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Assessment of Auditory Hazard Resulting from Air Bag Deployment Noise

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ABSTRACT

Data from animal exposures to impulse noise is reviewed and an auditory injury criterion is proposed. The criterion is based on A-weighted acoustic energy, normalized to an equivalent 8-hour exposure, for which a level of 92 dB is estimated to cause unacceptable permanent auditory injuries in 10% of the population. Auditory hazard of air bag noise was assessed by comparing recent fleet representative air bag noise data with four impulse noise occupational standards used in NATO countries and with the auditory injury criterion arising from this study. The data analysis indicates that air bag deployment produces intense noise that exceeds each of the current occupational standards for noise related ear injury. Dual air bag deployments produce peak sound pressure levels from 165 to 175 dB and A-weighted energies as large as 97 dB. The proposed auditory injury criterion, together with the observed distribution of energy levels from the air bags tested, suggests that air bag noise can produce permanent auditory injuries in about 1-2% of the deployments.

INTRODUCTION

Air bags are achieving wide use as effective safety restraints, but the nature and risk of air bag deployment noise has not been fully characterized. To perform their function, air bags must deploy explosively, producing intense noise that can injure human ears. Understanding this intense acoustic phenomenon can help guide research in reducing the risk of ear injury. The genesis of air bag noise has been postulated to come from three sources: (1) the expansion of the bag, (2) the unfolding of the air bag surface, and (3) effects from inflator ignition and gas flow. The three sources can produce a combined noise that is dependent on the particular air bag characteristics.

Occupational standards for impulse noise have been developed, but quantification of permanent auditory injury is still an area of active research. After exposure to intense noise, a person's hearing can become less sensitive, that is, requiring a greater sound pressure for the same level of loudness perception. This effect is measured as a shift in the hearing threshold level compared to the mean sound pressure value of the general population. If this threshold shift disappears within a short period of time, it is considered as a temporary threshold shift (TTS). If the hearing threshold shift does not completely disappear but persists at an elevated level, it is considered a permanent threshold shift (PTS) or permanent hearing damage. The period for TTS to disappear varies, but Pfander has shown that PTS is not expected to occur if TTS disappears within 24-hr [1]. The level of TTS that will result in PTS is also not definitively known, but a TTS less than 25 dB has often been taken as a subinjury level.

Recently, General Motors Corporation (GMC) sponsored a series of air bag tests to determine impulse noise during realistic deployments and the US Army Medical Research and Materiel Command (MRMC) sponsored work to quantify auditory injury in animals and occupational exposure limits in humans. GMC, in cooperation with the Army Research Laboratory (ARL), conducted a series of tests to evaluate impulse noise hazards due to air bag deployment [2, 3, 4]. A wide variety of air bags and compartment conditions were evaluated and the data were provided to NHTSA to support ear injury research efforts. MRMC provided data from blast overpressure (BOP) tests conducted during the period from 1990 to 1998 using human volunteer subjects wearing hearing protection [5]. This data has been previously analyzed to evaluate existing auditory injury criteria [6, 7]. Extensive chinchilla data, collected by the United States Army Aeromedical Research Laboratory (USAARL) and the State University of New York (SUNY), have also been obtained to aid in understanding the relationships between PTS and exposure conditions [8, 9].

The objective of this work is to use the MRMC animal test data to construct an auditory injury criterion and to apply that criterion to the GMC air bag tests data and to produce a framework for evaluating and estimating the occurrence of permanent ear injury.

The Ear

A brief description of the human ear is given here to help set a perspective for the noise injury discussion to follow. A detailed discussion of ear physiology can be found in the literature [10, 11]. Figure 1a shows the schematic cross-section of the human auditory system [10] that is presented in four gross anatomical divisions: the outer ear, middle ear, inner ear and the central auditory nervous system, each with its unique mode of operation and function. Sound in the form of pressure waves is transmitted from the outer ear to the inner ear to be processed by the brain.

The outer ear consists of the visible pinna and the external auditory canal (ear canal) that leads to the eardrum (Figure 1a). The pinna collects and funnels the external sound pressure into the ear canal that is about 2-3 cm long. The pinna helps in localizing high frequency sounds, distinguishing between noises in front and back of the head, and providing some filtering of the incoming sound wave [10].

The middle ear starts from the eardrum, which is a cone-shaped membrane about 55-90 mm² in area made up of tissue layers (Figure 1b). The eardrum, also known as tympanic membrane, is attached to the manubrium (handle) of the malleus, the first and outermost of the three middle ear ossicles (Figure 1b). The head of the malleus is connected to the incus, the next ossicle. The incus points downward and bends inwards to connect with the third ossicle, the stapes (Figure 1b). The footplate of the stapes is implanted in the oval window, which is part of the inner ear (Figure 1a, b). The three middle ear ossicles are suspended in the tympanic cavity by ligaments and muscles [11].

For incoming sound with frequency from 1.5-7 kHz, the outer ear amplifies the sound level by 10-15 dB when it reaches the eardrum due to the resonance characteristics of the concha and the ear canal. The sound waves then vibrate the tympanic membrane, and the vibration is transmitted through the middle ear ossicles to the fluid filled inner ear (Figure 1a, b). The impedance mismatch between the air in the ear canal and the fluid in the inner ear is compensated by the area ratio between the eardrum and the stapes footplate, the lever action of the ossicular chain, and the buckling motion of the tympanic membrane (Figure 1b), which together can increase the sound level from the outer ear to the footplate by as much as 33 dB, peaking at 1-2 kHz.

The middle ear also provides some protection against intense noise through acoustic reflex due to the contraction of the supporting ligaments and muscles for the ossicular chain. Since the supporting muscles are normally in tension, they exert an increased pull when excited by sound level above 80 dB. This

middle ear muscle reflex can reduce the sound level reaching the inner ear by as much as 10-30 dB but it is frequency dependent, being more effective below 2 kHz. Furthermore, it takes at least 10 ms to activate this reflex action for intense noise, and the activation time can be as long as 150 ms for low intensity noise. Consequently, middle ear protection for impulse noise with sudden onset and short duration is not expected to be significant [11]. At intense noise levels, the motion of the ossicular chain and the ear drum also change to provide some additional protection effects.

Sound vibration eventually reaches the cochlea in the inner ear where a fluid-mechanical interaction excites the basilar membrane. The cochlea is the snail-like coil shown in Figure 1a. Figure 1c shows the schematic cross-section of the cochlea that contains three chambers (scalae) [11]. In the middle is the scala media that is separated from the scala vestibuli above by Reissner's membrane and from the scala tympani below by the basilar membrane (Figure 1c). The scala vestibuli and scala tympani join at the apex by the opening helicotrema. The cochlea when unfolded is about 35 mm long, as shown in Figure 1d. The stapes transmits the vibration through the oval window onto the fluid in the scala vestibuli and fluid is displaced to the round window (Figure 1d). The fluid motion causes a wave-like displacement of the basilar membrane. Although the cochlea duct is larger near the base than the apex, the basilar membrane widens in the opposite way [11].

Sitting on the basilar membrane in the scalar media is the organ of Corti, which is the auditory mechano-electrical transducer (Figure 1c, d). The Corti contains many inner and outer hair cells that communicate via chemical synapses with the end branches of the auditory nerve fibers [11]. When the basilar membrane is displaced, the hair cells are deflected and neural firings are sent to the brain where they are interpreted as sound. High frequency sound causes stronger displacement of the basilar membrane near the base while low frequency sound produces stronger motion near the apex. The ear has the capability to analyze complex spectral contents in sound. When overexposed to noise, the hearing capability of the ear can be damaged as a result of damaged hair cells. In simple terms, continuous noise tends to damage the hair cells as a "fatigue" process over a long time period. In contrast, due to its intense nature, impulse noise can cause traumatic mechanical damage to the hair cells over a short duration, as observed in animal tests [8, 9]. The eardrum and the ossicular train can also be damaged by intense noise.

Auditory Injury Criterion

There are four criteria used by NATO countries to set occupational exposure limits to impulse noise, each defined in terms of an effective exposure level and a limit. The four criteria are the a) MIL-STD-1474D in the USA [12], b) Pfander in Germany [1, 13, 14], c) Smoorenburg in the Netherlands [15], and d) L_{Aeq8} in France [16]. The first three criteria are peak-based while the fourth one is based on energy. Human exposures at these limits are expected to be "safe" and produce no deleterious effects. Consequently, these are not injury criteria, but are measures that help set a framework for evaluating noise hazard.

The peak-based criteria use peak pressure and waveform durations to calculate the effective exposure level L_M which for the MIL-STD is the peak pressure level L_{pk} expressed in dB as

$$L_{pk} = 10 \log (P_{max}/P_{ref})^2 \quad (1)$$

Gross division	<i>Outer ear</i>	<i>Middle ear</i>	<i>Inner ear</i>	<i>Central auditory nervous system</i>
Anatomy	<p>The diagram shows a cross-section of the human ear. The outer ear includes the pinna, concha, external auditory canal, and external auditory meatus. The middle ear contains the malleus, incus, and stapes, along with the ear drum and eustachian tube. The inner ear consists of the vestibule, vestibular n., semicircular canals, cochlea, and round window. The central auditory nervous system includes the facial n., cochlear n., and internal auditory canal.</p>			
Mode of operation	<i>Air vibration</i>	<i>Mechanical vibration</i>	<i>Mechanical, Hydrodynamic, Electrochemical</i>	<i>Electrochemical</i>
Function	<i>Protection, Amplification, Localization</i>	<i>Impedance matching, Selective oval window stimulation, Pressure equalization</i>	<i>Filtering distribution, Transduction</i>	<i>Information processing</i>

Figure 1a. Cross section of human ear, showing divisions into outer, middle, and inner ears and central nervous system. Taken from Ch. 6 of Ref. [9].

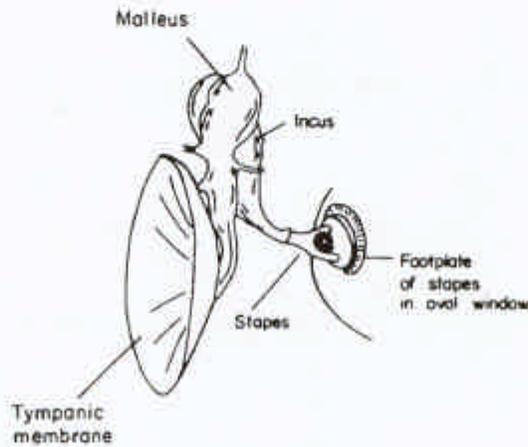


Figure 1b. The ear drum and three ossicles in the middle ear. Taken from Ch. 3 of Ref. [10].

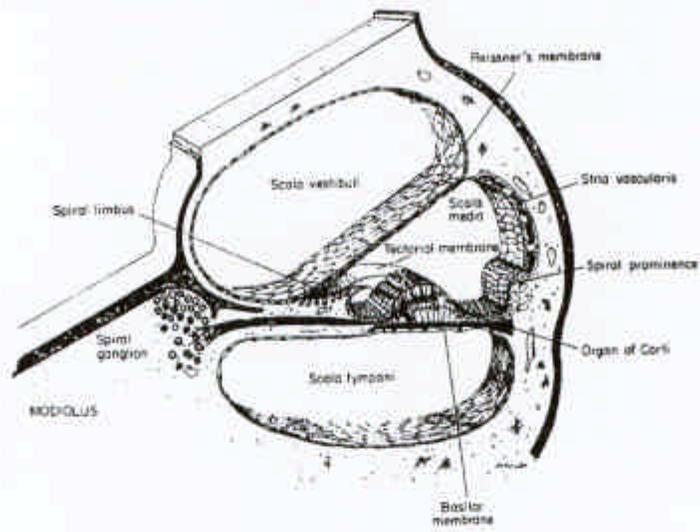


Figure 1c. A cross-section of the cochlear duct. Taken from Ch. 3 of Ref. [10].

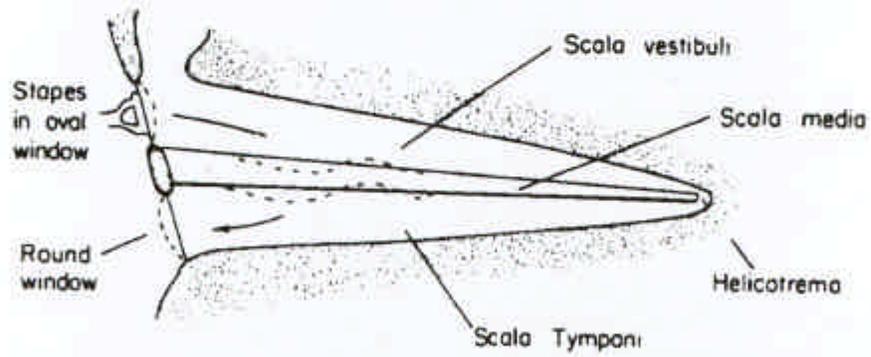


Figure 1d. The schematic diagram of the unfolded cochlea. Taken from Ch. 3 of Ref. [10].

Figure 1. Illustration of the human ear system.

where P_{max} is the peak pressure of the pulse and P_{ref} is the reference pressure of $20\mu\text{Pa}$. For unprotected ears, the MIL-STD-1474D limit is $L_M < 140$ dB. The definitions of four waveform durations are shown in Figure 2. The Pfander criterion calculates the effective exposure level L_P using L_{pk} and C-duration, T_C with the limit of $L_P \leq 160$ dB [13, 14]. Smoorenburg uses L_{pk} and D-duration, T_D , with a limit of $L_S \leq 166.2$ dB (Table 1).

Table 1. NATO Auditory Criteria for Impulse Noise

Criteria	Effective Exposure Level (dB)	Limit (dB)
MIL-STD-1474D (1991)	$L_M = L_{pk}$	$L_M \leq 140$
Pfander (1994)	$L_P = L_{pk} + 10 \log T_C$	$L_P \leq 160$
Smoorenburg (1982)	$L_S = L_{pk} + 10 \log T_D$	$L_S \leq 166.2$
France (L_{AeqB}) (1995)	$L_{AeqB} = SELA_B$	$L_{AeqB} \leq 85$

The French criterion uses A-weighted energy, which computes a total acoustic energy, emphasizing the frequencies to which the human ear responds. The French Committee on Weapon Noises (FCWN) proposed a criterion based on the A-weighted 8-hr equivalent sound exposure level, L_{Aeq8} . The unweighted energy of a pulse is called the sound exposure level (SEL), which is the integral of the pressure squared over time

$$SEL(\text{dB}) = 10 \log_{10} \left[\int_0^{\infty} \left(\frac{P(t)}{20 \mu\text{Pa}} \right)^2 \left(\frac{dt}{1 \text{ sec}} \right) \right] \quad (2)$$

SEL can also be calculated in the frequency domain using the Fourier transform of the pressure signal according to Parseval's Theorem [17]

$$\int_{-\infty}^{\infty} P^2(t) dt = \int_{-\infty}^{\infty} |P(f)|^2 df \quad (3)$$

where $P(f)$ is the Fourier transform, and f is frequency in Hz. When A-weighting is applied, the pressure spectrum squared is multiplied by a weighting function $A(f)$ as shown in Figure 3 [17]. The A-weighting function is a close approximation of the hearing threshold, indicating that the ear is much less sensitive to noise in the low and high frequencies than in the midrange frequency from 1-2 kHz (Figure 3) [17]. In discrete form, the A-weighted sound exposure level SELA of a single pulse is computed as

$$SELA = \frac{10 \log}{(20 \mu\text{Pa})^2} \sum_n |P_n e^{2\pi i f_n}|^2 A(f_n) \Delta f_n \quad (4)$$

where P_n is the coefficient of the Fourier component for each frequency f_n . Borrowing from the continuous noise concept, the A-weighted energy for one pulse can be expressed as an 8-hour equivalent dose, $SELA_8$, which is equivalent to dividing the integral of SELA by 8 hours (28,800 s) or subtracting 44.6 dB from the SELA calculated using the equation above. For the present analysis, since only single pulse conditions are analyzed (as dual bags deploy simultaneously), L_{Aeq8} is equal to $SELA_8$.

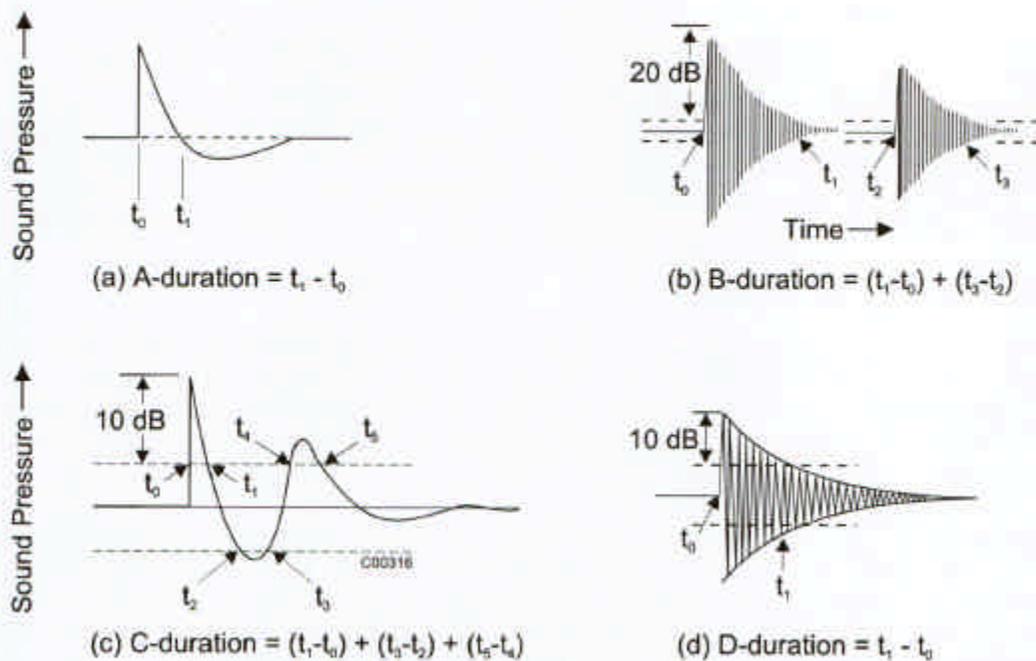


Figure 2. Definition of impulse duration (taken from [14]).

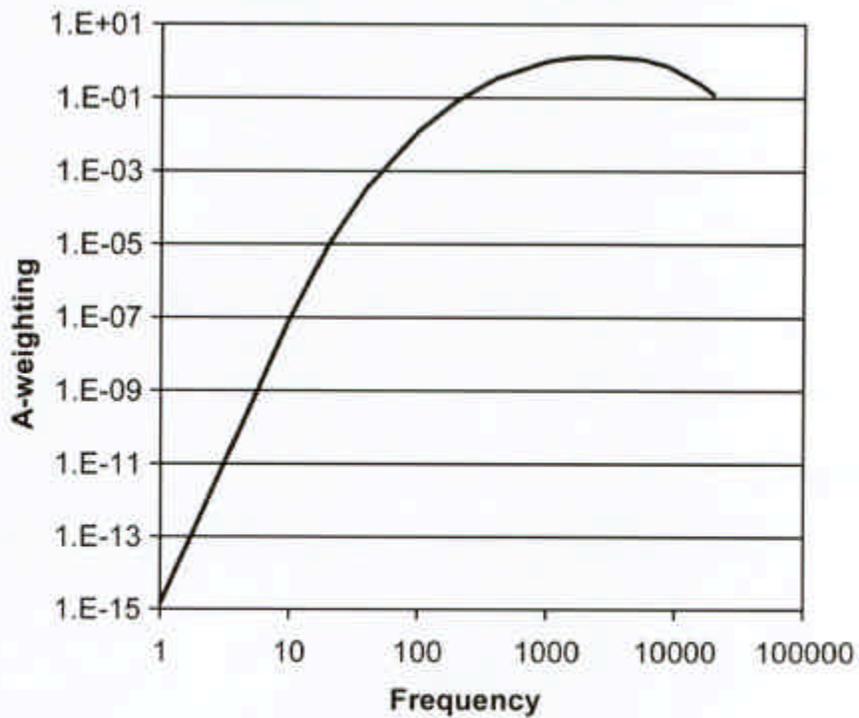


Figure 3. A-weighting function.

The four NATO criteria were analyzed against auditory data from SUNY using 888 chinchillas exposed to impulse noises [8, 9]. Nonlinear regression was used to determine the correlation of the chinchilla PTS data to each of NATO exposure criteria. Based on the variance of the regression coefficients, it was determined that A-weighted energy provided the best correlate of permanent auditory injury. This analysis was used to infer human auditory response because animal data is the best available for the determination of a relation between PTS and impulse noise and because human PTS data are not available. Figure 4 shows the growth of PTS averaged at 1,2 and 4 kHz with A-weighted energy covering the 90th percentile chinchilla injury data (most sensitive ears). The regression can be approximated by

$$PTS(dB) = 2 [L_{Aeq8} - L_{Aeq8}(\text{threshold})] \tag{5}$$

These findings are taken to be applicable to humans and so PTS may develop in the 10% most sensitive part of the population at a rate of 2 dB for every dB that L_{Aeq8} exceeds the human threshold for PTS. Dancer [16] used field data to show that $L_{Aeq8} = 85$ dB provides the same protection as Pfander's criterion, which is designed to not allow PTS. Therefore, the threshold of PTS in humans is taken as $L_{Aeq8} = 85$ dB.

A PTS greater than or equal to 15 dB is taken to be an unacceptable hearing loss, leading to the proposed injury criterion shown in Table 2. The Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) recommended that PTS should not exceed 10 dB at 1 kHz and below, 15 dB at 2 kHz or 20 dB at 3 kHz due to impulse noise [18, 19]. This limit represents an averaged PTS of 15 dB. Smoorenburg, supported by speech intelligibility data, uses a limit of 15 dB PTS averaged over 1, 2, and 3 kHz for establishing his damage risk criteria for impulse noise [15, 20]. While impairment is a subjective condition, we adopt 15dB as an unacceptable level of permanent hearing loss.

Table 2. Injury Guidelines Based on A-weighted Energy.

Auditory Injury Guidelines	
L_{Aeq8}	Expected Effect
< 85 dB	Safe by occupational standards. No permanent hearing effects.
> 85 dB	Permanent hearing loss generated in 10% of the population at the rate of 2 dB for every 1 dB above 85 dB
> 92 dB	Unacceptable PTS in 10% of the population

Analysis of Air Bag Noise

Pressure-time data from air bag deployments, measured at the inboard locations for both the driver and passenger sides, were obtained from General Motors Corporation and used to assess auditory injury potential. The data was provided in three sets.

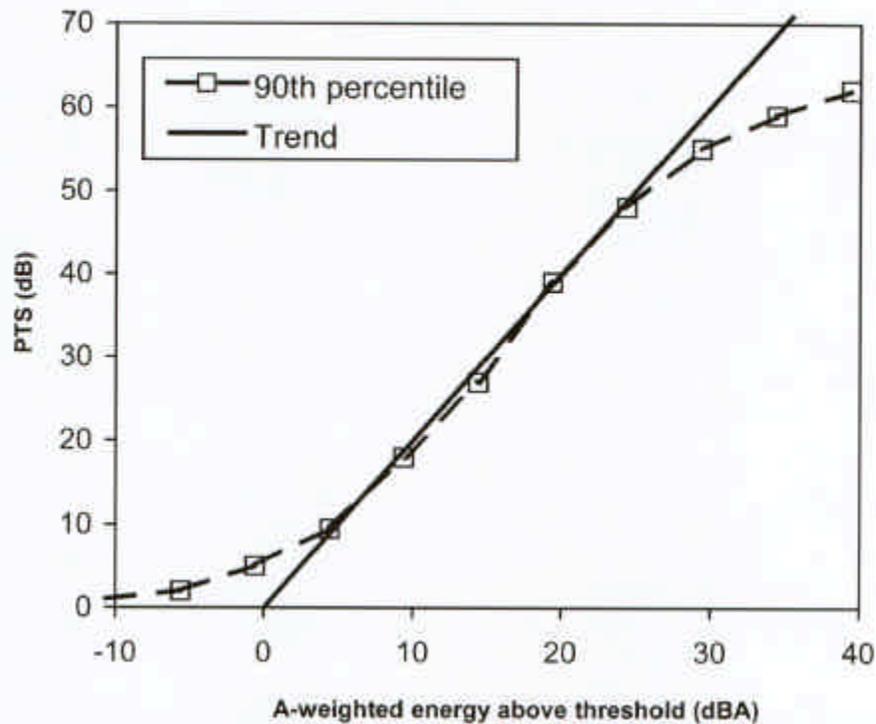


Figure 4. Growth of PTS above threshold for chinchilla.

Aberdeen Tests: Sixteen tests conducted using one vehicle type. The interior compartment volume was equal for all the vehicles in this series (62.8 cu ft) and the effects of open doors (with open windows), closed unsealed doors, and closed sealed doors were studied.

Repeatability Tests: Twenty tests, performed using the same interior volume as the Aberdeen tests to verify the instrumentation used. Only passenger air bags were deployed, and instrumented dummies were placed in the passenger compartment.

Competitive Tests: Forty-three tests, conducted with a selected set of vehicles with fleet representative interior volumes as well as air bag types. The interior volume varied from 62.9-122 cu ft. Most of the tests deployed dual air bags, with some using just the driver air bags.

The data was examined for consistency and pressure traces that were judged to be unrealistic were not included in the analysis. The data were aligned to a common time axis and a Fast Fourier Transform (FFT) was performed to determine spectral energy content needed to evaluate some of the auditory criteria.

Pressure peaks and duration generated by air bag deployment can vary widely depending on the door conditions, but A-weighted energies are nearly equal for different door conditions. Selected pressure waves and their accumulated A-weighted energies from the Aberdeen tests were compared for three compartment conditions: (1) doors sealed, (2) doors closed (but not sealed), and (3) doors open, representing a decreasing level of air-tightness of the compartment (Figure 5). For three selected driver side traces from dual bag tests, the peak pressure increases from 4.5 kPa with doors open to 7.8 kPa with

the doors sealed (Figure 5a). The positive A-duration increases from 5 ms with doors open to 130 ms with doors sealed (Figure 5a). When the doors are sealed, the pressure peak is primarily due to the compartment pressurization by the air bag expansion, resulting in a peak time at about 50 ms, which is also the typical inflation time for an air bag (Figure 5a). With the doors open, the pressure peaks in a few milliseconds, bearing a closer resemblance to a shock wave than the closed and sealed door cases (Figure 5a). Significant post-peak ringing is observed from 10-80 ms for the open door condition, showing that noise reverberation inside the compartment still continues even with doors open (Figure 5a). The pressure wave for the closed door (unsealed) compartment lies between the open and sealed door conditions, resulting in a peak time at 25 ms and an A-duration of 110 ms (Figure 5a). For all the three selected cases, the total accumulated A-weighted energy of about 94 dB is about 15 dB (30 times) higher than that up to 700 Hz (Figure 5b). This suggests that most of the A-weighted energy actually comes from vibrations higher than 700 Hz, which corresponds to a time scale of 1.4 ms that is much shorter than the typical air bag inflation time of about 50 ms (Figure 5b). Furthermore, the differences in the total A-weighted energies between the three door conditions amount to less than 2 dB (Figure 5b).

Analysis of all of the test data shows that the noise from deployment of the air bags tested exceeds all of the occupational impulse noise thresholds. Comparison of all the data from the "Aberdeen," "Repeatability" and "Competitive" tests against the four NATO criteria are shown in Figure 6. Most single bag data, and all the dual bag data, exceeded the L_{Aeq8} threshold by 3-12 dB (Figure 6a). Only some single bag cases fall below the L_{Aeq8} threshold (Figure 6a). All the data exceeded the Pfander and Smoorenburg thresholds by 10-25 dB (Figure 6b-c). Furthermore, as shown in Figure 6d, all the data exceeded the US L_{pk} limit of 140 dB, by as much as 30 dB.

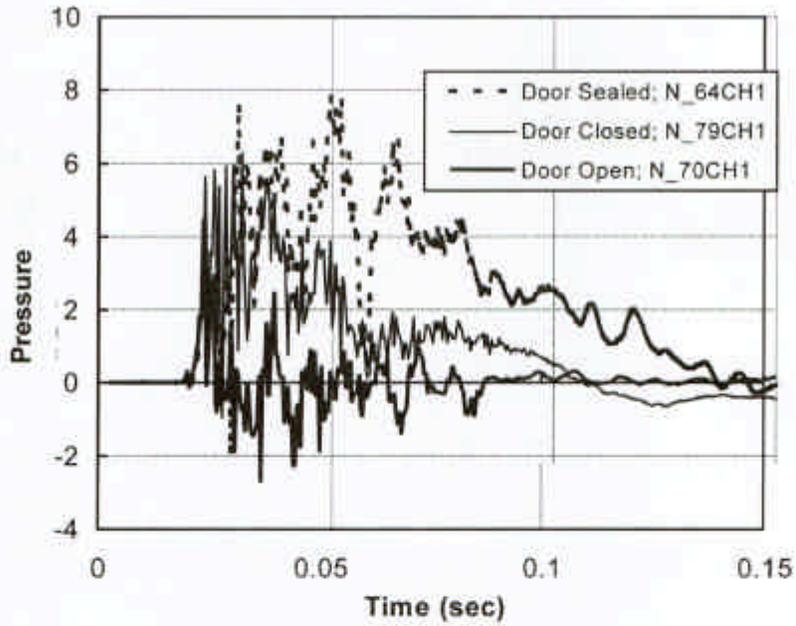
For the air bags tested, about 10% of the deployments exceed the level at which 10% of the population would exceed the unacceptable PTS of 15 dB. Using the auditory injury criterion developed in this study, we can estimate the rate of occurrence of unacceptable PTS due to air bag deployment. For the air bags tested, the most energetic 10% produced A-weighted energy 8-12 dB above the current occupational threshold (Figure 7). Based on the proposed injury criterion, the most susceptible 10% of the population would suffer 16-24 dB of PTS. Compounding these percentages, we would estimate that unacceptable PTS level could occur in about 1-2% of the air bag deployments.

SUMMARY

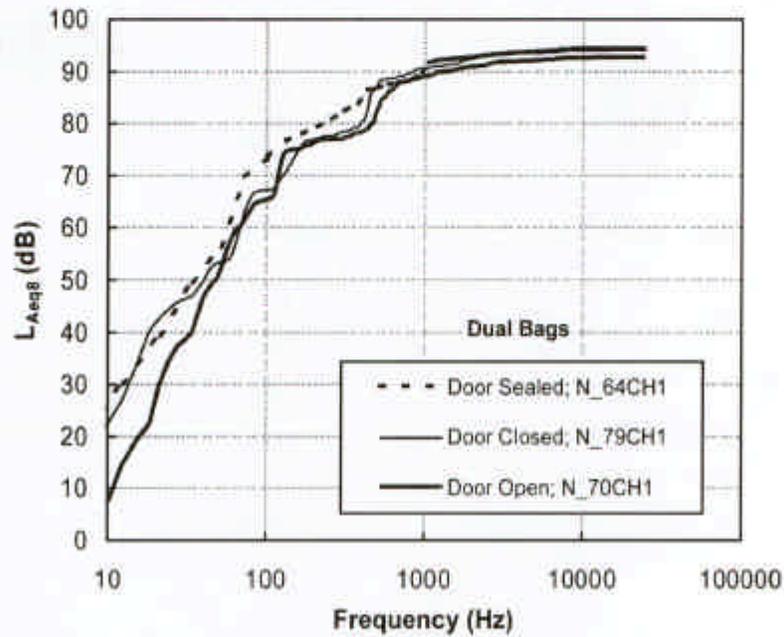
An auditory injury criterion based on A-weighted energy, L_{Aeq8} , that establishes a threshold and rate of generation of permanent auditory injury has been developed. This criterion uses $L_{Aeq8} = 92$ dB as the level at which 10% of the population will suffer significant hearing loss.

Based on the air bag tests analyzed, 10% of the air bags exceed the 92-dB criterion; resulting in the estimate that 1-2% of the population exposed to such deployments could incur unacceptable PTS.

Because of the large differences in the time scales of acoustic waves and the overall air bag inflation, they are probably controlled by different phenomena, so that acoustic measurements may be required.

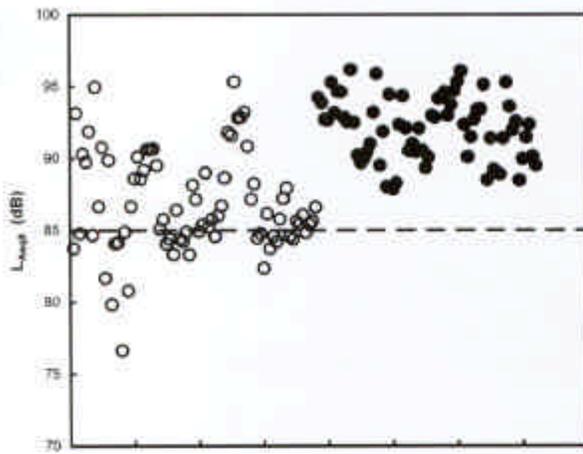


(a) Pressure history

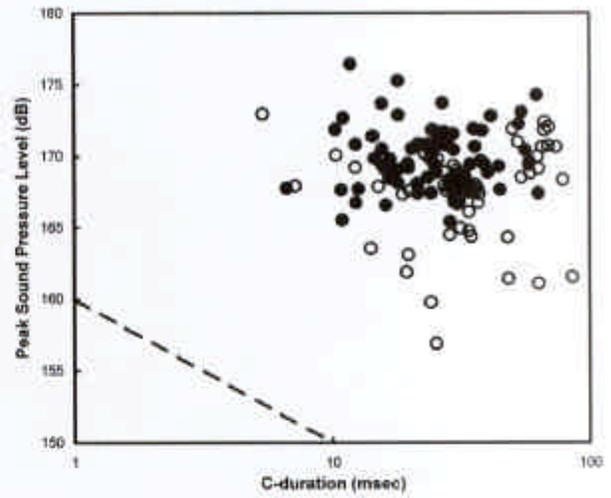


(b) Accumulated A-Weighted energy

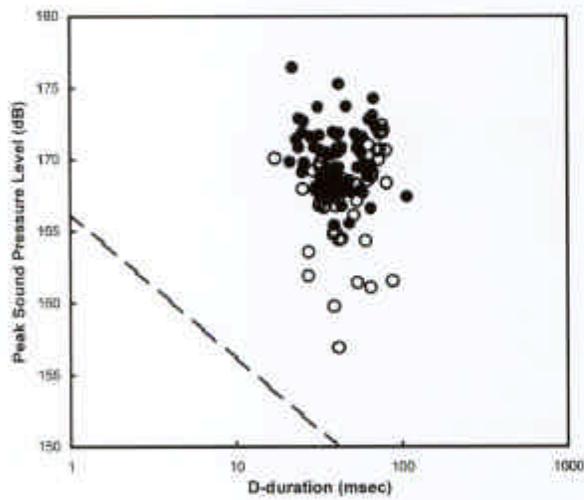
Figure 5. Waveform comparison (Aberdeen tests).



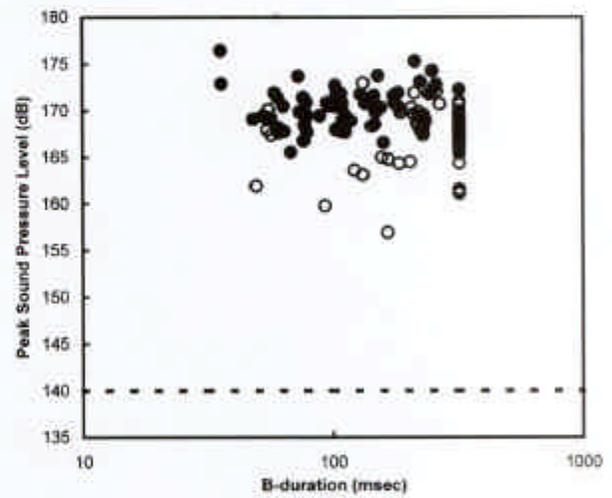
(a) LAeq8



(b) Pfander



(c) Smoorenburg



(d) Mil-Std-1474D

Figure 6. All data comparison with NATO criteria.

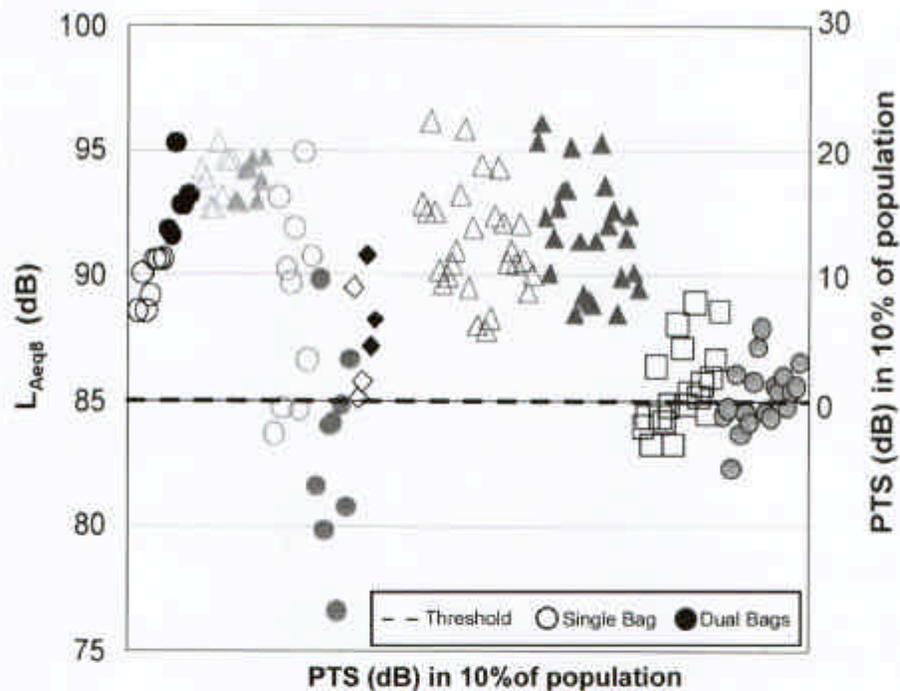


Figure 7. Estimated PTS in 10% of population due to air bag deployment.

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