

Impulse Noise from Automotive Inflatable Devices**FOREWORD**

All acronyms are defined in this document in **Section 3.0 "Definitions."**

a. Relationship of the document to other documents

The following organizations are involved in setting standards or recommendations for impulse noise analysis:

1. Arbeitskreis (AK)
2. American National Standards Institute (ANSI)
3. National Academy of Sciences/National Research Council, Committee on Hearing, Bioacoustics and Biomechanics (CHABA).
4. North Atlantic Treaty Organization (NATO) Research Study Group 29 on "Impulse Noise Effects"
5. U.S. Department of Defense (DOD)
6. U.S. Department of Transportation (DOT)

b. History, background, and introductory material.

1. **Evolution of Impulse Noise Risk Assessment**

- (a) **ca. 1960:** Research into damage risk criteria for impulse noise centers on occupational exposure from steady state noise. Military research established the threshold for eardrum rupture at 180 dB for an unprotected ear with a free-field sound pressure wave at grazing incidence.
- (b) **1966:** Criterion for steady state noise published by CHABA Working Group 46 (Kryter et al., 1966)

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- (c) **1968**: First criterion specifically for impulse noise published by CHABA based on Coles et al. (1968). This criterion: lowered the tolerable pressure by 5 dB for normal incidence of noise wave to ear, lowered the allowable pressure by another 5 dB to protect 95% of population instead of 75% as in Coles et al., established 179 dB peak SPL over 25 microsecond duration as single impulse limit to unprotected ear, accounted for acoustic reflex contraction of middle ear muscles, and established a correction factor for single impulse exposures by permitting a 10 dB increase in allowable pressure. The method of signal analysis was also specified in this paper using the A and B-durations (see **Definitions** section). Lacking other tools, passive restraint engineers adopted these methods and criteria. Typical driver airbag systems produced impulses in the range of 140 to 150 dB. These were considered to be associated with a low risk for PTS.
- (d) **1969**: Classic experiments with human volunteers exposed to automotive airbags performed and reported Nixon (1969).
- (e) **1971**: Bolt, Beranek, and Newman revised earlier impulse noise criteria to specifically address impulse noise produced by airbag deployment (Allen et al., 1971). Raw pressure-time data was low-pass filtered at 300 Hz for A-duration calculation and high-pass filtered at 300 Hz for B-duration calculation. This method analyzes the low and high frequency data as if they act independently on the ear, without interaction between them.
- (f) **1973**: Another classic set of human volunteer experiments conducted by Sommer and Nixon (1973). Volunteers were exposed to low frequency noise (by itself), high frequency noise (by itself) and low plus high frequency noise acting together. A protective effect of low frequency noise was suggested.
- (g) **1975**: MIL-STD-1474A "Noise Limits for Army Materiel" first published. This standard established maxima for combinations of peak Sound Pressure Level and B-duration beyond which varying types of hearing protection are required by military personnel. These B-durations are calculated using the wideband pressure-time data collected (with the low and high frequency noise analyzed together in contrast to the BBN method).
- (h) **1987**: SAE J247 (FEB87) Recommended Practice—Instrumentation For Measuring Acoustic Impulses Within Vehicles. Describes the instrumentation and procedure for measurement of airbag noise in vehicles.
- (i) **1992**: National Academy of Sciences/National Research Council (1992) reports that "The 1968 criterion should not be used for low-frequency impulses such as air bags, sonic booms, rapid pressurization etc." The NAS decision was primarily based on the fact that the 1968 criterion did not account for the spectral distribution of the energy, the number of impulses, or the temporal spacing of the impulses.
- (j) **1996**: A mathematical model of the feline ear is reported by Price and Kalb from the US Army Research Lab. The model calculates risk based on a hypothesis that damage to the hair cells in the cochlea correlates to a mathematical function of the number and amplitude of basilar membrane displacements in a manner analogous to mechanical fatigue of solid materials.

- (k) **1996:** Math model of the feline ear is validated for airbag impulses (Price, Rouhana and Kalb, 1996; Price and Kalb, 1996). The model has a movie function that shows the development of the risk of impulse noise-induced threshold shift as it relates to the impulse noise pressure-time history.
- (l) **1997:** MIL-STD-1474D "Noise Limits" a revision of MIL-STD-1474C. This standard continues the use of maxima for combinations of peak Sound Pressure Level and B-duration beyond which varying types of hearing protection are required by military personnel. The limits are referenced to the Curve X instead of Curve Y and Curve X is reduced by 1.5 dB from MIL-STD-1474B).
- (m) **1999:** The ARL Ear model is extended to a human ear model (Price and Kalb, 1999).
- (n) **1999:** ANSI Working Group S3-32 issued a draft report on the effects of impulse noise". The group recommended using the 8-hour equivalent energy (LAEQ8) criterion for impulse noise below a peak SPL of 140 dB, and the ARL criterion for impulse noise above a peak SPL of 140 dB.
- (o) **2001:** The ARL Ear Model was reviewed by a Peer Review Panel of the American Institute of Biological Sciences. The panel concluded that the Ear Model "represents a significant improvement over the Department of Defense Design Criteria Standard: Noise Limits of 12 February 1997 (MIL-STD-1474D).", that "the model was validated by human exposure data obtained in Albuquerque, New Mexico", and that "the HRED model can be used to test potential health hazards associated with impulse noise levels in excess of 140 dB".
2. **Biomechanics of Hearing**--Sound travels through the air as pressure waves. The external ear lobe (pinna) channels the sound into the ear canal and to the eardrum (tympanic membrane), where it is converted into vibrations of the ear ossicles called the malleus, the incus and the stapes (also known as the hammer, anvil, and stirrup). The ossicles are located in the middle ear cavity. The stapes is held in the oval window of the cochlea, or inner ear, by the annular ligament. When the stapes moves due to vibrations of incoming sound pressure, a pressure wave is transmitted down the fluid of the cochlea. The pressure wave distorts a membrane that runs along the length of the cochlea (basilar membrane). Within the cochlea's organ of Corti, thousands of microscopic hairs, embedded in hair cells resting on the basilar membrane, move when the basilar membrane is distorted. This causes the hair cells connected to the auditory nerve to generate electrochemical signals, which pass to the hearing centers of the brain, to be interpreted as sound. Hair cells near the base of the cochlea respond mainly to higher frequencies and those near the apex respond mainly to lower frequencies.
3. **Human Biovariability** Distinct age populations have different hearing acuity. For example, the elderly typically show distinct changes in hearing from their middle age capability (this is called presbycusis—45% of Americans over age 75 are affected). The feline subject is a human surrogate with hearing acuity similar to that of people, although it is viewed overall, as having significantly greater acuity than humans.

The presence of a middle ear infection can reduce the transmissivity of the middle ear and lower the effective hearing acuity. It is unknown whether age or illness have any effect on risk of noise-induced hearing loss.

4. Mechanisms of Hearing Loss

1. **Blow to the Head**--gross mechanical failure of structures, such as fracture of ossicles and tearing of the eardrum.
2. **Exposure to Continuous Noise**--long duration (hours, weeks, months) exposures to loud noises, such as a rock concerts, heavy equipment, and pneumatic drills without ear protection. Hearing loss in continuous exposure is believed to be biochemical in nature.
3. **Exposure to Impulsive Noise**--physical trauma to the cellular structures of the cochlea. For example, the ARL Ear Model risk algorithm identifies the peaks of the upward displacement of the stapes that put the inner ear tissues in tension where they are most likely to sustain damage. Using the calculated stapes displacement as the driving input to the cochlea, the model calculates the displacement history of the basilar membrane for the duration of the input waveform. Risk is calculated at 23 locations along the basilar membrane. The postulated mechanism of injury in the algorithm is similar to mechanical fatigue of the hair cells in general engineering and is calculated as a function of the amplitude of the vibration and the number of cycles of vibration. The output of the ARL model calculation is presented in values called Auditory Risk Units [ARU].

1. Scope

New methods are available to assist in evaluating the risk of impulse noise-induced hearing loss from inflatable devices, for example, airbags and seat belt pretensioners. This document presents some background on impulse noise measurement techniques and assessment criteria. Related information relative to test details, for example, preamplifier specifications and filtering methods and criteria, will be discussed in a future recommended practice.

1.1 Purpose

This document serves to disseminate information about these tools and techniques to assist the automotive restraint development process.

2. References

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

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2.1.3 ISO PUBLICATIONS

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2.1.4 DoD PUBLICATIONS

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2.1.5 NATO PUBLICATIONS

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3. Definitions

3.1 Acronyms

AHAAH	Auditory Hazard from Airbags—Human (human ear model from ARL)
ARU	Auditory Risk Units output from ARL ear model
AK	Arbeitskreis der Ruckhaltesysteme-Kooperation, Working Committee of German Automobile Manufacturers
ANSI	American National Standards Institute
AHTL	Average Hearing Threshold Level
ARL	Army Research Laboratory
BAEP	Brainstem Auditory Evoked Potentials
BBN	Bolt, Berenak, and Newman
CHABA	Committee on Hearing, Bioacoustics and Biomechanics, National Research Council, National Academy of Sciences
dB	Decibels, logarithmic scale for sound pressure or power units
DOD	Department of Defense (United States)
DOT	Department of Transportation (United States)
ISO	International Standards Organization
NATO	North Atlantic Treaty Organization
NIHL	Noise-induced hearing loss
OAE	Otoacoustic Emissions
PB	phonetically balanced
PTS	permanent threshold shift in hearing (hearing loss that does not fully recover; see Threshold Shift below)
SAE	The International Engineering Society for Advancing Mobility Land Sea Air and Space
SL	Sensation Level (speech intensity)
SPL	Sound Pressure Level = 20 log (measured Pressure/reference Pressure)
TC	Technical Committee
TTS	temporary threshold shift in hearing (hearing loss that recovers; see Threshold Shift below)
WG	Working Group

3.2 Definitions

3.2.1 ACOUSTIC REFLEX

Transmission of sounds through the middle ear can be attenuated by means of the middle ear muscles (Tensor Tympani and Stapedius Muscle). These muscles are triggered by the Trigeminal and Facial nerves. The Acoustic Reflex, can cause contraction of these muscles and can be elicited by loud sounds, vocalization, tactile stimulation of the head or general body movement (Pickles, 1988). This reflex is absent in 6.7% of "normal hearing" adults.

3.2.2 ACOUSTIC TRAUMA

Hearing loss or other auditory disturbance associated with exposure to a loud noise or series of loud noises.

3.2.3 A-DURATION

A measurement of the length of time of the low frequency component of an impulse noise pressure-time history. It is calculated from the first rise above the ambient pressure to the time the pressure first returns to zero.

3.2.4 ALPHA CABIN

A reverberation chamber having linear dimensions one-third of those of an international standard reverberation room. Its volume is 6.44 m³ and no two walls are parallel. The overall dimensions are (L x W x H): 3.22 x 2.37 x 2.03 m. The cabin may be lined in with absorptive material on walls and floor to match the reverberation of a typical passenger compartment. This can be achieved, for example, by using 20-60 mm thick fibrous cotton fleece. The absorption characteristics in closed spaces can be described by determining the reverberation time, which should lie between 30 and 100 ms for frequencies from 0.5 to 8 kHz.

An airbag module (driver, front passenger, side, kneeblocker airbag) can be attached to the interior of the cabin door. A dummy torso fitted with pressure transducers or microphones can be positioned in the cabin as it would be in a vehicle (i.e., sitting in a car seat) with respect to the airbag. The system is triggered externally. In the case of multiple inflatable systems, the triggering can take place simultaneously or with a time delay between devices. The pressure rise from initiation of the device can be used to trigger a data acquisition device (e.g., a tape recorder or computer).

3.2.5 ARMY RESEARCH LAB [ARL] MODEL

A mathematical model of the ear that calculates the risk of impulse noise-induced threshold shift from a pressure wave. The "risk" is a measure of the mechanical fatigue of the hair cells of the cochlea. The model consists of transfer functions that characterize the incident sound pressure as it moves from the free field to the inner ear. The feline model is validated for airbag exposure. The human version of the model has been validated using military volunteers who had been exposed to impulse noise from large weapons. The ARL Model represents the ear as electroacoustic elements with inductors representing mass, capacitors representing acoustic compliance, and resistors representing acoustic resistances. The model includes graphs of transfer functions—free-field pressure to eardrum pressure; external ear radiation impedance; eardrum acoustic input impedance; eardrum pressure to stapes volume velocity;

free-field pressure to stapes volume velocity; and stapes displacement to basilar membrane displacement. The model represents the stapes as nonlinear. At low intensities, the annular ligament exerts a linear restoring force on the stapes and can displace easily up to 5 to 6 μm . At high intensities, the restoring force is nonlinear, reaching an asymptote at about 20 μm , limiting the motion of the stapes. Under some circumstances, this nonlinearity appears to limit the transmission of higher frequency noise to the inner ear.

3.2.6 ASYMMETRIC HEARING LOSS

Hearing loss in an ear that is of different magnitude than that in the other ear. There is no general agreement on how big the difference must be, but some studies suggest that the difference must be ≥ 15 dB at two frequencies or there must be a difference in speech discrimination of $\geq 15\%$ in order for the hearing loss to be considered asymmetric.

3.2.7 AUDIOGRAM

A graph for a given ear of hearing thresholds obtained for various frequencies.

3.2.8 AVERAGE HEARING THRESHOLD LEVEL (ANSI, 1969)

The softest level at which a patient can correctly repeat 50% of presented "spondee words"; it is recorded in decibels hearing level (dBHL). A spondee word is a two-syllable word, each syllable of which can stand alone as a separate monosyllabic word. Some examples are "baseball, hotdog, airplane, and mushroom".

3.2.9 B-DURATION

A measurement of the decay time of the high frequency component of the pressure from an impulse noise waveform. It is measured from the time the pressure first rises above the baseline until the time that pressure is less than 20 dB of the peak, including all reflections. It is assumed that the B-duration represents the energy emitted at high frequencies, (e.g., the gas generation—gas jetting through a manifold, the airbag cushion unfolding, etc.

3.2.10 BRAINSTEM AUDITORY EVOKED POTENTIALS (BAEP)

Electrical activity within the auditory regions of the nervous system (auditory nerve or auditory regions of the brain) that is produced by sound and is measured via electrodes on the scalp.

3.2.11 C-WEIGHTING

Modification of the frequency content of a signal using a filtering network to more closely approximate the equal loudness contours of the human ear (see below).

3.2.12 COMPOSITE PULSE

The impulse noise waveform containing all the frequencies.

3.2.13 THE EAR

3.2.13.1 External Ear

Auricle or pinna and external auditory canal. The auricle and external auditory canal can amplify sound. The auricle also functions as a focusing organ and directs (high frequency) sounds into the ear canal.

3.2.13.2 Middle Ear

Tympanic membrane (ear drum), the malleus (hammer), incus (anvil), and stapes (stirrup) bones plus soft connective tissues (suspensory ligaments, the tensor tympani muscle, and the stapedius muscle). The middle ear functions as an acoustic transformer by matching the impedance of the air to that of the inner ear fluids.

3.2.13.3 Inner Ear

Cochlea and semicircular canals.

3.2.14 EARDRUM RUPTURE

A tear in the eardrum. A peak sound pressure level of 180 dB is commonly accepted as the threshold for eardrum rupture.

3.2.15 EQUAL LOUDNESS CONTOURS

Curves of perceived loudness as a function of frequency for pure tones arriving at the ear. The human ear responds differently to different frequencies. It is most sensitive to sounds at 4 kHz, and less sensitive at lower frequencies and higher frequencies (e.g., a 42 dB tone at 4 kHz sounds as loud as a 50 dB tone at 1 kHz and a 73 dB tone at 50 Hz).

3.2.16 DYNAMIC RANGE OF HEARING

20 μ Pa to 1 kPa at 20 Hz to 20 kHz; speech is transmitted between 500 Hz and 4 kHz.

3.2.17 GRAZING INCIDENCE

Noise wave directed parallel to the eardrum.

3.2.18 HEARING IMPAIRED / MILD HEARING LOSS (ANSI, 1969)

A hearing loss at least equal to 26 to 40 dB. Individual demonstrates difficulty understanding soft-spoken speech.

3.2.19 HEARING LEVEL

Audiometric test tones are specified in hearing level (HL) rather than SPL because the normal ear is not equally sensitive to low and high frequency sounds. According to current standards (ANSI, 1969) it takes 39 dB more SPL for the normal ear to barely hear a 125 Hz tone than it does to barely hear a 1000 Hz tone. Because it is desirable to have a 0 dB dial reading at the point where the normal ear can just barely hear the stimulus, regardless of frequency, the audiometer has been designed to compensate for differences in hearing sensitivity as a function of frequency.

3.2.20 HYPERACUSIS

See Recruitment.

3.2.21 IMPULSE NOISE

High amplitude, short duration noise, such as from military weapons or fireworks e.g. sound having a microsecond to millisecond rise of waveform with large amplitude (140 to 170 dB) and short durations of 2 to 500 ms; for example, airbags and seat belt pretensioners may produce impulse noise.

3.2.22 INTOLERANCE TO LOUDNESS

Patient is uncomfortable in loud/noisy environments after exposure to impulse/other noise.

3.2.23 MODERATE HEARING LOSS (ANSI, 1969)

41-55 dB. Individual demonstrates an understanding of speech at close range, but requires amplification.

3.2.24 NORMAL INCIDENCE

Noise wave directed perpendicular to the eardrum.

3.2.25 OCCULT SHIFT / HIDDEN SHIFT

Loss in the 4000+ to 6000 Hz range which is above the speech frequency range of 500 to 4000 Hz, and may not be apparent without comparison of pre- and post-exposure audiograms.

3.2.26 OTOACOUSTIC EMISSIONS (OAE)

Acoustical signals that can be detected in the ear canal spontaneously as narrow band tonal signals after stimulation of the ear and are thought to be due to vibrations produced at various locations within the cochlea.

3.2.27 PERMANENT THRESHOLD SHIFT

A change in hearing secondary to noise exposure that is permanent (remains longer than 6 months).

3.2.28 PEAK AMPLITUDE

The maximum value of sound pressure attained, expressed in psi (kPa). It may also be expressed as sound pressure level in decibels (dB).

3.2.29 PROFOUND HEARING LOSS (ANSI, 1969)

91+ dB. Person does not rely on hearing as the primary modality for communication.

3.2.30 RECRUITMENT

Abnormal phenomenon of loudness sensitivity. As one raises the intensity of a tone, the perceived loudness grows more rapidly than in a normal ear.

3.2.31 REVERBERATION TIME

The time in a closed compartment in which the sound pressure level is reduced by 60 dB after the sound source is cut off. To be representative of a passenger vehicle, the reverberation time should lie between 30 and 100 ms for frequencies from 0.5 to 8 kHz.

3.2.32 RISK

In the ARL model, a measure of the mechanical fatigue of the hair cells in the inner ear.

3.2.33 SENSATION LEVEL (SL)

A measure of stimulus intensity relative to the threshold of the individual being tested. Thus, 30 dB SL means 30 dB above the individual's threshold for the specific test stimulus. The term SL often is used to specify the level at which speech discrimination tests are administered.

3.2.34 SEVERE HEARING LOSS

71 to 90 dB. Loud speech may be understood at 1 ft from the ear.

3.2.35 SHADOWING

Head shadowing occurs when the pressure wave of a noise event passes the head of an individual exposed to the noise. Since the head is positioned between the noise source and the distal ear, if the distal ear falls in the shadow of the head relative to the noise source it is exposed to a lower pressure than the proximal ear. For example, the study by Price, Rouhana and Kalb (1996) showed an approximately ten-fold reduction in ARUs by head shadowing.

3.2.36 SOUND PRESSURE LEVEL

Twenty times the base 10 logarithm of the ratio of the pressure of a sound to a reference pressure, expressed in decibels. The standard reference pressure is equal to 20 μ Pa. A 50 dB SPL tone is 50 dB above the reference pressure, 0.0002 dynes/cm². $SPL = 20 \text{ Log}_{10} (P_{\text{measured}} / P_{\text{reference}})$

3.2.37 SPEECH DISCRIMINATION SCORE

The percentage of phonetically balanced (PB) words a person can correctly repeat at a given sensation level

3.2.38 TEMPORARY THRESHOLD SHIFT

A change in hearing secondary to noise exposure that recovers within 6 months.

3.2.39 THRESHOLD OF HEARING / HEARING LEVEL

The difference in decibels between a standard average threshold level (ISO R389) and the threshold of hearing for the individual being tested. The human ear perceives sound from 20 Hz to 20 kHz.

3.2.40 THRESHOLD SHIFT

A change in a person's hearing sensitivity after exposure to a sound; a temporary shift (TTS) disappears within 6 months and a permanent shift (PTS) is one that remains longer than 6 months.

3.2.41 THRESHOLD OF PAIN

120 to 140 dB, subject to human Biovariability.

3.2.42 TINNITUS

Subjective sensation of noise in the ear, ringing of the ears; an irritating repeatable sound in the ear.

3.2.43 VERTIGO

A sensation of motion when there is no physical movement.

3.3 Symbols

m ³	cubic meter
dB	decibels
dyne/cm ²	dyne per square centimeter = 1 newton per square meter
kPa	kiloPascals
m	meter
N/m ²	1 Newton per square meter
Pa	Pascal = 1 newton per square meter
μPa	1 microPascal
psi	1 pound per square inch
rms	root mean squared
μm	1 micrometer

4. Testing Considerations for Assessment of Impulse Noise from Inflatable Devices

A number of issues remain unresolved relative to the test procedures for impulse noise. These issues are discussed in this section, even as researchers continue to develop and compare various test methods. This section will likely be revised within a year of the publication of this Information Report.

One of the principal issues surrounding airbag noise measurement is whether to measure in a vehicle environment or in a chamber that simulates a vehicle. While research to-date has shown a strong effect of vehicle environment on the risk predicted by the ARL model of the ear, suppliers of automotive components do not usually have access to prototype vehicles when the development of an inflatable device begins. Thus, they have no way to assess the impulse noise-induced hearing loss risk until very late in the vehicle development process when changes can affect program timing. It is likely that a recommended practice will suggest initial tests in a simulated vehicle environment followed by confirmation tests when a prototype vehicle is available.

Dynamic testing for assessment of airbag noise-induced threshold shifts is not necessary for a number of reasons. First, the noise of a crash itself is typically much less than that of the deployment of inflatable devices (145 dB vs 165 dB for a typical full frontal airbag system, respectively). Second, most transducers available today possess significant acceleration sensitivity. This sensitivity to acceleration makes it difficult to obtain accurate measurements of the noise during the crash.

4.1 Simulation of a Vehicle Using a Reverberation Chamber

Issues to be considered in the selection of a standardized chamber include:

- What volume is typical of a vehicle's passenger compartment?
- What are the acoustic properties inside of a vehicle?
- Should the ratio of glass to plastic trim be simulated?
- Should dummies be included?
- Should the chamber be airtight or have calibrated pressure relief?
- Suitability of chamber for head curtain airbags?

One chamber that has been proposed for use is called the Alpha Cabin (by Rieter Automotive). The Alpha Cabin can be vented or have pressure relief. It can be trimmed to represent the vehicle's expected acoustic characteristics. For example, by using 20 to 60 mm thick fibrous cotton fleece, absorption characteristics similar to those in a vehicle can be simulated.

Dummies should be used to represent the volume taken up by humans in a vehicle—especially the acoustical influence of the upper body.

The measuring transducers should be located at positions closely related to human ear locations.

Whether the windows are open or closed has produced different results in different experiments: driver-only systems did not show a difference, but driver and passenger systems deployed together have shown a significant difference.

Since early in the design of an airbag system, an exemplar vehicle is not available, it is desirable to have a standard chamber or tank that can be utilized by the airbag supplier for initial evaluations of prototype systems. This chamber or tank dimensions and composition should be standard to allow its availability worldwide to reduce the likelihood of lab-to-lab variation such as that which occurs in anechoic chambers.

4.2 Test Setup

Issues considered in the definition of Test Setup:

4.2.1 ACCELERATION OF TEST FIXTURE

Dynamic testing for evaluation of airbag noise is not recommended, but if a dynamic vehicle crash is being measured with the measuring equipment inside the vehicle, this equipment must be protected from vehicle deceleration. Most pressure transducers have specified acceleration sensitivity. The transducer should be oriented with its least sensitive axis in the direction of principal vehicle deceleration.

4.2.2 GROUNDING/CHARGE COUPLING

All equipment including the dummies should be connected to a good earth ground. Sharp, large amplitude spikes in the data may indicate a grounding problem. Be careful not to introduce ground loops.

4.2.3 MOUNTING OF THE INFLATABLE DEVICE(S)

4.2.3.1 *In-Vehicle*

Mount airbags in design location

4.2.3.2 *In-Chamber*

Attach the inflatable device in a manner similar to its in-vehicle orientation relative to the dummy. In the Alpha Cabin the device is mounted on the interior of the door to the cabin. The dummy torso fitted with the pressure transducers/microphones is positioned appropriately with respect to the inflatable device(s).

4.2.4 ELECTROMAGNETIC INTERFERENCE

Care should be taken to ensure proper grounding of all segments of the dummy to a good earth ground to prevent electrostatic discharge during the tests. Electrostatic discharge can masquerade as a noise signal.

4.2.5 IMPACT BY INFLATABLE DEVICE

Impact by an airbag or other inflatable device can also masquerade as a noise signal. Therefore, care should be taken to mount the sensor (pressure transducer or microphone) in a location that is outside the zone of inflatable device deployment.

4.2.6 TEMPERATURE

Tests should be conducted at room temperature, e.g. $23\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$.

4.2.7 OCCUPANTS

Do not test the vehicle/chamber empty: simulate the space that occupants would take up in the vehicle. Upper body acoustic parameters are important. Research is underway to determine whether all occupant seating positions should be occupied during the assessment or if just occupying those positions closest to the inflator would be sufficient.

4.2.8 OCCUPANT POSITION RELATIVE TO THE INFLATABLE DEVICE

The head's closeness and orientation to the packaging of the inflator should to be considered. For example, a side airbag packaged in a right front passenger seat might be closer to the ear of a six-year-old dummy than to that of a 50th percentile Male dummy.

4.2.9 HEAD FORMS

SAE conducted testing in Weissach, Germany in 1998. Various head forms were evaluated (including Hybrid II head with low frequency, high intensity modified B&K 4136 microphones, Head Acoustics head with standard B&K 4136 microphones, Hybrid III head with Endevco 8510-B5 pressure transducers and free-field Dytran 2013V pressure transducers). Measurements made with the microphones or pressure transducers mounted inside the head in the location of the ear canal and eardrum were consistently higher than those made with the microphones mounted outside the dummies' heads, oriented normal to the eardrum. Several types of head forms are now on the market.

4.2.10 TRANSDUCER MOUNTING

Transducer mounting in a simulated head form ear can affect the quality of the impulse noise measurement. Therefore, mechanical and Gaussian noise in the signals should be carefully controlled by the experimenter. Mechanical noise is that caused by metal-to-metal contact or acceleration induced into the transducer. Gaussian noise refers to the electrical signal generated by the whipping motion of an unsecured cable exposed to an impulse noise pressure wave. Cable whipping has been documented as one source of electrical noise in blast type tests.

4.2.11 ORIENTATION OF THE PRESSURE TRANSDUCERS/ MICROPHONES

Pressure transducers and microphones oriented normal to the eardrum are recommended because this is the orientation of sound waves entering the human ear. This recommendation should be evaluated relative to the recommendation in 4.2.1. It may be preferable to mount transducers within a simulated ear canal. However, much of the published research has been done using dummy heads without ear canals and with the transducers suspended from the head.

4.2.12 PRESSURE TRANSDUCERS VS MICROPHONES

Issues considered in the selection of measuring equipment include:

- Should pressure transducers and microphones be used?
 - The German Arbeitskreis recommends two high level microphones (e.g., B&K 4136-WH2816 or equivalent). They specify mounting these in a dummy head mounted on a dummy torso.
 - Rouhana et al. (1994, 1998) recommended using pressure transducers. Many models are available that fulfill measurement requirements (Dytran piezoelectric 2013V and Endevco 8510B-2, 8510B-5, 8510B-50. Dytran current source, e.g., Model 4114.)

- Range of acceleration sensitivity: $<.0004$ psi/g
- Range of thermal sensitivity/Operating Temperature: $<.03\%$ / °F; -4 to +140 °F.
- Range of resonant frequency: > 50 kHz.
- System Flat Frequency Response: 0.16 Hz to 10 kHz; DC to 20 kHz (preferable).
- Pressure range: 0 to 2.5 psi rms (185 dB)
- Calibration issues: Dytran piezoelectric pressure transducers have no static response, but are calibrated using a shock tube. Endevco piezoresistive pressure transducers have static calibration, e.g., Series 8510B. The B&K 4136 condenser type microphone has piston phone calibration up to 124 dB, and a gated high-pressure calibrator up to 172 dB. (See also B&K 4136-WH 2816). B&K has Type 4231 sound level calibrator of 1000 Hz tone.
- Measuring instruments should be in accordance with SAE J247.
- Microphone preamplifier: e.g. B&K 2639 or B&K 2633 or equivalent; B&K measuring amplifier power supply 2609.

4.2.13 ALPHA CABIN ANALYSIS

- The determination of the reverberation times in the Alpha Cabin is carried out according to the following method: Excitation signals are generated in the Alpha Cabin by means of an octave impulse generator. The impulses have an octave bandwidth in which the center frequencies 0.5; 1; 2; 4 and 8 kHz are covered. A power amplifier amplifies the excitation signals and outputs them on two speakers, which are placed in the Alpha Cabin. The sound pressure in the relaxation process is recorded by a microphone at a height of approximately 0.75 m in the center of the Alpha Cabin and led to a measuring amplifier via a pre-amplifier.
- The reverberation time is measured and determined at a radius of 0.4 m at 12 positions for each of the five center frequencies. The measured signal is fed to a preprocessing unit where it is band pass filtered, digitized and intermediately stored. The preprocessing unit also carries out a compensation for basic noise and calculates the relaxation curve. The relaxation curve is determined according to the integrated impulse response method (Schroeder Method). The reverberation times used as a "measurement standard" and recommended for a "standard passenger compartment" are taken from Table 1 below:

TABLE 1—STANDARD PASSENGER COMPARTMENT

Frequency kHz	0.5	1	2	4	8
Reverberation time (ms)	92	58	39	37	35

4.2.14 DATA ACQUISITION

4.2.14.1 *Appropriate Methods of Data Acquisition Must be Used*

Data should be recorded wideband or sampled at no less than 50 kHz. The data acquisition rate appears to have an effect on the results obtained with the ear model and may need to be standardized to assure valid comparison of results from lab to lab.

4.2.14.2 *Test Initiation*

The system is triggered externally. In the case of multiple inflatable systems, the triggering can take place simultaneously or with a time delay between devices.

4.2.14.3 Test Signal Initiation

Devices should be deployed using the time spacing that would occur in real-world crash environments. For example, a side system might be deployed and then the frontal systems at a time phase that would represent first the side impact, then the vehicle spinning to hit in the front, thus firing the frontal airbags.

4.3 Analysis

4.3.1 RISK OF IMPULSE NOISE-INDUCED HEARING LOSS

The ARL Model calculates Auditory Risk Units (ARU) based on the fatigue hypothesis for the injury mechanism in the inner ear. This model was first created for the feline ear and was validated in experiments with anesthetized feline subjects exposed to non-depowered airbags (Price, Rouhana and Kalb, 1996) A human ear model version was created and is in the process of validation with data from human volunteer studies performed by the US Army. The pressure-time data recorded from tests with inflatable devices should be analyzed using the human ear model. No special format is necessary for the data. Data sets can be entered using the import function of the model.

4.3.2 WARNED VS UNWARNED EAR FOR USE WITH THE MODEL

The middle ear muscles can be evoked if an occupant "sees the collision" before an inflatable device deploys. Middle ear muscle contraction can be the response to a number of stimuli including: loud sounds, tactile stimulation of the head or general body movement. The model can simulate the muscles and some results show five-fold reduction in ARUs for a "warned" occupant compared with an "unwarned" occupant (with no middle ear muscle contraction).

4.3.3 SUSCEPTIBILITY

The model calculates the risk of impulse noise-induced hearing loss for the 95th percentile ear (i.e., an ear that is more susceptible than 95% of all ears in the population). Adjustments can be made for ears with other levels of susceptibility (e.g., the average or 50th percentile ear) by following the instructions in the "README" file associated with the model.

5. Key Findings of Previous Airbag Noise Studies

5.1 In-Vehicle Noise of a Barrier Crash With No Airbag Deployment

Rouhana et al. (1998) described results of a measurement made in a vehicle during a barrier crash. The peak SPL was approximately 145 dB. Hohmann (2000) also reported on measurements of crash noise from a car-to-car side impact crash at 50 km/h. The peak C-weighted SPL was 133 dB(C) at the inboard right front passenger's ear location.

5.2 Convertibles/Windows Down Vehicles vs Sedans/Windows Up Vehicles

(Rouhana, 1994, 1998): The ARL Model predicts a greater risk of noise-induced hearing loss for the convertible or open vehicle compartment. The low frequency carrier wave is absent or approaches zero when the vehicle compartment is open. With little low pressure to hold the stapes and annular ligament in tension, more high frequency oscillations are transmitted to the basilar membrane, producing a larger number of cycles of vibration and resulting in greater likelihood of fatigue. When the vehicle compartment is closed, the low frequencies push the stapes to its limit, restricted by the annular ligament, which appears to result in clipping the amount of high frequency noise that enters the inner ear. This produces fewer cycles of vibration of the Basilar Membrane and less risk of fatigue. The BBN method, now considered inappropriate for passive restraint impulse noise, predicts the risk to be exactly opposite the ARL Model's predictions.

5.3 SAE Tests Using Alpha Cabin

In 1998 SAE Researchers checked the first version of ARL model for humans against driver airbag signals measured in a trimmed Alpha Cabin.

5.4 1998 Weissach Tests Using Single Driver Side Airbags

SAE Researchers were perplexed that they did not replicate earlier findings that a closed compartment has lower risk than an open compartment. It appears that pressure from a driver side only restraint system, which is in the 140 dB range, either is not enough to cause NIHL or does not provide enough low frequency pressure to significantly affect the waveform; thus, the high frequency exposure shows the same risk. The ARUs calculated for these exposures indicated no risk.

5.5 ArbeitsKreis

Recent calculations using the Human Ear Model to analyze test data corroborated earlier findings that the risk caused by airbag inflation, as predicted by the model, can be lower in closed compartments than in open compartments. This is not always the case and may depend on the size of the airbag relative to the vehicle interior compartment size.

5.6 Head Position Relative to Sound Source

Anecdotal evidence shows a larger shift in hearing in ears that face the direction of the deploying airbag at the time of the crash (Rouhana, 1998; Yaremchuk, 1999). Military research has shown that ears exposed to noise at grazing incidence have a lower risk of noise-induced hearing loss than those exposed at normal incidence.

6. *Anecdotal Field Experience*

6.1 Saunders et al. (1995)

Presented details of six patients with threshold shifts who had been exposed to airbag deployment during a vehicle crash.