# Measurements of the vertical distribution of truck noise sources during highway cruise pass-bys using acoustic beam-forming

Paul R. Donavan, ScD. (Corresponding author)
Sr. Scientist
Illingworth & Rodkin, Inc
505 Petaluma Boulevard South
Petaluma, CA 94952
1-707-766-7700
1-707-766-7790 (fax)
pdonavan@illingworthrodkin.com

Bruce Rymer, M Eng., P.E. (CA)
Sr. Engineer
California Department of Transportation
Division of Environmental Analysis
1120 N Street
Sacramento, CA 95814
916-653-6073
916-653-5927 (fax)
Bruce_rymer@dot.ca.gov

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## ABSTRACT

A measurement program was completed to determine the vertical distribution of heavy truck noise sources for pass-by events on an in-service highway for vehicle operating under cruise conditions. In addition to heavy trucks, some data was obtained for medium trucks and light duty vehicles. The measurements were performed using acoustic beam-forming which provided visualization of the sound radiation of passing vehicles as well as means for calculating the vertical distribution of noise source level. The data set includes pass-by events for 125 heavy trucks, 30 medium trucks, and 9 light vehicles operating at nominally 55 mph on two asphalt surfaces. The purposes of the research were to compare the source height splits assumed in the Federal Highway Administration (FHWA) Traffic Noise Model® (TNM)® to the results of this work, examine the acoustic benefit of sound walls designed to block line-of-site of truck exhaust outlets, and to generally obtain a better understanding of truck noise sources. For heavy trucks, the pass-by noise is dominated by tire noise produced by the drive axles with other secondary sources related to the powertrain occurring in some cases. Noise from elevated exhaust outlets was not observed except in one or two special cases. For all vehicle types, ground level sources (tire noise) produced the highest levels. Further, the vertical source distributions were found to be virtually identical for heavy and medium trucks. For truck and light vehicles, it appears that the current source height splits assumed in TNM may be biased toward higher upper source strength.

## INTRODUCTION

At highway speeds, the pass-by noise level produced by heavy trucks is about 10 dB greater than that of light vehicles[1]. As a result, each heavy truck in the traffic flow contributes the same amount to Leq values as 10 light vehicles. Because of their contribution, a thorough understanding of the trucks as a noise source is crucial to the prediction and mitigation of traffic noise. Of particular concern is the vertical distribution of noise sources and the contribution of tire-pavement noise to the overall pass-by levels. The vertical distribution is critical in regard to the traffic noise modeling, especially the prediction of sound propagation and the noise abatement performance of sound walls. Vertical source distribution is also important because in some states, including California, highway sound walls are often designed so that line-of-sight to the top of the exhaust stack is obscured under the assumption that exhaust noise is a major source. In regard to tire-pavement noise, there is currently a great deal of interest in abating traffic using quieter pavements rather than more expensive sound walls. In order to understand the potential for abating truck noise with quieter pavement, it is necessary to know the typical contribution of tire/pavement noise relative to other sources such as powertrain and exhaust noise. In isolation, it has been found that truck tires can produce tire noise source levels up to 10 dB greater than typical passenger car tires[2]. This research also found that the effect of quieter pavement on the louder truck tires may be somewhat diminished relative to passenger car tires. Taking this further, it has been demonstrated that tire noise could account for a substantial portion of the 10 dB difference between cars and trucks and that expected reductions in level with pavement depends on the mix of tires used on any specific truck[3]. Given this ambiguity and concerns for noise modeling, the need for in-service determination of truck noise source distributions was identified.

In order to investigate truck noise distributions, acoustic beam-forming was selected as the appropriate technology. Prior to applying this technology to actual in-service truck noise mapping, measurements were made under controlled test track conditions. These measurements were made at, and with the cooperation of, International Truck and Engine in Fort Wayne, IN, using a variety of new production trucks[4]. With the successful completion of the preliminary testing, the beam-forming array was deployed adjacent to an active highway in California. The array was used to capture individual time histories of actual truck pass-bys in a fashion similar to conventional statistical pass-bys (SPB)[5]. The remainder of this paper discusses the methodology and results of these measurements.

## MEASUREMENT PROGRAM

### *Test Description*

Measurements were performed at two locations on Lakeville Highway in Sonoma County, California during the weeks of April 16 and 23, 2007. This portion of highway experiences an unusually high volume of heavy truck traffic for a rural, two-lane roadway with about 1 to 2 truck pass-by events per minute during the daytime hours. The individual sites were selected to conform to the requirements of FHWA pass-by measurement protocol[6]. From on-board sound intensity (OBSI) measurements, the two different asphalt pavements at each site were found to provide a range in tire-pavement noise performance of about 2 dB for ATSM Standard Reference

Test Tire[7]. The posted speed limit at both sites was 88 km/hr (55 mph). The test sites were selected to avoid grades in the direction of travel for the vehicles and were generally flat.

Photographs of the test set-up are provided in Figure 1 for the two test sites. The beam-forming array was comprised of 90 microphones arranged in a modified spiral pattern contained

**FIGURE 1: Measurement sites and instrumentation setups at the Veolia site (left) and the Rockin H site (right)**

in 2.4m (7.9 ft) diameter circle[4]. The array was positioned 7.5 m (25 ft) from the center of the near lane of vehicle travel and only vehicles in this lane were measured. The vehicles were tracked in the vicinity of the array using three pairs of photocell emitters and receivers. The first pair was used to provide a start point for data acquisition and analysis. The second, offset slightly from the center of the array microphone, provided the location of the front bumper relative to the array. The final pair was used in conjunction with the center pair to confirm vehicle speed and signal the end of the event. Speed was measured independently using a radar gun positioned "upstream' of the array so that the speed could be determined as the vehicle passed the array with minimal angular distortion. Target vehicles were selected to obtain a clean pass-by in front of the array, with no opposing vehicle in the adjacent lane. A still photograph of each vehicle was taken in order to later relate the vehicle geometry to the sound distribution "map". The entire test session was recorded with a video camera for later reference as required. In addition to array measurements, conventional SPB levels were acquired at distances of 7.5m (25 ft) and 15m (50 ft) from the centerline of the lane of vehicle travel. Individual pass-by data sets were only considered complete when all photographic, SPB, array signals, and radar speed were acquired. The vast majority of the heavy trucks had vertical mufflers and high exhaust outlets and a fairly even distribution of single and dual muffler configurations were noted. At each site, limited numbers of pass-bys of other vehicles including medium duty trucks, light vehicles, motor homes, buses, and motorcycles were acquired as they occurred and did not interfere with heavy truck measurements.

Prior to testing, initial site/array spatial calibration measurements were performed at each site. For this purpose a compact loudspeaker source (200 x 200 cm [4 x 4 in.]) was positioned 0.9m (3 ft) above the pavement centered on the array. The loudspeaker emitted pink noise and the resultant signals were captured by the array. The loudspeaker was then moved 1.8m (6 ft) to the right of center of the array (downstream direction) and the data acquired again. These data were then used to confirm the performance of the array as a function of frequency, scale the x-y coordinates of the measurement plane, and to assess reflected sound.

## *Data Analysis*

Given the task of analyzing the array data for the large number of pass-bys acquired, it was decided to determine if the commercially available software[8] would produce results comparable to the enhanced custom-coded beam-forming software developed specifically for the project[4]. The advantage of the "off-the-shelf" software was its ability to readily handle large amounts of data and to produce levels on a ⅓ octave band and an overall A-weighted level basis. The disadvantage is that the commercial processing software provides no source tracking or Doppler correction because it was developed for stationary noise sources.

The initial comparison of the two beam-forming processing codes was to evaluate the case with the loudspeaker positioned above the roadway. These results are presented in Figure 2 for the 1000 Hz ⅓ octave band using the commerce software. These compared quite favorably to

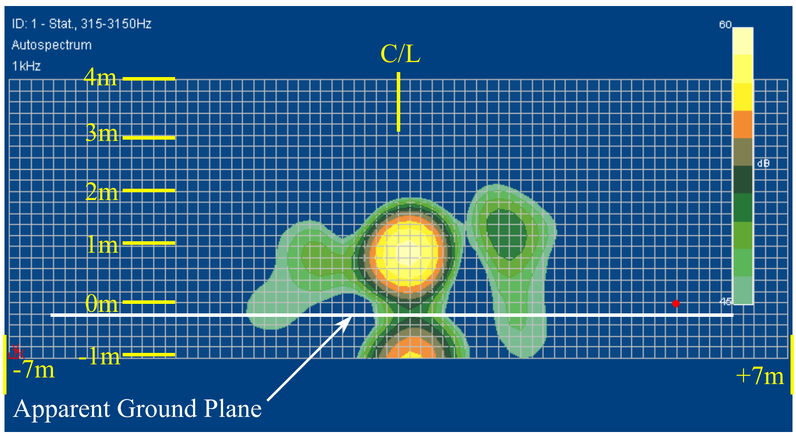


**FIGURE 2: Image of loudspeaker noise source used for site/array geometry calibration for the 1000 Hz one-third octave band**

those obtained with the enhanced code[4]. After some iteration, a measurement plane was selected with a horizontal dimension of ± 7 m (23 ft) centered on the array and vertical dimensions of –1 m (3.3 ft) to +4 m (13 ft) relative to the apparent ground plane. The measurement plane was fixed at a distance of 6m from the plane of array approximating the distance to the outside wheel path. A grid size of 0.2m (0.6 ft) was selected as an optimal choice as a finer grid size did not produce "sharper" images given the array configuration and distance from the measurement plane. As indicated in Figure 2, this produced a "spot" on the order of 1m in diameter which is comparable to that found with the enhanced code[4]. The results also indicate a reflection of the noise emitted from the loudspeaker of slightly lower amplitude. This reflection was used to define the effective ground plane relative the vertical elevation indicated by the array.

To quantify the source height distribution, the contour plots such as that for the loudspeaker (Figure 2) were translated into a two dimensional array of sound pressure levels corresponding to the beam-forming measurement plane. The columns of the array contained the levels from –1 to +4 m (-3.3 to +13 ft) at every 0.2 m (0.6 ft) while the rows contained the levels at each 0.2 m (0.6 ft) increment from –7 to +7 m (-23 to + 23 ft). The levels were converted to mean square pressures and summed across each row. The resultant column of values was then converted back into decibel levels to produce plots of sound level versus height. The resultant source height profiles for the loudspeaker calibration test are shown in Figure 3 for ⅓ octave bands from 315 to 3150 Hz. For the higher frequencies, the source and its reflection are localized with a sharper

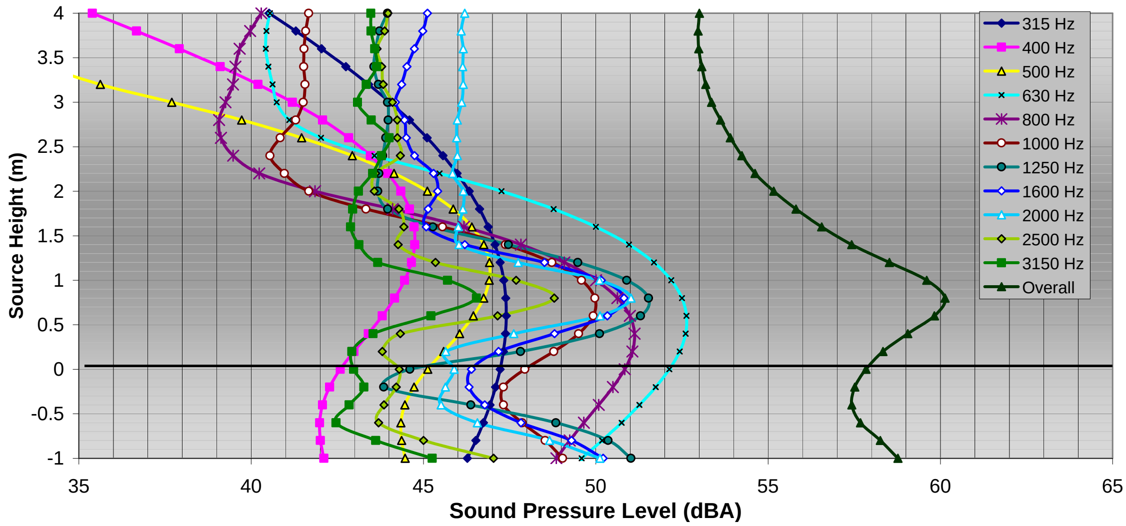


**FIGURE 3: Source height profiles for loudspeaker noise source used for site/array geometry calibration**

resolution than the 1000 Hz image of Figure 2. However, as the frequencies increase, the ability of the array to distinguish the source above the background diminishes due to the spacing of the microphones such that at 3150 Hz, the loudspeaker is only about 3½ dB above the residual level indicated where there is no source (i.e. heights greater than 1.5 m). For lower frequencies, the ability to localize the loudspeaker also diminishes due to the longer acoustic wavelength at these frequencies and the limited extent of the array size. At the lowest frequency, 315 Hz, the spot is seen to merge with its reflection creating a large apparent source region commensurate with the longer acoustic wavelength. Based on these results, localization is expected to be adequate over a range of 400 to 2500 Hz.

For application to pass-by events, further consideration of data processing is needed. The commercial software does not track the vehicle as it passes in front of the array and as result, "snap-shot" images are used to examine noise source distributions. For the purpose of this analysis, a 0.2 second window centered on the time of maximum overall A-weighted sound pressure level was used. As a result, some blurring of the acoustic image occurs in the direction of travel. At 88 km/hr (55 mph), this time equates to about 5m (16 ft) of vehicle travel. As a result, it is not possible to resolve the horizontal source location to the degree possible with the enhanced software. However, for the purposes of determining the vertical distribution of noise sources, the possibility of "smearing" the sources horizontally is not an issue in calculating the source profile. For each valid pass-by, both the contour plots and source height profiles were produced for each ⅓ octave band between 315 and 3150 Hz as well as for the overall A-weighted level.

For source visualization using the color contour plots, the photograph of the vehicle was scaled appropriately using the length indicated by the photocells and identifiable dimensions on the vehicles themselves. The photograph was positioned on the contour plot using the measured speed of the vehicle and time relative to first blip of the photocell positioned next to the array. It should be noted that the correspondence of color contours to the sound pressure level scale is variable from plot to plot with the level of the highest (yellow) color noted next the to color bar (see Figure 2). Further, the number of colors is limited to 10, however, the range of the scale is 15 dB

## RESULTS AND DISCUSSION

### *Profiles and Indicated Noise Sources for Heavy Trucks*

Upon review of the contour plots for the 125 truck pass-by events, it was found that the vertical distribution of sources was quite similar across all the trucks measured. A typical example of these is shown in Figure 4 for the 400, 800, and 1600 Hz bands and the overall A-weighted level. As would be expected from the loudspeaker tests, the localization of noise

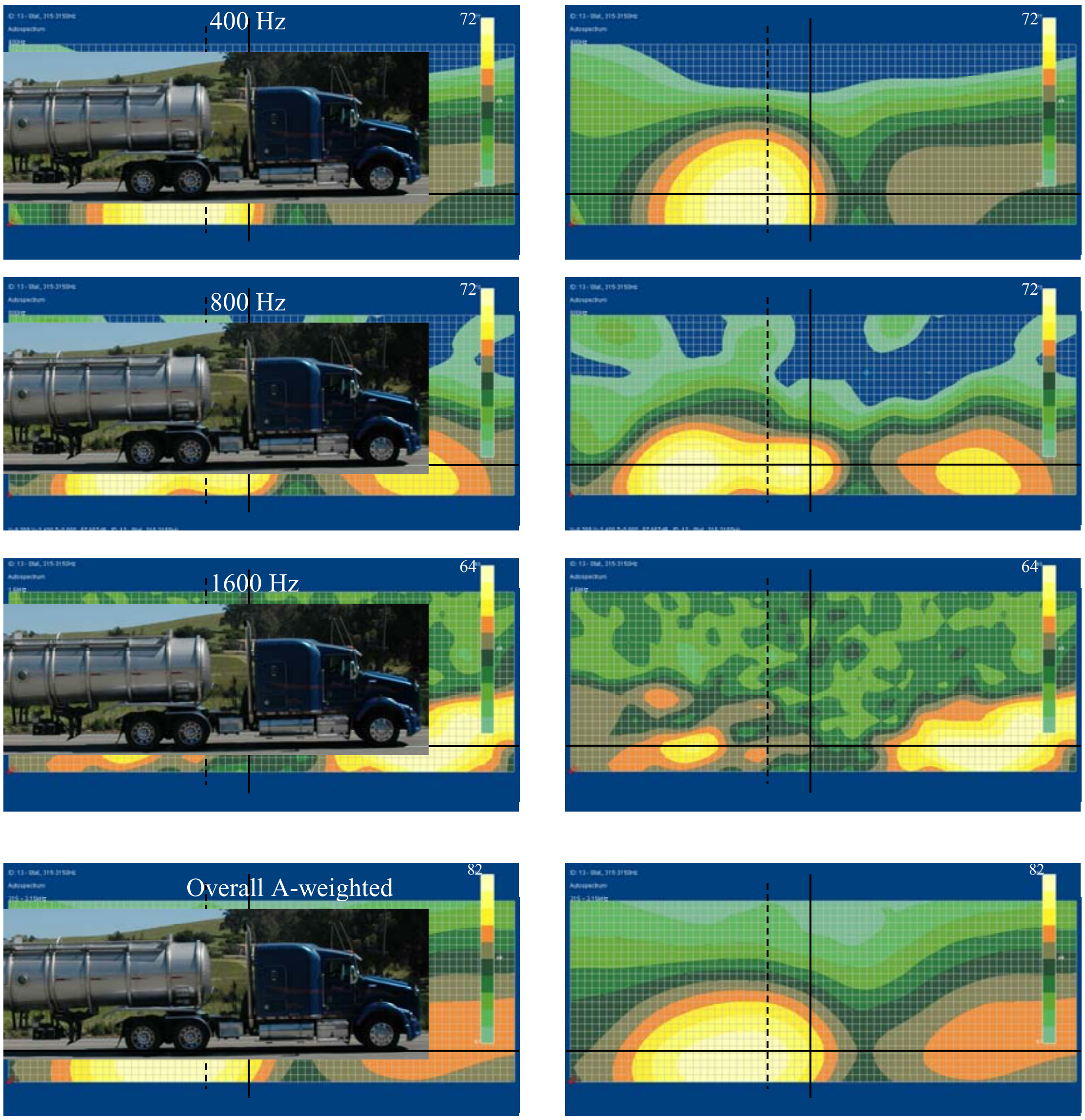


**FIGURE 4: Distribution of sound levels for typical truck passby - truck image superimposed on the left, without image on the right**

source region improves with increasing frequency. At 400 Hz, the source region is quite large and is split fairly symmetrically by the ground plane. The region is centered horizontally on the drive axles of the truck suggesting tire/pavement noise as the dominant source in this case. At 800 Hz, the source region at the drive axles is more concentrated at lower heights and a secondary sources are indicated at the front of the tractor and slightly ahead of the drive axle tires. The source region at the front of the truck is also split by ground plane indicating the possibility of noise from the steer axle tires and/or engine noise reflected from the pavement. The secondary source region in between the axles, corresponds to the muffler located at the base of the exhaust stack. At 1600 Hz, the level of color scale is reduced from a maximum of 72 dB to 64 dB. At this lower level more "ghost" images appear due, in part, to the performance of the array. At this frequency, a source region at the drive axles is still apparent; however the region at the front of the vehicle now dominates the visualization. Although tire noise may still be a factor for this source region, the forward most portion of the region is ahead of the vehicle and slightly elevated. This behavior is typical of most cases and it is speculated that it is due to engine noise (possibly, cooling fan noise) being radiated through the grille opening and adding to that produced by the front tires. Considering the overall A-weighted level plot of Figure 4, the primary source region is in the vicinity of the truck drive axles and almost certainly due to tire noise. A secondary region about 3 dB lower in level is indicated at the front of the vehicle that may be due to a combination of tire and engine noise.

The source height profiles corresponding to contours of Figure 4 are shown in Figure 5 for each ⅓ octave band between 315 and 3150 Hz. At the lower frequencies (315 and 400 Hz), the maximum deviation with height is on the order of 6 to 9 dB. In the middle frequencies, the

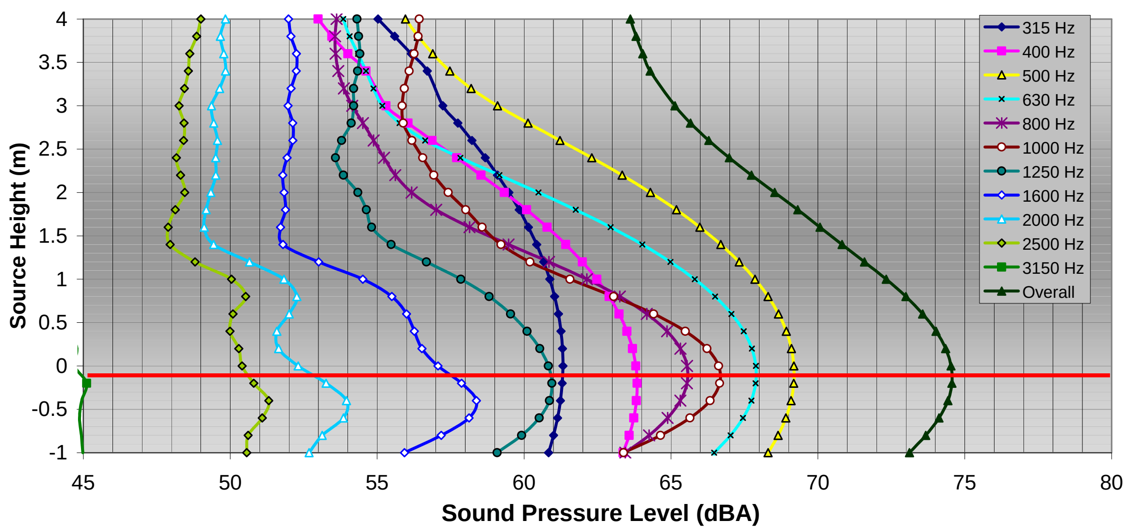


**FIGURE 5: Source height distribution for one-third octave band and overall levels – truck from Figure 4**

maximum deviation increases to about 10 to 13 dB. In the higher frequencies of 2000 Hz and above, the distributions once again flatten due to the side lobes of the beam producing ghost images essentially creating a lower signal-to-noise ratio. In the 2000 and 2500 Hz bands, a bump in the profile is apparent at a height of about 0.8 m. Given the height of this apparent source along the observations of Figure 4 at 1600 Hz, it is suspected that this source region is due engine noise escaping from the front wheelwell area and/or the front of the engine compartment. However, the levels for this source are quite low (more than 20 dB down) relative to the overall level at the same height.

To identify and evaluate unusual cases, the overall A-weighted source height profiles were plotted and reviewed for all of the pass-by events. To facilitate comparison of the profile shapes, the levels as a function of height were normalized such that maximum level in the profile was 80 dB. These profiles typically indicate some level variation (4 to 5 dB) for the higher source heights, however, the levels are 7 to 12 dB lower than those at ground level where the maximum levels occur. Atypical events can be readily identified in the set of profiles as illustrated in Figure 6. For this group, two trucks exhibit higher than usual levels at the upper source heights.

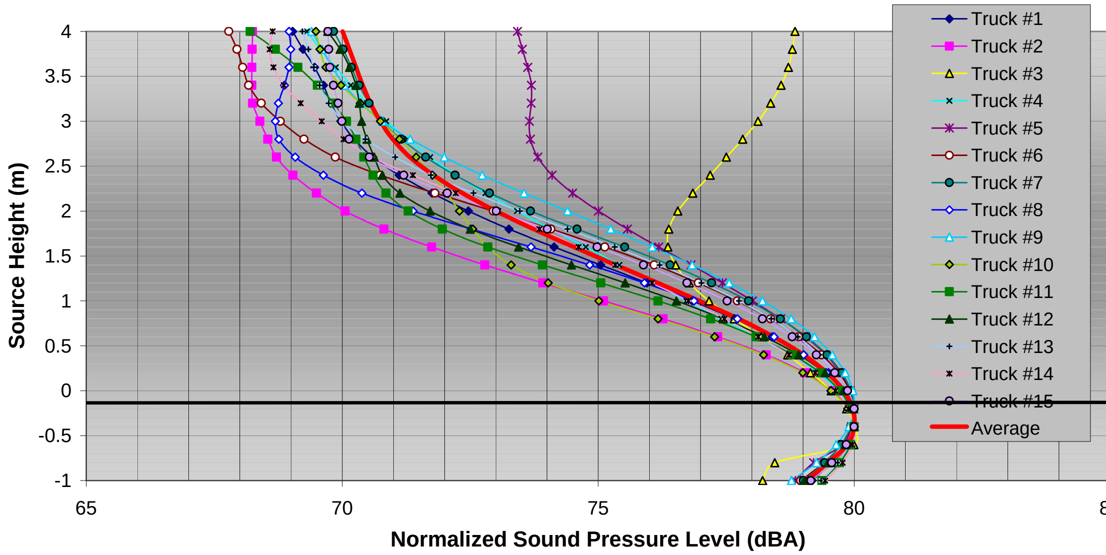


**FIGURE 6: Source height profiles for a set of heavy trucks including two atypical examples with high levels at higher source heights**

Examining the profiles of the truck identified as "Truck #3", a source of almost equal energy to that of drive axle tire noise is indicated near 4 m (13 ft) The contour plots for this truck confirm the presence of a source region approximately at the exhaust outlet 3.5 to 4 m (11.5 to 13 ft) above the ground plane (Figure 7).

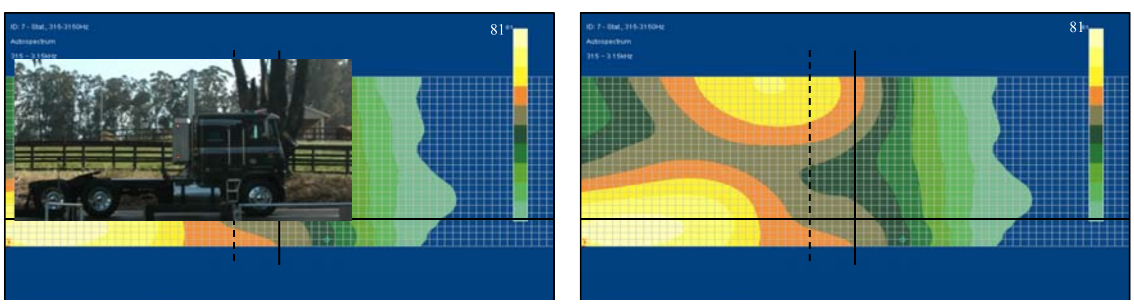

**FIGURE 7: Distribution of sound levels for a truck with an atypical exhaust outlet source in overall A-weighted level - truck image superimposed on the left, without image on the right**

To summarize the results of the heavy truck data, several general observations can be made. Based on examination of the contour plots as confirmed by the source height profiles, the dominant contributor to cruise pass-by levels is tire/pavement noise from the drive axle tires. Base on level and frequency of the occurrence, the next most important source is toward the front of the truck and located at near the ground plane. This source appears to be associated with tire/pavement noise from the steer axle tires and engine noise escaping from the engine compartment. The engine noise portion appears to be more of factor at higher frequency. In some cases, source regions that can be associated with the muffler are also indicated. In a few of the trucks, contributions from elevated exhaust stack outlets are indicated, however, this occurs at a low rate of 2 or 3 out of 125 pass-by events.

### *Average Profiles and Mean Source Heights*

To examine vehicle source heights across the entire data base, averages over the individual profiles for each vehicle category were made. This was done both on numerical and energy basis. Comparing these two methods, little difference was seen in the resultant profiles and as a result, only the numerical average results are presented to facilitate calculation of standard deviations about the averages. The overall A-weighted and ⅓ octave band average profiles for heavy and medium trucks are presented in Figures 8 and 9, respectively. Comparing these two

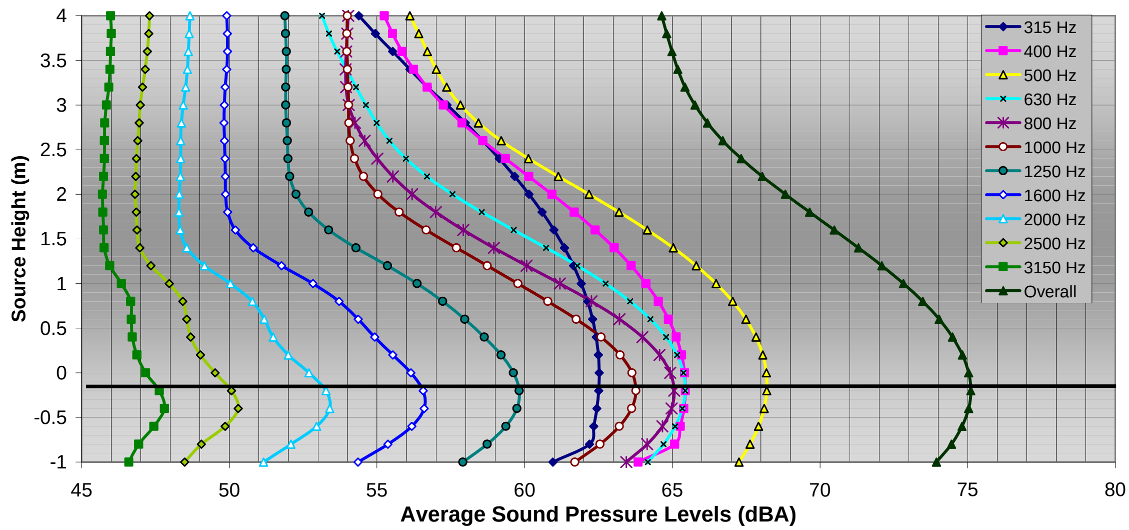


**FIGURE 8: Source height distribution for one-third octave band and overall levels averaged for all heavy trucks**

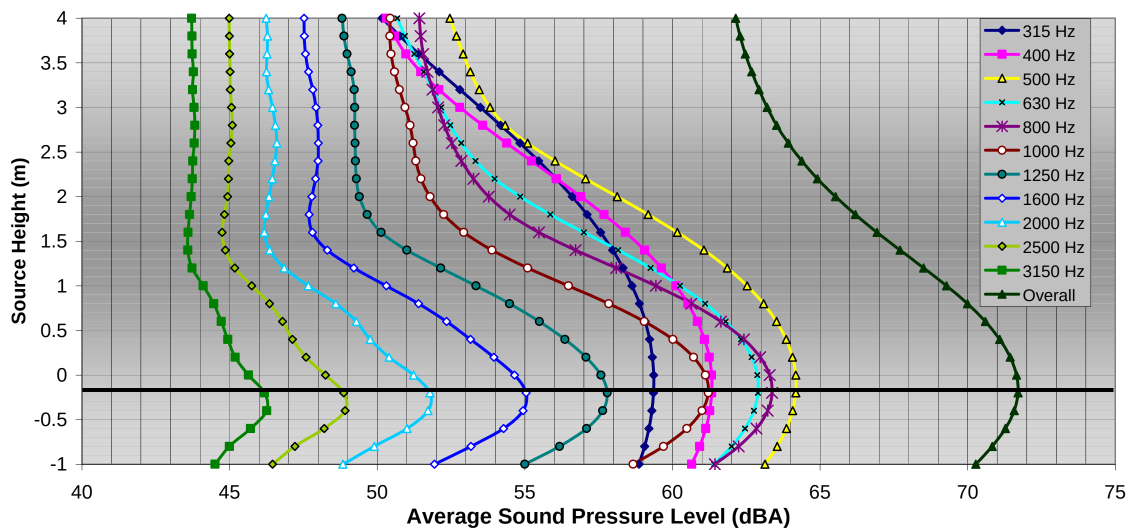


**FIGURE 9: Source height distribution for one-third octave band and overall levels averaged for all medium trucks**

sets of profiles, it is seen that they are quite similar in terms of shape and frequency content. The levels for the medium trucks are consistently lower than the heavy trucks by slightly more than 3 dB on average. However, the trends between the two truck categories are consistent. In both cases, the 500 Hz ⅓ octave band is the largest contributor to the overall A-weighted level. For all frequencies for both categories, the maximum levels occur at or very near the ground and fall-off of level with height is similar. The source height profiles for the nine light vehicles measured in the study are distinctly different than those of the trucks (Figure 10). For the light vehicles,

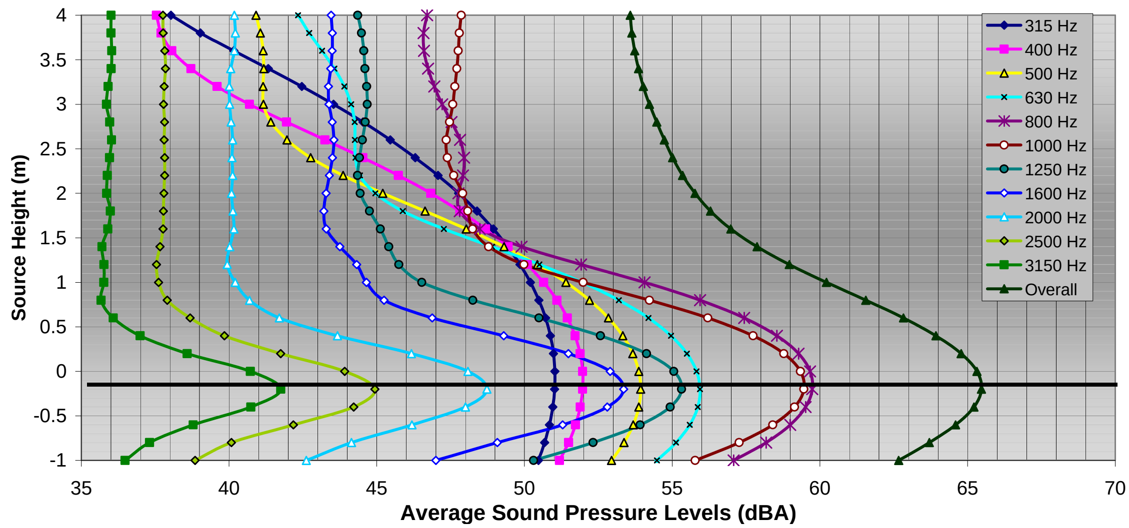


**FIGURE 10: Source height distribution for one-third octave band and overall levels averaged for all light vehicles**

highest concentration of energy is at ground level for each frequency as well as the overall level. Comparing the profiles of the light vehicles to those of the loudspeaker, it can be concluded that light vehicle profiles are virtually equivalent to a single source located at ground level. This result, along with a review of the contour images, indicates that tire/pavement noise accounts for nearly all of the contribution to pass-by noise under cruise conditions throughout the entire frequency range.

The profiles of overall A-weighted level for light vehicles, medium trucks, and heavy trucks are presented in Figure 11. Consistent with the REMELS data-base[1], the maximum levels for the light vehicle profile are about 10 dB lower than heavy trucks and about 6 dB lower than medium trucks. These average profiles can also be used to determine mean energy source height for each vehicle category. This was accomplished by summing the product of the mean square pressure and source height for each height and dividing it by the sum of mean square pressure for all source heights. In performing this summation, the reflected sound up to 1m below the roadway surface was included as part of the source distribution. Given that the source plane was virtually alongside of the vehicle, it was deemed that this energy should be considered as part of the noise source as it also propagates away from the vehicle and contributes to wayside levels. As would be expected from Figure 10, the 0.30 m (1 ft) mean height for light vehicles is a little more than half of that for the trucks with the heights of 0.53 and 0.48 m (1.7 and 1.6 ft) for medium and heavy trucks, respectively. The standard deviation of the average mean height for the medium trucks at 0.21 is somewhat larger than those for the light vehicles (0.09) and heavy trucks (0.12). Although the sample size was considerably smaller than that of the heavy trucks, it was also observed the range of profile behavior was more pronounced than for the other two

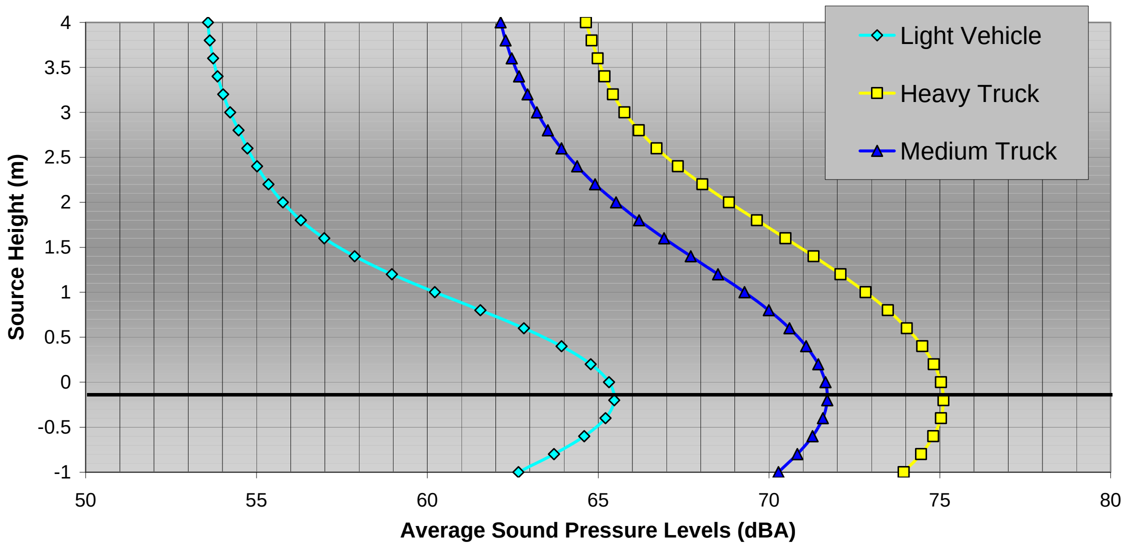


**FIGURE 11: Overall A-weighted Source height distributions for the average light vehicle, medium trucks and heavy trucks**

categories. For medium trucks, two sub categories became apparent, individual vehicles that produced profiles similar to heavy trucks and those that produced profiles similar to the light vehicles. As a result, it is possible that including more pass-by events may not improve the standard deviation.

The mean source heights determined in this research are slightly lower than those reported from previous studies completed in the US. In the mid 1990's, Florida Atlantic University performed a large number of vehicle noise source vertical distributions tests on active roadways using an eight element linear array[9]. With this system, source height was calculated using ground plane reflection/interference effects. For heavy trucks operating at in the highway speed range, average source heights from 500 to 3150 Hz ranged from about 0.7 to 1 m (2.3 to 3.3 ft) depending on frequency compared to the 0.48 m (1.6 ft) indicated in the current research. For medium trucks, the source heights range from about 0.6 to 1 m (2 to 3.3 ft) for frequency bands from 400 to 5000 Hz compared to 0.53 m (1.7 ft). For light vehicles, source heights were from 0.5 to 1 m (1.6 to 3.3 ft) for 315 to 5000 Hz. Similar to the current study, source height decreased with increasing frequency, at least up to 2000 Hz.

In the current version of the FHWA Traffic Noise Model, TNM 2.5, vertical source distribution for different vehicle categories are specified using "subsource-height splits"[10]. Under this approach a ratio is defined partitioning the source strength between an upper and lower source height location. For light vehicles, these heights are ground level and 1.5 m (4.9 ft). Below 800 Hz, 27% of the source strength is attributed upper height, while at 2000 Hz and above, the upper source strength is 2%. For medium trucks, the source height location also remain at 0 and 1.5 m (4.9 ft) and about 36% of the source strength is attributed to the upper position in the lower frequencies and 6% in the higher frequencies. For heavy trucks, the source height are 0 and 3.6 m (11.8 ft) and 57% of the source strength is attributed to the upper location in the lower frequencies and 46% in the higher frequencies. In TNM, these splits are further modified by calculations to account for sound propagation over acoustically soft ground at a distance of 15 m (50 ft) from the roadway to hard ground 7.5 m (25 ft) from the roadway. As a result, direct comparison of the effective source heights (i.e. modified by the propagation factors) in TNM to the current research is problematic. However, several differences can be noted. In the current work, the profiles for heavy and medium duty trucks are virtually identical unlike the model assumptions. Also, except for a very small number of exceptions, no source strength is indicated at heights of 3.6 m (11.8 ft) for heavy trucks.

## CONCLUSIONS

Bearing in mind the rather limited number of light vehicles and medium trucks included in this study, the following observations are made. For the light vehicle, medium truck, and heavy truck categories, the highest noise source levels generated are at and very close to the pavement surface for pass-by events in the speed range of 80 to 100 km/hr (50 to 62 mph). The source profiles for medium and heavy trucks are nearly identical once the 3 to 4 dB offset between the categories is taken into account. The truck profiles do not fall-off with height as rapidly as do the light vehicles indicating that sources beyond tire noise alone need to be included in characterizing the vertical distribution of sources. For heavy trucks, at 3.6 m (12 ft) approximately corresponding to exhaust stack height for most trucks, there is no indication of significant source regions compared to the stronger sources apparent at ground level. Out of 125 pass-by events, only one truck indicated appreciable overall noise being generated near a height of the 3.6 m (11.8 ft). This is consistent with the original subsource-height splits noted in the REMEL data-base, which reported only 2.6% to 5.4% of the energy (depending on frequency) being at 3.6 m (11.8 ft) for heavy trucks under cruise conditions[1].

In regard to vehicle noise emissions for purposes of noise modeling, the beam-forming technique appears to be a viable and well suited technique to determine vertical source distribution and to provide additional information on the nature of the noise sources. A significant advantage of this approach is determining source strength in a plane alongside the vehicle, thus conceptually negating the need to translate or "back propagate" data taken at 7.5 or 15 m (25 or 50 ft) distant from the vehicle as is done currently. Although the results of this work provide considerable insight about vehicle noise sources and vertical source distributions, more data for light vehicles and medium trucks are needed. Further, data for all vehicles types should be collected on a wider variety of pavements before generalizing the results of this research.

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