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# Noise source mapping for trucks, part 1: development and design

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Mapping and quantifying noise sources on trucks under actual operating conditions on the road are important for traffic noise modeling and mitigation. The purpose of this study is to develop a practical truck noise source localization technique using acoustic beam-forming. An experimental 70+ microphone elliptical array was designed and fabricated for truck testing. Beam-forming software was developed and implemented using a computerized data acquisition system. Proof-of-concept tests were performed at low-speed and high-speed truck testing facilities for a representative sample of trucks with widely different characteristics to validate the measurement system performance. The measurement system design parameters were verified experimentally, and certain improvements to the system were recommended for future implementation based on the field experience. The developed beam-forming measurement system provided adequate noise mapping and localization for various noise sources on trucks, stationary and moving with the speed up to 50 mph. The results of the proof-of-concept testing presented in an accompanying paper (Part 2) confirm that the developed microphone array, data acquisition system and beam-forming software performed generally as expected and required no major adjustments. This ongoing project is funded by the National Cooperative Highway Research Program of the Transportation Research Board of the National Academies, USA.

# 1 Introduction

Heavy trucks are significant contributors to overall traffic noise levels. At highway speeds, the noise level produced by heavy trucks is about 10 dB greater than that of light vehicles. As a result, every one truck in the traffic flow contributes the same amount to the average noise level 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. Noise from heavy trucks originates from a variety of sources, which include exhaust stack outlet, muffler shell, exhaust pipes, engine block, air intake, cooling fan, tires, and aerodynamics. The relative contributions of these sources vary with vehicle type, operating condition, and (for tire noise) the type of pavement.

For modeling and abatement of traffic noise, the barrier performance of sound walls depends on the assumed distribution of noise source heights. Since trucks contribute the tallest noise sources, highway noise walls are typically designed so the top of the exhaust stack was obscured from the receiver sight under the assumption that exhaust noise is a major source. The current treatment of truck noise for highway conditions is often simplistic, placing about 50% of the source strength at a height of 3.7 m (12 ft) and the other half at ground level, independent of vehicle speed or pavement type.

A number of recent observations, however, challenge the current treatment of trucks and lead to the need for new research. First, as a result of the federal regulations in the U.S., truck noise levels have been incrementally lowered over the past few decades. In achieving this lower level of noise performance, engine and exhaust noise have been effectively addressed.

From recent studies performed in Europe, a much larger contribution of tire/pavement noise, 63% to 84%, has been found for highway speeds. A few studies have also shown that there is a strong dependence on truck tire type. From research work related to the application of quieter pavements, reductions in traffic noise have been measured consistent with the reduction of tire/pavement source levels when pavement modifications have been made, which goes beyond what would be predicted based on the current 50-50 split of tire/pavement and elevated sources on trucks.

For all these reasons, it is essential to have more information about truck noise sources than what can be observed in typical passby measurements. The objective of this study is to use noise-source mapping techniques to accurately localize, identify, and quantify the noise sources on typical commercial trucks operating in the actual roadway environment. This paper demonstrates a practical technology developed for truck noise source localization and describes the experimental measurements performed during the proof-of-concept truck testing of the technique.

# 2 Noise mapping techniques

Acoustic beam forming is considered the most suitable noise mapping method for this application. It is capable of mapping both vertical and horizontal distributions, and implicitly conveys spectral information about sources under actual operating conditions. Traditional methods such as near field measurements, component wrapping, removal and substitution of components during stationary and moving tests are time- and labor-intensive, performed on a relatively small number of vehicles, and are not applicable in uncontrolled roadside conditions. Substantially higher productivity could be achieved with remote sensing methods, such as acoustic holography or acoustic intensity measurements. However, the microphone array used for acoustic holography must be physically as large as the source region of interest. It is also not suitable for passby applications when the array is stationary and the source is moving. As with traditional methods or sound intensity, this method could not be employed for uncontrolled passby testing.

The more compelling method of localizing sources has been the application of acoustic beam forming, as described in [1]. Beam forming techniques in a horizontal direction have also been employed in French research specifically on truck sources [2]. Acoustic beam forming uses an array of microphones to focus measurement on a specific point on an imaginary source plane near the actual source. This focus point is electronically swept across this plane, and the sound pressure level is determined.

In more advanced approaches, which should be used in the case of moving vehicles, the source plane moves with the vehicle and points are scanned over the time the vehicle goes by. This requires the algorithm to account for both the moving source plane and Doppler shifting of the sound during the passby. In this manner, several slices in time can be evaluated near the position of interest, such as the time when the maximum passby noise level occurs, which improves the accuracy of the resulting beam forming.

Because of the large physical size of the source plane for trucks, spherical beam forming is the only appropriate approach for the current application. It assumes that path lengths for different points on the source plane are different and are accounted for by including spherical divergence.

The algorithm used in this study incorporates a cross-spectral density (CSD) method, which was initially developed for resolving locations of stationary sources in wind tunnels [3]. This method has an advantage over the classical "delay and sum" method, e.g. [1], by providing a better reduction of background contamination over the frequencies of interest. In our case wind noise at microphones could be better reduced by employing a complete two-dimensional CSD matrix for all 70 microphones. The array response is otherwise analogous to that of a parabolic radio antenna for which the main lobe can be computationally directed to the source. The signal processing used here included spherical divergence, source tracking, and Doppler shift correction.

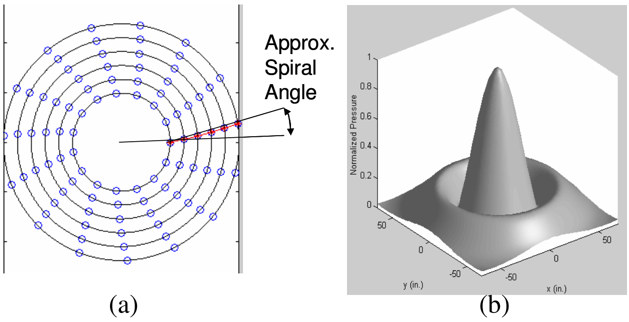
Several issues had to be resolved before the beam forming could be used for the truck application. The first was a spatial resolution of the technique for the frequencies of interest for truck noise. In several successful applications, the revealing "pictures" of sound are typically higher in frequency, above 1.5 kHz. In part because of the longer wavelengths and the limitations of the array, at frequencies below 1 kHz the source regions may appear quite large and source identification uncertain. The second was the source-to-array distance. For controlled tests, distance can be optimized to be relatively close to the vehicle. For roadside measurements, practical issues of safe access and not distracting drivers limit how close the array can be positioned to the lane of travel. Thirdly, practical issues such as the effect of large vehicle wakes, random turbulence and other background noise were of concern.

The design of the microphone array was built on lessons learned during the array-based demonstration tests of truck-noise source localization conducted under Caltrans sponsorship in 2005 [4]. That study utilized a 90-microphone commercial wheel array WA0890 developed by Bruel & Kjaer [5] with software that was an early prototype of that used here. Useful results were obtained, but there were limits associated with the system being general-purpose, not optimized for the specific type of measurements for moving trucks. The data from that project was used to optimize the methodology with regard to the number of microphones needed, the configuration of the array, and software enhancements to utilize the complete CSD matrix of all microphones.

The primary objectives for the new array design in this study were: (1) extend the directivity gain to frequencies below 400-500 Hz attained with the Bruel & Kjaer array in the Caltrans demonstration of 2005; (2) meet the Bruel & Kjaer array gain performance (side lobe suppression from -10 to -15 dB); (3) optimize array performance for an affordable 70+ element array; and (4) optimize array geometry to provide for (a) vertical directivity through vertical array aperture, (b) horizontal directivity through combined array aperture and cross-range spreading loss during vehicle pass-by, and (c) array dimensions for assembly/disassembly in the field.

# 3 Microphone array design

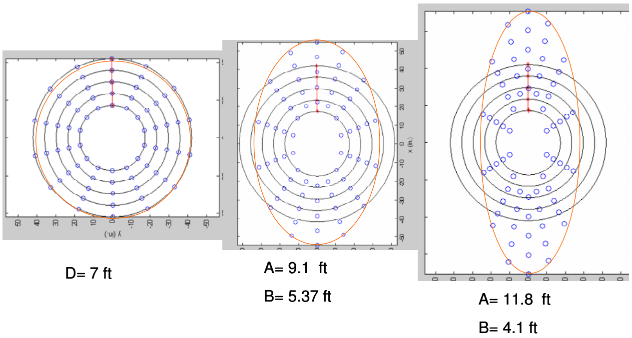
Performance of the notional array that is illustrated in Fig.1 was the baseline for the current design study. It represents one of the possible approximations to the array used in the 2005 demonstration tests mentioned above. The side lobe suppression method used here was developed in [6] to provide minimum number of redundant microphone separations to effectively optimize the required number of microphones per unit area needed for a given tolerated side lobe level. The resulting spiral angle and the spoke configuration introduce spatial irregularity into the circular array, thus enabling required side lobe suppression. The circular array for this application, however, provides unnecessary localization in the horizontal direction and insufficient localization in the vertical direction. Given the intrinsic horizontal localization afforded by the pass-by itself, a deformed array was considered to optimize the effective localization vertically and horizontally for enhanced performance at low frequencies. Deformation of the parent circular array into an ellipse provides a means to tailor these arrays for truck pass-by. This facet of the array design represents one of the new products of the current project.



(a) (b)

Fig.1 Notional 90-element circular spiral array with 15 spokes of 6 elements each and inner and outer radii of 0.5 and 1 m (20 and 50 in), respectively: (a) array pattern, (b) directivity pattern of array.

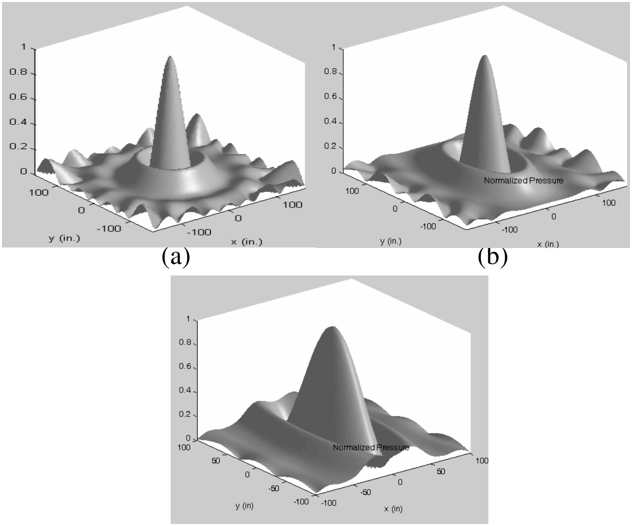
All of the arrays shown in Fig. 2 have the same area, i.e. AB=D$^2$, and all have the same area density of elements.



(a) (b) (c)

Fig.2 Patterns for various arrays of 70 elements distributed around 14 spokes of 5 elements each: (a) Circular spiral array, (b) Ellipse-1 array, (c) Ellipse-2 array. A – major axis, B – minor axis. Spiral angle = 0.5°.

Fig. 3 shows the similar lobe structures of these arrays at 1 kHz. The projection of the lobe structure has a shape outline which follows that of the array, but is rotated 90° relative to it, i.e. increased array length in X-axis results in narrow beam in X; conversely, reduced array length in Y-axis results in wider beam in Y.



(a) (b)

(c)

Fig.3 Directivity pattern projections in front of the array plane shown in Figure 2 at 1 kHz: (a) Circular spiral array, (b) Ellipse-1 array, (c) Ellipse-2 array.

Fig. 4 provides a chart that gives the approximate lobe width, here called "spot width", as it refers to the localization in the truck side plane 6 m (20 ft) from the array plane. It is seen that lengths on the order of 3.7 m (12 ft) are required to localize to within +/- 1.5 m (5 ft). Given the design requirement of constant area for all arrays, the degradation in horizontal beam width for the benefit of vertical discrimination can also be seen.

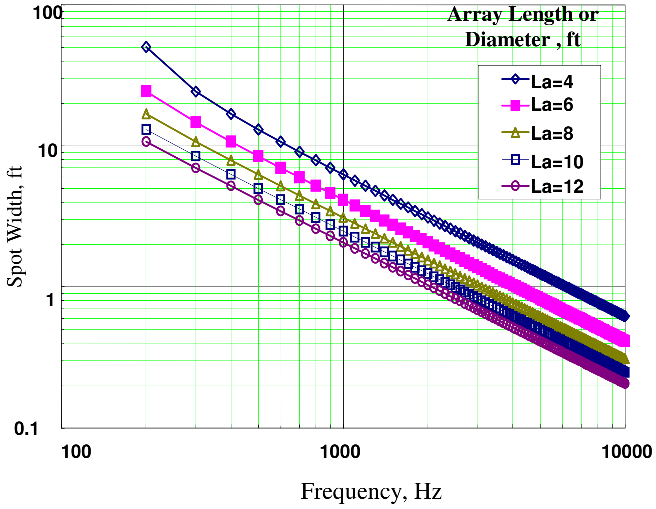


Fig.4 Width of the focus spot of arrays of various lengths or diameters as function of frequency at a distance of 6 m (20 ft).

As the truck sources pass by the microphone array, there is a sound level change at the array microphones that is due just to the spherical spreading loss resulting from the varying distance. Ignoring possible effects of source directivity, which are probably of little concern in the low-frequency range of interest, this variation in the sound level provides some localization along the truck. Fig. 5 illustrates this combined effect of spreading loss and directivity gain. The -6 dB – down points for the pass-by are indicated along with the -6 dB – down points (at 250 Hz) for the three arrays that are shown in Fig. 2. In all cases the closest point of approach (CPA) is 6 m (20 ft). This sketch shows that spreading loss provides added discrimination as the horizontal directivity is reduced to provide for an increased vertical dimension of the array. One cannot arbitrarily increase the horizontal dimension since this would provide degradation of the side lobe structure.

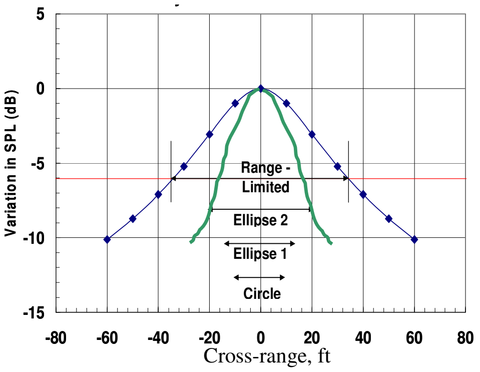


Fig. 5 Approximate profile of sound pressure level for simple source passing by the array at 250 Hz.

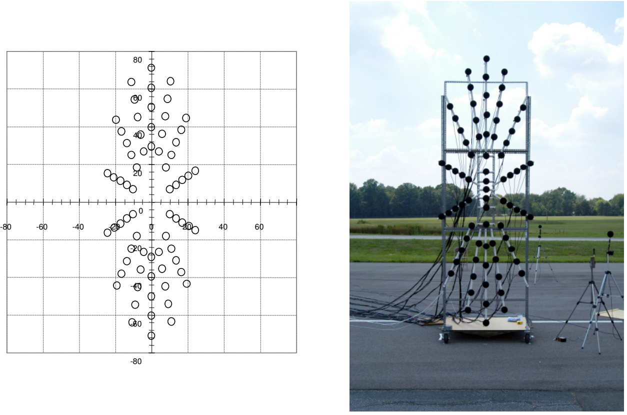
The following conclusions were drawn from the design analysis for the frequency range of the highest A-weighted sound levels of emissions (during cruise):

- A 70-element elliptical array provides adequate aperture with acceptable side lobe suppression;
- The aspect ratio 1.7 of an elliptic aperture array provides beam patterns that are geometrically similar to the array shape at all frequencies of interest;
- Vertical directivity provides a beam focus spot 1.2 m (4 ft) wide (-6 dB-down) at 465 Hz;
- Excellent side lobe suppression of approximately -14 dB over the range of 250 to 2250 Hz and approximately -11 dB at 8000 Hz;
- A minimum spiral angle is needed to suppress side lobes so element supports may be radial;
- Side lobes at high frequencies seem well distributed, i.e. appear amorphous, which minimizes the likelihood of unwanted highlights that may lead to false source images.

With regard to low frequency performance, it was concluded that:

- With a 3.7 m (12 ft) major (vertical) axis of the ellipse, the vertical beam half height (-6 dB) is about 1.4 m (4.5 ft) at 250 Hz. This will allow imaging resolution to the upper half of a large truck cab.
- The horizontal effective beam width during pass-by, including both beam width and spherical source spreading loss, would be about 2.7 m (9 ft) for the minor axis (horizontal dimension of 1.2 m (4 ft)).

The elliptical array described herein represents a new result of this study. Based on the design analysis for Ellipse-2 array, a 70-element array schematically shown in Fig. 6a was selected for experimental engineering and implementation through the proof-of-concept testing, as described in the following sections.



(a) (b)

Fig. 6 Experimental elliptical microphone array: (a) 70-element design; (b) array assembly (note 7 additional microphones in the array center).

## 4 Experimental array engineering

As the result of the development described above, a 70-microphone elliptical array was designed and constructed, with an aspect ratio of 1.7, a width of 1.2 m (4 ft), and a height of 3.7 m (12 ft). The assembly is shown in Fig. 6b.

The mechanical design of the array, due to a significant size of the array aperture, contains a metal frame composed of three separate sections mounted together vertically and installed on a four-wheel metal base. The sections, each of approximately 1.2 by 0.9 m (4 by 3 ft) in dimensions, could be easily disassembled for shipping. 14 PVC pipe spokes, each holding 5 microphones, were mounted on the frame sections, providing the 70-microphone elliptical pattern designed. The identical lower and upper frame sections hold five spokes each, with five microphones mounted equidistantly on each spoke. The middle frame section holds four spokes with five microphones each. During the field tests of the array, additional microphones were mounted along the central vertical axis of the middle frame section, raising the total number of microphones to 73 or 77 for some tests.

The array was equipped with the PCB ¼-inch electret microphones with ICP® preamplifiers. The microphones/ preamplifiers were inserted in holes predrilled in the spokes of the array, each provided with a windscreen.

The data acquisition system, shown in Fig. 7 (a), was completed using a National Instruments Model PXI-1044 embedded controller chassis with twelve data acquisition cards providing analog-to-digital conversion for total of 80 data channels providing simultaneous signal recording. The measurement signals from the array microphones were fed into the PXI channels through 17-meter (50 ft) long microphone cables. The software for running the system in real time and transferring data from the PXI to a laptop computer for post-processing was also developed. The measurement equipment setup is shown in Fig. 7 (b).

During the proof-of-concept testing described below, one of the remaining PXI channels was used for recording the time signal from a GPS-based time code generator for data synchronization. Another available channel received a signal from a pair of photo cells installed on tripods near the microphone array to register truck passbys. Another PXI channel was used for recording signals from the vehicle tracking system for determining the truck speed.

(a) (b)

Fig. 7 (a) Data acquisition system and (b) equipment setup.

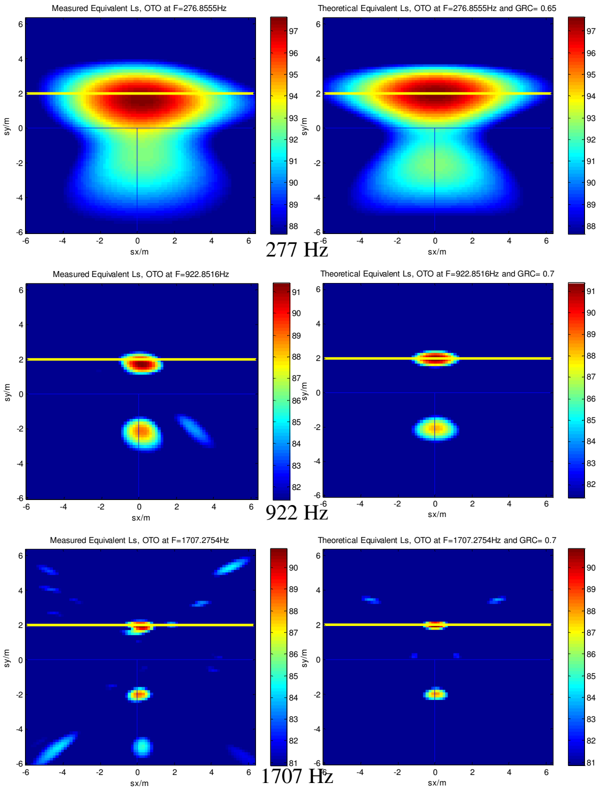
## 5 Proof-of-concept testing

The proof-of-concept testing was conducted at the International Truck and Engine Corp. (IT) test facilities in Fort Wayne, Indiana. This company has two test tracks. One is a low-speed pass-by sound pad used for standard truck pass-by noise emission measurements at speeds up to 56 km/h (35 mph). Fig. 8 shows how the array was calibrated at this track using an omni-directional (spherical) loudspeaker on a tripod. The speaker was used for initial evaluation of the fully assembled system as known stationary “point” source placed at several on- and off-axis locations with different distances and heights in front of the array.

Fig. 8 Array calibration using a spherical loudspeaker.

Fig. 9 shows calculated and measured images of the spherical source at a series of frequencies. The color bar legend indicates approximately equivalent one-third octave band sound levels in decibels. All images of a single acoustic source show a single “hot spot” above ground with its mirror image below ground. At 922 Hz, for example, Fig. 9 shows elliptical spots whose major and minor axes are complementary to those of the array. The vertical -6 dB width of the spot is about 0.38 m (1.25 ft), while the horizontal width is about 0.67 m (2.2 ft) at a distance of 6 m (20 ft) and an elevation of 2 m (6 ft). Fig. 9 also shows examples at lower and higher frequencies, respectively, for the same source at this distance and elevation. At higher frequencies, the existence of side lobes in the array directivity due to certain phase relationships (frequency and spatial aliasing) between the array microphones creates unreal ‘ghost’ images.

The lower and higher frequencies define the approximate limits of the array performance. It can be seen from the figure that the array shows adequate performance between approximately 250 and 2000 Hz. As the result of these and similar tests, it was determined that the array reliably images



(a) Measured (b) Calculated

Fig.9 Images of (a) measured and (b) calculated spherical source emission at three frequencies; source elevation 2 m (6 ft), array stand-off at road side 6 m (20 ft).

an omni-directional source at steering angles up to 45 degrees off axis and stand-off distances up to at least 20 m (65 ft) at road side.

A number of tests were performed with the same speaker mounted on a rear frame of a truck in stationary, idle, and moving operations. Those tests determined the array's ability to localize the truck noise sources (engine, tires and exhaust) in comparison with the known calibrated source, as the truck passed by the array at speeds up to 56 km/h (35 mph).

For high-speed tests, the microphone array and data acquisition system were transported to the second IT track. It consists of a one-mile long multiple-lane loop designed for conducting endurance truck testing with the maximum speed limit of 80 km/h (50 mph). The microphone array was placed at a distance of 6 m (20 ft) from the edge of the nearest asphalt driving lane. A number of the speaker and truck pass-by tests were carried out at this location, including three widely different types of trucks (all by International$^{®}$) in various configurations. A medium utility truck, a long-haul heavy-duty truck and a "severe" truck used for very heavy payloads were equipped with different engines, a variety of tires, diverse exhaust configurations (horizontal, vertical, muffled or "straight-through" exhaust with no muffler); some contained trailers, fuel tank skirts, or an aerodynamic wind fairing over the cabin. The trucks were tested at several speeds, engine RPM's and gear settings, in cruse, coast down, acceleration and compression brake modes. This testing was supplemented with conventional single microphone and sound intensity measurements. The experimental results of the proof-of concept testing are presented and analyzed in an accompanying paper [7].

# 6 Conclusion

This paper describes the microphone array, data acquisition system, and software developed and implemented for mapping truck noise sources using acoustic beam-forming. The measurement system design parameters were verified experimentally. The measurement system with the 70+ elliptical microphone array showed adequate performance at frequencies between 250 and 2000 Hz with side lobe suppression of -14 dB, optimized vertical and horizontal directivities, and suitable handling in the field application.

Proof-of-concept tests were performed at low-speed and high-speed testing facilities for a sample of trucks with widely different characteristics to validate the system performance. The results of the proof-of-concept testing are presented in an accompanying paper [7] and confirm that the developed beam-forming system provided adequate noise mapping and localization for various noise sources on trucks, stationary and moving at speeds up to 80 km/h.

# Acknowledgments

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# References

[1] A. Crewe, F. Perrin, V. Benoit, and K. Haddad, "Real-Time Pass-by Noise Source Identification Using a Beam-Forming Approach", *Proc. The Society of Automotive Engineers Noise and Vibration Conf.*, Paper No. 2003-01-1537, Traverse City, MI (2003)

[2] M. A. Pallas, "Acoustic Behavior of the Noise Sources of a Truck", *Proc., Inter-Noise 2004*, Prague, Czech Republic, International INCE (2004)

[3] R. P. Dougherty, "Beamforming in Acoustic Testing" in *Aeroacoustic Measurements*, Chapter 2, T .J. Mueller, ed., Springer Verlag (2002)

[4] W. Blake, P. Donovan, "A New Road-Side Array-Based Method for Characterization of Truck Noise During Passby", Paper NCAD2008-73056, *Proc., NCAD2008, NoiseCon2008-ASME NCAD,* July 28-30, Dearborn, Michigan, USA (2008)

[5] PULSE Beamforming – Type 7768. Product Data. Bruel & Kjaer Sound & Vibration Measurement A/S, Naerum, Denmark (2004)

[6] J. R. Underbrink, "Aeroacoustic Phased Array Testing in Low Speed Wind Tunnels", in *Aeroacoustic Measurements*, Chapter 3, T. J. Mueller, ed., Springer Verlag (2002)

[7] W. Blake, K. Plotkin, Y. Gurovich, P. Donavan, "Noise source mapping for trucks, Part 2: Experimental results", *Proc., Acoustics'08 Paris*, France (2008)