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16. Abstract

Traffic noise is a serious concern in urbanized areas in the United States and around the world. With the ever-increasing vehicle population, exterior vehicle noise is a growing problem that needs more extensive study by scientists and engineers. To develop more effective strategies for reduction of traffic noise levels, it is necessary to identify and characterize all sources contributing to the noise. The main objective of this study was to determine the levels of roadside noise generated by buses under various road surface and vehicle speed conditions typical for transit bus operations in urbanized areas.

After collecting and analyzing near- and far-field data for both a heavy truck and a transit bus at speeds of 10, 20, 30, and 40 mph over three pavement types, the following conclusions can be made. For the three types of pavement tested (chip seal, seal coat, and PCC), there is not a great deal of difference in tire noise generation. None of the three types of pavement tested seems to have an effect on the noise propagating to the far field. For the heavy truck the dominant contributor of far-field noise is tire-pavement contact, especially at higher speeds. For the transit bus the dominant contributor of far-field noise is the CNG engine. The far-field noise generated by the transit bus is significantly greater than that generated by the heavy truck. Transit buses could be quieted significantly by designing the engine compartment to absorb or redirect more of the acoustic energy generated by the engine.

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The Institute for Safe, Quiet, and Durable Highways

MEASUREMENT AND EVALUATION OF ROADSIDE NOISE GENERATED BY TRANSIT BUSES

Final Report
SQDH 2002 – 1; PTI 2002 – 33; HL 2002 - 20

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September 2002

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Measurement and Evaluation of Roadside Noise Generated by Transit Buses - Final Report

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Abstract

Traffic noise is a serious concern in urbanized areas in the United States and around the world. With the ever-increasing vehicle population, exterior vehicle noise is a growing problem that needs more extensive study by scientists and engineers. To develop more effective strategies for reduction of traffic noise levels, it is necessary to identify and characterize all sources contributing to the noise. The main objective of this study was to determine the levels of roadside noise generated by buses under various road surface and vehicle speed conditions typical for transit bus operations in urbanized areas.

After collecting and analyzing near- and far-field data for both a heavy truck and a transit bus at speeds of 10, 20, 30, and 40 mph over three pavement types, the following conclusions can be made. For the three types of pavement tested (chip seal, ID-2, and PCC), there is not a great deal of difference in tire noise generation. None of the three types of pavement tested seems to have an effect on the noise propagating to the far field. For the heavy truck the dominant contributor of far-field noise is tire-pavement contact, especially at higher speeds. For the transit bus the dominant contributor of far-field noise is the CNG engine. The far-field noise generated by the transit bus is significantly greater than that generated by the heavy truck. Transit buses could be quieted significantly by designing the engine compartment to absorb or redirect more of the acoustic energy generated by the engine.

Background

There have been many studies of the noise generated by tires contacting the pavement, as this is the major component of far-field noise at highway speeds (1). Various methods have been used to determine this noise, and theories about the noise-generating mechanisms have been developed. Many investigators have used a close-proximity method and attached microphones near the tire contact patch. This is typically done in one of two ways. In the trailer method, the tire and microphones are mounted to a specially designed trailer. The trailer encloses both the tire and microphones to minimize air noise. Data are collected as the trailer is towed at various speeds and over various pavements. In the drum method, a tire is pressed against a large drum that has been coated with paving material. The drum is then driven at different rotation speeds to simulate driving conditions. Here the experiments can be conducted in the laboratory and the temperature and humidity controlled. The motivation for these methods is to isolate the tire/pavement noise from other noise sources and minimize the propagation effect. However, with these methods the tire is not powered as it would be on an actual vehicle.

Other investigators have used the pass-by method to measure vehicle noise. In this method, stationary microphones are placed at a fixed distance from the roadway and sound is recorded as a vehicle passes by. In the statistical pass-by method, random vehicles are sampled and statistical averaging is used to determine sideline noise. This is adequate for characterizing the noise level's dependence on pavement type and estimating noise levels that are experienced by residents of the area. In the controlled pass-by method, specific vehicles with known tire types are driven under controlled conditions past a stationary microphone. Here, the dependence of far-field noise on vehicle speed and tire type can be more readily investigated. Both statistical and controlled pass-by methods use similar measurement techniques. The Federal Highway Administration (FHWA) and ISO have disclosed standardized methods for pass-by measurements (2, 3, 4) that have been adopted for use by the American Association of State Highway and Transportation Officials. The Society of Automotive Engineers has a standard for recording pass-by noise of heavy trucks and buses (5). While much easier to implement than the trailer method, it is difficult to determine the actual source of the noise with the pass-by methods.

Depending on what one is studying, both the close-proximity and pass-by methods have their benefits. If one is trying to determine how to develop new pavement surfaces or tire tread patterns to reduce tire/road noise, it is reasonable to use a close-proximity method. However, if one is interested in the overall noise generated by traveling vehicles and heard by nearby people, a pass-by method should be used. Because of the difference in how data are collected, the measurements taken by the pass-by and close-proximity methods have unfortunately not been shown to be comparable (6).

As stated in the objectives of the Institute for Safe, Quiet and Durable Highways, engine and exhaust noise have been reduced over time and noise from tire/road interaction has become the main source of traffic noise. While this may be true for passenger cars, it is not clear that engine and exhaust noise can be ignored as a noise source from transit buses. The speed regressions for the baseline maximum A-weighted sound pressure level with fast-response time-weighting characteristics,

$$L_{AFmx} = 10\log[10^{C/10} + s^{A/10}10^{B/10}], \qquad (1)$$

for buses ($A = 23.480, B = 38.006, C = 66.908$) and automobiles ($A = 41.741$, $B = 0.224$, $C = 47.861$) taken from the FHWA's Traffic Noise Model (TNM) (7) are shown in Figure 1. It should be noted that the value of C for buses was taken from the medium truck data, as there were insufficient bus data at low speeds. From Figure 1 it is clear that the noise generated by buses is less dependent on speed than is the noise generated by automobiles; the noise level at 70 mph is only 14.5 dB greater (about one and a half times louder) than the noise level at idle. For automobiles there is a 29.3 dB difference in noise level (about three times louder) when the speed is increased from 0 to 70 mph. At very low speeds bus noise is significantly (19 dB) higher than automobile noise. As engine and exhaust noise dominates at very low speeds, one must conclude that this noise source is more significant to the overall noise generated by transit buses than to that generated by automobiles. In addition, as buses normally operate at lower speeds than automobiles, bus engine and exhaust noise may be a significant portion of the total noise generated under normal conditions.

In the development of the FHWA's Traffic Noise Model, 337 bus passbys were recorded and analyzed. Of these, 96% were on dense-graded asphaltic cement (DGAC). For the entire study, just 62.5% of the passbys were on DGAC. Only 1.2% of the bus passbys were on portland concrete cement (PCC), compared to 18.7% for the entire study. Seven bus passbys on a grade were recorded but not used in the model. Very few low-speed bus data were collected; no low-speed data were taken for pavements other than OGAC. The low-speed bus data that were taken had to be corrected for noise caused by other vehicles. No idling data were recorded for buses. Because so few bus passby data were recorded, the data for medium trucks were used to supplement much of the bus data.

It is not clear from the FHWA TNM models what portion of the total noise is engine/exhaust noise and what portion is tire/road noise. What is clear is that at idle the predicted $L_{AFmx} = C$, and C characterizes the engine/exhaust noise. If one sets C = 0 in both the bus and automobile models, the FHWA TNM oddly predicts that for speeds below 15 mph the engine noise is a larger portion of the total noise for automobiles than for buses. This is obviously an anomaly of the curve fitting used and the few low-speed bus data taken. Thus, it is not clear from where the far-field noise is coming at a given speed. At idle, the far-field noise is entirely engine/exhaust noise, and at very high speeds it is dominated by tire/road noise; but where is the transition?

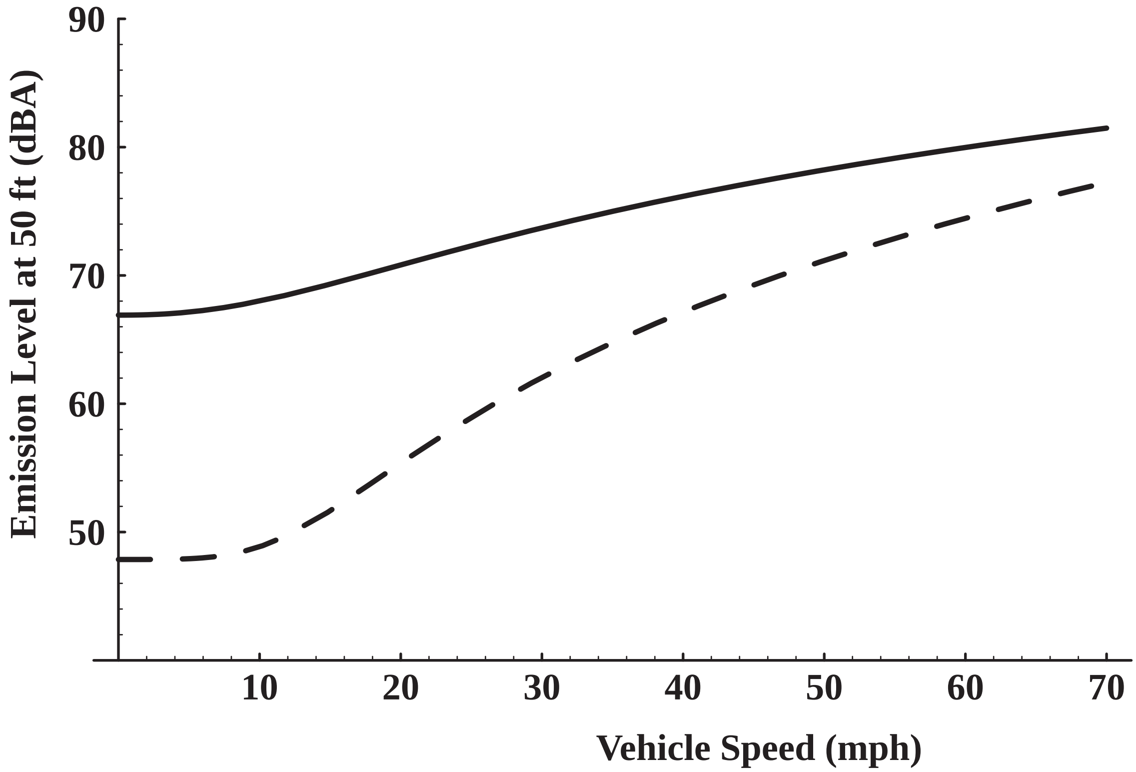

Figure 1: Regressions for passenger car (dashed) and bus (solid) data taken for the FHWA's Traffic Noise Model.

Objectives

Before engineers can make informed design changes to help reduce roadside noise generated by buses, they must have a clear understanding of the noise source. As mentioned above, the main vehicle noise sources are from the tire/road interaction, the engine, and the exhaust. While tire/road noise is the major contributor to far-field noise for automobiles traveling at highway speeds, this is not necessarily true for buses operating in typical urban environments. In these environments, the speeds are usually lower and the flow is interrupted with traffic frequently accelerating and decelerating. In this environment, and because of the inherent differences in bus and automobile design, one cannot rule out engine and exhaust noise as a significant contributor to far-field bus noise. Thus, in this project the researchers will determine the contributions of each of these noise sources to far-field bus noise under a variety of operating conditions.

Research Approach

The main problem in attaining the stated goals is trying to correlate near-field sound data with the far-field noise that is of most concern. It is clear that the various vehicle noise measuring techniques outlined above will not be adequate for the needs of this project. Thus, a different method was employed for this project.

Measurement Techniques

The close-proximity and pass-by methods are useful for different types of studies and complement each other well. The statistical pass-by method was excluded because more control over the pass-by vehicles is needed. The controlled pass-by method, in which buses would be driven at controlled speeds past a stationary microphone, was considered. However, as previous investigators have found (7), it is exceedingly difficult, if not impossible, to adequately determine the specific source of the noise reaching the microphone. Subsource-height noise levels have been recorded in an attempt to determine far-field noise sources using the pass-by methods (7). It was anticipated that the elevated measurement would contain mostly engine noise and be less dependent on speed than the ground measurement that would contain mostly tire/road noise. In this way, the far-field noise could be roughly decomposed. However, experiments showed that the ratio of upper to lower noise level was independent of speed. Thus, this method also seems inadequate to meet the objectives of this project. Close-proximity methods are good for measuring specific sources but, by definition, do not attempt to measure far-field noise levels.

The researchers first discussed using a combination of the controlled pass-by and trailer methods. The noise from the tire/road interaction would be correlated with the far-field noise measured by a stationary microphone. The basic problem with this idea is that the trailer method uses a very controlled and artificial environment for measuring tire/road noise. Even if the trailer were attached to the bus and near- and far-field data collected under identical conditions, near-field measurements would be made from one source (trailer tire) while far-field measurements would be made from a completely different source (bus tire). In addition, as mentioned previously, the trailer and pass-by methods have not been demonstrated to be comparable. The likelihood of successful correlation between them would be small. To estimate the engine/exhaust portion of the far-field noise, the close-proximity tire/road measurements would have to be theoretically propagated to the far field and removed from the noise recorded there. As so many factors influence noise propagation, this seemed an overly challenging task. For these reasons, this idea was dismissed and others considered.

It is clear that close-proximity (near-field) and far-field measurements need to be done simultaneously and from the same sources. After discussion with representatives of Penn State's Center for Acoustics and Vibrations (CAV), attention focused on mounting microphones on key areas of the bus to measure near-field sound levels. A similar method had been used to successfully pinpoint noise sources on high-speed trains in Europe. Brüel and Kjær high-speed wind shields designed for wind tunnel sound measurements were used to remove wind noise. With this knowledge the research group decided to measure near-field noise levels at four places on the bus. Measurements were taken at both curbside tires to detect the difference between sound emitted from driven and undriven wheels. Measurements were also taken near the engine compartment and the exhaust. In addition, a boom was attached to the top of the bus. A microphone with a wind shield was attached to the boom to continuously collect far-field data. Using this method, near- and far-field data from the same sources was collected simultaneously. It was the hope of the researchers that the far-field data would correlate well with the near-field data and the contributions of each of the four sources to the far-field noise could be determined.

Data Acquisition Equipment

Three PCB 130C10 Electret Array microphones with dynamic range of 15 to 128 dB were chosen for sound measurement. These microphones were considered cost-effective yet sensitive enough to take measurements at the desired level of accuracy for this project. PCB 130P series preamplifiers and PCB 480E09 ICP sensor signal conditioners were used with the microphones. The signal conditioners chosen were battery powered so it was not necessary to power them from the bus. A Larson Davis CAL 150B Acoustic Calibrator was used for calibrating the microphones. The calibrator has a nominal level of 114.0 dB SPL at 1000.0 Hz. Relatively inexpensive, its uncertainty of 0.11dB at 99% confidence level was more than adequate for the accuracy of the experiments.

Because there would be significant air flow over the microphones, they had to be shielded to prevent wind noise from dominating the signals. Foam wind screens were used on each microphone. These wind screens are rated to effectively eliminate wind up to 40 mph. Since tests were only planned to be conducted at bus speeds up to 40 mph, the foam wind screens appeared to be the best way to filter the wind noise. More sophisticated wind screens were also investigated but the cost of these was prohibitive for the relatively low air speeds that the microphones would experience.

A TEAC 110 T digital audiotape recorder (DAT) was used to record the signals from the microphones. This DAT was able to capture all of the microphone data simultaneously so that correlations could be made between the signals. It is also capable of simultaneously recording a voice track, which made it easy to identify the conditions of each test while data were recorded.

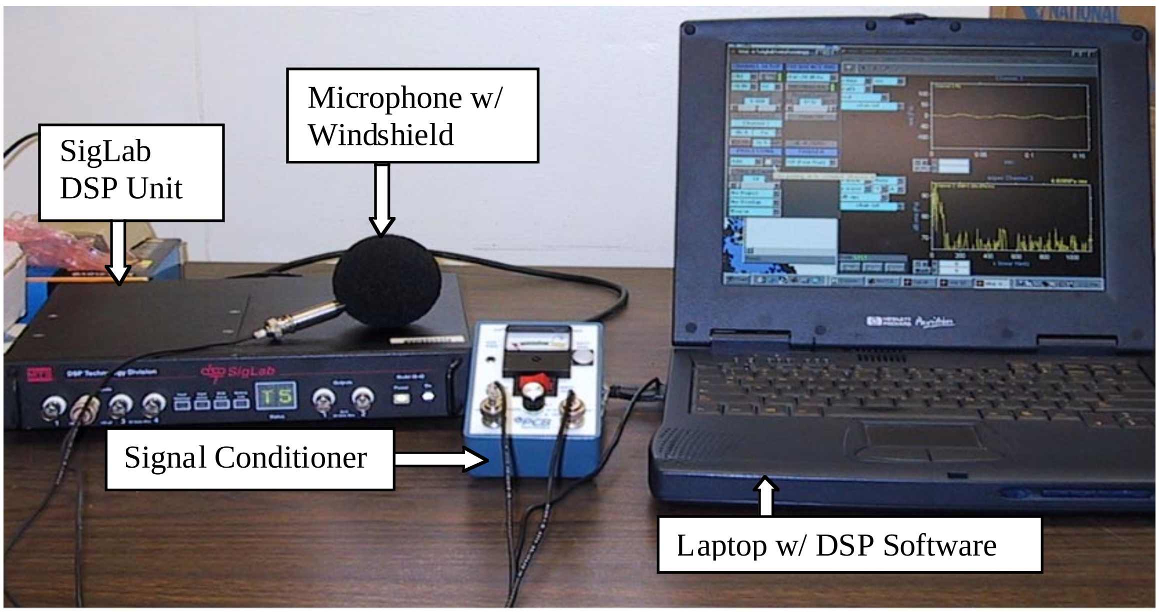

Figure 2: Data acquisition hardware and software.

A variety of hardware capable of processing the data was studied. After contacting several manufacturers about their products, a DSP Technologies SigLab model 40-22A (shown in Figure 2) was purchased. The system acquires data on four input channels, allowing all of the microphone measurements to be sampled simultaneously. Portability was also a benefit that SigLab possessed over the other devices. SigLab weighs only 5 lb. and can run on an internal battery, whereas the other systems weighed as much as 20 lb. and required an electrical outlet. SigLab offers a wide bandwidth range of 2kHz to 20kHz, with full alias protection in all bandwidths, and 95dB spurious-free dynamic range. Internal DSPs yield real-time bandwidths and frequency translations, making measurements highly accurate. It is also very simple to set up, requiring only a SCSI interface between it and a computer.

To keep the data acquisition system as portable as possible, a Hewlett-Packard notebook computer (shown in Figure 2) was connected to the SigLab hardware to store and process the data. With the addition of a SCSI PCMCIA card, the notebook was easily interfaced with the SigLab hardware and made for a portable and extremely powerful data acquisition system.

The SigLab package also comes with the software necessary to analyze the data. The software works in conjunction with MathWorks' MATLAB. The powerful data analysis routines included in MATLAB's Signal Processing Toolbox and the Octave Analyzer routines included in the SigLab package provided all the necessary tools for analyzing the data collected to the DAT.

Boom Construction

To take far-field noise measurements with a microphone traveling with the bus, a boom had to be constructed that could be easily attached without requiring any permanent alterations to the bus. Since the weight of the microphone carried by the boom is extremely small compared to the weight of the boom itself, the boom was designed to support its own weight and resist aerodynamic loading. To make the load acting on the bus from the boom as small as possible, the boom was constructed from aluminum tubing.

The boom itself was designed as a simple truss structure that extended 25 ft. from the center of the bus. It easily supported the attached microphone with a minimum of deflection. Designing a system to attach it to a transit bus without damaging or modifying the bus proved to be a much more challenging task. Additionally, because initial testing and system verification were to be done on a mini-bus that was readily available, the attachment mechanism had to be designed to fit both the transit bus and the mini-bus. The simplest approach was to make a variable length, inverted U-shaped clamping mechanism that fit over the buses. The legs of the clamp extended down each side of the bus and the variable-length cross member rested across the top of the bus. This assembly was made from aluminum angles, and foam padding was used to prevent damage to the bus and to more evenly distribute the load. The cross member consisted of overlapping L-shaped beams that had slots cut in the edges extending upward from the bus. Bolts extending through the overlapping slots secured the two beams and could be loosened to change the length of the cross member.

To install the boom on either the transit bus or the mini-bus, the inverted U-shaped clamping mechanism was first lowered over the top of the bus. Once the cross member was resting on the top of the bus, the bolts holding the two cross member beams together were loosened so the legs extending down the sides of the bus could be firmly pressed against the bus. The bolts were then tightened to provide a secure mounting system for the boom. The boom was then bolted to the support brace. Ratchet ties were also used to provide additional lateral stability to the boom.

Figures 3, 4, and 5 show, respectively, the boom attached to the mini-bus, the heavy truck, and the transit bus at the PTI test track. As seen in the figures, a plywood sheet was placed between the support leg the boom was attached to and the bus. This distributed the forces applied to the bus over a larger area to prevent damage. Both the boom and the support structure worked well during testing on both the transit bus and the mini-bus. It was stiff enough to hold the far-field microphone stationary even at the 40 mph test speeds and did not damage the buses.

Figure 3: Boom attached to mini-bus.

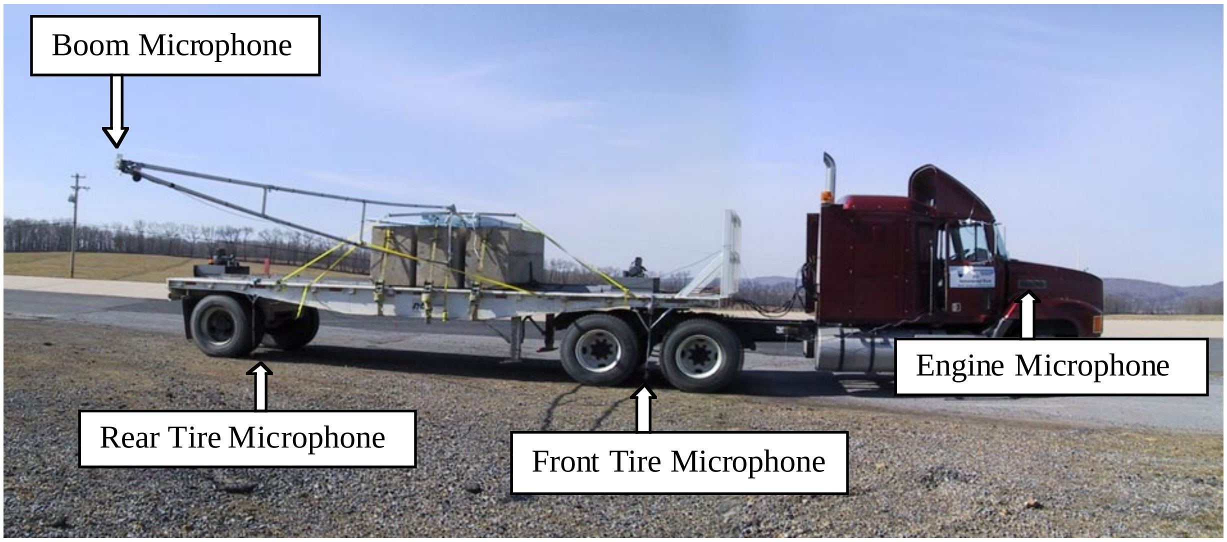

Figure 4: Boom and microphones attached to heavy truck.

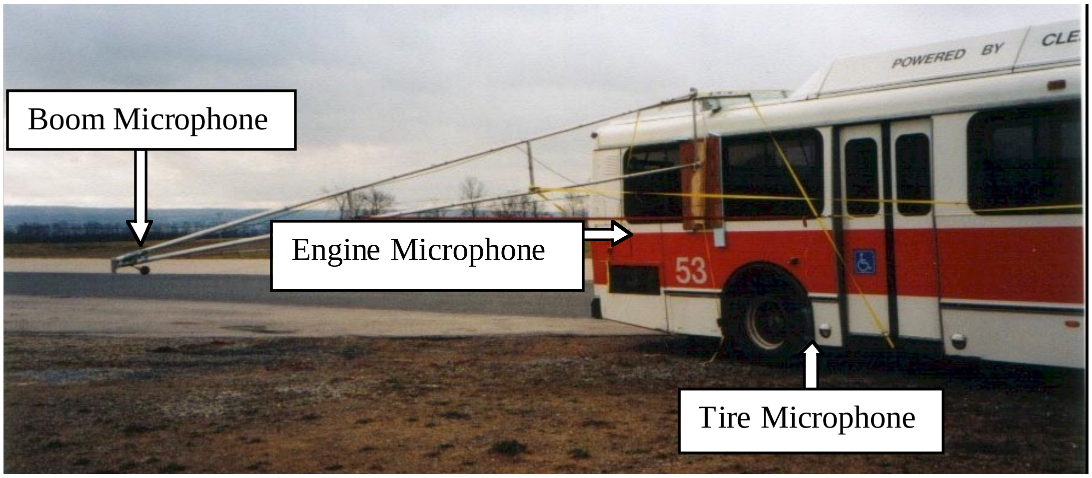

Figure 5: Boom and microphones attached to transit bus.

Testing

Shortly after the start of this project, the Centre Area Transit Authority (CATA), which had agreed to provide transit buses for testing, entered into an agreement with Penn State to provide no-fee on-campus bus service for all students and university employees. Thus, instead of having excess capacity and many idle buses that could be used for extensive testing, there was a severe shortage of transit buses available to this project. CATA was then only able to provide a bus for testing during periods when the university was not in session. This severely limited the ability of the researchers to collect sufficient data in the time frame originally proposed. The scope of the tests also had to be scaled back.

While waiting for a transit bus to become available for testing, other experiments related to this project were conducted. These tests proved to be very valuable. The student was able to learn and get accustomed to the newly acquired data acquisition system.

Anechoic Chamber Tests

Wheel Well Model

One idea for reducing far-field tire noise is to use tire shields that cover the wheel wells and absorb the sound emitted from the interaction of the tire with the pavement. To test this idea and gain experience with the data acquisition system, a full-scale model of a transit bus wheel well was constructed. The outer shell of the model consisted of a plywood box that was 50 inches wide, 48 inches high, 12 inches deep, and open at the base. As shown in Figure 6, a 48-inch-diameter semi-circular hole was cut in the outer surface to model the wheel opening. A 12-inch-wide aluminum sheet was cut to length and secured around the inner perimeter of the semi-circle to complete the wheel well model.

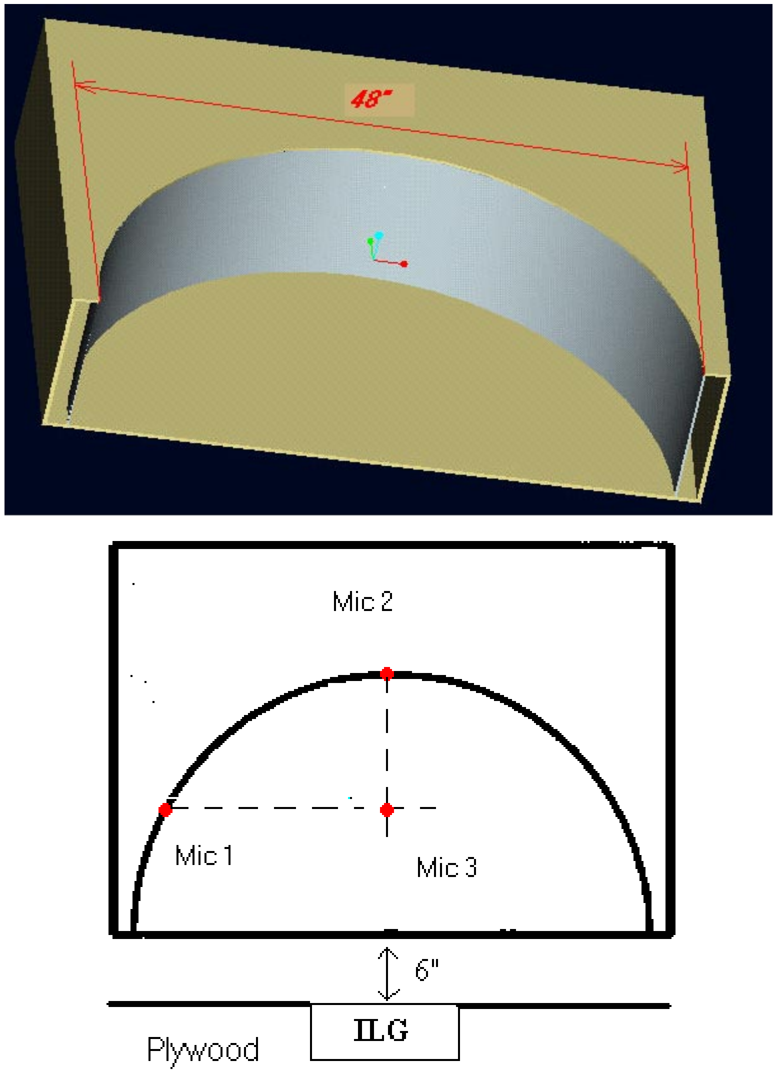

Figure 6: Schematic of simulated wheel well showing microphone and ILG placement.

A plywood board lined with acoustic soft foam was placed twelve inches away from the bottom opening of the wheel well model to simulate the pavement. An ILG noise source was then placed on this plywood board to generate noise. While the ILG source does not accurately simulate any kind of tire-pavement noise, it does generate a broad frequency spectrum. The transmission loss of the tire shields could then be measured over a wide range of frequencies.

The tire shield was constructed from a 1-inch foam sheet. It was cut to a 4-ft square so that it could entirely cover the width of the wheel opening. With a height of 4 ft, the shield could be extended to cover the entire front surface of the model, down to the simulated pavement. In this way the transmission loss over the tire shield could be measured as a function of the gap between the bottom of the shield and the simulated pavement.

Measurements

A microphone was placed 2 ft in front of the front surface of the wheel well model and 6 inches above the plane of the plywood board that simulated the pavement. Data were collected first without the tire shield to obtain a reference signal that could be compared to measurements taken with the tire shield in place. In this way the effect of the tire shield could be determined. Data were then collected with the tire shield extending down to six inches above the simulated pavement. The tire shield was then lowered in 1-inch increments until the shield extended all the way to the pavement and the gap was zero.

Results

The tire shields had very little effect on the noise transmitted out of the wheel well for gaps over 1 inch. Figures 7 through 9 show the frequency spectra of the signal collected by the microphone for the cases without the tire shield and with the tire shield extended to varying distances above the simulated pavement.

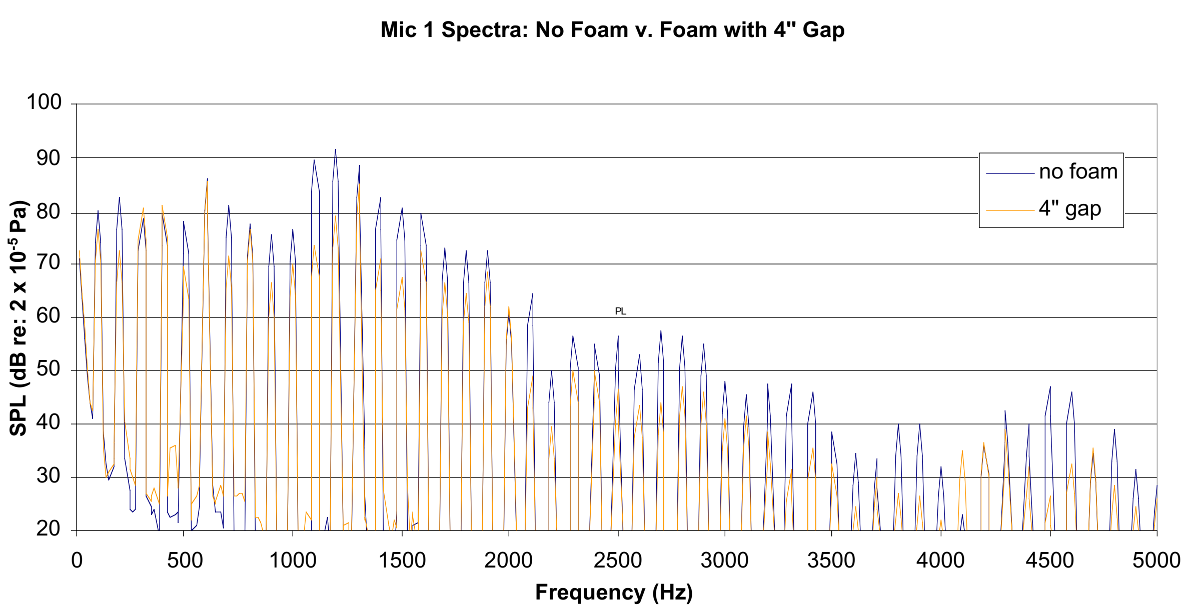

Figure 7: Frequency spectrum with no foam cover and 4-inch gap.

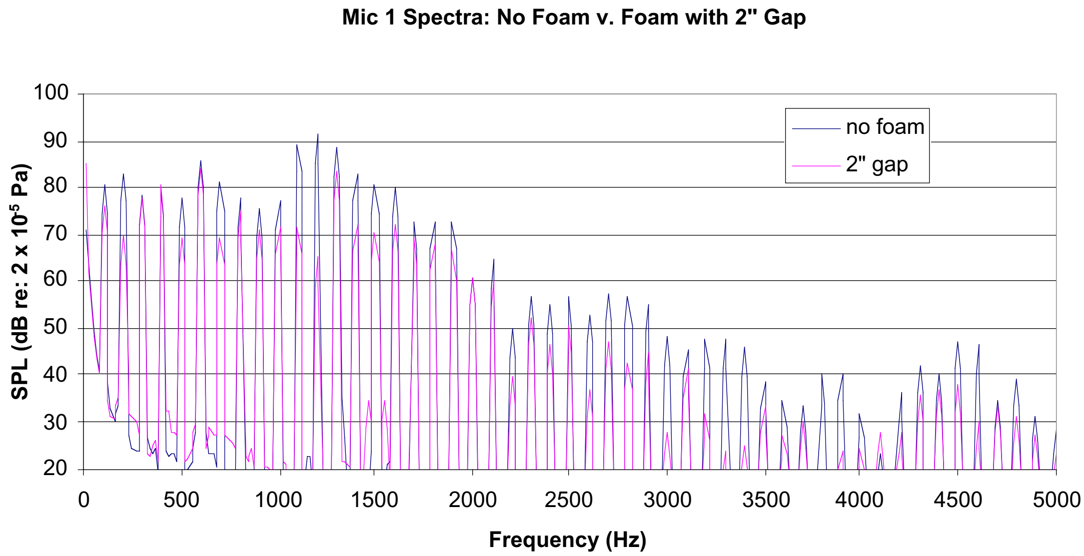

Figure 8: Frequency spectrum with no foam cover and 2-inch gap.

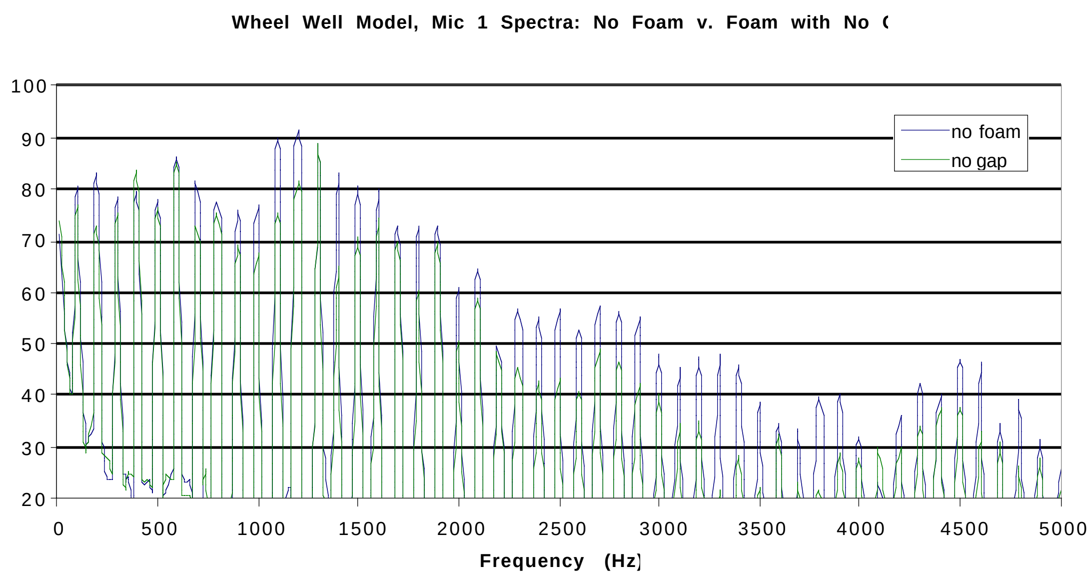

Figure 9: Frequency spectrum with no foam cover and complete coverage.

Mini-bus Tests

Because transit buses were only available for testing while the university was on break, the research team felt that it was important to do some preliminary tests on a readily available vehicle so that the data acquisition system and boom could be tested. Since access to a transit bus for testing was so limited, the team had to make sure that everything was working correctly when a transit bus was finally available.

Fortunately, the Pennsylvania Transportation Institute has a mini-bus that has been used for testing in the past and was readily available for this project. The mini-bus is a modified 1986 Chevrolet Suburban and is shown in Figure 3.

Boom Testing

It was especially important that the boom be tested to make sure that it was able to withstand the dynamic and aerodynamic loads acting on it at speeds up to 40 miles per hour. It was also important to confirm that the mechanism used to attach the boom to the bus was adequate and did not damage the bus in any way during testing. While the boom was designed to withstand the loads acting on it and the attachment assembly designed to not damage the bus, it was important that everything be tested before transit bus testing began.

Since the dimensions of the mini-bus are significantly different from those of the transit buses for which the boom attachment assembly was designed, some alterations had to be made for use with the mini-bus. These alterations were fairly minor and were made so that the same boom attachment assembly would still work with the transit buses.

When the boom was initially attached to the mini-bus, it became clear that additional modifications would have to be made. In the original design, the legs that extended down each side of the bus to counteract the moment from the boom were 3 ft long. As originally constructed, the boom attachment assembly could not securely hold the boom to the bus. After a number of different retrofits were considered, the simplest was to simply lengthen the side leg opposite the boom and use cables to secure it to the underside of the bus. Thus, the moment acting on the bus from the boom was counteracted mainly through the force in this cable and not by the forces acting between the bus and the side legs. Much lower forces then ac ted on the bus sides and therefore damage was much less likely.

The original boom was also designed to pivot about the attachment assembly so that the boom could be rotated flush with the side of the bus. This was done to facilitate transport of the bus from the garage to the test track. However, having the boom rotated flush against the bus generated a moment that acted to twist the attachment assembly. Because retracting the boom in this way could damage the attachment assembly and the bus, the hinges were removed and the boom welded directly to the attachment assembly.

With these modifications, the boom was attached to the mini-bus and driven to the test track to determine if the boom could withstand the dynamic and aerodynamic loads acting on it at speeds up to 40 mph. The modified boom performed well in these tests and required no further modification.

Data Acquisition Validation

Performing experiments with the mini-bus also allowed the data acquisition system to be tested. One microphone was attached to the end of the boom and directed back toward the mini-bus. A bracket was constructed to position a second microphone toward the rear of the front tire patch. The front tire was chosen to measure tire/pavement noise because the exhaust pipe was very near the curb-side rear tire patch. A third microphone was attached near the exhaust at the rear of the mini-bus. Data were then collected for speeds of 10, 20, 30, and 40 mph. The data were then analyzed to ensure they were being collected properly by the acquisition system.

Pavement Characterization

One of the most important characteristics of a pavement surface that affects the pavement safety, durability, and level of noise resulting from tire-pavement interaction is texture. Texture affects the level of frictional forces generated between tire and pavement surface when a vehicle tire rolls or slides over the pavement surface. The tire-pavement friction force has two components, a hysteresis component due to deformation of tire tread by large-scale asperities, and an adhesive component that is generated when the tire comes into contact with small-scale asperities in the pavement surface. The large-scale asperities constitute the pavement macrotexture, which is defined as the deviations of a pavement surface from true planar surface with characteristic dimensions of wavelength and amplitude greater than 0.02 in (0.5 mm). The small-scale asperities, less than 0.2 in (0.5 mm), constitute the surface microtexture. In general, microtexture determines the frictional capability of a dry pavement, while macrotexture determines the drainage ability and, therefore, how effective the microtexture will be when the pavement is wet.

A pavement's frictional characteristics are evaluated based on its skid resistance. Skid resistance is defined in the ASTM Standard E 867 as the retarding force generated by the interaction between a pavement and a tire under a locked, unrotating wheel condition [8]. The skid resistance measurements were conducted in accordance with the ASTM Standard E 274 [9]. In this method, a standard test tire is mounted on one wheel of a trailer towed by a pickup truck. While the towing vehicle maintains a speed of 40 mph, the test wheel is braked sufficiently to lock it up and the force necessary to pull the locked wheel along the pavement is measured and recorded. The average longitudinal force is divided by the static vertical wheel load and multiplied by 100 and the result is reported as the skid number (SN). Two standard tires, a ribbed tire and a blank tire, were used in the measurements. Tests performed using the blank tire represent the pavement macrotexture, while measurements made with the ribbed tire best represent the pavement's microtexture.

To further investigate the pavement surface macrotexture, mean texture depth (MTD) measurements were performed. This measurement involves spreading a known volume of glass spheres on a clean, dry pavement surface, measuring the area covered, and then calculating the average depth between the bottom of the pavement surface voids and the tops of surface asperities as a ratio of the volume of the glass spheres over the area. The macrotexture tests were conducted in accordance with ASTM Standard E 965[10].

Three pavement sections, each with different texture characteristics, were used in the testing program in this study: portland cement concrete (PCC), chip seal, and bituminous asphalt pavement (ID-2). Results of the measurements of the skid resistance conducted on the three pavements with both ribbed and blank tire are shown in Table 1. The results of macrotexture tests performed on the three pavements are listed in Table 2.

Table 1. Blank-tire and ribbed-tire skid numbers for PCC, Chip Seal, and ID-2 pavements.

	Skid Number (SN)					
	Blank Tire			Ribbed Tire		
	PCC	Chip Seal	ID-2	PCC	Chip Seal	ID-2
1	42.3	73.6	65.2	60.0	82.7	68.3
2	37.6	68.7	66.9	57.8	82.0	68.3
3	37.5	72.9	65.5	55.9	81.2	64.1
4	37.2	70.6	66.5	62.0	78.6	63.2
5	35.5	68.5	64.0	59.3	78.2	64.8
Average	38.0	70.9	65.6	59.0	80.5	65.7
SD	2.54	2.34	1.14	2.30	2.03	2.40

Table 2. Mean texture depth for PCC, Chip Seal, and ID-2 pavements.

	1	2	3	4	Average	MTD (in)
PCC	10.5	10.5	10.75	10.75	10.625	0.017
	10.5	10.25	10	10.375	10.281	0.018
	10.75	11.25	10.5	10.875	10.844	0.016
	10	10.75	10.5	10.25	10.375	0.017
	10.375	10.75	10.5	10.75	10.594	0.017
	Site Average				**10.544**	0.017
Chip Seal	5.5	5.5	5.5	5.25	5.438	0.063
	5.25	6	5.5	5.5	5.563	0.060
	5.625	5.75	5.5	5.75	5.656	0.059
	5.5	5.5	5.5	5.75	5.563	0.060
	5.75	5.375	5.5	5.5	5.531	0.061
	Site Average				**5.550**	0.061
ID-2	6.5	6	6.25	6	6.188	0.049
	5.875	6	6	6	5.969	0.053
	5.5	5.75	6	5.5	5.688	0.058
	5.875	6.25	5.875	6	6.000	0.052
	6.5	6.25	6	6.25	6.250	0.048
	Site Average				**6.019**	0.052

Note: The first five columns of data are auxiliary measurements (also in inches) that are then converted into MTD using ASTM Standard E965 [10].

While it is recognized that pavement surface macrotexture and microtexture are very important for pavement safety, there are other important contributing factors, such as traffic density and road geometric configuration [11]. All of these factors interact with each other in a manner that is difficult to evaluate in quantitative terms. This is the main reason for the lack of nationally accepted minimum skid resistance values that could be used as safety thresholds. Having recognized this fact, the ranges of 35 to 40 for ribbed tire skid resistance and 20 to 25 for blank tire skid resistance have been recommended in the past as the minimum required values. All three pavements used in this project have skid resistance values that considerably exceed the minimum values. The chip seal surface has the highest skid resistance, the PCC surface has the lowest skid resistance, and the bituminous asphalt surface falls in between the other two surfaces. The mean macrotexture measurements follow the same pattern, which is expected because the MTD usually correlates well with the blank tire skid resistance.

Transit Bus Tests

As discussed previously, the availability of transit buses for testing was extremely limited. The first sequence of experiments were conducted during a break in classes at the end of Fall 2000 semester when most students would be away from the State College area and bus service was reduced. These experiments appeared to go well; the boom performed well and the data acquisition system appear to be working properly. However, after the data were analyzed, it became clear that there was a problem with the data acquisition system that was not discovered during testing with the mini-bus. The far-field signal had been corrupted by electrical noise. This was not discovered during initial testing because the electrical noise level was fairly low and was not noticed in the DAT signal level indicators.

Transit Bus Information

This experiment involves the measurement of noise from a transit bus. The experiment was performed on a 40-ft-long Compressed Natural Gas (CNG) transit bus. The bus was a 1996 Orion Model 5, with a four-cylinder Detroit 50 Series CNG engine and Goodyear Metromiler, size 12.5R22.5 tires. All raw data are provided on an attached CD.

Test Setup

One microphone was attached to the tip of the boom. Standard BNC cables were used to make connections. The microphone was connected through a signal conditioner to channel 4 of the digital recorder. A second microphone was mounted near the contact patch of the rear tire on the curb side of the bus. The BNC cable connecting the microphone to a standard signal conditioner was taken through a window directly above the tire. This conditioner was connected to channel 2 of the digital recorder. While, ideally, it was desirable to have this microphone as close to the contact patch as possible on the trailing side of the tire, the microphone was actually placed slightly at the leading edge to prevent dislodged road dirt from making contact with the microphones. The third microphone was attached to the body of the bus directly below the rear vent near the engine. It was connected similarly through a signal conditioner to channel 3 of the digital recorder. Each microphone was calibrated using a Larson Davis CAL 150B Acoustic Calibrator. Next, windscreens were secured over each microphone and an ambient noise reading was taken.

Results and Discussion

Data were sampled and later analyzed using VCAP, VNA and VTO modules of DSP Technology's SIGLAB recorder/analyzer. Twenty-one, one-third octave bands and the A-weighting function of VTO were used. A sample shot of the VTO screen for segment 2 (chip seal) and a speed of 20 mph is shown in Figure 10. The air temperature at the time of testing (December 19, 2001) was 39°F (3.9°C). The auto spectra (VNA) of the noise signals (Figure 11) indicate that the dominant frequency ranges with respect to dBA levels are approximately as follows:

Tire: 0 – 4000 Hz

Engine: 0 – 8000 Hz

Above this range the effective contribution from the noise source toward the overall dBA level is considered minimal.

Examples of raw data collected in this study (and included on the attached CD) are shown in Figures 12, 13, and 14. The noise level plots for the transit bus are shown in Figures 15, 16, and 17. The noise levels again increase with increasing vehicle speed, as expected. For the transit bus tests, for all pavement types, the engine noise is loader than the tire noise. As with the heavy truck, the engine noise increases approximately 5 dB as the speed increases from 10 mph to 40 mph. Again, this is fairly consistent across pavement type. The type of pavement seems to have little effect on the tire noise for the transit bus. If any conclusion can be made, it appears that again the chip seal pavement causes the lowest level of tire noise. However, it is not as clear for the transit bus as the heavy truck. The difference in tires could explain this. For the transit bus, the difference in noise levels measured by the engine and tire microphone diminishes with increasing speed. The difference is approximately 15 dBA, 12 dBA, 7 dBA, and 5 dBA at 10, 20, 30, and 40 mph respectively. For the transit bus the far-field noise (boom) tends to more closely follow the trend of the engine (front) noise. This leads to the conclusion that the engine is contributing more to the far-field noise than the tires, even at high vehicle speeds.

Figure 10: Screen shot of VTO.

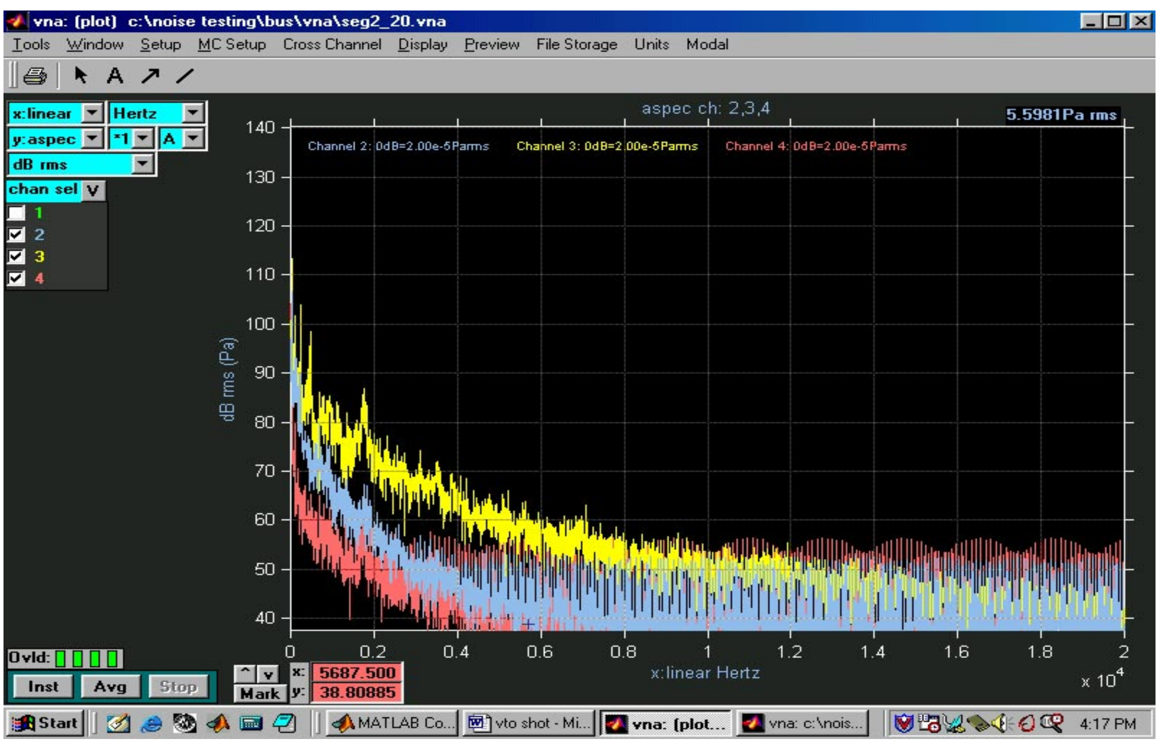

Figure 11: Screen shot of VNA.

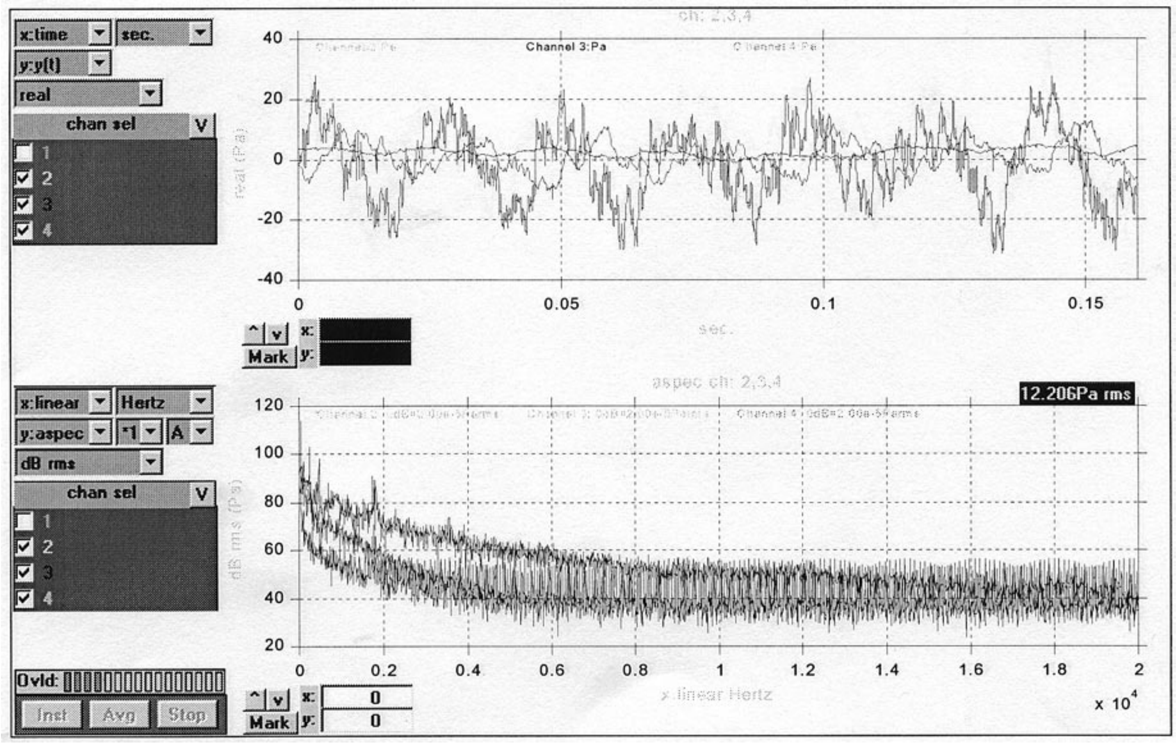

Figure 12: Bus Noise, Segment 3, 20mph.

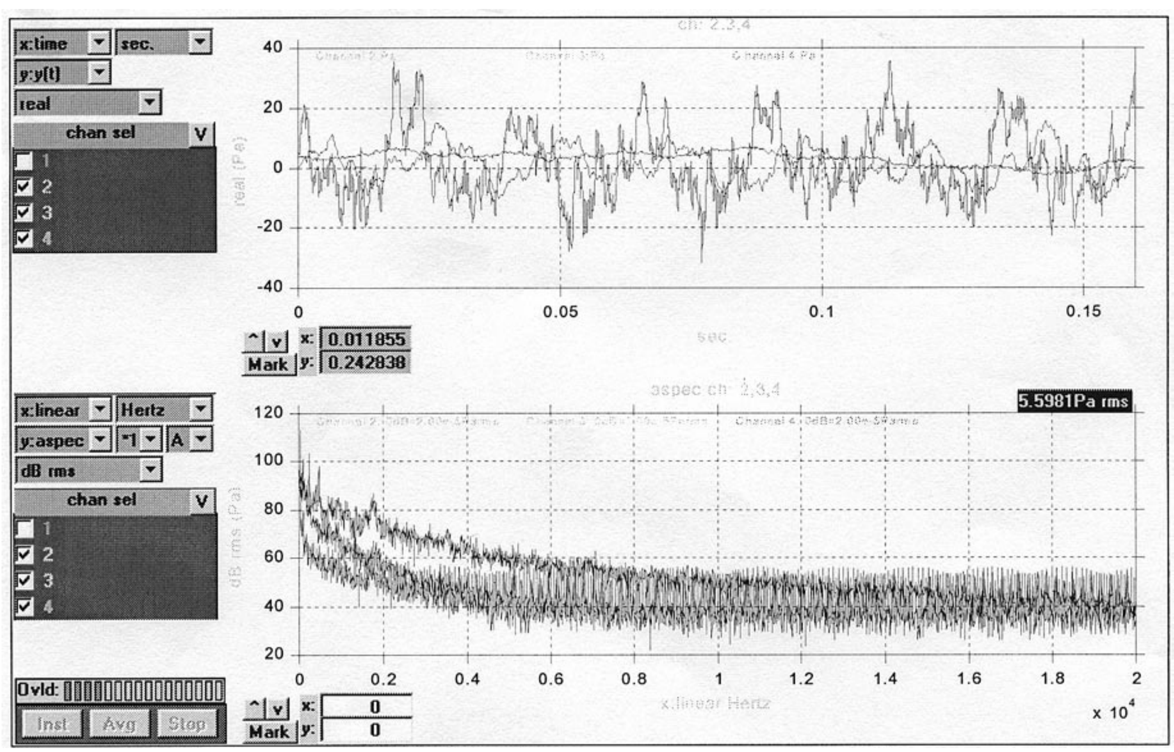

Figure 13: Bus Noise, Segment 2, 20mph

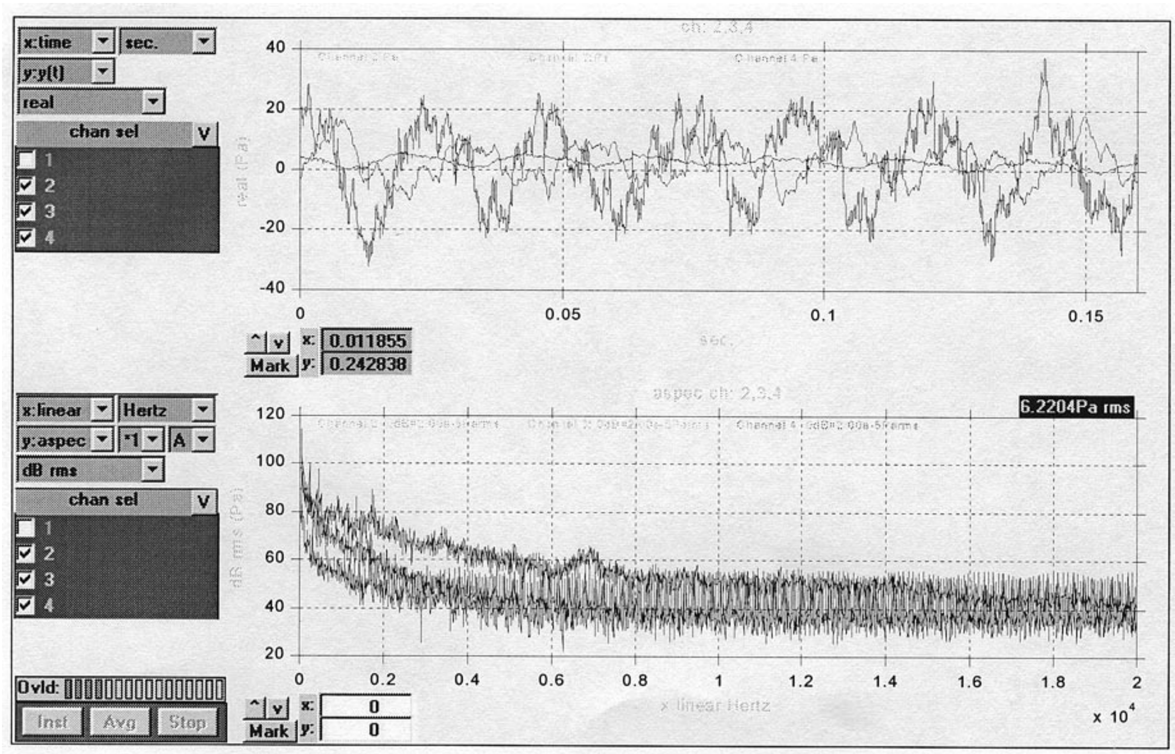

Figure 14: Bus Noise, Segment 1, 20mph

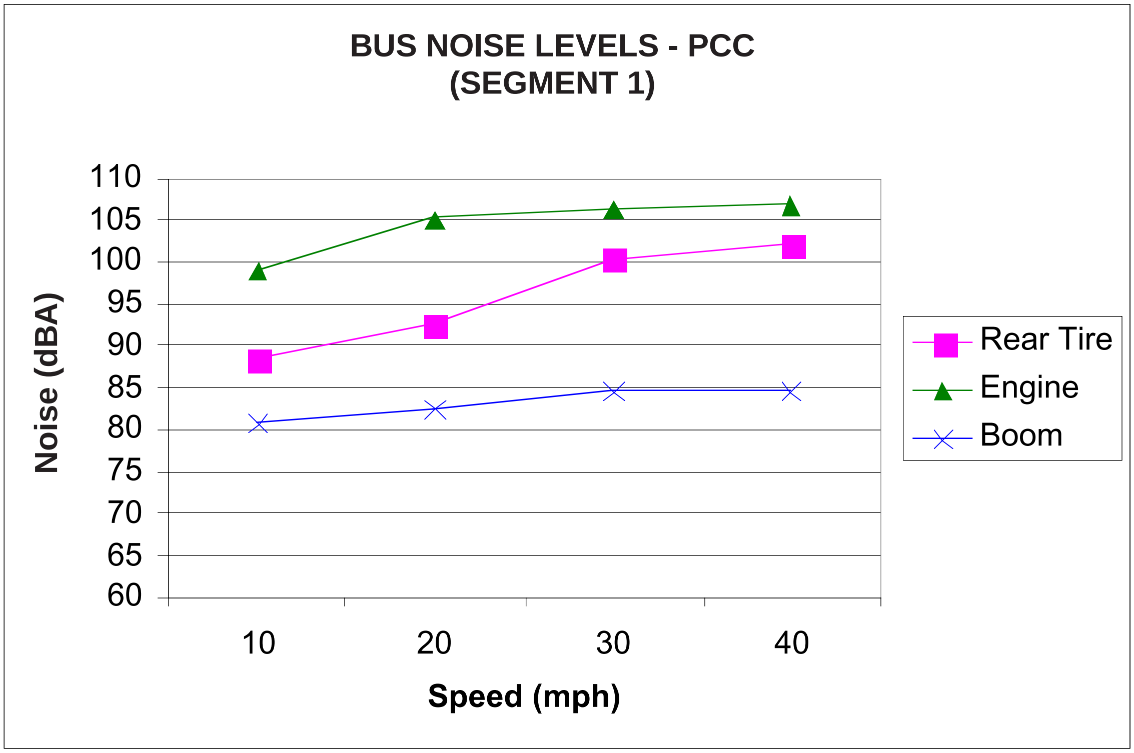

Figure 15: Bus noise (Surface – PCC).

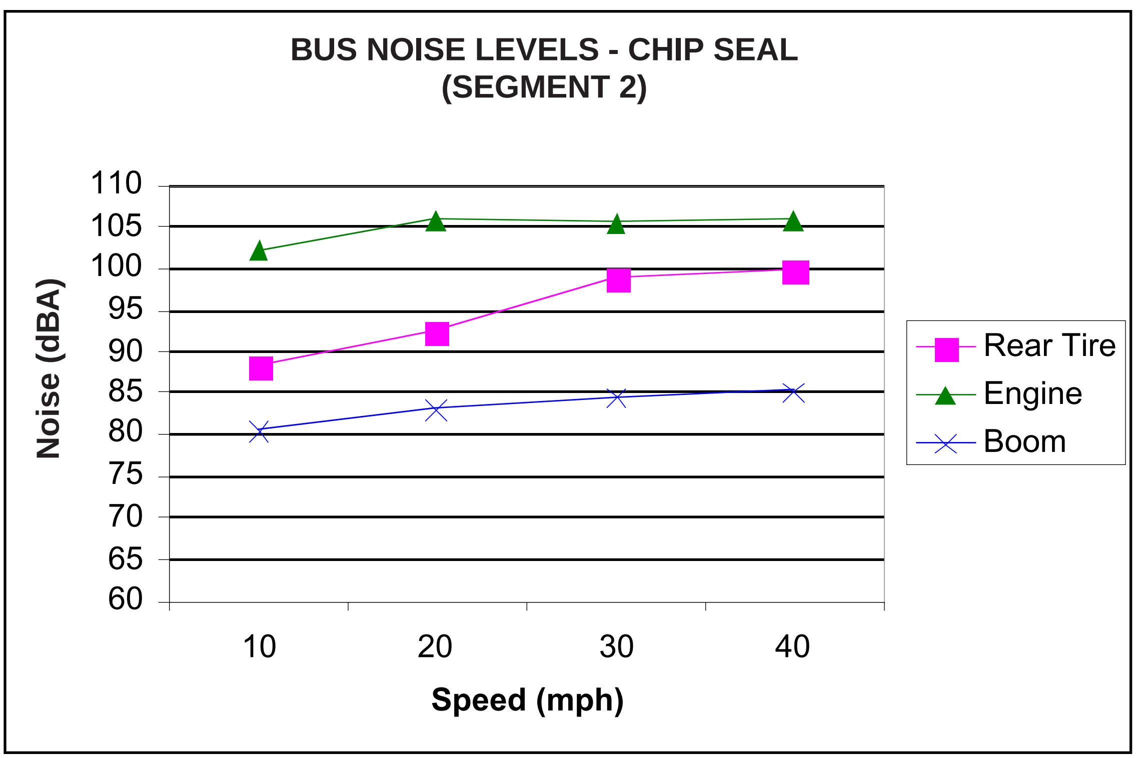

Figure 16: Bus noise (Surface – Chip Seal).

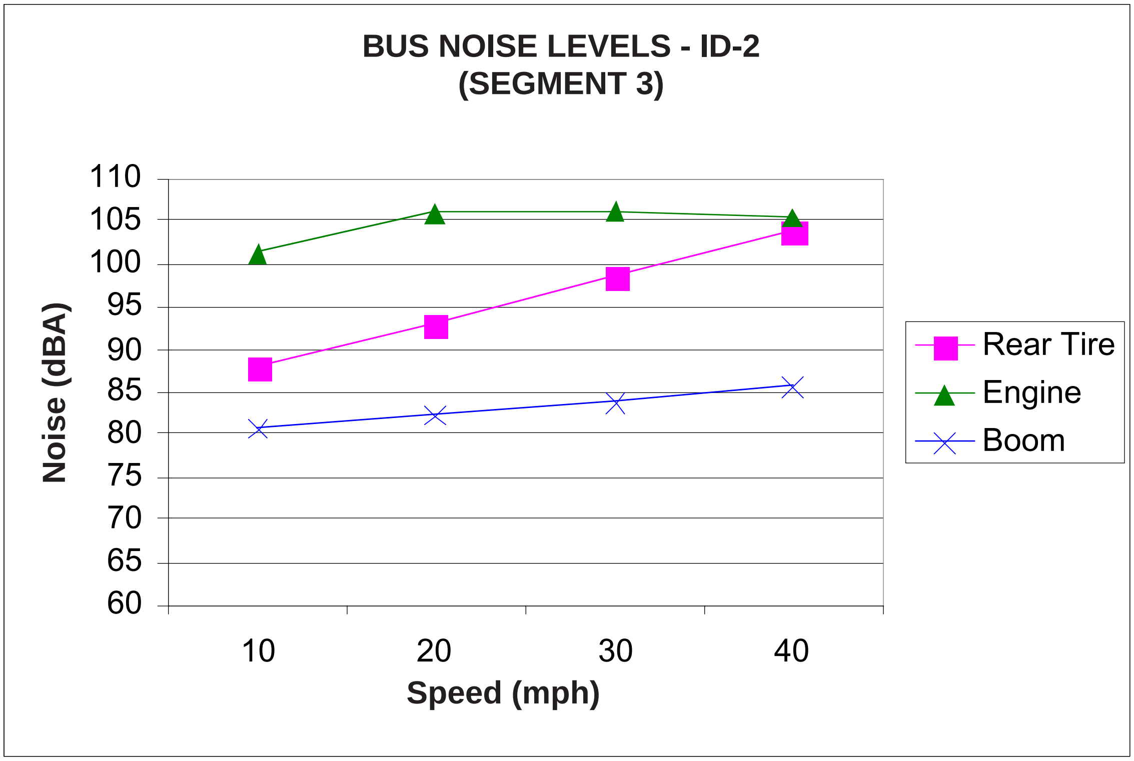

Figure 17: Bus noise (Surface – ID2).

Heavy Truck Tests

Though the project was primarily intended to study bus noise, an additional test was carried out on a loaded Mack truck-trailer (Figure 4) for comparison purposes.

Heavy Truck Information

The Mack truck used in the tests was a 1990 model LM7-300. It is powered by a 728 cubic inch, 6 cylinder turbo diesel engine that produces 300 hp at 1750 rpm. The tandem-axle, dual tires (referred to here as front tires) were Goodyear G167 unisteel, size 11R22.5, tubeless tires (conventional sized tires used on 15-degree rims). The dual trailer tires (referred to here as rear tires) were Michelin X2E, size 11R24.5, tubeless tires. The tires on the tractor's steering axle, which did not have a microphone nearby, were Goodyear G114 unisteel, size 295/75R22.5, tubeless tires (metric sized tires used on 15-degree rims). All raw data are provided on an attached CD.

Test Setup

The test equipment and testing procedure were kept exactly the same as for the transit bus. However, the important differences between the two tests were the location of the engine (rear for the bus and front for the truck-trailer) and the location of the front tire microphone that was located between the two axles of the rear tandem axle in the case of the trailer. In contrast to the bus test, two tire microphones were used, since it was felt that noise from the tandem axle could be important as it is close to the boom microphone.

Results and Discussion

Data were sampled and later analyzed using VCAP, VNA and VTO modules of DSP Technology's SIGLAB recorder/analyzer. Twenty-one, one-third octave bands and the A-weighting function of VTO were used. A sample shot of the VTO screen for segment 2 (chip seal) and a speed of 20 mph is shown in Figure 10. The air temperature at the time of testing (March 5, 2002) was 18°F (minus 7.8°C). The auto spectra (VNA) of the noise signals (Figure 11) indicate that the dominant frequency ranges with respect to dBA levels are approximately as follows:

Tire: 0 – 4000 Hz

Engine: 0 – 8000 Hz

Above this range the effective contribution from the noise source toward the overall dBA level is considered minimal.

The noise level plots for the heavy truck are shown in Figures 18, 19, and 20. As expected, the noise levels increase with increasing vehicle speed. The tire (front) noise is lower than the engine noise at low vehicle speeds but increases with increasing vehicle speed at a much faster rate than the engine noise. The engine noise increases approximately 5 dB as the speed increases from 10 mph to 40 mph. This is fairly consistent across pavement type, as expected. The type of pavement does, however, have an effect on the tire noise. From the figures, the chip seal appears to produce the least tire-pavement noise. At lower speeds the ID-2 is quieter than the PCC. However, at higher speeds the PCC produces less noise. Note also that the increase, from 10 mph to 40 mph, in noise produced by the trailer tires is greater than that for the tractor tires. This is likely due to the difference in type of tire, as noted above. For the heavy truck the far-field noise (boom) tends to more closely follow the trend of the tire (front) noise. This leads one to believe that the tire is contributing more to the far-field noise than the engine, especially at high vehicle speeds.

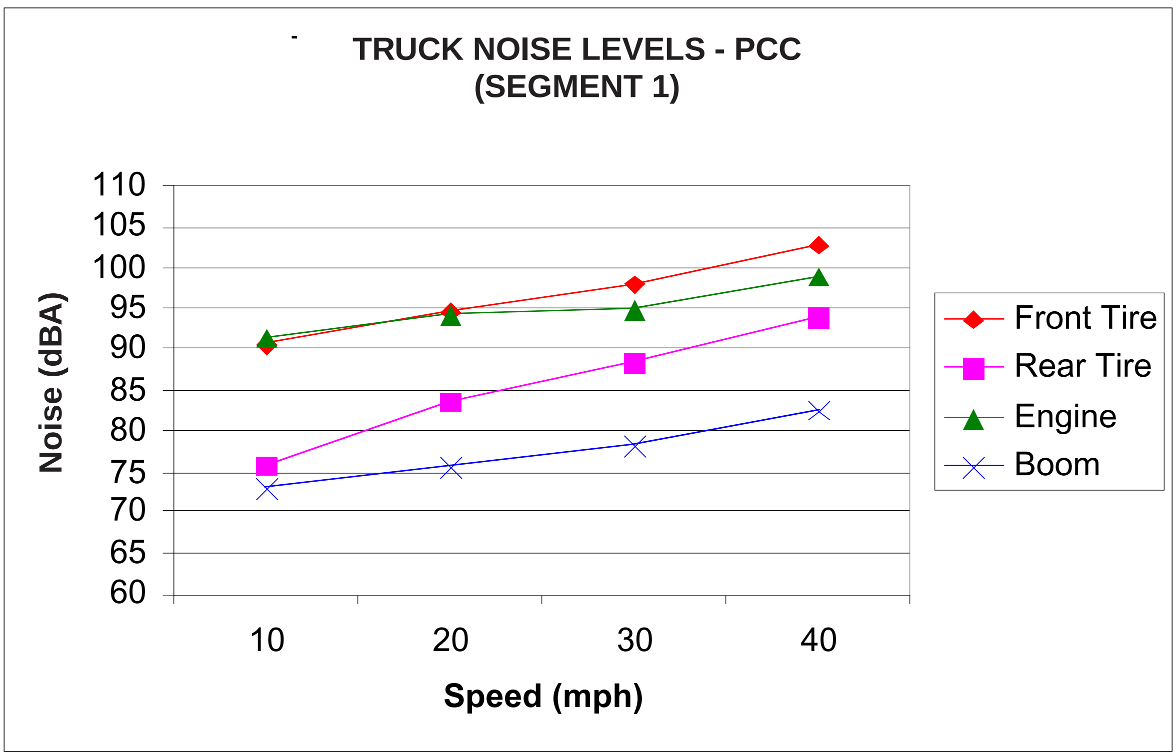

Figure 18: Truck noise (Surface – PCC).

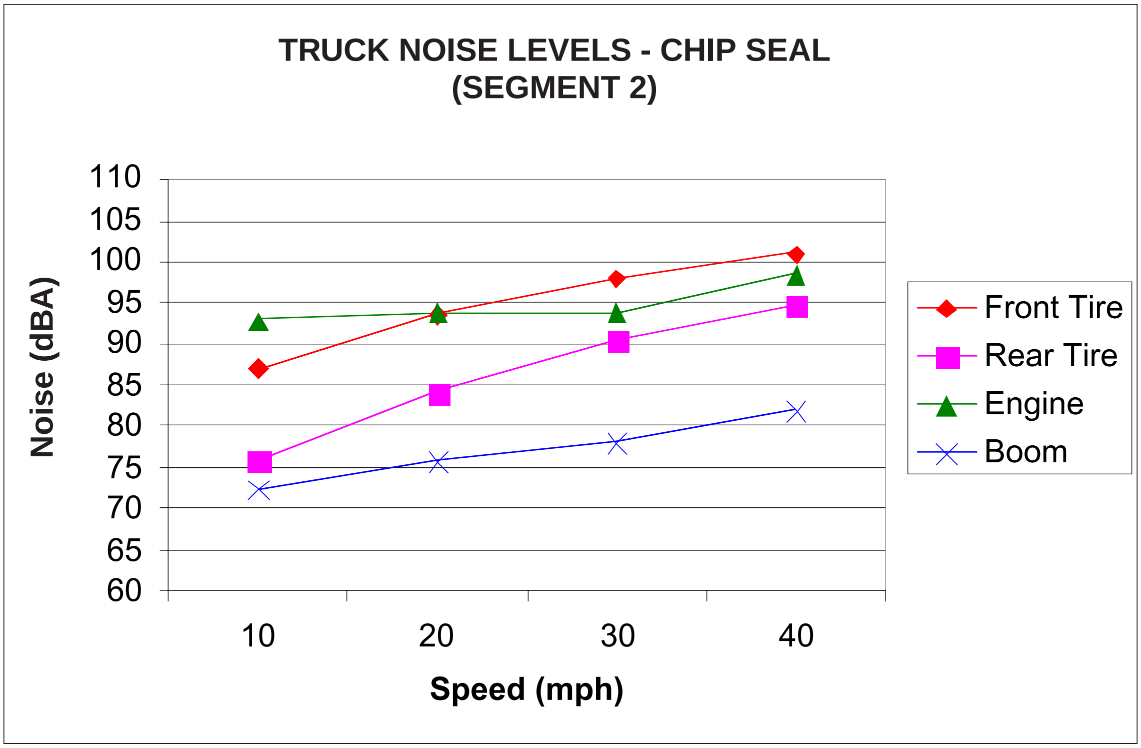

Figure 19: Truck noise (Surface – Chip Seal).

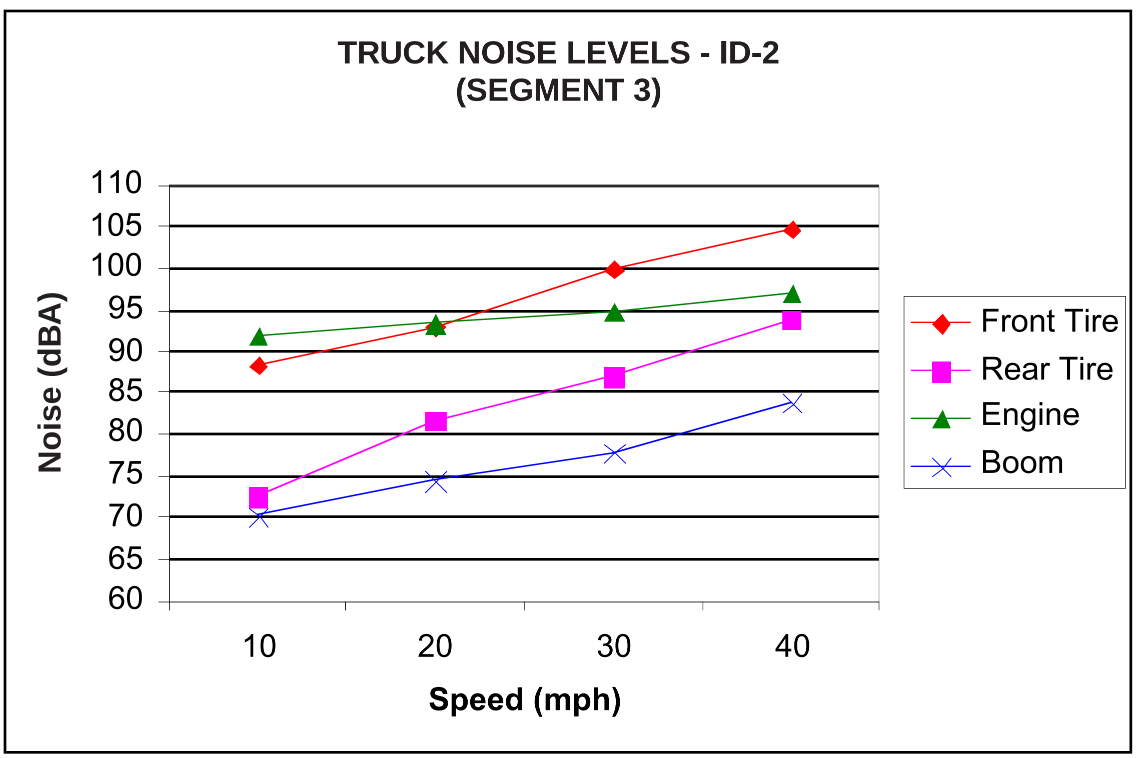

Figure 20: Truck noise (Surface – ID2).

Conclusion

A new method for continuously collecting far-field noise data has been demonstrated. The method uses a microphone attached to a boom that extends 25 feet from the center of the vehicle. Data were collected from this far-field microphone and also near-field microphones attached to points near the dominant noise sources, the engine and the tires. A heavy truck and a transit bus were used to collect data to validate the method. The collected data agree with observation and also with data collected using the pass-by method for far-field noise data collection. The boom method has advantages over the pass-by method. Far-field noise data can be continuously collected reducing the time required to collect such data. As the far-field data is collected from a point moving with the vehicle, difficulty trying to correlate near- and far-field data is reduced. For these reasons the boom method appears to be somewhat superior to the pass-by method for correlating near-field noise sources with far-field noise. Such an apparatus could be used in testing other vehicles.

After collecting and analyzing near- and far-field data for both a heavy truck and a transit bus at speeds of 10, 20, 30, and 40 mph over three pavement types, the following conclusions can be made. These conclusions are based on a relatively small set of measurements. Many more tests should be run to validate them. They however help to validate a new method for collecting far-field noise data.

1. For the three types of pavement tested (chip seal, ID-2, and PCC), there is not a great deal of difference in tire noise generation. If any conclusion can be made, the chip seal produces the least tire noise.

2. None of the three types of pavement tested seems to have an effect on the noise propagating to the far field as far-field noise levels were fairly consistent across pavement type.

3. For the heavy truck the dominant contributor of far-field noise is tire-pavement contact, especially at higher speeds.

4. For the transit bus the dominant contributor of far-field noise is the CNG engine.

5. The far-field noise generated by the transit bus is significantly greater than that generated by the heavy truck.

6. Transit buses could be quieted significantly by designing the engine compartment to absorb or redirect more of the acoustic energy generated by the engine.

References

1. Sandberg, U., “Low Noise Road Surfaces—A State-of-the-art Review,” *J. of the Japanese Acoustical Society*, vol. 20, 1999.

2. Regan, J.A., *Determination of Reference Energy Mean Emission Levels*, Report No. FHWA-OEP/HEV-78-1, Federal Highway Administration, Washington, DC, July 1978.

3. Lee, C.S.Y. and G.G. Fleming, *Measurement of Highway Related Noise*, Report No. FHWA-PD-96-046, U.S. Department of Transportation, Volpe National Transportation Center, Cambridge, MA, May 1996.

4. International Organization for Standardization, *Method for Measuring the Influence of Road Surfaces on Traffic Noise: “Statistical Pass-By Method*,” Draft Standard ISO/CD 11819-1, Delft, Netherlands: ISO/TC 43/SC 1/ WG 33 N 62, November 1994.

5. Society of Automotive Engineers, *Exterior Sound Level for Heavy Trucks and Buses—SAE J366 FEB87*, approved July 1969, revised November 1984, reaffirmed February 1987.

6. Transportation Research Board, National Cooperative Highway Research Program, *Relationship Between Pavement Surface Texture and Highway Traffic Noise: A Synthesis of Highway Practices*, Synthesis 268, 1998.

7. U.S. Department of Transportation, Federal Highway Administration, *Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model*, *Version 1.0*, FHWA-PD-96-008, DOT-VNTSC-FHWA-96-2, November 1995.

8. American Society for Testing and Materials, A Terminology Related to Traveled Surface Characteristics, Designation: E 867-97,@ in Annual Book of ASTM Standards, vol. 04.03 (Philadelphia, PA: ASTM, 2000).

9. American Society for Testing and Materials, A Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire, Designation E 274-97,@ in Annual Book of ASTM Standards, vol. 04.03 (Philadelphia, PA: ASTM, 2000).

10. American Society for Testing and Materials, A Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique, Designation: E 965-96,@ in Annual Book of ASTM Standards, vol. 04.03 (Philadelphia, PA: ASTM, 2000).

11. B. T. Kulakowski, D. W. Harwood, D. R. Hiltunen, J. M. Mason, W. E. Meyer, S. L. Simoneau, and J. C. Wambold, Skid Resistance Manual, Report No. FHWA-IP-90-013 (Washington, DC: Federal Highway Administration, 1990).