

# Highway Noise Reduction Experiment

**Appropriation Act Item 442 C.  
(2007)**

**Report to Delegate May**

Virginia Department of Transportation  
1401 East Broad Street  
Richmond, Virginia 23219

**December 2008**





## COMMONWEALTH of VIRGINIA

DEPARTMENT OF TRANSPORTATION  
1401 EAST BROAD STREET  
RICHMOND, VIRGINIA 23219-2000

David S. Ekern, P.E.  
COMMISSIONER

December 12, 2008

The Honorable Joe T. May  
Virginia House of Delegates  
P.O. Box 2146  
Leesburg, VA 20177-7538

Dear Delegate May:

Item 442 C. of Chapter 847 of the Acts of Assembly of 2007 requests the Virginia Transportation Research Council (VTRC), in conjunction with the Virginia Transportation Tech Institute, design and implement a highway noise reduction experiment at the Virginia Tech Transportation Institute facilities in Blacksburg which utilizes dense conifers as the noise barrier and privacy screen portion of the experiment. Additionally, a short section of test roadway will be paved with new reduced noise asphalt to determine its efficacy and utility in reducing roadway noise.

The specific objectives of this research were (1) to quantify the reduction in noise emanating from the state's interstate highways attributable to various types of evergreen trees commonly found in Virginia, and (2) to measure the reduction in road noise achievable from the use of a quiet pavement. To achieve the first objective, noise measurements were taken at 15 roadside locations in Virginia to measure the effects of the evergreen trees in mitigating highway noise. To achieve the second objective, four types of pavement were tested on the Virginia Smart Road in Blacksburg.

The results of this study are provided in the enclosed report. Overall, there was minimal noise attenuation that could be attributed to the coniferous trees at the 15 study sites examined. Attenuation was not correlated with tree stand age, height, species, or density for these sites. The quiet pavement section tested had a noise level slightly higher than that of an intermediate pavement, but less than that of a standard asphalt pavement and concrete pavement.

If you have questions or need additional information, please contact me.

Sincerely,

A handwritten signature in black ink that reads "David S. Ekern".

David S. Ekern

Enclosure

cc: The Honorable Pierce R. Homer



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**ROAD NOISE ATTENUATION STUDY:  
TRAFFIC NOISE, TREES, AND QUIET PAVEMENT:**

**A REPORT IN RESPONSE TO ITEM 442 C. OF CHAPTER 847 OF THE  
ACTS OF ASSEMBLY OF 2007**

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Performed for:  
The Virginia Department of Transportation

Under the supervision of:  
The Virginia Transportation Research Council

November 2008



# Executive Summary

## Introduction

The use of noise barriers in Virginia to reduce the noise associated with roadway traffic has become increasingly common as land development continues near interstates and other high-volume roadways. The Virginia Department of Transportation (VDOT) follows the criteria and procedures outlined in the U.S. Code of Federal Regulations, Part 772 (23 CFR 772), for determining the need for noise abatement (VDOT, 1996). Although noise barriers are an effective abatement measure, they are expensive to install and are often considered unattractive by those living near them. For this reason, efforts to find viable alternatives continue. The use of vegetation, specifically trees, is one such alternative that has been investigated.

With few exceptions, most noise attenuation studies have agreed that at least some reduction in noise level can be achieved by the use of roadside vegetation (Borthwick et al., 1978; Fang et al., 2005; Hendricks, 1989; Huddart, 1990; Ozer et al., 2007; Price, 1988). Among these studies, the greatest reduction was a 9 dB reduction with vegetation belts between 20 and 30 meters in width (Huddart, 1990). The findings of many studies are similar to those of a study supported by the Federal Highway Administration in which the researchers concluded that highway traffic noise was reduced on the order of 3 to 5 dBA by typical forest belts 10 to 30 meters in width (Borthwick et al., 1978). The differences in the findings of these studies can be attributed, at least in part, to the wide variety of measurement methods, tree species and heights, vegetation densities, and noise sources used. Although some studies, such as one conducted by the Caltrans Transportation Laboratory (Hendricks, 1989), found that vegetative barriers do not significantly reduce noise from a human perspective, none of these studies was conducted in Virginia and, therefore, do not directly reflect the reductions in noise resulting from species of vegetation found in the state.

Another mitigation strategy for noise emanating from highway sources is the use of “quiet pavement.” Because of their material properties, these pavements have a higher rate of acoustic absorption. These types of materials are specifically used for the surface course to reduce the level of noise resulting from the tire-roadway interaction.

The Virginia Transportation Research Council continues to study sound reducing methods. They are currently conducting a study titled *A Functionally Optimized Hot-Mix Asphalt Wearing Course*. This research project will oversee the design, production, and placement of a new-generation open-graded surface course. Although concerned with all functional aspects of a highway wearing-course, the data acquisition, analysis, and reporting goals of this project will conform to the requirements of the Federal Highway Administration’s Tire/Pavement Noise Research program. In that respect, the acoustic characteristics of the new surface, and the way in which these characteristics translate into reduced noise levels along the facility will be carefully measured and reported. In addition to noise and noise-related properties, safety and ride quality will be evaluated, as well as more subjective characteristics like splash & spray, wet-night and pavement marker visibility. A report on this study is tentatively scheduled to be released in early 2010.

## Purpose and Scope

This study was conducted in response to the directive in Item 442 C. of Chapter 847 of the Acts of Assembly of 2007. The directive states:

*C. From funding appropriated in this item for the Virginia Transportation Research Council (VTRC), the VTRC, in conjunction with the Virginia Tech Transportation Institute, shall design and implement a highway noise reduction experiment at the Virginia Tech Transportation Institute facilities in Blacksburg which utilizes dense conifers as the noise barrier and privacy screen portion of the experiment. Additionally, a short section of test roadway will be paved with new reduced noise asphalt to determine its efficacy and utility in reducing roadway noise. The Virginia Tech Forestry and Engineering Departments will provide assistance where appropriate.*

The specific objectives of this research were (1) to quantify the reduction in noise emanating from the state's interstate highways attributable to various types of evergreen trees commonly found in Virginia, and (2) to measure the reduction in road noise achievable from the use of a quiet pavement.

To achieve the first objective, noise measurements were taken at 15 roadside locations in Virginia to measure the effects of the evergreen trees in mitigating highway noise. To achieve the second objective, four types of pavement were tested on the Virginia Smart Road in Blacksburg. Originally, a larger section of quiet pavement placed on an existing roadway in Northern Virginia was to be monitored as well, but placement of the new pavement surface was not completed in time for inclusion in this research effort. The cost to complete this study was \$57,000.

## Methods

### Vegetation Study

A total of 15 sites were used to collect roadway noise. The selection criteria for these sites were as follows:

- coniferous dominant species
- tree depth of at least 20 meters
- accessibility for noise measurements
- safety with regard to team members taking noise measurements and traffic counts
- the absence of leafed-out deciduous trees.

Because of the mountainous topography in the western part of the state, most of the sites were located east of the Blue Ridge Mountains.

### Noise Measurements

Noise measurements at the different sites were made using two Larson-Davis 824 sound level meters: one device remained at the boundary between the roadway and the stand of trees, and the

other device was used at distances of 5, 10, 15, and 20 m from the boundary. Two measurements, each lasting 15 minutes, were taken at each of the four locations for a total of eight measurements at each site. The measurements at each location were averaged over the 15-minute measurement period using the Leq dBA setting, which weights sound levels at different frequencies in a manner that approximates the frequency response of the human ear.

### *Traffic Measurements*

Traffic volumes were also collected at each of the 15 sites. Vehicles were categorized as light or heavy. Light vehicles included passenger cars, SUVs, and light trucks. Heavy vehicles included multi-axle vehicles and any light trucks or SUVs pulling large trailers. From this information, traffic density and traffic mix (the percentage of heavy vehicles) were calculated.

### *Tree Data*

A variety of tree data were made during noise collection intervals at each site:

- the dominant and co-dominant tree species
- the age, total height, and height of live crown of three trees of the dominant species
- the basal area and density of the dominant species.

### **Quiet Pavement Study**

Four pavement sections, each approximately 300 feet long, were used for the quiet pavement component of the study:

1. standard asphalt pavement
2. quiet pavement
3. intermediate pavement (one with texture characteristics between those of quiet pavement and standard asphalt pavement)
4. concrete pavement.

Traffic density was simulated using three setups: (1) one light vehicle running by the noise meter, (2) two light vehicles running together by the noise meter, and (3) one heavy vehicle (15-passenger van) running by the noise meter. Vehicles were run at two speeds, 25 mph and 45 mph, and in both uphill and downhill directions. Noise measurements were taken 20 meters from the roadway centerline.

## **Results and Discussion**

### **Vegetation Study**

The average noise reading at 20 meters from the roadway for all 15 sites under all traffic densities and traffic mixes was 70.5 dBA. The reductions in noise from the baseline values (those measured 20 meters from the roadway, in front of the trees) were the result of the increased distance from the roadway, not a result of any mitigating effects of the trees. More

specifically, there was no attenuation of noise resulting from tree density, tree age, tree height, percent live crown, species, or diameter at breast height. The largest differences measured were in the range of  $\pm 2.5$  dB, and most were within  $\pm 1.0$  dB.

Many of the species of pine trees examined had lost their lower branches as the trees matured. This problem appeared to be worse when the trees were more densely planted; the trees on the perimeter of the stand had a higher overall density (tree biomass volume per unit area) than those just inside the stand. The interior portion of most of the stands served as little or no impediment to noise propagation.

## Quiet Pavement Study

The intermediate pavement had the lowest noise readings, 61 dBA, under all conditions tested, and the quiet pavement had the second lowest noise readings, 62 dBA, for all conditions tested. In general, the standard asphalt and concrete sections had similar overall readings (approximately 63 dBA), but the readings were different under different speed and traffic density conditions.

The quiet pavement section did have the lowest readings in the mid-range frequency (1250 through 5000 Hz). Noise resulting from tire-roadway interaction tends to occur in this frequency, so it appears that the surface performed as advertised by attenuating the noise in this range. It is also interesting to note that the intermediate pavement had lower readings than the other three pavements in the frequency range below 1250 Hz, resulting in greater attenuation of engine noise.

## Conclusions

- *There was minimal noise attenuation that could be attributed to the coniferous trees at the 15 study sites examined. Attenuation was not correlated with tree stand age, height, species, or density for these sites.*
- *The quiet pavement section tested had an overall noise level (62 dBA) that was slightly higher than that of an intermediate pavement (61 dBA) but less than that of a standard asphalt pavement and a concrete pavement (approximately 63 dBA). The quiet pavement did have lower readings in the mid-range frequencies.*

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## Abstract

Most of the previous research reviewed for this study concluded that a vegetation barrier *can* help reduce traffic noise to a certain degree, although the highest attenuation obtained was approximately 9 dB. However, study results were not all positive; some of the studies concluded that the noise attenuation obtained was so small it would not be perceived by humans. The differences in results among these studies is likely due to the wide variety of measurement methods, tree species, planting densities, tree heights, and noise sources used. None of the previous studies were conducted in the Commonwealth of Virginia, using tree species that are currently known to thrive in the roadway environments found there. Likewise, very few studies used live road noise, and in particular, live road noise using today's vehicles and traffic mixes. The current study was designed to overcome some of these shortcomings and provide results more applicable to conditions in Virginia.

Fifteen roadside sites were thus examined across the Commonwealth of Virginia, examining factors such as tree height, tree age, tree species, tree density, tree diameter, distance from roadway, traffic density, and traffic mix. Two hours worth of measurements were taken at each site (two 15-minute measurements at each of four distances from the edge of the trees). No matter how the sites were examined analytically, there was no measurable difference in road noise. All differences at the more distant measurement locations were due simply to the distance effect rather than to any additional mitigating effects of trees, whether measured by planting density, age, height, or average tree diameter. An attenuation of at least 1 dB is required for a listener to just be able to notice a difference in the noise level, and most average attenuations measured for this study were within  $\pm 1.0$  dB. One of the problems appeared to be the types of tree plantings available for measurement. It is a characteristic of all three species of pine trees located at the sites that the interior trees lose their lower branches as the stand grows up. This means that the interior of most stands consisted primarily of empty air with little or no impediment to noise propagation. The results of the live road study were in agreement with previous studies conducted in other locations and with different species of trees.

Another study was conducted on the Smart Road located adjacent to the Virginia Tech Transportation Institute (VTTI). This study compared four types of pavement in terms of their noise characteristics, under varying conditions of traffic density, traffic direction, and traffic speed. One aspect of the study that could not be completed was a series of measurements of quiet pavement on one or more live road segments. This would have made a nice bridge between the live road study and the Smart Road study, and allowed direct comparisons between the studies. Nevertheless, the study conducted on the Smart Road had interesting results. The four pavement types were quiet pavement (designed to lessen road/tire noise), standard asphalt, in-between (asphalt with characteristics in-between those of quiet pavement and standard pavement), and concrete. The in-between pavement consistently resulted in the lowest noise levels across all conditions studied. Further analysis revealed that this was likely due to greater absorption of low frequency engine noise. The quiet pavement outperformed the other three types in the mid-high range of frequencies, which is where tire/pavement noise would be expected to be greatest. The standard asphalt and concrete surfaces performed worst under all conditions, and may have reflected both tire and engine noise, rather than absorbing these types of noise. In terms of the conditions studied, traffic speed had the greatest impact on the noise, with higher speeds resulting in greater noise. Traffic direction and traffic density both had impacts on noise levels, but these effects were lower than for traffic speed.

Although trees have not generally been found to be effective noise barriers, they do have aesthetic (and perhaps environmental) benefits. Trees may also produce a psychological benefit in terms of noise reduction – people may perceive the trees to have a greater noise reduction effect than can be measured. Nevertheless, many issues must be considered before a tree planting program can be put into place, including:

- Everything related to the noise problem and trees is a *moving target*. In the 40 or so years that have passed since many of the trees along Virginia's interstates were planted, vehicles and tires have changed significantly. The biggest moving target is the trees themselves. Trees grow measurably year by year, and there is probably a one to five year period when the noise reduction offered by a stand of trees is at its optimum
- Stands of trees attract *deer and other wildlife*, which may increase the incidence of vehicle/deer crashes.
- *Wildfires* have dominated the news over the past year, and there have even been wildfires in Virginia during that time. Wildfires adjacent to interstates can be caused by careless disposal of smoking materials while driving by the tree stands, or can spread from other nearby wildfires. Once a fire starts near the interstate, the state police must monitor carefully to make sure that the smoke does not impede visibility; when it does, they must close the road. Tall trees adjacent to the interstate can fall into the roadway during the fire, necessitating clean up before the road can be opened.
- Trees can be damaged by *weather events*, including snow, ice, wind storms, and tornados.
- *Disease and insects* can attack certain species of trees. Both disease and insect outbreaks can occur quite rapidly, in terms of the lifespan of a tree.
- Development and maintenance of such stands requires a *long-term commitment*. Any program involving tree plantings must provide for long-term care and maintenance of the trees, and should include contingency plans for what to do in case of some disaster or infestation.
- One of the biggest issues to consider is the *cost of land*. The irony of the situation is that large rights-of-way often exist in rural areas, where the right-of-way abuts pastureland. In heavily populated areas, where traffic is heaviest and noise reduction most desirable, there is often almost no right-of-way, with a shoulder (sometimes used as a traffic lane during rush hour) adjacent to a noise barrier, and houses right behind the noise barrier. In such situations, there is no place to plant trees or other vegetation in enough quantity to have any effect on noise.
- Trees that are too close to the roadway provide two possible *accident hazards*: the risk of a vehicle leaving the roadway and crashing into the tree, and the risk of the tree falling into the roadway.
- Certain species of trees spread easily, often by means of birds, and can become *weed-like*.
- Certain plants can be susceptible to tree *damage from vehicle emissions*.
- Stands of trees may prove to be attractive to different species of *birds*.

Several recommendations are also included at the end of this report, including suggestions for how a noise abatement program based on tree plantings can be made most successful. If a decision is made to plant stands of trees along Virginia's interstates to reduce noise in the areas beyond the trees, several provisions should be put in place to maximize the success of such a venture. These include suggestions for which species to plant, how deep to plant them (in terms of distance from the roadway), planting density, the distance from the roadway to the edge of the trees, topography, long-term maintenance, planning, and care, and pavement type.



## Introduction

As the population of Virginia continues to grow and land for development grows more scarce, more and more people find themselves living near interstates and other busy roadways. One of the biggest issues with living near such roadways is the attendant noise associated with the steadily increasing traffic flow. Where space is limited, the most common solution for noise is noise barriers. Although these are effective, they can be quite expensive to install initially. Depending on the noise barrier design, many people find them unattractive, and find living near these barriers to be almost as undesirable as the noise they are intended to ameliorate. For this reason, people have wondered over the years whether there are viable alternatives to noise barriers for reducing the noise associated with road noise.

One method for reducing noise is a barrier of vegetation, typically trees. Although previous research (summarized in this report) has not found any great degree of noise reduction for such vegetation-based barriers, none of these studies have been conducted in Virginia, using road noise from Virginia's roadways and the existing tree plantings found along Virginia's interstates.

Such a study was thus undertaken to answer the question: Can a barrier of trees help measurably reduce road noise in Virginia? The study focused on evergreen trees, since these would be expected to be equally effective at all times of the year. Tree factors considered in making these measurements included tree height, stand density, tree age, tree species, tree diameter, and distance into the stand. Traffic count was also considered, as was the percentage of heavy truck traffic.

Fifteen sites along Virginia's interstates were used as data collection sites, and the sites were equalized to the degree possible (each site was at least 20m (65.6 ft) deep, and each site was both flat and level with the roadway, so that the measurements taken at each site could be compared. Sites differed in tree species, tree age, tree height, tree density, the amount of traffic, and the amount of heavy truck traffic. Fifteen-minute Leq dBA measurements were taken at four distance into the stand, and repeated twice at each distance. A reference noise measurement was taken at the edge of the stand of trees nearest the roadway so that the amount of noise reduction provided by the trees could be calculated. Several types of tree measurements were also taken at each site, including tree age, tree height, tree species, tree diameter, and density. The results of these measurements are detailed in this report.

Another, and more recent, method to reduce road noise is to change the characteristics of the road surface itself so that the sound created by the tires as they roll over the road is reduced. Such pavements are popularly known as "quiet pavement." There is a short section of quiet pavement on Virginia's Smart Road, located near the Virginia Tech Transportation Research Institute (VTTI). The section of quiet pavement is located adjacent to several other short sections of pavement, so an experiment was developed to test the effectiveness of the quiet pavement in reducing road noise using similar measurement methods as were used in the live road study. Different speeds, different traffic mixes, and different levels of acceleration were examined in the Smart Road study. The methods and results of this study are also presented in this report.

The final component of the report are the conclusions and recommendations. If tree plantings are to be used to reduce noise, what type of trees should be used and how should they be planted? What other factors must be considered in adopting such a program? It is hoped that the reader of this report will be able to make informed decisions regarding such questions.

## **Background**

A number of studies over the years have been conducted to investigate the effectiveness of vegetation for attenuation of road noise. The studies have been conducted in various locations within the U.S. and in other countries, and have used a variety of tree species and measurement methods. A review of these previous studies provided insight into the research design used for the current study. The previous studies are briefly discussed in this section to provide background and context for the current study.

A study conducted in England by Huddart (1990) found a maximum noise reduction at a location with spruces 30 m deep. The reduction was 6 dB greater than in a location with only grass. The study also found that greater noise reduction was achieved with vegetation closer to the road. Different types of barriers were investigated. Solid barriers at least 8 ft high and at least 4 inches thick are expected to reduce noise by about 10 dB. The barrier material (earth mound, wood, steel, or concrete) is unimportant. With vegetation, noise can be reduced by up to 8 dB, and vegetation belts that are 20 to 30 m deep can reduce up to 9 dB.

Traffic noise from busy roads was recorded at sites with different types of vegetation and with depths of up to 30 m. Chosen sites had vegetation growing close to the road. All of the sites used in the study had straight and level roads. Vehicular traffic was at least 600 vehicles per hour. The ground at each site was flat and covered in vegetation. Six sites were used for the study. Site 1 was chosen as the control site; the ground was slightly uneven and covered only by grass. Site 2 had red oak and silver birch trees with diameters of about 20 cm (7.8 in) spaced at 2.5 m (8.2 ft). The average tree height was about 25 m (82 ft). Site 3 had rhododendron bushes about 3 m tall, and interspersed with bracken. The trees were irregularly spaced silver birch with heights of up to 30 m. Site 4 had rhododendron bushes about 4 m tall and 10 m deep; the bushes had lost most of their foliage. There were also pine trees with diameters of about 30 cm and spaced at 3 m. This site also had some silver birch trees. Site 5 had gorse and bramble bushes up to 3 m high. Bushes were dense and difficult to penetrate close to the road for the first 5 to 10 meters. Behind the dense belt were oaks and Scots pines spaced at about 5 m. The ground was covered with leaves and pine needles. Site 6 had spruce trees spaced closely at about 1 m. The trunk diameters averaged about 12 cm and the average height about 20 m.

Four microphones were used and connected to tape recorders. The first microphone was located 5 m from the source, measured from the center of the traffic lane. The second microphone was located every 10 m up to 35 m. Another option considered for microphone location was 4m, 8m, 16m and 32m. The microphone was placed 1.5 m above the ground. Noise was recorded for 15 minutes and 2 sets of measurements were taken at each site. While noise was recorded, traffic counts were being tallied. The classifications used for traffic counts were light (2-axle, single rear tires) and heavy (2-axle, double rear tires or multi-axle).

One important finding of this study is that foliage can reduce high frequencies, greater than 2000 Hz. On the other hand, the ground's absorbing qualities can reduce low frequencies, from 250 to

500 Hz. These absorbing qualities can be further enhanced by leaf litter and the plants' root systems. The study concluded that all sites with vegetation had a greater attenuation than the control site, with the dense spruce plantation having the maximum attenuation over a distance of 30 m. Deciduous woods provide the least attenuation, only about 2dBA more than grass.

Vegetation was found to be important for maintaining a soft ground cover, which greatly helps to reduce low frequency noise. It can also help filter high and low frequencies. At the spruce plantation, vegetation was completely interlocking, with no gaps. The study concluded that dense, interlocking vegetation could be more important than actual vegetation type for providing a noise screen. An important benefit provided by a vegetation barrier is psychological; perception of noise reduction can be greater than the actual reduction provided by the vegetation barrier. This suggests that a vegetation barrier is preferable than an artificial one in terms of people's perception. In terms of vegetation type, broadleaf vegetation was found to be effective for reducing traffic noise. The study recommends dense plantings of broadleaf evergreens and deciduous shrubs along with some conifers.

A study was conducted at Penn State in the 1970's by Borthwick, Halverson, Heisler, McDaniel, and Reethof (1978). The report concluded that forest belts from 10 to 30 m deep can reduce noise by 3 to 5 dB. Ten forest belts were chosen for this study. The vegetation belts chosen for the study had depths ranging from 10 to 30 m. The species found in the locations included red spruce, Norway spruce, Virginia pine, white pine, and red pine. Sites with conifers were chosen because they provide year round visual screening. Average heights ranged from 5 to 15 m.

The study used sound generating equipment rather than live traffic noise. Noise measurements were taken with a sound level meter with a 1.25 cm microphone on a 3 m extension cable and placed on a tripod, whose height could be adjusted up to 4 m. Microphones were placed at 12, 45 and 60 m from the source and 3 m behind the belt. The height of the microphone was 1.3 and 4 m above the ground.

Sites 1, 2 and 3 consisted primarily of red and white pine with open fields on either side. There were also oats (15 to 20 cm tall) and corn (10 to 15 cm tall). The trees at Site 4 were white spruce (5 to 8 m tall) and 3 to 15 cm diameter at breast height (DBH). The belt was 9 m wide. The ground was covered with grass and there were also some shrubs up to 1 m tall. Site 5 consisted of red pine, self-pruned for about one third of the lower trunk length, while Site 6 was mostly Norway spruce with a sparse row of red pine in the back. Site 7 was a mixture of red spruce and Norway spruce. Site 8 had a single row of Norway and white spruce with the branches extending to the ground. The ground had a low cover. Site 9 consisted of a young stand of red spruce about 7 m tall, while Site 10 consisted of a single row of closely planted young white pines.

The study concluded that forest belts with widths ranging from 10 to 30 m can reduce traffic noise by 3 to 5 dBA. The study also found that tree belts that are deliberately planted as densely as possible can be expected to yield higher insertion loss (attenuation) values. The greatest insertion loss at a high frequency was found in the site composed of red and white pines where the noise source and receiver were 61 m apart. However, the report did not specify what species should be used to obtain the highest attenuation possible. Data collected in this study was found to support a highway noise prediction model for determining the effects of vegetation barriers.

The study also concluded that more research needs to be done in order to be able to quantify the relationship between belt width and insertion loss and the role of soil absorption in noise reduction. It was found that forest vegetation, when used as a noise barrier, has several advantages over a conventional noise barrier. These advantages include an aesthetic value, a naturally renewable characteristic, which can help reduce costs, and the possibility of obtaining wood products from lands not being currently used for such purposes.

Hendriks (1989) conducted a noise study for the state of California. The study reports noise measurements at various distances in shielded and unshielded locations. Three sites were used and included the following species: Site 1, oleander; Site 2, combination of oleander and redwoods; and Site 3, pine trees. Noise reductions ranged from 0 to 2.7 dB. This level of reduction was not considered significant for human perception.

Three sites were chosen for the study. Each site consisted of a shielded and an unshielded region. The following criteria were considered in site selection:

- Shielded areas should have enough vegetative mass and height.
- Unshielded areas should be open and have no obstacles.
- There should be similar site geometry between shielded and unshielded areas.
- Noise sources should be almost equivalent (same traffic, same lane distributions)
- Enough traffic to reduce chances of contamination by background noise.
- Enough distances available for noise measurements.
- Two microphones have to be settled, one in the shielded and one in the unshielded area. They should both be at the same distance and height from the noise source (the traffic lane).

Traffic volumes were videotaped and later counted to ensure that no contamination from background noise occurred. Wind speed and direction was also measured. Both microphones measured noise simultaneously for at least 15 minutes for each run. At least seven runs were measured at each site. Traffic observations and wind conditions were recorded for each run. The study found that attenuations of up to 5 dBA were achieved 3 feet behind a 6 ft high right-of-way fence covered with thick, dense ivy. At 20 ft behind the fence, these attenuations decreased to 2 dBA. Measurements taken behind an oleander strip, about 8 ft high and 17 ft wide, resulted in attenuations from less than 1 dBA to almost 3 dBA. The oleander strip was located parallel to a freeway. Noise reduction found at each of the sites was the following:

- At the site with a combination of oleander and redwoods, noise attenuation ranged from 0.3 to 0.8 dBA.
- At the site with only oleanders, noise attenuation ranged from 0.7 to 2.7 dBA.
- At the site with only pine trees, attenuation ranged from 0.0 to 1.0 dBA.

The study states that noise reductions of less than 3.0 dBA are generally not perceived by humans. It was concluded that the attenuations obtained were not significant from a human perspective. Therefore, it was determined that using vegetation is not an effective measure for reducing traffic noise. The study recommends that an oleander vegetation belt can be used to conform to noise standards, given that it can attenuate noise by up to 2 dBA. The belt should have a width of 15 to 20 ft, be sufficiently dense and have a height of 8 ft. The study recommends including vegetation with conventional noise barrier designs basically for aesthetic reasons.

A recent study out of Taiwan reported on six kinds of tree belts located in flat areas (Fang and Ling, 2005). The belts were dense and narrow and each exceeded 50m. Parameters evaluated in the study included: visibility, tree height, belt width, the heights of the receiver and the noise source, and the distance between the noise source and the receiver. Artificial noise sources were located 2m from the edge of trees at a distance of 2.5m from the centerline. Measuring devices were located 5m behind the edge of the trees and at subsequent 5m intervals through the depth of the belt. Both the noise source and measuring device were placed at the same height as one another, although the heights were varied across conditions.

Visibility was measured to indicate the density of tree leaves and branches. The method used to measure visibility was the following: Researcher A stood at one side of tree belt while Researcher B, wearing a white glove, stretched a hand by 10cm increments into the trees until Researcher A was unable to see the white glove. At this point, the distance between researchers was measured and defined as the visibility of the tree belt. Two measures were averaged for each belt.

Three dimensionless parameters were calculated from the studied parameters (receiver and noise source height/tree height, distance between noise source and receiver/tree height, and belt width/visibility). These formulas for these parameters are:

$h'$  (height ratio)

$$h' = \frac{\text{receiver and noise source height}}{\text{tree height}}$$

$m'$  (width to visibility ratio)

$$m' = \frac{\text{belt width}}{\text{visibility}}$$

$d'$  (distance to height ratio)

$$d' = \frac{\text{distance to measuring device}}{\text{tree height}}$$

The attenuation obtained at the six sites was similar. It was observed that the lower the artificial noise source and receiver were placed, the greater the noise attenuation obtained. Attenuation declined slowly as distance increased up to 40 m; after 40 m, attenuation declined rapidly. The study identified a negative correlation between visibility, receiver and noise source height, and distance with noise attenuation. On the other hand, tree height and belt width were found to have a positive correlation with noise attenuation. The study proposes that an effective tree belt in terms of noise reduction is one that is high and wide, and the distance between the noise source and the receiver is less than eight times the tree height. For example, to obtain an attenuation of 4

dB(A), the receiver and noise source should have a height of 1.2 m, should be 28 m away from the tree belt, and the tree belt should be 3.6 m wide and 4 m high with a visibility of 2 m.

Kragh (1981) studied the effects of tree belts on noise in Denmark. Six kinds of tree belts were studied with widths ranging from 3 to 25m. The distance from the road to the front of the belts varied from 0 to 90m. Chosen tree belts were mainly composed of deciduous trees and bushes between 5 to 10 yrs of age. At all sites, roads were at grade level of the adjacent ground. All measurements were taken at moderate wind speeds of 1.5 m/s to 5.5 m/s (3.4 mph to 12.3 mph) measured 10m (32.8') above the ground. Four microphones, at a height of 1.5 m above the ground, recorded measurements simultaneously. Chosen belts produced only insignificant increases in noise attenuation, although higher attenuation values were obtained for frequencies higher than 2 kHz.

The study found that the insertion losses measured were so small they would not be relevant for noise reduction. The study only describes the sites in terms of belt width and does not include tree height; other characteristics are shown in Table 1.

**Table 1. Site characteristics for the Kragh study.**

Site Name	Belt Width (m)	Ground Cover	Attenuation diff. (dB)	Site Observations
Asserbo	3	20 cm grass	5.2	Extremely dense, conifer belt
			3.2	
Lejre	10	50 cm cornfield	0.0	Front of belt is 30m from road
Darup	11	50 cm cornfield	0.0	
Svansbjerg	19	Stubblefield	0.6	Upwind
			2.6	
Gundsø	19	40 cm grass	1.3	Front of belt 90 m from road
Oppe Sundby	25	Plowed ground	0.4	

The attenuation difference is the difference between the attenuation through the tree belt and at the reference section. The main conclusion of the study is that the insertion losses were so small they are not relevant for noise reduction purposes.

Price, Attenborough, and Heap (1988) studied three woodlands in England to compare frequency-dependent attenuation of broadband sound to the predictions of a model that adds the contributions of the ground, trunks and branches and the foliage. The three sites selected for this study were located in a flat area planted by the Forestry Commission in the United Kingdom. Site 1 was a mature mixture of Norway spruce and oak in alternating bands. The ground was covered with needles under spruce and Hawthorne leaves under oak leaves. There were no lower branches or undergrowth. The visibility was less than 24m. Site 2 was a mature growth of Norway spruce. The trees were between 11 and 13 m tall with dead branches below 4 m forming a dense layer that impeded visibility, but to a lesser degree than Site 1. The ground was covered

with a thick layer of spruce needles. Site 3 was a young mixed coniferous stand composed of alternating rows of red cedar, Norway spruce, and Corsican pine. The rows of red cedar formed a continuous barrier.

The measurements were averaged by displacing the microphone 0.5 m to each side of the first position, totaling three measurements at each site. The recordings at each position were 120 s in duration. The receiver heights were 1.2 and 2.4 m above the ground. The reference microphone was located 2 m from the white noise source, which was a loudspeaker. Both microphones were protected with foam windshields. At every location, wind speed and direction was recorded, as well as relative humidity and temperature at two heights.

Measurements at all sites were taken during summer and winter. At Site 1, they were taken at distances of 12, 24, 48 and 72 m from the noise source. At Site 2, the measurements were at distances of 12, 24, 48 and 96 m from the noise source, while measurements at Site 3 were taken at distances of 12, 24, 26 and 40 m from the noise source.

The study found a strong link between high-frequency attenuation and vegetation density. The square-root law was found to be highly applicable for site 2 analysis but not for the other two sites. The study also concluded that scattering by trunks is an important factor for attenuation as well as branches and leaves. Scattering by trunks accounts for a higher proportion of attenuation in the spruce and mixed woodland (in winter) sites than for the mixed coniferous or mixed woodland in summer.

Ozer, Akif Irmak, and Yilmaz, conducted a noise study in Turkey (2007). The study was conducted at one of the largest cities in the east of Turkey, Erzurum. The city has a population of about 402,000 and has had an increase in the number of vehicles over the past 30 years, from 2,764 in 1970 to 32,543 in 2003. Two of the sites chosen for the study were two man-made urban forest areas found along the E-80 state highway, each with a different species of tree. The third site was a control site located along the same highway.

Site 1 had 440 pine trees (*Pinus sylvestris*), with ages ranging from 20 to 25 years. The trees were pruned 2 to 2.5 m from the ground. The trees were arranged in 16 lines, 5 m from one another. There was no elevation difference throughout the site. Tree height at the sites was not clearly described. Site 2 consisted of 625 poplar trees (*Populus nigra*) with ages ranging from 15 to 20 years. The trees were pruned 2 to 2.5 m from the ground. They were arranged in 21 lines, 4 m away from one another. The site is also approximately flat and free of steep slopes. The Site 3 control site was an open area, relatively flat and without slopes (similar to the study sites in grade). It was located close to the other sites and had no shrubs covering the ground. The only covering was weedy grass with a length of 5 to 10 cm.

Measurements were taken during the summer, when poplar trees had their leaves. The noise source used for the measurements was a water pump that produces a noise value of 100.3 dB. The measuring device was placed 1.2 m above the ground. At the control site, measurements were first taken near the noise source. The next measurements were taken at 25, 50 and 75 m from the source. At every distance, 21 measurements were taken for 3 minutes and then averaged to obtain the measurement for the site. This same procedure was then followed for Sites 1 and 2.

The study found that the noise reduction effectiveness of the sites diminished as the distance increased. The maximum attenuation was found in the pine tree site at 25 m from the source. The minimum attenuation was measured at a distance of 75 m in the poplar site. The study identified the following factors as important for a forest area to attenuate noise effectively: crown width, height, and density of plants, tree species (deciduous or not), plantation density, whether plants branch from the bottom, and the position of the leaves.

The study concluded that the *Pinus sylvestris* species provides a considerable degree of noise attenuation. Pine trees reduced noise by 9.3 dB in the first 25 m, 5.3 dB at 50 m and 5.7 dB at 75 m. Poplar trees reduced noise by 3.0 dB at 25 m, 2.5 dB at 50m and 2.4 dB at 75 m. One of the study recommendations is that trees should be planted more closely together to reduce noise more effectively. The reduction by pine trees can be observed year round since they are evergreens. Although the pine trees reduced noise, they did not reduce the value to the target acceptable level of 55 dB.

### ***Summary of Literature Reviewed***

Most of the research reviewed for this study concluded that a vegetation barrier can help reduce traffic noise to a certain degree; the highest attenuation obtained was approximately 9 dB. Vegetation barriers are perceived more positively than conventional noise barriers, which can be more effective but are not as aesthetically pleasing. The studies also concluded that in order for a vegetation belt to reduce traffic noise it should be densely planted, with no windows to let noise through. Ground cover at the different sites was also found to be helpful. Some of the studies suggested a mixture of evergreens, conifers and shrubs interspersed at the sites to increase noise reduction effectiveness, especially if some of the trees had lost their lower foliage. The *Pinus sylvestris* species was found to be quite effective at noise attenuation over a 75 m distance. As distance increased, noise reduction effectiveness was found to lessen.

The majority of studies did not use live traffic noise for taking measurements. Most used either recorded noise or had artificial noise generators located at the sites. An important finding is that foliage can reduce frequencies greater than 2000 Hz, while the ground's absorbing qualities can help reduce lower frequencies ranging from 250 to 500 Hz. Higher attenuation values were usually obtained for higher frequencies, above 2000 Hz. However, study results were not all positive; some of the studies concluded that the noise attenuation obtained was so small it would not be perceived by humans. The differences in results among these studies is likely due to the wide variety of measurement methods, tree species, planting densities, tree heights, and noise sources used.

None of the previous studies were conducted in the Commonwealth of Virginia, using tree species that are currently known to thrive in the roadway environments found there. Likewise, very few studies used live road noise, and in particular, live road noise using today's vehicles and traffic mixes. The current study was designed to overcome some of these shortcomings and provide results more applicable to conditions in Virginia.

## **Objectives of Study**

There were three main objectives for this study:

- To characterize the road noise found on Virginia’s interstate highways.
- To measure the effect of various types of evergreen tree plantings on the road noise on Virginia’s interstate highways, using different traffic density and mixes.
- To measure the noise reduction offered by the “quiet pavement” found on the VDOT/VTTI Smart Road.

These objectives were accomplished via two studies. The first study was a live road study, using existing tree plantings and live road noise under a variety of traffic conditions. The second study was a controlled study on the Smart Road comparing four pavement types under several simulated traffic conditions. The methods used for these studies and their results are discussed in the next sections of the report.



# Live Road Study

## Research Design

The original research design was based on the belief that an adequate number of sites could be located so that factors such as traffic mix, tree species, traffic density, and tree age/size could be systematically studied. Ideally, 16 sites would have been located to fit into the cells shown in Table 1. Instead, sites meeting the other important site criteria were difficult to find (this is discussed in a subsequent section), and only 15 sites meeting the general site criteria could be found. Thus, traffic mix, tree species, traffic density, and tree age/size were measured and then slotted into categories once all sites were measured. This resulted in unequal numbers of sites for each category, and in some cases, different numbers of categories than originally proposed. For example, Traffic density was divided into three categories rather than the original two proposed in Table 2. The final number of sites in each category for each factor is presented in Table 3, while more details about the sites are presented in a later section of the report. As can be seen in Table 2, the sites were quite varied in their characteristics, despite not matching the original research design.

**Table 2. Original research design: Factors for site selection for live road measurements.**

Traffic mix	Species 1		Species 2	
	Light Density	Heavy Density	Light Density	Heavy Density
Low percentage of truck traffic	1. Younger, shorter stand	3. Younger, shorter stand	5. Younger, shorter stand	7. Younger, shorter stand
	2. Older, taller stand	4. Older, taller stand	6. Older, taller stand	8. Older, taller stand
High percentage of truck traffic	9. Younger, shorter stand	11. Younger, shorter stand	13. Younger, shorter stand	15. Younger, shorter stand
	10. Older, taller stand	12. Older, taller stand	14. Older, taller stand	16. Older, taller stand

**Table 3. Revised research design: Site characteristics and number of sites for live road measurements (15 sites total).**

<b>Dominant Tree Species</b>	<b>Tree Density, BA method</b>	<b>Tree Height</b>	<b>Tree Age</b>	<b>Road Surface</b>	<b>Traffic Density</b>	<b>Truck Traffic</b>
Virginia pine, 2 sites	Sparse, 5 sites	Short, 7 sites	Young, 4 sites	Concrete, 3 sites	Light, 2 sites	Light, 2 sites
Loblolly pine, 8 sites	Medium, 5 sites	Tall, 8 sites	Mid, 6 sites	Asphalt, 12 sites	Moderate, 6 sites	Medium, 10 sites
White pine, 5 sites	Heavy, 5 sites		Old, 5 sites		Heavy, 5 sites	Heavy, 3 sites
					Very heavy, 2 sites	

## ***Method***

### **Site Selection Criteria**

Several scouting trips were conducted to identify appropriate sites for the noise measurements. At first it was hoped that aerial photographs and GIS records could be used to identify sites, but when the first sites were investigated in person, it was found that they had undesirable characteristics which could not be filtered through either of these methods. Thus, several trips were required to identify enough sites that would meet the criteria and be appropriate for the measurement methods. The final criteria included:

- The dominant species must be coniferous (the dominant species is defined as the species that dominates the forest canopy)
- The site must be at least 20 m (65.6 ft) deep (tree depth)
- The site must be level in grade and even with the road
- The site must be accessible for measurements (researchers able to enter woods to take measurements; no posted private land; stay within VDOT right-of-way to the degree possible)
- The site must be safe for the roadside researcher to take noise measurements and traffic counts
- There must be a safe place to park the research vehicle
- If there are deciduous trees at the site, they must not yet be leafed out

The researchers thought that there would be a surplus of sites to include in the study, but only 15 suitable sites were identified despite intense scouting (scouting included all of Virginia's interstates, except for the very northern and southern tips of I-81, the area of I-64 from Hampton Roads eastward, and the section of I-66 from Manassas eastward). The primary difficulty was in finding sites that were both level throughout the site and level with the road. This criterion was

necessary to isolate the effects of the trees on the road noise. Sites with hills and embankments (both upward and downward sloping) provide several sources of difficulty in making such measurements. First, the hills and embankments have an effect on the road noise, reflecting and redirecting it in ways that make it difficult to make comparisons between sites. Second, measurements at such sites are logistically difficult, requiring the placement of both tripods and experimenters on slopes on which it is difficult to maintain position over the lengths of time required for the measurements. Third, the measurement of linear distance from the roadway is complicated in such conditions, requiring the use of surveying equipment beyond the scope of the study. Finally, measurements at such sites make it almost impossible to achieve equal height of the measuring equipment above the roadway to ensure controlled experimental conditions. It should be noted, however, that sites with hills and embankments are ultimately desirable, both for aesthetic and noise reduction reasons, whether or not there are trees at the sites.

### Final Sites

Despite the fact that the research design had to be modified from that originally proposed, it was still hoped that 16 suitable sites could be identified. However, the final site considered for inclusion was spoiled by the presences of a large deer carcass, which would have made the measurements very unpleasant on the part of the experimenters. The 15 final sites are shown graphically in Figures 1 through 3, and described in Tables 4 and 5. Due to the mountainous topography in the western part of the state, most of the sites were located east of the Blue Ridge Mountains. Each data collection trip lasted two or three days due to the distances away from Blacksburg and the length of data collection at each site.



Figure 1. Overview of the 15 sites selected for inclusion in the study. Note that all but two sites are located east of the Blue Ridge Mountains.

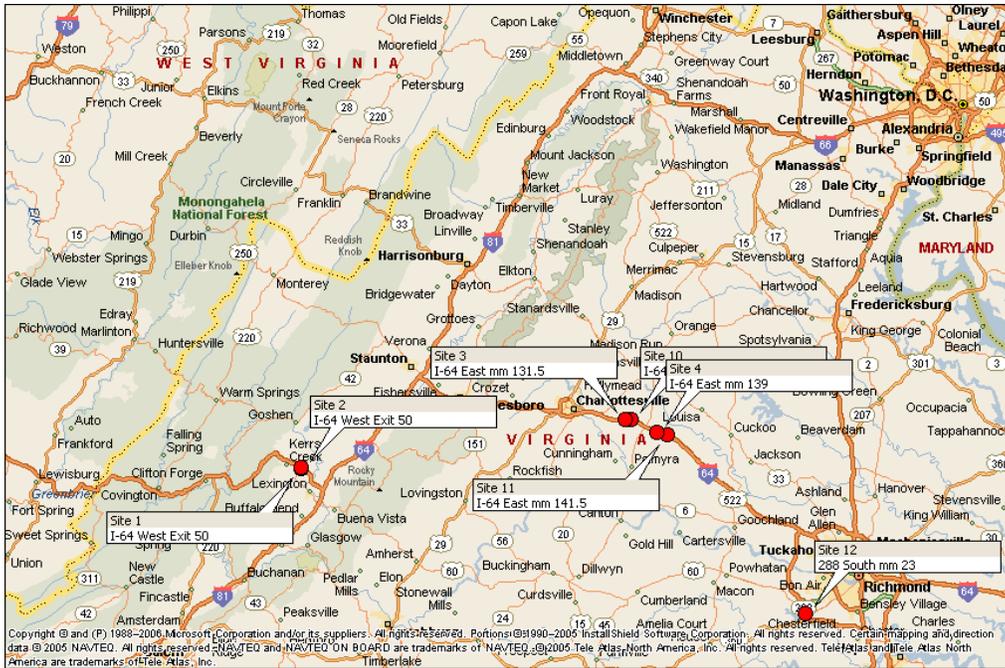


Figure 2. Close view of the seven northernmost sites selected for inclusion in the study.

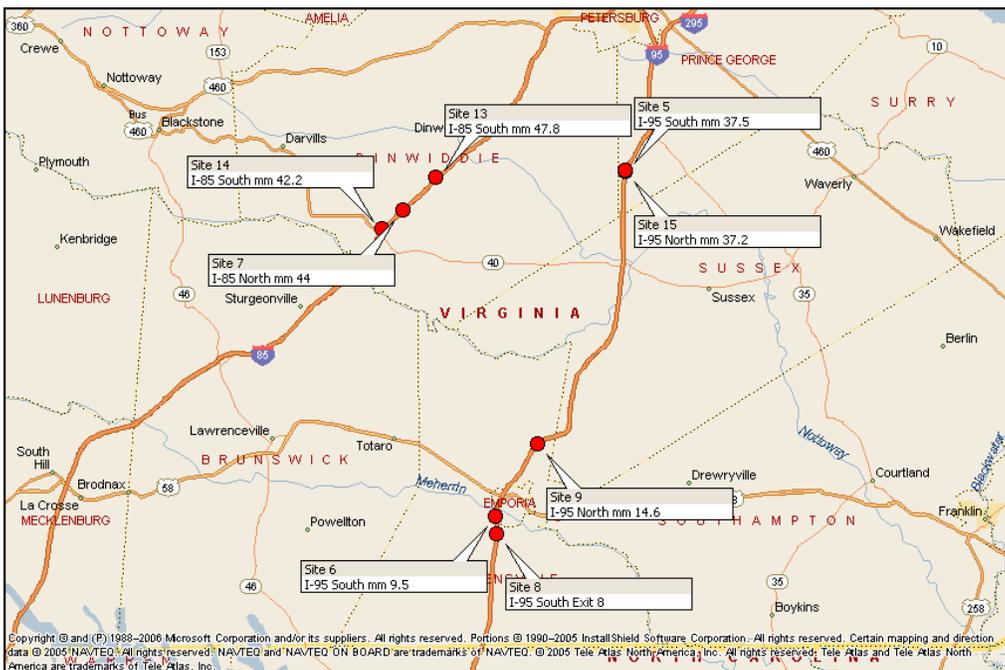


Figure 3. Close view of the eight southernmost sites selected for inclusion in the study.

**Table 4. Road and Traffic Site Characteristics. Eight measurements were taken at each site; the characteristics shown reflect those present during the majority of measurements for each site.**

<b>Site No.</b>	<b>Description</b>	<b>Dist. from Rd., ft</b>	<b>Rd. Surf.</b>	<b>Traffic Density per 15 minutes</b>	<b>Traffic Mix (% heavy veh.)</b>
1	I-64 WB Exit 50 A	73.0	Asphalt	Light (<250)	>20% Trucks
2	I-64 WB Exit 50 B	43.6	Asphalt	Light (<250)	>20% Trucks
3	I-64 EB MM 131.5	43.3	Asphalt	Moderate (251-500)	10-20% Trucks
4	I-64 EB MM 139	32.9	Asphalt	Heavy (501-750)	10-20% Trucks
5	I-95 SB MM 37.5	24.6	Asphalt	Very heavy (>750)	<10% Trucks
6	I-95 SB MM 9.5	37.2	Asphalt	Very heavy (>750)	10-20% Trucks
7	I-85 NB MM 44	35.7	Asphalt	Moderate (251-500)	<10% Trucks
8	I-95 SB Exit 8	37.4	Asphalt	Heavy (501-750)	10-20% Trucks
9	I-95 NB MM 14.6	53.8	Asphalt	Heavy (501-750)	10-20% Trucks
10	I-64 EB MM 132.5	41.3	Asphalt	Moderate (251-500)	10-20% Trucks
11	I-64 EB MM 141.5	45.7	Asphalt	Heavy (501-750)	10-20% Trucks
12	288 SB MM 23	57.0	Concrete	Moderate (251-500)	10-20% Trucks
13	I-85 SB MM 47.8	48.0	Concrete	Moderate (251-500)	>20% Trucks
14	I-85 SB MM 42.2	41.2	Concrete	Moderate (251-500)	10-20% Trucks
15	I-95 NB MM 37.2	39.0	Asphalt	Heavy (501-750)	10-20% Trucks

**Table 5. Tree Site Characteristics.**

Site No.	Description	Species1	Species2	Species3	Avg. Age	Avg. Height, ft	Live Crown Percent	Density, basal area	Density, trees per acres	Avg. DBH, in
1	I-64 WB Exit 50 A	white pine	NA	NA	young, <25	short, <55	heavy, >31%	medium, 180-200	sparse, <750	large, >5.9
2	I-64 WB Exit 50 B	VA pine	juniper	NA	young, <25	short, <55	heavy, >31%	medium, 180-200	medium, 751-1000	medium, 5-5.9
3	I-64 EB MM 131.5	VA pine	juniper	NA	mid, 25-40	short, <55	heavy, >31%	dense, >200	medium, 751-1000	large, >5.9
4	I-64 EB MM 139	white pine	sweet gum	maple	mid, 25-40	tall, >55.1	light, <30%	medium, 180-200	sparse, <750	large, >5.9
5	I-95 SB MM 37.5	loblolly pine	sweet gum	NA	young, <25	short, <55	light, <30%	medium, 180-200	dense, >1001	small, <5
6	I-95 SB MM 9.5	loblolly pine	sweet gum	sassafras	mid, 25-40	tall, >55.1	light, <30%	dense, >200	dense, >1001	medium, 5-5.9
7	I-85 NB MM 44	loblolly pine	sweet gum	maple	mid, 25-40	tall, >55.1	light, <30%	sparse, <180	sparse, <750	medium, 5-5.9
8	I-95 SB Exit 8	loblolly pine	sweet gum	oak	mid, 25-40	tall, >55.1	light, <30%	sparse, <180	medium, 751-1000	medium, 5-5.9
9	I-95 NB MM 14.6	loblolly pine	sweet gum	oak	old, >40	tall, >55.1	heavy, >31%	dense, >200	medium, 751-1000	large, >5.9
10	I-64 EB MM 132.5	white pine	cedar	sweet gum	young, <25	short, <55	heavy, >31%	dense, >200	dense, >1001	small, <5
11	I-64 EB MM 141.5	white pine	sweet gum	maple	old, >40	tall, >55.1	heavy, >31%	dense, >200	sparse, <750	large, >5.9
12	288 SB MM 23	white pine	holly	sweet gum	mid, 25-40	short, <55	light, <30%	medium, 180-200	dense, >1001	medium, 5-5.9
13	I-85 SB MM 47.8	loblolly pine	sweet gum	oak	old, >40	tall, >55.1	light, <30%	sparse, <180	sparse, <750	medium, 5-5.9
14	I-85 SB MM 42.2	loblolly pine	sweet gum	maple	old, >40	short, <55	heavy, >31%	sparse, <180	sparse, <750	small, <5
15	I-95 NB MM 37.2	loblolly pine	juniper	holly	old, >40	tall, >55.1	heavy, >31%	sparse, <180	sparse, <750	small, <5

## Equipment

Noise measurements at the different sites were taken using two Larson-Davis 824 sound level meters like the one shown in Figure 4. The devices and their associated microphones and preamplifiers were factory-calibrated to ISO and ANSI standards in November of 2007 (calibrations are good for one year).



**Figure 4. Larson-Davis 824 Sound Level Meter.**

One of the sound level meters (SLMs), the Primary Device, was always placed at the edge of the band of trees. This device stayed in one location throughout the series of noise measurements at the site. The other meter, the Secondary Device, was always used to take the measurements at various distances within the wooded area. Both devices are shown in Figure 5. Both SLMs were placed on tripods and raised to a height of 59.5 in (1.5 m) above the ground (and thus above the roadbed, since the sites were at grade level with the roadbed). In a handful of cases where there was very minor elevation change within the band of trees, the Secondary Device was adjusted to be level with the height of the Primary Device, which did not vary.



**Figure 5. Primary and Secondary Device setup for a 5 m measurement.**

A windscreen was placed at the end of each microphone to prevent distortion during the measurements as shown in Figure 6.



**Figure 6. Use of windscreen on an SLM.**

Two six foot ladders were used for those sites that required climbing over a fence in order to take measurements with the secondary device. Ladders were only used at a handful of sites, and only when the adjoining property was not posted and the woods were a continuation of the tree band being studied. The placement of ladders required for climbing the fence is shown in Figure 7.



**Figure 7. Ladder setup for climbing VDOT fences.**

Additionally, in order to prevent any noise distortion during the measurements, the van used to travel to the sites and carry the equipment was parked far from the sound level meters as shown in Figure 8.

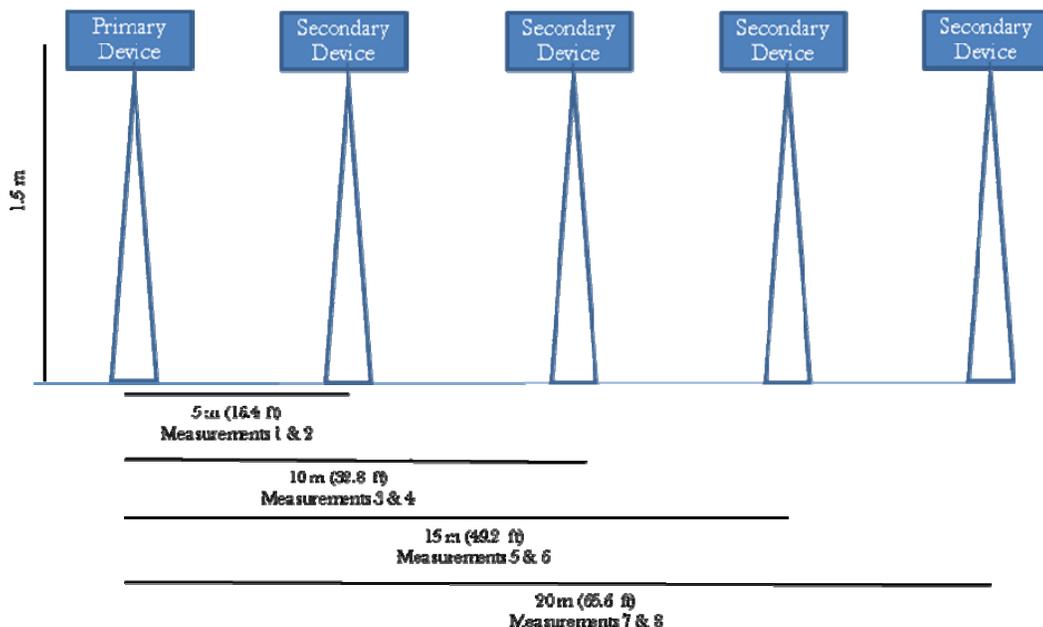


**Figure 8. Van location during measurements.**

### **Measurement Process**

*Noise measurements.* Eight measurements were taken at each site. The Primary and Secondary SLMs were placed at a distance of 5m from one another for the first and second measurements, at 10m apart for the third and fourth measurements, at 15m apart for the fifth and sixth measurements, and at 20m apart for the seventh and eighth measurements. The Primary Device position did not change during the course of measurements at each site; instead, the Secondary Device was moved after every two measurements to the positions shown in Figure 9.

### Sound Level Meters Setup



**Figure 9. Sound Level Meter positions for the eight measurements taken at each site.**

Noise measurements were taken in sets of two at every distance. The duration of each measurement was fifteen minutes. Both meters were started at the same time; this was accomplished by counting to three out loud, and then silently continuing the count up to five. When reaching five, the start buttons on each meter were pressed nearly simultaneously.

Sound level meters were calibrated after every battery change, which usually occurred after completing a site. The calibrator used was the Larson Davis CAL200 model Serial 1080. The calibrator itself was factory calibrated in November of 2007. It was set to 94 dB and every calibration measurement for both sound level meters was recorded. The distance from the outermost traffic lane edge marking to the Primary Device was measured and recorded at each site. Both the noise measurements and calibration values were recorded on the form shown in Figure 10.

*Noise Study*  
Noise Measurements

TIME: \_\_\_\_\_ DATE: \_\_\_\_\_  
SITE: \_\_\_\_\_ LOCATION: \_\_\_\_\_

CALIBRATION VALUES		MEASUREMENT NUMBER	MEASURING DEVICE LOCATION	MEASUREMENT TIME		Leq
Instrument	Value			START	END	
1		1	edge of wooded area			
2			5m (16.4') into wooded area			
		2	edge of wooded area			
			5m (16.4') into wooded area			
		3	edge of wooded area			
			10m (32.8') into wooded area			
		4	edge of wooded area			
			10m (32.8') into wooded area			
		5	edge of wooded area			
			15m (49.2') into wooded area			
		6	edge of wooded area			
			15m (49.2') into wooded area			
		7	edge of wooded area			
			20m (65.6') into wooded area			
		8	edge of wooded area			
			20m (65.6') into wooded area			

*Noise Study*

*Noise Measurements Data Collection Sheet*

**Figure 10. Noise measurement data collection sheet.**

*Traffic measurements.* One experimenter monitored and controlled the Primary Device, and also performed traffic counts. Traffic volume was recorded during the 15-minute period while the SLMs were running. Each vehicle was classified as light or heavy. Light vehicles were passenger vehicles, SUVs, and light trucks; heavy vehicles were multi-axle vehicles, including light trucks or SUVs hauling large trailers. In cases in which the traffic count experimenter was unsure whether the vehicle was heavy or light, the engine noise was used as a guide, since that was the focus of the study. For most sites, traffic was counted in one direction and then for use during the study’s analysis was multiplied by two to account for traffic moving in the opposite direction. Traffic was only counted in one direction for several reasons. In most cases, the high vehicle density did not allow for counting in both directions; in other cases, the travel lanes in the other direction were not visible due to blockage from trees or a low embankment. The percentage of heavy vehicle traffic was calculated for data analysis. Figure 11 shows the form used for traffic counts.

*Noise Study  
Traffic Count*

TRIP: \_\_\_\_\_ SITE: \_\_\_\_\_  
 DATE: \_\_\_\_\_

MEASUREMENT NUMBER	TRAFFIC COUNT	
	LIGHT	HEAVY
1		
2		
3		
4		
5		
6		
7		
8		

Noise Study

Traffic Count Data Collection Sheet

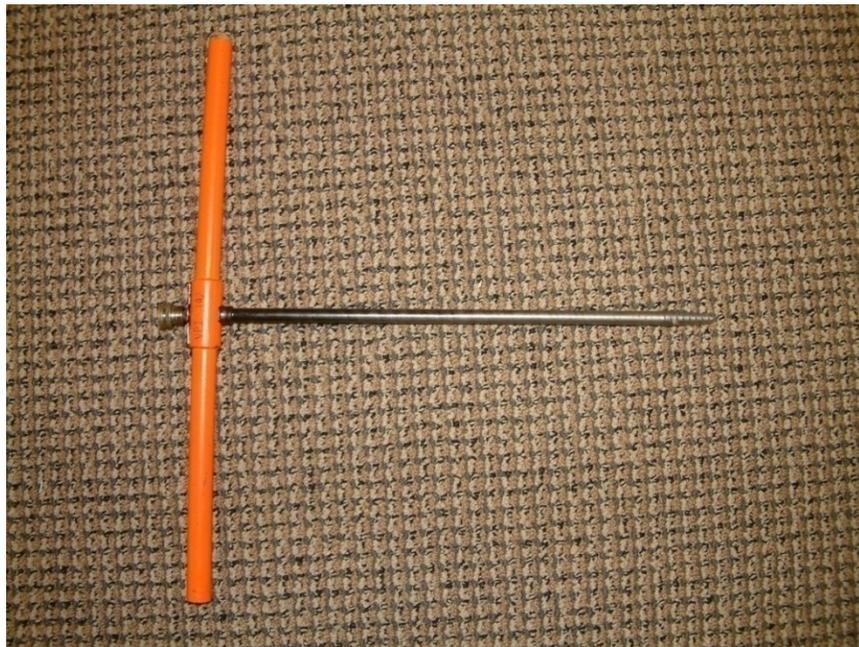
**Figure 11. Traffic count data collection sheet.**

There were two resultant summary measures of traffic:

- *Traffic density* reflects the number of vehicles counted per 15 minutes (vehicles per quarter hour or VPQH). Four categories of traffic density were developed: Light (<250 VPQH), Moderate (250-500 VPQH), Heavy (501-750 VPQH), and Very Heavy (>750 VPQH).
- *Traffic mix* reflects the percentage of traffic that consists of heavy vehicles. Three categories were used: Light Truck Traffic (<10% heavy vehicles), Moderate Truck Traffic (10-20% heavy vehicles), and Substantial Truck Traffic (>20% heavy vehicles).

*Tree measurements.* There were two researchers involved in the live road data collection effort. While the first experimenter monitored the Primary Device and performed traffic counts, the second experimenter monitored and controlled the Secondary Device and performed several measurements of the trees. A research associate from the Virginia Tech Forestry Department accompanied the research team on one trip and trained the second experimenter in the methods to be used. A variety of tree measurements was obtained during the eight 15-minute intervals when the SLMs were collecting noise data. Tree measurements included:

- Identification of the dominant and co-dominant tree *species* (those that dominate or share dominance of the tree canopy). Tree that were not dominant, but were found frequently in the understory, were also noted. Up to three species were listed for each site.
- Measurement of the *age* of three trees that were dominant or co-dominant (these were typically three of the oldest trees located at the site). Age was typically measured with an increment borer, shown in Figure 12. The tree rings on the resultant cores (Figure 13) were then counted to provide the age. The borer was used at approximately breast height. In a few cases, the age of Virginia pine could be accurately estimated by counting the tree whorls (the rings of branches up the trunk, each of which signifies one year of growth). Based on final results, tree age was categorized into three categories: Young (<25 years old), Mid (25-40 years old), and Old (>40 years old).



**Figure 12. Increment borer for growth ring counting.**



**Figure 13. Examples of cores taken from measurement sites.**

- Measurement of the *heights* of three trees that were dominant or co-dominant. These were sometimes the same trees used for the age measurements. Height was measured in feet, using the clinometer shown in Figure 14. Use of the clinometers required that the experimenter be either 50 or 66 ft away from the tree being measured, with a clear line of sight to the tree. A viewing port (not visible in the picture) was used to line up and measure first the bottom of the tree, then the top of the live growth. Height was categorized into two levels, Short (<55 ft) and Tall (>55.1 ft tall).



**Figure 14. Clinometer used to measure the height of the trees.**

- Measurement of the *height of live crown* of same three trees used for the height measurements. Most of the trees measured in the study did not have branches extending to the ground, especially those trees in the interior of the stands. The clinometer was also used for this measurement. The height of the bottom of the live growth was measured and subtracted from the height of the tree to provide the height of the area with live foliage. This was later converted to a percentage of live crown as compared to height for use in analysis. For example, a tree that was 60 ft tall with a live crown of 20 ft would have 33.3% live crown. Height of live crown was categorized into two levels based on percentage of live crown: Light (<30% live crown) and Heavy (>31% live crown).
- *Basal area* is a measure of forest density. It was measured in two ways for the current project. The first measurement was made with a prism, shown in Figure 15. The prism used was a basal area factor 10 (BAF 10) prism. To use the prism, one stands in the center of the area of woods to be measured (typically at the same point used for the 10 m measurement for the current study) and holds the prism at arm's length. Tree trunks that are overlapping within the view of the prism are considered to be "in," and they are counted. Those whose trunks do not overlap within the prism are "out" and are not counted. Those that are borderline are counted every other time. The experimenter turns in a circle at this central location and counts all of the trees that are in, and half of those that are borderline. The resulting number is multiplied by 10 to produce a basal area estimate of density.



**Figure 15. The BAF 10 prism used to measure basal area of each plot (a measure of tree density).**

- The second method of measuring *basal area* (BA) was to measure the diameter of all trees within a 50<sup>th</sup> acre plot centered on the center of the tree stand. Only trees with a diameter of >1.5 in were measured. The diameter of each tree within this plot was measured at breast height, and the resultant measurement is referred to as diameter at

breast height (DBH). These measurements were converted into a cross sectional area measurement known as basal area. Because the two measurement techniques are different, the basal area measured using this method tended to differ slightly from the basal area measured using the prism. The values resulting from the two methods were averaged, and the resultant BA was categorized into three categories: Sparse (BA <180), Medium (BA of 180-200), and Dense (BA >200).

- A second overall measure of density was developed using *trees per acre* (TPA). As mentioned earlier, each tree within a 50<sup>th</sup> acre plot with a diameter of greater than 1.5 in was measured. The overall number of trees within the 50<sup>th</sup> acre plot was multiplied by 50 to obtain the estimated number of trees per acre. TPA was categorized also categorized into three categories of density: Sparse (TPA <750), Medium (TPA of 750-1000), and Dense (TPA >1000).
- The final tree measurement was of average *diameter at breast height* (DBH) in the 50<sup>th</sup> acre plot. The three categories used for this measurement were Small (avg. DBH < 5 in, Medium (avg. DBH of 5.1-5.9 in), and Large (DBH >5.9 in).

*Other notes.* Each site required approximately 2.5 hours of time (15 min/measurement times eight measurements, plus time to set up, move equipment, and remove and pack equipment when data collection was complete). There was thus a total of about 40 hours of data collection, not including driving time to and from the sites and the initial scouting trips. The team encountered two deer carcasses and experienced five deer tick bites. One state trooper stopped to see what was being done by the experimenters. Because the measurements were taken in winter and early spring before the deciduous trees leafed out, temperatures tended to be on the cool or cold side (<40° F for a couple of sites). Data could not be collected on rainy or extremely windy days (the equipment was not waterproof, and the tripods would blow over on extremely windy days). Three planned days of data collection were lost due to rainy, icy, or windy weather.

## **Results**

### **Descriptive Statistics**

*Noise measurements.* The 15-minute measurements were taken using the Leq dBA Slow setting of the SLM. This provides an equivalent, or average, measure of the sound level over the 15 minutes of the measurement. The dBA scale weights sound levels at different frequencies in a manner which approximates the frequency response of the human ear. The A-weighting tends to under-represent the levels of low frequency sounds, which make up much of the energy encountered in truck-cab noise. However, these low frequency components are generally thought to be less harmful to the human ear in terms of hearing loss than are the high frequency components (Hessel, Heck, and McJilton, 1982). Furthermore, the ear is less sensitive to low frequency sounds than midrange (about 1000-4000 Hz) or high frequency (above about 4000 Hz) sounds. The dBA weighting is also commonly used in measures of community noise. The measurements were corrected for the minor calibration differences between the two SLMs. The SLMs also provided measurements of 1/3 octave bands and 1/1 octave bands (these both provide information regarding frequency of the noise). Table 6 provides information regarding measurements taken at the primary SLM, which thus characterizes the existing road noise, since this instrument was positioned in front of the stand of trees. This table presents the 20 m

equivalent noise levels for the various levels of Traffic Density and Traffic mix. The measurements are equalized to the equivalent measurements if all had been taken at 20 m from the roadway (65.6 ft). As can be seen, the averages readings vary somewhat, but are closely clustered around the overall average of 70.5 dBA.

**Table 6. Average 20 m equivalent noise measurements (Leq) for Primary Device under various traffic density and traffic mix conditions.**

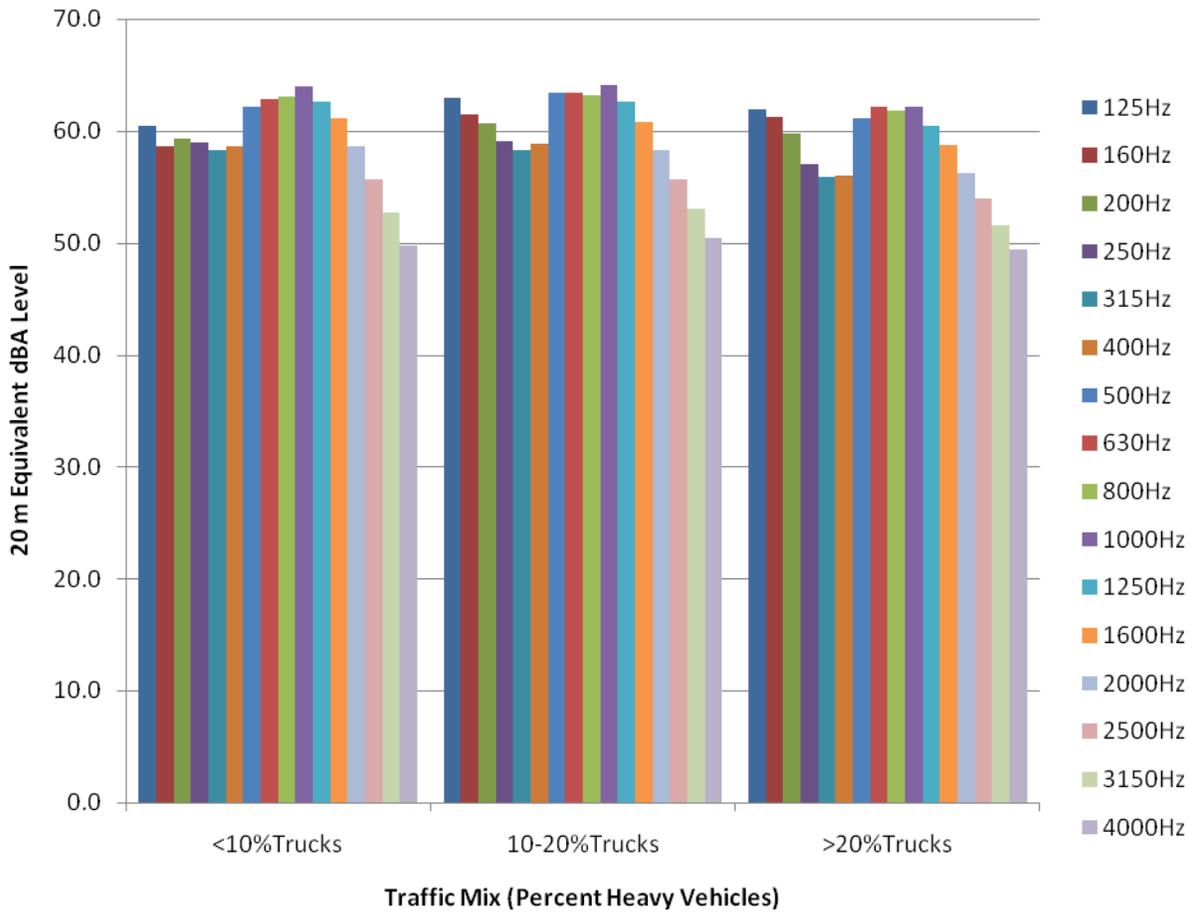
Traffic Density (VPQH)	Traffic Mix			Average
	Light Truck Traffic <10% Trucks	Moderate Truck Traffic 10-20% Trucks	Substantial Truck Traffic >20% Trucks	
Light (<250)			68.8 dBA	<b>68.8 dBA</b>
Moderate (251-500)	73.4 dBA	69.7 dBA	70.7 dBA	<b>71.4 dBA</b>
Heavy (501-750)	69.9 dBA	68.5 dBA		<b>69.3 dBA</b>
Very heavy (>750)	71.6 dBA	72.4 dBA		<b>72.0 dBA</b>
<b>Average</b>	<b>71.8 dBA</b>	<b>70.7 dBA</b>	<b>68.9 dBA</b>	<b>70.5 dBA</b>

Table 7 presents the 1/3 octave band measurements from 125 Hz to 4000 Hz for various levels of traffic mix. These measurements are also corrected for distance (20 m equivalent) as in Table 6. Figure 16 presents the same information in graphic form. Heavy vehicle (truck) noise is generally greater at low frequencies (below 500 Hz), while light vehicle (car) noise tends to be greater in the 500 to 1000 Hz range (Lee, 1998). It can be seen that the lower frequencies have higher values in the two categories with a higher percentage of truck traffic, while all three categories are above 60 dBA in the 125 to 500 Hz range, dropping off rapidly at the higher frequencies above 500 Hz. This represents the noise from the light vehicles, since all sites except for one had at least 70% light vehicles.

**Table 7. Average 20 m equivalent 1/3 octave noise measurements for Primary Device under various levels of traffic mix.**

Traffic Mix	Light Truck Traffic <10% Trucks	Moderate Truck Traffic 10-20% Trucks	Substantial Truck Traffic >20% Trucks	Average
<b>1/3 Octave Band Freq.</b>				
125Hz	60.5	62.9	61.9	62.2
160Hz	58.6	61.4	61.2	60.9
200Hz	59.2	60.6	59.8	60.2
250Hz	59.0	59.1	57.1	58.6
315Hz	58.3	58.3	55.9	57.8
400Hz	58.6	58.8	56.0	58.2
500Hz	62.1	63.4	61.1	62.6
630Hz	62.8	63.4	62.1	63.0

800Hz	63.1	63.1	61.8	62.8
1000Hz	64.0	64.1	62.1	63.7
1250Hz	62.6	62.6	60.4	62.2
1600Hz	61.1	60.8	58.7	60.4
2000Hz	58.6	58.3	56.3	57.9
2500Hz	55.7	55.7	53.9	55.3
3150Hz	52.7	53.0	51.6	52.7
4000Hz	49.8	50.4	49.4	50.1

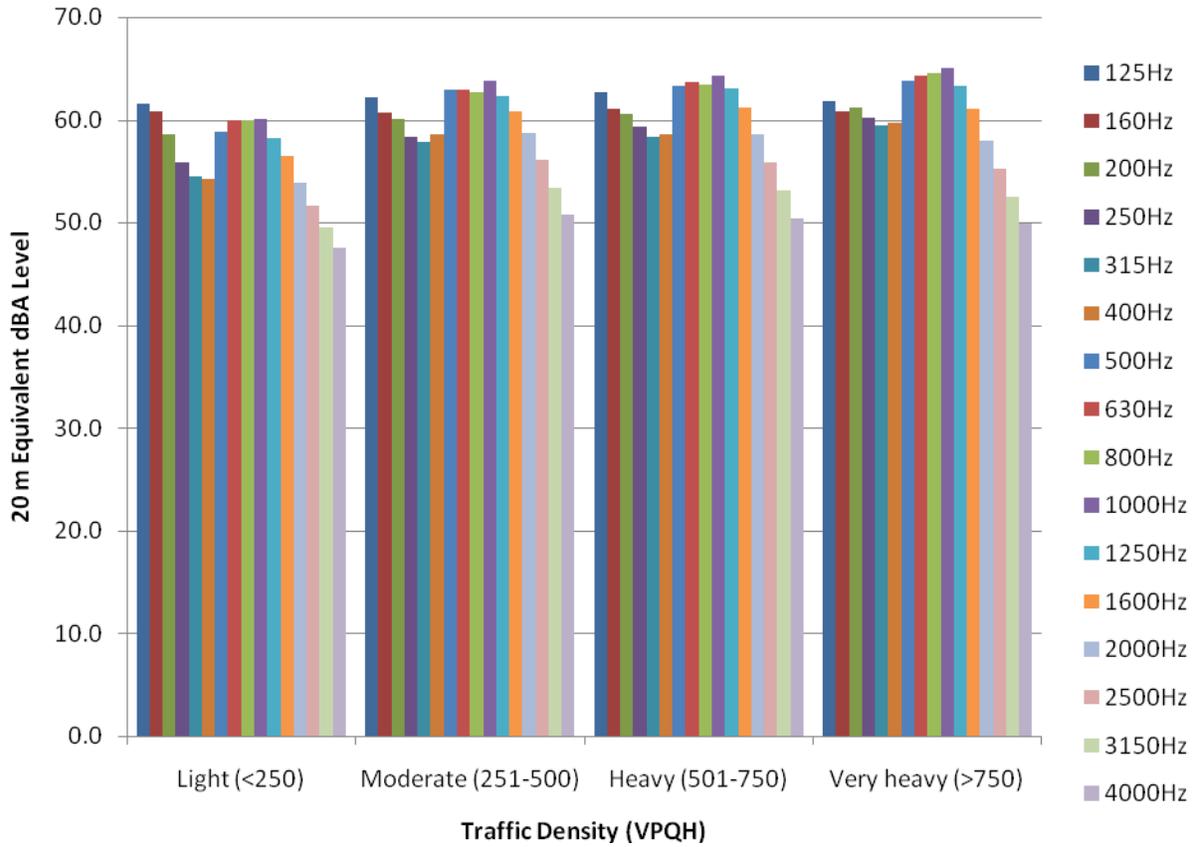


**Figure 16. 1/3 octave band measurements from 125-4000 Hz for three levels of traffic mix.**

Table 8 presents the 1/3 octave band information for the four categories of traffic density. Figure 17 presents the information graphically. It can be seen that with light traffic (<250 VPQH), there is a decline in noise level in the 125 to 400 Hz range, and then higher values from 500 to 1000 Hz, before another and more severe decline above 1000 Hz. At higher levels of traffic density, the first decline lessens, so that by the time traffic becomes very heavy, the noise level is greater than 58 dBA from 125-1600 Hz.

**Table 8. Average 20 m equivalent 1/3 octave noise measurements for Primary Device under various levels of traffic density.**

<b>Traffic Density(VPQH)</b>	<b>Light (&lt;250)</b>	<b>Moderate (251-500)</b>	<b>Heavy (501-750)</b>	<b>Very heavy (&gt;750)</b>	
<b>1/3 Octave Band Freq.</b>					<b>Average</b>
125Hz	61.5	62.2	62.7	61.8	62.2
160Hz	60.8	60.7	61.1	60.8	60.9
200Hz	58.6	60.0	60.6	61.2	60.2
250Hz	55.8	58.3	59.3	60.3	58.6
315Hz	54.5	57.8	58.3	59.5	57.8
400Hz	54.2	58.6	58.6	59.7	58.2
500Hz	58.8	63.0	63.3	63.8	62.6
630Hz	60.0	62.9	63.7	64.3	63.0
800Hz	59.9	62.6	63.4	64.6	62.8
1000Hz	60.0	63.8	64.3	65.0	63.7
1250Hz	58.2	62.3	63.0	63.4	62.2
1600Hz	56.5	60.8	61.2	61.1	60.4
2000Hz	53.9	58.7	58.6	58.0	57.9
2500Hz	51.7	56.2	55.9	55.2	55.3
3150Hz	49.5	53.4	53.1	52.5	52.7
4000Hz	47.5	50.8	50.3	49.9	50.1



**Figure 17. 1/3 octave band measurements from 125-4000 Hz for four levels of traffic density.**

*Traffic Measurements.* As previously described, the experimenter in charge of the Primary device conducted traffic counts during the 15 minutes that the SLM was running for each measurement. With 15 sites and 8 measurements per site, there were 120 of these 15-minute traffic counts (30 hours of traffic counts). In sites with poor visibility or extremely heavy traffic, only one side of the traffic was counted and the result was multiplied by two to get the total traffic count. Traffic appeared to be fairly equal in both directions at all sites. Traffic was free-flowing at all sites for all measurements. No accidents occurred, nor were there any sirens of more than two or three seconds during the measurements. All measurements were taken on weekdays, between the hours of 8:00 am and 5:30 pm. Altogether, 55,943 light vehicles were counted, and 8,565 heavy vehicles, for a total of 64,508 vehicles. Table 9 presents the summary information for each site.

**Table 9. Average traffic counts for each site (each table entry is an average of eight 15-minute measurements).**

<b>Site No.</b>	<b>Description</b>	<b>Light Vehicles Avg. / 15 min</b>	<b>Heavy Vehicles Avg. / 15 min</b>	<b>Tot. Vehicles Avg. / 15 min</b>	<b>Percent Heavy Vehicles</b>
1	I-64 WB Exit 50 A	67	33	100	33%
2	I-64 WB Exit 50 B	84	36	120	30%
3	I-64 EB MM 131.5	378	70	448	16%
4	I-64 EB MM 139	621	68	689	10%
5	I-95 SB MM 37.5	824	87	911	10%
6	I-95 SB MM 9.5	938	112	1,050	11%
7	I-85 NB MM 44	462	32	494	7%
8	I-95 SB Exit 8	527	114	641	18%
9	I-95 NB MM 14.6	567	82	649	13%
10	I-64 EB MM 132.5	405	77	482	16%
11	I-64 EB MM 141.5	532	62	595	11%
12	288 SB MM 23	359	57	416	14%
13	I-85 SB MM 47.8	314	92	406	23%
14	I-85 SB MM 42.2	338	79	416	19%
15	I-95 NB MM 37.2	578	71	649	11%
<b>Total Vehicles</b>		<b>55,943</b>	<b>8,565</b>	<b>64,508</b>	<b>16%</b>

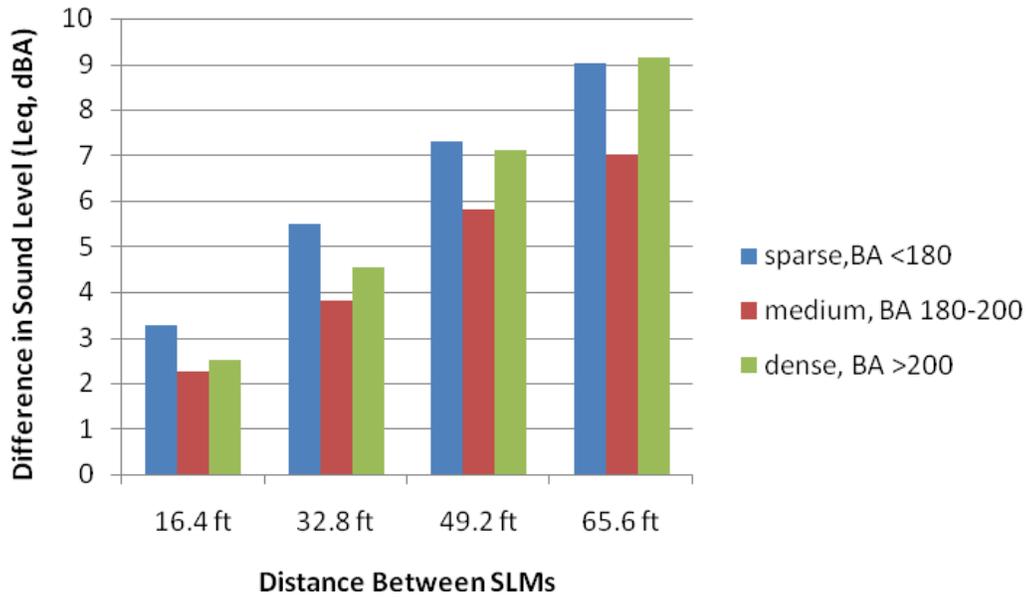
*Tree Measurements.* The average age of the trees studied was 36.5 years; these were trees that were dominant or co-dominant at each site. Age was measured on three trees per site, so 45 trees were measured in all. The average height of the dominant and co-dominant tree was 58.8 ft, with an average of 34% of the height being represented as live crown (recall that the lower branches of these trees almost always shed, especially for interior trees). Height and live crown were also measured for three dominant or co-dominant trees per site. Density as measured by average basal area (averaged from two different methods of calculating basal area) was 179.9. Average density as measured in trees per acre (TPA) was 907. The average diameter at breast height for all trees was 5.8 inches (this represents an average of all trees within the 50<sup>th</sup> acre plot). The tree characteristics of all sites are provided in Table 10.

**Table 10. Average characteristics of the trees located at each site.**

Site No.	Description	Avg. Age (yr)	Avg. Height (ft)	Avg. Live Crown Pct.	Avg. Basal Area	Avg. TPA	Avg. DBH (in)
1	I-64 WB Exit 50 A	21.0	47.8	38%	195.2	350	10.8
2	I-64 WB Exit 50 B	21.3	46.2	41%	195.6	1,000	5.5
3	I-64 EB MM 131.5	29.0	53.1	49%	201.1	950	6.4
4	I-64 EB MM 139	29.0	70.5	25%	197.7	700	6.1
5	I-95 SB MM 37.5	21.0	53.6	29%	186.6	1,750	4.3
6	I-95 SB MM 9.5	39.0	69.1	22%	237.9	1,150	5.2
7	I-85 NB MM 44	35.0	64.0	20%	124.5	600	5.0
8	I-95 SB Exit 8	39.7	66.3	20%	179.4	950	5.4
9	I-95 NB MM 14.6	62.3	81.7	40%	203.1	850	6.0
10	I-64 EB MM 132.5	24.7	40.8	54%	201.1	1,900	4.2
11	I-64 EB MM 141.5	41.0	64.3	35%	221.2	450	9.2
12	288 SB MM 23	31.3	52.3	28%	193.0	1,100	5.2
13	I-85 SB MM 47.8	60.3	59.2	29%	117.0	450	5.8
14	I-85 SB MM 42.2	42.3	54.3	39%	124.2	700	3.8
15	I-95 NB MM 37.2	50.0	59.0	47%	121.6	700	4.2
<b>Grand Average</b>		<b>36.5</b>	<b>58.8</b>	<b>34%</b>	<b>179.9</b>	<b>907</b>	<b>5.8</b>

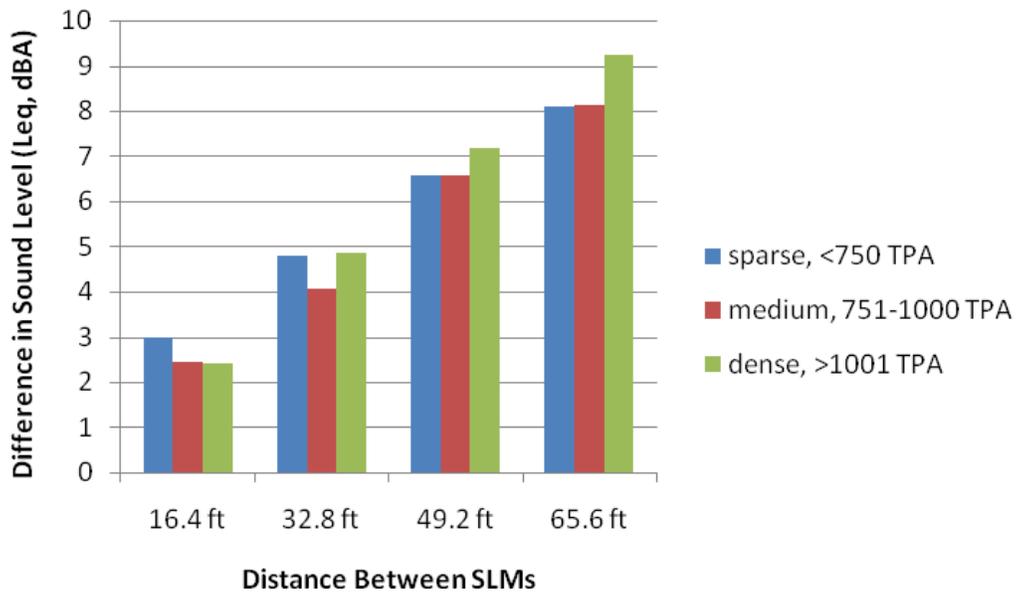
### **Effect of Tree Density on Attenuation of Road Noise**

The next set of analyses were conducted to determine whether there was any effect on road noise due to the characteristics of the trees being studied. For the results reported in this and following sections, the Leq dBA reading from the Secondary Device was subtracted from the Leq dBA reading of the Primary Device that was taken at the same time. The Leq readings from both SLMs were corrected for minor calibration differences prior to this calculation. The resultant difference is known as *attenuation* (the reduction in sound pressure level in decibels as one moves further and further from the noise source; Ostergaard, 1986, p. 27). Figure 18 presents the attenuation at three levels of tree density (as determined by basal area) for the four distances into the stands of trees. Note that there appears to be no effect of density on the average Leq, although there is an effect of distance. In this and subsequent graphs, a positive value on the Y-axis represents increasing attenuation, or a greater degree of noise reduction.



**Figure 18. Difference in sound level by tree density (with density categorized as average basal area).**

Figure 19 present the same information, but with density dependent on the TPA measurement rather than on basal area. In this graph, there does appear to be some effect of density for the densest stands at the two furthest distances.



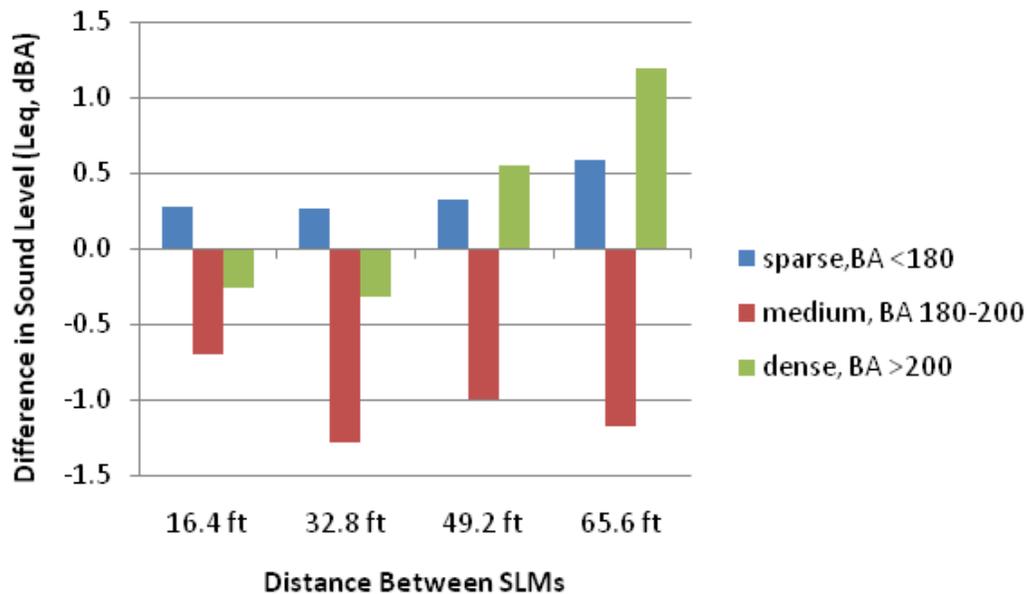
**Figure 19. Difference in sound level by tree density (with density categorized as trees per acre).**

The information presented in Figures 18 and 19 shows a clear decline in sound level with increasing distance. This decline over distance occurs in a predictable fashion for all noise. The

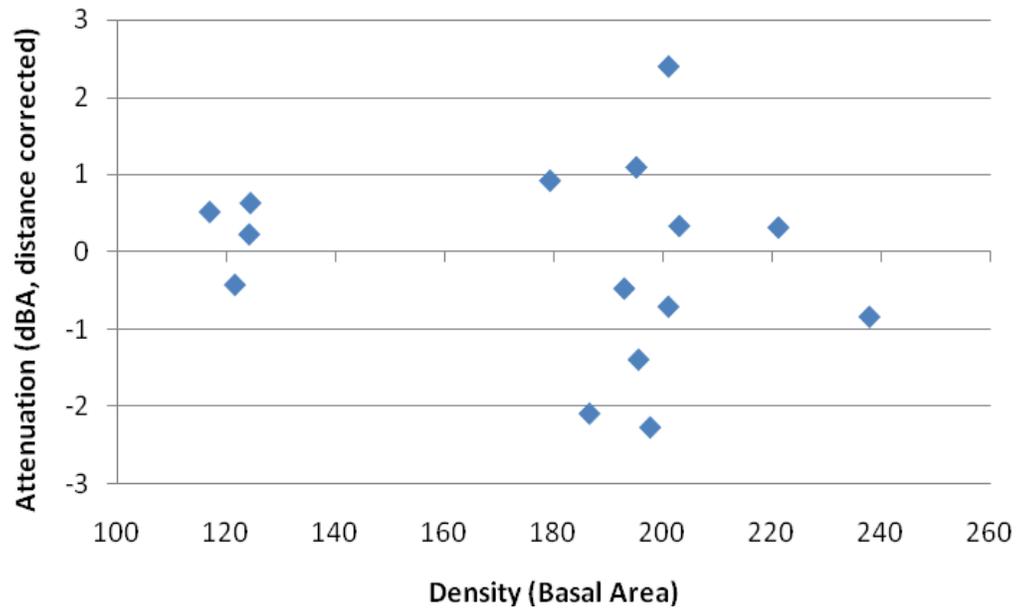
predicted drop in sound level as a function of distance was calculated for each measurement to account for this effect. In other words, was the observed attenuation any different than what would be expected due to distance alone? The predicted value for the noise at the distance from the road where it was measured was calculated using the following formula:

$$Leq_1 - Leq_2 = 20 \log_{10} \frac{D_1}{D_2}$$

where  $D_1$  is the distance from the Primary Device to the lane edge,  $D_2$  is the distance from the Secondary Device to the lane edge, and  $Leq_1$  and  $Leq_2$  are the sound level readings from the Primary and Secondary Devices, respectively. As can be seen in Figure 20, in all cases, the observed value differed from the predicted value only  $\pm 1.2$  dBA, with no obvious systematic pattern. Values less than zero reflect attenuation that is less than would be predicted by distance alone, and those above zero reflect attenuation that is greater than would be predicted by distance alone. Due to the small variability observed with this corrected attenuation, it is likely that all of the differences observed in the previous two graphs were due to distance alone, and not to the tree density. As a result, all future discussions use only this distance corrected  $Leq$  attenuation value. In order to examine this issue another way, the individual  $Leq$  attenuations (corrected for distance) were plotted against the density (BA method) readings to show whether there was any systematic variation that was obscured by separating tree density into only three categories. The result, shown in Figure 21, shows no clear relationship between basal area and attenuation.



**Figure 20. Difference in sound level by tree density, adjusted for expected attenuation due to the distance between the sound level meters (with density categorized as basal area).**



**Figure 21. Plot of density (basal area) by attenuation (distance corrected).**

### Effect of Tree Age on Attenuation of Road Noise

Figure 22 shows that there was virtually no effect of tree age on the attenuation of road noise. Recall that the tree age was only measured for three of the dominant or co-dominant (usually older and larger) trees at each site.

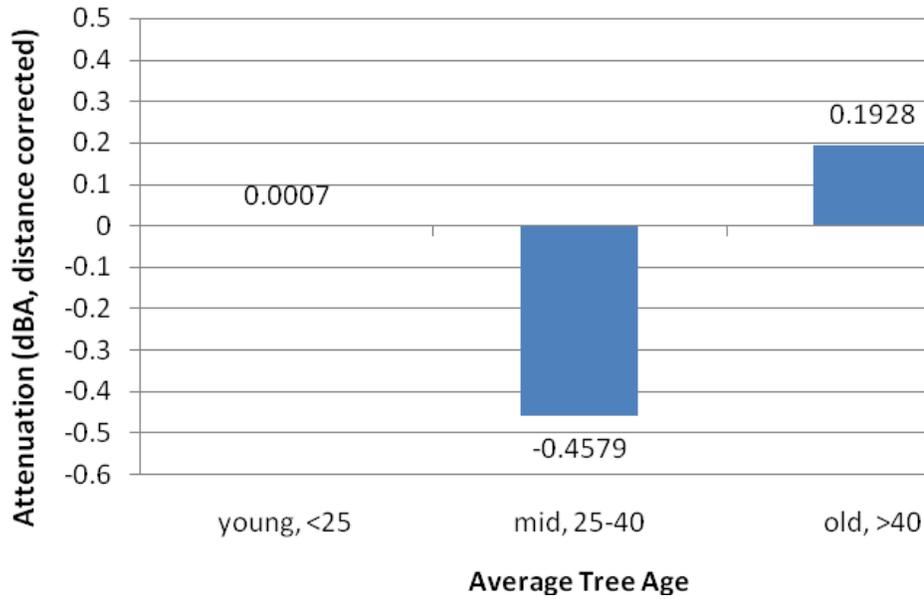
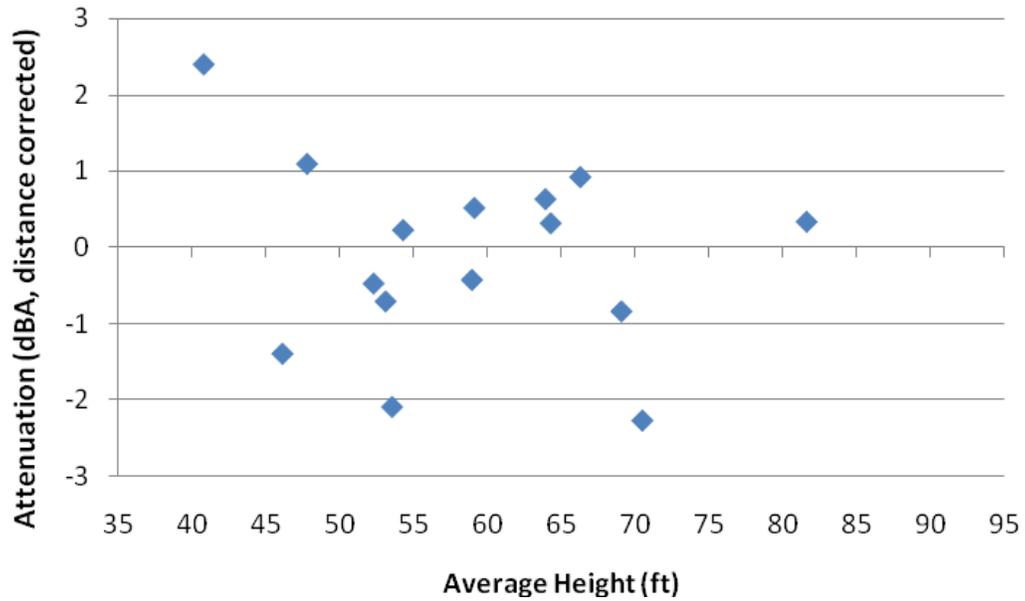


Figure 22. Effect of average tree age on attenuation (distance corrected).

### Effect of Tree Height on Attenuation of Road Noise

Since height was only categorized into two categories, the actual average values for height were plotted against the attenuation, as shown in Figure 23. There is no observable effect of tree height on the attenuation of road noise. As with age, tree height was only measured for three trees within the site.



**Figure 23. Plot of average tree height by attenuation (distance corrected).**

### Effect of Live Crown Percent on Attenuation of Road Noise

The percent of the dominant and co-dominant tree height that consisted of live crown was also plotted against the distance corrected attenuation, as shown in Figure 24. This measure was taken on only three trees per site, and was then categorized into only two levels, so the scatter plot seemed to be more informative than a bar graph. There is no obvious effect of percent of live crown on attenuation of road noise.

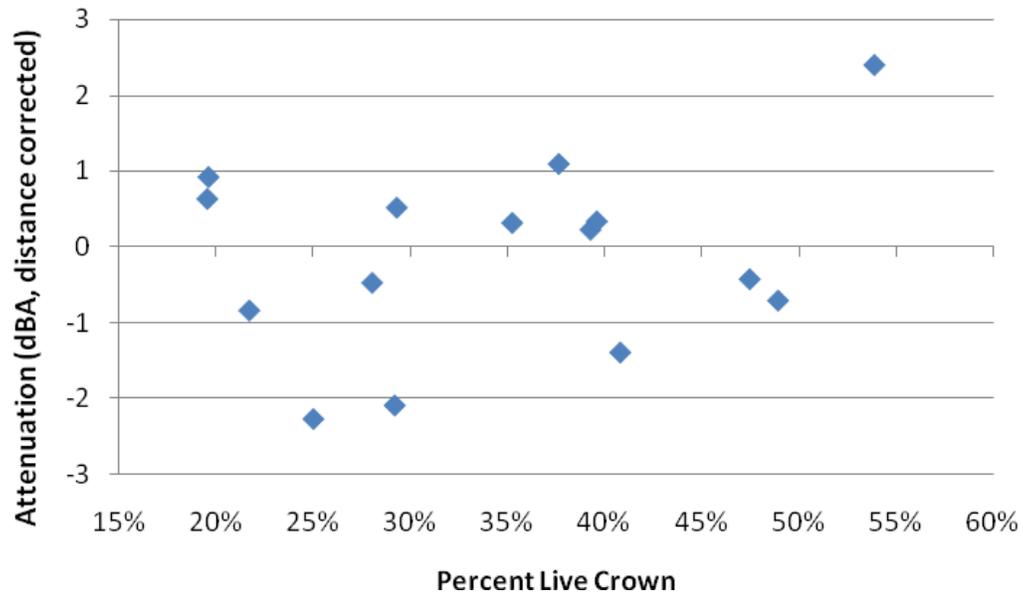
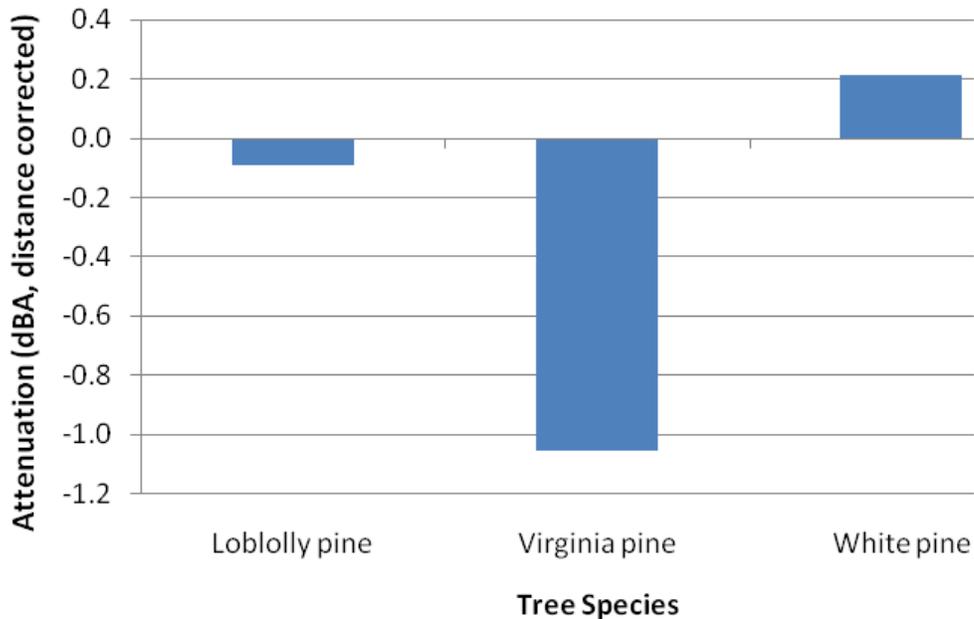


Figure 24. Plot of average live crown percent by attenuation (distance corrected).

### Effect of Species on Attenuation of Road Noise

As shown in Figure 25, there was no discernible effect of tree species on distance corrected road noise attenuation. Note that there were only three dominant or co-dominant species in the sites, and all were some variation of pine. It should be noted that at some sites, the trees appeared to have been deliberately planted at the time of road construction (based on the age of the trees, the uniform size/age of trees within the site, and evidence of regular spacing and rows). In other sites, the trees appeared to have self-propagated after the road was constructed (younger trees and non-uniform age/height/spacing). Finally, in some sites it appeared that existing trees were allowed to remain during and after road construction, based on the age of the trees, their irregular spacing, and the irregular spacing of younger trees within the stand.



**Figure 25. Effect of tree species on attenuation (distance corrected).**

### Effect of DBH on Attenuation of Road Noise

The DBH measurement provides a measure of the size of all the trees within the 50<sup>th</sup> acre plot (all trees with a diameter of at least 1.5 in). As shown in Figure 26, there appeared to be a small effect of DBH on noise attenuation, although the effect appears to be small and not in the expected direction. To further investigate this possible effect, attenuation was plotted against DBH in a scatter plot as shown in Figure 27. When viewed this way, the seeming effect disappears.

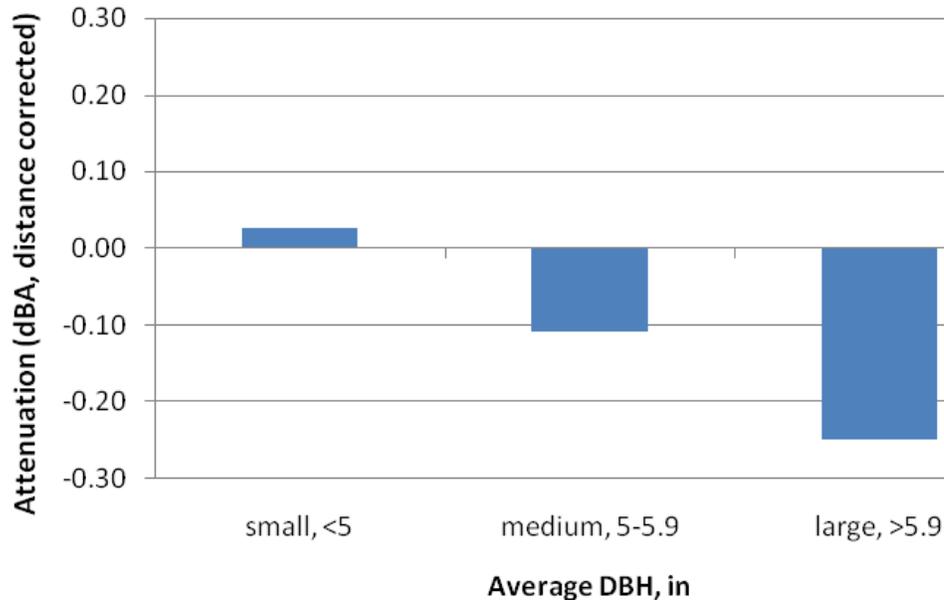


Figure 26. Effect of DBH on attenuation (distance corrected).

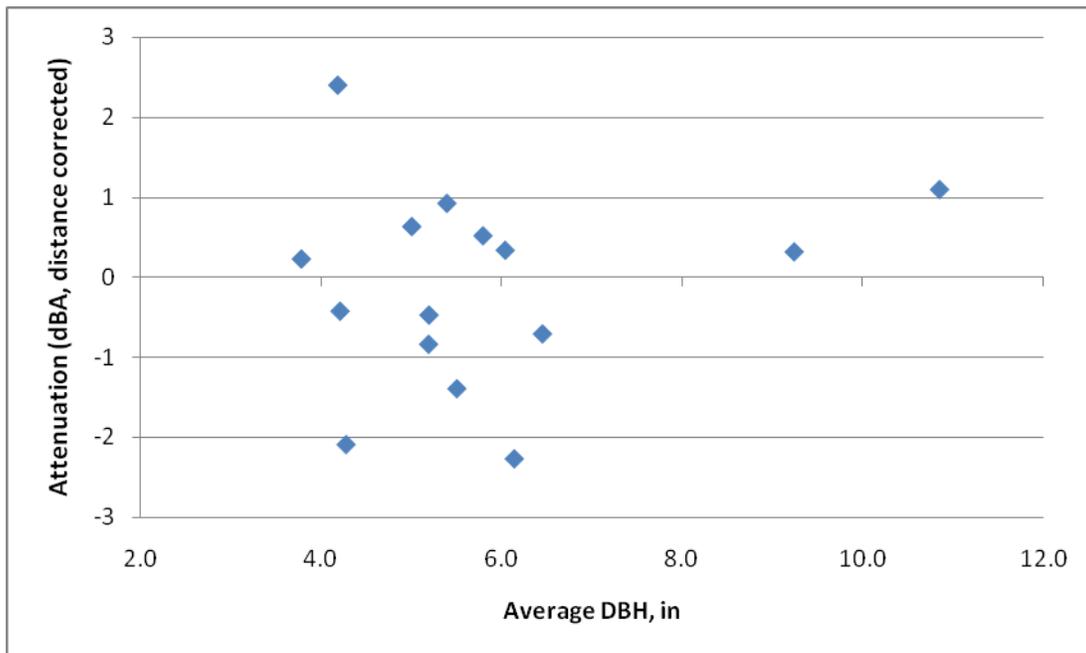
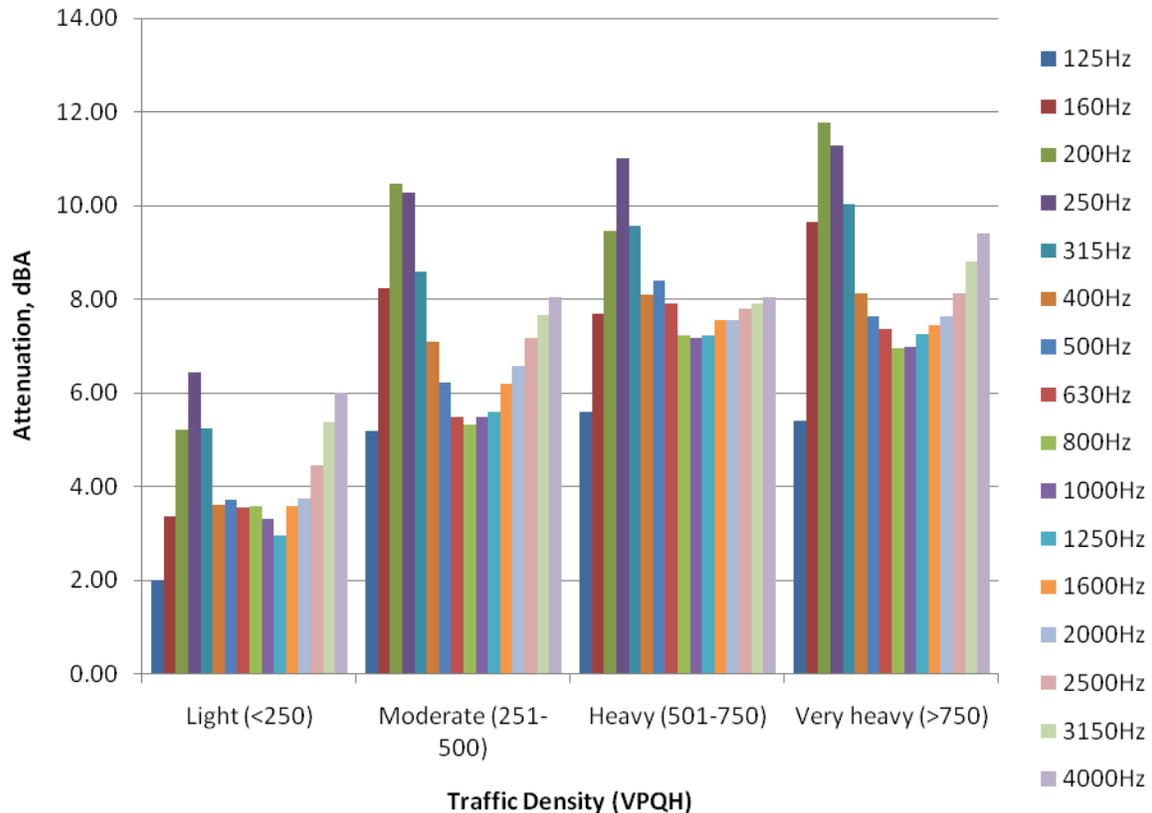


Figure 27. Plot of average DBH by attenuation (distance corrected).

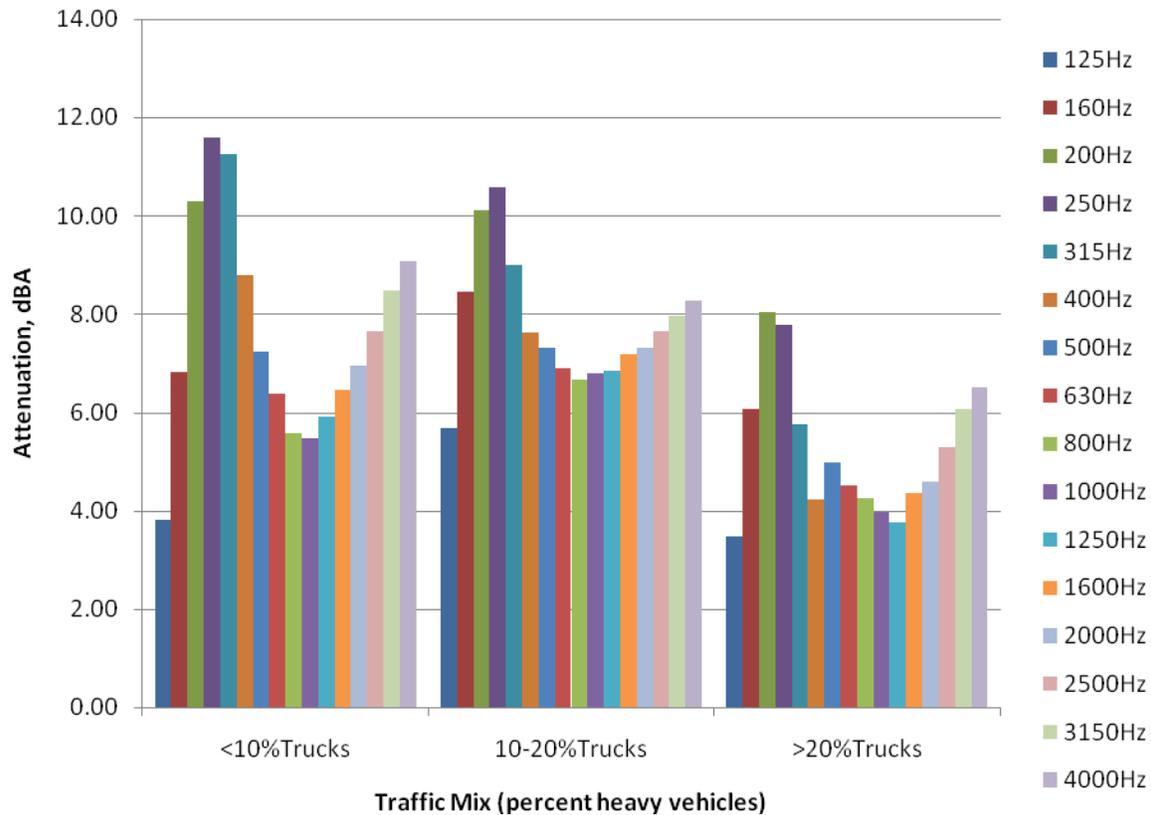
## Frequency Effect for Attenuation of Road Noise

In order to examine the effect of the deepest level of trees on road noise of various frequencies, the attenuations achieved at 65.6 ft (20 m) was examined for each 1/3 octave band between 125 Hz and 4000 Hz. The results are shown in Figures 28 and 29. The attenuations shown in these figures are not distance corrected, since they are all taken from the same distance. Figure 28 shows that as traffic becomes heavier, there is greater attenuation of the noise at these frequencies and for this distance. This indicates that a deep stand of trees may be more effective for heavier levels of traffic. However, these results are based on only 30 measurements (only those at 65.6 ft, which were 25% of the total measurements taken).



**Figure 28. 1/3 octave band road noise attenuation from 125-4000 Hz for four levels of traffic density (attenuation at 65.6 ft into the stand of trees).**

Figure 29 shows that as the percent of trucks increase, the level of attenuation decreases at the 1/3 octave bands from 125 to 4000 Hz. The shape of the graphs also changes. With very low levels of truck traffic (<10% trucks), there is a deep trough in the attenuation from 400 to 2500 Hz. This trough gradually flattens out as truck traffic increases. As for Figure 28, this graph represents only 30 measurements (those taken at 65.6 ft). The combined results of these two graphs indicate that deep stands of trees



**Figure 29. 1/3 octave band road noise attenuation from 125-4000 Hz for four levels of traffic mix (attenuation at 65.6 ft into the stand of trees).**

### ***Discussion***

No matter how the sites were examined, there was no measurable difference in road noise. All differences at the more distant measurement locations were due simply to the distance effect rather than to any additional mitigating effects of trees, whether measured by planting density, age, height, or average tree diameter. An attenuation of at least 1 dB is required for a listener to just be able to notice a difference in the noise level (just noticeable difference; Encyclopedia Britannica Online, 2008). The largest differences measured were in the range of  $\pm 2.5$  dB, and most average attenuations were within  $\pm 1.0$  dB. One of the problems appeared to be the types of tree plantings available for measurement. It is a characteristic of all three species of pine trees located at the sites that the interior trees lose their lower branches as the stand grows up. Figure 30 shows an exterior view of Site 1, which from the roadway appeared to be both densely planted and with dense foliage. Figure 31 shows an interior view of the same stand of trees.

This problem may become even worse as trees are more densely planted. Thus, even a site that appeared at first sight to be ideal for noise reduction purposes consisted mainly of tree trunks once past the first row of trees. Tree trunks are hard surfaces that may reflect noise in unpredictable directions. This also means that the interior of most stands consisted primarily of empty air with little or no impediment to noise propagation.



**Figure 30. Exterior view of Site 1 showing apparent dense foliage.**



**Figure 31. Interior view of Site 1 showing how there was no foliage at the lower levels in the interior of the site (photo take at the 10m measurement area).**

# Smart Road Study

## Introduction

Virginia’s Smart Road, located adjacent to VTTI, contains several areas of experimental pavement. One of the segments is so-called “quiet pavement,” which is meant to reduce the noise caused as tires run over the pavement. Pavement/tire noise is typically measured very near the roadway with special measuring devices. However, for the purposes of this study, the noise was measured in the same way as for the live road study, in order to determine the effect on a listener away from the roadway.

## Research Design

*Independent variables.* There were four segments of pavement available for study. Each was approximately 300 ft (91.4m) long. The four types are shown in Figure 32. In addition to standard asphalt and quiet pavement, there was an asphalt that had characteristics that were “in-between” standard asphalt and quiet pavement, and thus it was given this name. There was also a section of concrete pavement adjacent to the other three, so it was also included.



**Figure 32. Smart Road surfaces measured. Clockwise from top left: Quiet pavement, in-between, standard asphalt, and concrete.**

The next independent variable was traffic density. Given the relatively short sections of roadway available for study, traffic density was simulated with the following conditions: single light vehicle, dual light vehicles, and single heavy vehicle (in this case, a 15 passenger van). Heavier vehicles were not used because it was believed that the engine noise of these heavier vehicles would dominate and wash out any measurable effect of the pavement/tire interaction.

The third independent variable was traffic speed. Given the short distances to be covered by the vehicles, only two speeds were used – 25 mph and 45 mph. The fourth independent variable was direction – uphill or downhill. Since the Smart Road is on a grade, the effect of engine noise

from vehicle acceleration required to maintain the directed speed was measured on the uphill, while for the downhill, the engine was basically coasting.

*Dependent Variables.* Noise measurements were taken using the Leq dBA Slow setting of the same SLM used for the live road study. This provided an equivalent, or average, measure of the sound level over the time of the measurement (which was in the range of a few seconds per measurement). Spectral measurements (1/3 octave band) were also available.

## **Method**

### **Site Description**

The site was four adjacent pavement sections on the Smart Road. Each was 300 ft (91.4m) long, for a total site measurement of 1,200 ft (366m). A 200 ft (61m) section was marked with cones in the center of each segment to ensure that all measurements would be strictly based on the pavement section (and not entering and leaving it). One of these areas is shown in Figure 33.



**Figure 33. Area 200 feet long marked with cones for measurements on Smart Road.**

### **Equipment**

The equipment used for taking measurements on the Smart Road was the same used at the live road study sites. Both Larson Davis 824 devices were set up 65.4 ft (20m) from one another, on a tripod at a height of 59.5in (1.5m) above the ground and 65.4 ft (20m) from the center of the roadway. The setup is shown in Figure 34. The sound level meter labeled as Primary Device on the sites was also called Primary Device for the Smart Road measurements. The same was true for the Secondary Device. The original intent was to average the readings from the two devices. However, the Primary Device failed during a number of measurements, so only the results from the Secondary Device are reported here. The devices were set up on the graded but unpaved adjacent roadway, as shown in Figure 35.

## Sound Level Meter Setup for Measurements taken on Smart Road

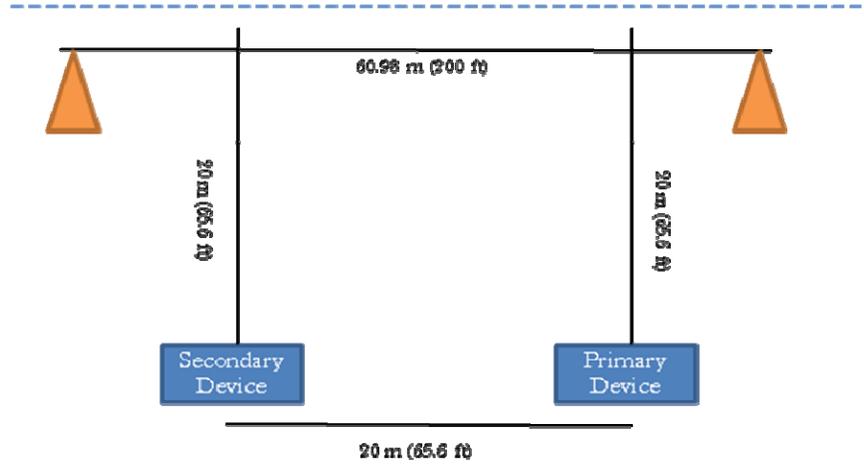


Figure 34. Sound Level Meter setup on Smart Road.



Figure 35. Sound level meter setup on the Smart Road.

### Measurement Process

For the Smart Road measurements the following conditions were established using the independent variables discussed previously:

1. Single, light vehicle going downhill at a speed of 45 mph

2. Single, light vehicle going downhill at a speed of 25 mph
3. Single, light vehicle going uphill at a speed of 45 mph
4. Single, light vehicle going uphill at a speed of 25 mph
5. Dual, light vehicles going downhill at a speed of 45 mph
6. Dual, light vehicles going downhill at a speed of 25 mph
7. Dual, light vehicles going uphill at a speed of 45 mph
8. Dual, light vehicles going uphill at a speed of 25 mph
9. 15-passenger van going uphill at a speed of 45 mph
10. 15-passenger van going uphill at a speed of 25 mph

Note that the 15-passenger which was only measured uphill, which was considered the worst case scenario for this experiment: a heavy vehicle accelerating to maintain speed. Three measurements were taken on each of the four Smart Road surfaces for each of the above conditions, totaling 120 measurements. The duration of each measurement was determined by starting the measurement when the front of the car passed the first cone and ending when the car's rear end had passed the second cone. Figures 36 through 38 show some of the conditions measured.



**Figure 36. Single light vehicle going downhill, just entering the measurement zone.**



**Figure 37. Single light vehicle going uphill, about to enter the measurement zone.**

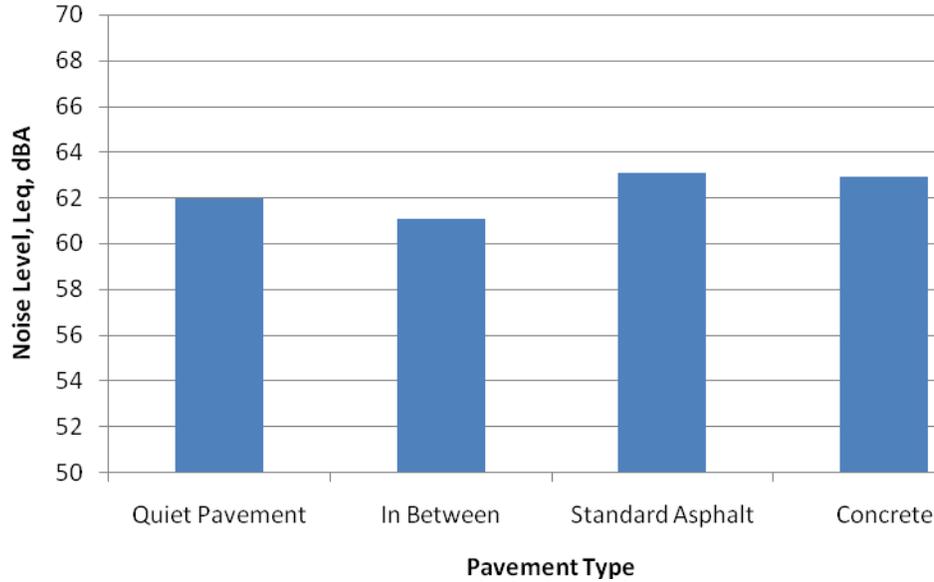


**Figure 38. Dual light vehicles going downhill. Measurement started when the front of the first vehicle crossed the entrance cone and ended when the rear end of the second vehicle crossed the exit cone.**

## Results

### Effect of Pavement Type on Road Noise

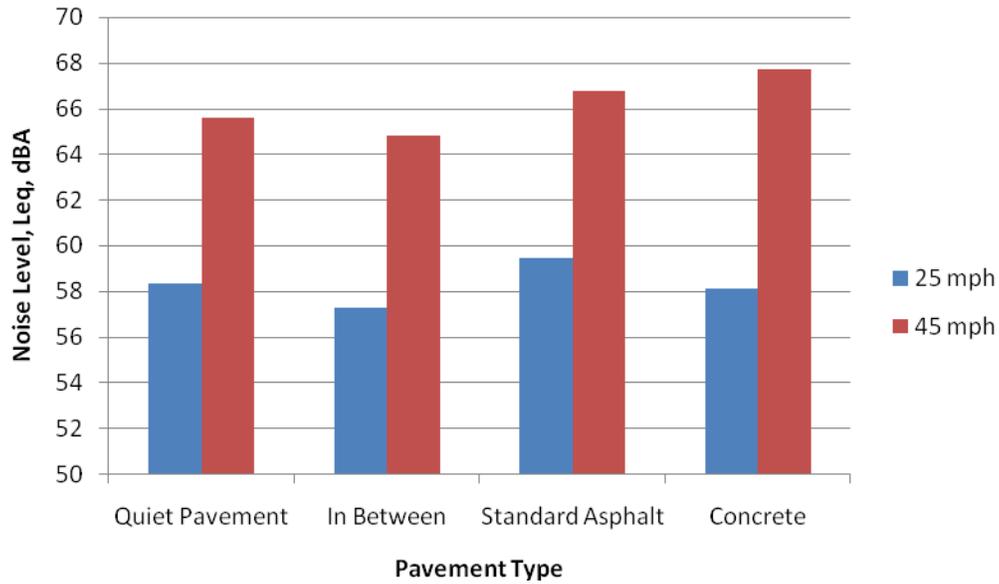
As shown in Figure 39, the in-between pavement resulted in the lowest overall noise measurement, followed by quiet pavement, and then by standard asphalt and concrete, which were nearly equal.



**Figure 39. Effect of pavement type on road noise.**

### Effect of Traffic Speed on Road Noise

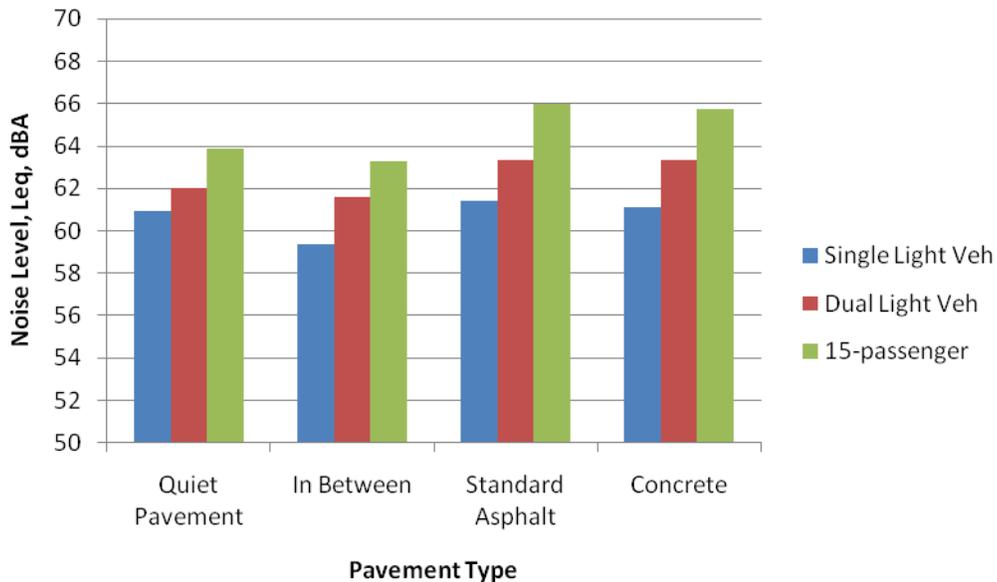
Higher traffic speeds resulted in higher measured noise levels, as shown in Figure 40. The difference due to speed was approximately 7dBA for quiet pavement, in-between, and standard asphalt, but approximately 10dBA for the concrete pavement.



**Figure 40. Effect of traffic speed on road noise.**

### Effect of Traffic Density on Road Noise

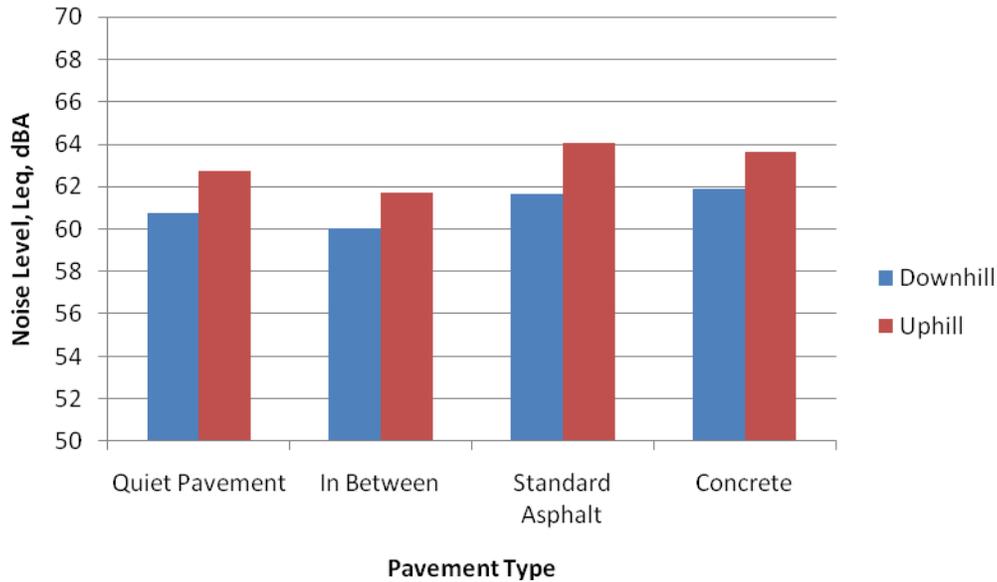
Figure 41 presents the results for the traffic density conditions. For each condition of traffic density, the in-between pavement resulted in the quietest readings, followed closely by quiet pavement, and then the standard asphalt and concrete, which were almost equal. As might be expected, the single light vehicle resulted in the lowest noise levels, followed by the dual light vehicle, and then the 15-passenger van (heavy vehicle).



**Figure 41. Effect of traffic density on road noise.**

## Effect of Traffic Direction on Noise

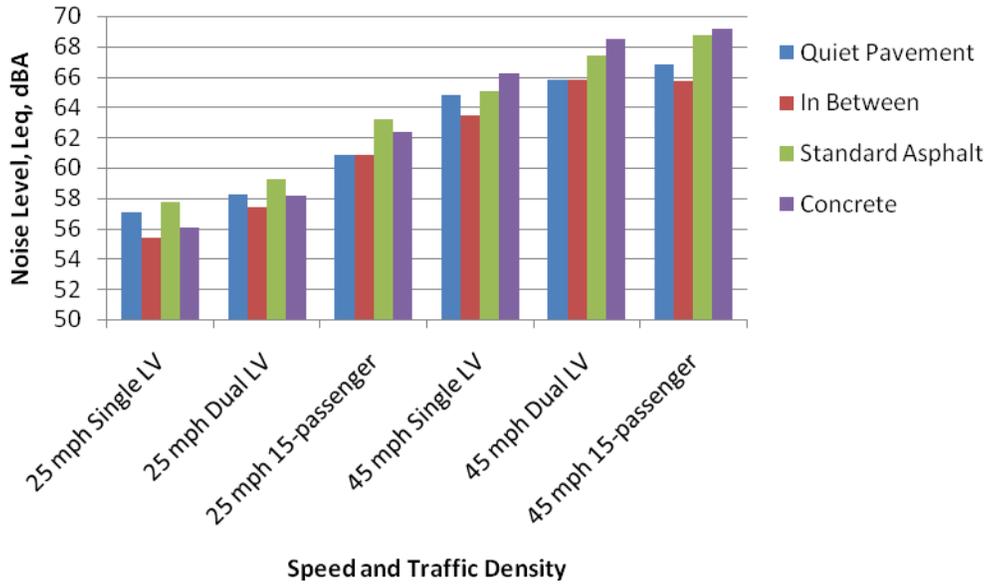
The uphill conditions with acceleration required to maintain speed resulted in higher noise levels than the downhill (coasting) conditions. This result is shown in Figure 42. As was true for the other measured conditions, the in-between pavement type had the lowest noise levels, followed by the quiet pavement and then the standard asphalt and concrete pavements.



**Figure 42. Effect of traffic direction on road noise.**

## Speed and Density

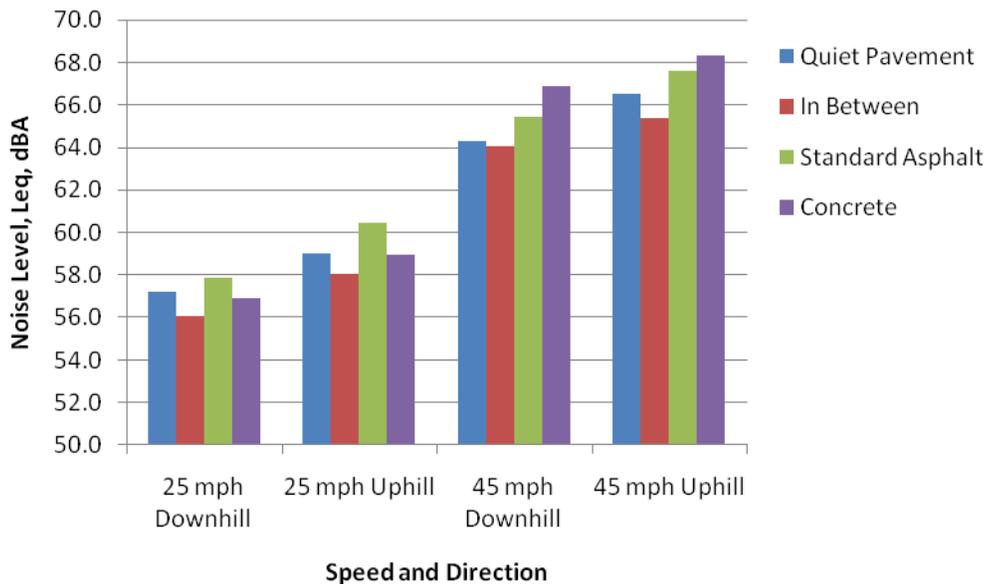
Figure 43 shows the combined impact of traffic speed and traffic density on the noise levels. The lowest measurements were for the 25mph, single lead vehicle condition, while the 45mph, 15-passenger van had the highest noise levels. The 45mph, single lead vehicle resulted in greater noise levels than the 25mph, 15-passenger van condition, which indicates that travel speed has a greater impact on traffic noise than does traffic density, at least under the conditions measured in this study.



**Figure 43. Effect of traffic speed and density on road noise.**

### Speed and Direction

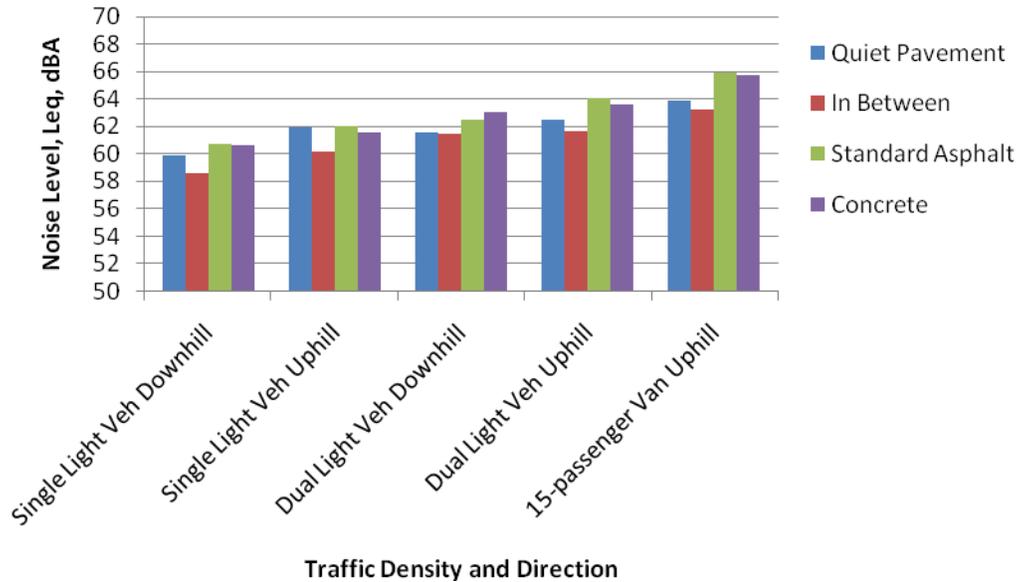
The combined effects of traffic speed and traffic direction are shown in Figure 44. Again, traffic speed dominates the results, with the 25 mph conditions resulting in lower noise levels, regardless of traffic direction. For example, the 45mph downhill (coasting) condition resulted in higher noise levels than the 25mph uphill (accelerating) conditions.



**Figure 44. Effect of traffic speed and direction on road noise.**

## Traffic Density and Direction

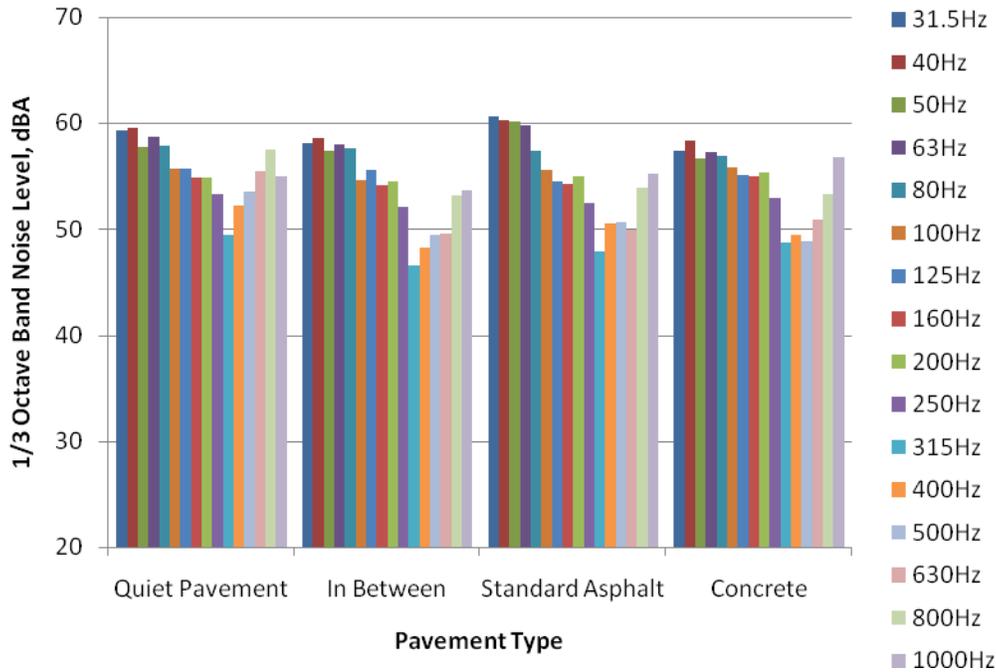
Figure 45 presents the results for the combination of traffic density and traffic direction. With this interaction, traffic density seems to dominate, with both single light vehicle conditions resulting in lower readings, followed by the two dual light vehicle conditions, and finally by the 15 passenger van (which was only measured uphill, which was considered the worst case scenario for this experiment – a heavy vehicle accelerating).



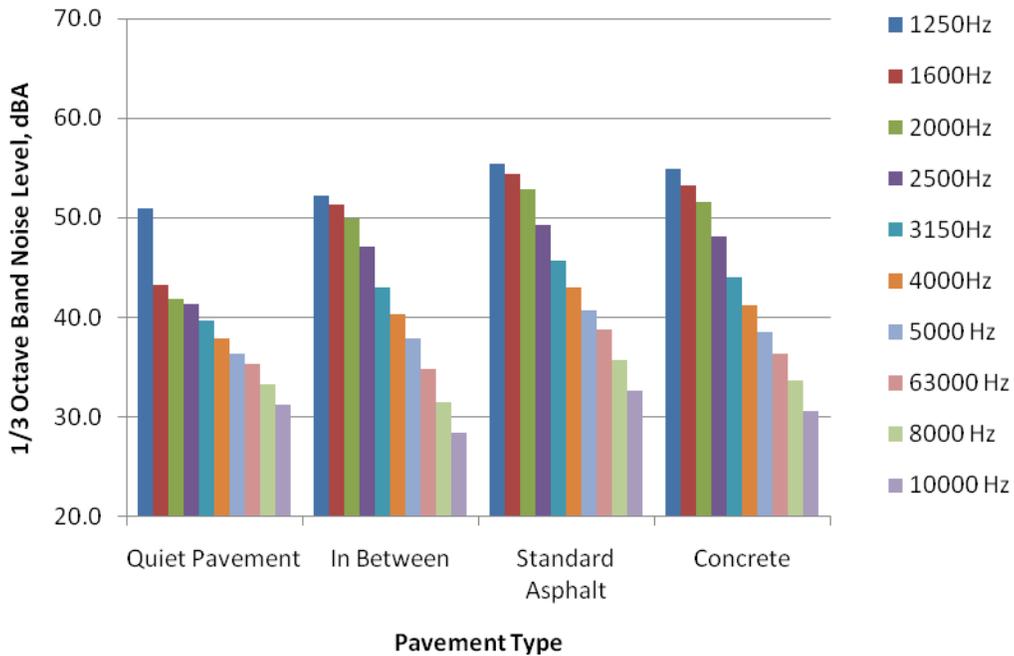
**Figure 45. Effect of traffic density and direction on road noise.**

## Effect of Pavement Type on Frequency

The 1/3 octave bands were examined for patterns resulting from pavement type/traffic condition interactions. Figure 46 presents the results for the lower frequencies from 31.5 to 1000 Hz. The in-between pavement resulted in lower readings for nearly every 1/3 octave band at these lower frequencies. However, Figure 47 shows that the quiet pavement resulted in lower readings from 1250-5000 Hz, which is a mid-range of frequencies. This indicates that the quiet pavement was performing as advertised for road/tire noise, which tends to dominate in this range. The in-between pavement, on the other hand, outperformed the other three pavement types below 1250 Hz (where engine noise dominates) and above 5000 Hz. The in-between pavement may have had characteristics that resulted in greater absorption of engine noise, while the standard asphalt and concrete pavements were not ideal for either engine noise or road/tire noise. In fact, these surfaces may have reflected both types of noise and made it measurably louder.



**Figure 46. Effect of pavement type on 1/3 octave band frequencies between 31.5 Hz and 1000 Hz.**



**Figure 47. Effect of pavement type on 1/3 octave band frequencies between 1250 Hz and 10000 Hz.**

## ***Discussion***

One aspect of the study that could not be completed was a series of measurements of quiet pavement on one or more live road segments. This would have made a nice bridge between the live road study and the Smart Road study, and allowed direct comparisons between the studies. Nevertheless, the study conducted on the Smart Road did result in some interesting findings. The in-between pavement consistently resulted in the lowest noise levels across all conditions studied. Further analysis revealed that this was likely due to greater absorption of low frequency engine noise. The quiet pavement outperformed the other three types in the mid-high range of frequencies, which is where tire/pavement noise would be expected to be greatest. The standard asphalt and concrete surfaces performed worst under all conditions, and may have reflected both tire and engine noise, rather than absorbing it. In terms of the conditions studied, traffic speed has the greatest impact on the noise, with higher speeds resulting in greater noise. Traffic direction and traffic density both had impacts on noise levels, but these effects were lower than for traffic speed.

## Conclusions and Recommendations

Most of the previous research reviewed for this study concluded that a vegetation barrier *can* help reduce traffic noise to a certain degree, although the highest attenuation obtained was approximately 9 dB. However, study results were not all positive; some of the studies concluded that the noise attenuation obtained was so small it would not be perceived by humans (as was found for the conditions available for study in Virginia). The differences in results among these studies is likely due to the wide variety of measurement methods, tree species, planting densities, tree heights, and noise sources used. The studies also concluded that in order for a vegetation belt to reduce traffic noise it should be densely planted, with no windows to let noise through.

Ground cover at the different sites was also found to be helpful. Some of the studies suggested a mixture of evergreens, conifers and shrubs interspersed at the sites to increase noise reduction effectiveness, especially if some of the trees had lost their lower foliage. None of the previous studies were conducted in the Commonwealth of Virginia, using tree species that are currently known to thrive in the roadway environments found there. Likewise, very few studies used live road noise, and in particular, live road noise using today's vehicles and traffic mixes. The current study was designed to overcome some of these shortcomings and provide results more applicable to conditions in Virginia.

Fifteen roadside sites were thus examined across the Commonwealth of Virginia, examining factors such as tree height, tree age, tree species, tree density, tree diameter, distance from roadway, traffic density, and traffic mix. Two hours worth of measurements were taken at each site (two 15-minute measurements at each of four distances from the edge of the trees). No matter how the sites were examined analytically, there was no measurable difference in road noise. All differences at the more distant measurement locations were due simply to the distance effect rather than to any additional mitigating effects of trees, whether measured by planting density, age, height, or average tree diameter. An attenuation of at least 1 dB is required for a listener to just be able to notice a difference in the noise level (just noticeable difference; Encyclopedia Britannica Online, 2008). The largest differences measured were in the range of  $\pm 2.5$  dB (with measurements as likely to be greater than zero than less than zero), and most average attenuations were within  $\pm 1.0$  dB. One of the problems appeared to be the types of tree plantings available for measurement. It is a characteristic of all three species of pine trees located at the sites that the interior trees lose their lower branches as the stand grows up. For example, Site 1 appeared to be both densely planted and with dense foliage as seen from the roadway. However, the interior of the same stand of trees consisted mainly of tree trunks once past the first row of trees. Tree trunks are hard surfaces that may reflect noise in unpredictable directions. This also means that the interior of most stands consisted primarily of empty air with little or no impediment to noise propagation. The results of the live road study were in agreement with previous studies conducted in other locations and with different species of trees.

One aspect of the study that could not be completed was a series of measurements of quiet pavement on one or more live road segments. This would have made a nice bridge between the live road study and the Smart Road study, and allowed direct comparisons between the studies.

Nevertheless, the study conducted on the Smart Road did result in some interesting findings. The in-between pavement consistently resulted in the lowest noise levels across all conditions studied. Further analysis revealed that this was likely due to greater absorption of low frequency engine noise. The quiet pavement outperformed the other three types in the mid-high range of frequencies, which is where tire/pavement noise would be expected to be greatest. The standard asphalt and concrete surfaces performed worst under all conditions, and may have reflected both tire and engine noise, rather than absorbing it. In terms of the conditions studied, traffic speed has the greatest impact on the noise, with higher speeds resulting in greater noise. Traffic direction and traffic density both had impacts on noise levels, but these effects were lower than for traffic speed.

Although trees have not generally been found to be effective noise barriers, they do have aesthetic (and perhaps environmental) benefits. Trees may also produce a psychological benefit in terms of noise reduction – people may perceive the trees to have a greater noise reduction effect than can be measured. This is likely because in order for a stand of trees to have any effectiveness in noise reduction, it must be fairly deep. Thus, the people who are perceiving the noise are further removed from the source, which provides a psychological barrier as well as a distance barrier. Nevertheless, many issues must be considered before a tree planting program can be put into place. Several of these are described briefly below, followed by a list of recommendations for how a program might be made most effective.

- Everything related to the noise problem and trees is a *moving target*. In the 40 or so years that have passed since many of the trees along Virginia's interstates were planted, vehicles and tires have changed significantly. Although pavement has not changed as much in that time, there is a good likelihood that pavement will change significantly over the next 40 years. The introduction of hybrid vehicles, electric vehicles, and fuel cell vehicles into the nation's vehicle fleet will likely lead to ever quieter conditions on the roadways. Truck noise, the greatest contributor to road noise, has decreased dramatically over the past 40 years (at least as measured in the interior of the cabin, but likely in the exterior as well; Lee, 1998). Tires have also undergone significant changes, and further changes are to be expected. For example, all new cars will be expected to have automatic tire pressure warning systems. It is expected that more and more tires will be properly inflated with these systems, which will affect the amount of tire/road noise. The biggest moving target is the trees themselves. Trees grow measurably year by year, and there is probably a one to five year period when the noise reduction offered by a stand of trees is at its optimum. Before that time, the trees are too small to have much impact on the noise; after that window, lower branches begin to drop off and create open space in the stand of trees.
- Stands of trees attract *deer and other wildlife*, which may increase the incidence of vehicle/deer crashes. Although most of the sites studied had VDOT wildlife fencing present at the back tree line or through the interior of the site, two sites still had deer carcasses. Site 1 was clear when the noise measurements were taken, but when the researchers went back to take photographs, a deer had been hit and had gone into the woods to die. The other site with a carcass was supposed to be Site 16, but contained a deer carcass that prohibited spending the two hours required to take noise and tree measurements. A second wildlife fence on the edge of the trees nearest the roadway may

help improve this problem, but would increase the cost and decrease the aesthetic value of the stand.

- *Wildfires* have dominated the news over the past year, and there have even been wildfires in Virginia during that time. One fire burned a stand of trees adjacent to I-81 in Roanoke County during the course of the study (although this was not a potential study site). Wildfires adjacent to interstates can be caused by careless disposal of smoking materials while driving by the tree stands, or can spread from other nearby wildfires. Once a fire starts near the interstate, the state police must monitor carefully to make sure that the smoke does not impede visibility; when it does, they must close the road. Tall trees adjacent to the interstate can fall into the roadway during the fire, necessitating clean up before the road can be opened.
- Trees can be damaged by *weather events*, including snow, ice, wind storms, and tornados. During the course of the study, both ice and wind storms brought down trees within a few of the study sites. Some of the trees studied were both tall enough and close enough to the roadway that they could have come down into the roadway if blown over by a wind storm or tornado. Ice storms typically bring down branches or tops of trees, so do not often endanger the roadway users in the same way, but ice storms can do severe damage to stands of trees, making them more susceptible to insect and disease, and altering their noise reduction characteristics.
- *Disease and insects* can attack certain species of trees. Both disease and insect outbreaks can occur quite rapidly, in terms of the lifespan of a tree. Twenty years ago, flowering dogwoods filled understory of the tree stands along Virginia's interstates; today, thanks to dogwood anthracnose, there are very few beautiful flowering dogwoods left to delight travelers in the springtime. There are many other examples of devastating tree diseases and insects in Virginia, and it is impossible to predict when a new outbreak may develop which would leave dedicated noise reduction tree stands barren and useless.
- Development and maintenance of such stands requires a *long-term commitment*. Although it appears that the trees along Virginia's interstates have been left to fend for themselves for the most part over the past 40 years, there was a culling or maintenance effort observed during the course of the study (although not at any of the selected study sites). Contractors appeared to be removing large trees nearest the edge of the interstates which could come down in a fire or wind event and block the roadway. Many of the trees observed were also quite valuable, in terms of their size and quality. Thus, there may come a time when the value of the trees is such that it makes sense to harvest them rather than let them continue growing. At some point, if the trees have managed to survive weather, wind, insects, and ice, they will either reach a size where they will become dangerous to roadway users (should they fall) or they may die. Thus, any program involving tree plantings must provide for long-term care and maintenance of the trees, and should include contingency plans for what to do in case of some disaster or infestation.
- One of the biggest issues to consider is the *cost of land*. Unlike standard noise barriers, trees must be somewhat removed from the roadway, and then there must be a large enough band of them (10-20m, or 32.8-65.6 ft) to provide an attenuation effect. Trees

cannot be planted too close to the roadway for reasons discussed in the next bullet. Thus a large right-of-way must be obtained in order to plant the trees. The irony of the situation is that these large rights of way often exist in rural areas, where the right-of-way abuts pastureland. In heavily populated areas, where traffic is heaviest and noise reduction most desirable, there is often almost no right-of-way, with a shoulder (sometimes used as a traffic lane during rush hour) adjacent to a noise barrier, and houses right behind the noise barrier. In such situations, there is no place to plant trees or other vegetation in enough quantity to have any effect on noise. The best possibility for use of tree barriers would thus be in the marginal areas of large population centers – locations where large rights of way were obtained many years ago, when the cost of the land was reasonable, and where pastureland is now being converted to housing, and the traffic density is steadily increasing. One related issue is that as traffic density increases, more travel lanes are added, often at the cost of the right-of-way and the tree plantings.

- Trees that are too close to the roadway provide two possible *accident hazards*: the risk of a vehicle leaving the roadway and crashing into the tree, and the risk of the tree falling into the roadway. Noise barriers do not provide quite the same crash risk as trees. Trees are often hit head-on on rural roads, but noise barriers are often side-swiped, which is typically a less serious type of accident.
- Certain species of trees spread easily, often by means of birds, and can become *weed-like*. Some of the dense stands of cedar found along Virginia’s interstates (stands that were too dense and brushy to enter and take noise measurements on) are abutted by pastureland. The pastures are often dotted with small cedar trees that have spread from the roadside stand. Farmers consider these trees as weedy pests, and spend considerable time and effort eradicating them.
- Certain plants can be susceptible to tree *damage from vehicle emissions*. This damage is more likely in areas with heavy traffic, where emissions are worst. However, most of the sites studied did not show evidence of unhealthy trees, except in cases of insect or disease damage. Thus the trees which currently grow well along Virginia’s interstates do not appear to have this susceptibility vehicle emissions.
- Stands of trees may prove to be attractive to different species of *birds*. This may be a positive, but at times, birds that flock heavily can prove disruptive. This is probably the least important issue of those raised in this section.

## ***Recommendations***

If a decision is made to plant stands of trees along Virginia’s interstates to reduce noise in the areas beyond the trees, several provisions should be put in place to maximize the success of such a venture. Certain of these recommendations flow naturally from the issues presented above, while others were suggested by various project team members.

1. *Species*. One of the team members, after studying the types of trees which seem to grow well along Virginia’s interstates, recommended that the plantings consist of interspersed pines trees (Virginia pine, white pine, or loblolly pine, depending on the area of the state) mixed with holly. Holly is an evergreen shrub which retains foliage down to the ground,

even when older and in the interior of stands, and it would provide the low-level vegetation barrier once the pine trees lost their lower branches. If other species are used, they should be certified to be insect and disease resistant in regard to current known outbreaks, to be resistant to damage from vehicle emissions, and to not spread easily onto adjacent pastureland.

2. *Planting depth.* It is recommended that the tree stands be at least 10m (32.8 ft) deep, but twice that depth would be even better. Again, much of the noise reduction attributed to stands of trees is simply due to the distance added between the noise source (the road) and the listener. The greater the distance, the less the noise, even in the absence of a barrier. If the combination of tree age, tree species, and planting density has an effect on the road noise, then a deeper stand will have more of an effect.
3. *Planting density.* The planting density should be specified by a forester with the following rule in mind for each species: Plant at the greatest possible density which will also allow for healthy growth of trees and allow lower branches to remain intact for as long as possible.
4. *Topography.* Although the sites studied in the live road study were all flat and level with the roadway to help ensure comparable measurements, this is not the ideal situation for noise reduction. Both natural and man-made topographic features can help reduce noise. Slopes should be planted with ground cover or trees to help absorb sound, rather than reflect it. Sites should be carefully studied to ensure that a “noise tunnel” effect is not accidentally created, especially if they are located near curves.
5. *Distance from roadway.* At least a 15m (49.2 ft) roadside to tree line distance is recommended. This will allow the trees to grow for quite a few years before there is any possibility of them falling over the road in a wind or fire event. Beginning the plantings even further away, in an area with a large right-of-way, would be preferred in case the roadway needs to be widened later.
6. *Long-term maintenance, planning, and care.* Proper provision must be made for long-term maintenance and care of the trees. This could be done in one of two ways: either have someone from the Division of Forestry whose responsibility it is to monitor the health and status of the stands of trees, or create a position within VDOT for the same purpose. Long-term planning is also important. Contingency plans should be made for cases of extreme damage to stands of trees (fire, weather, insect, or disease). Finally, plans should be made for the life-cycle of the stands. If there is an optimum period of time for the noise reduction characteristics of a stand of trees, then perhaps the trees should be harvested and replanted after that time. However, passers-by may object to the harvesting, not understanding the purpose of the stand.
7. *Pavement type.* Results of the Smart Road study indicated that the quiet pavement type does perform as advertised in reducing the noise created by road/tire interactions. The in-between pavement performed better at reducing engine noise, perhaps by better absorption of these frequencies, and had lower overall noise levels, although only slightly better than the quiet pavement. Use of these new pavement types, in combination with ongoing changes in the nation’s vehicle fleet (smaller and quieter vehicles) would result in greater noise reduction than can be provided by trees, and in a shorter time frame.



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