

Localization of Truck Noise Sources under Passby Conditions Using Acoustic Beamforming Methods

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ABSTRACT

Acoustic beamforming was used to visualize the sound radiation of trucks under test track passby and actual highway operating conditions. The purpose of these measurements was to obtain an understanding of which sources contribute to the overall passby noise level and to determine the vertical distribution of noise sources. For trucks, drive axle tires were found to be the major contributor to passby noise at highway speeds, followed by powertrain noise to a much less degree, and very occasionally, exhaust stack outlet noise. For medium and heavy trucks, the acoustic mean source height was found to be about 0.5m and about 0.3m for light vehicles.

INTRODUCTION

Current vehicle passby test procedures for regulatory compliance address only low speed operating conditions¹. Although these regulated levels may address city street operating modes, they do not address noise at highway operating conditions. In the United States, requirements for noise abatement almost exclusively deal with highway noise and the exposure of adjacent residences. As a result of the vehicle level

regulations, the source contributions at low speeds are routinely investigated and abated as necessary. On the other hand, source contributions under higher speed operating conditions are not well understood and result in the construction of expensive sound walls along highways. For light vehicles under cruise conditions, tire/pavement noise is generally known to be the major contributor to noise emission at speeds of 30 km/h and above². For medium and heavy trucks, tire/pavement noise does not dominate the noise emission until higher speeds (70 to 80 km/h) are reached. Even at these speeds, other truck sources such as powertrain and exhaust noise may still be significant contributors. To understand the effectiveness of highway noise abatement in the forms of sound walls and/or quieter pavement, it is necessary to first understand the source contributions and their vertical distribution. This is even more important when it is realized that the passby noise level produced by heavy trucks at highway speeds is about 10 dB greater than that of light vehicles³. As a result, each heavy truck in the traffic flow contributes the same amount to Leq values as 10 light vehicles.

Abatement of noise emission from trucks is also problematic for other reasons. For trucks, the reductions in wayside level are typically smaller than tire/pavement noise reductions measured at the source by either close

proximity (CPX) or on-board sound intensity (OBSI) procedures based on passenger car tires^{4,5}. This disparity is often attributed to a difference in noise source contribution between cars and trucks, however, it has also been found that the disparity may be at least partially due to the nature of truck tires relative to passenger car tires⁶. In addition, the vertical source distribution is also important as four states require that highway sound walls be 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. To address both of these issues, tire/pavement and exhaust outlet noise, the research reported in this paper was conducted.

To identify and localize noise source distributions under passby conditions, beamforming technology was employed. To demonstrate this technology and gain familiarity with it, as a first phase of this research, measurements were made under controlled test track conditions at and with the cooperation of International Truck and Engine in Fort Wayne, IN, using a variety of new production trucks⁶. With the success of this phase and other applications reported in the literature^{7,8}, the second phase of the research was to use beamforming to capture the source distribution of actual truck passbys adjacent to an active highway in California.

MEASUREMENT METHODS

For both the test track and highway measurements, a commercially available ninety element beamforming array from Brüel & Kjaer (B&K) was used to acquire the passby sound pressures. The array consisted of ninety microphones arranged in 15 arms of 6 elements forming a circular area 2.4 m in diameter (Figure 1). The signals were acquired with a B&K Pulse Platform front-end and stored for processing. The processing for both the test



Figure 1: Ninety element acoustic beamforming array installed at the ITE test track

track and highway measurements was done with two different methods. The first method was based on the inversion of the cross spectral density matrix done in MatLab⁹. This code featured the ability to steer the array and track the vehicle as it passed the array and applied correction for Doppler shifting. The images produced

could also be further enhanced using the Deconvolution Approach to the Mapping of Acoustic Sources (DAMAS) methodology¹⁰. Although this approach provided very detailed information for individual vehicle passbys, it was somewhat cumbersome to apply to the 150+ passby events to be analyzed. To remedy this, B&K's conventional beamforming analysis software was also used. At the time, this software could only provide "snapshots" in time of noise source images as the vehicle passed without any Doppler shift correction or vehicle tracking. However, for the bulk of the processing, this did not appear to be much of a limitation as the primary interest in the analysis was evaluating the image at the time of maximum noise level. This typically occurs when the vehicle is directly opposite the array for cruise-by conditions.

COMPARISON OF ANALYSIS METHODS – As a first comparison of the two approaches of processing the array data into beamforming images, the case of a static loudspeaker was considered. In Figure 2, the array was used to capture data for a 100 by 100 mm (4 by 4 in.) loudspeaker placed 0.9 m (3 ft) above the pavement at two of the highway measurement sites. Results from B&K software in the 1000 Hz third octave band and those from custom software at 1090 Hz both indicate a dynamic range of the image is about 15 dB. The size of

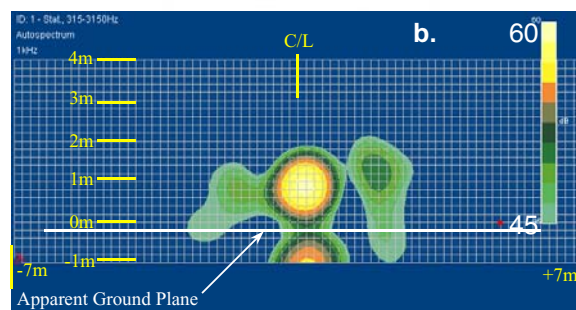
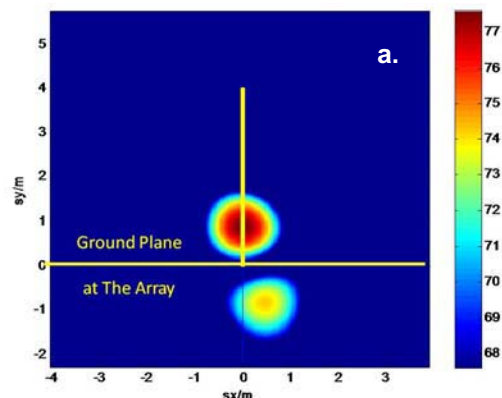


Figure 2: Acoustic image of a compact loudspeaker source 0.9 m above the pavement using MatLab based custom software (a.) and B&K software (b.)

the source "spot" is about the same although the custom software eliminates some of the lower amplitude "ghosts" present in the B&K results. These data were not acquired at the same site and as a result the slight

skew ness of the reflection for custom software is likely due to a small misalignment of the array.

Good agreement between the two analysis methods was also verified on actual passby testing at the ITE test track. In Figure 3, the results for both methods are presented for an 80 km/h (50 mph) passby under cruise

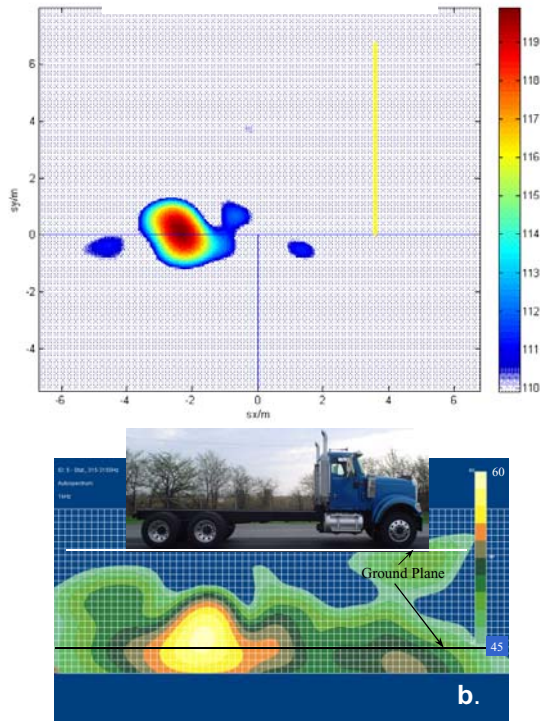


Figure 3: Acoustic images at 1000 Hz for 80 km/h cruise using MatLab based custom software (a.) and B&K software (b.)

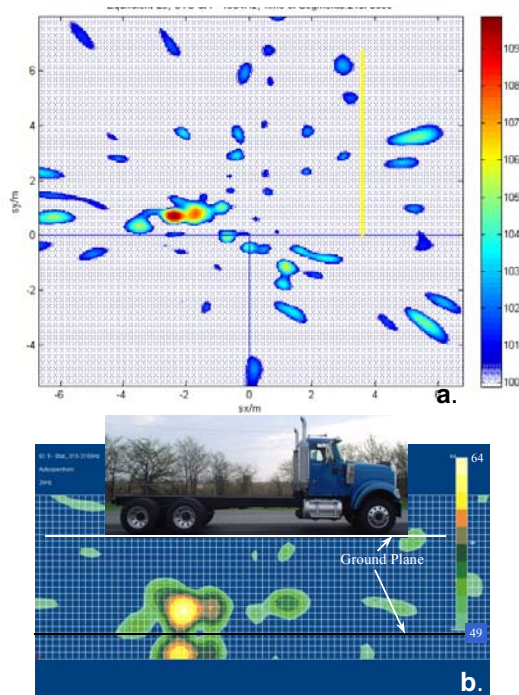


Figure 4: Acoustic images at 2000 Hz for 80 km/h cruise using MatLab based custom software (a.) and B&K software (b.)

conditions for the 1000 Hz one-third octave band (B&K) and at 960 Hz (custom). These data both indicate the major source region is at the drive axle tires essentially on the ground plane implying tire/pavement noise as the source. Both also indicate some low level acoustic energy more forward on truck and reflected by the pavement surface. This implies some small amount of reflected engine noise contributes to the source level. Also, both indicate a lower level source slightly ahead of the drive axle tires up in the vicinity of the frame rails near what appears to be a universal joint in the drive shaft. At higher frequencies (~ 2000 Hz) for this same passby, the major contribution is above the ground and centered between the two drive axles (Figure 4). In both, a secondary source is indicated just in front of the primary. The nature of this source it is not known, however, its location implies that it may be related to the drive axle differential. In any case, the localization of the two beamforming approaches indicate the same behavior.

TEST SITES AND DATA ANALYSIS – The configurations used the ITE test track and along Lakeville Highway in Northern California are generally similar to each other. In both cases, the array was located approximately 7.5 m (25 ft) from the centerline of vehicle travel. Vehicles were measured as traveling from left to right in the lane closest to the array. In addition to the array data, conventional sound pressure level passby measurements were made at distances of 7.5 m and 15 m (50 ft). Vehicle position was located within the test sections using a series of photo cells. For the track measurements, the test speeds (56 km/h and 80 km/h) were controlled by the vehicle operator. For the highway tests, the speed of each vehicle was determined using a radar gun. Photographs of each vehicle measured on the highway were taken for later superposition on the acoustic images and to verify vehicle identification. The signals from the two conventional passby microphones at 7.5 and 15 m were also recorded as wave files with a solid state recorder for listening and further processing, if required.

For the highway measurements, the operating conditions were nominally identical for the test sites used in the study. These three sites were located within about at 16 km (10 mi) stretch of two-lane, rural highway. Each site had somewhat different asphalt concrete pavements producing tire/pavement noise source levels spanning a range of 5 dB as measured with a passenger car tire. The test sites were selected to avoid grades in either direction and to produce primarily cruise conditions. The average speed of the trucks measured at each site was essentially 88 km/h (55 mph), which corresponded to the posted speed.

To apply the B&K software, a 0.2 second window centered on the time of maximum overall level was