities throughout the state.

The Commonwealth of Virginia has also recently taken steps towards implementing noise compatible land use planning. Currently, several local municipalities have implemented controls on noise compatible land use planning through the use of setbacks. These setback requirements range from 50 to 200 feet, depending on the municipality. Setbacks require a certain amount of distance be placed between the receiver and the highway system and obviously, as the setback requirement increase, the greater the benefit will be to the community. Setback requirements are an excellent planning tool to use when trying to avoid or minimize potential noise impacts.

5.4.5 Acquisition of Land to Serve as a Buffer to Preempt Development

FHWA regulations detailed in 23 CFR 772, specifically state that the acquisition of vacant land to act as buffers is a viable noise mitigation technique. Also, federal funds can be used for the acquisition of highway buffers to serve as noise mitigation. Buffer zones are created when a highway agency purchases land or development rights, in addition to normal right-of-way, so that future dwellings cannot be constructed close to the highway. This prevents the possibility of constructing dwellings that would otherwise have an excessive noise level from nearby highway traffic.

The subject of buffers for noise mitigation must begin at the highway planning phase. Additional right-of-way must be acquired during the planning and design phases to act as the physical separation between any existing or future residential communities. An additional benefit of buffer zones is that they improve roadside appearance. However, because buffer lands require a tremendous amount of space to effectively preclude future development and potential noise impacts, they can prove to be a very costly mitigation option. Additionally, since many areas adjacent to transportation improvement projects are already developed, the purchase of buffer lands is not often possible along existing highway corridors.

In addition to the physical and financial limitations, the use of buffer zones also has some legal limitations in Ohio. The Ohio Revised Code, §5501.32, limits ODOT's ability to purchase lands, and indicates that property may be purchased strictly for "highway purposes". It is unclear if noise mitigation can be grouped into this category; however, (regardless of the limitations) the purchase of land to serve as a buffer zone to preempt development has not commonly been applied as a noise mitigation measure in Ohio. This choice is due to physical, financial, and legal limitations of this measure. Given this reality, buffer zones have traditionally been more successful as a noise mitigation strategy when they become the responsibility of the developer for new developments near existing highways.