EFFECTS OF PAVEMENT TYPE ON TRAFFIC NOISE LEVELS

FINAL REPORT

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16. Abstract

Tire/road noise levels for Ohio Department of Transportation (ODOT) pavement types were investigated to provide an additional criterion for pavement selection in noise sensitive areas. Tire/road noise measurements were conducted in accordance with the International Organization of Standardization (ISO) 11819-1 Statistical Pass-By Method, the first use of this standard in the U.S. A Statistical Pass-By Index (SPBI) was determined for each pavement test, which enabled the ranking of the pavement types according to tire/road noise levels, as well as a means of comparing results with other studies conducted according to the standard. There was found to be a difference of 6.7 dB between the lowest (open graded asphalt) and the highest (random-transverse grooved concrete) SPBI for all of the pavements measured. Additionally, the data was analyzed to produce Reference Energy Mean Emission Levels for future use with traffic noise prediction modeling.

17. Key Words

tire pavement noise; statistical pass-by method; reference mean emission levels

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NOTATIONS

A-weighting network: An electronic filter in a sound level meter which approximates under defined conditions the frequency response of the human ear. The A-weighting network is most commonly used.

Ambient noise: All-encompassing sound that is associated with a given environment, excluding the analysis system's electrical noise and the sound source of interest.

Background noise: All-encompassing sound of a given environment that includes ambient, as well as analysis system noise, excluding the sound source of interest.

Calibration: Adjustment of a sound measurement system so that it agrees with a reference sound source.

Decibels (dB): A unit of logarithmic measure based on ratios of power-related quantities, thereby compressing a wide range of amplitude values into a small set of numbers.

Exponential time-averaging: A method of stabilizing instrumentation response to signals with changing amplitudes over time using a low-pass filter with a known, electrical time constant. The time constant is defined as the time required for the output level to reach 67 percent of the input, assuming a step-function.

Fast time weighting: The response speed of the detector in sound measurement system using a time constant is 1/8 second (125 ms) to detect changes in sound level more rapidly.

Free field: A sound field whose boundaries exert a negligible influence on the sound waves. In a free-field environment, sound spreads spherically from a source and decreases in level at a rate of 6 dB per doubling of distance from a point source, and at a rate of 3 dB per doubling distance from a line source.

Frequency: The number of cyclical variations (periods) unit of time. Expressed in cycles per second (cps) also denoted as Hertz (Hz).

Grazing incidence (90° incidence): The orientation of a microphone in a way that the sound waves impinge at an angle that is parallel to, or grazing, the plane of the microphone diaphragm.

Hard ground: Any highly reflective surface in which the phase of the sound energy is essentially preserved upon reflection; examples include water, asphalt, and concrete.

Hertz (Hz): The unit of frequency measurement, representing cycles per second.

Maximum sound level (L_{AFMX}): The maximum, A-weighted sound level associated with a given event.

Maximum spectrum: The maximum signal level measured in each filter band for a given event.

Normal incidence (0° incidence): The orientation of a microphone in a way that the sound waves impinge at an angle perpendicular, or normal, to the microphone diaphragm.

Octave: Two frequencies are an octave apart if the ratio of the higher frequency to the lower frequency is two.

Octave (frequency) bands: Frequency ranges in which the upper limit of each band is twice the lower limit. An octave band is often subdivided into 1/3 octaves (3 bands per octave) for finer frequency resolution.

REMEL: Reference Energy Mean Emission Level. The statistical mean of acoustic energy emitted by a vehicle class as measured at a reference distance perpendicular to the centerline of the vehicle path.

Receiver: One or more observation points at which sound is measured or evaluated. The effect of sound on an individual receiver is usually evaluated by measurements near the ear or close to the body.

Rise and fall: The difference between the maximum and minimum measured sound level associated with either the start or end of a given event.

Soft ground: Any highly absorptive surface in which the phase of the sound energy is changed upon reflection; examples include terrain covered with dense vegetation or freshly fallen snow.

Source: An object (ex. traffic) which radiates sound energy.

Spectral, spectrum: Description, for a function of time, of the resolution of a signal into components, each of different frequency and usually different amplitude and phase.

Statistical Pass-By Index (SPBI): A noise index for comparison of road surfaces which is based on the Vehicle Sound Levels and takes into account the mix and speeds of vehicles.

NOTE : Unless indicated otherwise, all sound pressure levels referenced in this report are the maximum A-frequency weighted sound pressure levels.

1. INTRODUCTION

Traffic noise mitigation strategies are developed by considering the source, path, and receiver of the noise. Within the United States, strategies involving the path of traffic noise have dominated noise abatement efforts on Federal and State levels. As a result, many miles of barriers have been constructed to shield affected receivers from traffic noise. Strategies aimed at reducing the source of traffic noise are appealing in light of the potential for reducing these abatement costs.

Vehicle noise has been divided into six noise-producing components: engine, fan, intake, exhaust, drive train, and tires. Due to market forces, vehicle manufacturers have been motivated in recent years to reduce the noise generated by these components. As progress has been made by manufacturers to reduce the noise emitted by the various sub-sources within motor vehicles, tire/road noise has emerged as the dominant component of traffic noise for speeds greater than 35-40 mph. Recent European studies have concluded that tire/road noise levels vary substantially according to pavement type [Herman and Bowlby 1993].

The quantification of the noise generated by different pavement types has important economic considerations. The identification of the differences in noise levels expected by pavement type provide an additional criteria for designers. The selection of a lower noise pavement type from a list of approved pavements can result in reduced costs for abatement design. It has been estimated that the reduction of traffic noise barrier heights by approximately two feet can result in the saving of over $10 million per year nationally [Transportation Research Board 1991]. Typically such a height reduction would increase noise levels approximately 1 dB.

However, levels could be maintained or reduced with the selection of lower noise pavements.

Ohio is a large transportation state with many urban areas. As a result, noise analysis has been and will be a significant component of new project planning. In a recent report to the Ohio legislature, the Ohio Department of Transportation (ODOT) has stated that "unless definite knowledge is available on pavement type, condition, and noise generating characteristics, no adjustments can be made for pavement type in the prediction of highway traffic noise levels". "Additional research is needed to determine what extent different types of pavements and tires contribute to traffic noise" [Pakush and Pinckney 1996].

Since noise is not a criterion in the pavement selection process, traffic noise levels could inadvertently be increased (or an opportunity forfeited to decrease levels) through the use of otherwise acceptable pavement types.

The investigation of tire-road noise for ODOT pavement types described in this report provides an additional criterion for pavement selection in noise sensitive areas. Further, the effect of different pavement types on noise impact assessment and abatement design can be quantified by using pavement specific reference noise levels, developed as part of the project, with the Federal Highway Administration's traffic noise model (FHWA TNM).

As a result of the project, ODOT will have increased control over traffic noise at the source. The possession of greater control of the source will expand the range of abatement options beyond simply the consideration of the path, which is current practice. Further, the quantification of the noise generating characteristics of Ohio's current pavement types will serve as the basis for evaluation of the noise generating characteristics of pavements developed in the future.

The tire/road noise measurement method chosen for this study was the statistical pass-by method. There were several advantages to using this method as opposed to other tire/road measurement methods. First, there was a direct correlation of measured levels with expected roadside levels. Therefore, the significance to roadside receivers of any difference in levels between pavement types were found to be readily apparent. Second, the data resulting from the measurements was useful beyond the determination of noise level categories for different pavement types. Pavement specific Reference Energy Mean Emission Levels (REMELs) for Ohio's pavement types were developed from the data collected. The effects of pavement type can then be considered for future projects by using the REMELs developed from the acquired data.

The material covered in this report will begin with a literature review of pavement noise sources and the methods which can be used to measure tire pavement noise. Second, the criteria that was followed to determine which sites would qualify for measurement will be described. This will also include a listing of the sites that were used for the research. Third, the procedure and instrumentation which was used to collect the data for this project will be described in detail. Fourth, the data analysis procedures will be outlined. Finally, the results of the research shall be provided and discussed and then conclusions will be drawn.

2. RESEARCH OBJECTIVES

1. Measure tire/road noise for various ODOT pavement types in the first year of their service.
2. Quantify changes in noise levels versus the age of each pavement type.
3. Classify pavement types according to tire/road noise level categories.
4. Develop Reference Energy Mean Emission Levels (REMELs) for each category of pavement for use with the FHWA model.

After the project began, another objective developed which involved using a pavement test site located on Route 23 in Delaware county. This site allowed acoustical measurements to be performed on similar pavement surfaces that had different base thicknesses. By performing acoustical measurements on different test sections, the acoustical effects that were contributed to by pavement stiffness could be quantified.

Also, a study of the significance of the emission levels of sport utility vehicles (SUV) was performed. This study did not require the acquisition of any additional data, because acoustical data would be collected as this vehicle type appeared in the normal stream of traffic.

3. LITERATURE REVIEW

The literature review on tire/road noise has indicated that there has been substantial research done on this topic. Previous research has been performed related to the contribution that both the tire and the pavement have in the overall noise levels associated with tire/road noise. Researchers have developed different types of measurement methods used to quantify the noise produced by tire/road interaction and will be discussed in the literature review. Therefore, the literature review will focus on two topics: the noise sources involved with tire/road noise and tire/road noise measurement methods.

3.1. Tire/Road Noise Sources

The noise emissions from a vehicle traveling on a roadway is composed of two components: tire/road noise and power/train noise. Power/train noise consists of the vehicle's fan, engine, and gearbox, where the engine can be further broken down into exhaust, air intake, and the cylinder block. If a vehicle is in a good operating condition and has a reasonably good exhaust system, then the effect that power train noise has on the overall noise level will be negligible at moderate to high speeds. There is a "cross-over speed" where tire/road noise begins to dominate the overall noise level of a vehicle. This speed lies in the range of 30-50 km/h for automobiles and 40-70 km/h for trucks [Sandberg 1992].

3.1.1. Tire/Road Noise Producing Mechanisms

There are several mechanisms which contribute to the generation of noise from tire-pavement interaction. Three mechanisms which are considered to contribute most significantly are the radial vibration mechanism, the air resonant mechanism, and the adhesion mechanism.

The radial vibration mechanism occurs due to the impact of the tire tread blocks or other pattern elements on the road surfaces and is typically noticeable at frequencies below 1 kHz. This impact induces vibrations which are caused by small deflections in the tread which are propagated in the air as noise [Sandberg 1992].

The air resonant mechanism usually occurs at frequencies above 1 kHz. This mechanism consists of three components that are referred to as pipe resonance, Helmholz resonance, and pocket air-pumping. The pipe resonance mechanism occurs when the grooves of the tire tread form an "air tube" in which standing waves can be present [Sandberg 1992]. The Helmholz resonance occurs when the volume of air in a cavity within the tire tread acts as a spring resonating with the mass of air in the "throat" between the tire tread cavity and the external air as the tire rotates [Sandberg 1992]. Air pumping occurs when air is trapped in small cavities on the tire surface as the tire contacts the road surface. The air is compressed then expanded with great speed causing a large amount of turbulence and thus noise [Leasure and Bender 1975].

The adhesion mechanism consists of two components. The first component occurs when there is horizontal slippage between the tire and the road surface causing tire vibrations. The second component occurs when the rubber adheres to and then is released vertically from the road surface during the tire rotation. The adhesion mechanism is similar to the air resonant mechanism in that it usually occurs at frequencies above 1 kHz.

3.1.2. Components that Influence the Amplitude of Tire/Road Noise Producing Mechanisms

There are other components of tire/road noise which may influence the amplitude of the mechanisms that were mentioned above. They are as follows:

- The horn effect.
- Sound absorption in the road surface.
- The mechanical impedance effect.
- The loading effect.

The horn effect occurs at the leading and trailing edges of the tire contact area on the pavement. An acoustical horn is formed with the curvature of the tire and the road surface and may cause an amplification of noise generated at the interface between the tire and the road surface in the directions fore and aft of the tire [Sandberg 1992].

The amount that the previously mentioned mechanisms contribute to the overall noise level for a roadside receiver can be somewhat attributed to the sound absorption of the road surface. A more absorptive pavement surface can be achieved by increasing its porosity which, in general, will reduce the amount of reflected noise propagated to a receiver. Porosity can also influence the noise generated by specific mechanisms. For example, when the tire is rolling over the surface of a pavement, the compression and expansion of air entrapped in the tire/road interface can be reduced by a more porous surface. Additionally, by increasing the porosity in a pavement, the amplifying effects of the acoustical horn mechanism will be reduced.

The mechanical impedance effect, a less understood mechanism which relates to the pavement stiffness, can affect the propagation of noise generated by the impact of the tire tread with the road surface. Therefore, noise levels can be increased with a stiff road or attenuated with a soft road. The most apparent effects of pavement stiffness is with the radial vibration mechanism. However, the contribution that the pavement stiffness has on overall tire/road noise levels is minimal [Sandberg 1992].

Another important parameter that affects the amplitude of tire/road noise is tire loading. Tests by General Motors Corporation (GM) have shown that for truck tires, in general, an increase in maximum A-weighted sound levels occurs due to an increase in loads. The GM tests show that there is a 15 dB increase in maximum sound level when the load per tire increases from 562 to 2041 kg [Tetlow 1971].

3.1.3. Road Surface Influence on Tire/Road Noise

There are several parameters which affect the amount that the road surface contributes to the generation of tire/road noise. These parameters include the texture, age, thickness, and binder material of the pavement.

The overall texture of the pavement has a significant impact on tire/road noise levels. The texture of a pavement surface can be divided into two subcategories, microtexture and macrotexture. Microtexture can be defined as the small scale roughness or harshness of a road surface, within the individual aggregate, and extends down to molecular sizes [Sandberg 1979]. The function of the microtexture is to provide high dry friction on the pavement surface. Macrotexture is the roughness or texture that encompasses the tire tread elements and road aggregate up to the size of the tire/road interface area. The function of the macrotexture is to provide a dry pavement surface creating channels where water can escape to create high friction even on wet roads and at high speeds [Sandberg 1987].

Studies have been performed by the Washington State Department of Transportation to evaluate how tire/road noise changes with pavement age. These studies have shown that asphalt pavements start out quieter than portland cement concrete pavements, but the asphalt pavements exhibit an increase in noise levels over time [Chalupnik and Anderson 1992]. The reason that the noise levels for asphalt pavements increase over time can be attributed to the pores in the pavement becoming clogged causing the pavement loose some of its absorptive properties. Another reason for the increase in noise levels is due to an increase in stiffness from traffic loading. Finally, as the asphalt surface wears over time, the coarse aggregate becomes exposed which causes an increase in noise.

The same study by the Washington Department of Transportation has shown that noise levels from portland cement concrete pavement decrease with age for approximately the first eight years of service. After eight years have passed, the noise levels generated by the portland cement concrete pavement increase. Treatments, such as grooving and tining, are applied to the portland cement concrete surfaces during the finishing process to enhance surface traction. Over time, the irregularities in this treatment are worn down and smoothed causing a reduction in noise levels. Around the eighth year, the aggregate begins to emerge causing an increase in surface texture and in turn an increase in noise levels.

The effect of pavement thickness has been evaluated for open graded asphalt surfaces and shown to have an influence on tire/road noise. In general, the effect of increasing the thickness of a pavement is to displace the frequency at which the maximum sound level occurs to lower frequencies [Sandberg 1992]. A previous study has shown a reduction in traffic noise of one dB by using a double layer of open graded asphalt surface instead of a single layer (80 instead of 50 mm) [Storeheier and Arnevik 1990]. This was accomplished by using a higher voids content in the top layer, but the maximum aggregate size was similar between the two layers.

There has been further research performed using super-thick open graded asphalt pavements with thicknesses up to 700 mm. In relation to conventional dense graded asphalt pavements, the preliminary results indicated that a total noise reduction of approximately 8 dB was achieved as opposed to 4 dB reduction for thin layers [Pipien and Bar 1991].

Binders such as pure bitumen, cement, "plastic", bitumen with added fibers, and bitumen with added rubber powder have been tested to determine the influence that they have on tire/road noise. There have not been any differences in noise levels in cases where a direct comparison has been performed to determine the effects of the binder [Sandberg 1992]. Although a study showed that for a 500 mm thick pavement consisting of a cement binder, the same noise reduction was achieved as with using a bitumen binder [Stenschke 1990]. However, an additional noise reduction of one dB was achieved using a "plastic" binder.

When looking at the effect of the binder to the overall noise level of a pavement, the long term effects must be considered. The binder can indirectly influence how rapidly a surface becomes clogged with debris, affecting tire/road noise levels [Sandberg 1992].

3.1.4. Strategies to Reduce Tire/Road Noise

A number of strategies have been developed to reduce tire/road noise by altering the typical design of a pavement based on an understanding of the mechanisms discussed above. These tire/road noise reducing methods have been developed for both asphalt and portland cement concrete pavements.

In Sweden and Norway, tests have been performed on a road surface composed of rubber granulate made of used tires and bound by polyurethane [Zetterling and Nilsson 1990] and [Storeheier and Arnevik 1990]. Compared to a conventional dense asphalt surface, a reduction of 5 - 10 dB in traffic noise was found. Due to problems with wet friction and adhesion to the base, the testing was stopped after 2 - 4 months. Since there has not been any long term testing performed on this pavement, questions still remain concerning its durability. Although by closer examination of the pavement composition, in two respects the pavement has the potential to be durable. First, since the rubber is resilient to tire stud impacts, it can be resistant to wear from studded tires. Secondly, it is likely that clogging may be less of a problem than on conventional asphalt surfaces due to the resilient properties. Since the rubber layer is constantly moving when a tire rolls over it, the dirt which accumulates may be less likely to become stuck in the pores. Although this pavement mixture is high in cost, after further research, it could become another tool to use for reducing traffic noise [Sandberg 1992].

Open graded asphalt surfaces have shown to provide the greatest amount of reduction in traffic noise. One of the main purposes of an open graded asphalt surface is to provide drainage of water away from the surface, which gives it a great advantage over other pavements with respect to safety. However, the surface may become extremely slippery if water were to freeze on the surface. Salt is typically placed upon the pavement as a de-icing mechanism. More salt would be required on a open graded surface since some of the salt would be lost in the pores having no effect on the surface [Sandberg 1992].

Another disadvantage of open graded surfaces is that they become clogged over time causing them to lose their noise reducing properties. However, cleaning performed with high pressure water jets has shown an improvement in noise reduction by 1.6 - 2.0 dB in reference to the noise levels before and after cleaning occurred [Steven 1990]. The cleaning process may not be very economical if it were to be used on long sections of roadway. Finally, an experiment in France has shown that when a open graded asphalt has become completely clogged, it can be recycled. A 20 km section of pavement was recycled with an addition of 6 - 8 percent pre-coated aggregate 6 - 10 mm and 0.3 - 0.8 percent binder [Weyringer 1991].

There is little agreement whether an open graded surface is more expensive to produce than other pavement surface types. Open graded surfaces have an advantage over dense graded surfaces because they require less bitumen [Sandberg 1992]. However, open graded surfaces have higher maintenance costs that are due to the de-icing process, shorter service life, and cleaning the surface once it becomes clogged. In urban areas, the construction of water drainage systems may be a significant expense incurred with the installation of a roadway. Using a open graded surface, as opposed to a dense graded or portland cement concrete surface, will reduce the requirements on the drainage systems since there is a natural accumulation capacity in open graded surfaces. This could prove to be an advantage in the overall cost associated with the design of such a system.

Dense graded asphalt pavements can have a variation in tire/road noise levels that are in the range of plus-or-minus 3 dB, based on experience in Sweden [Sandberg 1992]. The variation among dense graded asphalt pavements is due to the different macrotextures that can develop on the surface based on wear as the pavement ages and the selection of the aggregate gradation curve. It has been determined that dense graded asphalt surfaces with larger aggregate (up to 16 mm) produce higher noise levels and dense graded asphalt surfaces with smaller aggregate (8 mm) produce lower noise levels. However, the density of the surface and the degree to which areas between the large particles are filled with smaller particles may be more significant than aggregate size [Sandberg 1992].

Portland cement concrete pavements have been shown to have higher noise levels than asphalt pavements. However, there are several treatments for portland cement concrete pavements that can be used to reduce their noise levels [Sommer 1992-I]. These include longitudinal texturing, exposed aggregate, and thin overlays or surface dressings.

The type, method, and direction of texturing portland cement concrete surfaces has been known to be a significant factor when considering reducing tire/road noise. The most successful technique has been to groove the concrete surface in a longitudinal direction as opposed to transverse or random-transverse grooving techniques. A longitudinal groove pattern causes the tire tread to ride on the smooth and flat longitudinal ridges and not push down parts of the tire rubber into the groove each time a new groove is impacted which would induce tire radial vibrations. A previous study showed that a burlap drag longitudinal finish reduces noise by 2 dB when compared to a transverse finish produced by a broom [Sommer 1992-II].

Longitudinal grinding has also been shown to reduce noise on both old and new portland cement concrete surfaces based on measurements performed in Sweden [Sandberg 1992]. The grinding produced longitudinal grooves that had a groove spacing of approximately 5 mm with each groove being 2 - 3 mm in width. A noise level reduction was achieved in the range of 0.5 - 3.0 dB directly after grinding an old portland cement concrete surface. The study showed that over time, older portland cement concrete surfaces retain their noise reduction properties better than new portland cement concrete surfaces that were ground during construction. The grooves were worn out after only one year on the younger surface because the grinding was performed primarily on a relatively "soft" mortar on the top. On older surfaces, the grinding was performed on much harder aggregate that would be able to maintain the grooves for a longer time [Sandberg 1992].

If transverse grooving is necessary, randomization of the groove spacing is the simplest method that can be used to reduce the noise. Not only will the overall noise level of the pavement be reduced by randomizing the spacing of the grooves, but the energy will be spread out in the frequency domain over a couple of octaves. Spreading the energy over a greater frequency range will result in a less subjective annoying tonal quality or "whine" which is frequently associated with transverse grooved PCC pavements.

The most advantageous method to reduce tire/road noise levels on portland cement concrete surfaces is to use an exposed aggregate finish. This type of finish can be used on new, reconstructed, or recycled portland cement concrete pavements. The grain size of the exposed aggregate should preferably be 4 - 7 mm in order to give optimum macrotexture [Descornet and Sandberg 1980]. There are two methods which can be used to expose the aggregate. The first method, which is older and less preferred today, involves simultaneously watering and brushing the fresh concrete surface by means of a rotary brush. The second method involves spraying an appropriate setting retarder on the fresh concrete right after it hardens. After the concrete hardens (24 - 30 hours after laying), the surface is mechanically brushed in order to remove the mortar that has not yet set [Sandberg 1992].

From an economical standpoint, the additional costs for the exposed aggregate procedure cause and increase of approximately 10 % of the total pavement cost [Sommer 1992-I].

Thin overlays, or surface dressings, can be used to reduce noise on smooth portland cement concrete surfaces. To obtain the greatest potential reduction in noise, the aggregate size should be kept as small as possible with respect to wear and drainage. These surfaces have the ability to produce reductions in noise levels equivalent to those of open graded asphalt cements. However, when the thin overlays are worn, they gradually reach the level similar to a dense graded asphalt pavement [Sandberg 1992].

3.2. Tire/Road Noise Measurement Methods

Methods of tire/road noise measurement can be categorized as either mobilized, stationary, or laboratory. A mobilized measurement method uses a microphone that is positioned near the tire/road interface to measure the noise levels as the vehicle is moving over a given pavement. Stationary measurement methods typically use a microphone at a roadside position to measure the noise levels as a vehicle passes by. Laboratory methods may use mechanical systems to test tire/road noise.

3.2.1. Mobilized Measurement Methods

Two mobilized measurement methods that are commonly used to measure tire/road noise are the trailer method and the on-board microphone method. The trailer method involves using a test tire which is mounted on a trailer that is towed by a vehicle. One or more microphones are positioned close to the test tire, typically within 0.1-0.5 m. The trailer usually has an enclosure around the microphone and test tire to provide screening from traffic noise and wind. The noise level is then measured as an average over a given time interval, typically 4-60 seconds [Sandberg 1992].

The advantages of the trailer method are that it is fast, simple, precise, the topography and areas adjacent to the road do not have to meet strict requirements, and it is almost independent of the surrounding traffic [Sandberg 1992]. This method, however, has several disadvantages.

First, reference tires and a special measurement trailer are required. Second, only the tire/road noise is measured, therefore causing any relationship to traffic noise at roadside receivers to be estimated from this data. Third, the noise reduction properties of open graded road surfaces is underestimated due to the position of the microphone being so close to the test tire. The position of the microphone does not account for the noise absorption of a open graded surface over longer distances.

The on-board microphone measurement method is similar to the trailer method except that rather than using a trailer with a test tire, the on-board microphone method uses one of the tires of the test vehicle as a test tire. The microphone is positioned near the test tire and the microphone and tire are not screened from the surrounding environment.

An advantage of the on-board method is that a trailer is not needed. A disadvantage of this method is that the microphone can be influenced by disturbances from nearby traffic noise and air turbulence near the microphone since they are not screened from the surrounding environment. Additionally, the noise levels will be significantly influenced from the noise generated by the test vehicle.

3.2.2. Stationary Measurement Methods

There are three stationary measurement methods that can be used to measure tire/road noise. They are the coast-by method, the controlled pass-by method, and the statistical pass-by method. The coast-by method is primarily used to classify the influence that the road surface has on the noise, rather that a combination of vehicle and tire/road noise. A test vehicle is equipped with test tires and rolls or coasts-by with the engine switched off past a roadside microphone.

The microphone is positioned 7.5 m from the center of the test or road track on which the vehicle coasts. Using a FAST time response, the peak noise level is recorded as the vehicle coasts by.

While an advantage of this method is that there are no acoustical influences from the engine components, it does have several disadvantages. First, it is impractical and sometimes impossible to use on highways because there needs to be a low enough traffic intensity in order for the measurements not to be disturbed by traffic noise emissions. Second, a test vehicle is required along with a set of reference tires which must always be used on all of the road surfaces being compared. Third, while the this method is intended to isolate tire/road noise, wind noise and drive train noise remain factors in the measured levels.

The controlled pass-by method is similar to the coast-by method, except that the vehicle is passing the microphone at a constant speed with the engine turned on. A microphone is positioned 7.5 m from the center of the test or road track on which the vehicle coasts. Using a FAST time response, the peak noise level is recorded as the vehicle coasts by. For this method, the test vehicle must be continually available and must always remain in the same condition. This method is also similar to the coast-by and trailer methods in that reference tires must be used. The controlled pass-by method has been the preferred method of measurement in a extensive French-German cooperation project [Sandberg 1992].

An advantage of the controlled pass-by method is that noise levels between different road surfaces can easily be compared using different speeds and individual pass-bys can be repeated as necessary. A disadvantage of this method includes a loss of accuracy over time from change in vehicle noise due to engine and tire wear. Also, noise levels from the test vehicle are not representative of the types of vehicles/tires found in the overall stream of traffic on a roadway, including light and heavy vehicles.

The final method, which uses actual traffic situations, is the statistical pass-by method. This method requires the setup of one or several microphones placed at the roadside, typically at 7.5 m or 10 m, but no more than 15 m from the road. As an isolated vehicle passes in front of the microphone(s), the sound levels and/or spectral data and speed of the vehicle are recorded. The measured levels are a summation of all vehicle sub-sources in addition to tire/road noise. Vehicle pass-bys are recorded for a statistically significant amount of different vehicle types as they normally appear in the traffic stream.

The advantages of the statistical pass-by method are that actual traffic noise levels are measured for different vehicles, light and heavy, that normally appear in the flow of traffic. Also, differences in noise levels measured for different pavement types directly correlate to levels experienced in residential neighborhoods adjacent to roadways. Disadvantages of this method are that there are strict site requirements that must be met for traffic volumes, roadside topography, and wind conditions. The roadways used for the measurement sites must have sufficient traffic volumes to produce a large enough sample size. However, there will not be enough spacing between vehicles to permit the measurement of individual vehicles if the traffic volumes are too great. This method also requires a great deal of time to collect individual vehicle pass-bys for a statistically significant amount of vehicles. Another disadvantage is that comparison of different surfaces over time becomes inaccurate due to changes in vehicle noise emission levels.

3.2.3. Laboratory Methods

Two laboratory methods which can be used to measure tire/road noise are the sound propagation or sound absorption method and the laboratory drum method. The sound propagation or sound absorption method used to study sound propagation between the source and the receiver. With this method, either a loudspeaker emits a "reference" noise which is picked up by a microphone at some distance (typically the same source-receiver setup as in the coast-by method) or road surface samples are mounted at the end of a tube (Kundt's tube) and the sound absorption coefficient is measured [Sandberg 1992]. By using the loudspeaker method on different surfaces, the relative influence on propagation can be studied.

The advantage of this method is that the significance of open graded asphalt surfaces on sound absorption can be quantified and compared with other surface types. The main disadvantage of this method is that information related to the noise properties of road surfaces in general cannot be obtained since the influence that the road surface has on vehicle emissions is not being considered.

There has been research performed in Europe using mechanical systems to test tire/road noise. The laboratory drum method is one example where the surface textures for various types of pavement are formulated and bonded to cylindrical steel cylinders which rotate against a test tire at specified loads. The noise generated by these different surfaces are monitored by microphones which are placed near the tire-pavement interaction.

4. MEASUREMENT SITES

This section describes the measurement sites used to develop the noise characteristics of the pavements selected for the study. This section also includes a description of the characteristics each site must possess to qualify for measurement, a definition of the vehicle types considered, and the pavement types and ages that were used. Also the locations and descriptions of the specific sites which were used for the study are provided. The measurement sites used for this study met all qualifications for both the United States Department of Transportation (USDOT) noise measurement procedures for Measurement of Highway Related Noise [Lee and Fleming 1996] and the International Organization of Standardization (ISO) 11819-1 Statistical Pass-By Method [International Organization of Standardization 1994].

4.1. Site Requirements

Through coordination with ODOT, several potential sites were identified within the state of Ohio. The sites were then evaluated and selected based on the following requirements:

1. The roadway test sections extended at least 50m on each side of the microphone locations. This space was free of large reflecting surfaces, such as parked vehicles, signboards, buildings, or hillsides.
2. The roadways were relatively level and straight. It was permissible to have roads with slight bends or with grades less than or equal to 1%.
3. The sites exhibited constant-speed vehicle operating conditions with cruise conditions of at least 88 km/h. Therefore, the site was located away from intersections, lane merges, or

any other feature that would cause traffic to accelerate or decelerate.

4. The sites had a prevailing ambient noise level that was low enough to enable the measurement of uncontaminated vehicle pass-by sound levels.
5. The road surfaces were in good condition and were homogeneous over the entire measurement sections. The surfaces were free from cracks, bitumen bleeding, and excessive stone loss.
6. The traffic volumes for each vehicle category were large enough to permit an adequate numbered sample to be taken to perform the statistical analysis but also low enough to permit the measurement of individual vehicle pass-bys.
7. The sites were located away from known noise sources such as airports, construction sites, rail yards, and other heavily traveled roadways.
8. The ground surface within the measurement area was essentially level with the road surface, varying by no more than 0.6 m parallel to the plane of the pavement along a line from the microphones to the pavement. The ground was also no more than 0.6 m above or below the roadway elevation at the microphones. Any roadside ditch or other significant depressions were at least 5 m from the center of the test lane.
9. At least half of the area between the center of the test lane and the microphone had acoustical properties similar to the pavement being measured. The ground surface was free from any vegetation which was higher than 0.6 m or could be cut down at any sites which did not meet this requirement.
10. To ensure free field conditions, at least 25 m of space around the microphones was free of any reflecting objects. Also, the line-of-site from the microphones to the roadway was unobscured within an arc of 150 degrees.

4.2. Vehicle Categories

The vehicle categories were selected in accordance with those specified in the USDOT method and the ISO standard that were mentioned above. This selection was done to ensure that each vehicle category contained vehicles that have common features which are easily identified in the traffic stream and have similar acoustical characteristics when traveling under the same road conditions. Vehicle categories which are not described below were not used for the study because they did not give any additional information about the influence of the road surface. The categories are defined as follows:

Category 1 - Automobiles (A): All vehicles which have two axles and four tires which includes passenger cars and light ("pick-up") trucks. The gross vehicle weight is generally no more than 4500 kg.

Category 2 - Heavy Vehicles: All trucks, buses, and coaches with at least 2 axles and more than 4 wheels. Category 2 consists of subcategories 2a and 2b.

Category 2a - Medium Trucks (M): All cargo vehicles having two axles and six tires. The vehicle weight for this category is more than 4500 kg, but less than 12,000 kg.

Category 2b - Heavy Trucks (H): All cargo vehicles having three or more axles. The gross vehicle weight is more than 12,000 kg.

4.3. Pavement Types and Ages Selected

Sites were also selected in accordance with ODOT officials based on pavement type and age. Pavement types selected varied with materials, aggregate type, thickness, and surface texture. The pavements consisted of dense-graded asphaltic concrete (DGAC), open-graded asphaltic concrete (OGAC), stone mastic asphaltic concrete (SMA), and portland cement concrete (PCC). DGAC sites were chosen that composed of limestone, gravel, and slag. The PCC sites consisted of different types of textures that included transverse (T), random-transverse (R/T), and longitudinal (L) grooving. Pavements were selected with ages that varied from seven years to one year, with the majority of pavements being one year in age. The ODOT mix specifications for each pavement type for all sites are given in Appendix A.

4.4. Measurement Site Locations and Descriptions

From the potential sites provided by ODOT, a total of fifteen sites were chosen for acoustical measurement of which twelve were used to develop the Statistical Pass-By Index (SPBI) and REMELs. Table 1 gives a detailed description of each site used to collect both the SPBI and REMEL data including its site number, location, roadway, pavement type, surface type (for PCC), year constructed, aggregate type (where applicable), and date measured. Measurement site plan and profile drawings are provided in Appendix B for all twelve SPBI/REMEL sites.

Four PCC sites which did not meet the traffic speed and volume requirements were used for a separate study to compare different concrete surfaces. To accurately compare all of the PCC pavements, sites 8 and 12 were also included in this study. Table 2 describes each site including the site number, location, roadway, year constructed, date measured, and groove type. The ODOT specifications for a random-transverse grooved PCC surface state that grooves are spaced 10 - 45 mm apart with at least 50 percent of the grooves being less than 25 mm with a depth 4 mm and width of 3 mm. The specifications for the uniformly transverse grooved PCC pavements state that the grooves are spaced 15.9 mm, center on center, with a depth of 4 mm and

Table 1. Measurment sites and characteristics for SPBI and REMEL data.

Site #	Location	Type	Year Const.	Surface Thickness	Aggregate Type	Date Measured
1	US 30 WB, Allen Co., Between Rt. 115 and Rt. 309.	DGAC	1997	32 mm	Limestone	7/6/98
2	US 30 WB, Van Wert Co., Between Rt. 418 and Rt. 185.	DGAC	1997	38 mm	Limestone	7/9/98
3	US 30 WB, Wayne Co., Near the Stark Co. Line.	SMA	1995	38 mm	Limestone	7/1/98
4	I-480 NB, Summit Co., Between Ohio Turnpike and SR 82.	OGAC	1997	19 mm	N.A.	6/24/98
5	I-70 WB, Licking Co., West of Buckeye Lake.	DGAC	1996	32 mm	Limestone/ Gravel	7/8/98
6	SR 32, WB, Pike Co., Near SR 335.	DGAC	1991	32 mm	Gravel	6/18/98
7	SR 32 EB, Pike Co., Between Schuster and Shyville Rd.	DGAC	1997	32 mm	Gravel/ Limestone	6/17/98
8	I-77 SB, Noble Co., Between MM 20 and 19.	PCC, Random-Transverse	1997	229 mm	N.A.	9/26/98
9	I-70 EB, Belmont Co., Before Morristown/ Belmont Exit.	DGAC	1997	32 mm	Slag	6/22/98
10	I-470 EB, Belmont Co., Between I 70 Exit and W.V. State Line.	DGAC	1997	38 mm	Gravel	6/23/98
11	I-77 SB, Tuscarawas Co., Between Dover Rest Area and Strasburg Exit.	DGAC	1997	51 mm	Gravel	7/1/98
12	SR 39 EB, Tuscarawas Co., Approximately 5 miles West of I 77.	PCC, Transverse	1994	229 mm	N.A.	6/30/98

width of 3 mm. The longitudinally grooved PCC pavement was textured by use of a milling machine which ground down the existing surface.

Table 2. Measurement sites and characteristics for PCC comparison.

Site #	Location	Groove Type	Year Placed	Surface Thickness	Date Measured
8	I-77 SB, Noble Co., Between MM 20 and 19.	Random-Transverse	1997	229 mm	11/6/98
12	SR 39 EB, Tuscarawas Co., Approximately 5 miles West of I 77.	Transverse	1994	229 mm	11/6/98
13	SR 50 EB, Athens Co., Between US 33 and E. State St. Exit.	Longitudinal	1994	203 mm	10/21/98
14	SR 50 EB, Athens Co., Between E.State St. Exit and SR 690.	Transverse	1997	254 mm	10/21/98
15	SR 50 EB and WB, Athens Co., Near SR 7.	Random-Transverse	1998	254 mm	11/6/98 10/21/98

A Strategic Highway Research Program (SHRP) test road site in Delaware County provided two comparisons: similar DGAC surfaces with different base thicknesses; and different DGAC surfaces with similar base thicknesses. This site did not meet the volume requirements, but was used for a separate study to quantify the acoustical effects of increasing the thickness of the pavement base. The comparison of noise levels for pavements with different base thicknesses was designed to provide a correlation between pavement stiffness and noise levels. This site also offered an opportunity to measure and compare other ODOT DGAC surfaces which were not included in the SPBI/REMEL study. The characteristics for each section measured at the Delaware County site, including surface types and base thicknesses, are given in Table 3.

Table 3. Measurement site and characteristics for pavement stiffness study.

			Thickness (mm)		
Location	**Date Measured**	**Section**	**AC**	**Base**	**Base Type**
SR 23 SB, Delaware Co.	10/9/98	108	178	305	102mm PATB/203mm DGAB
		109	178	407	102mm PATB/305mm DGAB
		110	178	204	102mm ATB/102mm PATB
		901	102	559	AC-20 305mm ATB/102mm PATB/152mm DGAB
		902	102	559	PG 64-28 305mm ATB/102mm PATB/152mm DGAB
		903	102	559	PG 58-28 305mm ATB/102mm PATB/152mm DGAB

PATB = Permeable Asphalt Treated Base, DGAB = Dense Graded Aggregate Base
ATB = Asphalt Treated Base

5. MEASUREMENT INSTRUMENTATION

This section describes the instrumentation used for the field data collection. Full descriptions of instruments and settings are included for both acoustical and supplemental equipment. A complete listing of the equipment used can be found in Appendix C.

5.1. Acoustical Instrumentation

The system used to acquire the acoustical data included two Bruel and Kjaer Free Field ½ inch Type 4189 pre-polarized microphones each connected to a Larson-Davis Model PRM900B Preamplifier. Correction factors were supplied by the manufacturer and applied when reducing the data to provide the correct acoustical response for each microphone orientation.

The microphones and preamplifiers were positioned in nylon holders and then mounted on tripods located at distances of 7.5 m and 15 m from the centerline of the near travel lane. The microphone at 7.5 m, used to collect data for the SPBI, was positioned at a height of 1.2 m (+/- .1 m) above the plane of the roadway and its reference axis for free field conditions was orientated horizontal and directed perpendicularly towards the path of the vehicles. This microphone position and orientation was in accordance with ISO standard 11819-1 for the Statistical Pass-by Method.

The 15 m microphone, used to collect data for the REMEL development, was set at a height of 1.5 m (+/- .1 m) above the plane of the roadway and orientated vertically with respect to the diaphragm of the microphone for grazing incidence. This microphone position and orientation was in accordance with the procedures described in USDOT's Measurement of

Highway-Related Noise [Lee and Fleming 1996]. Figure 1 shows a plan and profile view of the microphones and their positions.

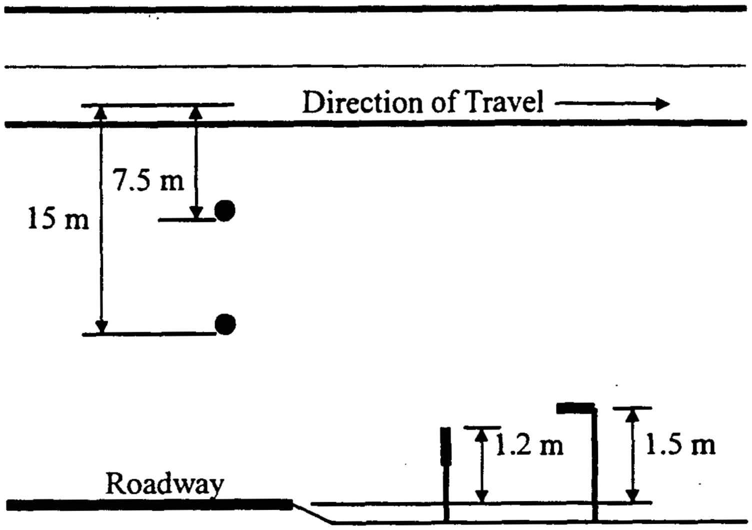

Figure 1. Plan and profile views of typical microphone layout (not to scale).

The microphones and preamplifiers were connected to a Larson Davis Model 2900B, dual channel, one-third octave band analyzer by cables which were 30 m in length. Recording and storage of the measured acoustical data was achieved by the 2900B. Data was stored for the frequency range of 50-10,000 Hz every 1/2 second using a fast response, 1/8th second exponential averaging method. The instrument was also programmed to capture the spectrum when the A-weighted sound level reached its maximum during a vehicle pass-by. The data from the internal memory of the 2900B was transferred to floppy disk for later off-site processing and analysis.

To ensure that each measured vehicle pass-by produced at least a 6 dB rise above ambient noise levels, which included other vehicles in the traffic stream, the 2900B was programmed to SLM+A mode. This function graphically displayed the continuous sound level of a vehicle pass-by to indicate the rise and fall of sound level relative to ambient levels.

5.2. Supplemental Instrumentation

To record the vehicle speeds, a Laser Tech, Ultralyte 20-20 hand-held laser-gun was used. The laser-gun recorded speeds with an accuracy of +/- 1 km/h and was positioned approximately 120 m upstream of traffic flow, relative to the microphones, and no more than 10 m from the centerline of the near travel lane. These distances were measured and recorded for each site, and correction factors were supplied by the manufacture to give the true vehicle speed based on these distances. These factors were then applied in the data reduction phase of the project.

A Davis Instruments, Weather Wizard II digital weather station was used to continuously monitor the temperature, wind speed, and wind direction. Temperatures were recorded at an accuracy of +/- 0.5° C and wind speeds of +/- 5%. The relative humidity was measured using a Hygrocheck digital hygrometer with an accuracy of +/- 3% full scale. The road surface temperature was measured at the wheel path using an Omega OS520 hand held infrared thermometer. The instrument was positioned at a height of 0.9 m (+/- 0.1 m) above the roadway surface with an accuracy of +/- 1% of the reading.

Calibration of the 2900B was done using a Larson Davis Model CA200 acoustic calibrator. The calibrator produced a signal of 1000 Hz at a sound pressure level of 94 dB. Additionally, the measurement microphones were replaced with a Larson Davis ADP005 passive microphone simulator (dummy microphone) prior to each measurement to determine the electronic noise floor of the Larson Davis 2900B which could be influenced by any sources of electromagnetic radiation near the site.

6. MEASUREMENT PROCEDURES

The following section will describe in detail the procedure which was used to collect the SPBI and REMEL data. Also included are the procedures which were used to collect the data to compare the different PCC surfaces and the acoustical data related to the pavement stiffness.

6.1. Statistical Pass-By Index/REMEL Procedure

This procedure includes the methodology to collect acoustical data to produce both the SPBI and REMELs simultaneously. This methodology involved meeting the measurement requirements of both the ISO standards for the Statistical Pass-by Method and the USDOT's requirements for Measurement of Highway Related Noise.

6.1.1. Road Speed Category

There were three road speed categories (low, medium and high) which could be used in accordance with the ISO Statistical Pass-by Method. For this study, the "high" speed road category, which describes the road conditions relating to cars that operate at an average speed of 100 km/h or more, was chosen.

6.1.2. Minimum Vehicle Sample Size

The minimum number of samples recorded for each site, as specified by the ISO Statistical Pass-by Method, are:

Category 1 (Automobiles):	100
Category 2a (Medium Trucks)	30
Category 2b (Heavy Trucks)	30
Categories 2a and 2b together (Heavy Vehicles)	80

For the case of the heavy vehicle category, if 30 medium trucks were measured, for example, then 50 heavy trucks would need to be measured to provide the required combination of 80 heavy and medium trucks.

6.1.3. Identification of Vehicles for Measurement

In order for a vehicle to be considered for a measurement, several criteria needed to be met. First, the vehicles needed to fit into one of the three categories that were described in Section 4.2. Secondly, a separation distance between vehicles was to be large enough so that the A-weighted noise level during the pass-by, just before and just after the passage of a vehicle intended to be measured, was at least 6 dB below the measured maximum A-weighted noise level during the pass-by at the 7.5 m microphone. This distance was increased when the vehicle considered for measurement was in the vicinity of a medium or heavy truck.

Third, any vehicles which distinctly displayed unusual or atypical noise characteristics due to faulty exhaust systems or other noticeable sources were disqualified. Care was also taken to make sure that noise from vehicles in the opposing direction of travel did not influence the noise level of the vehicle being measured.

Noise levels of each individual pass-by were measured for vehicles traveling at a constant speed in the center of the near travel lane without deviating from their lateral position. Any vehicles which were not moving at a constant speed or moved noticeably from their lateral position from the center of the test lane were not used for the measurement.

6.1.4. Documentation of Pass-By Events

Documentation for each vehicle pass-by included the event number, event acoustical quality, vehicle type, and any distinguishing features which the event may have had. Event numbers were coordinated on both the site logging sheets and the Larson Davis 2900B so that off site analysis of individual vehicles could be performed.

The event acoustical quality for each pass-by was recorded based on the difference between the maximum and minimum sound level at the beginning or ending of an event (whichever value was smaller). The highest quality event would have a difference of at least 10 dB between the maximum and minimum sound level and would be designated as a Type-1 event. Pass-bys which had a rise and fall in the range of 6 - 10 dB were considered acceptable events and were designated as Type-2 events. A pass-by which did not have at least a 6 dB rise and fall were designated as Type-3 events and were not used for the study.

The vehicle types were recorded as A (Automobile), M (Medium Truck), and H (Heavy Truck). For automobiles, the make, model, and whether it was a sport utility vehicle, were recorded for each event. Also, for all events, any unique vehicle characteristics which were observed during the pass-by were documented.

6.1.5. Statistical Pass-By Index/REMEL Data Collection Procedure

To collect the acoustical data for Sites 1 through 12, two microphones were placed at 7.5 m and 15 m from the centerline of the near travel lane as shown in Figure 2. The 7.5 m

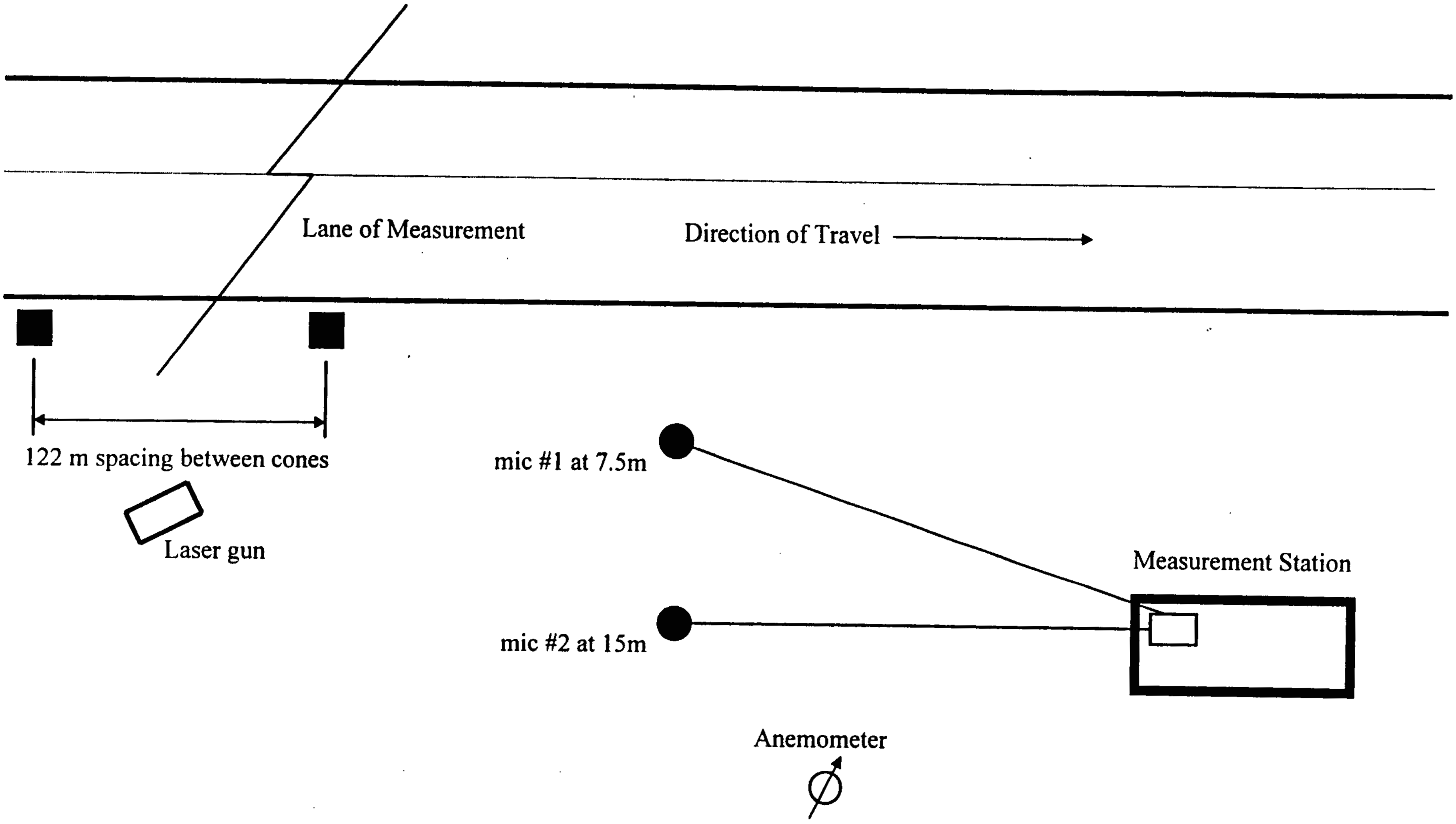

Figure 2. Typical site layout (not to scale).

microphone was used to collect the SPBI data which would be used to compare the different pavements. REMELs were developed from the acoustical data which was collected at the 15 m microphone location.

Measurements were performed using three people, which included a vehicle observer, acoustical instrument operator, and team coordinator. The acoustical instrument operator and team coordinator were located at the operator's position along with the acoustic and meteorological instrumentation. The microphones were positioned downstream relative to the traffic flow at a distance of 30 m in relation to the operator's station. Depending on the roadside conditions, the operator's position was located as far away as possible from the roadside and microphones. This was done to avoid changes in vehicle speed due to driver curiosity and to eliminate possible contributions to measured noise levels due to the noise from the operator's station.

The vehicle observer was positioned at a distance of at least 200 m upstream from the microphone locations. Orange cones were positioned along the roadway, 120 m apart, to assist the vehicle observer in determining the separation distance between vehicles.

When a potential vehicle for measurement was identified, the vehicle observer notified the acoustical instrument operator and the team coordinator of the type of vehicle approaching and its make and model (if automobile). The vehicle observer then monitored the vehicle's speed before, during, and after the microphone position. Prior to the capture of acoustical data, the acoustical instrument operator observed the traffic in the opposing direction to ensure that there would be no contamination of the measured pass-by level. If the acoustical conditions were acceptable, the acoustical instrument operator initiated data collection on the Larson Davis 2900B and observed the noise levels to determine the quality of the event. At the same time, the team coordinator viewed the wind speed to ensure that it was within the limits mentioned below. Once the vehicle passed the microphones and before other vehicles approached the site, data collection was stopped. Acoustical data for each pass-by was then stored in the analyzer. The stored data included the event number, vehicle type, the A-weighted spectrum at ½ second intervals, and the maximum A-weighted spectrum at the moment that the maximum A-weighted noise level occurred.

Information was recorded on data logging sheets at the conclusion of each event. The team coordinator recorded the event number, event time, event quality, vehicle type (make and model if automobile), and vehicle speed. It was the responsibility of the team coordinator and acoustical instrument operator at hourly intervals to make sure that the event numbers in the Larson Davis 2900B corresponded with those on the data sheets.

Calibration of acoustical instrumentation was performed before, at hourly intervals, and after the measurements were performed. The calibration readings of the acoustical measurements did not differ by more than 0.5 dB during any given interval. Therefore, no hourly measurement intervals were considered invalid. The electronic noise floor of the Larson Davis 2900B, which was checked and recorded prior to the initialization of any measurement, never exceeded 30 dB for all sites. A value greater than 40 dB would have disqualified the site. The accuracy of the laser gun was also checked on an hourly basis by using the instrument's distance option to measure a given distance. It was determined that if the instrument's reading did not fluctuate +/- .1 m between hourly intervals, that it was functioning accurately.

Meteorological conditions were monitored continuously and recorded at 15 minute intervals. This included the atmospheric temperature, wind speed and direction, relative humidity, and cloud cover. The wind speed was monitored at the microphone height and did not exceed 5 m/s during any measurement. Previous studies have concluded that wind speeds below 5 m/s have no apparent effect on measurements performed at a distance within 30 m of the noise source [Lee and Fleming 1996]. Air temperature was measured in a position where the air was flowing freely and the instrument was out of direct sunlight. Pavement temperature was also measured at 15 minute intervals. The listing of meteorological data can be found in Appendix D.

Moisture on or within the pavement structure was a concern. Therefore, all measurements were performed only when the road surfaces were dry. At least two days passed since the latest precipitation for all pavements measured except in the case of the open graded asphalt concrete (OGAC), where at least four days passed.

6.2. Concrete Surface and Pavement Stiffness Procedure

To collect acoustical data for Sites 13, 14, 15, 16 and the Route 23 site, a separate procedure was developed due to site constraints from traffic conditions (speeds and/or volumes). It was realized that collecting data from these sites would be valuable in the ranking of ODOT's different pavement types, but would also permit a separate study to determine the significance that pavement stiffness may have on the acoustical properties of a pavement.

To make the comparison of the pavement surfaces as accurate as possible, an automobile test vehicle was used at each site. The automobile test vehicle was a 1998 Dodge Stratus mid-sized automobile that was equipped with Michelin Radial MX4 All Season (P195/65 R15) tires. This automobile test vehicle was also used to collect acoustical data at Sites 8 and 12, which were used for the SPBI/REMEL study, to give a more accurate comparison of ODOT's PCC types.

The microphone was positioned at 7.5 m from the near travel lane next to the pavement section that was to be measured. Since the objective for both the concrete surface and pavement stiffness studies was to compare the acoustical properties of different pavement surfaces, rather than developing REMELs, only the 7.5 m microphone was used. The height of the microphone, orientation, and position relative to the operator's position along with the settings for the Larson Davis 2900B, were the same as the SPBI/REMEL procedure mentioned in the previous section. Calibration and determination of the acoustical instrumentation's noise floor were also determined as stated above.

The measurements required two people: a automobile test vehicle operator and an acoustical instrument operator. When there was not a presence of vehicles in either direction of traffic, the automobile test vehicle operator drove the automobile test vehicle at a constant speed passed the microphones at the same time the acoustical instrument operator recorded the acoustical data. At the Route 23 site, the lanes used for measurement were closed to traffic, which was then re-routed to roadways adjacent to those used for testing. To avoid noise contamination, measurements were only made when there were gaps in the traffic on the adjacent lanes.

Measurements were recorded for a minimum of five pass-bys for speeds of 88.5 km/h and 104.6 km/h. After each pass-by, the acoustical instrument operator recorded the maximum A-weighted sound level. For each test section, a successful event occurred when maximum A-weighted sound level did not differ by more than +/- 1 dB from each other event taken from that section.

Before and after each pavement surface was measured, the tire pressure, atmospheric temperature, wind speed/direction, and pavement temperature were recorded. The meteorological data can be found in Appendix D.

For the pavement stiffness study, an ODOT tandem axle dump truck test vehicle was used for Sections 108, 109, and 110 in addition to the automobile test vehicle. Due to the limited distance available for vehicle acceleration, a constant pass-by speed of 72.4 km/h was used and three samples were recorded. The weight of the vehicle was also recorded for the measurement.

7. DATA REDUCTION

Once the measurements were completed, the data for each site was downloaded into separate spreadsheets in Microsoft Excel Version 7.0 for further analysis. Correction factors were then applied to the acoustical data collected at 7.5 m and 15 m based on their microphone orientation. Then the corresponding measured vehicle speed from the field logging sheets was input for each vehicle pass-by. The data was then categorized by its event quality and vehicle type and sorted into individual spreadsheets based on vehicle category. This process is discussed in further detail in the following sections.

7.1. Correction Factors

Correction factors were applied to the acoustical data and the speed data during the data reduction process. Based on the microphone angle of incidence, correction factors were provided by Bruel and Kjaer for each microphone. The 7.5 m microphone was corrected for zero degree incidence and the 15 m microphone was corrected for ninety degree incidence.

The vehicle speeds were also corrected based on the values provided by the manufacturer, Laser Tech. Corrections were based on the distance the laser gun was positioned from the centerline of the near travel lane and the distance to the target. Distances were rounded to the nearest value that corresponded to the distances provided by the manufacturer.

7.2. Event Quality

After the data was downloaded into a spreadsheet, the event quality for each corresponding vehicle pass-by was input. All data which was categorized as a Type-3 event (rise and fall in sound level less than 6 dB) was separated and not included any further in the analysis. Only data for Type-1 (rise and fall in sound level greater than 10 dB) and Type-2 (rise and fall in sound level between 6 and 10 dB) were used in the data analysis process.

7.3. Vehicle Types

Once the data was downloaded, the vehicle types which corresponded to each event number were input. Vehicles were classified as follows: "A" for automobile, "M" for medium truck, and "H" for heavy truck. Automobiles were further classified by whether or not they were a sport utility vehicle. After the data was classified by vehicle type, it was sorted and placed into separate spreadsheets for automobiles, medium trucks, and heavy trucks for further analysis.

8. DATA ANALYSIS

This section describes the methods which were used to develop the SPBI, REMELs, and acoustical results for the concrete and stiffness studies. The methodology used to determine the SPBI was based on a procedure developed by the International Organization for Standardization [International Organization for Standardization 1994]. Determination of the REMELs was based on a procedure developed jointly by Harris Miller Miller and Hanson Inc., Vanderbilt University, the University of Central Florida, and the Volpe Center [Anderson et al. 1995] and as also described in USDOT's Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model [Fleming, Rapoza, and Lee 1995].

8.1. Methodology for Statistical Pass-By Index (SPBI)

This section describes the methods which were used to calculate the Statistical Pass-by Index for the acoustical data collected at the 7.5 m microphones. The SPBI is a noise index for comparing different road surfaces based on vehicle sound levels that take into account different types and speeds of vehicles. Data pairs consisting of maximum A-weighted vehicle noise levels and logarithm of speed (base 10) were linearly regressed for each vehicle category. Using a given reference speed, the maximum A-weighted sound level was determined from the regression line. This level is referred to as the "vehicle sound level", Lveh.

For each pavement, the vehicle sound levels for the automobiles, medium trucks, and heavy trucks were logarithmically added, assuming certain proportions of these vehicle categories, to determine a final result, the SPBI. The SPBI was then used to compare different road surfaces to determine their influence on noise levels for a mixed traffic flow.

This methodology was also used to calculate the maximum A-weighted spectrum for each pavement. By using each frequency associated with the maximum A-weighted spectrum, rather than the overall maximum A-weighted sound level, as mentioned in the following section, a SPBI was calculated for each frequency in the range of 50 to 10,000 Hz. Therefore, not only are the maximum A-weighted sound levels compared between pavements, but the maximum A-weighted spectrums are as well.

8.1.1. Regression Analysis

Using data pairs containing the maximum A-weighted sound level and the logarithm of speed (base 10) for each vehicle pass-by, a linear regression analysis was performed using the least squares method. This analysis was performed for each vehicle category.

8.1.2. Vehicle Sound Level

Table 4 shows the reference speeds for each vehicle category for the high road speed category. The vehicle sound level, Lveh, is the ordinate noise level of the regression line for each vehicle category at the corresponding reference speed. Three Lveh's were found for each road surface: for automobiles, medium trucks, and heavy trucks.

To determine the Lveh, the reference speed must be within a certain range of the speeds which were measured for each vehicle pass-by. For automobiles, the reference speed must be within the range of plus-or-minus one-and-a-half standard deviations for the speed measured or that road surface. For medium and heavy trucks, the range is plus-or-minus one standard deviation.

Table 4. Reference speeds and weighting factors used to determine vehicle sound levels.

Vehicle Category	**Reference Speed (km/h)**	**Reference Speed (mi/h)**	**Weighting Factor**
Automobiles	110	68	0.700
Medium Trucks	85	53	0.075
Heavy Trucks	85	53	0.225

8.1.3. Calculation of the SPBI

Once the vehicle sound levels were obtained for each vehicle category for a given road surface, the overall sound level was determined. This overall level, or SPBI, was calculated using the procedure given in the ISO standard using Equation 8-1 [International Organization for Standardization 1994].

$$SPBI = 10\bullet\log[W_1\bullet 10^{L1/10} + W_{2a}\bullet(v_1/v_{2a})\bullet 10^{L2a/10} + W_{2b}\bullet(v_1/v_{2b})\bullet 10^{L2b/10}]\ [\mathrm{dB}] \qquad (8\text{-}1)$$

where

SPBI	Statistical Pass-By Index, for a standard mix of light and heavy vehicles.
L_1, L_{2a}, and L_{2b}	vehicle sound levels for vehicle categories 1, 2a, and 2b.
W_1, W_{2a}, and W_{2b}	weighting factors, which are equivalent to the assumed proportions of vehicle categories in the traffic, according to Table 4 .
v_1, v_{2a}, and v_{2b}	reference speeds of individual vehicle categories, according to Table 4.

According to the ISO standard, the weighting factors used in Table 4 are a global representation of the most typical cases, which allows simple comparisons of road surfaces.

8.1.4. Reference Pavement

A reference pavement was determined by averaging the SPBI data from all dense graded asphaltic concrete pavements that were one year old. Noise levels for the reference pavement were normalized to zero decibels and the noise levels on all other pavement surfaces were represented as differences from this reference pavement.

8.2. Determination of REMELs

This section describes how the Reference Energy Mean Emission Levels used in the FHWA TNM were determined for the acoustical data collected at the 15 m microphone. The first step in finding the REMELs involved calculating the level-mean emission levels by regressing the measured maximum A-weighted values as a function of vehicle speed, which is explained in Section 8.2.1. Next, the level-mean emission levels were adjusted upwards by a fixed value. This fixed value is a function of the relationship between the level-mean regression and the individual maximum A-weighted values, which is discussed in Section 8.2.2.

Due to the lack of low speed acoustical data collected during the measurement, it is strongly recommended that use of the REMEL coefficients be restricted to situations where the speed range considered is more than 72.4 km/h.

8.2.1. Level-Mean Emission Level Regression

The maximum A-weighted sound levels were regressed as a function of speed for each vehicle type and roadway surface to compute the level-mean emission levels. The functional form of the level-mean regression equation is as follows:

$$L(s) = 10\log_{10}(10^{C/10} + 10^{((A\log s+B)/10)}) \tag{8-2}$$

$$= 10\log_{10}(10^{C/10} + s^{A/10}10^{B/10}) \tag{8-3}$$

where

$L(s)$	vehicle emission level for a given vehicle speed.
C	engine/exhaust coefficient independent of vehicle speed.
$A\log_{10}(s) + B$	tire/road term that increases with increasing vehicle speed.

8.2.2. Adjustment from Level-Mean to Energy-Mean

The adjustment from level-mean to energy mean was done by using a correction factor, ΔE. This adjustment factor was calculated by using the level residuals, which are equivalent to the value of each data point at its corresponding speed minus the value of regression at that speed, and the energy residuals which are equal to $10^{(\text{Level Residual}/10)}$. The equation used to calculate ΔE is as follows:

$$\Delta E = 10\log_{10}((1/n)\Sigma RE_i) - (1/n)\Sigma RL_i \tag{8-4}$$

where

ΔE	energy-mean adjustment factor
n	number of samples
RE	energy residuals
RL	level residuals

The energy-mean adjustment factor was added to both the engine/exhaust term and the tire/road term of the L (s) equation, i.e., the C and B coefficients. This was done as follows:

$$L_e(s) = 10\log_{10}(10^{C+\Delta E/10} + s^{A/10}10^{B+\Delta E/10}) \tag{8-5}$$

The ΔE adjustment factor converted the level-mean regression to an energy-mean regression. In determining the REMELs, a ΔE term was computed separately for the engine/exhaust term and the tire/road term. This was done once the C coefficient was computed, giving a ΔE_C term, and once during the computation of the B coefficient, giving a ΔE_B term.

8.2.3. Confidence Interval

The 95-percent confidence interval (CI) was calculated for the average pavement (as defined in Section 7.2.4) energy-mean regression. Equation 8-6 was used to calculate the 95-percent CI.

$$\text{95-percent CI } (s) = L_E\,(s) +/- \; 19.6\varepsilon_{regr}\,(s) \tag{8-6}$$

The 95-percent CI describes the bounds within which one can be 95 percent sure that the energy-mean regression lies. The ε_{regr} (s) term is the standard error of the energy-mean regression as a function of speed as shown in Equation 8-7.

$$\begin{aligned} \varepsilon_{regr}(s) = \frac{1}{E}\{ & (s^{A/10}10^{B/10})^2[(\log_{10} s)^2 \varepsilon_A{}^2 + \varepsilon_B{}^2] + (10^{C/10})^2 \varepsilon_C{}^2 \\ & + 2(s^{A/10}10^{B/10})^2 (\log_{10} s)\rho_{AB}\varepsilon_A\varepsilon_B + 2(10^{C/10})(s^{A/10}10^{B/10}) \\ & [(\log_{10} s)\rho_{AC}\varepsilon_A\varepsilon_B + \rho_{BC}\varepsilon_B\varepsilon_C] + \frac{\sigma_{RL}{}^2\sigma_{RE}{}^2}{N(\overline{RE})^2}\}^{1/2} \end{aligned} \tag{8-7}$$

where

E	equals $10^{C/10} + s^{A/10}10^{B/10}$	(8-8)
ε_A, ε_B, ε_C	standard errors of the A, B, and C coefficients.	
ρ_{AB}, ρ_{AC}, ρ_{BC}	a measure of the correlation between coefficients.	
σ_{RL}	the standard deviation of the level residuals.	
σ_{RE}	the standard deviation of the energy residuals.	

$\overline{RE}$ the mean of the energy residuals.

N the number of data points.

8.2.4. Average Pavement

For the calculation of REMELs, the average pavement is defined as a combination of all one year old DGAC pavements. An average pavement was calculated for each vehicle category: automobiles, medium trucks, and heavy trucks.

The relationship between vehicle sound levels and speed in nonlinear. Therefore, to perform the regression of the functional form for the computation for L_E (s), a non-linear regression model was used. SYSTAT Version 5.03 for DOS, a statistical analysis software package, was used to estimate the A, B, and C coefficients. The estimation of the coefficients was done using the Simplex and/or Quasi-Newton non-linear regression methods.

Since tire/road noise is the primary contributor to emission levels for automobiles, the transformation between the tire/road portion of the regression and the engine/exhaust portion occurs at a very low speed. To account for the engine/exhaust portion of the regression, acoustical data for idling automobiles was needed. However, no idle data was collected for this project. Since vehicle noise emission at idle is independent of pavement type, other data bases could be used. After consultation with the John A.Volpe National Transportation System Center, it was determined that the idle data collected during USDOT's development of REMELs could be used in the computation, assuming that there has not been a change in vehicle noise emission levels in the past four years [Rapoza 1998]. Computation of the level-mean regression for the average pavement for the automobile data was done using the following equations:

$$L(s) = 10\log_{10}(10^{C/10}), \text{ for zero speed (idle); and} \tag{8-9}$$

$$L(s) = 10\log_{10}(s^{A/10}10^{B/10}), \text{ for speed greater than zero.} \tag{8-10}$$

The adjustment from level-mean to energy-mean was calculated as described in Section 8.2.2. ΔE_C was calculated from the zero speed regression and data set, and ΔE_B was calculated from the speed greater than zero regression data set. To form the final average pavement REMEL, the two regression equations and adjustments were combined. The 95-percent CI was calculated as in Section 8.2.3; ε_{AC} and ε_{BC} were equal to zero; σ_{RL} , σ_{RE}, RE, and N were computed using the data set with the non-zero speed data.

Due to the lack of low speed acoustical data collected in the field for the medium and heavy truck categories, the nonlinear regression method described above could not be used to calculate the engine/exhaust transition in the data. The John A. Volpe National Transportation System Center was consulted again and it was decided that the data would be used from the previously mentioned USDOT study for all sound-level data for speeds below 72.4 km/h on DGAC for the medium and heavy truck categories [Rapoza 1998]. For medium and heavy trucks, the average pavement REMEL equation and 95-percent CI were calculated as described in Sections 8.2.1, 8.2.2, and 8.2.3.

8.2.5. Specific Roadway Pavement REMELs

REMELs were calculated for seven types of pavements as follows: one year old DGAC, two year old DGAC, seven year old DGAC, three year old SMA, one year old OGAC, one year old PCC - Random, Transverse Grooves, and four year old PCC - Transverse Grooves. For each of these seven pavements, emission levels were further quantified for automobiles, medium trucks, and heavy trucks. The level-mean, L (s), was calculated using Equation 8-5 by changing the B coefficient, i.e., the coefficient which governs the vertical position of the tire/road portion of the regression. The other coefficients, A and C, were used from the average pavement regression. By using this method, it is assumed that within each type of pavement, neither the engine/exhaust-portion of the curve or the slope of the tire/road-portion of the curve changes (Fleming, Rapoza, and Lee 1995).

The adjustment from level-mean to energy-mean was computed as described in Section 8.2.2. ΔE_C was used from the baseline conditions and ΔE_B was computed from the specific pavement data set and regression.

8.3. Data Reduction Methodology for Concrete Comparison and Pavement Stiffness Studies

Similar data reduction methods were used in analyzing the data collected for both the concrete comparison and the pavement stiffness study. For each pavement surface, the maximum A-weighted sound levels that were obtained for each vehicle pass-by at a given speed were arithmetically averaged. This result allowed the different pavements to be compared at speeds of 88.5 km/h and 104.6 km/h (for the stiffness study, an ODOT tandem axle dump truck was included at 72.4 km/h). The standard deviations of the sound levels were also computed for statistical purposes. For the spectral analysis of each pavement, noise levels in individual frequency bands were arithmetically averaged to obtain the overall average maximum A-weighted spectrum for each pavement.

Falling weight deflectometer data from May of 1998 was obtained from ODOT for the three pavement sections in Delaware County to be used as a measure of pavement stiffness. This data gave a value for each pavement section that could be compared with the other sections to indicate relative stiffness. The stiffness data was cross-correlated with the maximum A-weighted sound levels to identify any association of measured sound levels for the vehicle pass-bys with the stiffness of a pavement.

9. RESULTS

A measurement goal was to collect the highest quality vehicle pass-bys for each measurement site. Therefore it was imperative that almost all of the vehicle pass-bys that were used for data analysis be of Type-1 quality. Table 5 shows the distribution of the quality of events sampled for each site by vehicle type. The total number of vehicle samples taken for each site is also shown. The sample size was in full accordance with ISO 11819-1, except for Site 7, where the number of medium trucks was 28 rather than the minimum of 30. However, for this site the minimum number of medium and heavy trucks combined (88) exceeded the minimum required value of 80.

An attempt was made to perform all measurements when the atmospheric temperature was between 5 - 30° C and the pavement temperature was between 5 - 50° C. However, meeting this requirement for all of the sites was not feasible due to the average summer temperature levels in Ohio. While the air temperature requirement was exceeded at times during the measurement period for several sites, the average temperature during the measurement periods was only exceeded at Sites 4 and 7 by 3.1° C and 1.2° C, respectively. The maximum pavement temperature during any measurement was only exceeded for three of the sites, but the average pavement temperature for an entire measurement never exceed the maximum allowable value.

Measurements were made at roadway sections where the speed limit was at least 88.5 km/h (55 mi/h), with the majority having speed limits of 104.6 km/h (65 mi/h). These sites were selected so that the standard deviation of the average speed for each vehicle class for each pavement would meet the requirements set forth in the ISO standard for the useful portion of the

Table 5. Event quality distribution by number of events.

Site No.	Event Quality	Vehicle Class		
		A	MT	HT
1	1	110	28	59
	2	0	2	1
	Total	110	30	60
2	1	106	30	59
	2	2	0	0
	Total	108	30	0
3	1	105	28	60
	2	4	5	0
	Total	109	33	60
4	1	109	32	60
	2	1	0	0
	Total	110	32	60
5	1	105	26	55
	2	7	9	4
	Total	112	35	59
6	1	109	29	60
	2	2	1	0
	Total	111	30	60
7	1	99	28	60
	2	1	0	0
	Total	100	28	60
8	1	114	28	58
	2	0	3	2
	Total	114	31	60
9	1	107	29	60
	2	2	1	0
	Total	109	30	60
10	1	107	29	60
	2	2	1	0
	Total	109	30	60
11	1	100	29	50
	2	6	5	3
	Total	106	34	53
12	1	112	27	44
	2	3	3	6
	Total	115	30	50

regression line. However, this requirement was not entirely met for all of the sites. The average speeds for the automobiles were in full compliance (except for Sites 3, 6, 7, and 12), but the average speeds for the medium and heavy truck categories were typically higher than the reference speed given in the standard. Efforts were made in the field to select vehicles that were traveling relatively close to the reference speed, but due to variable driver characteristics and time constraints, this was not entirely possible.

The chairman of the committee that developed the ISO standard was consulted about the problems with the data collected for the heavy and medium truck categories. As a result of the conversation, and after numerous attempts to correct the problems, it was decided that the sample size and reference speeds used for the medium and heavy vehicle categories were satisfactory [Sandberg 1998].

9.1. Specific Pavement SPBIs

This section presents the results of the regressions performed to calculate the specific pavement SPBIs. Appendix E shows the sound level and speed regression data for each specific pavement type. Table 1 of Section 4.4 should be referred to for specific information about each test site.

9.1.1. Comparison with Reference Pavement

This section contains the values obtained by comparing the SPBI values for each specific pavement with those of the reference pavement. Table 6 and Figure 3 show the relative differences in SPBI levels, positive or negative, that were calculated for each pavement.

Table 6. Comparison of SPBI values relative to the reference pavement.

Site #	Surface Type	S.P.B.I. (dB)	Difference Relative to Average (dB)
1	Dense Graded Asphalt, 1 yr old	85.1	0.1
2	Dense Graded Asphalt, 1 yr old	84.5	-0.5
3	Stone Mastic Asphalt, 3 yrs old	86.8	1.8
4	Open Graded Asphalt, 1 yr old	82.2	-2.8
5	Dense Graded Asphalt, 2 yrs old	85.5	0.5
6	Dense Graded Asphalt, 7 yrs old	86.4	1.4
7	Dense Graded Asphalt, 1 yr old	85.0	0.0
8	Concrete, Random Transverse Grooves, 1 yr old	88.9	3.9
9	Dense Graded Asphalt, 1 yr old	85.2	0.2
10	Dense Graded Asphalt, 1 yr old	85.6	0.6
11	Dense Graded Asphalt, 1 yr old	84.6	-0.4
12	Concrete, Transverse Grooves, 4 yrs old	87.0	2.0
	Average Pavement (Average of all 1 yr old DGAC)	85.0	

By examining the differences in SPBIs for all of the one year old DGAC pavements and comparing them based on their aggregate type, there are no indications that aggregate type has any influence on tire/road noise.

The most significant reduction in sound levels occurred with the OGAC pavement where there was a difference of -2.8 dB relative to the average pavement. The lower noise level measured on the OGAC pavement was unexpected since the OGAC surface tested had a relatively small thickness of 19 mm. The OGAC pavement was on a 32 mm ODOT Type 1 pavement, which is typical of all ODOT's OGAC pavements. Measurements of the OGAC pavement were performed after the first year of its service. The tire/road noise levels can be expected to increase over time as the pavement pores become clogged.

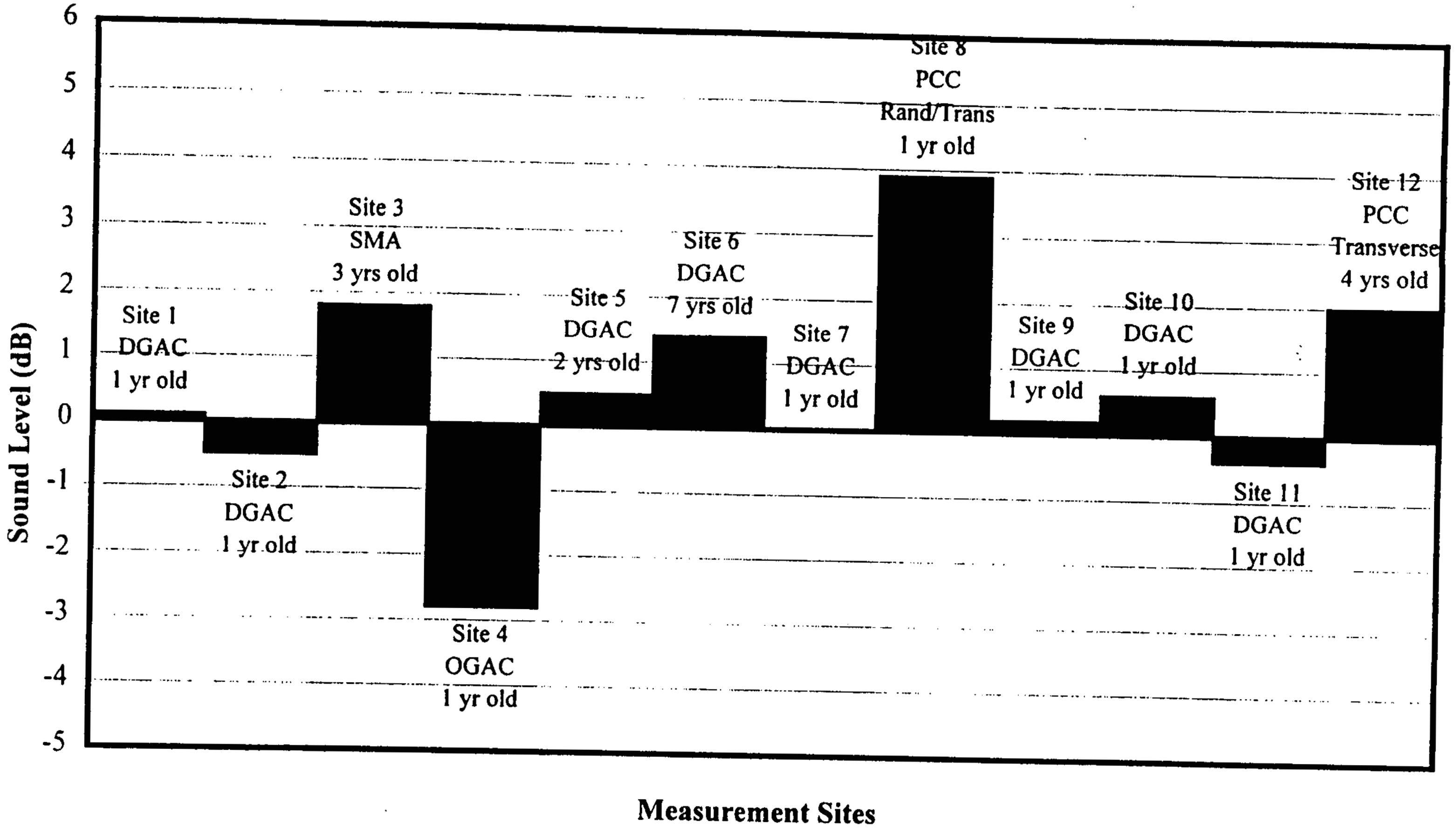

Figure 3. SPBI comparison for specific pavements relative to reference pavement.

The effect that pavement age has on tire/road noise can be seen by comparing SPBIs for Sites 5 and 6 in Table 6. There is not much evidence from the data to show an increase in sound levels after two years. However, Site 6 is seven years old and has a difference of 1.4 dB relative to the average pavement. While this is considered significant, a seven year old DGAC pavement is typically nearing the end of its design life and will be considered for resurfacing.

The highest noise levels from an asphalt pavement were measured at Site 3, which is a three year old SMA pavement. The SPBI was 1.8 dB higher relative to the average pavement. Unlike a typical dense graded aggregate mixture, SMA is a gap graded asphalt mixture, which means that there is an increased amount of coarse aggregate, mineral dust, and asphalt cement in the mix [Bukowski 1993]. The higher noise levels for the SMA pavement may be due to an increase in coarse aggregate in the mix design which would affect the surface texture of the pavement. Considering that SMA is an asphalt pavement, it was unexpected to find the SPBI for the SMA pavement to be very close to the SPBI for Site 12, which is a transverse grooved PCC pavement.

9.1.2. Maximum A-Weighted Spectrum Results

The maximum A-weighted spectrums for each specific pavement and the differences in sound levels for each specific pavement maximum A-weighted spectrum relative to the reference spectrum are shown in Appendix F. Figure 4 shows a comparison of spectrums for three asphalt surfaces, a one year old DGAC (average of all one year old DCAC pavements measured), a one year old OGAC, and a three year old SMA. The SPBI levels for the three pavements ranked the OGAC pavement as the quietest and the SMA as the loudest of the asphalt pavements. By examining the spectrums for the three pavements, it can be seen that all three pavements exhibit similar sound levels in the low frequency range of 50 to around 630Hz.

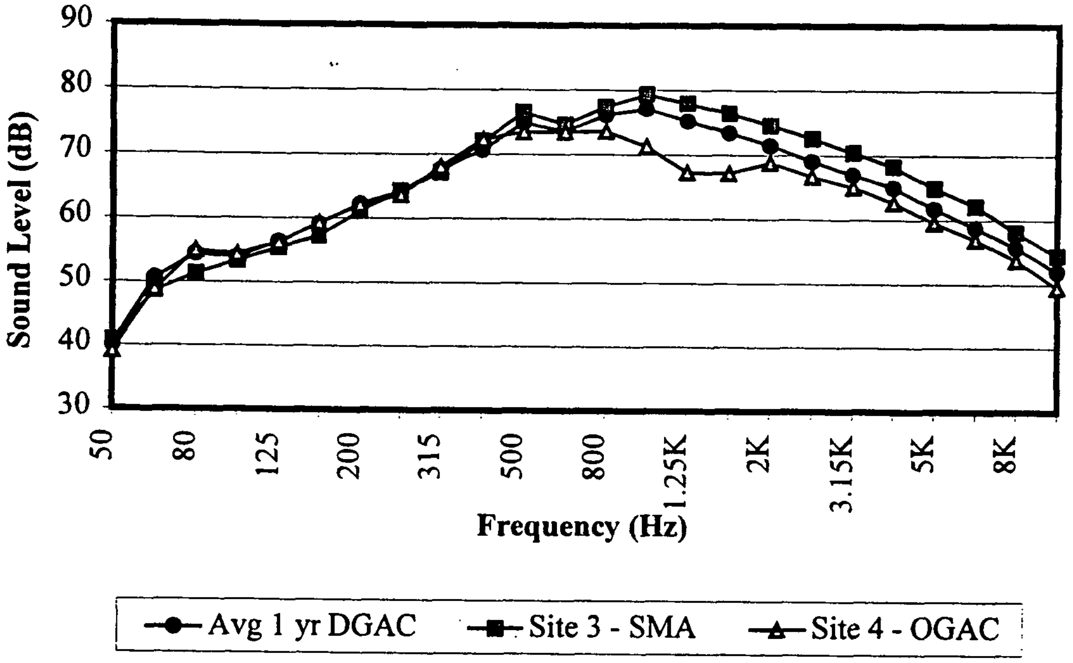

Figure 4. Comparison of spectrums for different asphalt pavements.

However, above 630 Hz, the spectrum for the OGAC pavement begins to decrease in sound level relative to the DGAC pavement. The opposite can be said for the SMA pavement where an increase in sound level for frequencies greater than 630 Hz occurs relative to the DGAC pavement. The overall lower tire/road noise levels exhibited by the OGAC pavement results from the attenuation of the higher frequencies, while the SMA pavement exhibits overall higher tire/road noise levels due to an increase in levels associated with the higher frequencies.

The three pavements exhibit similar shapes in spectrum, except that the OGAC pavement changes shape in the frequency range of 800 to 2000 Hz. This is very significant since the human ear is most sensitive to sound levels in this range.

The spectrums for the one year old DGAC pavement and the transverse and random-transverse grooved PCC pavements are shown in Figure 5. Although the DGAC and transverse grooved PCC pavement spectrums are different in magnitude, the shape of their spectrums are similar. The random-transverse PCC pavement has a similar spectral shape to the other two pavements for the frequencies greater than 1.0 kHz, but there are several fluctuations in sound level relative to the other two pavements in the frequency range from 50 to 315 Hz. The spectrum for the random-transverse grooved PCC pavement exhibits higher sound levels in the frequency range of 315 to 2000 Hz. The measured increase in overall sound level for the random-transverse grooved pavement compared to other pavements appears to be due to both the fluctuation and noise associated with the frequency range of 315 to 2000 Hz. The mechanisms that cause this spectral difference are not understood and should be investigated.

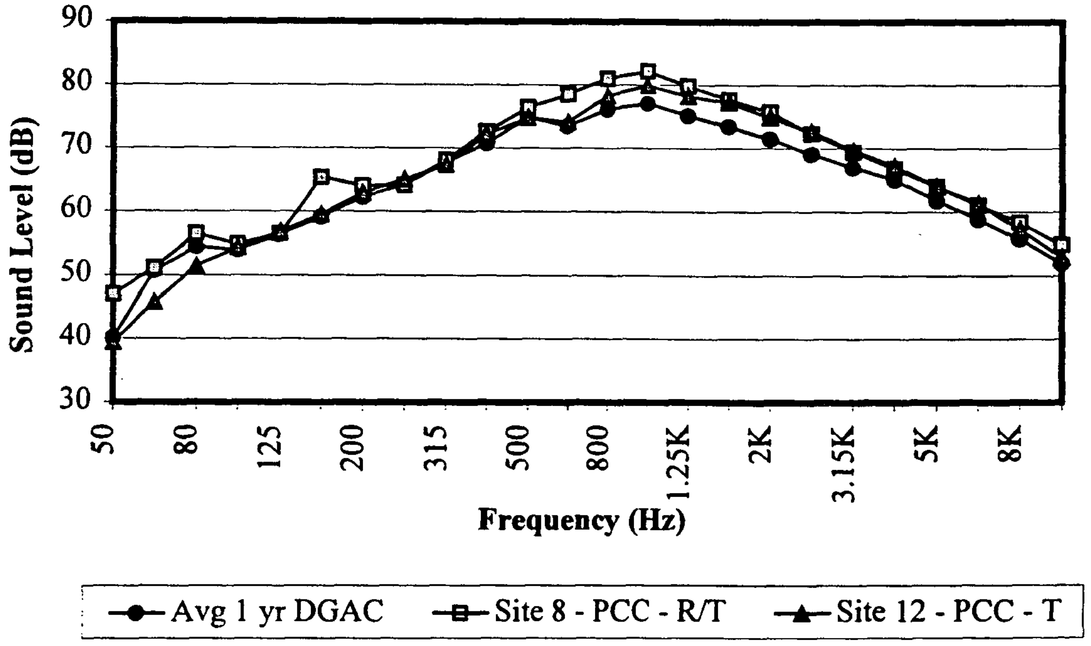

Figure 5. Comparison of spectrums for DGAC and PCC pavements.

9.1.3. Sport Utility Vehicle Sound Level Results

Sound level results for the significance of sport utility vehicles are shown in Table 7. For each of the pavement types, the average maximum A-weighted sound levels were compared to those of the automobiles and shown as relative differences.

Table 7. Comparison of sport utility vehicles with automobiles on different pavement types.

Number of SUVs	Pavement Type	Sound Level Autos (dB)	Sound Level SUVs (dB)	Difference (dB)
41	DGAC, 1 year old	80.8	81.1	0.3
7	SMA, 3 years old	83.6	83.9	0.3
11	OGAC, 1 year old	77.7	78.2	0.5
10	DGAC, 2 years old	81.6	83.4	1.8
13	DGAC, 7 years old	83.1	83.3	0.2
15	PCC-Random-Transverse, 1 year old	86.3	86.6	0.3
5	PCC-Transverse, 4 years old	84.6	85.7	1.1

The differences in sound levels for sport utility vehicles relative to automobiles on all of the pavement types tested are relatively small for the data collected. However, the sound levels for the two year old DGAC pavement and the four year old PCC-transverse grooved pavement are 1.8 dB and 1.1 dB higher for SUVs than automobiles. The pavement types with the most SUV samples (one year old DGAC and one year old PCC-random-transverse) indicate a difference between automobiles and SUVs of 0.3 dB. There are other pavement types that indicate similar differences in the range of 0.2 to 0.5 dB. Therefore, the results of the comparison between automobiles and SUVs may or may not be accurate for the two year old DGAC pavement and the four year old PCC-transverse grooved pavement due to the number of SUV samples that were collected for these two pavements.

9.2. REMEL Results

This section gives the results of the regression analysis performed to calculate the REMELs for the average pavement case and for each specific pavement. Appendix G presents the REMEL regressions for automobile, medium truck, and heavy truck vehicle categories for the average pavement conditions including the 95-percent confidence interval (CI), and the associated maximum A-weighted sound levels (L_{AFmx}).

9.2.1. Average Pavement REMELs

For the automobile category, the 95-percent CI ranges from +/- 1.002 dB at 1.6 km/h to +/- 0.252 dB at 88.5 km/h to +/- 0.347 dB at 128 km/h. The regression coefficients and the statistics used to compute the 95-percent CI and the adjustments from level-mean to energy-mean are as follows:

A	19.969	ε_A	1.945	ρ_{AB}	-1.000	N	718
B	36.374	ε_B	3.519	ρ_{AC}	0.000		
C	47.861	ε_C	0.514	ρ_{BC}	0.000		
ΔE_b	0.299	σ_{RL}	1.592	RL	-0.001		
ΔE_c	2.267	σ_{RE}	0.420	$\overline{RE}$	1.071		

For the medium truck category, the 95-percent CI ranges from +/- 23.325 dB at 1.6 km/h to +/- 2.153 dB at 88.5 km/h to +/- 1.328 dB at 128 km/h. It should be noted that the large value calculated at 1.6 km/h for the 95% CI was due to the lack of data for low vehicle speeds. The regression coefficients and the statistics used to compute the 95-percent CI and the adjustments from level-mean to energy-mean are as follows:

A	20.514	ε_A	2.991	ρ_{AB}	-0.999	N	333
B	41.432	ε_B	5.398	ρ_{AC}	0.867		
C	60.522	ε_C	11.979	ρ_{BC}	-0.885		
ΔE_b	1.229	σ_{RL}	3.111	RL	-0.000		
ΔE_c	1.229	σ_{RE}	1.321	$\overline{RE}$	1.327		

For the heavy truck category, the 95-percent CI ranges from +/- 1.388 dB at 1.6 km/h to +/- 3.468 dB at 88.5 km/h to +/- 3.413 dB at 128 km/h. The regression coefficients and the statistics used to compute the 95-percent CI and the adjustments from level-mean to energy-mean are as follows:

A	18.455	ε_A	0.715	ρ_{AB}	-0.999	N	760
B	48.736	ε_B	3.164	ρ_{AC}	0.837		
C	72.458	ε_C	0.715	ρ_{BC}	-0.851		
ΔE_b	0.875	σ_{RL}	2.608	RL	-0.001		
ΔE_c	0.875	σ_{RE}	0.989	$\overline{RE}$	1.223		

9.2.2. Specific Pavement REMELs

This section presents the results of the REMEL regressions for each specific pavement type.

9.2.2.1.REMELs for a One Year Old DGAC Pavement

For automobiles on a one year old DGAC pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	19.969	σ_{RL}	1.592	RL	-0.001	N	642
B	36.374	σ_{RE}	0.420	$\overline{RE}$	1.071		
C	47.861	ΔE_b	0.299	ΔE_c	2.267		

For medium trucks on a one year old DGAC pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	20.514	σ_{RL}	2.543	RL	0.000	N	181
B	41.393	σ_{RE}	0.886	$\overline{RE}$	1.204		
C	60.522	ΔE_b	0.806	ΔE_c	1.229		

For heavy trucks on a one year old DGAC pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	18.455	σ_{RL}	1.938	RL	-0.003	N	351
B	48.612	σ_{RE}	0.644	$\overline{RE}$	1.116		
C	72.458	ΔE_b	0.480	ΔE_c	0.875		

9.2.2.2.REMELs for a Three Year Old SMA Pavement

For automobiles on three year old SMA pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	19.969	σ_{RL}	1.185	RL	0.000	N	108
B	39.182	σ_{RE}	0.281	$\overline{RE}$	1.037		
C	47.861	ΔE_b	0.158	ΔE_c	2.267		

For medium trucks on a three year old SMA pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	20.514	σ_{RL}	2.485	RL	-0.000	N	32
B	43.911	σ_{RE}	0.744	$\overline{RE}$	1.184		
C	60.522	ΔE_b	0.734	ΔE_c	1.229		

For heavy trucks on three year old SMA pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	18.455	σ_{RL}	1.412	RL	-0.003	N	59
B	50.527	σ_{RE}	0.386	$\overline{RE}$	1.056		
C	72.458	ΔE_b	0.240	ΔE_c	0.875		

9.2.2.3.REMELs for a One Year Old OGAC Pavement

For automobiles on a one year old OGAC pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	19.969	σ_{RL}	1.850	RL	-0.001	N	109
B	33.857	σ_{RE}	0.582	$\overline{RE}$	1.107		
C	47.861	ΔE_b	0.442	ΔE_c	2.267		

For medium trucks on a one year old OGAC pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	20.514	σ_{RL}	3.112	RL	0.000	N	31
B	40.532	σ_{RE}	0.949	$\overline{RE}$	1.272		
C	60.522	ΔE_b	1.045	ΔE_c	1.229		

For heavy trucks on a one year old OGAC pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	18.455	σ_{RL}	2.138	RL	0.006	N	59
B	46.954	σ_{RE}	0.644	$\overline{RE}$	1.136		
C	72.458	ΔE_b	0.548	ΔE_c	0.875		

9.2.2.4.REMELs for a Two Year Old DGAC Pavement

For automobiles on a two year old DGAC pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	19.969	σ_{RL}	1.468	RL	-0.000	N	111
B	39.180	σ_{RE}	0.379	$\overline{RE}$	1.059		
C	47.861	ΔE_b	0.249	ΔE_c	2.267		

For medium trucks on a two year old DGAC pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	20.514	σ_{RL}	2.010	RL	-0.001	N	31
B	43.036	σ_{RE}	0.615	$\overline{RE}$	1.117		
C	60.522	ΔE_b	0.482	ΔE_c	1.229		

For heavy trucks on a two year old DGAC pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	18.455	σ_{RL}	1.361	RL	-0.003	N	58
B	49.383	σ_{RE}	0.366	$\overline{RE}$	1.052		
C	72.458	ΔE_b	0.223	ΔE_c	0.875		

9.2.2.5.REMELs for a Seven Year Old DGAC Pavement

For automobiles on a seven year old DGAC pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	19.969	σ_{RL}	1.145	RL	-0.000	N	110
B	39.115	σ_{RE}	0.283	$\overline{RE}$	1.036		
C	47.861	ΔE_b	0.154	ΔE_c	2.267		

For medium trucks on a seven year old DGAC pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	20.514	σ_{RL}	2.258	RL	0.002	N	29
B	42.893	σ_{RE}	0.677	$\overline{RE}$	1.149		
C	60.522	ΔE_b	0.601	ΔE_c	1.229		

For heavy trucks on a seven year old DGAC pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	18.455	σ_{RL}	1.306	RL	-0.005	N	64
B	49.579	σ_{RE}	0.335	$\overline{RE}$	1.046		
C	72.458	ΔE_b	0.200	ΔE_c	0.875		

9.2.2.6.REMELs for a One Year Old PCC - Random, Transverse Grooved Pavement

For automobiles on a one year old PCC - random, transverse grooved pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	19.969	σ_{RL}	1.482	RL	0.000	N	113
B	43.075	σ_{RE}	0.418	$\overline{RE}$	1.064		
C	47.861	ΔE_b	0.269	ΔE_c	2.267		

For medium trucks on a one year old PCC - random, transverse grooved pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	20.514	σ_{RL}	1.692	RL	-0.000	N	30
B	44.965	σ_{RE}	0.438	$\overline{RE}$	1.077		
C	60.522	ΔE_b	0.322	ΔE_c	1.229		

For heavy trucks on a one year old PCC - random, transverse grooved pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	18.455	σ_{RL}	0.781	RL	0.003	N	59
B	52.323	σ_{RE}	2.085	$\overline{RE}$	1.139		
C	72.458	ΔE_b	0.562	ΔE_c	0.875		

9.2.2.7.REMELs for a Four Year Old PCC - Transverse Grooved Pavement

For automobiles on a four year old PCC - transverse grooved pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	19.969	σ_{RL}	1.652	RL	0.000	N	114
B	40.143	σ_{RE}	0.458	$\overline{RE}$	1.078		
C	47.861	ΔE_b	0.326	ΔE_c	2.267		

For medium trucks on a four year old PCC - transverse grooved pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	20.514	σ_{RL}	2.673	RL	-0.001	N	29
B	44.169	σ_{RE}	0.746	$\overline{RE}$	1.197		
C	60.522	ΔE_b	0.782	ΔE_c	1.229		

For heavy trucks on a four year old PCC - transverse grooved pavement, the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean are as follows:

A	18.455	σ_{RL}	1.304	RL	-0.002	N	49
B	50.271	σ_{RE}	0.298	$\overline{RE}$	1.043		
C	72.458	ΔE_b	0.185	ΔE_c	0.875		

9.3. Concrete Comparison Results

This section presents the results that were obtained by comparing six different portland cement concrete pavement sections. All of the sound level and spectral data collected for the concrete comparison study is presented in Appendix H.

The maximum A-weighted sound levels measured for each pass-by were averaged to obtain a mean value for each pavement section. The mean values for each pavement section were then averaged to obtain an average value for all pavements combined. The relative differences in sound levels for each pavement for the automobile test vehicle operating at speeds of 88.5 km/h and 104.6 km/h are presented in Table 8 and are also shown in Figure 6 and Figure 7. A standard deviation was calculated for each of the five pass-bys that were performed for each test section. The standard deviations ranged from 0.2 to 0.8 dB.

As expected, the PCC pavement with the longitudinal grooving produced the lowest sound levels out of all of the PCC pavements tested. However, it was also expected that the random-transverse grooved PCC pavements would produce lower sound levels than transverse grooved PCC pavement. This was not the case. For Site 14, a transverse grooved PCC pavement, the sound level for the automobile test vehicle operating at 88.5 km/h was 82.3 dB. The sound levels at 88.5 km/h for Sites 8 and 15 (eastbound and westbound) were 86.2, 85.9, and 87.5 dB, respectively. This was a difference in the range of 2.6 to 5.2 dB by comparing Site 14, the transverse grooved PCC pavement, with Sites 8 and 15 WB, the random-transverse grooved PCC pavements.

Table 8. Comparison of noise levels for PCC pavements relative to the mean.

Location	**Groove Type**	**Sound Level at 88.5 km/h (dB)**	**Sound Level at 104.6 km/h (dB)**	**Difference from Average at 88.5 km/h (dB)**	**Difference from Average at 104.6 km/h (dB)**
Site 8 I-77 (SB Lane)	Random-Transverse (R/T)	86.2	87.7	1.8	1.3
Site 12 SR 39 (EB Lane)	Transverse (T)	82.6	84.5	-1.8	-1.9
Site 13 SR 50 (EB Lane)	Longitudinal (L)	82	83.5	-2.4	-3.0
Site 14 SR 50, West Section (EB Lane)	Transverse (T)	82.3	84.3	-2.1	-2.2
Site 15 SR 50, East Section (EB Lane)	Random-Transverse (R/T)	85.9	88.6	1.5	2.2
Site 15 SR 50, East Section (WB Lane)	Random-Transverse (R/T)	87.5	89.6	3.1	3.2
	Average	84.4	86.5		

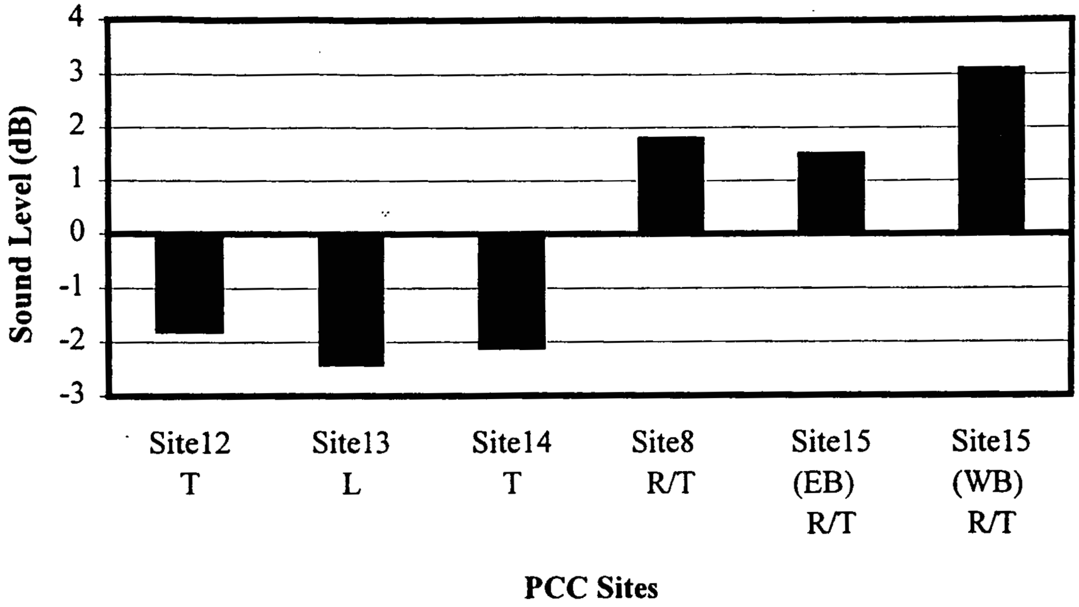

Figure 6. Specific differences in noise levels for automobile test vehicle at 88.5 km/h on PCC pavements relative to the mean noise level for the pavements shown.

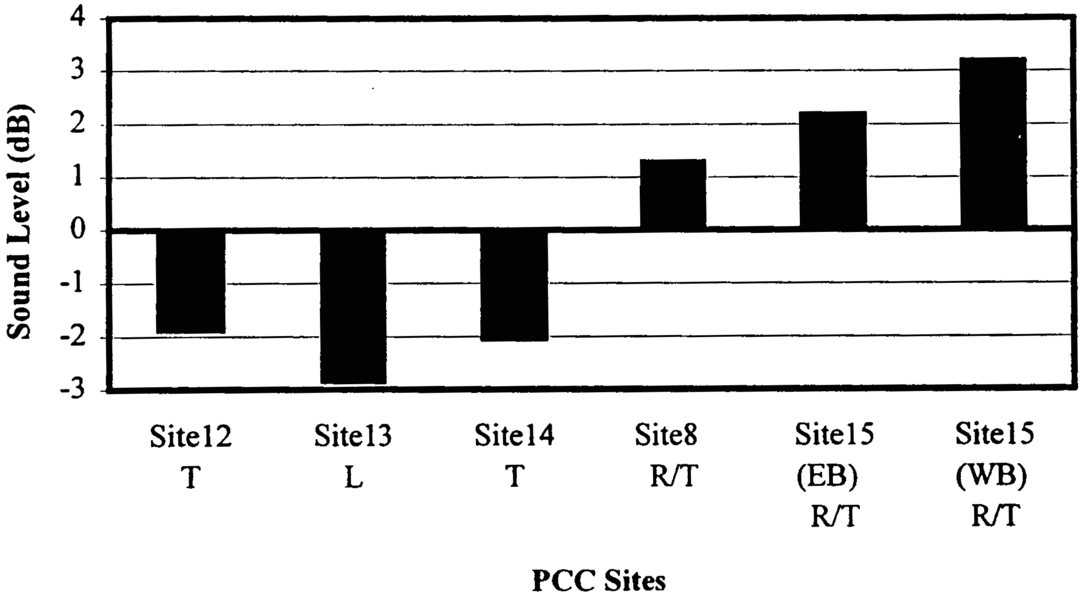

Figure 7. Specific differences in noise levels for automobile test vehicle at 104.6 km/h on PCC pavements relative to the mean noise level for the pavements shown.

More significant than the differences between the sound levels for the transverse and random-transverse grooved PCC pavements was the difference in sound levels between the three random-transverse grooved PCC pavements. Sites 12 and 14 are both transverse grooved with differences in sound levels at 88.5 and 104.6 km/h of 0.3 and 0.1 dB, respectively. It can then be stated that both sites with transverse grooved PCC pavements produce the same amount of tire/road noise. However, by comparing all three random-transverse grooved sites, there was a substantial difference in sound levels. The greatest difference occurred between Sites 8 and 15 (westbound), where the difference in sound levels was 1.9 dB at the 104.6 km/h speed. There was even a difference in sound levels between the eastbound and westbound lanes for Site 15 of 1.6 dB (at 88.5 km/h) and 1.0 dB (at 104.6 km/h). These two test sections were both constructed on the same project.

The spectrums for the Sites 8 and 12, the two transverse grooved PCC pavements, are shown in Figure 8. The spectrums exhibit similar shapes except the peak sound level occurs at 800 Hz for Site 12 and 1000 Hz for Site 13. The measured increase in overall sound level between Site 12 and Site 8 appears to be due to the noise associated with the frequency range of 2.0 to 10.0 kHz.

The spectrums for the three random-transverse PCC pavements tested with the automobile test vehicle operating at 88.5 km/h are shown in Figure 9. The shape and magnitude of the spectrum for each of the pavements are similar except at the frequencies where the peak sound levels occurred. The peak sound level for Site 8 and Site 15 EB occurred at 1.0 kHz. The peak sound level occurred at 1.25 kHz for Site 15 WB and was greater than the other two pavements. While the spectrums for Site 8 and Site 15 EB had the same shape and magnitude of sound levels from 1.0 kHz to 10 kHz, Site 15 WB had greater sound levels in the frequency range of 1.25 kHz to about 4.0 kHz.

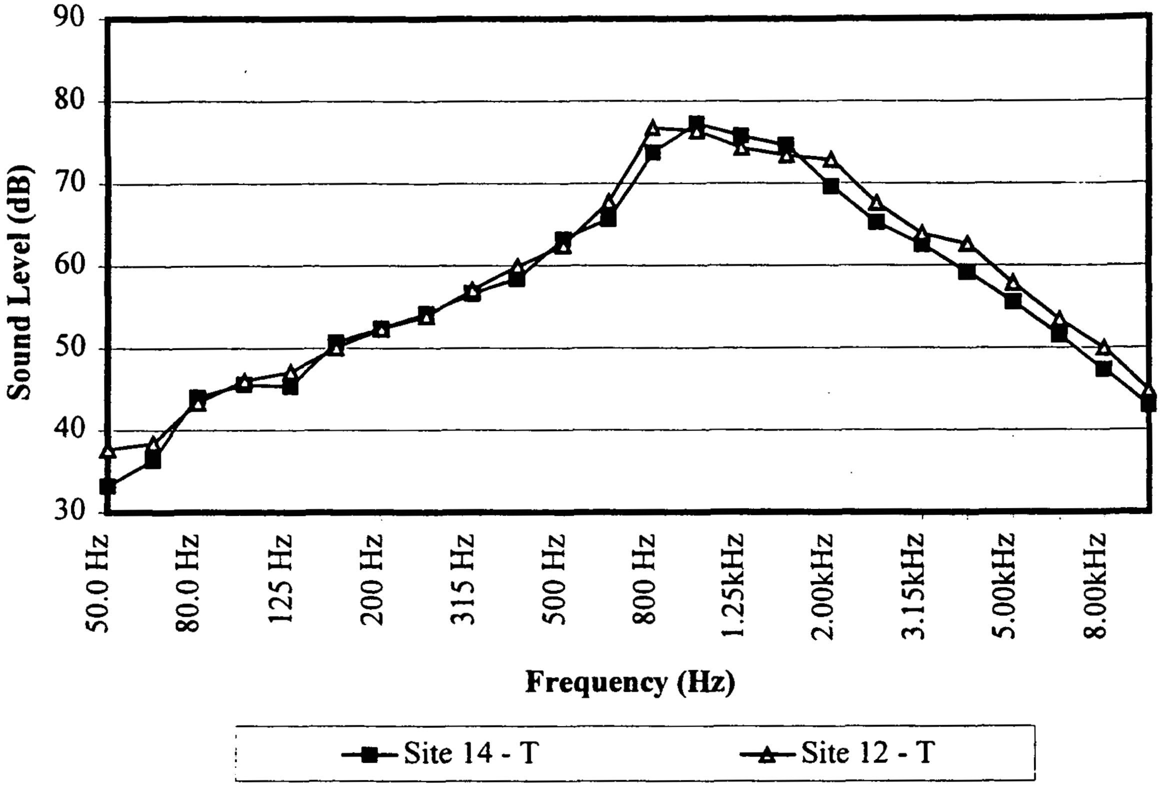

Figure 8. Spectrums for transverse grooved PCC pavement for a automobile test vehicle operating at 88.5 km/h.

Another significant finding in comparing the different PCC surfaces was found by comparing the spectrums for the transverse and random-transverse pavements. It was expected from research performed by others in the field of tire/road noise that the transverse grooved PCC pavements would exhibit some sort of "whine" or tonal peak sound level associated with a frequency that is typically found when measuring tire/road noise on transverse grooved PCC surfaces. To combat the "whine" problem associated with transverse grooved PCC pavements, ODOT had changed the groove specifications for tined PCC pavements to a random-transverse groove pattern. This design change was made to spread the peak sound level over a wider range

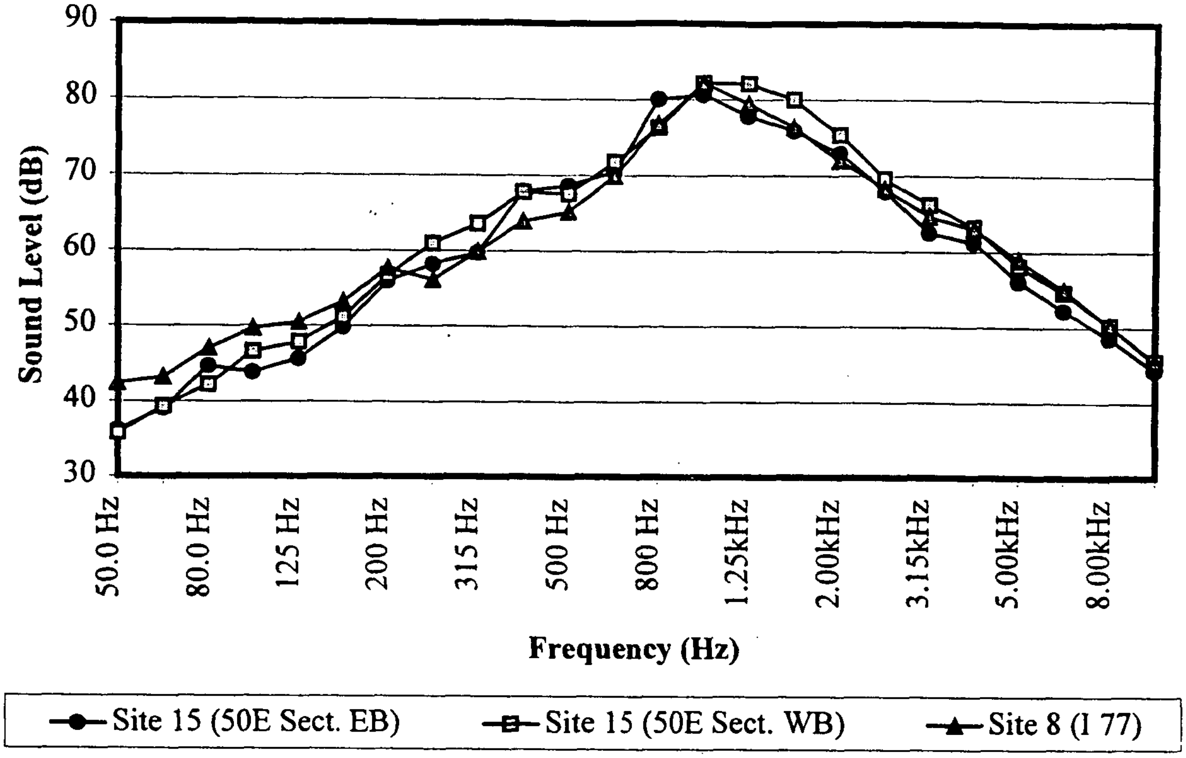

Figure 9. Comparison of spectrums for random-transverse grooved PCC sites for automobile test vehicle operating at 88.5 km/h.

of frequencies. Therefore, it was expected that the transverse grooved PCC pavement would exhibit higher tire/road noise levels than the random-transverse PCC pavement. However, by comparing the overall sound levels for both types of PCC surfaces, the sound levels for the random-transverse grooved PCC surfaces were significantly greater than those with the transverse grooves. Also, a comparison of the spectrums between the transverse and random-transverse grooved PCC pavements gave no indication that the random-transverse grooving pattern used by ODOT spreads the peak sound levels over a wider range of frequencies. Additionally, the spectrums for the transverse grooved PCC pavements shown in Figure 9 do not exhibit a significant tonal peak sound level associated with any given frequency that would indicate the presence of a “whine.” Although no tonal peaks were detected using one-third octave band analysis, their existence is not precluded. An analysis which would discriminate the energy at various frequencies in narrow bands may reveal tonal peaks.

The spectrums for the longitudinal, transverse, and random-transverse grooved PCC pavements are shown in Figure 10. The spectrums shown for the transverse and random-transverse grooved PCC pavements are the arithmetically averaged spectrums for each groove type. There are differences in sound level between the random-transverse grooved pavement and the longitudinal grooved pavement by as much as 9.1 dB at 400 Hz and 8.4 dB at 1.25 kHz. There are also differences in the frequency range of 1.0 to 4.0 kHz where the longitudinal grooved PCC pavement exhibits lower sound levels compared to the other two groove types. The frequency where the peak sound level occurs for the longitudinal grooved PCC pavement was at 800 Hz, which is at a lower frequency than the other two groove types. The lower levels measured longitudinal grooved pavement compared to other pavements appears to be due to both the sound levels associated with the frequency range of 1.0 to 4.0 kHz.

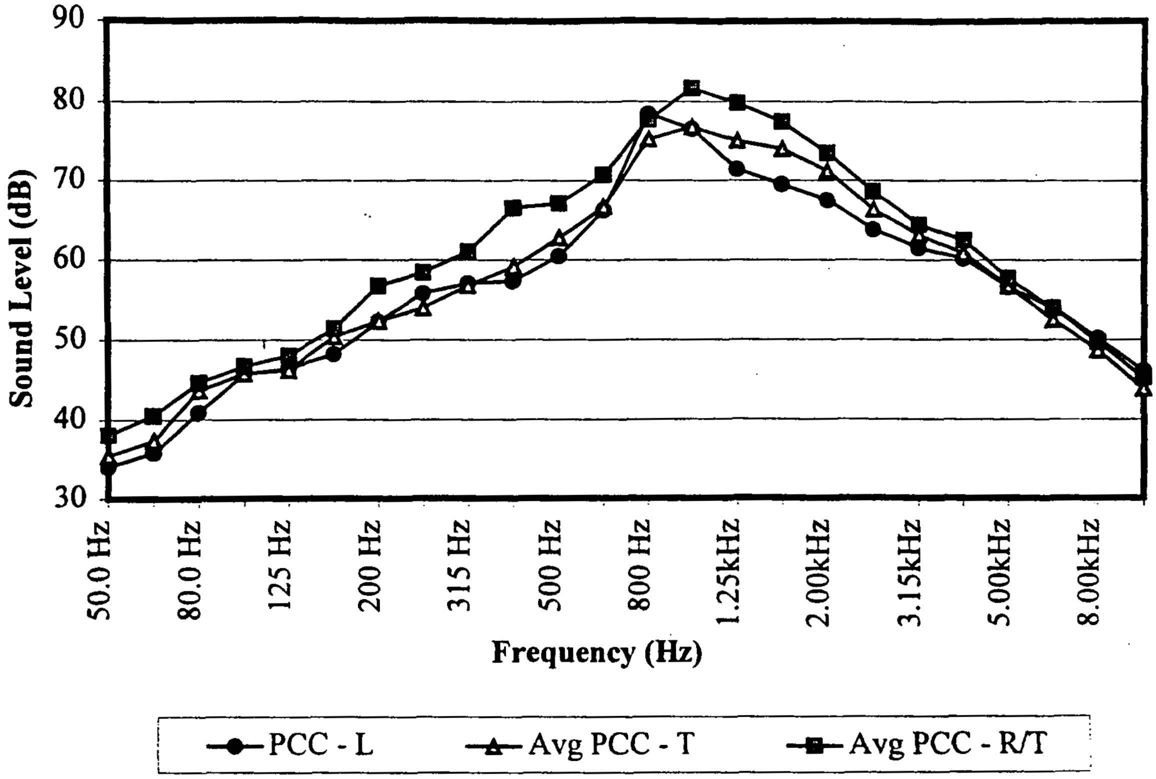

Figure 10. Comparison of spectrums for longitudinal, transverse, and random-transverse grooved PCC sites for automobile test vehicle operating at 88.5 km/h.

9.4. Pavement Stiffness Results

This section presents the acoustical data which was collected to determine the effects that the pavement stiffness had on the sound levels produced by a pavement.

Sound level data for the stiffness study that was collected for each of the three different sections was arithmetically averaged. The relative differences in maximum A-weighted sound level are shown below in Table 9 for the automobile test vehicle and in Table 10 for the tandem axle dump truck test vehicle. A standard deviation was calculated for each of the pass-bys performed for each test section. The values ranged from 0.3 to 0.6 dB for the automobile test vehicle and 0.2 to 0.9 dB for the ODOT tandem axle truck test vehicle. All of the sound level data that was collected for the pavement stiffness study is presented in Appendix I.

Table 9. Comparison of sound levels for stiffness study for automobile test vehicle operating at 104.6 km/h.

Section	Surface Thickness (mm)	Base Thickness (mm)	Sound Level (dB)	Difference from Average (dB)
108	178	305	78.3	0.2
109	178	406	77.7	-0.4
110	178	203	78.2	0.1
		Average	78.1	

Table 10. Comparison of sound levels for pavement stiffness study for an ODOT tandem axle dump truck test vehicle operating at 72.4 km/h.

Section	Surface Thickness (mm)	Base Thickness (mm)	Sound Level (dB)	Difference from Average (dB)
108	178	305	91.7	1.5
109	178	406	89.4	-0.8
110	178	203	89.6	-0.6
		Average	90.2	

Stiffness data which was collected using the Falling Weight Deflectometer method by ODOT was cross-correlated with the maximum A-weighted sound level data in Table 11 for the ODOT tandem axle truck test vehicle and in Table 12 for the automobile test vehicle. A high, negative value would indicate that there was a high correlation between a stiff pavement and high sound levels. However, after the measurements were performed, ODOT was further consulted to obtain more data related to the properties of the pavement surface at the test site. It was then determined that the surfaces of the pavements that were originally thought to be similar may have changed since their original date of construction due to traffic loading. If the surfaces of the pavement did change, then it would not be possible to accurately determine the significance of pavement stiffness for this site using the measured sound levels. The data was reported for the record of the research that was performed. Since the study was not in the original listing of research objectives, it was not pursued any further in light of the problems encountered.

Table 11. Correlation of sound levels with falling weight deflectometer data for ODOT single axle dump truck operating at 72.4 km/h.

Section	**Sound Level (dB)**	**Deflection (mils)**
108	91.7	0.93
109	89.4	0.86
110	89.6	0.57
	Correlation Coefficient	0.589

1 mil = 0.0254 mm

Table 12. Correlation of sound levels with falling weight deflectometer data for automobile test vehicle operating at 104.6 km/h.

Section	**Sound Level (dB)**	**Deflection (mils)**
108	78.3	0.93
109	77.7	0.86
110	78.2	0.57
	Correlation Coefficient	-0.182

1 mil = 0.0254 mm

Combining the fact that there was no accurate data regarding the surface of the pavement with the fact that the standard deviation of the sound levels exceeded the difference in sound levels measured for each section, the results from the study on the influence of pavement stiffness on tire/road noise were considered invalid.

9.5. Results on Effects of Different DGAC Pavement Specifications

The results from the comparison of the asphalt pavement sections with the different surfaces and similar bases are shown in Table 13 and Figure 11. The sound levels were compared for the automobile test vehicle operating at 104.6 km/h. The standard deviations for the sound levels ranged from 0.2 to 0.5 dB.

Table 13. Comparison of sound levels for different asphalt surfaces with similar bases for a automobile test vehicle operating at 104.6 km/h.

Section	**Surface Thickness (mm)**	**Base Thickness (mm)**	**Sound Level (dB)**	**Difference from Average (dB)**
901	229	559	77.1	-0.6
902	229	559	79.2	1.5
903	229	559	76.7	-1.0
		Average	77.7	

The sound levels for Sections 901 and 903 are quite similar, but Section 902 is louder than the other two sections by at least 2.1 dB. The significance of this difference is apparent when the variations among all the dense graded asphalt sections measured with the Statistical Pass-By Method are considered. The difference between the highest and lowest SPBI values measured for all one year old DGAC pavements was no greater than 1.1 dB. Therefore, pavement designers should be cautioned that a change in DGAC specifications could lead inadvertently to increased tire/road noise levels.

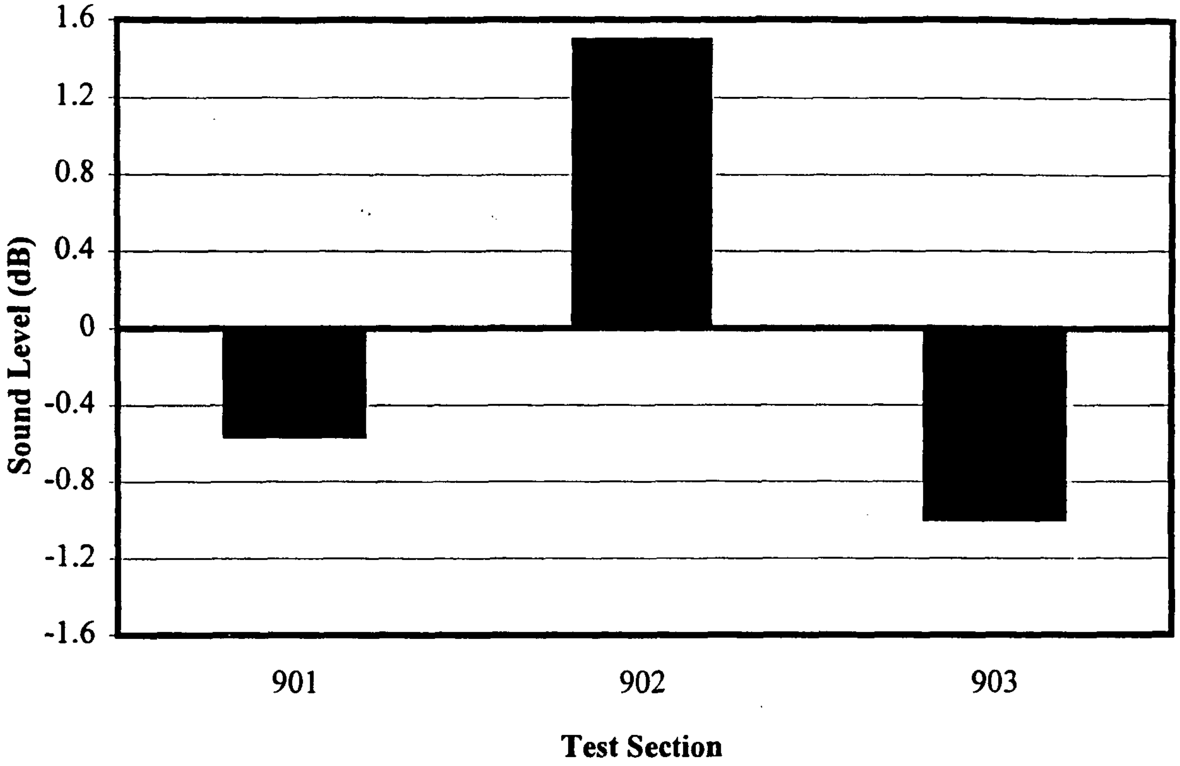

Figure 11. Comparison of sound levels for different asphalt surfaces with similar bases relative to the mean noise level for a automobile test vehicle operating at 104.6 km/h.

10. CONCLUSIONS AND RECOMMENDATIONS

10.1. Conclusions

Sound level data was collected using ISO 11891-1, The Statistical Pass-By Method, for twelve different pavement types. The sound level data was used to develop statistical pass-by index (SPBI) values and reference energy emission level (REMEL) coefficients for each pavement type. The pavements are ranked in Table 14 according to their SPBI values which should be used as an additional criterion for the selection of pavement types for projects.

Table 14. Ranking of ODOT pavements according to SPBI levels

Rank	Pavement Type	Age (years)	SPBI (dB)
1	OGAC	1	82.2
2	DGAC	1	85.0
3	DGAC	2	85.5
4	DGAC	7	86.4
5	SMA	3	86.8
6	PCC-Transverse Grooves	4	87.0
7	PCC-Random, Transverse Grooves	1	88.9

Data analysis was performed using the collected sound level data to develop consistent and reasonable REMEL coefficients. The coefficients are provided for future use if there is a need for state specific pavement REMEL coefficients to be input into the Federal Highway Transportation Noise Model. Due to the lack of low speed acoustical data collected during the measurement, it is strongly recommended that use of the REMEL coefficients be restricted to situations where the speed range considered is more than 72.4 km/h.

The data collected to calculated the SPBIs was further analyzed to develop spectrums for each pavement and allow a comparison between tire/road noise levels for automobiles and sport utility vehicles. The spectrums were then compared to determine what frequencies were attenuated or increased for each pavement type.

Sound level data was collected for two separate studies using a automobile test vehicle. The first study compared tire/road noise levels for six portland cement concrete (PCC) sites. The six sites included three different groove types: longitudinal, transverse, and random-transverse. The second study was an attempt to identify the significance of pavement stiffness on tire/road noise levels. A SHRP test road in Delaware county was used for this study. Sound level data was collected at this site for three asphalt sections which had the same surface type and thickness, but different base thickness.

Additionally, three asphalt sections which had the same base and surface thickness, but a different surface mix design, was used for comparison.

The findings of the research are as follows:

1. There was a difference of 6.7 dB between the lowest (open graded asphalt concrete) and the highest (random-transverse grooved PCC) SPBI for all of the pavements measured.
2. There were no significant differences in SPBIs due to aggregate type for all one year old dense graded asphalt concrete pavements.
3. Sound levels for two year old dense graded asphalt concrete pavements do not increase significantly from a one year old dense graded asphalt pavement. However, there is an increase in sound levels of approximately 1.4 dB over a period of seven years.
4. Sound levels for a three year old stone mastic asphalt are approximately 1.8 dB greater than those for the average one year old dense graded asphalt concrete based on a

comparison of SPBIs. Compared to the average one year old dense graded asphalt concrete pavement, a stone mastic asphalt pavement exhibits greater sound levels in the frequency range of 630 to 10,000 Hz.

5. The lowest tire/road noise levels were measured for the open graded asphalt concrete pavement. The SPBI for this pavement was 2.8 dB less than the average one year old dense graded asphalt concrete pavement. Compared to the spectrum for an average one year old dense graded asphalt concrete pavement, an open graded asphalt concrete pavement has lower sound levels in the frequency range of 630 to 10,000 Hz. The differences in sound level are quite substantial since the thickness of the open graded surface was only 19 mm.

6. The SPBI data revealed that random-transverse grooved PCC pavement produced the highest sound levels of all the different pavement types measured. Compared to the average one year old dense graded asphalt concrete pavement, the SPBI was 3.9 dB greater for random-transverse grooved PCC pavements.

7. From a comparison of the three types of PCC grooving types tested, longitudinal grooves produced the lowest sound levels, followed by transverse, then random-transverse grooves. The tire/road noise levels produced by the two transverse grooved PCC pavement were consistent. However, the three random-transverse PCC pavements measured were found to be inconsistent. Variations of as much as 1.9 dB were found between sites with a difference of 1.6 dB difference found between two sites on the same project.

8. A comparison of three different DGAC pavement surfaces with similar surface and base thicknesses indicated a difference in sound levels by as much as 2.1 dB for DGAC pavements with different design specifications.

10.2. Recommendations

The following issues should be considered for further investigation of tire/road noise or for action by transportation officials:

1. Strategies should be developed for ODOTs asphalt and concrete pavements to optimize the characteristics that result in lower tire/road noise levels.
2. More research should be performed to analyze the noise reducing properties of open graded asphalt concrete pavements. Experiments should be performed to determine the amount of absorption that can be achieved by increasing the thickness of the open graded surface, while still taking into consideration safety and economy.
3. ODOT should reevaluate the specification for the spacing of its random-transverse grooves for its PCC pavements. The groove spacing should calculated based on a dimension that will move the frequency at which the peak sound level occurs to lower frequencies to reduce sensitivity to the human ear.
4. Stricter tolerances should be enforced for the placement of grooves on PCC surfaces to create a greater consistency, not only for a single project, but for any PCC pavement in the state.
5. Tire/road noise measurements should be performed annually on the twelve sites which were used to develop the SPBIs and REMELs. This should be done to further and more

comparison of SPBIs. Compared to the average one year old dense graded asphalt concrete pavement, a stone mastic asphalt pavement exhibits greater sound levels in the frequency range of 630 to 10,000 Hz.

5. The lowest tire/road noise levels were measured for the open graded asphalt concrete pavement. The SPBI for this pavement was 2.8 dB less than the average one year old dense graded asphalt concrete pavement. Compared to the spectrum for an average one year old dense graded asphalt concrete pavement, an open graded asphalt concrete pavement has lower sound levels in the frequency range of 630 to 10,000 Hz. The differences in sound level are quite substantial since the thickness of the open graded surface was only 19 mm.

6. The SPBI data revealed that random-transverse grooved PCC pavement produced the highest sound levels of all the different pavement types measured. Compared to the average one year old dense graded asphalt concrete pavement, the SPBI was 3.9 dB greater for random-transverse grooved PCC pavements.

7. From a comparison of the three types of PCC grooving types tested, longitudinal grooves produced the lowest sound levels, followed by transverse, then random-transverse grooves. The tire/road noise levels produced by the two transverse grooved PCC pavement were consistent. However, the three random-transverse PCC pavements measured were found to be inconsistent. Variations of as much as 1.9 dB were found between sites with a difference of 1.6 dB difference found between two sites on the same project.

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APPENDIX A

ODOT PAVEMENT MIX SPECIFICATIONS FOR SPBI/REMEL MEASUREMENT SITES

Pavement Specifications

Site 1

Project: 357-96
JMF: B416192
Material: Dense Graded Asphalt
Age: 1997
Roadway: SR 30
County: Allen
Location: Between RT 115 and Rt 309 in Westbound lane.
Mix Type: 446-1H

Sieve	% Passing
2"	100
1 ½"	100
1"	100
¾"	100
½"	97
3/8"	84
No. 4	49
No. 8	32
No. 16	20
No. 30	12
No. 50	7
No. 100	5
No. 200	4.6

AC Content @ Median Voids: 5.5
Optimum AC Content: 5.5
F/AC: 0.8%
F/T: -3
AC Grade: AC-20
Stability: 2520
Flow: 9.4
% Air Voids: 4.0
VMA: 15.3
Unit Weight: 2.040 ton/yd^3
Thickness: 32 mm T1
44 mm T2

Coarse Aggregate:

%	Size	Type
38	78's	Limestone
22	8's	Limestone

Fine Aggregate:

%	Size	Type
35	Sand	Limestone
5	Sand	Natural Sand

RAP:

%	Description

Pavement Specifications

Site 2

Project: 219-97
JMF: B417478
Material: Dense Graded Asphalt
Age: 1997
Roadway: SR 30
County: Van Wert
Location: Between MM 18 and 19 in Westbound lane.
Mix Type: SP 12.5 mm

Sieve	% Passing
2”	100
1 ½”	100
1”	100
¾”	100
½”	99
3/8”	95
No. 4	51
No. 8	30
No. 16	20
No. 30	13
No. 50	10
No. 100	7
No. 200	5.0

AC Content @ Median Voids: 5.6
Optimum AC Content: 5.6
F/AC: 0.9%
F/T: -4
AC Grade: PG64-28 w/SBS polymer
Stability: 3020
Flow: 9.7
% Air Voids: 4.0
VMA: 15.0
Unit Weight: 2.017 ton/yd^3
Thickness: 38 mm
65 mm

Coarse Aggregate:

%	Size	Type
52	8’s	Limestone

Fine Aggregate:

%	Size	Type
23	Sand	Limestone
5	9’s	Limestone

RAP:

%	Description
20	US-30 RAP (from project)

Pavement Specifications

Site 3

Project: 804-94	JMF: B415134
Material: SMA	Age: 1995
Roadway: SR 30	County: Wayne

Location: Westbound lane before West Lebanon Rd.
Mix Type: SMA

Sieve	% Passing	
2"	100	AC Content @ Median Voids: 6.2
1 ½"	100	Optimum AC Content: -
1"	100	F/AC: -
¾"	100	F/T: -
½"	87	AC Grade: AC-20
3/8"	71	Stability: 1830
No. 4	28	Flow: 17.1
No. 8	21	% Air Voids: 4.0
No. 16	19	VMA: 15.5
No. 30	17	Unit Weight: 1.983 ton/yd^3
No. 50	16	Thickness: 1.50" Surface
No. 100	11	1.75" Intermediate
No. 200	7.7	12" 301
		6" of 304

Coarse Aggregate:

%	Size	Type
43	8's	Limestone
35	67's	Limestone

Fine Aggregate:

%	Size	Type
7	Sand	Limestone
14.7	Filler	Gravel

RAP:

%	Description
0.3	Fiber from Interfibe, Portage, Michigan

Pavement Specifications

Site 4

Project: 241-96
JMF: B177705
Material: Open Graded Asphalt
Age: 1997
Roadway: I-480
County: Summit
Location: From Ohio Turnpike to ½ mile north of SR 82.
Mix Type: NA

Sieve	% Passing
2"	NA
1 ½"	NA
1"	NA
¾"	NA
½"	NA
3/8"	NA
No. 4	NA
No. 8	NA
No. 16	NA
No. 30	NA
No. 50	NA
No. 100	NA
No. 200	NA

AC Content @ Median Voids: NA
Optimum AC Content: NA
F/AC: NA
F/T: NA
AC Grade: NA
Stability: NA
Flow: NA
% Air Voids: NA
VMA: NA
Unit Weight: NA
Thickness: 19 mm OGR
32 mm T-1
51 mm T-2

Coarse Aggregate:

%	Size	Type
NA		

Fine Aggregate:

%	Size	Type
NA		

RAP:

%	Description

Pavement Specifications

Site 5

Project: 544-96
JMF: B416245
Material: Dense Graded Asphalt
Age: 1996
Roadway: IR 70
County: Licking
Location: Between MM 125 and 124 in the Westbound land.
Mix Type: T-1H-RAP

Sieve	% Passing
2"	100
1 ½"	100
1"	100
¾"	100
½"	95
3/8"	85
No. 4	50
No. 8	33
No. 16	25
No. 30	17
No. 50	10
No. 100	7
No. 200	5.4

AC Content @ Median Voids: 5.4
Optimum AC Content: -
F/AC: 1.0
F/T: -1
AC Grade: AC-20
Stability: 2815
Flow: 11.5
% Air Voids: 4.0
VMA: 13.0
Unit Weight: 1.984 ton/yd^3
Thickness: 1.25" Surface
1.75" Intermediate

Coarse Aggregate:

%	Size	Type
17	7's	Limestone
36	8's	Gravel

Fine Aggregate:

%	Size	Type
14	#10	
13	Sand	Gravel

RAP:

%	Description
20	RAP, ODOT Project 544-96

Pavement Specifications

Site 6

Project: 1156-90
Material: Dense Graded Asphalt
Roadway: SR 32
Location: After SR 335 in Southbound lane.
Mix Type: T-1H

JMF: B910263
Age: 1991
County: Pike

Sieve	% Passing
2"	100
1 ½"	100
1"	100
¾"	99
½"	85
3/8"	76
No. 4	58
No. 8	44
No. 16	35
No. 30	24
No. 50	9
No. 100	5
No. 200	3.0

AC Content @ Median Voids: 5.6
Optimum AC Content: 5.6
F/AC: -
F/T: -
AC Grade: AC-20
Stability: 1915
Flow: 7.7
% Air Voids: 4.0
VMA: 15.3
Unit Weight: 1.916 ton/yd^3
Thickness: 1-1/2" 826
1-1/4" 404
1-1/4" T-1H

Coarse Aggregate:

%	Size	Type
25	57's	Gravel
25	8's	Gravel

Fine Aggregate:

%	Size	Type
40	Sand	Natural Sand
10	Sand	Limestone

RAP:

%	Description

Pavement Specifications

Site 9

Project: 552-95	JMF: B417080
Material: Dense Graded Asphalt	Age: 1997
Roadway: SR 32	County: Pike

Location: Between Schuster and Shyville Road in Eastbound lane.
Mix Type: 446 Type-1

Sieve	% Passing
2"	100
1 ½"	100
1"	100
¾"	100
½"	100
3/8"	97
No. 4	54
No. 8	40
No. 16	28
No. 30	18
No. 50	8
No. 100	4
No. 200	3.3

AC Content @ Median Voids: 6.2
Optimum AC Content: 6.2
F/AC: 0.5
F/T: -
AC Grade: AC-20
Stability: 2720
Flow: 9.4
% Air Voids: 4.0
VMA: 15.6
Unit Weight: 1.940 ton/yd^3
Thickness: 1-1/4" T-1
1-3/4" T-2
11" 301
4" Base

Coarse Aggregate:

%	Size	Type
28	8's	Gravel
28	8's	Limestone

Fine Aggregate:

%	Size	Type
22	Natural Sand	Gravel
22	Mfg. Sand	Limestone

RAP:

%	Description

Pavement Specifications

Site 8

Project: NA
JMF: C130343
Material: PCC - R/T
Age: 1997
Roadway: I-77
County: Noble
Location: South bound lane between MM 20 and 19.
Mix Type: NA

Sieve	% Passing
2"	NA
1 ½"	NA
1"	NA
¾"	NA
½"	NA
3/8"	NA
No. 4	NA
No. 8	NA
No. 16	NA
No. 30	NA
No. 50	NA
No. 100	NA
No. 200	NA

AC Content @ Median Voids: NA
Optimum AC Content: NA
F/AC: NA
F/T: NA
AC Grade: NA
Stability: NA
Flow: NA
% Air Voids: NA
VMA: NA
Unit Weight: NA
Thickness: 229 mm

Coarse Aggregate:

%	Size	Type
NA		

Fine Aggregate:

%	Size	Type
NA		

RAP:

%	Description

Pavement Specifications

Site 9

Project: 580-95
JMF: B417015
Material: Dense Graded Asphalt
Age: 1997
Roadway: IR 70
County: Belmont
Location: Before Morristown/Belmont exit #208 in Eastbound lane.
Mix Type: T-1H

Sieve	% Passing
2"	100
1 ½"	100
1"	100
¾"	100
½"	99
3/8"	77
No. 4	44
No. 8	34
No. 16	26
No. 30	17
No. 50	9
No. 100	4
No. 200	2.1

AC Content @ Median Voids: 7.5
Optimum AC Content: 6.6
F/AC: 0.3
F/T: -1
AC Grade: PG 64-22
Stability: 3080
Flow: 12.4
% Air Voids: 4.0
VMA: 16.6
Unit Weight: 1.920 ton/yd^3
Thickness:

Coarse Aggregate:

%	Size	Type
55	7's	Slag

Fine Aggregate:

%	Size	Type
23	Mfg. Sand	Slag
22	Sand	Nat. Sand

RAP:

%	Description

Pavement Specifications

Site 10

Project: 277-97
JMF: B417137
Material: Dense Graded Asphalt
Age: 1997
Roadway: IR 470
County: Belmont
Location: Before Exit #3 in Eastbound direction.
Mix Type: T-1H w/ SBS

Sieve	% Passing
2"	100
1 ½"	100
1"	100
¾"	100
½"	95
3/8"	84
No. 4	45
No. 8	28
No. 16	20
No. 30	13
No. 50	7
No. 100	5
No. 200	3.1

AC Content @ Median Voids: 6.0

Optimum AC Content: 6.0

F/AC: 0.52

F/T: -1

AC Grade: PG 58-28

Stability: 3610

Flow: 11.8

% Air Voids: 4.0

VMA: 14.8

Unit Weight: 1.995 ton/yd^3

Thickness:

Coarse Aggregate:

%	Size	Type
47	8's	Gravel
18	6's	Gravel

Fine Aggregate:

%	Size	Type
16	Sand	Nat. Sand
19	Sand	Mfg. Sand

RAP:

%	Description

Pavement Specifications

Site 11

Project: 288-97
Material: Dense Graded Asphalt
Roadway: IR 77

JMF: B417345
Age: 1997
County: Tuscarawras

Location: North of rest area in southbound lane south of bridge past the Strasburg exit.
Mix Type: 446-1H

Sieve	% Passing
2”	100
1 ½”	100
1”	100
¾”	100
½”	96
3/8”	84
No. 4	49
No. 8	26
No. 16	19
No. 30	14
No. 50	9
No. 100	4
No. 200	2.2

AC Content @ Median Voids: 5.4
Optimum AC Content: 5.4
F/AC: 0.4
F/T: 0
AC Grade: PG 58-28
Stability: 2140
Flow: 10.4
% Air Voids: 4.0
VMA: 13.6
Unit Weight: 1.949 ton/yd^3
Thickness:

Coarse Aggregate:

%	Size	Type
55	8’s	Gravel
30	617	Gravel

Fine Aggregate:

%	Size	Type
15	Sand	Nat. Sand

RAP:

%	Description

Pavement Specifications

Site 12

Project: 907-90 JMF: B416309
Material: PCC - Transverse Age: 1994
Roadway: SR 39 County: Tuscarawas
Location: EB lane across from X-mas Chalet.
Mix Type: NA

Sieve	% Passing
2"	NA
1 ½"	NA
1"	NA
¾"	NA
½"	NA
3/8"	NA
No. 4	NA
No. 8	NA
No. 16	NA
No. 30	NA
No. 50	NA
No. 100	NA
No. 200	NA

AC Content @ Median Voids: NA
Optimum AC Content: NA
F/AC: NA
F/T: NA
AC Grade: NA
Stability: NA
Flow: NA
% Air Voids: NA
VMA: NA
Unit Weight: NA
Thickness: 229 mm

Coarse Aggregate:

%	Size	Type
NA		

Fine Aggregate:

%	Size	Type
NA		

RAP:

%	Description

APPENDIX B

MEASURMENT SITE PLAN AND PROFILE DRAWINGS

Plan and Profile

Site 1

Measurement Date: 7/6-7/7/98

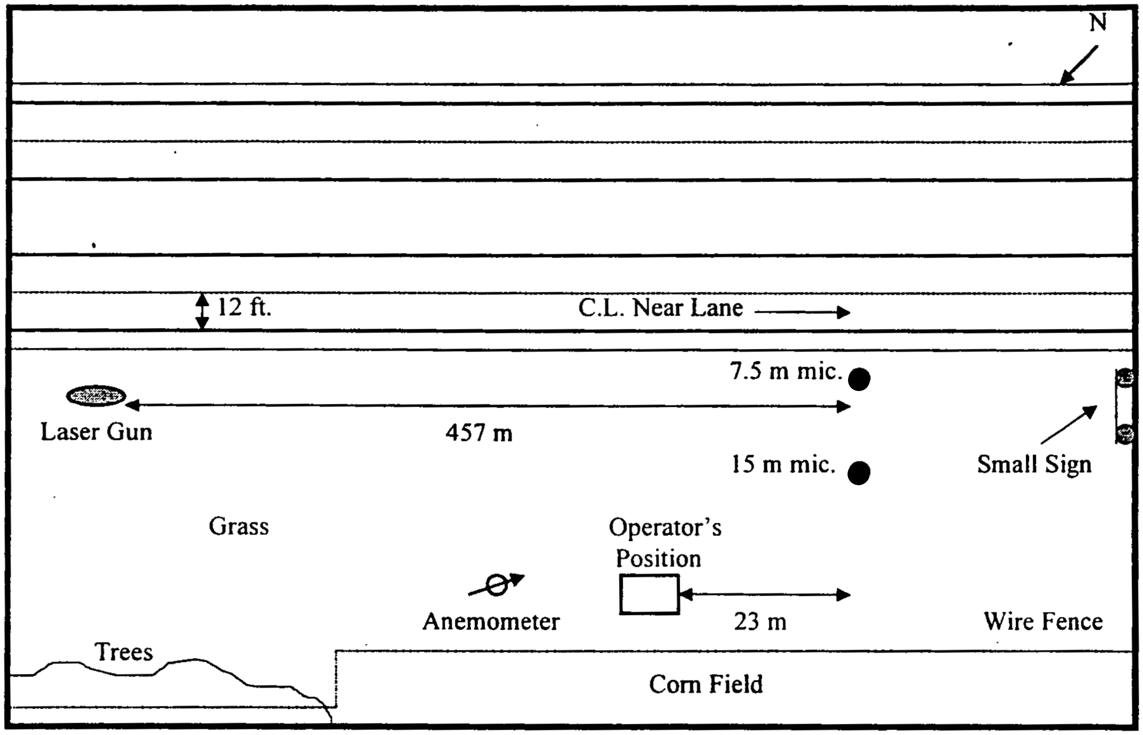
Location: US-30 WB, Allen County, Between Rt. 115 and Rt. 309.

Pavement Type: DGAC (Limestone)

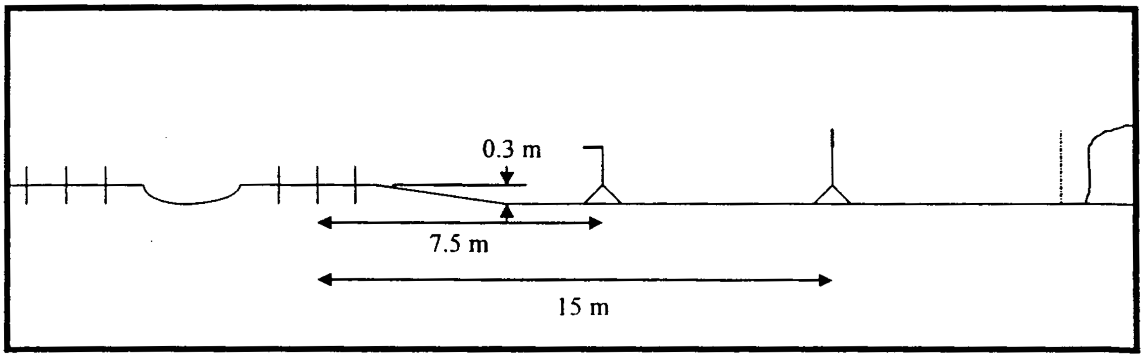
Year Constructed: 1997

Average Daily Traffic: 5,750 vehicles

Plan View



Profile View



Not to scale

Plan and Profile

Site 2

Measurement Date: 7/9/98

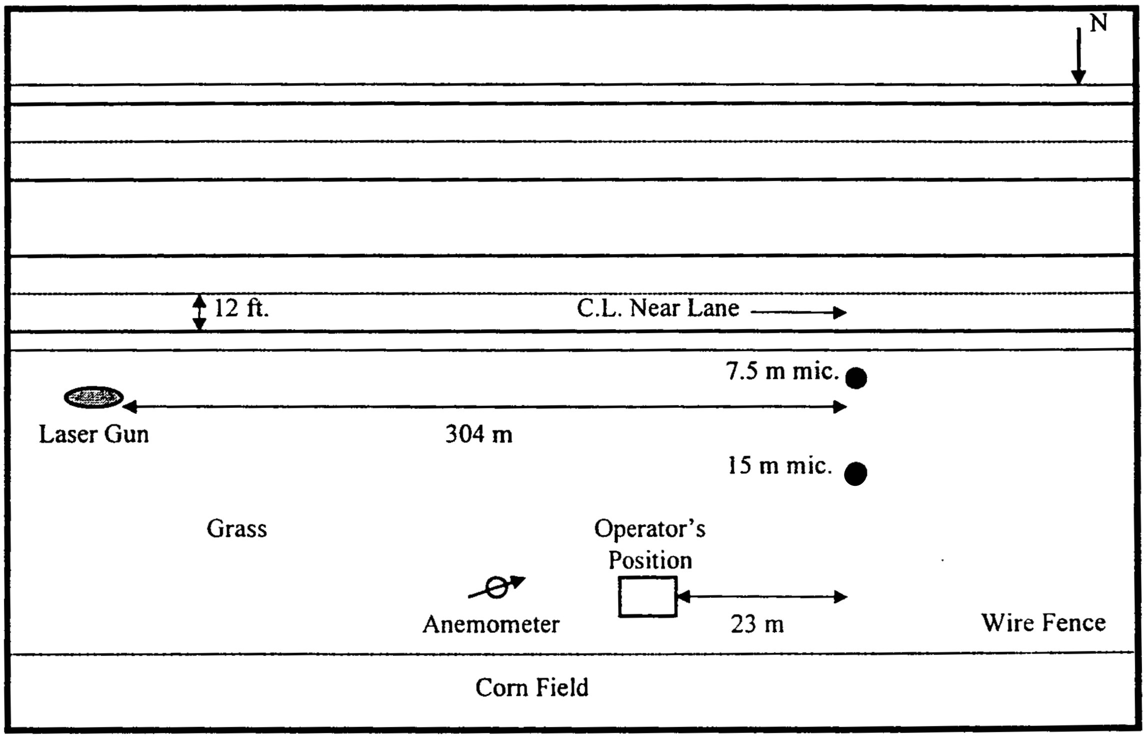
Location: US-30 WB, Van Wert County, Between Rt. 418 and Rt. 185.

Pavement Type: DGAC (Limestone)

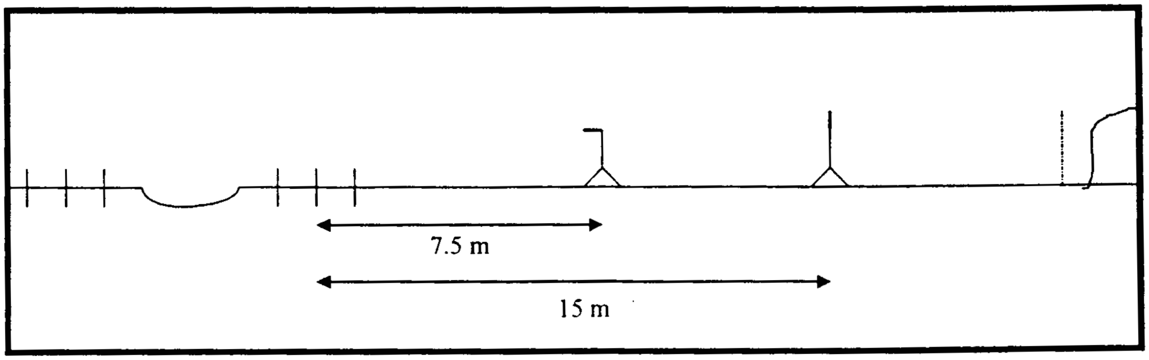
Year Constructed: 1997

Average Daily Traffic: 7,670 vehicles

Plan View



Profile View



Not to scale

Plan and Profile

Site 3

Measurement Date: 7/1-7/2/98

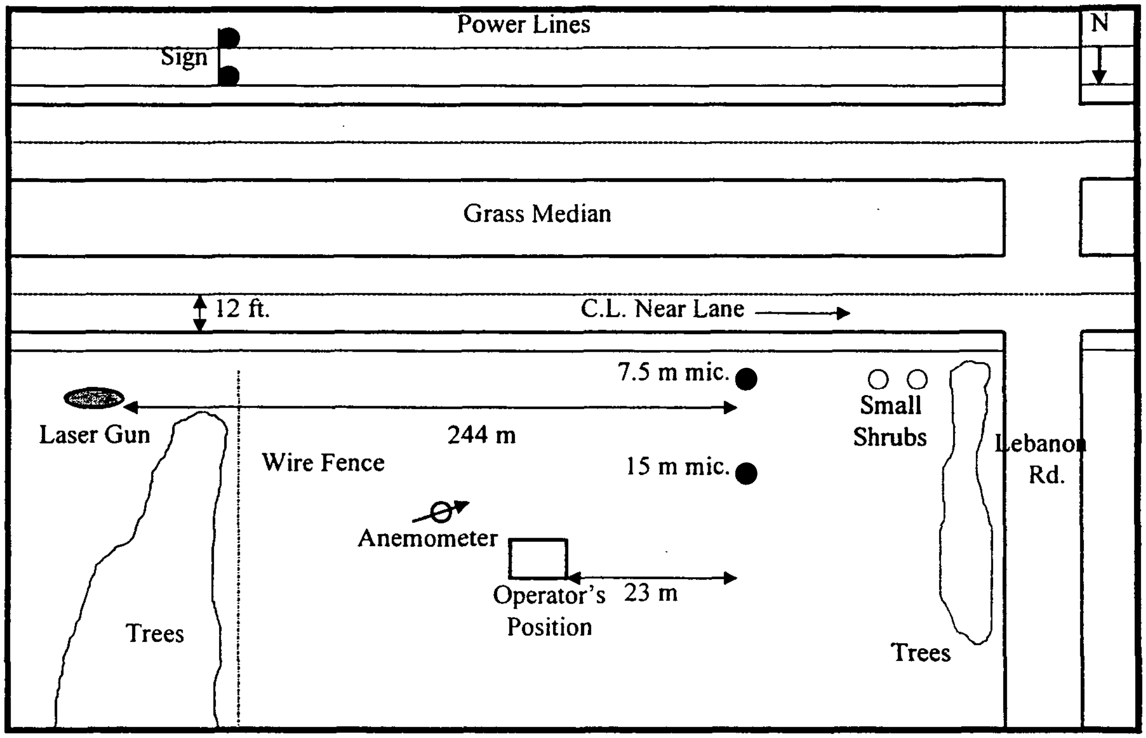
Location: US 30 WB, Wayne County, Near the Stark County Line.

Pavement Type: SMA

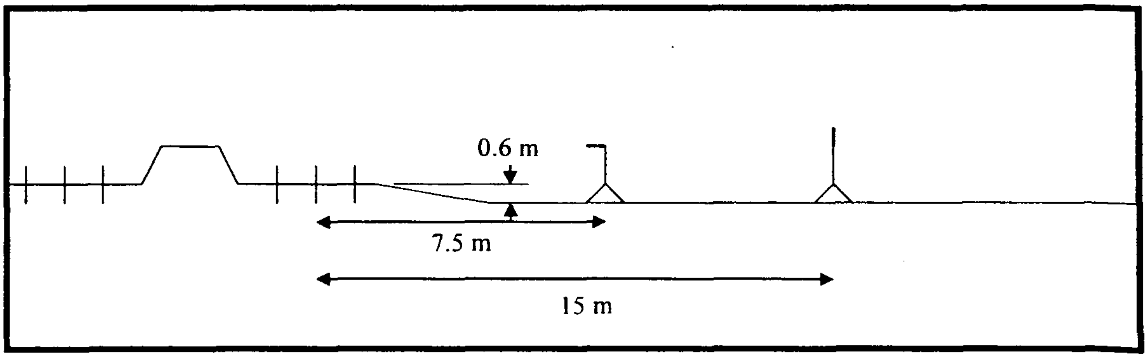
Year Constructed: 1995

Average Daily Traffic: 15,330 vehicles

Plan View



Profile View



Not to scale

Plan and Profile

Site 4

Measurement Date: 6/24/98

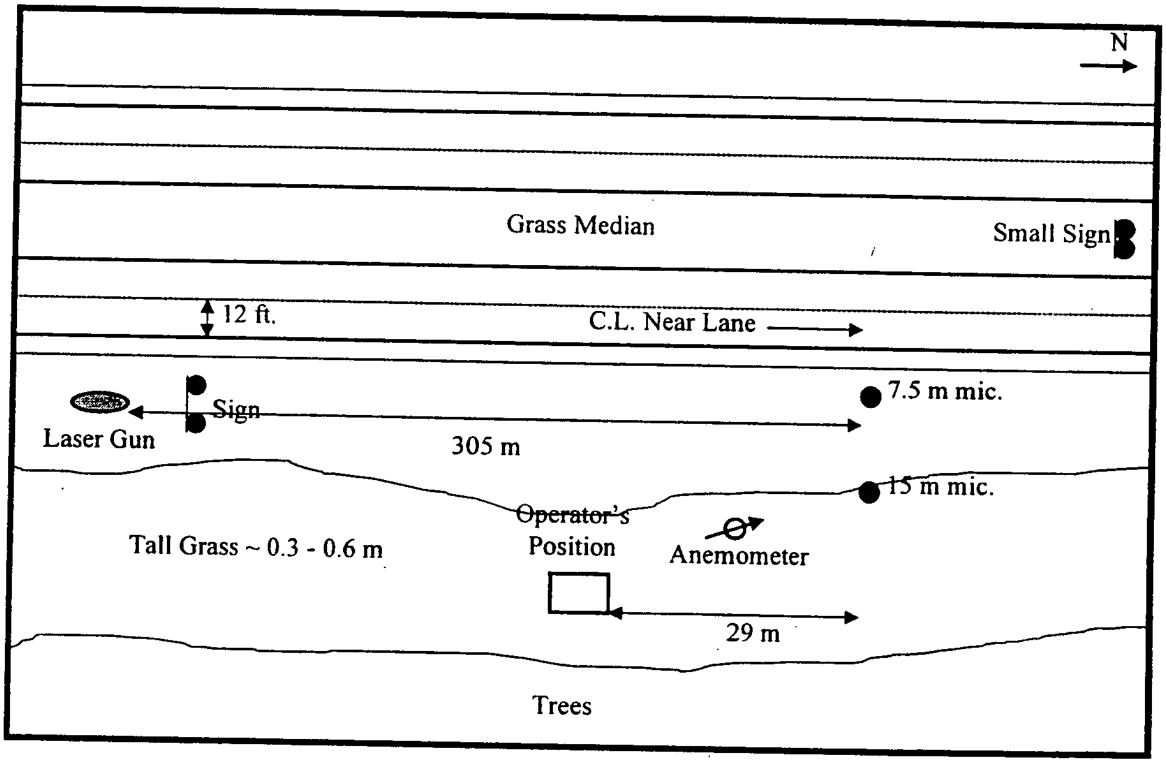
Location: I 480 NB, Summit County, Between Ohio Turnpike and SR 82.

Pavement Type: OGAC

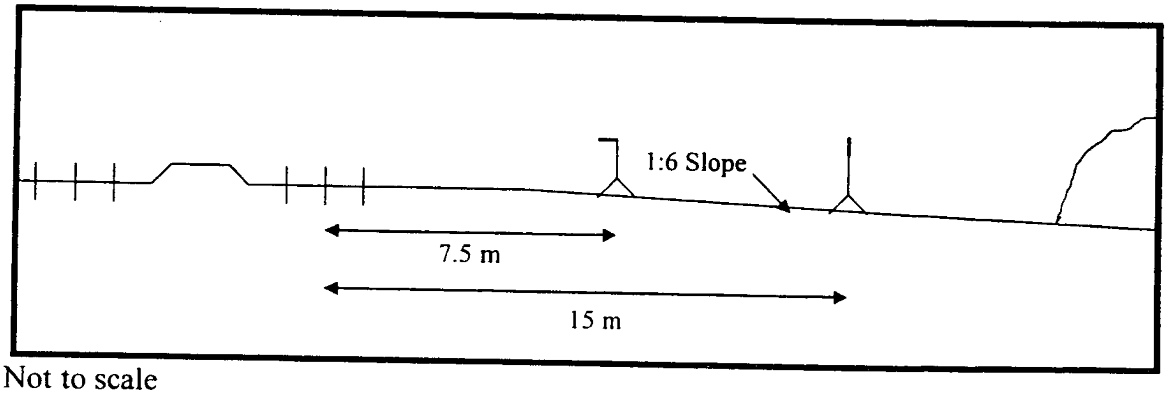
Year Constructed: 1997

Average Daily Traffic: 34,550 vehicles

Plan View



Profile View



Not to scale

Plan and Profile

Site 5

Measurement Date: 7/8/98

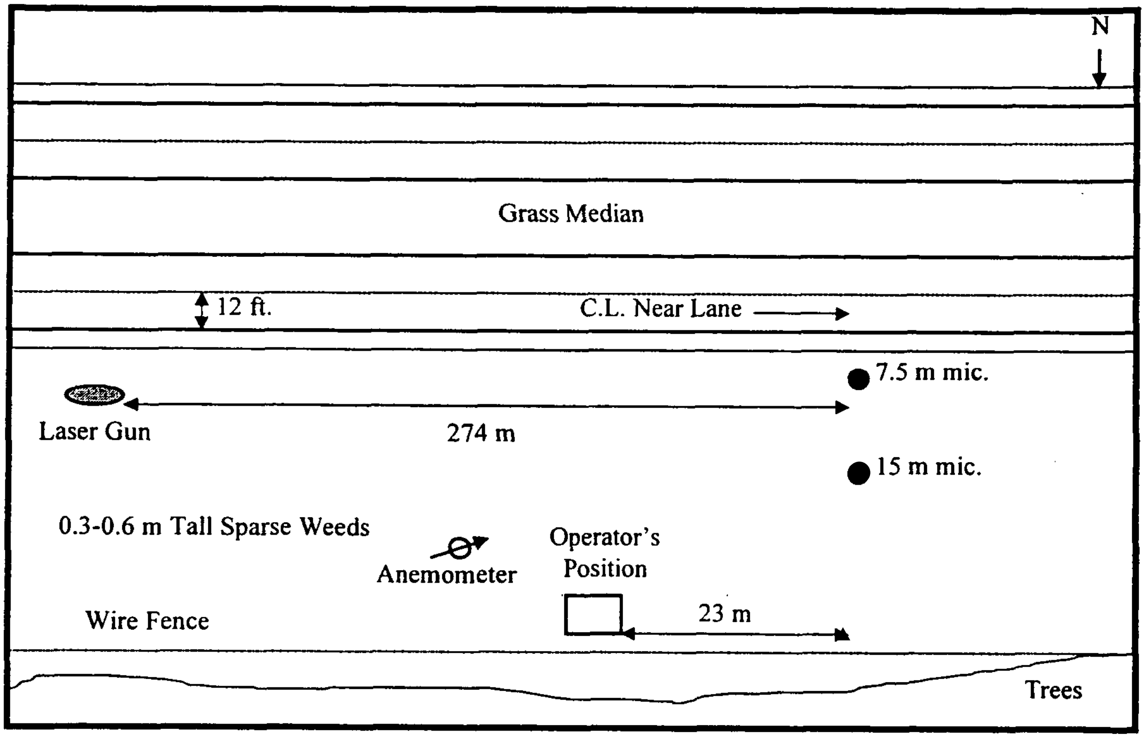
Location: I-70 WB, Licking County, West of Buckeye Lake.

Pavement Type: DGAC (Limestone/Gravel)

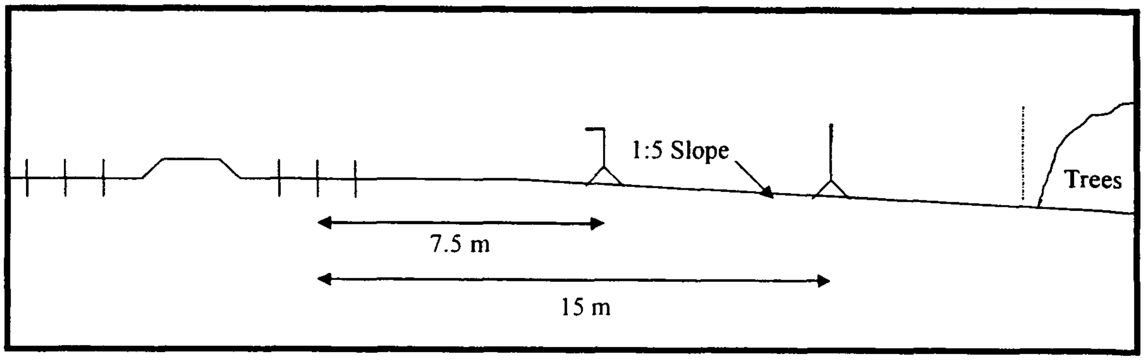
Year Constructed: 1996

Average Daily Traffic: 28,000 vehicles

Plan View



Profile View



Not to scale

Plan and Profile

Site 6

Measurement Date: 6/18/98

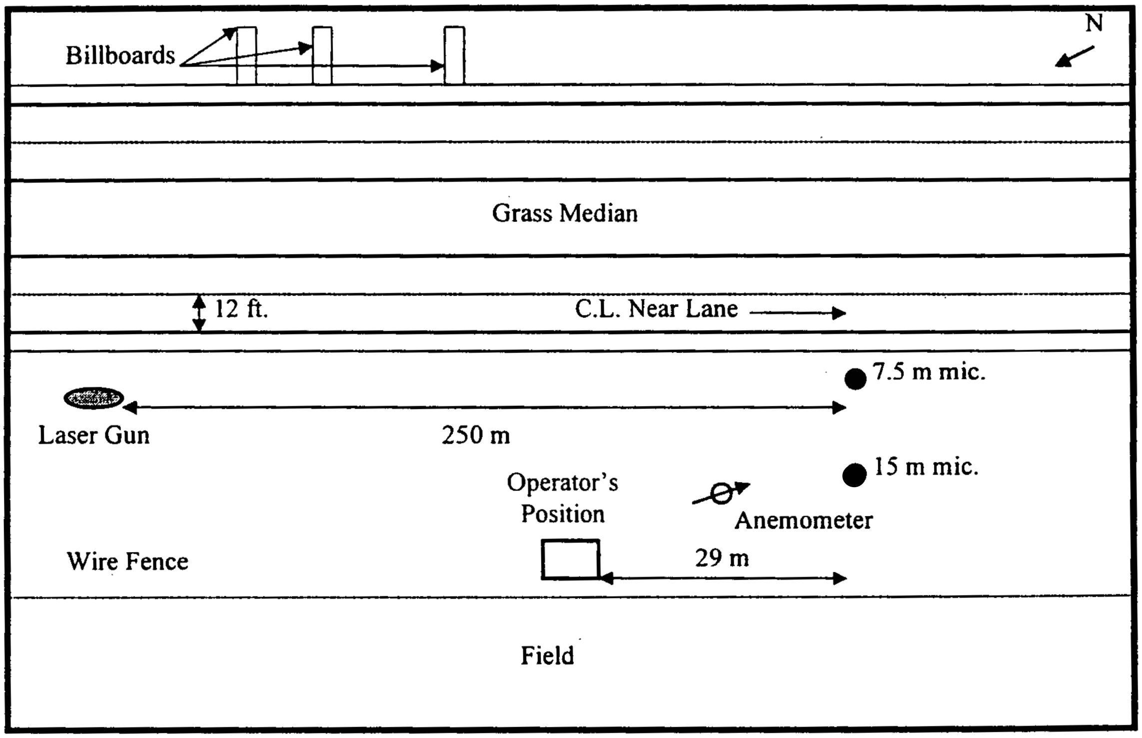
Location: SR 32 WB, Pike County, Near SR 335.

Pavement Type: DGAC (Gravel)

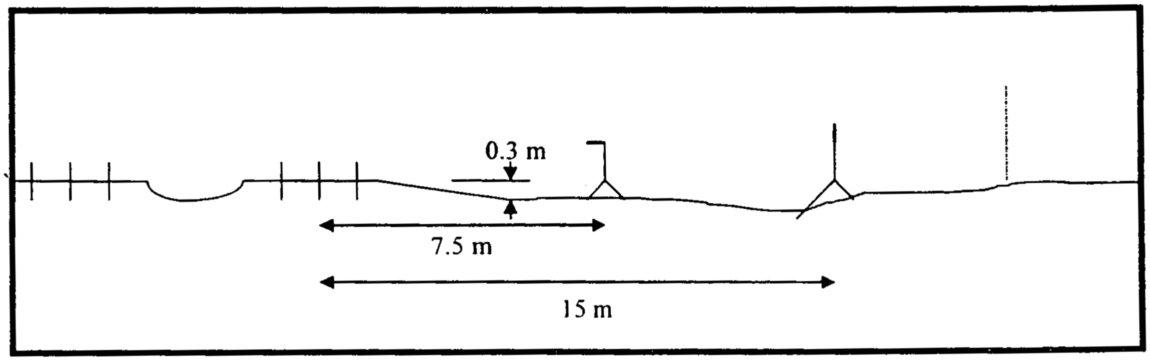
Year Constructed: 1991

Average Daily Traffic: 3,950 vehicles

Plan View



Profile View



Not to scale

Plan and Profile

Site 7

Measurement Date: 6/17/98

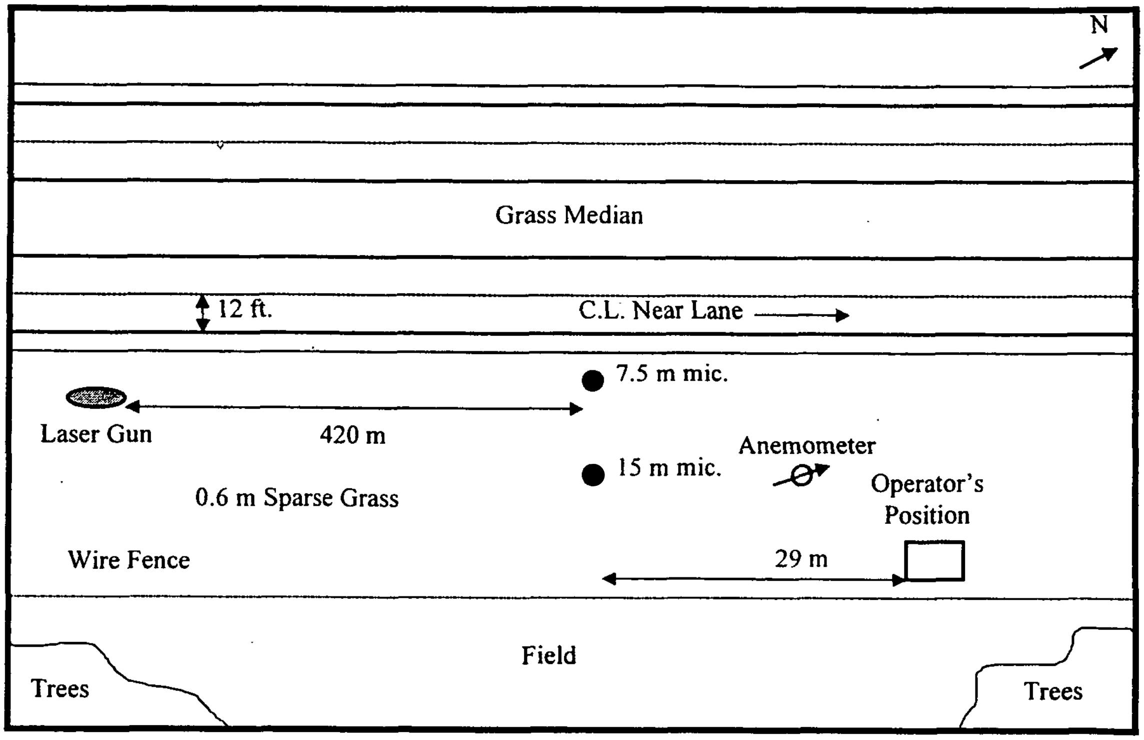
Location: SR 32 EB, Pike County, Between Schuster and Shyville Rd.

Pavement Type: DGAC (Gravel/Limestone)

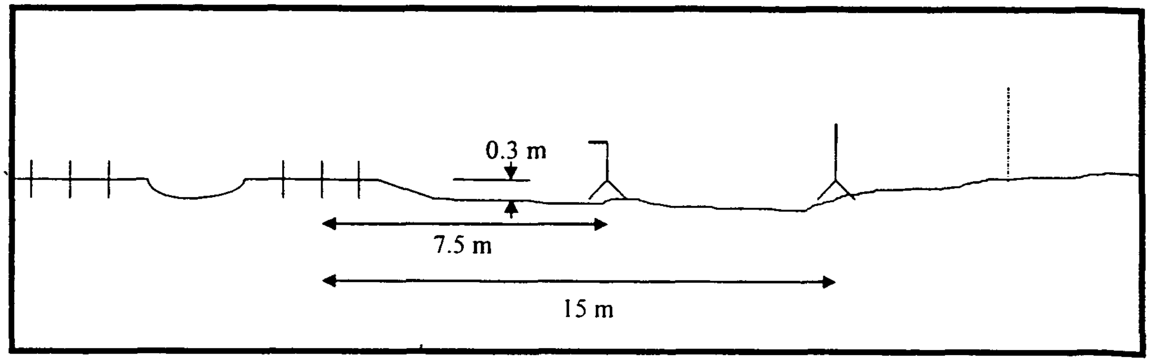
Year Constructed: 1997

Average Daily Traffic: 5,170 vehicles

Plan View



Profile View



Not to scale

Plan and Profile

Site 8

Measurement Date: 9/26/98

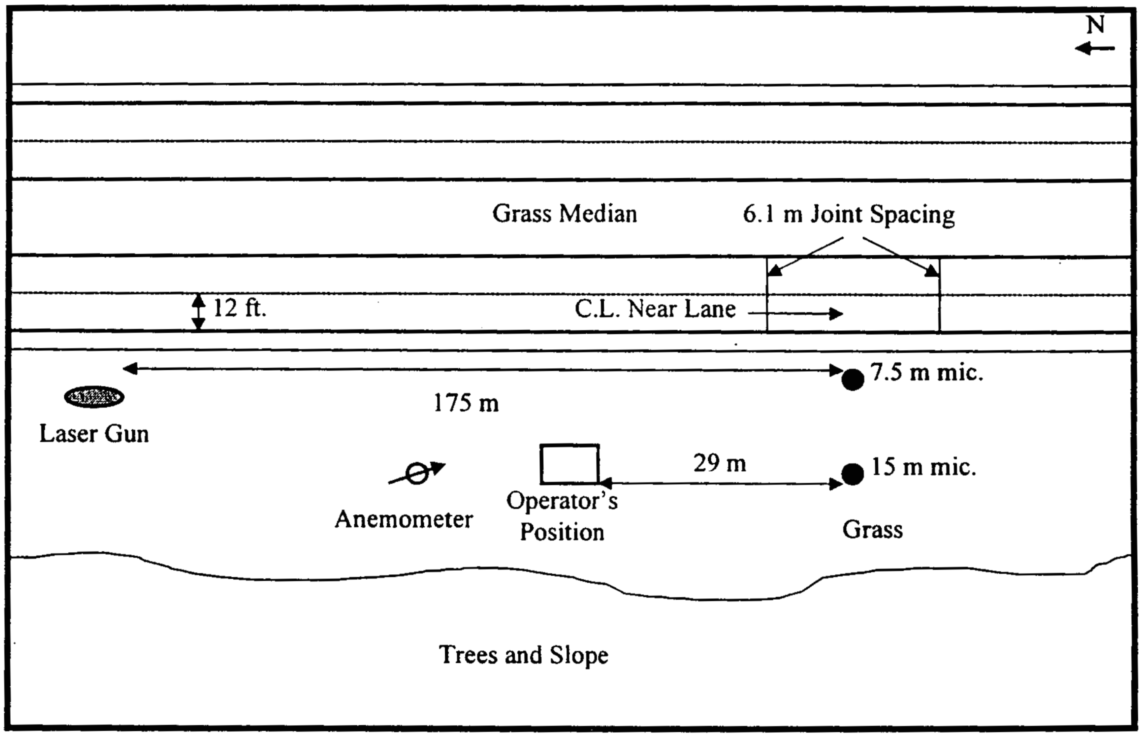
Location: I 77 SB, Noble County, Between Mile Markers 20 and 19.

Pavement Type: PCC, Random-Transverse Grooves

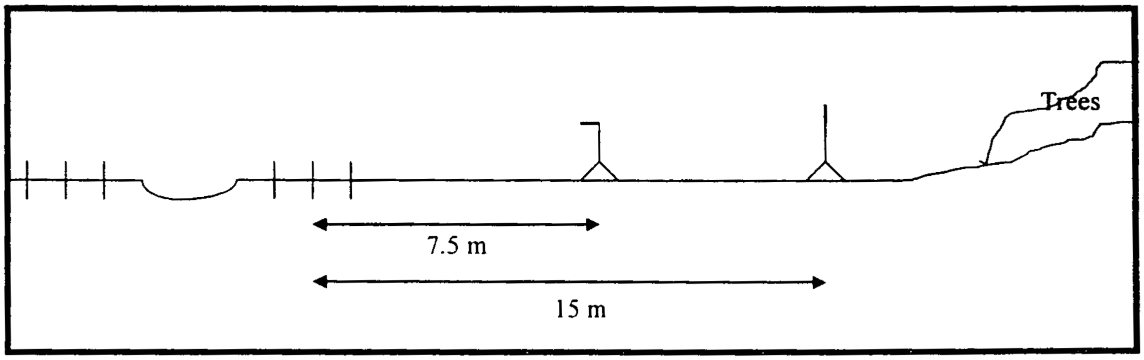
Year Constructed: 1997

Average Daily Traffic: 10,740 vehicles

Plan View



Profile View



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Plan and Profile

Site 9

Measurement Date: 6/22/98

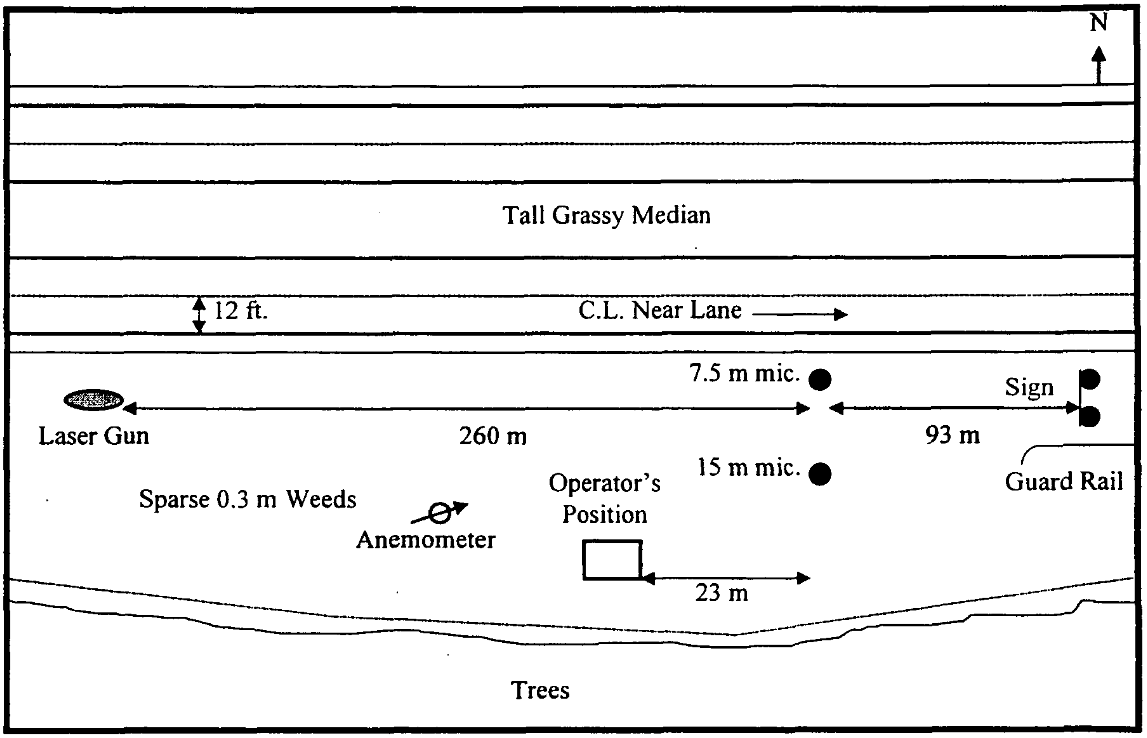
Location: I-70 EB, Belmont County, Before Morristown/Belmont Exit.

Pavement Type: DGAC (Slag)

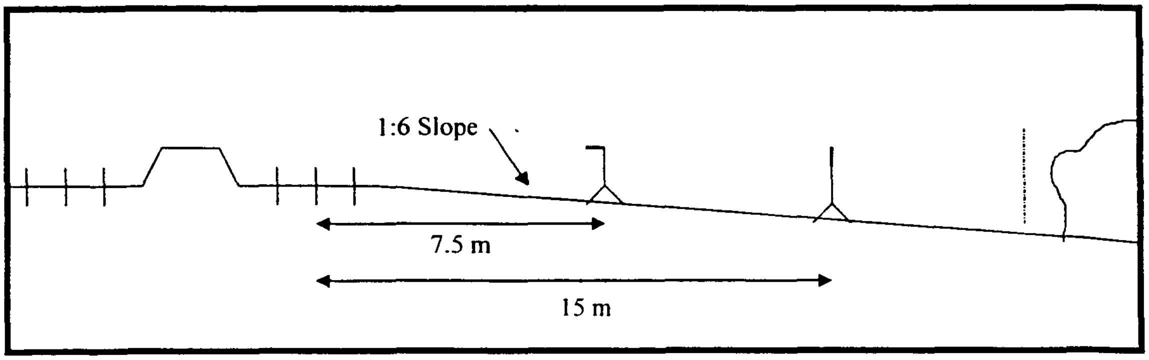
Year Constructed: 1997

Average Daily Traffic: 38,750 vehicles

Plan View



Profile View



Not to scale

Plan and Profile

Site 10

Measurement Date: 6/23/98

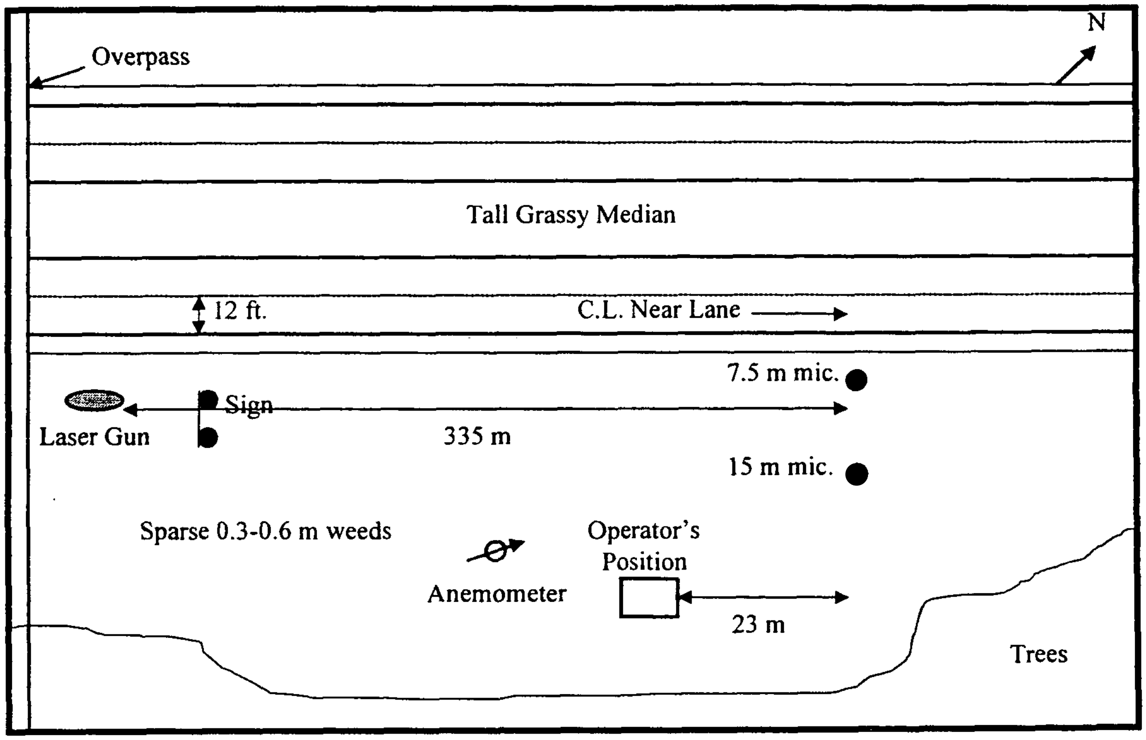
Location: I-470 EB, Belmont County, Between I-70 Exit and W.V. State Line.

Pavement Type: DGAC (Gravel)

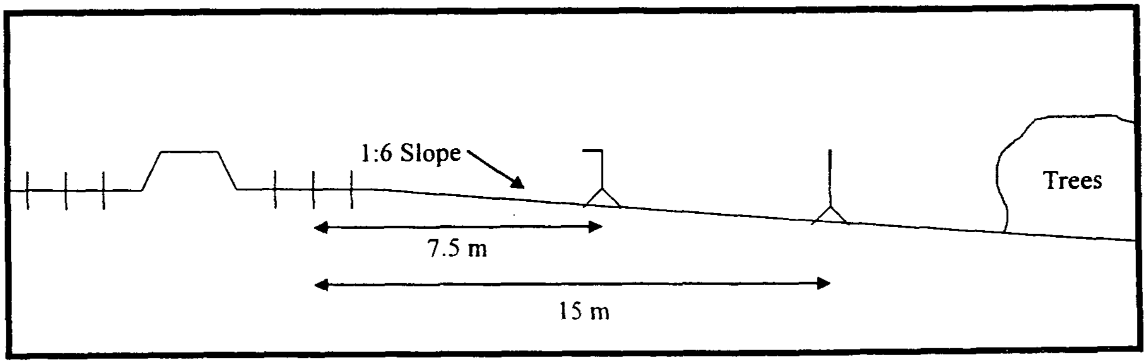
Year Constructed: 1997

Average Daily Traffic: 26,910 vehicles

Plan View



Profile View



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Plan and Profile

Site 11

Measurement Date: 7/1/98

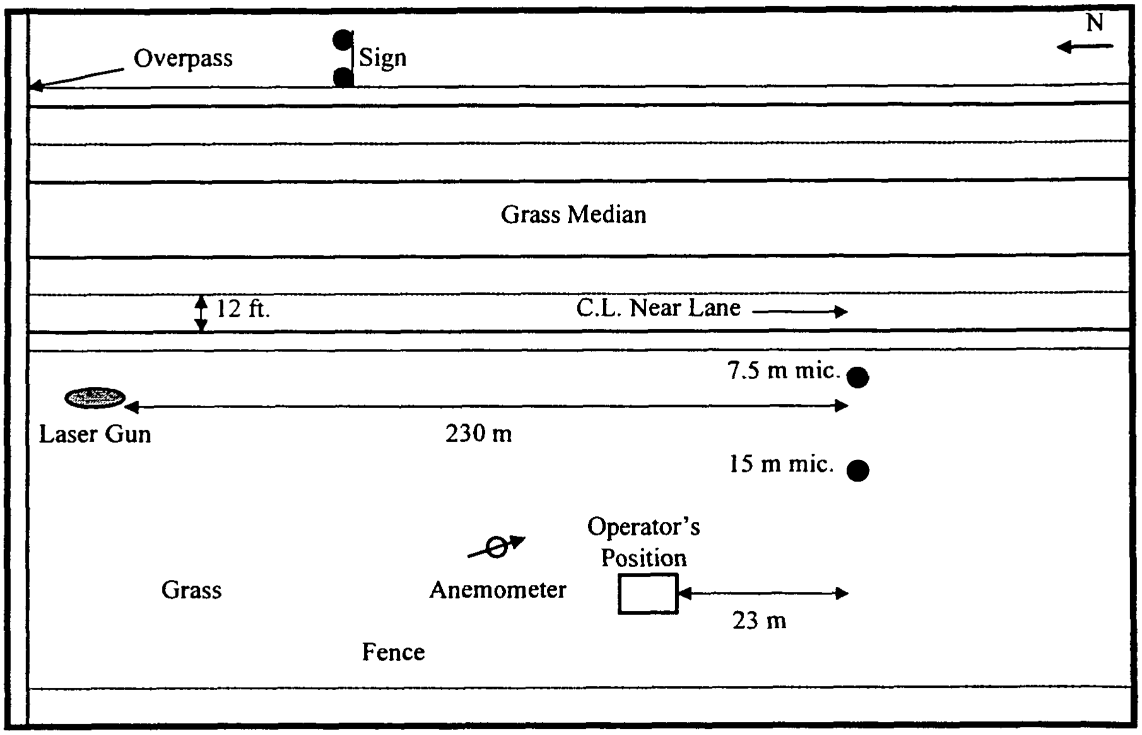
Location: I-77 SB, Tuscarawas County, Between Dover Rest Area and Strasburg Exit.

Pavement Type: DGAC (Gravel)

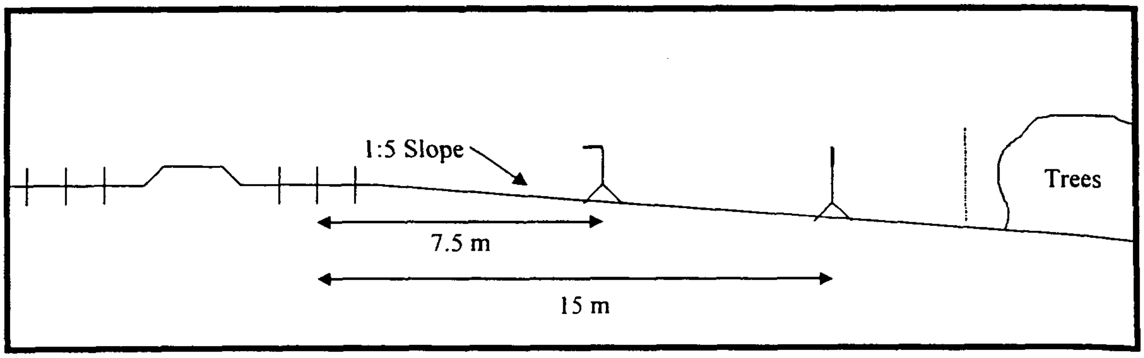
Year Constructed: 1997

Average Daily Traffic: 30,440 vehicles

Plan View



Profile View



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Plan and Profile

Site 12

Measurement Date: 6/30/98

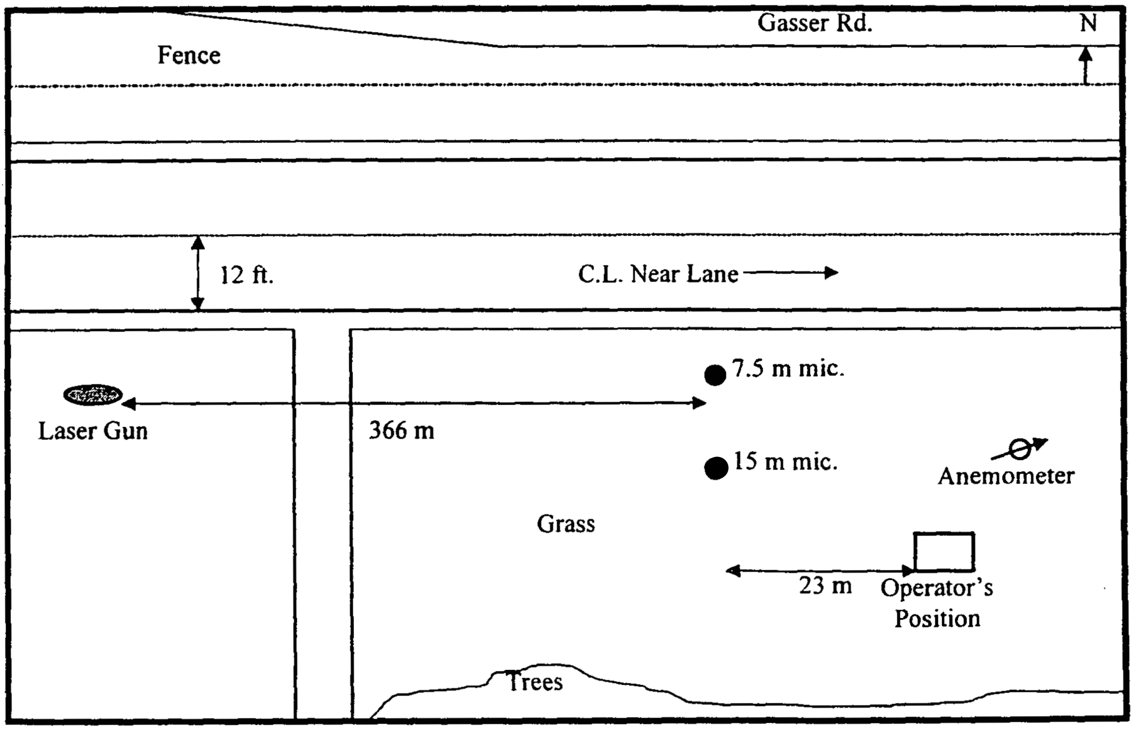
Location: SR 39 EB, Tuscarawas County, Approximately 5 miles West of I 77.

Pavement Type: PCC, Transverse Grooves

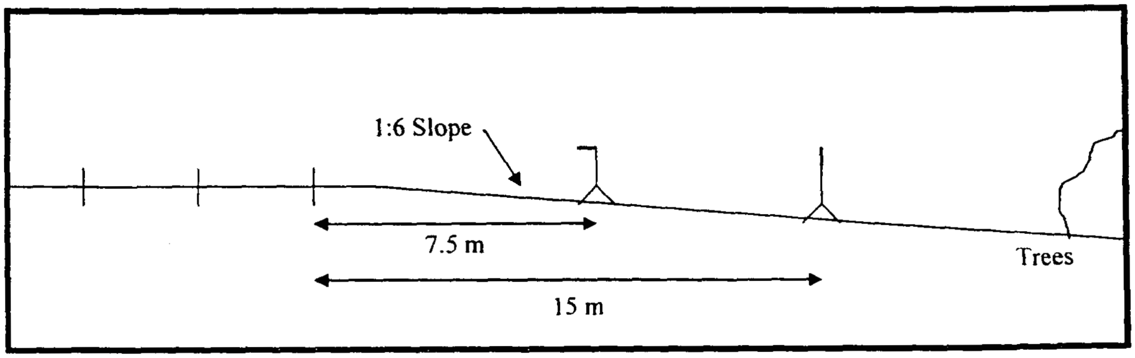
Year Constructed: 1994

Average Daily Traffic: 8,200 vehicles

Plan View



Profile View



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APPENDIX C

LISTING OF EQUIPMENT

Equipment	Model	Serial Number
Larson-Davis Real Time Analyzer	2900B	0740
Larson-Davis Preamplifier	PRM900B	0417
Larson-Davis Preamplifier	PRM900B	03751
Bruel and Kjaer Microphone	4189	2021001
Bruel and Kjaer Microphone	4189	2021000
Larson-Davis Acoustic Calibrator	CA 200	0423
Laser Tech Ultralyte Laser Gun	LTI 20-20	UL000267
Davis Instruments Weather Wizard	III	WC80224A51
Hygrocheck Digital Hygrometer	NA	5851
Omegascope Hand Held Infrared Thermometer	OS520	7012794
Larson-Davis "Dummy" Microphone	ADP005	74868 UG-1094/U

APPENDIX D

METEOROLOGICAL DATA

Meteorological Data-Site 1

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Cloud Cover
7/6/98	3:10 PM	48	29.2	52.5	11	N	Ptl. Cldy
	3:25 PM	49	31.2	52.5	13	N	Ptl. Cldy
	3:40 PM	49	32.9	50	11	E	Ptl. Cldy
	4:00 PM	48	30.1	54.2	11	N	Ptl. Cldy
	4:17 PM	48	28.3	53.3	6	N	Ptl. Cldy
	4:33 PM	49	31.5	49.5	15	N	Ptl. Cldy
	4:48 PM	49	31.6	51.6	15	NE	Ptl. Cldy
	5:05 PM	47	30.5	51.7	13	N	Ptl. Cldy
	5:20 PM	46	31.2	56.9	11	NE	Ptl. Cldy
	5:40 PM	43	29.8	54.8	11	NE	Ptl. Cldy
	5:55 PM	43	28.5	57.2	6	NE	Ptl. Cldy
	6:20 PM	42	30	56.2	8	N	Ptl. Cldy
	6:38 PM	41	29.2	59.4	5	N	Ptl. Cldy
	6:55 PM	41	28.6	59.5	6	N	Ptl. Cldy
	7:10 PM	40	28.4	60.4	11	NE	Ptl. Cldy
7/7/98							
	10:30 AM	40	28.7	58.2	11	NE	Hazy
	10:46 AM	39	29.8	55.2	11	NE	Hazy
	11:00 AM	41	29.6	51.4	5	NE	Hazy
	11:16 AM	39	29.2	57.3	6	N	Hazy
	11:31 AM	41	29.6	57.5	2	N	Hazy
	11:46 AM	36	27.9	69.5	3	NE	Cloudy
	11:52 AM	36	28.3	70.7	8	N	Cloudy

Meteorological Data-Site 2

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Cloud Cover
7/9/98	9:40 AM	24	26.8	52.5	5	E	Sunny
	9:55 AM	24	25.9	60.3	3	E	Ptl. Cldy
	10:10 AM	32	25.4	66.1	6	E	Ptl. Cldy
	10:25 AM	33	25.6	75.4	6	SE	Cloudy
	10:40 AM	35	26.3	74.5	6	E	Cloudy
	11:00 AM	35	28.1	64.3	3	E	Cloudy
	11:15 AM	39	29.7	62	3	E	Cloudy
	11:32 AM	37	27.6	76.9	3	S	Cloudy
	11:44 AM	39	30.1	63.4	6	E	Cloudy
	12:00 PM	36	26.3	70.7	5	S	Cloudy
	12:22 PM	37	26.9	80.3	2	S	Cloudy

Meteorological Data-Site 3

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Cloud Cover
7/1/98	6:20 AM	36	26.9	54.2	13	SE	Clear
	6:40 AM	36	26.6	50.2	13	SE	Clear
	6:55 AM	38	25.9	53.1	10	SE	Clear
	7:10 AM	32	25.7	48.9	10	SE	Clear
	7:25 AM	36	25.1	52.7	8	SE	Clear
	7:45 AM	34	24.2	54.1	10	SE	Clear
	8:00 AM	31	23.4	63.1	3	SE	Clear
	8:15 AM	29	22.4	67.7	3	S	Clear
	8:35 AM	27	21.1	71.2	5	SW	Clear
	8:36 AM	26	20.3	77	5	W	Clear
7/2/98	10:25 AM	N.A.	27.3	55.8	8	W	Clear
	10:40 AM	28	27.5	62.1	8	W	Clear
	11:02 AM	33	30.3	63.7	3	NW	Clear
	11:17 AM	N.A.	28.5	53.1	6	W	Clear

Meteorological Data-Site 4

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Cloud Cover
6/24/98	10:05 AM	37	30.6	75.3	2	N	Clear
	10:20 AM	40	30.9	75.9	8	N	Clear
	10:35 AM	42	32.1	72.5	11	N	Clear
	10:55 AM	43	31.5	72.9	10	N	Clear
	11:15 AM	44	32.3	58.7	18	N	Clear
	11:40 AM	48	32.8	54.8	5	NW	Clear
	12:06 PM	49	33.4	49.2	13	N	Clear
	12:30 PM	52	36.1	47.1	5	N	Clear
	12:38 PM	51	37.9	54.9	6	N	Clear

Meteorological Data-Site 5

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Cloud Cover
7/8/98	5:25 PM	41	33.1	68.1	3	SE	Ptl. Cldy
	5:45 PM	38	31	72.8	2	N	Ptl. Cldy
	6:00 PM	38	31	76.8	0	N.A.	Ptl. Cldy
	6:15 PM	38	30.2	77.7	3	N	Ptl. Cldy
	6:30 PM	34	28.1	81.7	3	NW	Ptl. Cldy
	6:47 PM	34	27.4	87.4	0	N.A.	Ptl. Cldy
	7:00 PM	34	29.4	85.5	0	N.A.	Ptl. Cldy
	7:15 PM	37	27.7	83	0	N.A.	Ptl. Cldy
	7:30 PM	32	26.8	78	0	N.A.	Ptl. Cldy
	7:47 PM	31	26.4	88.8	0	N.A.	Ptl. Cldy
	8:00 PM	30	25.6	89.1	0	N.A.	Ptl. Cldy
	8:06 PM	30	25.5	88.4	0	N.A.	Ptl. Cldy

Meteorological Data-Site 6

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Cloud Cover
6/18/98	9:57 AM	39	28.7	43.8	0	E	Sunny
	10:16 AM	40	31.8	57.8	0	SE	Sunny
	10:31 AM	41	33.2	56.8	0	N	Sunny
	10:46 AM	41	31.4	44.2	5	N	Sunny
	11:08 AM	39	30.9	46.2	2	NE	Sunny
	11:30 AM	40	33.1	54.2	5	E	Sunny
	11:45 AM	43	34.8	48.3	0	E	Sunny
	12:00 PM	46	36	51.9	0	E	Sunny
	12:18 PM	43	34.7	51.2	3	E	Sunny
	12:32 PM	47	35.9	56.2	3	E	Sunny
	12:47 PM	48	36.2	52.7	0	N	Sunny
	1:02 PM	49	36.3	52.3	8	E	Sunny
	1:18 PM	51	36.7	52.8	5	E	Sunny
	1:35 PM	50	35.5	50.3	10	E	Sunny
	1:50 PM	51	37	51.2	6	N	Sunny
	2:05 PM	52	37.1	49.7	10	E	Sunny
	2:25 PM	53	37.7	51.7	6	NE	Sunny
	2:45 PM	49	38.6	50.1	5	N	Sunny
	3:01 PM	52	37.4	51.6	6	NE	Sunny
	3:16 PM	52	38.8	51.2	8	NE	Sunny
	3:31 PM	51	38.2	58.3	8	N	Sunny
	3:46 PM	50	38.5	51.8	8	N	Sunny
	4:01 PM	51	35.9	54.7	6	E	Sunny
	4:17 PM	46	31.8	57.5	5	E	Sunny
	4:54 PM	45	32.4	61.1	5	NE	Ptl. Cldy.

Meteorological Data-Site 7

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Cloud Cover
6/17/98	11:25 AM	43	31	61.3	6	E	Prt. Cldy
	11:40 AM	43	31	54.7	8	E	Prt. Cldy
	11:55 AM	43	31	62.1	8	E	Prt. Cldy
	12:10 PM	43	33	58.1	10	E	Prt. Cldy
	12:26 PM	45	30	60.9	11	E	Prt. Cldy
	12:40 PM	47	31	60	6	E	Prt. Cldy
	1:04 PM	46	31	55.7	5	E	Prt. Cldy
	1:20 PM	46	30	58.1	10	E	Prt. Cldy
	1:50 PM	45	29	56.3	8	E	Prt. Cldy
	2:05 PM	48	29	50.6	3	E	Prt. Cldy
	2:20 PM	51	36	50.9	8	E	Prt. Cldy
	2:39 PM	50	31.5	56.6	13	E	Prt. Cldy
	2:55 PM	53	30.3	55.5	16	E	Prt. Cldy
	3:10 PM	48	34.3	51.8	6	E	Prt. Cldy
	3:25 PM	48	32.2	53.4	8	E	Prt. Cldy
	3:40 PM	42	29.1	58.2	8	E	Prt. Cldy
	3:55 PM	41	28.8	58.9	5	E	Prt. Cldy
	4:13 PM	47	34.3	52.4	11	E	Prt. Cldy
	4:28 PM	48	30.7	53.6	8	E	Prt. Cldy
	4:49 PM	44	28.5	57.1	3	SE	Prt. Cldy
	5:05 PM	47	33.7	52.7	5	SE	Prt. Cldy
	5:20 PM	46	31.7	50.1	11	E	Prt. Cldy
	5:35 PM	46	31.4	49.5	8	E	Prt. Cldy
	5:50 PM	45	31.7	51	13	E	Prt. Cldy
	6:03 PM	46	30.4	48.1	10	E	Prt. Cldy

Meteorological Data-Site 8

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Cloud Cover
9/26/98	10:37 AM	31	28.8	62	3	N.	Clear
	11:04 AM	26	29.3	60	1	N	Clear
	11:20 AM	28	30.4	57.5	2	N	Clear
	11:35 AM	32	29.9	61.5	3	NE	Clear
	11:53 AM	36	31.1	59.6	3	N	Clear
	12:08 PM	37	31.5	58	3	NE	Clear
	12:25 PM	37	31.2	57.5	3	NE	Clear
	12:38 PM	38	32.2	57.6	2	N	Clear
	12:55 PM	40	32.2	56.5	4	SE	Clear
	1:10 PM	39	32.1	57	3	NW	Clear
	1:25 PM	39	32.6	55.2	3	N	Clear
	1:40 PM	41	33.3	53.5	0	N	Clear
	1:55 PM	41	34.2	55.7	4	E	Clear
	2:10 PM	40	32.4	55.5	6	NW	Clear
	2:25 PM	42	34.6	51.5	1	NE	Clear
	2:40 PM	43	34.5	50.6	2	N	Clear
	2:55 PM	39	32.6	52	4	N	Clear
	3:10 PM	41	32.8	52	4	N	Pt. Cldy
	3:25 PM	41	33.7	52.4	1	E	Pt. Cldy
	3:40 PM	42	34.1	50	2	E	Pt. Cldy

Meteorological Data-Site 9

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Cloud Cover
6/22/98	2:45 PM	49	34.4	51.1	6	NE	Pt. Cldy.
	3:05 PM	46	30.6	56.5	3	NE	Pt. Cldy.
	3:23 PM	46	31.7	50.9	6	NE	Pt. Cldy.
	3:38 PM	43	32.8	56.4	13	E	Pt. Cldy.
	4:00 PM	45	33.9	58	13	E	Pt. Cldy.
	4:19 PM	41	30.6	61.6	15	E	Pt. Cldy.
	4:40 PM	41	33.9	53.5	10	E	Pt. Cldy.
	5:03 PM	42	33.3	50.1	6	E	Pt. Cldy.
	5:18 PM	40	33.3	49.6	8	E	Pt. Cldy.
	5:36 PM	42	32.2	49.5	8	E	Pt. Cldy.
	5:55 PM	40	31.3	59.3	8	E	Pt. Cldy.
	6:16 PM	41	30.6	53.6	3	E	Pt. Cldy.
	6:36 PM	31	29.6	62.7	5	E	Pt. Cldy.
	6:51 PM	34	28.9	64.6	2	N	Pt. Cldy.
	7:02 PM	36	29.6	63.8	2	N	Pt. Cldy.

Meteorological Data-Site 10

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Cloud Cover
6/23/98	10:00 AM	39	27	67.5	0	E	Cloudy
	10:16 AM	37	29	83	3	E	Cloudy
	10:32 AM	37	28	78.2	2	E	Cloudy
	10:50 AM	27	24	85	2	SE	Cloudy
	11:10 AM	29	24	87.5	2	E	Cloudy
	11:40 AM	29	23	89.6	0	E	Cloudy
	11:57 AM	29	23	92.7	3	E	Cloudy
	12:15 PM	29	23	88.8	5	E	Cloudy
	12:32 PM	35	26	79.9	8	SE	Cloudy
	12:46 PM	30	23	84.4	6	E	Cloudy
	1:05 AM	31	23	83.9	8	E	Cloudy
	1:17 AM	32	25	78.9	5	E	Cloudy

Meteorological Data-Site 11

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Cloud Cover
7/1/98	1:25 PM	38	28.5	64.4	11	S	Ptl. Cldy
	1:40 PM	41	29.2	66.6	13	SE	Ptl. Cldy
	1:55 PM	42	29.1	57.7	11	E	Ptl. Cldy
	2:10 PM	43	29.3	63.2	13	SE	Ptl. Cldy
	2:25 PM	36	25.3	66.7	11	S	Ptl. Cldy
	2:47 PM	44	30.8	65.5	15	S	Ptl. Cldy
	3:05 PM	38	27.7	57.2	11	S	Ptl. Cldy
	3:20 PM	40	29.2	52.3	8	E	Ptl. Cldy
	3:45 PM	41	29.8	49.2	13	S	Ptl. Cldy
	4:00 PM	41	29.8	52.3	8	S	Ptl. Cldy
	4:16 PM	41	30	48.7	13	S	Ptl. Cldy

Meteorological Data-Site 12

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Cloud Cover
6/30/98	12:45 PM	36	26.9	71.2	10	E	Ptl. Cldy
	1:05 PM	41	30.8	72.1	10	E	Ptl. Cldy
	1:20 PM	37	27.3	71.6	16	E	Ptl. Cldy
	1:40 PM	38	28.7	71.3	16	E	Ptl. Cldy
	2:20 PM	37	26.6	71	8	E	Ptl. Cldy
7/1/98							
	7:45 AM	27	20.6	89.2	3	E	Clear
	8:15 AM	20	22.4	90.6	3	E	Clear
	8:37 AM	21	22.4	92.5	10	E	Clear
	9:00 AM	21	23.7	89	3	E	Clear
	9:15 AM	29	25.2	87	11	E	Clear
	9:35 AM	28	25.3	84.4	5	E	Clear
	9:55 AM	29	25.8	84.3	10	E	Clear
	10:15 AM	29	24.4	80.3	10	E	Clear
	10:40 AM	32	25.2	80.1	8	E	Clear
	11:10 AM	36	29.1	82.1	2	E	Clear
	11:30 AM	36	28.8	75.5	8	SE	Clear
	11:47 AM	38	28.7	71.5	8	E	Clear

Meteorological Data - PCC Comparison

Site 13, SR 50

							Tire Pressure			
Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Front right	Front left	Rear right	Rear left
10/21/98	12:15pm	21	14	72	8	-	26	27	26	24
	1:10pm	17	16	68	5	-	29	28	27	24

Site 14, SR 50 - West Section

							Tire Pressure			
Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Front right	Front left	Rear right	Rear left
10/21/98	1:40pm	17	16	73	0	-	28	28	27	24
	2:30pm	17	16	69	0	-	29	28	27	24

Meteorological Data - PCC Comparison

Site 15, SR 50 - East Section (WB)

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Tire Pressure Front right	Tire Pressure Front left	Tire Pressure Rear right	Tire Pressure Rear left
10/21/98	3:10pm	17	16	72	0	-	28	28	27	24
	3:50pm	19	16	71	0	-	29	28	27	24

Site 12, SR 39

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Tire Pressure Front right	Tire Pressure Front left	Tire Pressure Rear right	Tire Pressure Rear left
11/6/98	12:45pm	5	6	NA	5	-	26	26	26	22
	1:40pm	8	6	NA	6	-	27	26	26	23

Meteorological Data - PCC Comparison

Site 8, I-77

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Tire Pressure			
							Front right	Front left	Rear right	Rear left
11/6/98	3:00pm	5	6	NA	10	-	26	26	25	22
	3:45pm	5	6	NA	10	-	27	27	25	22

Site 15, SR 50 - West Section (WB)

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Tire Pressure			
							Front right	Front left	Rear right	Rear left
11/6/98	4:45pm	6	6	NA	0	-	26	26	26	22
	5:20pm	6	6	NA	0	-	27	26	26	22

Meteorological Data - Pavement Stiffness Comparison

Date	Time	Pavement Temp (deg C)	Ambient Temp (deg C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Dir	Tire Pressure Front right	Front left	Rear right	Rear left
10/9/98	11:20am	21	15	89	4	NW	27	27	25	27
	12:08pm	22	16	79	2	NW	28.5	29	26	27
	1:23pm	19	17	72	7	N	-	-	-	-
	2:07pm	23	18	79	0	-	29	29	26	27
	2:34pm	24	18	79	0	-	-	-	-	-
	2:45pm	22	18	79	0	-	28	29	26	27
	3:18pm	23	18	79	0	-	-	-	-	-
	3:43pm	23	17	78	4	NW	28	29	26	28
	4:16pm	23	17	80	6	NW	27	30	28	29
	4:36pm	22	17	80	6	NW	-	-	-	-
	4:51pm	22	17	80	8	NW	29	30	27	28
	5:07pm	22	17	82	8	NW	29	30	27	28

APPENDIX E

MAXIMUM A-WEIGHTED SPECTRUMS AT 7.5 M

Sound level and speed regression data

Site 1 - DGAC, 1 year old

Aggregate Type: Limestone
Surface Thickness: 32 mm
Date Measured: 7/6/98
(Uncorrected for Temperature)
Road speed category: High

Regression Parameter	Veh. cat. 1 (cars)	Veh. cat. 2a (dual-axle)	Veh. cat. 2b (multi-axle)
Number of Vehicles	110	30	60
Regression line intercept	32.453	13.320	60.244
Slope of Regression Line	24.24	36.181	14.522
Correlation coefficient	0.43	0.59	0.20
Average sound level (dB)	81.7	85.6	89.3
Std. deviation of sound level (dB)	1.6	2.4	1.7
Std. deviation of sound level residuals (dB)	1.4	1.9	1.6
Laser Gun Correction Factor	0.9987	0.9987	0.9987
Average Speed (km/h)	105	96	95
Std. deviation of speed (km/h)	7	8	5
Reference Speed (km/h)	110	85	85
Lveh (at reference speed) (dB)	81.9	83.1	88.3
Statistical Pass-By Index (SPBI)			
Speed range considered:	High		
Proportion of vehicles (weighting factors):			
Cat. 1 (cars)	0.700		
Cat. 2a (dual-axle)	0.075		
Cat. 2b (multi-axle)	0.225		
SPBI of this test surface (dB):	85.1		
Meteorological Data			
Average Atmospheric Temperature (C)	29.7		
Minimum Atmospheric Temperature (C)	27.9		
Maximum Atmospheric Temperature (C)	32.9		
Average Pavement Temperature (C)	43.4		
Maximum Pavement Temperature (C)	49		
Minimum Pavement Temperature (C)	36		
Average Wind Speed (km/h)	9		
Maximum Wind Speed (km/h)	15		
Minimum Wind Speed (km/h)	2		
Average Relative Humidity (%)	56.3		
Maximum Relative Humidity (%)	70.7		
Minimum Relative Humidity (%)	49.5		

Sound level and speed regression data

Site 2 - DGAC, 1 year old

Aggregate Type: Limestone
Surface Thickness: 38 mm
Date Measured: 7/9/98
(Uncorrected for Temperature)
Road speed category: High

Regression Parameter	Veh. cat. 1 (cars)	Veh. cat. 2a (dual-axle)	Veh. cat. 2b (multi-axle)
Number of Vehicles	108	30	59
Regression line intercept	34.807	5.7633	39.537
Slope of Regression Line	22.367	40.169	25.107
Correlation coef	0.29	0.41	0.25
Average sound level (dB)	80.5	86.1	89.6
Std. deviation of sound level (dB)	1.5	3.0	2.0
Std. deviation of sound level residuals (dB)	1.7	2.7	2.0
Laser Gun Correction Factor	0.997	0.997	0.997
Average Speed (km/h)	107	95	95
Std. deviation of speed (km/h)	6	7	4
Reference Speed (km/h)	110	85	85
Lveh (at reference speed) (dB)	80.5	83.3	88.0
Statistical Pass-By Index (SPBI)			
Speed range considered:	High		
Proportion of vehicles (weighting factors):			
Cat. 1 (cars)	0.700		
Cat. 2a (dual-axle)	0.075		
Cat. 2b (multi-axle)	0.225		
SPBI of this test surface (dB):	84.5		
Meteorological Data			
Average Atmospheric Temperature (C)	27.2		
Minimum Atmospheric Temperature (C)	25.4		
Maximum Atmospheric Temperature (C)	30.1		
Average Pavement Temperature (C)	33.7		
Maximum Pavement Temperature (C)	39		
Minimum Pavement Temperature (C)	24		
Average Wind Speed (km/h)	4.4		
Maximum Wind Speed (km/h)	6		
Minimum Wind Speed (km/h)	2		
Average Relative Humidity (%)	67.9		
Maximum Relative Humidity (%)	80.3		
Minimum Relative Humidity (%)	52.5		

Sound level and speed regression data

Site 3 - SMA, 3 years old

Aggregate Type: Limestone
Surface Thickness: 38 mm
Date Measured: 7/1/98
(Uncorrected for Temperature)
Road speed category: High

Regression Parameter	Veh. cat. 1 (cars)	Veh. cat. 2a (dual-axle)	Veh. cat. 2b (multi-axle)
Number of Vehicles	109	33	60
Regression line intercept	22.824	46.996	28.909
Slope of Regression Line	29.778	20.579	31.566
Correlation coefficient	0.62	0.24	0.47
Average sound level (dB)	81.6	88	91
Std. deviation of sound level (dB)	1.6	2.8	1.5
Std. deviation of sound level residuals (dB)	1.3	2.7	1.3
Laser Gun Correction Factor	0.9997	0.9997	0.9997
Average Speed (km/h)	92	88	91
Std. deviation of speed (km/h)	7	6	5
Reference Speed (km/h)	110	85	85
Lveh (at reference speed) (dB)	83.6	86.7	89.8

Statistical Pass-By Index (SPBI)

Speed range considered:	High
Proportion of vehicles (weighting factors):	
Cat. 1 (cars)	0.700
Cat. 2a (dual-axle)	0.075
Cat. 2b (multi-axle)	0.225
SPBI of this test surface (dB):	86.8

Meteorological Data

Average Atmospheric Temperature (C)	25.4
Minimum Atmospheric Temperature (C)	20.3
Maximum Atmospheric Temperature (C)	30.3
Average Pavement Temperature (C)	32.2
Maximum Pavement Temperature (C)	36
Minimum Pavement Temperature (C)	26
Average Wind Speed (km/h)	7.5
Maximum Wind Speed (km/h)	13
Minimum Wind Speed (km/h)	3
Average Relative Humidity (%)	59.1
Maximum Relative Humidity (%)	71.2
Minimum Relative Humidity (%)	48.9

Sound level and speed regression data

Site 4 - OGAC, 1 year old

Aggregate Type: N.A.
Surface Thickness: 19 mm
Date Measured: 6/24/98
(Uncorrected for Temperature)
Road speed category: High

Regression Parameter	Veh. cat. 1 (cars)	Veh. cat. 2a (dual-axle)	Veh. cat. 2b (multi-axle)
Number of Vehicles	110	32	60
Regression line intercept	8.512	48.192	38.949
Slope of Regression Line	33.913	17.867	24.207
Correlation coefficient	0.49	0.14	0.24
Average sound level (dB)	77.6	84.3	87.5
Std. deviation of sound level (dB)	2.1	2.9	2.1
Std. deviation of sound level residuals (dB)	1.8	2.8	2.3
Laser Gun Correction Factor	0.9997	0.9997	0.9997
Average Speed (km/h)	105	94	95
Std. deviation of speed (km/h)	7	5	5
Reference Speed	110	85	85
Lveh (at reference speed) (dB)	77.7	82.7	85.7

Statistical Pass-By Index (SPBI)

Speed range considered:	High
Proportion of vehicles (weighting factors):	
Cat. 1 (cars)	0.700
Cat. 2a (dual-axle)	0.075
Cat. 2b (multi-axle)	0.225
SPBI of this test surface (dB):	82.2

Meteorological Data

Average Atmospheric Temperature (C)	33.1
Minimum Atmospheric Temperature (C)	30.6
Maximum Atmospheric Temperature (C)	37.9
Average Pavement Temperature (C)	45.1
Maximum Pavement Temperature (C)	52
Minimum Pavement Temperature (C)	37
Average Wind Speed (km/h)	8.7
Maximum Wind Speed (km/h)	18
Minimum Wind Speed (km/h)	2
Average Relative Humidity (%)	62.4
Maximum Relative Humidity (%)	75.9
Minimum Relative Humidity (%)	47.1

Sound level and speed regression data

Site 5 - DGAC, 2 years old

Aggregate Type: Limestone/Gravel
Surface Thickness: 32 mm
Date Measured: 7/8/98
(Uncorrected for Temperature)
Road speed category: High

Regression Parameter	Veh. cat. 1 (cars)	Veh. cat. 2a (dual-axle)	Veh. cat. 2b (multi-axle)
Number of Vehicles	112	32	59
Regression line intercept	36.625	40.314	34.586
Slope of Regression Line	22.168	23.515	28.003
Correlaion coef	0.34	0.29	0.40
Average sound level (dB)	81.8	87.6	90.2
Std. deviation of sound level (dB)	1.6	2.5	1.7
Std. deviation of sound level residuals (dB)	1.5	2.4	1.5
Laser Gun Correction Factor	0.9998	0.9998	0.9998
Average Speed (km/h)	106	96	94
Std. deviation of speed (km/h)	6	6	5
Reference Speed (km/h)	110	85	85
Lveh (at reference speed) (dB)	81.9	85.7	88.6
Statistical Pass-By Index (SPBI)			
Speed range considered:	High		
Proportion of vehicles (weighting factors):			
Cat. 1 (cars)	0.700		
Cat. 2a (dual-axle)	0.075		
Cat. 2b (multi-axle)	0.225		
SPBI of this test surface (dB):	85.5		
Meteorological Data			
Average Atmospheric Temperature (C)	28.5		
Minimum Atmospheric Temperature (C)	25.5		
Maximum Atmospheric Temperature (C)	33.1		
Average Pavement Temperature (C)	34.8		
Maximum Pavement Temperature (C)	41		
Minimum Pavement Temperature (C)	30		
Average Wind Speed (km/h)	0.9		
Maximum Wind Speed (km/h)	3		
Minimum Wind Speed (km/h)	0		
Average Relative Humidity (%)	81.4		
Maximum Relative Humidity (%)	89.1		
Minimum Relative Humidity (%)	68.1		

Sound level and speed regression data

Site 6 - DGAC, 7 years old

Aggregate Type: Gravel
Surface Thickness: 32 mm
Date Measured: 6/18/98
(Uncorrected for Temperature)
Road speed category:

Regression Parameter	Veh. cat. 1 (cars)	Veh. cat. 2a (dual-axle)	Veh. cat. 2b (multi-axle)
Number of Vehicles	111	30	65
Regression line intercept	33.801	115.26	32.017
Slope of Regresion line	24.164	14.652	29.444
Correlation coefficient	0.55	-0.24	0.45
Average sound level (dB)	82.3	87.1	90.3
Std. deviation of sound level (dB)	1.4	2.1	1.7
Std. deviation of sound level residuals (dB)	1.1	2.1	1.5
Average Speed (km/h)	100	91	93
Std. deviation of speed (km/h)	8	7	6
Lveh (at reference speed) (dB)	83.1	87.0	88.8

Statistical Pass-By Index (SPBI)

Speed range considered:	High
Proportion of vehicles (weighting factors):	
Cat. 1 (cars)	0.700
Cat. 2a (dual-axle)	0.075
Cat. 2b (multi-axle)	0.225
SPBI of this test surface (dB):	86.4

Meteorological Data

Average Atmospheric Temperature (C)	35.1
Minimum Atmospheric Temperature (C)	28.7
Maximum Atmospheric Temperature (C)	38.8
Average Pavement Temperature (C)	46.8
Maximum Pavement Temperature (C)	53
Minimum Pavement Temperature (C)	39
Average Wind Speed (km/h)	4.6
Maximum Wind Speed (km/h)	10
Minimum Wind Speed (km/h)	0
Average Relative Humidity (%)	52.3
Maximum Relative Humidity (%)	61.1
Minimum Relative Humidity (%)	43.8

Sound level and speed regression data

Site 7 - DGAC, 1 year old

Aggregate Type: Gravel/Limestone
Surface Thickness: 32 mm
Date Measured: 6/17/98
(Uncorrected for Temperature)
Road speed category: High

Regression Parameter	Veh. cat. 1 (cars)	Veh. cat. 2a (dual-axle)	Veh. cat. 2b (multi-axle)
Number of Vehicles	100	28	60
Regression line intercept	42.891	78.637	58.113
Slope of Regression Line	18.125	3.0324	15.9
Correlation coefficient	0.32	0.03	0.26
Average sound level (dB)	79.3	85.7	89.9
Std. deviation of sound level (dB)	1.9	3.1	2.1
Std. deviation of sound level residuals (dB)	1.8	3.1	2.0
Laser Gun Correction Factor	0.9987	0.9987	0.9987
Average Speed (km/h)	97	92	94
Std. deviation of speed (km/h)	8	6	7
Reference Speed	110	85	85
Lveh (at reference speed) (dB)	79.9	84.5	88.8
Statistical Pass-By Index (SPBI)			
Speed range considered:	High		
Proportion of vehicles (weighting factors):			
Cat. 1 (cars)	0.700		
Cat. 2a (dual-axle)	0.075		
Cat. 2b (multi-axle)	0.225		
SPBI of this test surface (dB):	85.0		
Meteorological Data			
Average Atmospheric Temperature (C)	31.2		
Minimum Atmospheric Temperature (C)	28.5		
Maximum Atmospheric Temperature (C)	36		
Average Pavement Temperature (C)	46		
Maximum Pavement Temperature (C)	53		
Minimum Pavement Temperature (C)	41		
Average Wind Speed (km/h)	8.3		
Maximum Wind Speed (km/h)	16		
Minimum Wind Speed (km/h)	3		
Average Relative Humidity (%)	55.4		
Maximum Relative Humidity (%)	62.1		
Minimum Relative Humidity (%)	48.1		

Sound level and speed regression data

Site 8 - PCC. Random-Transverse, 1 year old

Aggregate Type: N.A.
Surface Thickness:
Date Measured: 9/26/98
(Uncorrected for Temperature)
Road speed category:

Regression Parameter	Veh. cat. 1 (cars)	Veh. cat. 2a (dual-axle)	Veh. cat. 2b (multi-axle)
Number of Vehicles	114	31	60
Regression line intercept	11.83	42.29	76.52
Slope of Regression Line	36.51	23.11	7.81
Correlation Coefficient	0.59	0.42	0.12
Average sound level (dB)	86.0	88.4	92.4
Std. deviation of sound level (dB)	1.9	1.8	2.0
Std. deviation of sound level residuals (dB)	1.6	1.6	2.0
Laser Gun Correction Factor	0.9987	0.9987	0.9987
Average Speed (km/h)	7	7	7
Std. deviation of speed (km/h)	105	95	94
Reference Speed (km/h)	110	85	85
Lveh (at reference speed) (dB)	86.4	86.9	91.6
Statistical Pass-By Index (SPBI)			
Speed range considered:	High		
Proportion of vehicles (weighting factors):			
Cat. 1 (cars)	0.700		
Cat. 2a (dual-axle)	0.075		
Cat. 2b (multi-axle)	0.225		
SPBI of this test surface (dB):	88.9		
Meteorological Data			
Average Atmospheric Temperature (C)	32.2		
Minimum Atmospheric Temperature (C)	28.8		
Maximum Atmospheric Temperature (C)	34.6		
Average Pavement Temperature (C)	37.7		
Maximum Pavement Temperature (C)	43		
Minimum Pavement Temperature (C)	26		
Average Wind Speed (km/h)	4.3		
Maximum Wind Speed (km/h)	10		
Minimum Wind Speed (km/h)	0		
Average Relative Humidity (%)	55.8		
Maximum Relative Humidity (%)	62.0		
Minimum Relative Humidity (%)	50.0		

Sound level and speed regression data

Site 9 - DGAC. 1 year old

Aggregate Type: Slag
Surface Thickness: 32 mm
Date Measured: 6/22/98
(Uncorrected for Temperature)
Road speed category: High

Regression Parameter	Veh. cat. 1 (cars)	Veh. cat. 2a (dual-axle)	Veh. cat. 2b (multi-axle)
Number of Vehicles	109	30	60
Regression line intercept	35.180	122.94	26.233
Slope of regression line	22.043	18.068	32.175
Correlation coefficient	0.33	-0.24	0.47
Average sound level (dB)	80.3	87.9	91
Std. deviation of sound level (dB)	1.7	3.0	2.3
Std. deviation of sound level residuals (dB)	1.6	2.9	2.0
Laser Gun Correction Factor	0.9987	0.9987	0.9987
Average Speed (km/h)	107	100	99
Std. deviation of speed (km/h)	6	9	8
Reference Speed	110	85	85
Lveh (at reference speed) (dB)	80.2	88.1	88.3

Statistical Pass-By Index (SPBI)

Speed range considered:	High
Proportion of vehicles (weighting factors):	
Cat. 1 (cars)	0.700
Cat. 2a (dual-axle)	0.075
Cat. 2b (multi-axle)	0.225
SPBI of this test surface (dB):	85.2

Meteorological Data

Average Atmospheric Temperature (C)	31.8
Minimum Atmospheric Temperature (C)	28.9
Maximum Atmospheric Temperature (C)	34.4
Average Pavement Temperature (C)	41.1
Maximum Pavement Temperature (C)	49
Minimum Pavement Temperature (C)	31
Average Wind Speed (km/h)	7.2
Maximum Wind Speed (km/h)	15
Minimum Wind Speed (km/h)	2
Average Relative Humidity (%)	56.1
Maximum Relative Humidity (%)	64.6
Minimum Relative Humidity (%)	49.5

Sound level and speed regression data

Site 10 - DGAC. 1 year old

Aggregate Type: Gravel Surface Thickness: 38 mm Date Measured: 6/23/98 (Uncorrected for Temperature) Road speed category: High			
Regression Parameter	Veh. cat. 1 (cars)	Veh. cat. 2a (dual-axle)	Veh. cat. 2b (multi-axle)
Number of Vehicles	109	30	60
Regression line intercept	50.648	47.442	53.688
Slope of Regression Line	14.775	19.561	18.451
Correlation coefficient	0.24	0.29	0.26
Average sound level (dB)	80	86.4	90.4
Std. deviation of sound level (dB)	1.9	1.9	2.0
Std. deviation of sound level residuals (dB)	1.8	1.8	2.0
Average Speed (km/h)	103	93	91
Std. deviation of speed (km/h)	7	6	6
Lveh (at reference speed) (dB)	80.8	85.2	89.3
Statistical Pass-By Index (SPBI)			
Speed range considered:	High		
Proportion of vehicles (weighting factors):			
Cat. 1 (cars)	0.700		
Cat. 2a (dual-axle)	0.075		
Cat. 2b (multi-axle)	0.225		
SPBI of this test surface (dB):	85.6		
Meteorological Data			
Average Atmospheric Temperature (C)	24.8		
Minimum Atmospheric Temperature (C)	23		
Maximum Atmospheric Temperature (C)	29		
Average Pavement Temperature (C)	32		
Maximum Pavement Temperature (C)	39		
Minimum Pavement Temperature (C)	29		
Average Wind Speed (km/h)	3.7		
Maximum Wind Speed (km/h)	8		
Minimum Wind Speed (km/h)	0		
Average Relative Humidity (%)	83.3		
Maximum Relative Humidity (%)	92.7		
Minimum Relative Humidity (%)	67.5		

Sound level and speed regression data

Site 11 - DGAC. 1 year old

Aggregate Type: Gravel
Surface Thickness:
Date Measured: 7/1/98
(Uncorrected for Temperature)
Road speed category: High

Regression Parameter	Veh. cat. 1 (cars)	Veh. cat. 2a (dual-axle)	Veh. cat. 2b (multi-axle)
Number of Vehicles	106	34	53
Regression line intercept	55.539	39.057	-19.93
Slope of Regression Line	12.559	24.126	55.695
Correlation coefficient	0.24	0.24	0.56
Average sound level (dB)	81.2	87.4	91.1
Std. deviation of sound level (dB)	1.6	2.4	2.2
Std. deviation of sound level residuals (dB)	1.6	2.4	1.8
Laser Gun Correction Factor	0.9997	0.9997	0.9997
Average Speed (km/h)	104	94	96
Std. deviation of speed (km/h)	8	5	5
Reference Speed (km/h)	110	85	85
Lveh (at reference speed) (dB)	81.2	85.6	87.5
Statistical Pass-By Index (SPBI)			
Speed range considered:	High		
Proportion of vehicles (weighting factors):			
Cat. 1 (cars)	0.700		
Cat. 2a (dual-axle)	0.075		
Cat. 2b (multi-axle)	0.225		
SPBI of this test surface (dB):	84.6		
Meteorological Data			
Average Atmospheric Temperature (C)	30		
Minimum Atmospheric Temperature (C)	25.3		
Maximum Atmospheric Temperature (C)	30.8		
Average Pavement Temperature (C)	40.5		
Maximum Pavement Temperature (C)	44		
Minimum Pavement Temperature (C)	36		
Average Wind Speed (km/h)	11.5		
Maximum Wind Speed (km/h)	15		
Minimum Wind Speed (km/h)	8		
Average Relative Humidity (%)	58.5		
Maximum Relative Humidity (%)	66.7		
Minimum Relative Humidity (%)	48.7		

Sound level and speed regression data

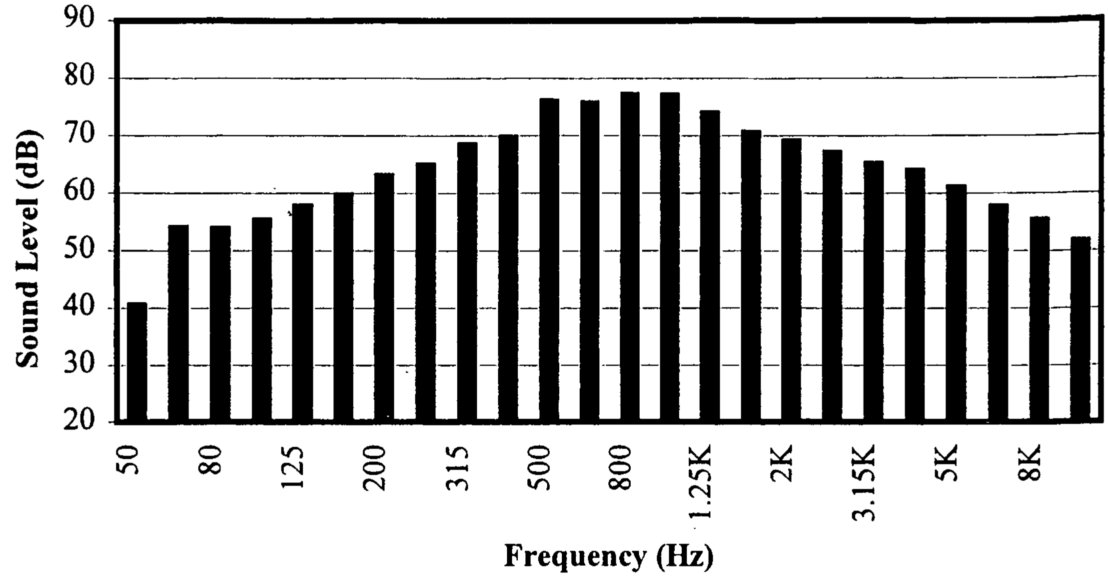
Site 12 - PCC, Transverse, 4 years old

Aggregate Type: N.A.
Surface Thickness: 229 mm
Date Measured: 6/30/98
(Uncorrected for Temperature)
Road speed category: High

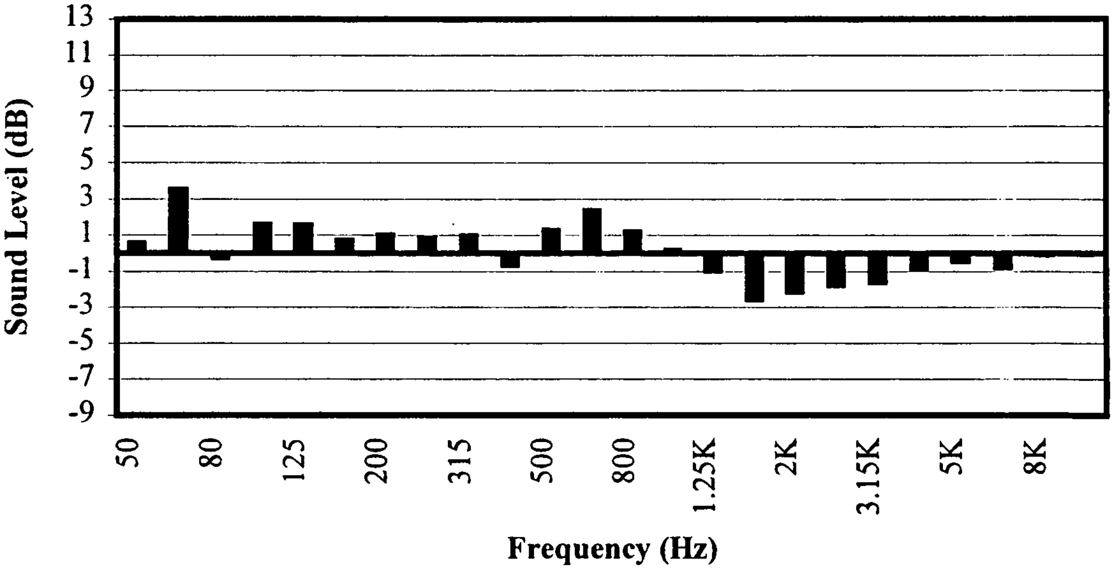
Regression Parameter	Veh. cat. 1 (cars)	Veh. cat. 2a (dual-axle)	Veh. cat. 2b (multi-axle)
Number of Vehicles	115	30	50
Regression line intercept	38.021	15.615	49.445
Slope of Regression Line	22.854	36.631	20.64
Correlation coefficient	0.45	0.39	0.39
Average sound level (dB)	83.2	88.0	90.2
Std. deviation of sound level (dB)	1.8	2.9	1.4
Std. deviation of sound level residuals (dB)	1.6	2.6	1.2
Laser Gun Correction Factor	0.9997	0.9997	0.9997
Average Speed (km/h)	91	90	92
Std. deviation of speed (km/h)	7	6	5
Reference Speed (km/h)	110	85	85
Lveh (at reference speed) (dB)	84.7	86.3	89.3
Statistical Pass-By Index (SPBI)			
Speed range considered:	High		
Proportion of vehicles (weighting factors):			
Cat. 1 (cars)	0.700		
Cat. 2a (dual-axle)	0.075		
Cat. 2b (multi-axle)	0.225		
SPBI of this test surface (dB):	87.0		
Meteorological Data			
Average Atmospheric Temperature (C)	26		
Minimum Atmospheric Temperature (C)	20.6		
Maximum Atmospheric Temperature (C)	30.8		
Average Pavement Temperature (C)	31.5		
Maximum Pavement Temperature (C)	41		
Minimum Pavement Temperature (C)	20		
Average Wind Speed (km/h)	8.3		
Maximum Wind Speed (km/h)	16		
Minimum Wind Speed (km/h)	2		
Average Relative Humidity (%)	80.2		
Maximum Relative Humidity (%)	92.5		
Minimum Relative Humidity (%)	71		

APPENDIX F

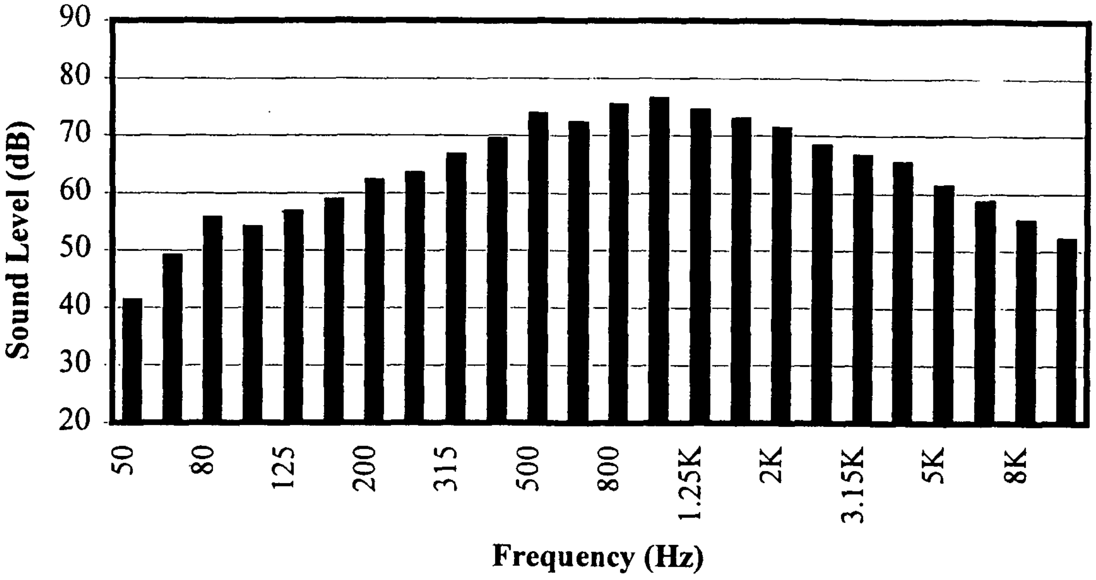
MAXIMUM A-WEIGHTED SPECTRUMS AT 7.5 M



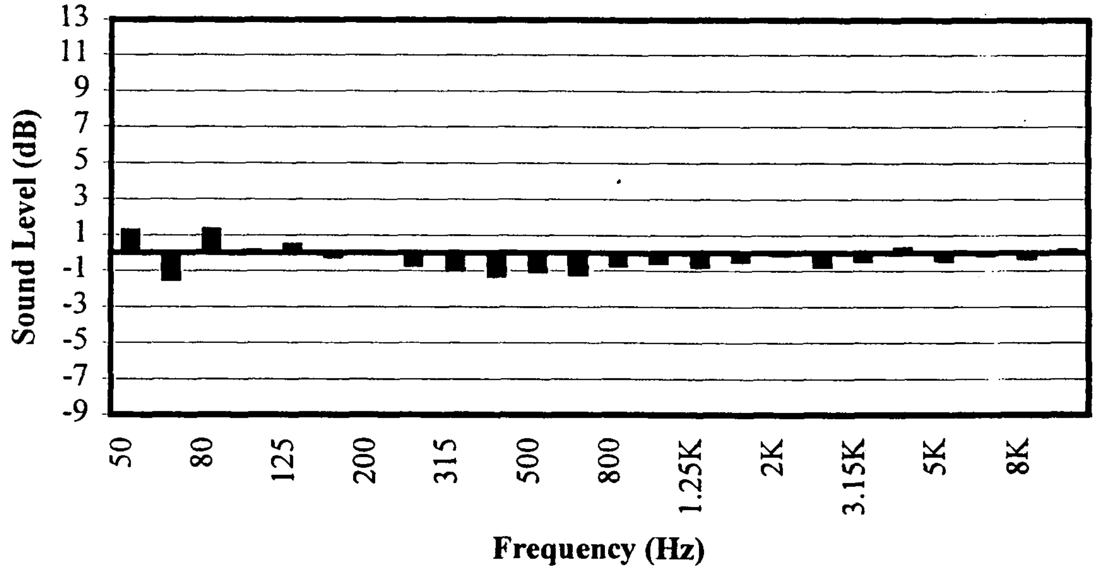
Maximum A-weighted spectrum at 7.5 m for Site 1, a 1 year old DGAC pavement.



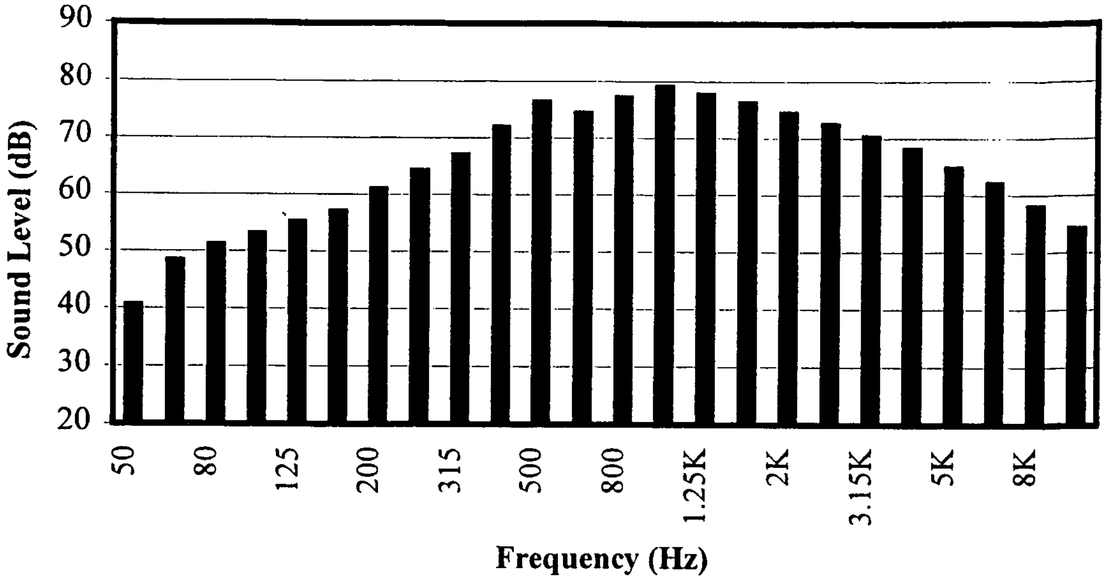
Differences in sound levels for maximum A-weighted spectrum for Site 1, a 1 year old DGAC pavement, relative to the reference spectrum.



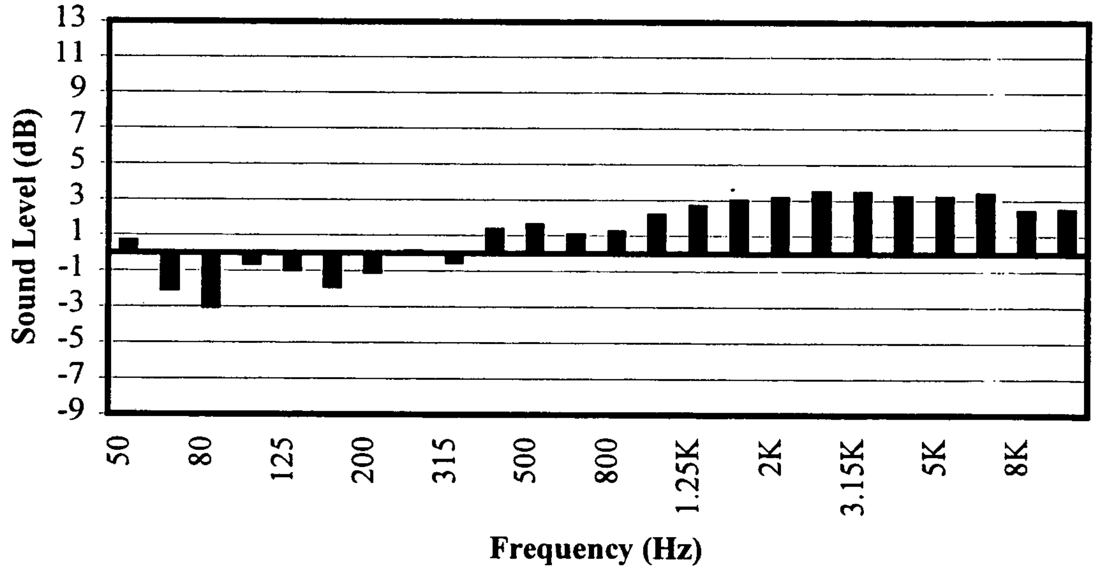
Maximum A-weighted spectrum at 7.5 m for Site 2, a 1 year old DGAC pavement.



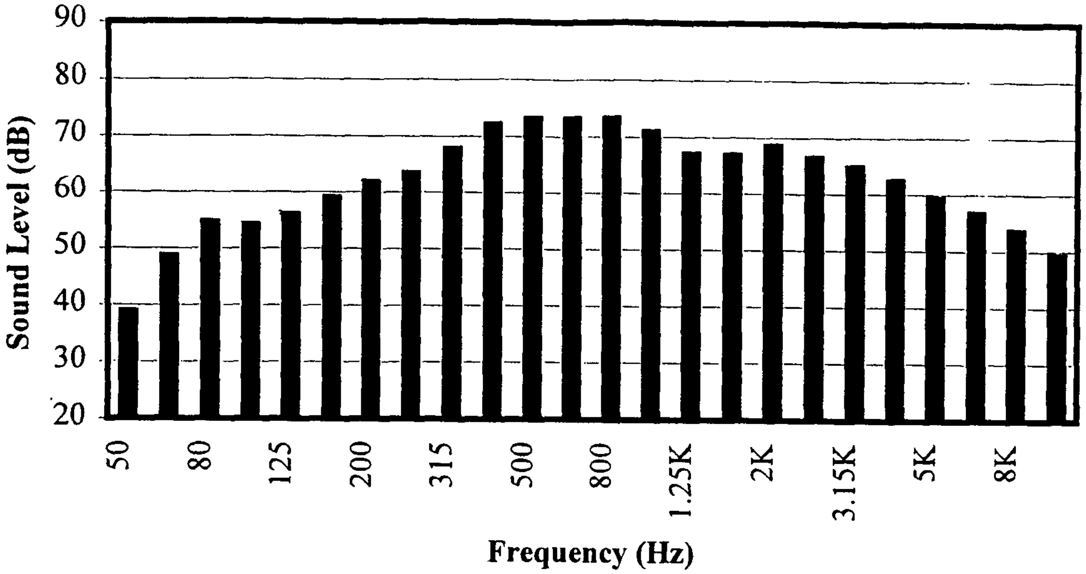
Differences in sound levels for maximum A-weighted spectrum for Site 2, a 1 year old DGAC pavement, relative to the reference spectrum.



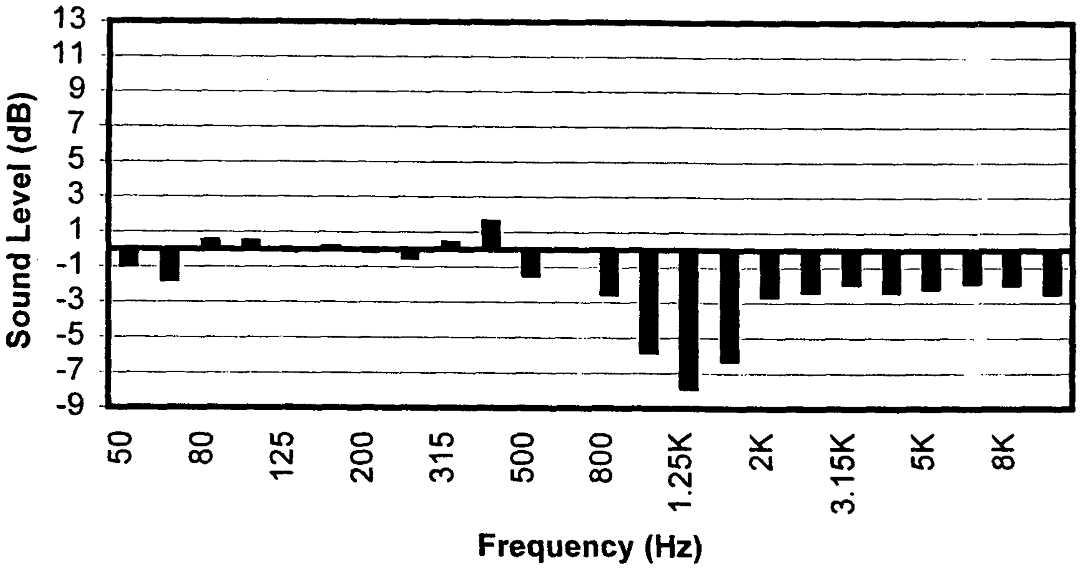
Maximum A-weighted spectrum at 7.5 m for Site 3, a 3 year old SMA pavement.



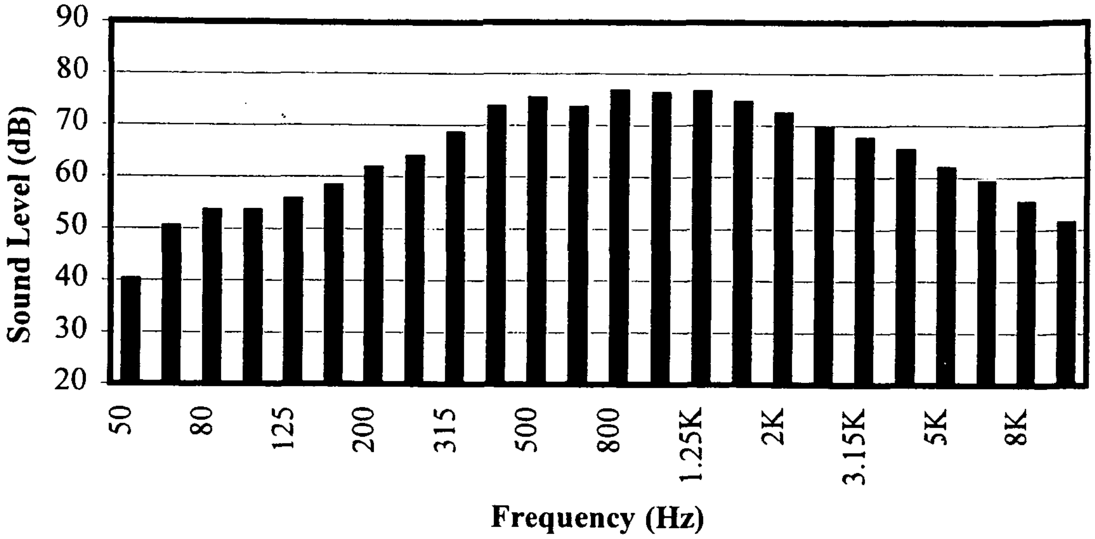
Differences in sound levels for maximum A-weighted spectrum for Site 3, a 3 year old SMA pavement, relative to the reference spectrum.



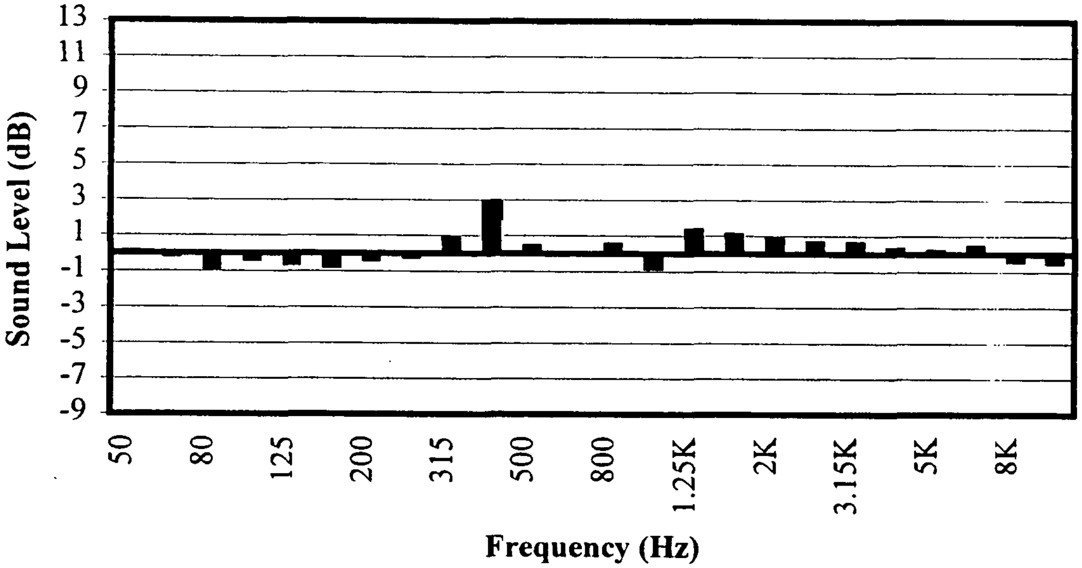
Maximum A-weighted spectrum at 7.5 m for Site 4, a 1 year old OGAC pavement.



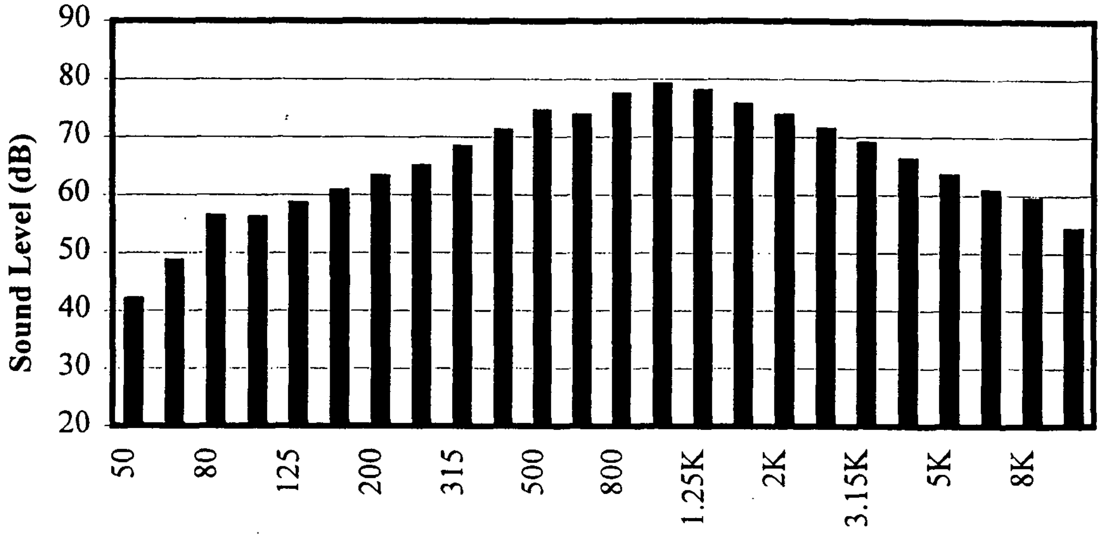
Differences in sound levels for maximum A-weighted spectrum for Site 4, a 1 year old OGAC pavement, relative to the reference spectrum.



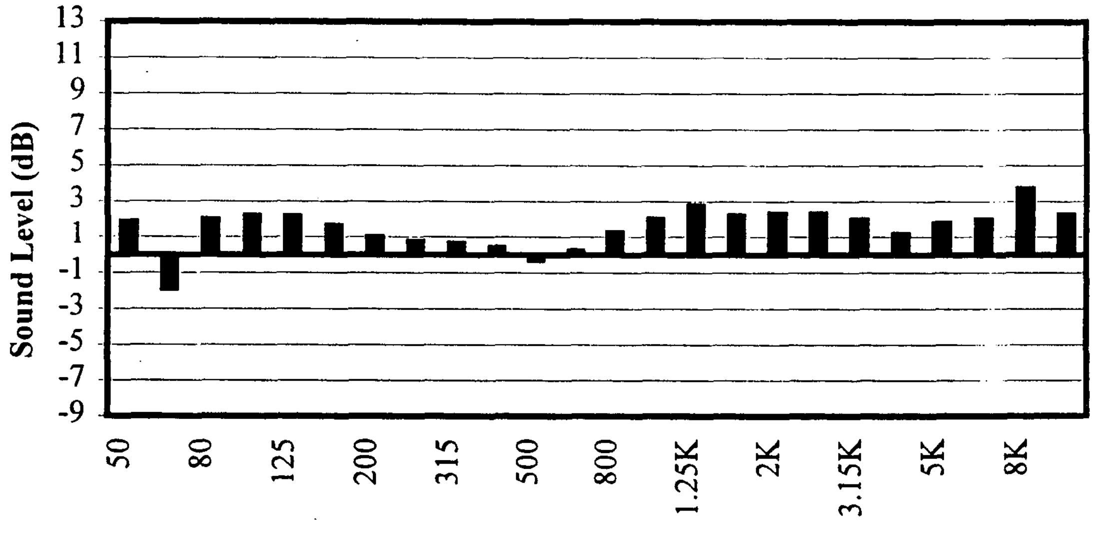
Maximum A-weighted spectrum at 7.5 m for Site 5, a 2 year old DGAC pavement.



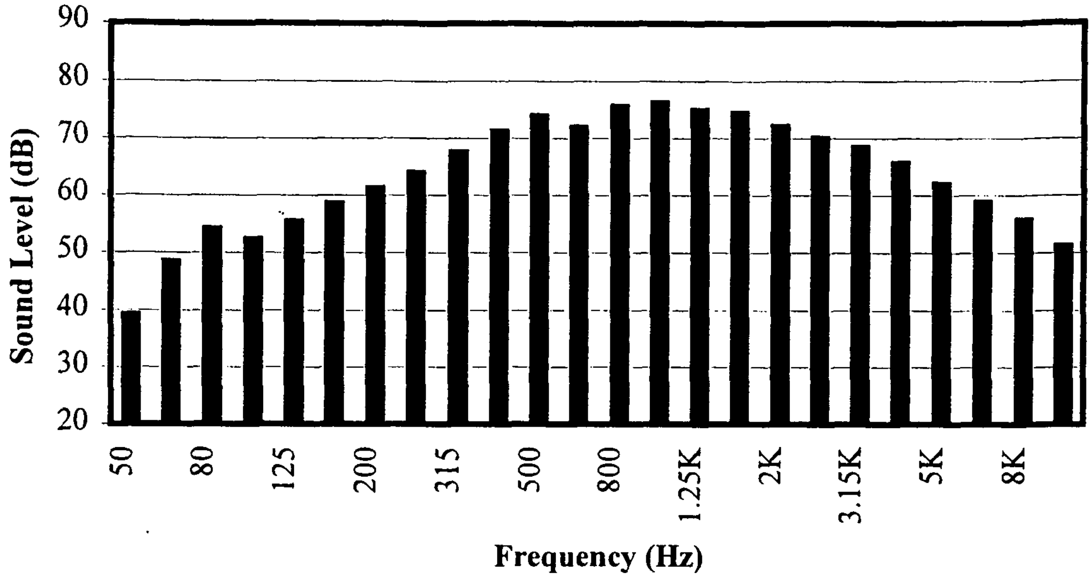
Differences in sound levels for maximum A-weighted spectrum for Site 5, a 1 year old DGAC pavement, relative to the reference spectrum.



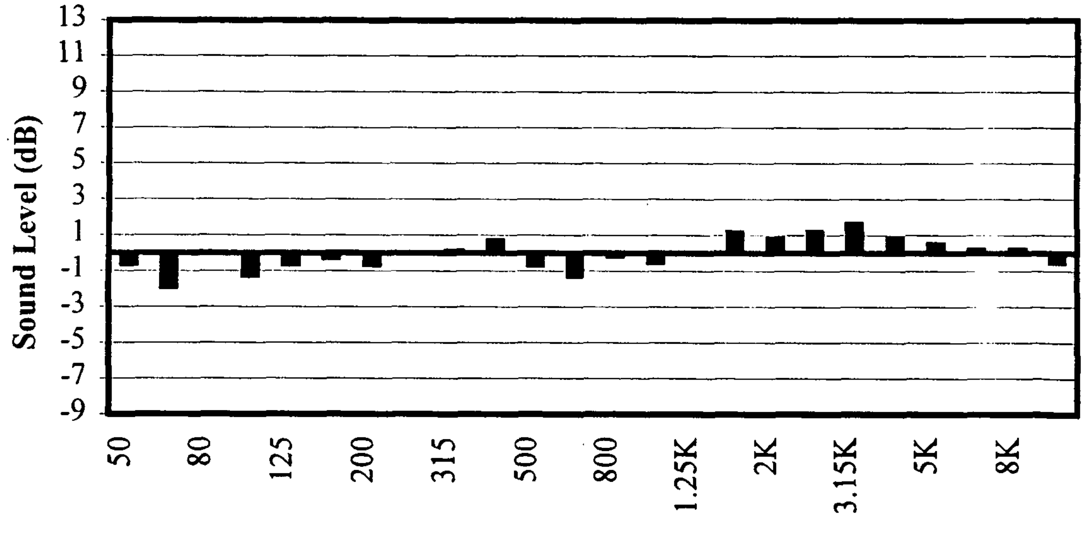
Maximum A-weighted spectrum at 7.5 m for Site 6, a 7 year old DGAC pavement.



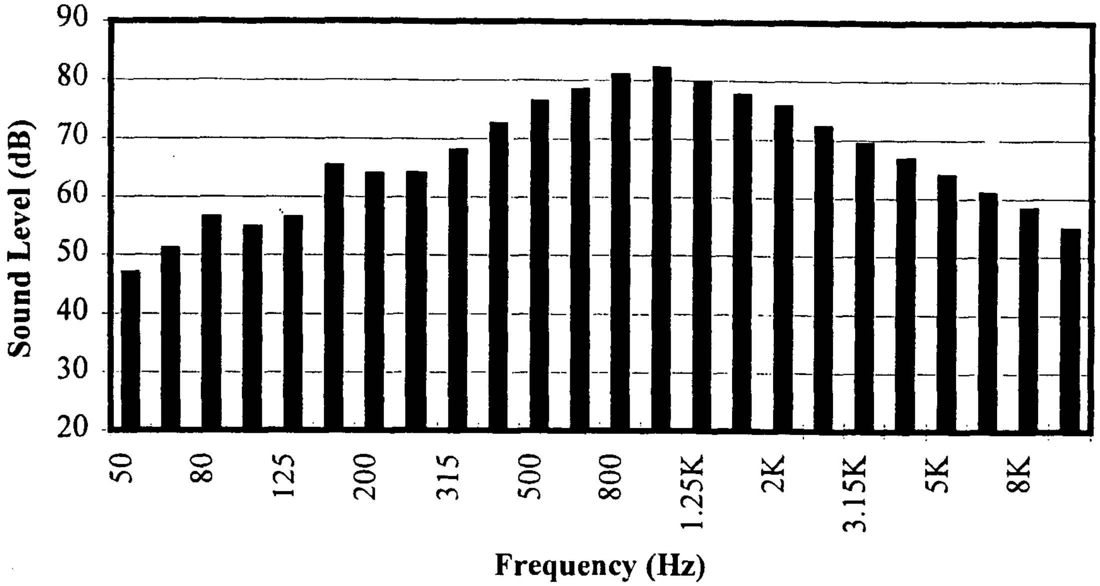
Differences in sound levels for maximum A-weighted spectrum for Site 6, a 7 year old DGAC pavement, relative to the reference spectrum.



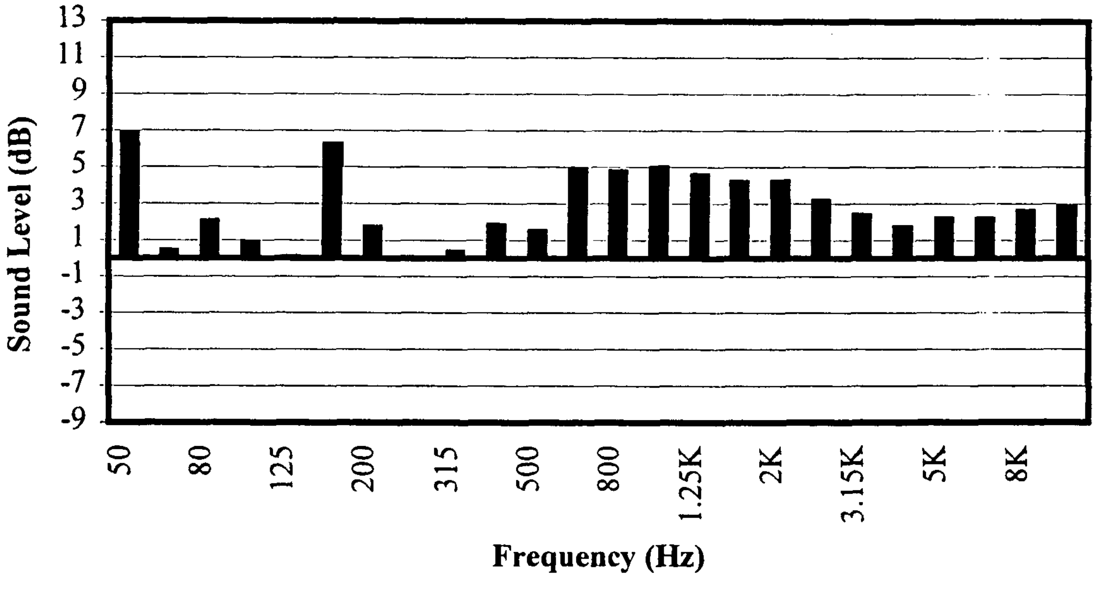
Maximum A-weighted spectrum at 7.5 m for Site 7, a 1 year old DGAC pavement.



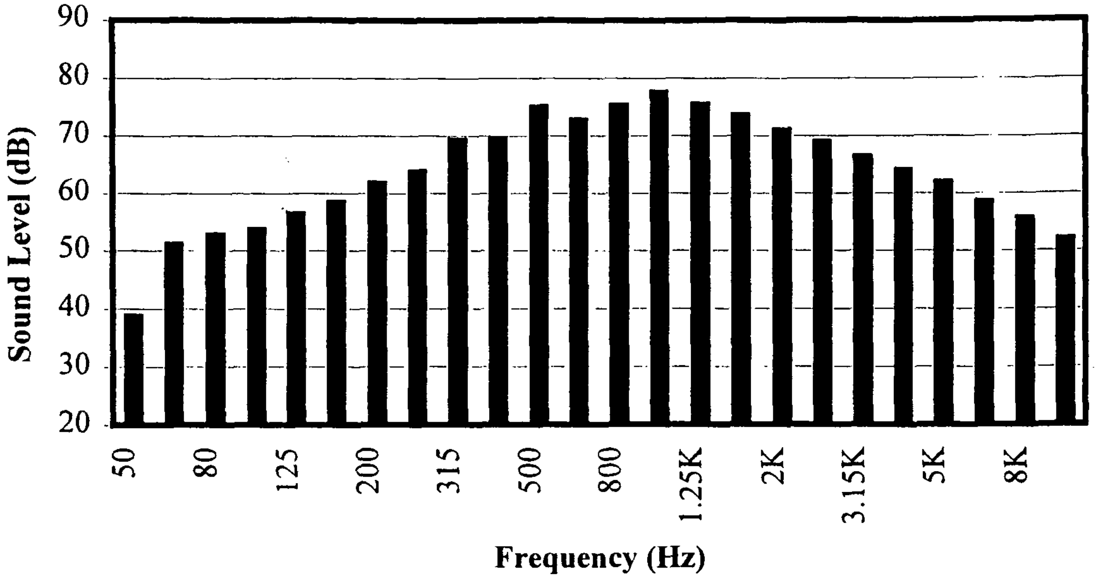
Differences in sound levels for maximum A-weighted spectrum for Site 7, a 1 year old DGAC pavement, relative to the reference spectrum.



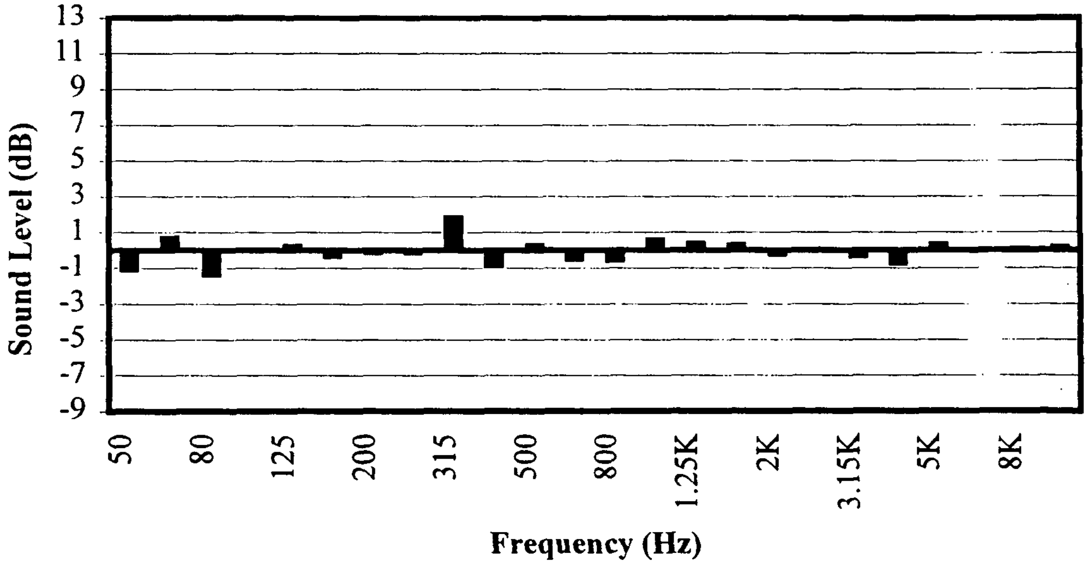
Maximum A-weighted spectrum at 7.5 m for Site 8, a 1 year old PCC-random, transverse grooved pavement.



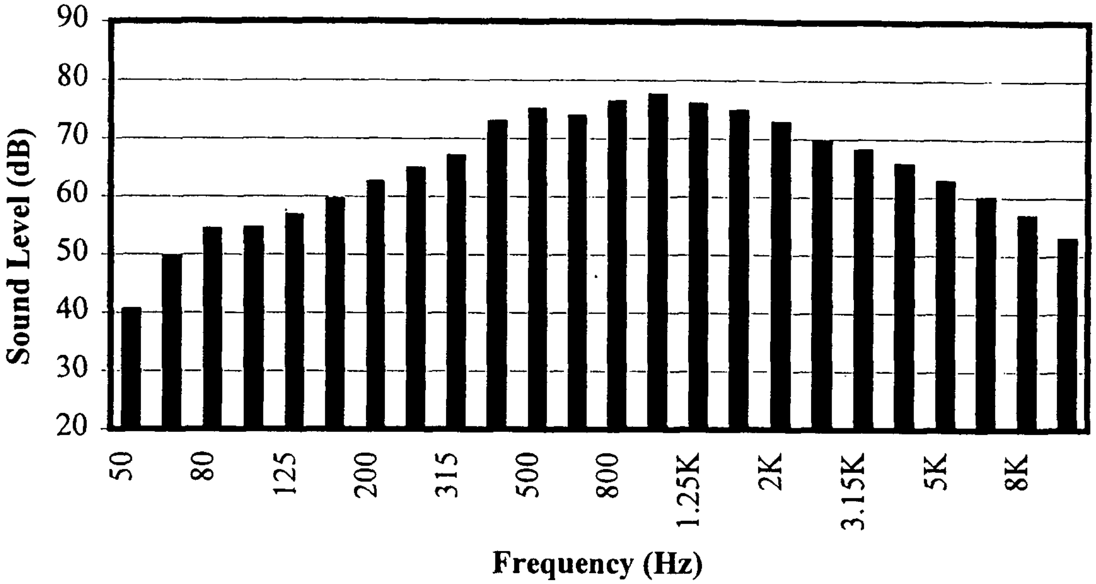
Differences in sound levels for maximum A-weighted spectrum for Site 8, a 1 year old PCC-random, transverse grooved pavement, relative to the reference spectrum.



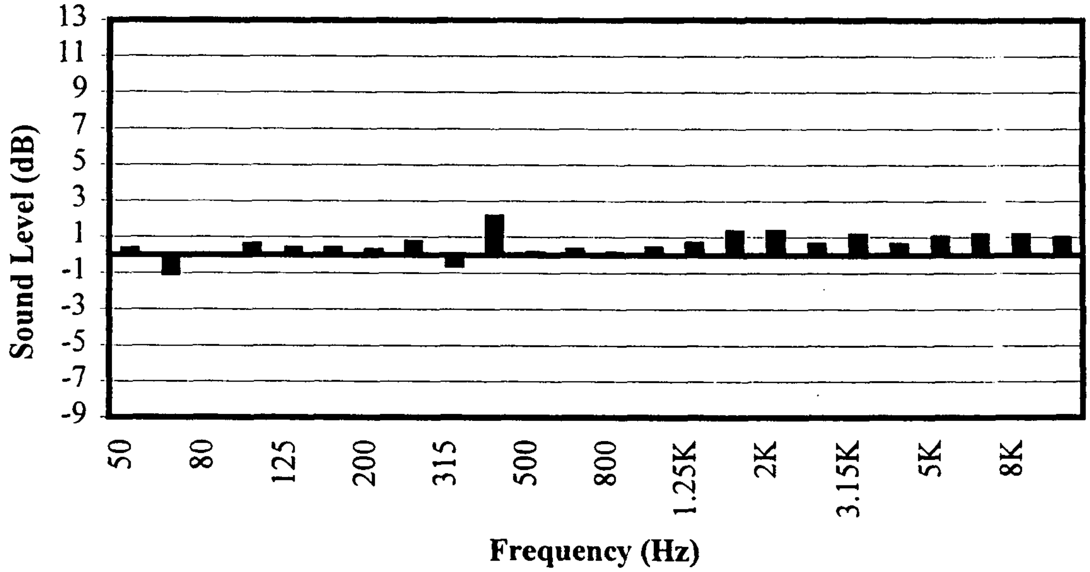
Maximum A-weighted spectrum at 7.5 m for Site 9, a 1 year old DGAC pavement.



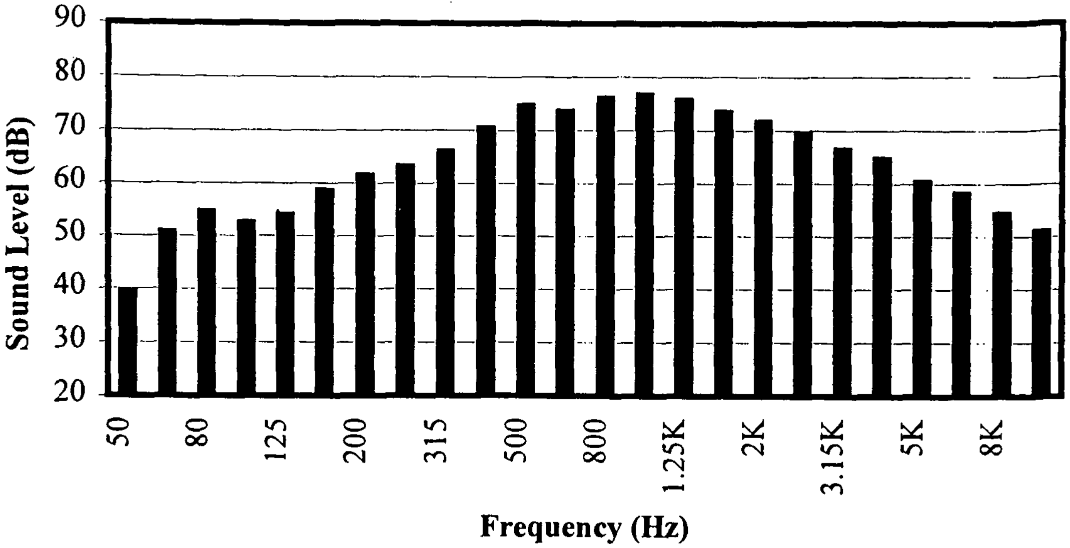
Differences in sound levels for maximum A-weighted spectrum for Site 9, a 1 year old DGAC pavement, relative to the reference spectrum.



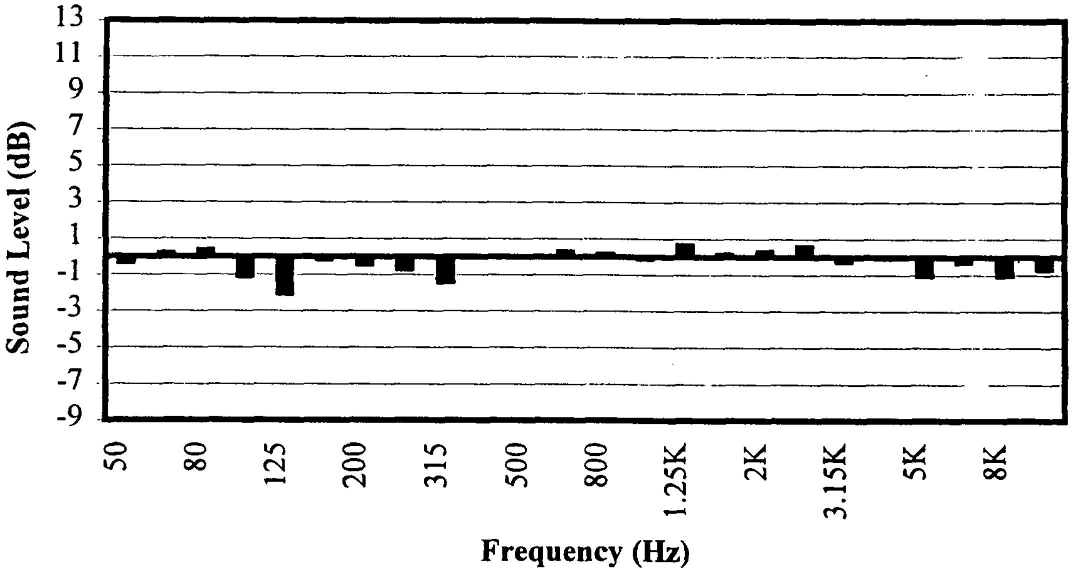
Maximum A-weighted spectrum at 7.5 m for Site 10, a 1 year old DGAC pavement.



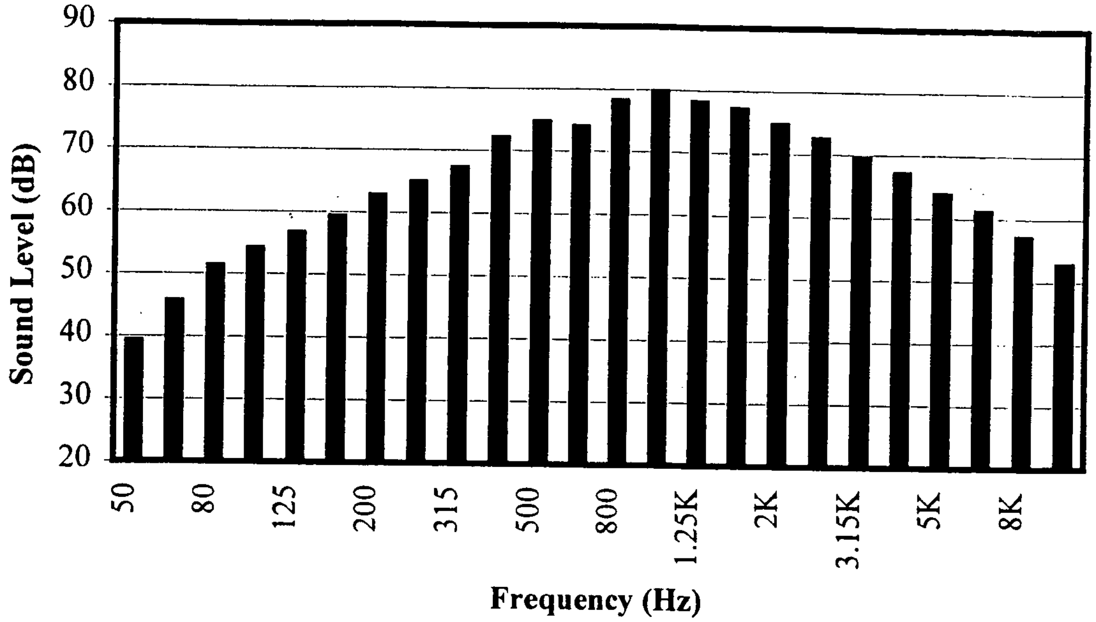
Differences in sound levels for maximum A-weighted spectrum for Site 10, a 1 year old DGAC pavement, relative to the reference spectrum.



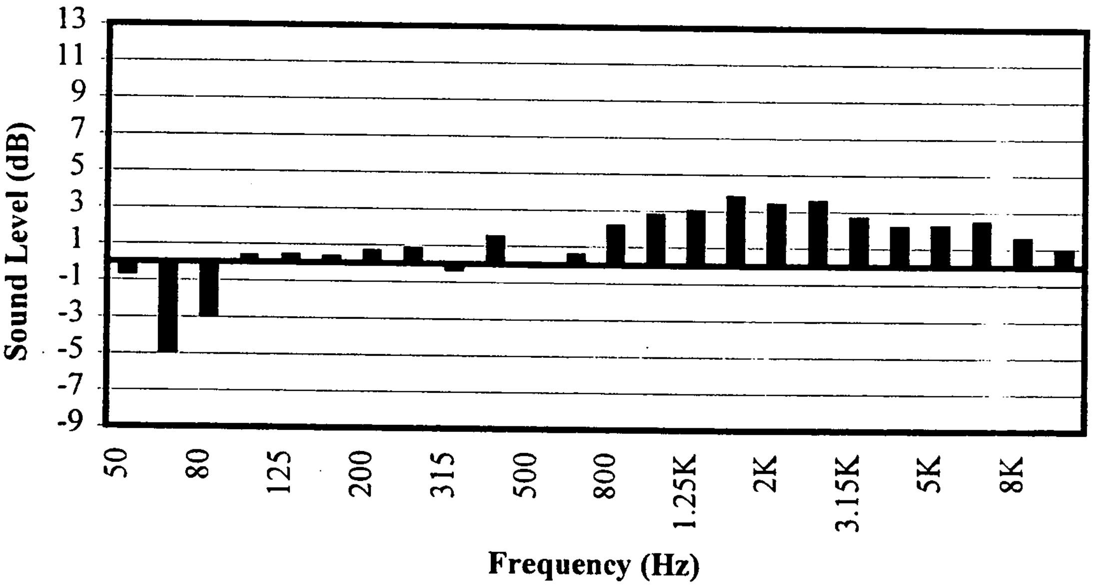
Maximum A-weighted spectrum at 7.5 m for Site 11, a 1 year old DGAC pavement.



Differences in sound levels for maximum A-weighted spectrum for Site 11, a 1 year old DGAC pavement, relative to the reference spectrum.



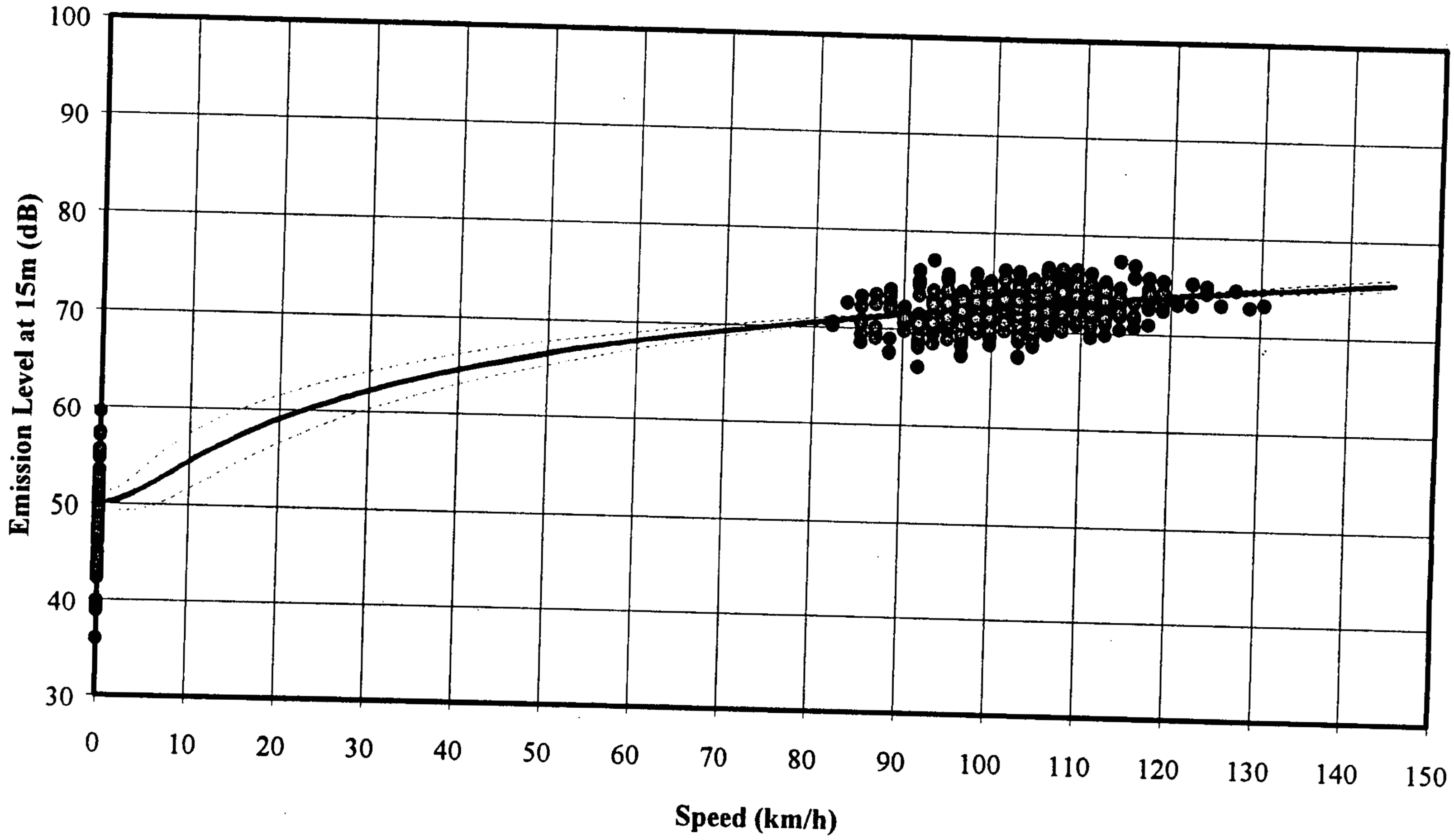
Maximum A-weighted spectrum at 7.5 m for Site 12, a 4 year old PCC-transverse groove pavement.



Differences in sound levels for maximum A-weighted spectrum for Site 12, a 4 year old PCC-transverse grooved pavement, relative to the reference spectrum.

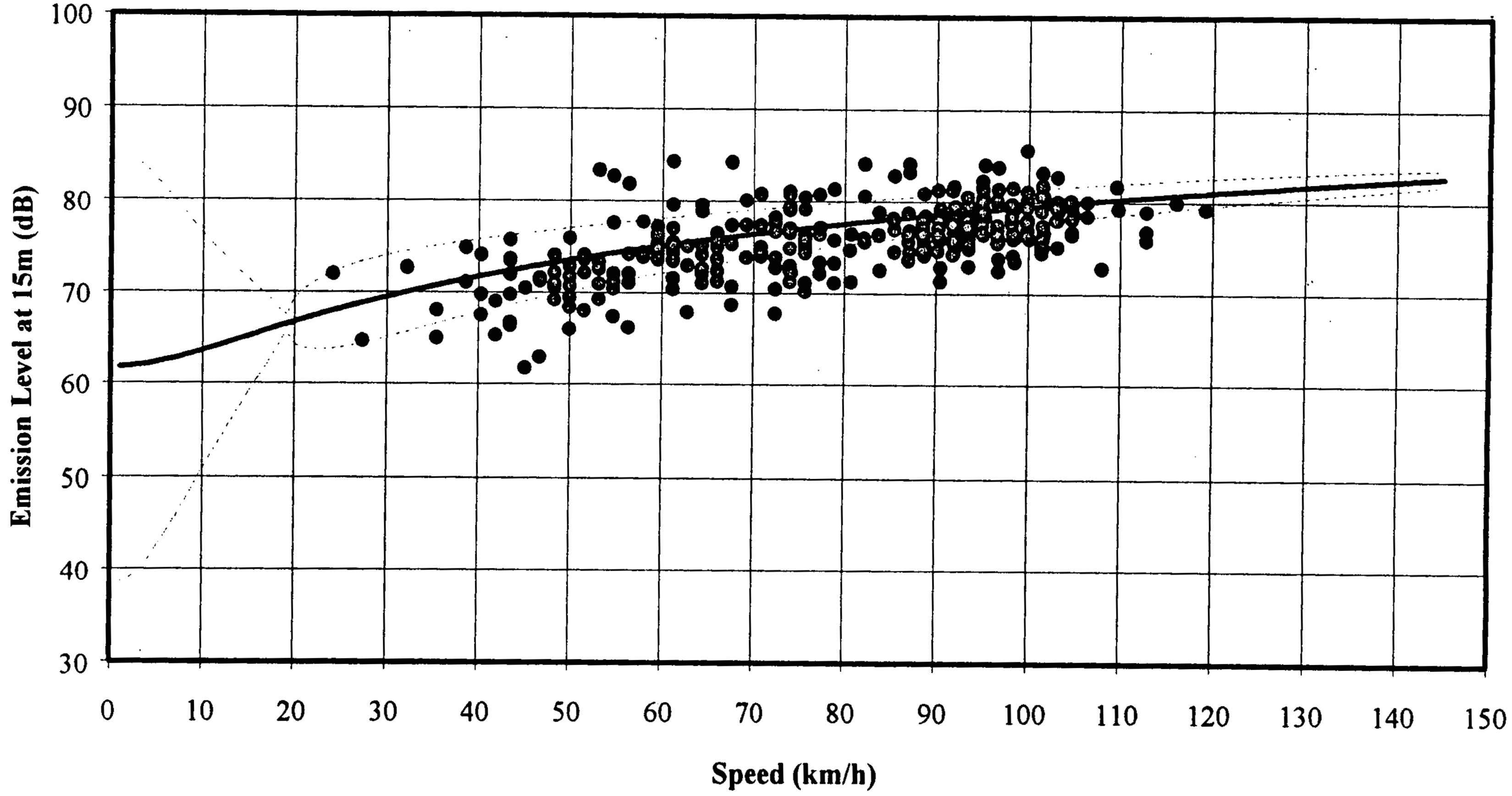
APPENDIX G

REMEL REGRESSIONS FOR AVERAGE PAVEMENT



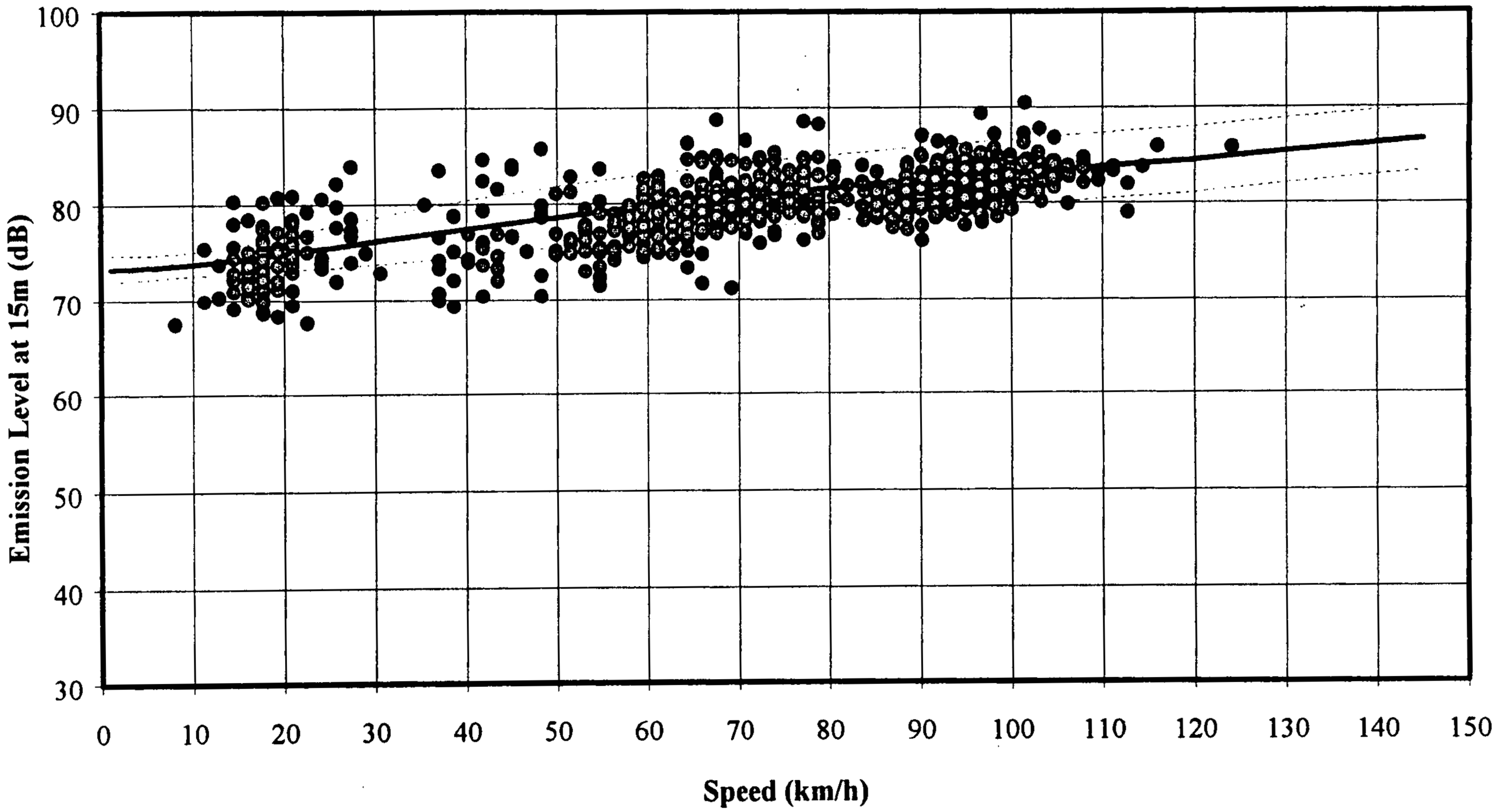
Emission Level Regression - Average Pavement, Automobiles

.... +/- 95% CI



Emission Level Regression - Average Pavement, Medium Trucks

+/- 95% CI



Emission Level Regression - Average Pavement, Heavy Trucks

+/- 95% CI

APPENDIX H

CONCRETE COMPARISON FIELD DATA

FIELD DATA

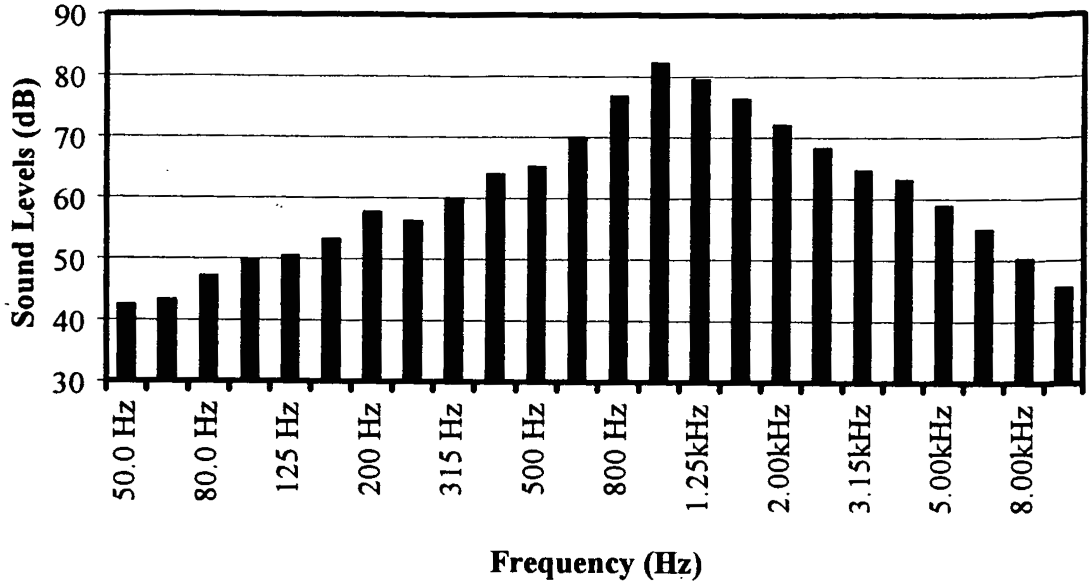
Sound levels and spectral data for PCC comparison

Site #	Groove Type	Event #	Speed (km/h)	Sound Level (dB)		
8	Random Transverse	12	88.5	86.7		
		13	88.5	86.0		
		14	88.5	86.1		
		15	88.5	86.1	Avg.	Std. Dev.
		16	88.5	85.5	86.2	0.4
		17	104.6	88.4		
		18	104.6	88.0		
		19	104.6	87.2		
		20	104.6	88.1	Avg.	Std. Dev.
		21	104.6	87.0	87.7	0.6
12	Transverse	1	88.5	83.2		
		3	88.5	82.2		
		4	88.5	82.2		
		5	88.5	81.8	Avg.	Std. Dev.
		6	88.5	83.6	82.6	0.7
		7	104.6	84.2		
		8	104.6	84.9		
		9	104.6	84.5		
		10	104.6	84.5	Avg.	Std. Dev.
		11	104.6	84.3	84.5	0.2
13	Random Transverse	30	55	88.0		
		31	55	86.9		
		32	55	87.3		
		33	55	88.3	Avg.	Std. Dev.
		34	55	86.9	87.5	0.7
		37	65	89.6		
		38	65	88.9		
		39	65	89.0		
		40	65	89.5	Avg.	Std. Dev.
		41	65	90.8	89.6	0.8

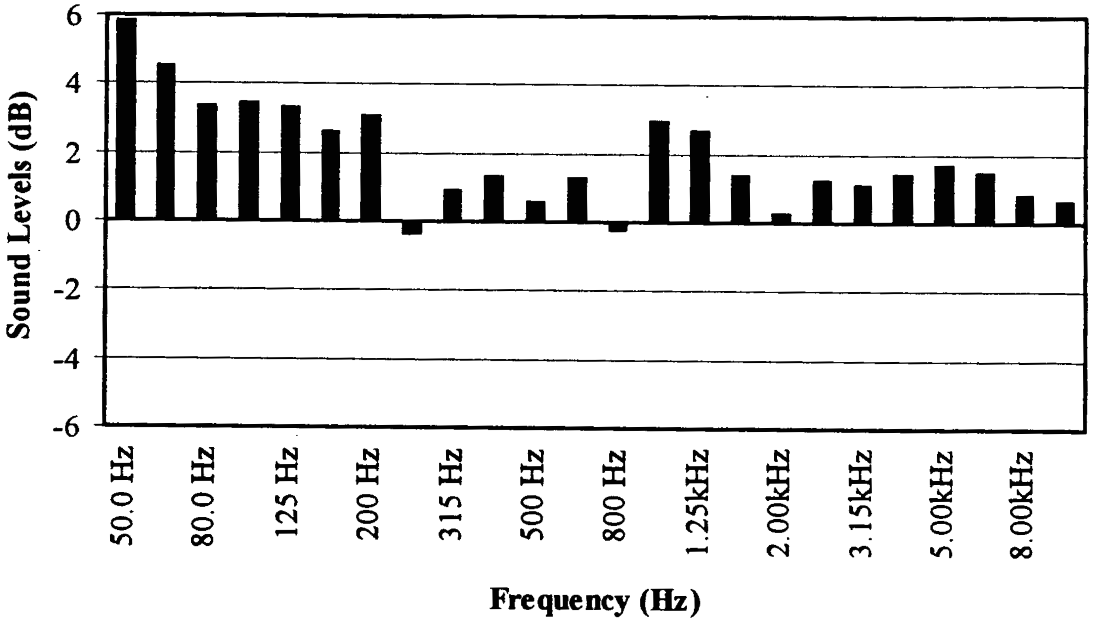
FIELD DATA

Sound levels and spectral data for PCC comparison

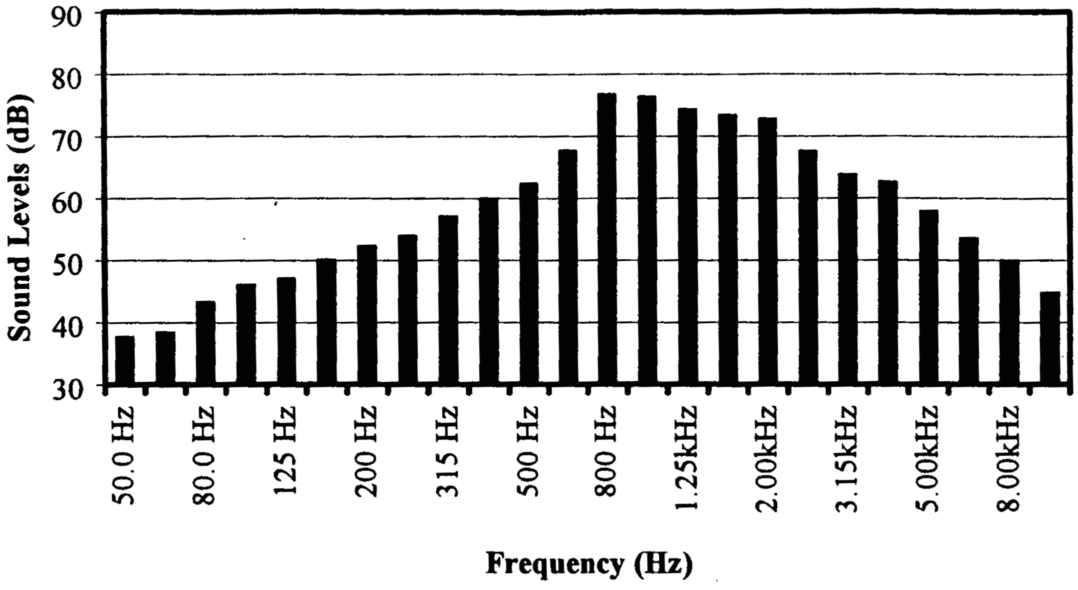
Site #	Groove Type	Event #	Speed (km/h)	Sound Level (dB)		
14	Random Transverse	19	88.5	82.6		
		20	88.5	82.1		
		21	88.5	82.2		
		22	88.5	82.4	Avg.	Std. Dev.
		24	88.5	82.1	82.3	0.2
		25	104.6	84.4		
		26	104.6	84.0		
		27	104.6	85.1		
		28	104.6	84.0	Avg.	Std. Dev.
		29	104.6	84.0	84.3	0.5
15	Random Transverse	22	88.5	86.4		
		23	88.5	85.6		
		24	88.5	86.1		
		25	88.5	86.0	Avg.	Std. Dev.
		26	88.5	85.4	85.9	0.4
		27	104.6	88.6		
		28	104.6	88.1		
		29	104.6	89.1		
		30	104.6	87.9	Avg.	Std. Dev.
		31	104.6	89.1	88.6	0.5
16	Random Transverse	30	88.5	88.0		
		31	88.5	86.9		
		32	88.5	87.3		
		33	88.5	88.3	Avg.	Std. Dev.
		34	88.5	86.9	87.5	0.7
		37	104.6	89.6		
		38	104.6	88.9		
		39	104.6	89.0		
		40	104.6	89.5	Avg.	Std. Dev.
		41	104.6	90.8	89.6	0.8



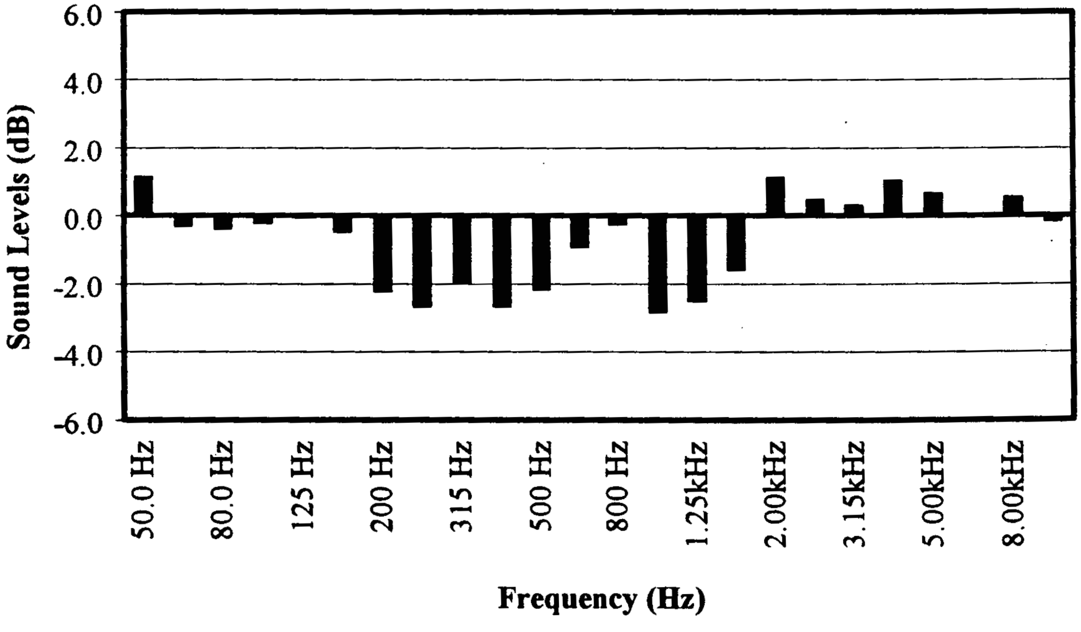
Maximum A-weighted spectrum for Site 8, a random-transverse grooved PCC pavement for a test vehicle operating at 88.5 km/h.



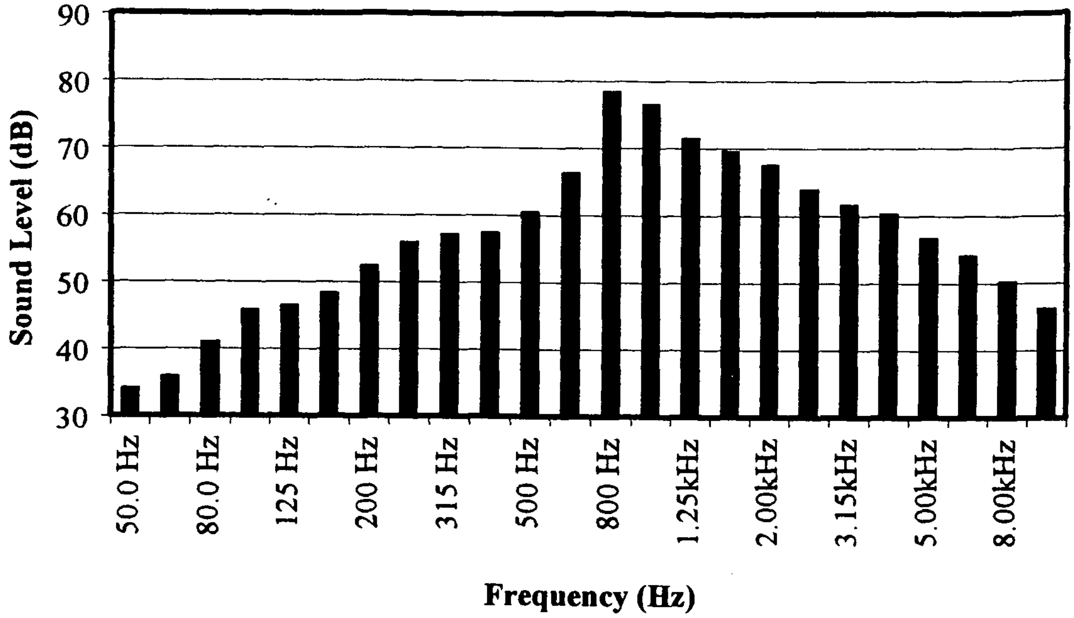
Differences in sound levels for maximum A-weighted spectrum, relative to the average for all PCC pavements measured, for Site 8, a random-transverse grooved PCC pavement for a test vehicle operating at 88.5 km/h.



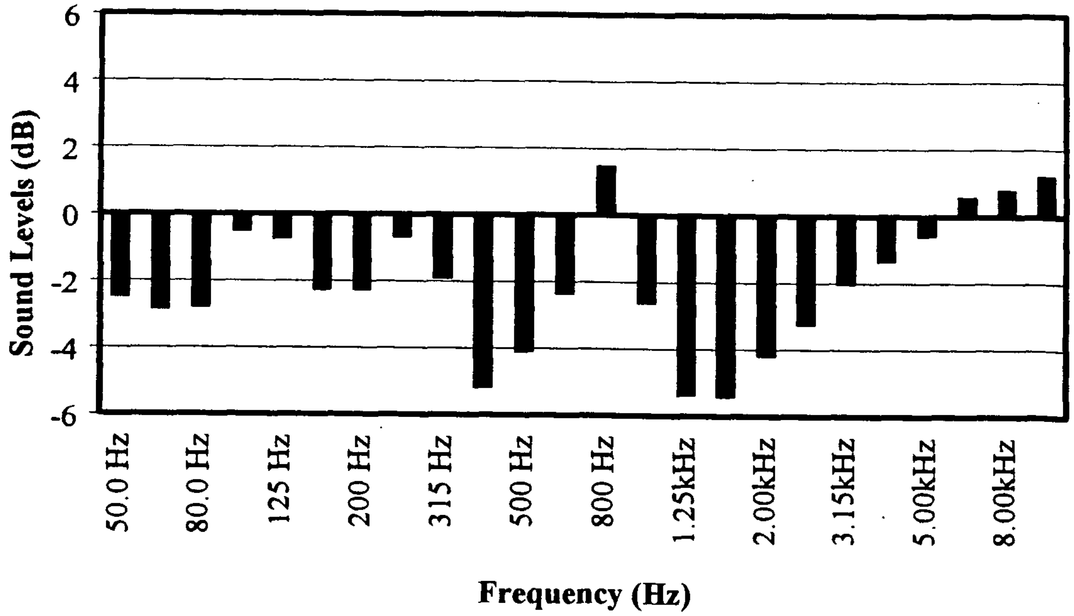
Maximum A-weighted spectrum for Site 12, a transverse grooved PCC pavement for a test vehicle operating at 88.5 km/h.



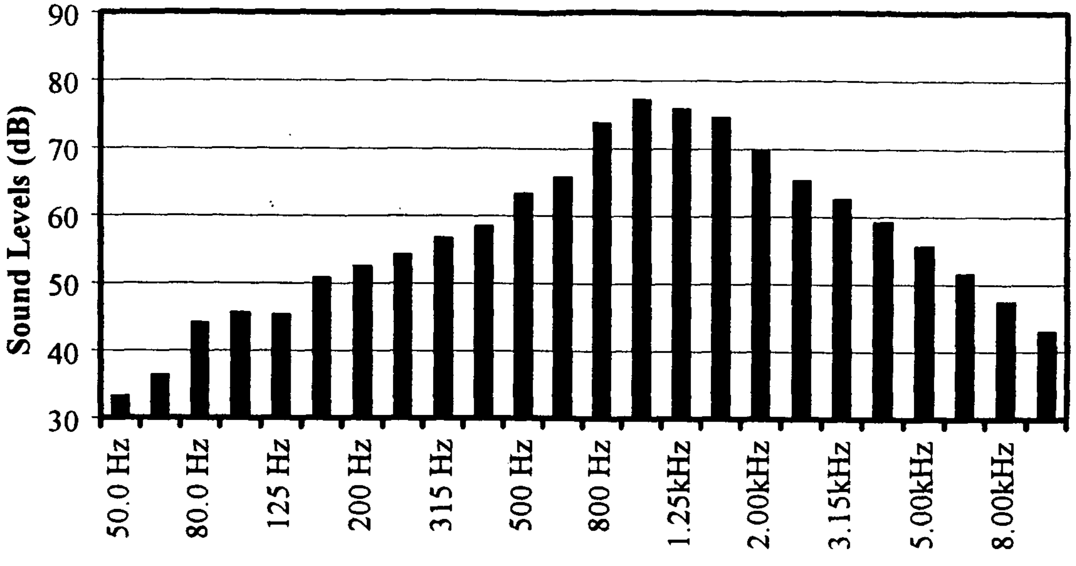
Differences in sound levels for maximum A-weighted spectrum, relative to the average for all PCC pavements measured, for Site 12, a transverse grooved PCC pavement for a test vehicle operating at 88.5 km/h.



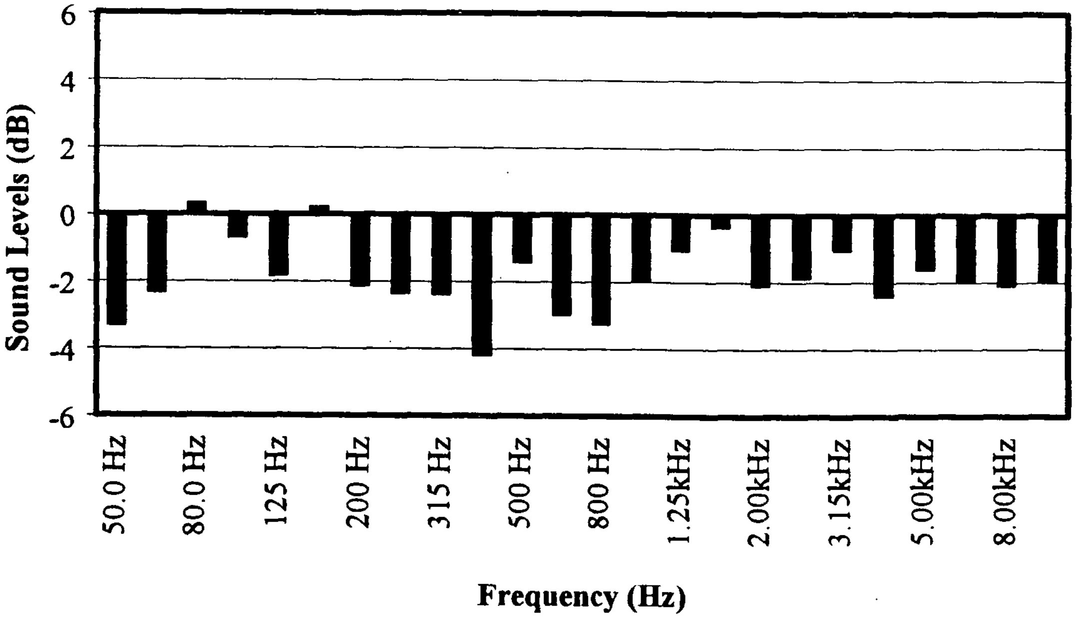
Maximum A-weighted spectrum for Site 13, a longitudinal grooved PCC pavement for a test vehicle operating at 88.5 km/h.



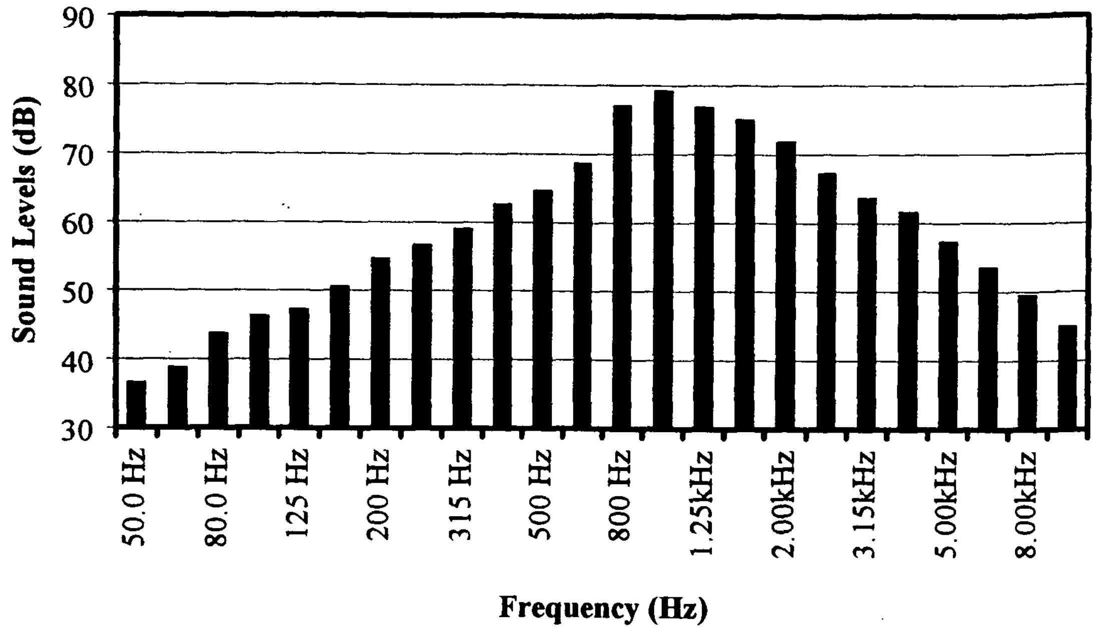
Differences in sound levels for maximum A-weighted spectrum, relative to the average for all PCC pavements measured, for Site 13, a longitudinal grooved PCC pavement for a test vehicle operating at 88.5 km/h.



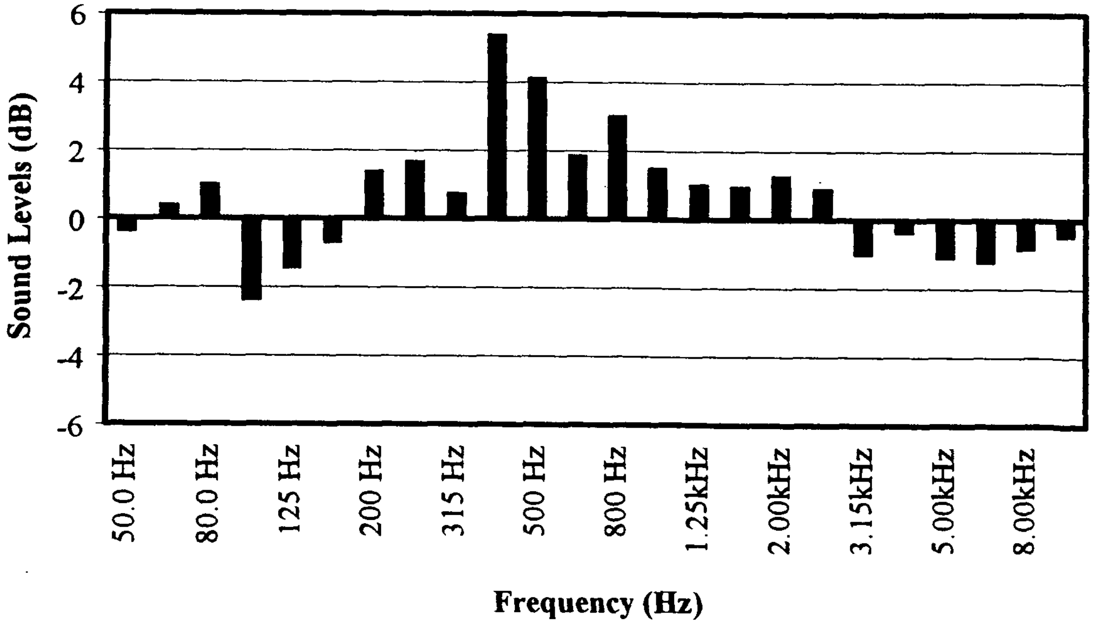
Maximum A-weighted spectrum for Site 14, a transverse grooved PCC pavement for a test vehicle operating at 88.5 km/h.



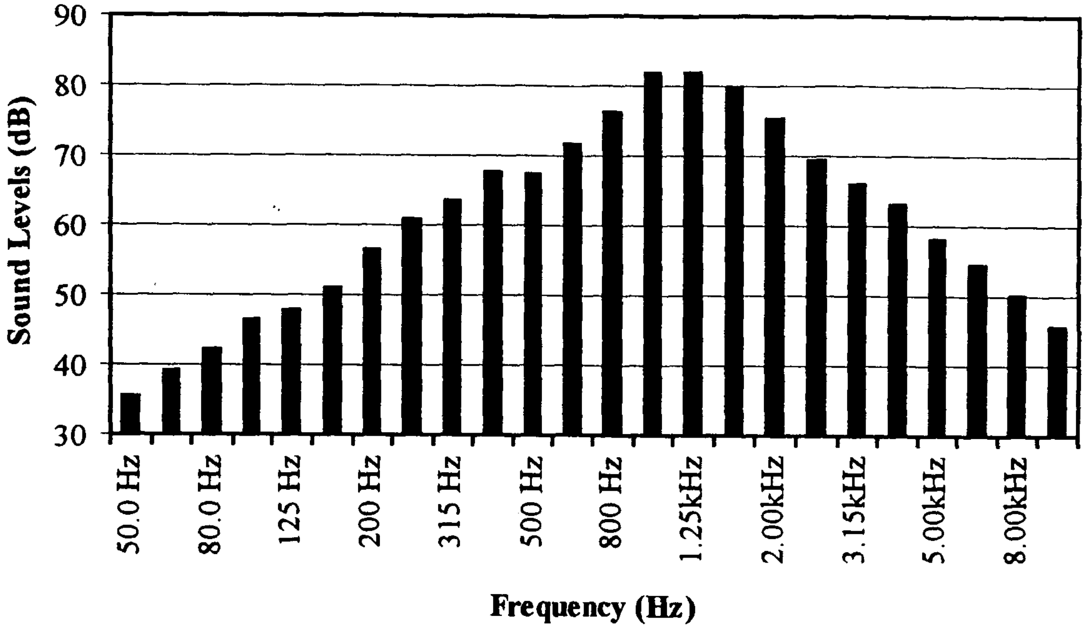
Differences in sound levels for maximum A-weighted spectrum, relative to the average for all PCC pavements measured, for Site 14, a transverse grooved PCC pavement for a test vehicle operating at 88.5 km/h.



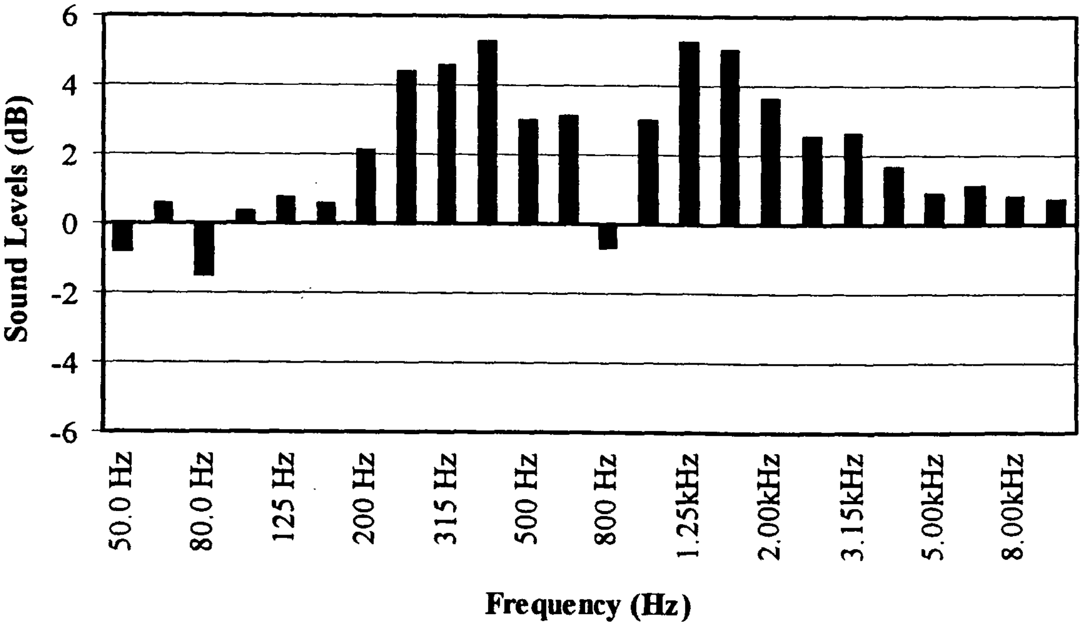
Maximum A-weighted spectrum for Site 15 (EB), a random-transverse grooved PCC pavement for a test vehicle operating at 88.5 km/h.



Differences in sound levels for maximum A-weighted spectrum, relative to the average for all PCC pavements measured, for Site 15 (EB), a random-transverse grooved PCC pavement for a test vehicle operating at 88.5 km/h.



Maximum A-weighted spectrum for Site 15 (WB), a random-transverse grooved PCC pavement for a test vehicle operating at 88.5 km/h.



Differences in sound levels for maximum A-weighted spectrum, relative to the average for all PCC pavements measured, for Site 15 (WB), a random-transverse grooved PCC pavement for a test vehicle operating at 88.5 km/h.

APPENDIX I

PAVEMENT STIFFNESS STUDY FIELD DATA

FIELD DATA

Sound Levels for Pavement Stiffness Study

Section #	Event #	Vehicle Class	Speed (km/h)	Sound Level (dB)		
108	43	h	72.4	90.7		
	48	h	72.4	92.3	Average	Std. Dev.
	54	h	72.4	92.1	91.7	0.9
	56	a	104.6	78.2		
	57	a	104.6	78.6		
	58	a	104.6	78.0		
	59	a	104.6	78.2	Average	Std. Dev.
	60	a	104.6	78.7	78.3	0.3
109	37	h	72.4	89.2		
	41	h	72.4	89.6	Average	Std. Dev.
	42	h	72.4	89.4	89.4	0.2
	16	a	104.6	77.8		
	17	a	104.6	78.3		
	18	a	104.6	77.1		
	19	a	104.6	77.3	Average	Std. Dev.
	20	a	104.6	77.9	77.7	0.5
110	22	h	72.4	89.9		
	28	h	72.4	89.3	Average	Std. Dev.
	33	h	72.4	89.6	89.6	0.3
	6	a	104.6	79.0		
	7	a	104.6	78.3		
	8	a	104.6	77.2		
	9	a	104.6	78.4	Average	Std. Dev.
	10	a	104.6	78.1	78.2	0.6

FIELD DATA

Sound Levels for Pavement Stiffness Study

Section #	Event #	Vehicle Class	Speed (km/h)	Sound Level (dB)		
901	86	a	104.6	77.0		
	87	a	104.6	77.2		
	88	a	104.6	77.8		
	89	a	104.6	76.5	Average	Std. Dev.
	90	a	104.6	76.7	77.1	0.5
902	66	a	104.6	79.0		
	67	a	104.6	79.2		
	68	a	104.6	79.2		
	69	a	104.6	79.5	Average	Std. Dev.
	70	a	104.6	79.2	79.2	0.2
903	76	a	104.6	76.5		
	77	a	104.6	76.9		
	78	a	104.6	76.7		
	79	a	104.6	76.8	Average	Std. Dev.
	80	a	104.6	76.6	76.7	0.2