WIND-NOISE, HEARING LOSS AND MOTORCYCLISTS

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ABSTRACT

An investigation was undertaken to establish the source and effects of noise to which motorcyclists are exposed. Various methods of noise reduction and their effects have also been assessed.

It would appear that at about 40mph, wind noise caused by turbulent airflow around the rider's helmet becomes the dominant sound source, exceeding vehicle noise and the safe occupational maximum of 90dB(A). It continues to increase, linearly with $\log_{10}$ speed, to reach levels of 110dB(A) at 100mph. Wind tunnel work indicates that the source of this noise is random pressure fluctuations in the thin boundary layer adjacent to the helmet shell. As currently designed, crash helmets provide no useful attenuation against this low frequency noise.

These sound levels have been found to cause significant temporary threshold shift after only 1 hour of typical motorway speed riding, and with time, significant persistent hearing loss at 0.25, 0.5, 1 and 2kHz when compared to appropriate controls from the MRC National Study of Hearing.

Most riders are unaware of this noise problem; only 15-25% of riders regularly wear earplugs which are currently the only available protection. Although providing a set of earplugs with a new crash helmet at the point of sale can significantly improve the useage rate to 83%. Soft yellow foam plugs (EARfit, Cabot Safety Ltd, UK) appear to be the optimal choice on the grounds of their low cost, easy availability and most importantly comfort. They are without doubt effective as shown by their ability to abolish the temporary threshold shift associated with high speed riding.
In addition, with earplugs in place, for speeds of 40mph and greater the rider is at a significant sensory advantage with regard to the detection of typical traffic signals.

Efforts to try and produce a "quiet" helmet using a variety of aerodynamic modifications have been singularly unsuccesful. However, incorporating a set of standard earmuffs under the helmet shell has achieved highly significant reductions in "at ear" wind noise levels. A working prototype using earmuffs and a pneumatic control system now exists, and should ultimately prove to be an acceptable solution to this unpleasant problem.

PUBLICATIONS ARISING FROM THIS WORK

1. McCombe AW, Binnington J, Donovan D and McCombe TS. Wind noise and motorcyclists. The Lancet, 1992, 340, 911-912.

2. McCombe AW, Binnington J and Donovan D. Hearing loss in Grand Prix motorcyclists: occupational hazard or sports injury? British Journal of Sports Medicine, 1994, (In press).

3. McCombe AW, Binnington J and McCombe TS. Hearing protection for motorcyclists. Clinical Otolaryngology, 1993, 18, 465-469.

4. Binnington J, McCombe AW and Harris M. Warning signal detection and the acoustic environment of the motorcyclist. British Journal of Audiology, 1994, (In press).

5. McCombe AW, Binnington J and Bose R. Wind noise and motorcyclists (Abstract). Clinical Otolaryngology, 1993, 18, 464.

6. McCombe AW, Binnington J and Nash D. Two solutions to the problem of noise exposure for motorcyclists. Occupational Medicine, 1994, (In press).

DECLARATION OF COMPOSITION

I declare that this thesis and the contained work are completely my own. The planning and described experimental methods have been mine alone. I have been the lead investigator for all experiments except for the one exception described below.
Mr D Nash undertook the wind tunnel work described in Chapter 2 as part of his 2nd year engineering degree project. This project followed discussions between us and was guided by the results of work I had already performed. It is published in full elsewhere (Nash, 1993) and only a small part is reproduced in this thesis.

In addition, I have had a great deal of practical help in performing many of the experiments from Mr J Binnington. My wife, Tracy, helped with the interviews described in Chapter 4 and the survey of chemists shops described in Chapter 5.

I further declare that the work contained in this thesis has not been submitted by me for any other degree, diploma or professional qualification.

Andrew W McCombe 15/3/94

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As a mark of respect to all those people who have helped and supported me with this work the plural pronoun "we" has been used throughout the text rather than the singular "I".

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LIST OF ABBREVIATIONS

BS: British Standard

BSA: British Society of Audiology

MDL: Minimum detection level

mph: miles per hour

m/s: metres per second

NIHL: Noise-induced hearing loss

NSH: National Study of Hearing

PTS: Permanent threshold shift

TTS: Temporary threshold shift

WN: Wind noise

CHAPTER I

1. INTRODUCTION AND LITERATURE REVIEW

2. HYPOTHESES AND PLAN OF THESIS

1. INTRODUCTION AND LITERATURE REVIEW

THE NATURE OF SOUND

(Acton and Grime, 1978; Beagley, 1981; Beynon, 1993; Goodwin, 1987; Ludman, 1988; Pickles, 1988)

Sound is a form of energy transmitted through a medium (solid, liquid or gas) by means of pressure waves whose oscillations are parallel to the direction of wave travel. They are defined as longitudinal waves and differ in this respect from electromagnetic energy waves which have a wave motion perpendicular to the direction of wave propagation. There are a number of important parameters that describe the character of a sound wave as it passes a fixed point in space.

1. Velocity of wave propagation (c)
This depends on the density and elastic modulus of the medium carrying the sound. In air the velocity is given by the formula:

$$c = 331 + 0.6t$$

where c = the speed of sound in metres per second (m/s), and t = temperature in degrees Celsius.
For typical atmospheric conditions this equates to a speed of approximately 340m/s.

2. Wavelength (Lambda: λ)
This is the distance in metres between corresponding points on the waveform. Sound can be represented by a series of compressions and rarefactions in the density of the air, which move away from the source of the sound, with no net displacement of the air molecules. If we consider our fixed point in space, the wavelength of a sound will be the distance that the wavefront advances in the time that a solitary particle of the transmitting

medium moves from its rest position to that of maximal positive displacement, back past its rest point to its position of maximal negative displacement and finally back to its resting position.

3. Frequency (Hertz: Hz)
This is the number of full cycle oscillations as described above that occur in the time period of 1 second; it has a subjective correlate in pitch.

These 3 parameters are closely interelated as is shown by the formula:

$$c = f \lambda$$

4. Wave amplitude
To complete the description of a sound requires some indication of its "magnitude", which is subjectively correlated with loudness. Measurement of the amplitude of the displacement of the transmission medium particles is difficult; measurement of the average rates of energy flow past a given point in space is much simpler. Consequently sound intensity and sound pressure level are the measures used. Sound intensity is defined in terms of the average rate of energy flow per unit area and is measured in terms of watts per square metre (W/m^2). This measure is based on the principle that sound radiates spherically from a point source and will obviously become less intense as it radiates further from the source. This phenomena obeys the inverse square law:

$$\text{sound intensity} \propto 1/r^2$$

where r = the distance from the sound source in metres.

Under typical atmospheric conditions sound intensity is proportional to the square of sound pressure which is measured in Newtons per square metre (N/m^2) or Pascals (Pa).

The range of pressures required for measurement of the human ear is so great that a logarithmic system has been developed to cope: the decibel (dB). In this system the sound intensity or sound pressure level is expressed as a ratio against a reference value as shown:

$$\text{Sound intensity (dB)} = 10\log_{10} Im/Iref$$

where Im = the measured intensity and Iref = the reference intensity.

With the previously noted relationship between Intensity and pressure we also get:

$$\text{Sound pressure level (dB SPL)} = 10\log_{10} Pm^2/Pref^2$$

$$= 20\log_{10} Pm/Pref$$

Obviously these equations are meaningless without their reference values. For sound pressure levels the reference value is defined as 2×10^{-5} Pa and for sound intensity as 10^{-12} W/m^2.

In general, pressure measurement is easier than intensity measurement, and this is therefore the more widely used measure [dB Sound Pressure Level (SPL)].

Although these measurements will define a pure-tone completely, sound as it occurs in the real world is rarely if ever a pure tone and is invariably a mixture of tones. In fact it is this very mixture that gives various sounds their unique "character". (The breakdown of these complex waveforms into their component pure-tones is described as a Fourier analysis and is to some extent performed within the human ear.) That said, these criteria will still provide an adequate description for most situations.

THE HUMAN EAR

The human ear is traditionally divided into 3 parts: the outer, middle and inner ears.
The outer ear consists of the external pinna, with its convoluted shape, and the external auditory meatus and canal. The outer ear displays several properties. It acts as a "funnel" to direct sound onto the tympanic membrane (Ludman, 1988; Pickles, 1988). The convoluted shape of the pinna leads to resonances at certain frequencies which are direction dependent (Pickles, 1988; Fischer and Schafer, 1991), an important property for sound localisation. Finally, the ear canal exhibits its own natural resonance which is maximal around 3kHz and may be important for augmenting sounds in the "speech frequencies" (Pickles, 1988; Beynon, 1993).
The middle ear is an air-filled space bounded by the tympanic membrane laterally and the promontry with the oval and round windows medially. It contains the 3 ossicles: malleus, incus and stapes. The function of the middle ear is essentially as an impedance matching mechanism converting the low-pressure, high amplitude air born sound waves into higher-pressure, lower-amplitude waves in the fluid filled cochlea. It also acts as an acoustic baffle, separating movements of the round and oval windows by way of its air cushion and contains two muscles involved in protective acoustic reflexes, with the stapedius muscle being particularly important (Henderson, 1993). These muscles appear to have a greater attenuating effect on low-frequency sounds (Pickles, 1988).
The inner ear or labyrinth consists of the semi-circular canals which are responsible for the detection of angular acceleration, the utricle and saccule which are responsible for the detection of linear acceleration and the cochlea, which we are particularly concerned with, which is responsible for the detection of sound by

converting the mechanical pressure fluctuations of sound into electro-chemical neural impulses. This is achieved in the Organ of Corti by a remarkably elegant and sensitive system of fluid compartments, neural and supporting cells (Figure 1-1). Although a coiled structure, the cochlea can be thought of as a U-shaped tube around the basement membrane and organ of corti with the oval and round windows at each end. There is 1 row of inner hair cells (IHC) and 3 rows of outer hair cells (OHC), numbered 1-3 from centrally to peripherally. The IHC do not make direct contact with the tectorial membrane although the OHC, and particularly those in row 1, are embedded in it (Saunders, 1985; Lim, 1986). There are other fundamental differences between the IHC and OHC, the OHC receive efferent innervation via the olivo-cochlear bundle, contain contractile proteins and exhibit motility, whereas the IHC do not and have a richer afferent innervation (Collet, 1993; Johnstone, 1986; Kemp, 1980; Kim, 1984; Khanna, 1984; Zenner, 1993; Ashmore, 1993). These facts all have a bearing on cochlea function.

Sound waves are transmitted to the cochlear perilymph by vibrations of the stapes, moving with a piston-like action at low frequencies and with a rocking motion at higher frequencies. The basilar membrane varies in width, thickness and stiffness along its length, being narrower, thicker and stiffer at the basal end. This physical characteristic gives rise to "travelling waves": trains of waves in the perilymph which cause vibration of the basilar membrane. This vibration will reach a maximum amplitude at a specific point along the basilar membrane that is frequency specific and intensity dependent. Travelling waves caused by high frequencies reach a maximum at the basal end of the cochlea and low frequencies at the apical end (Von Bekesy,1960; Burns, 1973a; Thornton, 1981; Pickles, 1988).

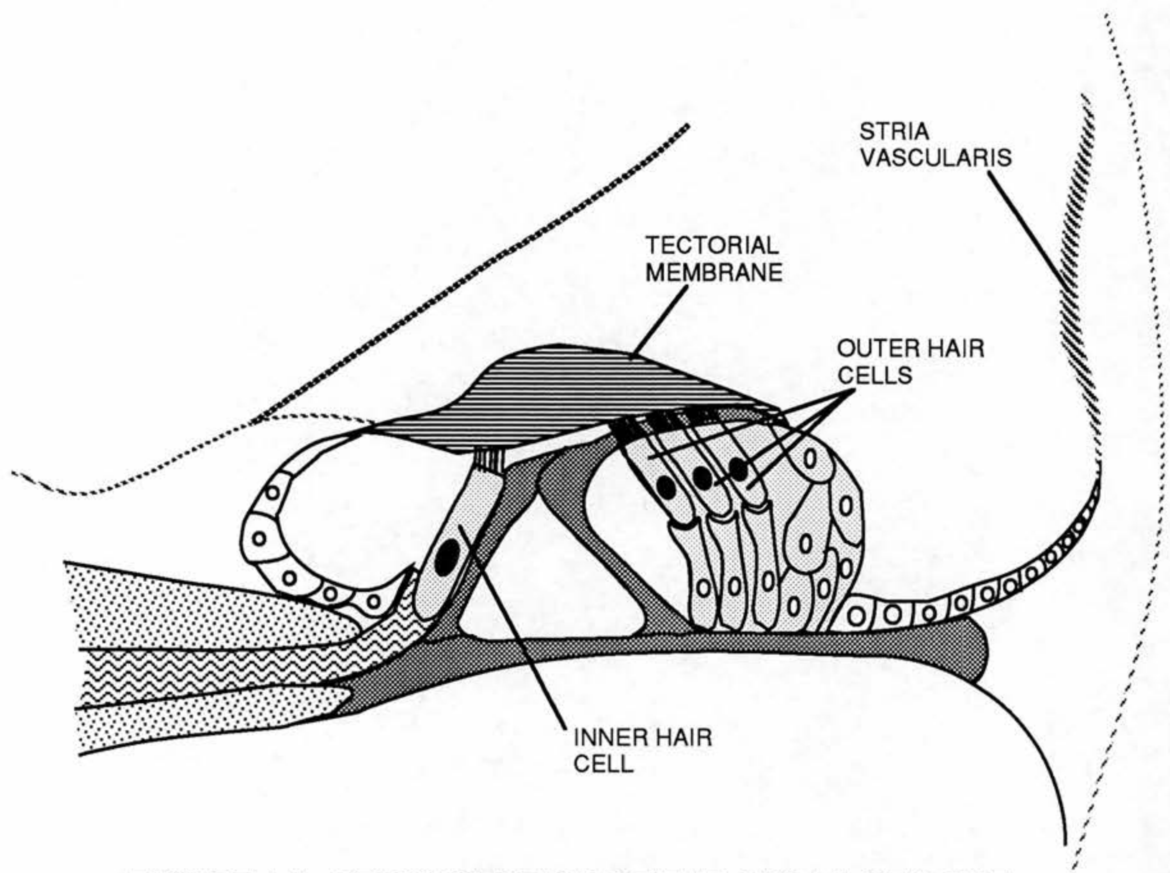


FIGURE 1.1 CROSS SECTION OF THE ORGAN OF CORTI

Increasing the intensity of the sound tends to move the point of maximal vibration towards the basal turn by as much as 0.5-1 octave (McFadden,1982). As their points of attachment and arcs of rotation are different, movements of the basilar membrane lead to shearing of the hair cells against the tectorial membrane. This bending of the stereo-cilia on the hair cells leads to either hyper- or de-polarization depending on the direction. If the depolarization is of sufficient magnitude an action potential will result (Burns, 1973a; Pickles, 1988).
The cochlea displays far more "fine tuning" than is accounted for by this passive mechanism alone. Further "fine tuning" is provided by the outer hair cells acting as the so-called "second filter". In essence they work as follows: the travelling wave reaches its point of maximum amplitude at some point along the basilar membrane. This is sensed by the OHC in this region, active processes and OHC motility then come into play with the OHC at the region of maximum amplitude acting to increase the vibration, up to 100-fold, with the result that there is a marked increase in the maximum vibration limited to a very narrow region of the basilar membrane. The IHC at this point may then function in a purely sensory fashion with depolarisation leading to stimulation of the cochlea nerve, which in turn relays to higher centres to provide the perception of sound (Ashmore, 1993; Johnstone, 1986; Khanna, 1984; Kim, 1984; Lim, 1986; Pickles, 1988; Patuzzi, 1993).
By their property of motility, OHC are also thought to offer some protection against NIHL (Henderson, 1993), possibly by reducing the overall excursion of the basilar membrane in response to loud sound stimulation (Zenner, 1993). They are also the source of otoacoustic emmissions (Kemp, 1980).

It is noteworthy that the human ear responds to both frequency and intensity in a geometric rather than arithmetic fashion. Indeed a doubling of the presented frequency is perceived as an octave and a 10dB increase is usually perceived as a doubling of sound intensity (Moore, 1989).

The ear has a functional frequency range of 20 to 20000 Hz but is not equally sensitive to sounds in this range. It exhibits maximal sensitivity to sounds in the "speech frequencies" i.e. between 500 and 4000Hz. In an effort to relate measured sound level with the subjective perception of loudness, a suitable correction factor can be applied to each frequency of perceived sound. A variety of scales exist for this purpose but the A-weighting scale is most commonly used as it most closely matches measured and perceived sound levels. It is shown in Table 1-1 and uses 1000Hz as the reference frequency. To give an example a tone of 500Hz of intensity 100dB SPL would in fact have a perceived intensity of 97dB(A) as the ear is 3dB less sensitive to sound at this frequency than at 1000Hz (Goodwin, 1987; Beynon, 1993).

TABLE 1.1 CORRECTION FACTORS FOR CONVERTING dB (SPL) to dB(A)

FREQUENCY (Hz)	36	125	250	500	1000	2000	4000	80000
A WEIGHTED CORRECTION FACTOR (dB)	-26	-16	-8.5	-3	0	+1	+1	-1

DAMAGING EFFECTS OF NOISE

Noise can be described as any unwanted or obtrusive sound and in excessive amounts can damage the very organ which has developed for its detection; in this case the human ear (Godlee, 1992).

Aetiology and Pathophysiology

Like all biological insults, the effects on any individual organism from exposure to excessive noise levels are extremely variable and relatively unpredictable, especially at moderate exposure levels. Although many theories and suggestions have been made for this phenomena, with variations in intrinsic protective responses coming in for recent scrutiny, a satisfactory explanation is still lacking (Humes, 1984; Henderson, 1993). However, there is no doubt that with increasing exposure to excessive noise levels, the occurrence of noise damage becomes inevitable. It is generally agreed that, for the human ear, sound levels below about 80dB(A) are unlikely to cause any hearing damage no matter how long one is exposed to them. Sounds of 130dB(A) or greater will cause hearing damage after very short periods of exposure in almost all repeatedly exposed individuals. Between these extremes the "safe" period of exposure decreases as the sound level increases, although the degree of noise damage displayed by any one individual is variable and relatively unpredictable as a result of natural biological variability (Alberti, 1987; NIH, 1990; Saunders, 1985).

Although the tympanic membrane may be damaged and ossicles dislocated in high impulse noise such as an explosion, in general it is the cochlea that is the predominant site for the pathological manifestations of noise damage.

There have been many studies examining the pathophysiological effects on the cochlea of exposure to various frequencies and intensities of sound. To this end there has been great sacrifice by a variety of animals; in particular the cat, guinea pig and the chinchilla! (Morest, 1982; Nilsson, 1982; Spoendlin, 1971; Hunter-Duvar, 1982; Miller, 1963; Beagley, 1965; Davis, 1935; Salvi, 1982; for example) All of these studies are not without certain problems. Although the noise exposure of laboratory animals can be strictly controlled throughout their lifespan, they do not have human ears! This point is not without some importance; given the huge intra-species variation in response to noise one can only assume that a similarly large inter-species variation exists (Saunders, 1982). To obtain (prior) audiometric correlates, laboratory animals must be trained, by behavioural techniques, to perform "audiograms". This takes a great deal of time and patience and provides at best an approximation of the animals hearing thresholds (Alberti, 1987). Histological examination of human ears has been undertaken but in these cases the noise exposure history is retrospective and therefore much less accurate (Wright, 1981). In addition, for all histological studies, there are artefacts associated with the preparation of material for both light and electron microscopy (Saunders, 1985). Despite these problems a number of consistent findings have been described for the clinical correlates of temporary and permanent threshold shift (TTS & PTS respectively). It is worth making the point at this stage that to establish permanency of threshold shift requires periodical audiometric assessment as some degree of recovery, after removal from noise, is possible over quite prolonged time periods (Knight and Coles, 1966; Burns, 1973). Although persistent is therefore a better term, permanent will continue to be used in this thesis for both uniformity and to make the contrast with temporary or non-permanent threshold shift.

Temporary threshold shift is, as it says, a temporary worsening of the auditory threshold. Despite many histological analyses there are few consistent associated structural features. There is some evidence of subtle intracellular changes in the hair cells and a decrease in the stiffness of the stereocilia as well as swelling of the auditory nerve endings. All these changes appear to be reversible and can be considered as metabolic "exhaustion" of the sensory cells (Cody, 1985; Alberti, 1987; NIH, 1990; Saunders, 1985).

Permanent threshold shift reflects irreversible damage to the cochlea and is invariably associated with structural damage. It appears that the sensory hair cells are most susceptible with initial damage to the rootlet structures that anchor the stereocilia to the cell body, particularly those of the outer hair cells in row 1. With continued exposure, the stereocilia can become floppy, fused or eventually disappear. These changes are associated with various intracellular changes such as lysosomal and nuclear swelling, mitochondrial changes and vacuolization of the smooth endoplasmic reticulum. Ultimately there is cellular degeneration. Once lost, these sensory cells are not replaced (Alberti, 1987; NIH, 1990; Miller at al, 1963; Hunter-Duvar, 1982; Spoendlin, 1971; Nilsson, 1982; Saunders, 1985). As the damage progresses, these changes spread to involve the other two rows of outer hair cells and the inner hair cells, which are affected along with the supporting cells. More extreme changes include rupture of Reissners membrane and damage to the striae vascularis (Alberti, 1987; NIH, 1990; Miller at al, 1963; Hunter-Duvar, 1982; Spoendlin, 1971; Nilsson, 1982; Saunders, 1985). With loss of sufficient sensory cells, there is often degeneration of the central neural pathways (Morest, 1982; Saunders, 1985; NIH, 1990; Alberti, 1987). Regardless of the frequency of the damaging noise it would seem that in the human, it is the basal turn of the cochlea that is most prone to noise damage.

This early susceptibility of the OHC in row 1 is almost certainly due to their position over the middle of the basilar membrane where its excursion and the resulting shear forces are greatest, and to their firm attachment to the overlying tectorial membrane (Beagley, 1965). The susceptibility of the basal turn is less well understood but possibly relates to the preferential frequency amplification by the external and middle ears of the usually broadband sound; there is evidence that long-term exposure to a tonal sound can lead to a hearing loss at the place serving the frequency half to one octave higher, regardless of its position in the cochlea (Alberti, 1987; Knight, 1963).

Clinical and audiometric correlates

Although there are a great many experimental tools available for measuring the function of the cochlea, in clinical practice the "work-horse" is the pure-tone audiogram (PTA). An understanding of this allows a basic understanding of many principles involved in other psychoacoustic tests. The hearing threshold of any individual is not at a fixed point but exists more as a narrow "range" (Lutman, 1987; Moore, 1989). An audiogram involves estimation of this level by presenting pure-tones at octave intervals from 250 to 8000Hz in a quiet acoustic environment and asking the subject to respond when he hears the tone. The threshold is taken as that level at which the subject responds correctly for more than 50% of the test presentations. For any individual there will be a level at which the test signal will never be heard and at a slightly louder level (say 10dB) at which the signal will always be heard (Lutman, 1987). The true hearing threshold lies somewhere in this range and the actual point at which the subject responds will therefore depend on many factors. These include the degree of motivation and arousal of the subject, the subjects personality, the instructions he was given by the tester, the attitude and encouragement (or lack of it) by the tester, and the technique used (Stephens, 1971). The recorded threshold will also be influenced by the presence of background or environmental noise during the testing and by any calibration errors of the machinery used (King, 1992). On this basis the PTA would appear to be a fairly crude tool with a standard error of the order of 3-5dB (Burns, 1973b; Leijon, 1992). In an effort to try and improve the accuracy of the PTA, uniform guidelines on acceptable conditions, equipment and methodology have been proposed by a number of professional bodies (Anon., 1981; King, 1992). As a result, despite its obvious shortcomings, the pure-tone audiogram remains a swift and internationally reproducible technique and is still one of the most widely used clinical measure of noise damage (King, 1992).

Exposure to excessive noise levels of insufficient duration to cause permanent threshold shift (PTS) is likely to cause temporary threshold shift (TTS). TTS is a temporary worsening of the hearing thresholds and is familiar to most people as tinnitus ("ringing in the ears") following exposure to loud noise (Alberti, 1987). TTS tends to be maximal at 0.5-1 octave above the frequency of the stimulating sound (Mills, 1979; McFadden, 1982), although this may not be the case for low frequency stimulating sounds (Jerger, 1966; Burdick, 1982; Paterson, 1977) and increases in response to increasing intensity and duration of exposure in an asymptotic fashion, i.e. once a certain degree of TTS has been reached, it increases so slowly that it effectively increases no further. This maximal TTS is also thought to represent the maximal PTS that can occur at that frequency (Alberti, 1987). It has also been described that individuals who have suffered prolonged noise exposure demonstrate less TTS than non-exposed individuals with the same audiometric thresholds, for an identical noise exposure. This may reflect an alteration of metabolic processes (NIH, 1990) or protective mechanisms (Henderson, 1991). There is also evidence that a combination of sound and vibration will produce a greater TTS than exposure to the same sound alone (Okada, 1972; Kile, 1980). TTS by definition will recover and tends to do so in an exponential and predictable fashion, after the initial R1 recovery phase which occurs in the first 2 minutes following noise exposure (Ward, 1959). It is probable that repeated exposure to noise sufficient to cause TTS will ultimately lead to PTS. A predictive link between PTS and TTS has long been sought and although a relationship does exist, it is not strong enough to allow predictions of an individual's PTS based on his TTS (Burns, 1971; Glorig, 1961; Jerger, 1956; Burns, 1973c).

In permanent threshold shift (PTS) as would be expected with an initial loss of the outer hair cells and consequently cochlear fine tuning, one of the earliest complaints by the affected individual is loss of speech discrimination particularly in background noise (Alberti, 1987; NIH, 1990, King et al, 1992). This can be measured by a marked reduction in the performance of tests involving the detection of competing signals or signals in noise, out of proportion to the pure-tone audiogram. Early noise-induced hearing loss (NIHL) displays itself as a "dip" in the pure tone audiogram in the region of 3-6 kHz, the frequency range served by the basal turn of the cochlea. However, as the damage progresses, there is a progressive hearing loss in the frequencies on either

side of this region with the higher frequencies being more severely affected (Ward, 1969; NIH, 1990); the affected individual complains of becoming progressively hard of hearing. The progressive loss of hearing leads to difficulties in communication in occupational, social and domestic environments and can result in social isolation, domestic dysharmony, strained relationships and even depression (Stephens, 1980; Lalande, 1988).
Many sufferers of NIHL will also complain of tinnitus. This can also produce serious adverse effects on the quality of the individuals life.
Noise-induced hearing loss and its consequences are irreversible. Treatment is essentially supportive and involves counselling, auditory rehabilitation and amplification (hearing aids) (Alberti, 1987).

One of the great problems with NIHL particularly as regards epidemiology and individual assessment is the problem of age related hearing loss: Presbyacusis, which also tends to produce a high frequency sensori-neural hearing loss that progresses with time (Salomon, 1991). Noise induced hearing loss may take from 5-20 years to display its effects, although there is good evidence that its progress, for the higher frequencies (3,4 and 6kHz), is most rapid in the first few years and then becomes progressively slower (Robinson, 1971; Burns and Robinson, 1970). In the same time period an individual may suffer a substantial hearing loss as a consequence of presbyacusis. It is therefore essential that any audiometric assessment take account of the patients age and correct for it (Davis, 1987; Browning and Davis, 1983; Erdreich and Erdreich, 1982). To this end a number of studies to provide this normative presbyacusis data have been undertaken (Hinchcliffe, 1959 & 1971; Robinson, 1971; Robinson and Sutton, 1979; Robinson, 1988; Davis, 1987). These controls may be otologically normal (ON) or typical population (TP), both take account of age-related changes. However, as the ON group are by definition more carefully screened than the TP group, their hearing thresholds are usually better (Lutman and Spencer, 1991). In an epidemiological survey to establish noise damage, ideally a prospective, longitudinal study using an identical but non-noise exposed control group should be used. However, the logistics involved mean that this is rarely feasible in the real world and consequently cross-sectional population surveys are usually undertaken using standardised control data (Erdreich and Erdreich, 1982; Davis, 1987). Thus the choice of control is important as an inappropriate control group can create a hearing loss where none in fact exists.

Other factors which can influence hearing levels are sex and occupation, with males and manual workers displaying significantly poorer thresholds than their counterparts (Lutman and Spencer, 1991; Davis, 1989). These should also be accounted for in any epidemiological survey.

PROTECTION FROM NOISE INDUCED HEARING LOSS

Legislation

Noise induced hearing loss (NIHL) is not uncommon, a recent concensus statement by the American National Institute of Health has indicated that currently 10 million people are affected in the united states (NIH, 1990). With the advent of heavy industry it began to become apparent that excessive noise exposure could result in hearing damage for exposed workers (Ward, 1969; Tempest and Bryan, 1981). Over the years there were many papers documenting hearing loss in various groups of workers; certain notable contributions looked at ship builders, boiler makers, aviators and jute weavers (Barr, 1886; Dickson, 1939; Taylor, 1965). As a result, NIHL was well recognised in medical textbooks as early as the late 1930's, and probably also by the public at this time (Tempest and Bryan, 1981). However, it was not until increasing public concern, and outcry, in the 1950's led to a governmentally directed committee, which reported in 1963 (Committee on the problem of noise, 1963), that "official" recognition could be said to exist (Bryan and Tempest, 1971). Despite this, occupationally induced deafness did not become compensable as a prescribed disease until 1975 (Tempest and Bryan, 1981).
One of the most important works in recent years has been the survey by Burns and Robinson published in 1970: "Hearing and Noise in Industry" (Burns and Robinson, 1970) which has provided much of our present day knowledge on the subject of noise induced hearing loss. This work is really a landmark in this field. It was essentially a huge cross-sectional survey of the hearing levels and noise histories of screened industrial workers. It provided a wealth of information on many aspects of industrial NIHL including "safe" noise levels, the validity of using the A-weighted sound levels, the

relative unimportance of the noise frequency spectra and the applicability of the equal energy principle. Their work has indicated that below 80dB(A) the likelihood of occurrence of noise damage is extremely small. Above this level the risk of noise damage increases with increasing sound intensity, such that at 85dB(A) about 5% of a given population will be "at-risk" and at 90dB(A) the figure is 15% (Alberti, 1987; NIH, 1990). They also proposed and experimentally supported the suggestion that sound frequency is unimportant and that average noise damage can be predicted from the average sound level or "equivalent continuous noise level" (Leq) in dB(A) over a period of time measured in years. This measure is the "noise immission level" (NIL). This has also received support from other sources (Burdick, 1982). This also lends support to the equal energy principle which says that for every 3 dB(A) increase in the sound level (which is equivalent to a doubling of the sound intensity) the safe time of exposure must be halved. This holds for continuous noise exposure but less so for intermittent exposure which is probably more common (Ward and Turner, 1982; Ward, 1969; Anon., 1991). Some American regulations have taken this factor into account by recommending a 5dB(A) trade-off in the work place, although this too is not completely satisfactory (Alberti, 1987; Mills, 1982; Anon., 1991). It is largely as a result of the aforementioned problems that the Health and Safety at Work Act exists to try and prevent the occurrence of NIHL in the workplace (Health and Safety Executive, 1989). The regulations in the act are based on the available scientific evidence, particularly works such as that by Burns and Robinson described above. As a consequence, the most recent UK regulations (HSE, 1989) describe three action levels, the first of 85dB(A) and the second of 90dB(A) for an 8 hour working day in a 40 hour working week. The third is the peak action level where peak sound levels reach 140dB.

Above 85dB(A) voluntary hearing protection should be used and noise levels monitored. If noise levels exceed 90 dB(A), an employer has a statutory duty to protect the hearing of his employees.
This hearing protection should include the reduction of (machinery) noise at source, the provision of personal hearing protection and education as to its purpose, and ideally the regular monitoring of employees' hearing. Should hearing damage occur despite these precautions, claims for compensation may be made, either by an action at common law, for all individuals, or as an industrial injury for those employed in prescribed occupations (Hinchcliffe, 1981; Tempest and Bryan, 1981).
A common law action demands several requirements but is based on negligence. First the plaintiff must demonstrate by medical examination a hearing loss that "on the balance of probabilities" is due to noise exposure. Second it must be shown that there exists or existed excessive noise levels at the work place. Finally it is necessary to prove negligence on the part of the defendant, usually the employer, in allowing the noise exposure to occur and/or failing to protect the employee from its effects. To prove negligence it is essential to show that the defendant had reasonable knowledge of the hazard or if he did not, that he should have had such knowledge (Hinchcliffe, 1981; Tempest and Bryan, 1981). For employers in industry this date could reasonably be put at 1963 with the publication of the Ministry of Labour guide "Noise and the worker" following the Wilson committee report mentioned above (Ministry of Labour, 1963). If all these requirements are fulfilled a compensatory award is made, usually based on the degree of hearing loss, social handicap and any actual or potential loss of earnings.
To pursue a social security claim as an industrial "disease" demands its own requirements which were originally as described below (Tempest and Bryan, 1981).

First the plaintiff had to be employed for at least 20 years in one of the prescribed occupations. These were defined as occupations involving:

1. the use of pneumatic percussive or high speed grinding tools to work on cast metal, ingets, billets or blooms.
2. the use of pneumatic percussive tools in ship building.
3. work wholly or mainly in a drop-forging or forging press plant.

Second the plaintiff had to make his claim within 12 months of ceasing employment in the prescribed occupation. In these cases awards were made in a standardised way on the basis of the hearing loss, at particular frequencies, as measured by pure-tone audiogram. Recent years have seen alterations in the requirements with a considerable widening of the range of occupations covered, a reduction in the duration of employment to 10 years and alterations in the method of assessing the hearing disability (Coles, 1994; King, 1992).

Personal hearing protection

Currently available personal hearing protection means either insert earplugs or earmuffs. Insert earplugs have been used in the work-place for over 100 years (Barr, 1886). They are made from a variety of materials including silicone rubber, acrylics and closed cell foams. They may be moulded to the individuals ear or "off the shelf" and designed to fit all ears. Ear muffs are a more recent invention and consist of two plastic earcups with a soft cushion seal against the head held in place by a connecting metal spring clip. Various methods have been used to assess the sound attenuation provided by ear protectors. It would seem that they all give similar results except for minor differences at low frequencies (Martin, 1977, 1982; Nixon, 1982; Berger, 1985).

The current British standard (BS5108:Part 1:1991) uses a subjectively based, insertion loss technique. In this technique 16 trained listeners are used. The subject sits in an anechoic chamber surrounded by a quadrophonic arrangement of speakers that emit third-octave bands of pink noise (noise that has equal energy in each octave) centred on the octave frequencies from 125 to 8000Hz. The subject's free-field auditory thresholds are established using a method of limits. This test is then repeated with the hearing protector in place and the hearing thresholds will be correspondingly worse by an amount that represents the insertion loss of the ear protectors at each test frequency. This score is then averaged for the 16 subjects and represents the sound attenuation performance of the protector. Usually because of the individual variation in test scores, the assumed protection, for each frequency, is taken as the mean attenuation score minus 1 standard deviation.

On this basis, most ear protectors offer good sound attenuation scores, with earmuffs in general scoring slightly better than 'plugs. However it has been well documented that measures of the sound protection offered in the "real world", in other words to workers having fitted and wearing their own protectors, is significantly worse, often by as much as 10-15dB (Berger, 1980a, 1980b, 1983; Alberti et al, 1982). This phenomena invariably relates to comfort but may be due to education with the wearer not fitting the device correctly or altering it in order to make it more comfortable (Berger, 1980b; Alberti at al, 1982).

Individuals often express concern or difficulty with the perception of other signals and speech when wearing hearing protection. This is often cited as a reason for the removal of protectors despite a noisy environment although there is good evidence to show that signal detection in the normal hearing individual is not impaired by the wearing of hearing protection. In fact in very high background noise levels it may even be improved when compared to wearing no protection (Berger, 1980c; Martin, 1976; Wilkins and Martin, 1982).
The explanation for this is suggested in current masking theory (Moore, 1989) in which the cochlea can be regarded as a bank of band-pass filters. In the presence of high background noise levels these filters become "swamped"; any additional increment in excitation due to an extra signal is negligible. The addition of ear protection significantly reduces the level of noise reaching the filters. This allows a relative increase in the excitation increment due to the test signal and a consequent improvement in signal detection.
It has also been shown that removal of an ear protector, even for a very short period, in the presence of excessive noise levels can effectively negate any benefit (Tengling and Lundin, 1982).
There is evidence though that after an initial 2-3 week acclimatisation period, the improvment in general

wellbeing from wearing ear-protectors, in an environment of high background noise, is sufficient to encourage their continued use (Berger, 1981).

Ultimately though, personal motivation, however achieved, is the main requirement for succesful hearing protection (Loftgren et al, 1982; Berger, 1981).

MOTORCYCLES

Not all noise exposure need be occupational or the result of industry. In recent years it has become increasingly apparent that individuals are exposed to noise from a multitude of sources, many of them recreational. This problem has relatively recently been examined by a thorough review of the available literature on recreational noise exposure, undertaken by the MRC Institute of Hearing Research (MRC, 1985). They concluded that the main recreational risk to hearing was from amplified music but that the methodology and overall design of much of the reviewed research was poor. There were five references to noise exposure and motorcycles.

Motorcycles have been around as a source of transport since the latter part of the 19th century, and have long been regarded as irritating and noisy. It is therefore no surprise to find that regulations exist to prevent excess vehicular noise in both urban and sports settings (EEC, 1989; ACU, 1993). These regulations would appear to be reasonably successful as Kamperman (1980) has shown accelerating motorcycles with standard exhausts to be no louder than motor-cars in an urban setting, and measurements by the Transport Research Laboratory (Waters, 1984) have shown overall motorcycle noise to be within UK legislative limits. However the presence of a non-standard exhaust system may allow excessive exhaust noise (Kamperman, 1980).

One might assume that, as well as "protecting" the public from noise nuisance, these regulations might also protect the rider. There are certainly regulations that are specifically designed to protect the rider such as the compulsory wearing of a protective helmet approved to BS 6658 (1985) (The Road Traffic Act, 1988) which has no doubt saved lives and prevented many serious injuries

(Capewell et al, 1984; Muller, 1980; National Highway Traffic Safety Administration, 1979). However, over the past decade, as motorcycle development has led to quieter machines with radically improved performance, there has been increasing concern that riders are suffering excessive noise levels as a result of turbulent airflow around the riders' helmet, so-called "wind noise" (Maue, 1991; Harrison, 1974; Ross, 1989; Van Moorhem, 1981; Aldman et al, 1983; Jongepier and Van der Weerd, 1989; Huttenbrink, 1982; Iho and Jonasson, 1981).
The seminal work on this topic is usually attributed to Van Moorhem (1981), although there was one earlier work published in 1974 (Harrison, 1974) that showed broadly similar results.

Although Van Moorhem's helmets would now be considered dated and the speeds rather low by European standards (<60mph), he was able to conclude, by recording wind noise at increasing speeds and then analysing these tapes, that there were excessive noise levels at the rider's ear. He also stated that wearing a crash helmet reduces this noise level yet because of minimal sound attenuation, does not disadvantage the rider in the detection of warning signals.

Certainly his conclusion that excessive noise levels are due to "airflow generated noise" has stood the test of subsequent scientific scrutiny. However, there have been only six published scientific reports on the noise levels experienced by motorcyclists since Van Moorhem's work (Aldman et al, 1983; Jongepier and Van der Weerd, 1989; Huttenbrink, 1982; Iho and Jonasson, 1981; Maue, 1991; Ross, 1989).
All have used essentially similar techniques: a miniature microphone has been placed at the rider's ear under the helmet and sound levels recorded in a variety of riding conditions using high fidelity tape and subsequent

analysis. Only one of these studies used a personal dose-meter for noise measurement (Jongepier and Van der Weerd, 1989). One particularly elegant variation on the theme was performed by Aldman et al (1983) who measured noise levels with the motorcycle freewheeling down an incline to eliminate engine noise. All of these studies have confirmed that motorcyclists are exposed to excessive noise levels due to "wind noise" around the rider's helmet, with noise levels of around 90 dB(A) at 45 mph and over 100 dB(A) at 80 mph. There has been reasonable agreement in the sound levels reported by these various investigators. In addition, they have all identified the potential risk to the motorcyclist's hearing from these noise levels.

Unfortunately, bare headed noise measurements were NOT made in Van Moorhem's study, instead the data of two other groups (Harrison, 1974; Kristianson, 1978) were quoted. Indeed both Harrison and Kristianson in their original papers point out potential flaws in their measurements from the direct effects of the airflow on the microphone. This obviously casts some doubt on the reported noise levels for the bare-headed rider and Van Moorhem's conclusion that sound level reduction may be achieved by wearing a helmet.

With regard to his conclusion on the perception of warning signals, this is based on the calculation of relative sound levels and the measured sound attenuation characteristics of motorcycle helmets. In fact only two other papers have actually measured the sound attenuation characteristics of helmets (Bess et al, 1974; Aldman et al, 1983). The first of these looked at 2 old style, open face helmets and demonstrated similar results to Van Moorhem with no low frequency attenuation (<1kHz) and increasing attenuation from 2kHz and above. Unfortunately the second and later of these studies only measured attenuation from 1 to 8kHz and ignored low frequency attenuation. Although the results for higher frequencies were similar, this omission is particularly unfortunate as wind noise is well recognised to be low frequency in nature (Maue, 1991; Huttenbrink, 1982; Hay, 1964; Kristiansen and Pettersen, 1978). There have been other papers that have specifically addressed the problem of warning signal detection for helmeted motorcyclists and arrived at similar conclusions to Van Moorhem (Henderson, 1975; Aldman et al, 1983). Unfortunately these supporting papers suffer from identical failings in that they are based on theory. Although their conclusions may well be correct, and with the minimal helmet sound attenuation scores it would seem likely on common sense grounds alone, they still have not been tested in practice!

Unfortunately none of the papers quoted have described or examined the actual source of this "wind noise", nor have they proposed any course of remedial action to reduce the levels of noise exposure for the rider. The only available evidence of any efforts to reduce the problem are to be found in 2 internal reports from the Dutch State Police (Van Der Weerd, 1990a, 1990b), one Swedish technical report (Iho and Jonassen, 1981) and one American report (Tangorra and George, 1991). In all these papers the exact source of the "wind noise" is not described and the remedial efforts are very much empirical. The Dutch Police looked at a variety of helmets and a number of handle-bar and fairing modifications to try and reduce sound levels. Unfortunately these met with only limited success; the best improvement being only 6 dB with a particular handlebar/fairing combination (1990a). The American paper by Tangorra and George involved making a number of modifications to some standard helmets. All their modifications were external with cones to make the helmet shape more aerodynamic, seals around the visor and seals around the neck to try and reduce the noise levels at source. All testing and noise measurement was performed in a wind-tunnel. Again their best improvement was only of the order of 5 dB. The Swedish report also describes various helmet modifications with limited success although incorporating a set of earmuffs under the helmet did lead to significant sound reduction, of the order of 10dB. Unfortunately these results do not appear to have been followed up or developed in a commercial sense.

There is no doubt a great shortage of work on this topic and yet the popular motorcycle press has become aware of the problem and started voicing its concerns (Motorcycle Sport, 1992; Performance Bikes, 1989). One notable omission to date is the lack of any reliable epidemiological data. To achieve this requires close attention to methodological detail. For results to be statistically reliable and generally applicable requires a large sample size and a standardised method of measuring hearing thresholds. Consideration must be given to possible exclusion factors such as the presence of a conductive hearing loss, previous noise exposure and other relevant factors in the subjects' past medical history. These are important if one aims to identify the effects of a single potentially damaging activity. The choice of a control group is crucial to the validity of any statistical analysis; ideally it must match the study group in all but the activity under investigation. Finally, the analysis must take full account of age-related changes in hearing thresholds (Davis, 1987). Given these fairly stringent requirements, it is probably no surprise that there are only two reports that have looked at the hearing levels of motorcyclists (Fletcher and Gross, 1977; Jongepier and Van der Weerd, 1989). One of these is of very poor scientific quality (Fletcher and Gross, 1977): they used non-standard audiometric measurements in poor acoustical conditions and inappropriate analysis, and concluded that the high frequency hearing of motorcyclists was poorer than expected. The second is another internal report from the Dutch Police which looked at 169 of its riders and also concluded that their hearing was poorer than expected (Jongepier and Van der Weerd, 1989). Although their method was better, their data analysis was still questionable. They pooled the audiometric data for their 169 riders (age range 26-49) and compared it to standard audiometric data for 35 year olds (source not disclosed), so adaquete account of age was not taken. Nor do they control for previous occupational or firearms noise, to which they acknowledge ubiquitous exposure. These controls are essential if meaningful results are to be achieved. Consequently this epidemiological question remains inadequately answered.

Finally, at no stage have investigators made any effort to ascertain the awareness or views of the motorcycling community, and as there are currently 5.6 million full motorcycle licence holders in the United Kingdom (Department of Transport, 1991), this is not an insignificant group. Their views are certainly important if one hopes to implement an acceptable and workable solution to any problem arising from excessive wind noise exposure.

2. HYPOTHESES AND PLAN OF THESIS

Hypotheses:

1. Given the previously described wind noise levels when riding, motorcyclists will demonstrate significant adverse effects upon their hearing, as a direct consequence.
2. Motorcyclists as a group are unaware of this problem.
3. If 1 and 2 are correct, some form of remedial action will be required.

Plan of Thesis:

I hope to investigate these hypotheses by performing a number of experiments as detailed below. Each experiment will be designed to look at a specific aspect of this overall problem and as such will be presented as a separate chapter. Each chapter will follow the same format:

1. Brief introduction of the aims of the experiment.
2. Experimental design, materials and methods.
3. Results.
4. Discussion of results, in particular any deficiencies, errors or assumptions involved.

CHAPTER 2. A reassessment of the wind noise levels to which motorcyclists are exposed, both with and without a helmet, an investigation into the source of this "wind noise", and an examination of the sound attenuation characteristics of modern motorcycle crash helmets.

CHAPTER 3. Investigate the adverse effects (if any) of these excessive wind noise levels on the hearing of motorcyclists.

CHAPTER 4. To ascertain the awareness and views of the average motorcyclist to the risks and possible methods of avoiding excessive noise exposure.

CHAPTER 5. An investigation of various personal hearing protectors (earplugs) available to motorcyclists to discover the most appropriate, and its efficacy.

CHAPTER 6. An investigation into the effects of wearing earplugs on warning signal detection, for the motorcyclist.

CHAPTER 7. "Field testing" of two possible methods of reducing the noise exposure for motorcyclists.

Finally, in CHAPTER 8, I hope to draw all the results together, discuss their implications and draw conclusions as to the most appropriate way forwards.

CHAPTER 2

THE SOURCE AND LEVELS OF WIND NOISE

INTRODUCTION

This first experiment was designed to reassess the previously described wind noise levels for both the bareheaded and the helmeted rider. We hoped to improve on previous research by using a noise-logging dosimeter rather than analysis of taped wind noise, and to describe the generated wind noise levels by taking account of the sound attenuation characteristics of currently available, typical motorcycle crash helmets. Our final aim in this section was to identify the exact source of this so called "wind noise".

MATERIALS

1. Helmet attenuation

Fifteen different helmets were used for the sound attenuation work. The BS5108 testing detailed below was performed by Inspec Laboratories at the University of Salford facility. Three helmets were used for this sub-section: one open face and two integral (full face) helmets (Jebs GTO, Bieffe B3R, Kiwi K22 Racing).

2. Wind noise levels

Six experienced motorcyclists with a variety of head sizes participated. Three motorcycles were used: an unfaired Kawasaki Z400, a BMW K100 RS which has a large touring fairing and a Kawasaki GPz900 which is a sports-tourer with an aerodynamic sports fairing. (A fairing is the aerodynamic plastic shell over the front of a motorcycle) Over 30 different helmet makes were tested for wind noise with especially detailed measurments on five: Arai Giga, FM Grand Prix, Driver Prima, BMW System 2 and a Driver Alien 2.

Wind noise levels were measured using a Quest M28 multiple memory noise-logging dosimeter and 8mm omnidirectional ceramic microphone (IEC 651 type 2). The dosimeter was calibrated to record dB(A) Leq and will adhere to the A-weighting curve down to 20Hz, with a dynamic range of 50-146dB. It was recalibrated prior to each test session.

The Bruntingthorpe test track (East Midlands, UK) was used for most of the testing, the remainder being undertaken on a quiet stretch of motorway. All testing was done on dry and relatively windless days.

3. Source of wind noise

A high speed sub-sonic computerised wind tunnel based at the University of the West of England, Bristol, was used to investigate the sound source. Studies were made using a life-size, general purpose, dummy torso and an AGV3000 helmet secured in a representative riding position. Sound levels were measured using a Breul & Kjaer analyser type 4433 (IEC Type 2) with the microphone positioned at "ear level".

METHODS

1. Helmet attenuation

As wind noise levels were to be measured with the miniature microphone under the rider's helmet it was felt to be important to first establish values for the sound attenuation of a typical helmet. Two insertion loss techniques were utilised. In the first, which is in essence similar to the former American standard ASA Z24.22 (1957), 14 motorcyclists with normal hearing (thresholds of 20dB or better) were recruited with their own crash helmets (12 types in all). They sat in a sound proof room (BS 6655, 1986) 1 metre from a single Graystad speaker stack connected to a Graystad GSI 16 audiometer emitting pure tones. A free field audiogram was performed using a method of limits, with and without the helmet in place. The difference between thresholds with and without the helmet represents the "insertion loss" and thus the sound attenuation of that helmet.

In the second, 3 popular helmets (2 full face and 1 open face) were studied in more detail using the technique described by BS5108: Part 1: 1991. There was one important deviation from the standard in that only 5 subjects were used rather than the specified 16 due to time and financial constraints.

2. Wind noise levels

The procedure was identical for all helmets tested. The miniature microphone was secured in the rider's concha in a position that would not compromise its function or the fit of the helmet. Sound levels in dB(A) Leq were recorded for at least 2 minutes for each 10mph (4.3m/s) increment from 40mph (17m/s) to 100mph (44m/s) for each test condition, using the 6 subjects. Wind noise levels were measured for various test conditions including different helmet types, helmet fit, riding position and motorcycle type.

Measurement of the wind noise levels for the bareheaded rider presented a number of difficulties: The direct effects of the airflow on the microphone must be avoided and, the wearing of a helmet is a prudent and obligatory safety requirement. Our solution was to fit a pair of Audimed prosthetic ears to the outside of a motorcycle helmet in a position representative of that on the rider's head (Figure 2-1). These ears are anatomically correct silicone representations of the outer ear but have a shortened external ear canal of 8mm as measured on the posterior wall and are mounted on a pedestal base measuring 50mm by 30mm by 15mm thick. A 6mm hole exists, passing in an anterior direction through the base to emerge at right angles in the "ear canal". This hole was then partially occluded with a small plug of open cell polyurethane foam to act as a windshield for the dosimeter microphone which was a snug push fit.

FIGURE 2.1 HELMET WITH PROSTHETIC EARS FOR "BAREHEADED" SOUND MEASUREMENT

The insertion loss effect of this prosthetic device was less than 1dB over the dynamic range 60 to 90dB(A) at wind noise frequencies (.25-2kHz). "Bareheaded" noise levels were then measured in an identical fashion to the method described above for helmet noise levels.
Prior to this testing the reproducibility of the wind noise measurements was ascertained by having a single rider with the same helmet and motorcycle repeat the test run on 5 occasions. These were performed within 1 hour to allow for minimal change in atmospheric conditions.
24 further helmets were tested slightly less rigorously using identical techniques to those described above except that 2 subjects were used and sound levels were only recorded at 50mph (22m/s) and 80mph (34m/s).

Forty miles per hour (17m/s) was selected as the starting point for wind noise measurement as previous work has indicated that at this speed it becomes greater than vehicle noise. To confirm this the microphone was mounted in a polystyrene vibration and wind shield on (a) the head stock and (b) the petrol tank of the 3 vehicles and sound levels measured at 10mph (4.3m/s) intervals from 20mph (8.6m/s) to 60mph (27m/s) with the engine in top gear to maintain a constant relationship between road and engine speed. Although these positions are closer to the engine than the rider's ear and will therefore give higher noise levels, they are the only feasible site in which to position the microphone to get representative noise levels AND adequate wind protection. The end result will be a slight overestimate of the speed at which wind noise becomes dominant.

3. Source of wind noise

With the helmet in the wind tunnel 2 different flow visualisation techniques were used to examine the pattern of flow around it: smoke and a yellow paraffin based dye. Following this sound measurements were made in the wind tunnel and on the road of the helmet in standard condition. A layer of demerara sugar over the anterior face was then used to ensure that the boundary layer was tripped from laminar to turbulent at an early stage in its course over the helmet. Sound levels were again measured in the tunnel and on the road. Details of this portion of the investigation have been published in full elsewhere (Nash, 1993).

All results have been subject to appropriate statistical analysis (analysis of variance and two-sample t test) using Minitab Release 8 (Minitab Inc., 1991).

RESULTS

1. Helmet attenuation

The average sound attenuation for the 12 various crash helmets is shown in Figure 2-2 and demonstrates minimal attenuation below 2000Hz. The results for the 3 helmets subject to the modified BS5108 testing are shown in Table 2-1 and display very similar attenuation curves. There was slight negative attenuation in the majority of helmets at 500Hz which was felt to be due to resonance.
Wind noise is predominantly low frequency noise with its maximal A-weighted energy centered around 500Hz and a steep drop off of about 15dB per octave above this as demonstrated in Figure 2-3.

2. Wind noise

The results for reproducibility of measurements are shown in Table 2-2, and display little variation for one set of sound measurements with an average standard deviation of the order of 1dB. In addition this table demonstrates the very high coefficients of linear regression for each set of wind noise data when plotted against $\log_{10}$ speed.
(In fact these very high coefficients of linear regression were found for all sets of test data (0.95 or greater). Consequently all graphs are plotted as wind noise level against $\log_{10}$ speed.)

These results are also shown graphically alongside the results for the vehicle noise measurements in Figure 2-4 and demonstrate that at approximately 45mph (20.5m/s), wind noise surpasses vehicle noise and becomes the dominant sound source.

A summary of the mean values and standard deviations for all the helmeted test combinations is given in Table 2-3 and a summary of the significant differences is shown in Table 2-4. An analysis of variance has shown that road-speed has a very powerful and highly significant effect on wind noise levels in all test conditions ($F=340$, $p<0.001$). There is a significant increase in noise levels for the "bare-headed" situation ($F=73$, $p<0.001$). The only other factor that has a significant but small effect is the type of helmet worn ($F=5.4$, $p<0.01$). These comparisons are shown graphically in Figures 2-5, 2-6 & 2-7.

Finally a summary of all this helmet test data, and the noise levels of a further 25 recently tested helmets (Motorcycle News, 1993a), are shown graphically in Figure 2-8 as an "average noise plot" with mean values, 95% confidence intervals and previous workers results. It can be seen that all previous noise levels fit comfortably into our "average noise plot". Indeed the 95% confidence intervals are relatively narrow with a total spread of 12dB.

FIGURE 2.2 SOUND ATTENUATION OF TYPICAL MOTORCYCLE HELMETS

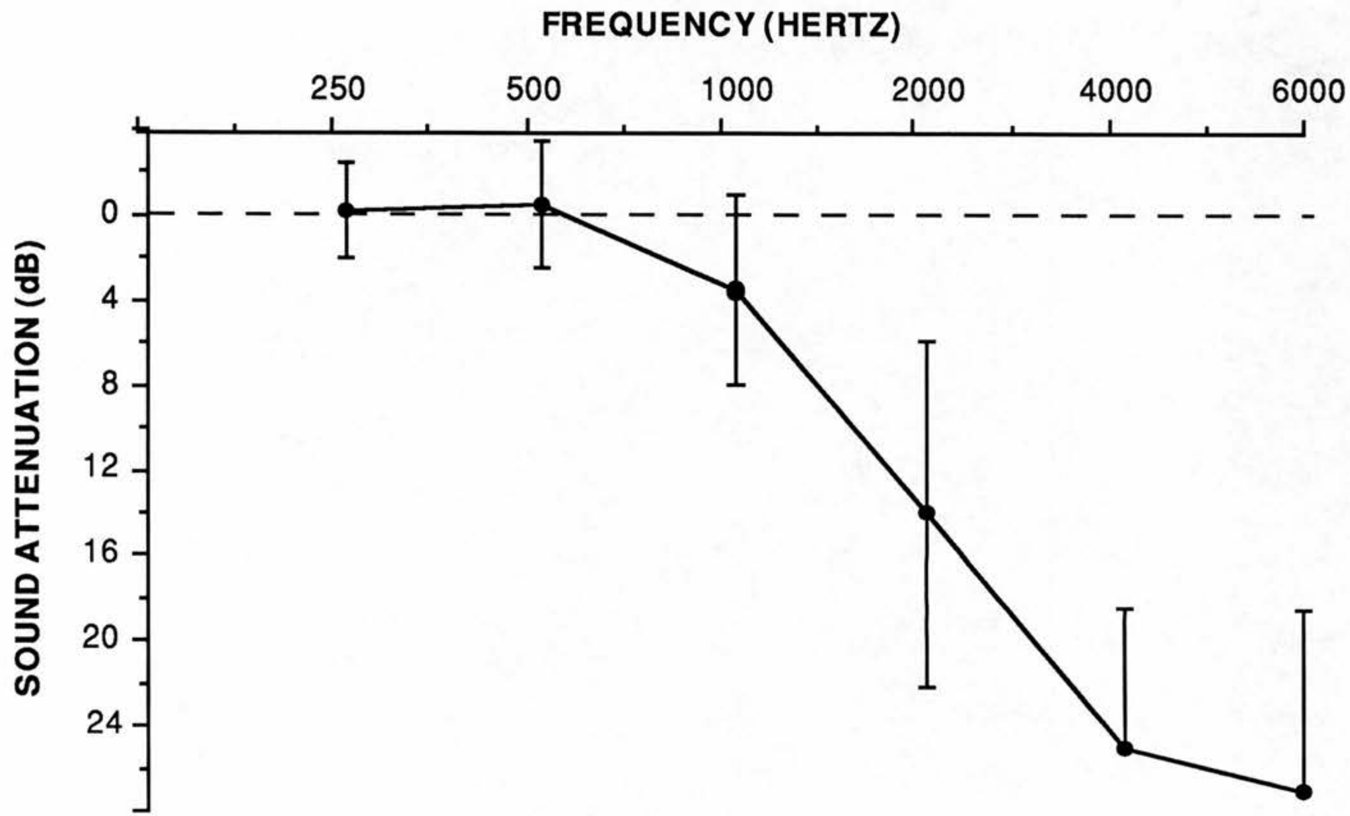


TABLE 2.1 - SOUND ATTENUATION OF 3 HELMETS (BS5108)
(MEAN ATTENUATION WITH 1 STANDARD DEVIATION IN BRACKETS(dB)

	Frequency (Hertz)						
	125	**250**	**500**	**1K**	**2K**	**4K**	**8K**
Helmet							
Jebs	-0.4	-1.2	-3.6	-3.2	5.2	16.2	20.8
	(0.8)	(1.6)	(2.0)	(2.1)	(1.0)	(2.1)	(1.4)
Bieffe	1.6	3.2	-1.2	4.0	10.6	27.0	26.4
	(1.6)	(1.6)	(2.0)	(2.2)	(2.1)	(1.4)	(5.0)
Kiwi	4.0	4.2	5.2	10.4	18	34.6	41.4
	(1.4)	(1.6)	(2.0)	(2.0)	(2.2)	(2.6)	(6.4)

FIGURE 2.3 REPRESENTATIONAL THIRD OCTAVE FREQUENCY CURVE OFWIND NOISE (80MPH) : dB (SPL) +dB(A)

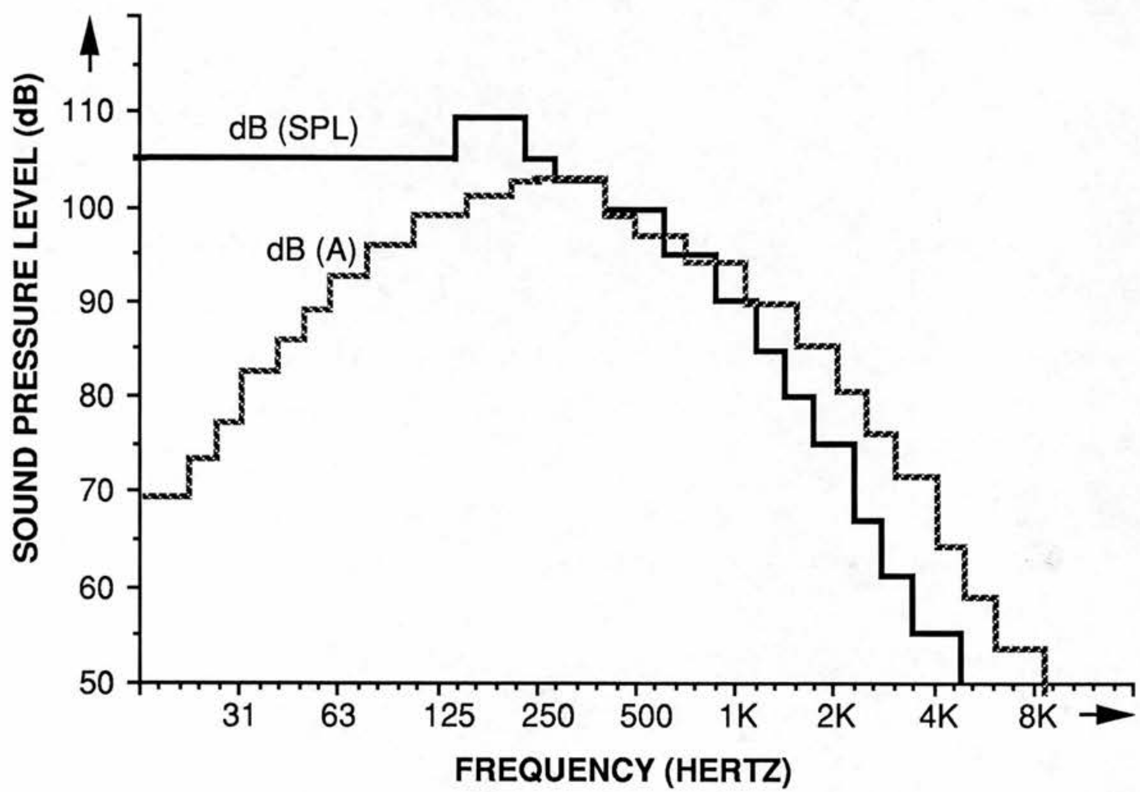


TABLE 2 .2 - REPRODUCIBILITY OF NOISE MEASUREMENT (RIDER,MACHINE,HELMET: ALL CONSTANT)

Speed (mph)	Log 10	Noise level (dBA Leq)					Mean value	Standard deviation
40	1.60	90. 8	88.8	91.2	90.9	89.9	90.3	0.7
50	1.70	92.5	93.8	95.8	94.6	94.0	94.1	1.3
60	1.78	97.7	98.0	95.1	98.5	97.3	97.3	1.3
70	1.88	103.1	102.1	100.9	102.5	102.1	102.1	0.8
80	1.90	105.4	107.4	104.9	107.1	106.2	106.2	1.1
90	1.95	109.4	110.0	108.3	109.3	110.2	109.4	0.9
100	2.00	111.2	111.2	111.5	111.1	111.4	111.3	0.2
Co- efficient of Linear regression		**0.99**	**0.99**	**0.96**	**0.99**	**0.99**		

FIG 2.4 COMPARISON OF VEHICLE NOISE AND HELMET WIND NOISE WITH SPEED (MEAN ± 1SD)

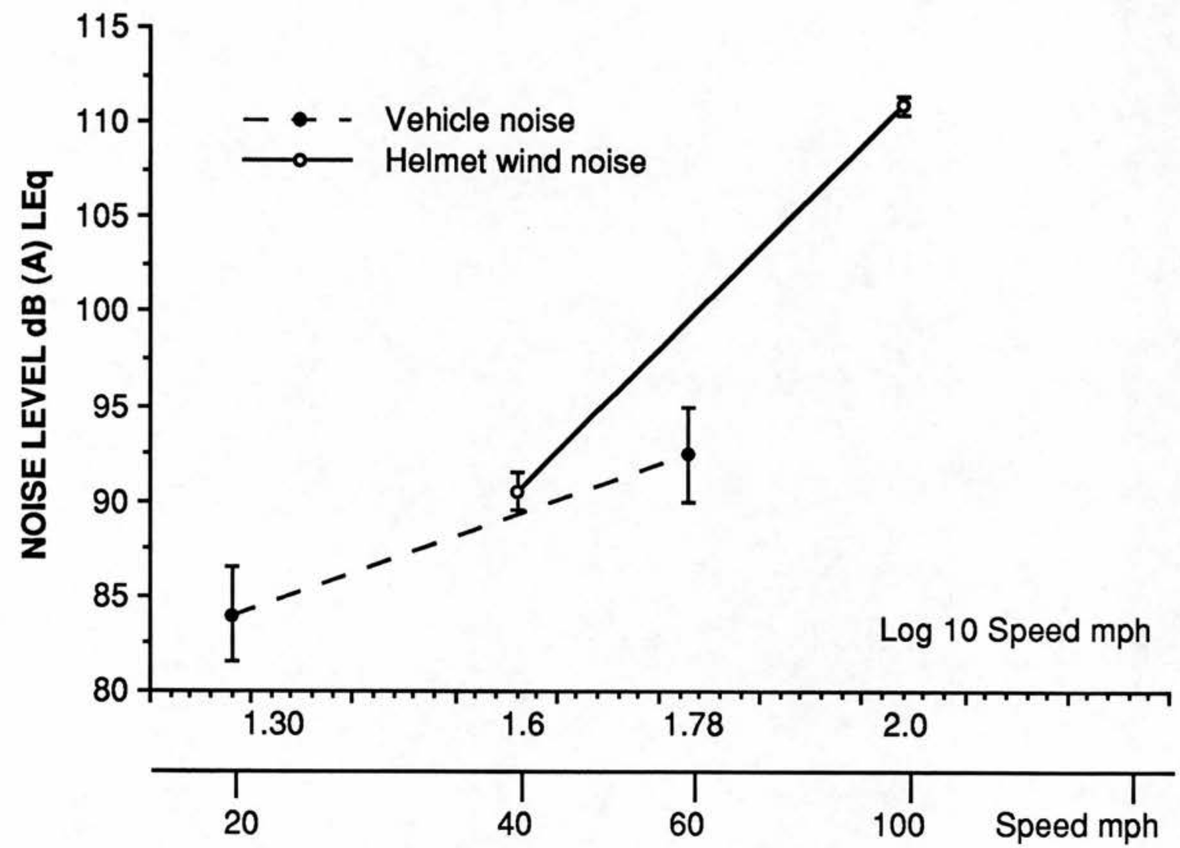


TABLE 2.3 - HELMET TEST CONDITIONS AND RESULTS [MEAN & 1SD-dB(A)]

Speed mph	A	B	C	D	E	F	G	H	I	J	Grand mean
40	89.7	88.7	90.7	91	88.9	89.7	88.3	92.7	90	90.8	90
	(1.5)	(3.4)	(2.2)	(1.8)	(1.7)	(0.4)	(2.3)	(2.6)	(2.2)	(2.7)	(2.3)
50	94	92.5	91.4	94.5	92.3	94.2	91.4	94.8	94	95.2	93.7
	(2.5)	(2.9)	(2.7)	(2.1)	(1.9)	(1.2)	(2.4)	(1.7)	(2.5)	(3.4)	(2.5)
60	97.8	96.6	98.2	99.0	96.2	98.1	96.1	98.5	98.3	97.5	97.7
	(3.4)	(4.1)	(3.0)	(2.9)	(2.3)	(1.8)	(3.2)	(3.3)	(2.7)	(2.7)	(2.9)
70	101.4	101.1	100.7	102.7	100.1	101.5	99.5	102.5	102.9	101	101.4
	(2.2)	(3.0)	(3.3)	(2.3)	(1.9)	(1.9)	(4.1)	(2.8)	(2.7)	(2.7)	(2.9)
80	104.6	103.2	104.7	105.8	103.7	104.1	102.9	107.4	107.5	105	104.9
	(2.8)	(3.3)	(3.7)	(2.8)	(1.5)	(2.1)	(2.7)	(2.7)	(3.9)	(3.5)	(2.9)
90	107.3	106	107.5	108.8	106.7	107	106.3	110	110	109.2	107.8
	(2.6)	(3.1)	(2.7)	(2.3)	(1.8)	(1.9)	(2.8)	(2.0)	(3.8)	(2.5)	(2.7)
100	109.4	108.2	109	110.6	108.4	109	108	111.4	112.5	111.8	109.8
	(2.8)	(3.2)	(3.6)	(2.6)	(1.8)	(2.5)	(3.5)	(1.9)	(3.9)	(2.6)	(2.9)

KEY

A = FM Grand Prix;Tight Fit;GPZ900 **B** = Aria Giga;Tight Fit;GPZ900
C = Driver Prima;Tight Fit;GPZ900 **D** = Alien 2;Tight Fit;GPZ900
E = BMW System 2;Tight Fit;GPZ900 **F** = Driver Prima;Loose Fit;GPZ900
G = Aria Giga ;Loose Fit;GPZ900 **H** = Driver Prima;Passenger;GPZ900
I = Alien 2 ;Tight Fit;Z400 **J** = Alien 2 ;Tight Fit;BMW

TABLE 2.4 - TEST CONDITIONS AND RESULTS

TEST VARIABLE	COMPARISON	CONSTANTS	SOUND LEVEL DIFFERENCE	
Helmet Type	Helmet 'v'Helmet	Motorcycle Helmet Fit	Small but significant	$F = 5.4$ $p<0.01$
Helmet Fit	Tight 'v' Loose	Motorcycle Helmet Type	Not significant	
Riding position	Pilot 'v'Passenger	Helmet Fit & Type	Not significant	
Motorcycle (Fairing)	Motorcycle 'v' Motorcycle	Helmet Type & Fit	Not significant	
Barehead	helmet 'v' "barehead"	Motorcycle helmet type	Significant	$F=73$ $p<0.001$

FIGURE 2.5 COMPARISON OF HELMET & BAREHEAD WIND NOISE WITH SPEED

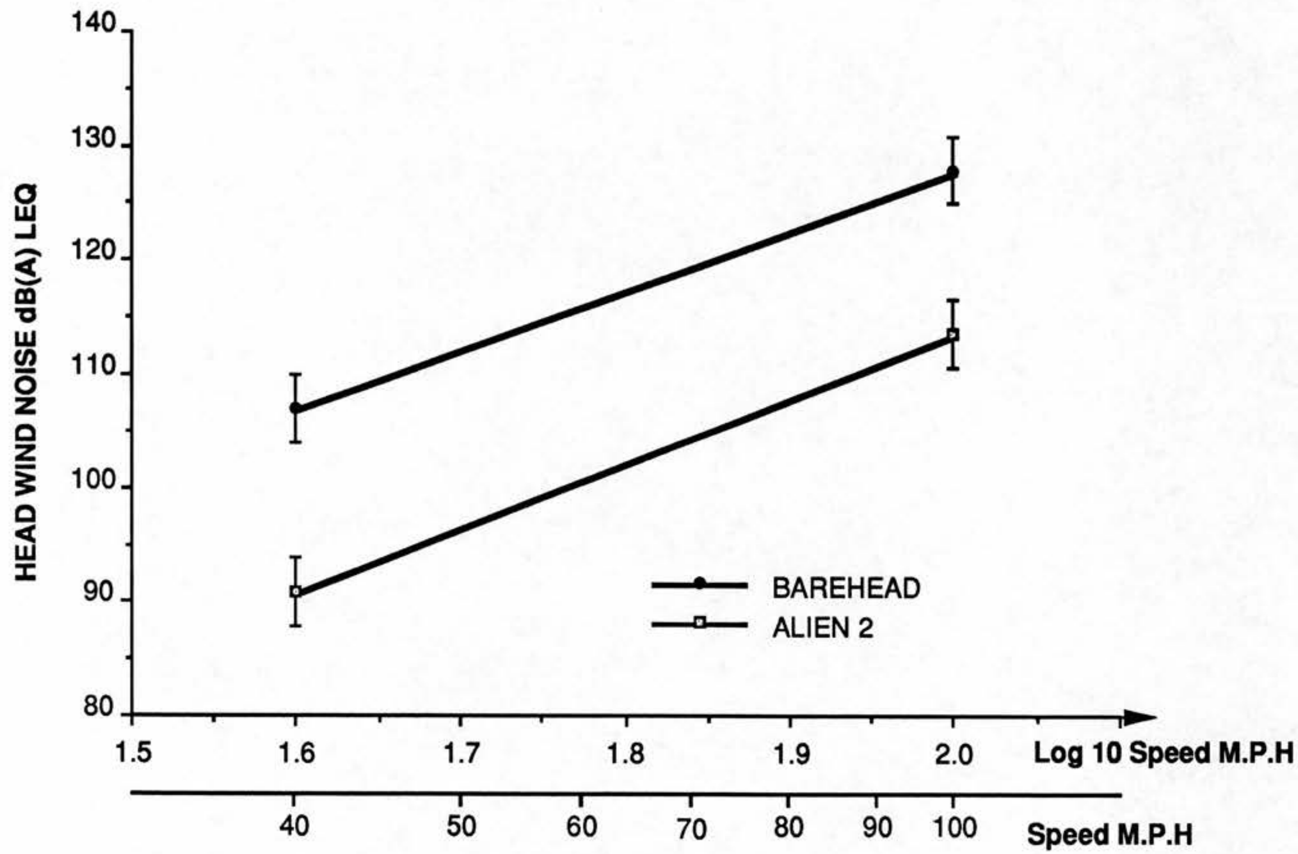


FIGURE 2.6 COMPARISON OF WIND NOISE WITH SPEED FOR DIFFERENT MOTORCYCLES

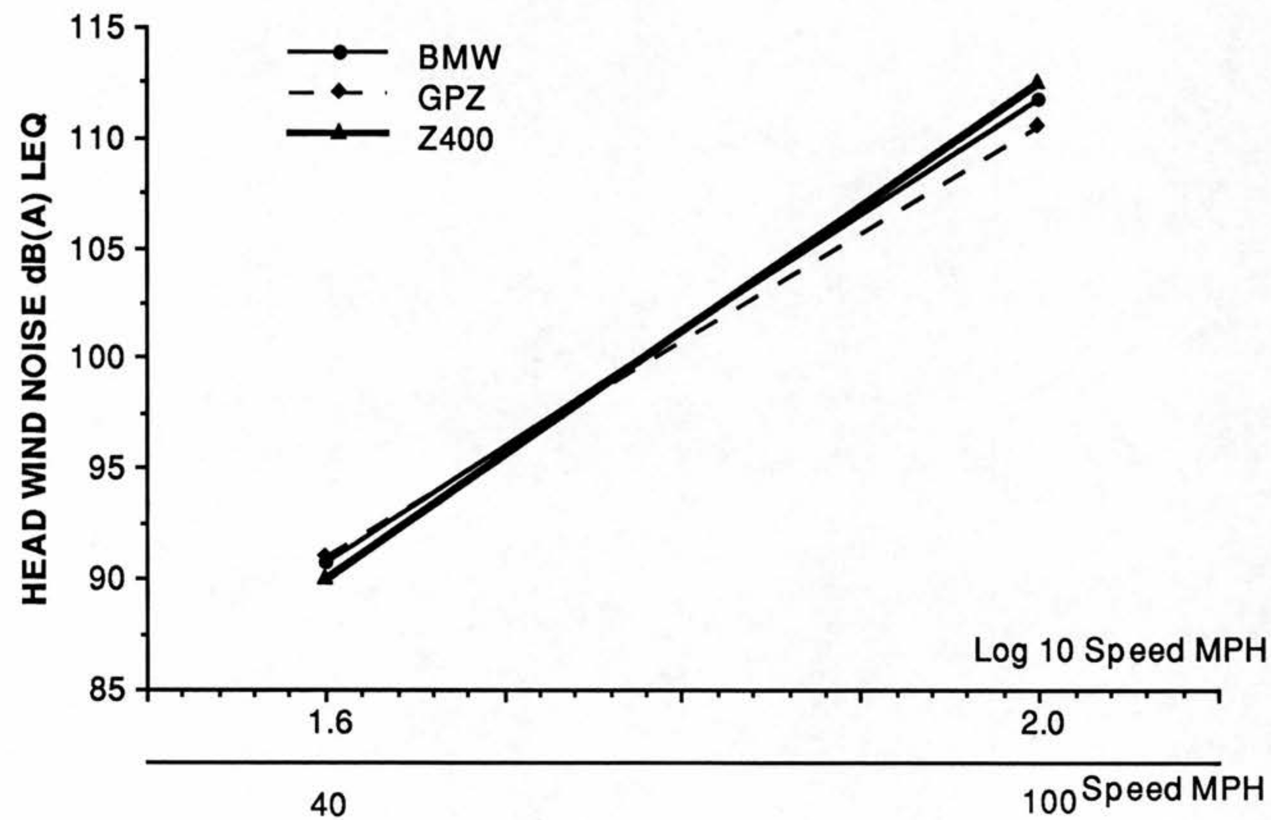


FIGURE 2.7 COMPARISON OF WIND NOISE WITH DIFFERENT HELMETS

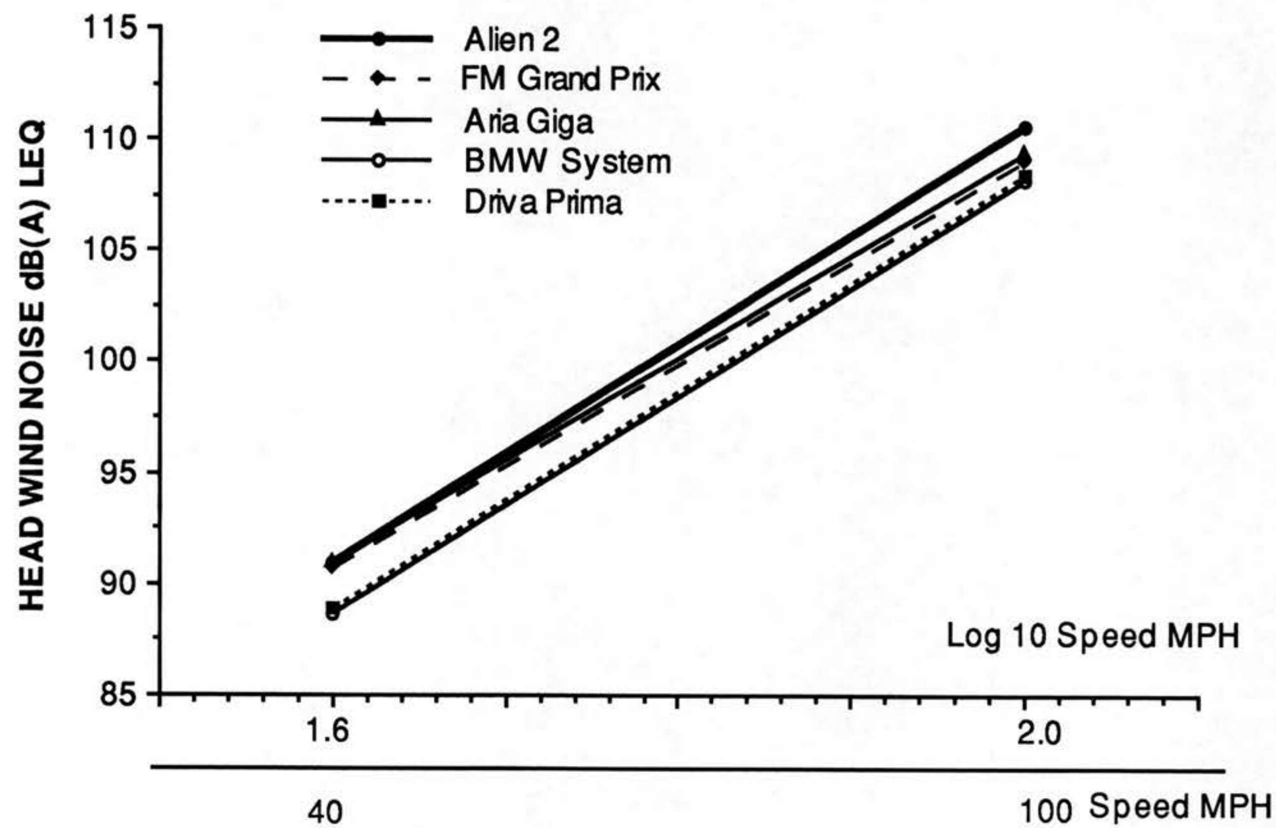
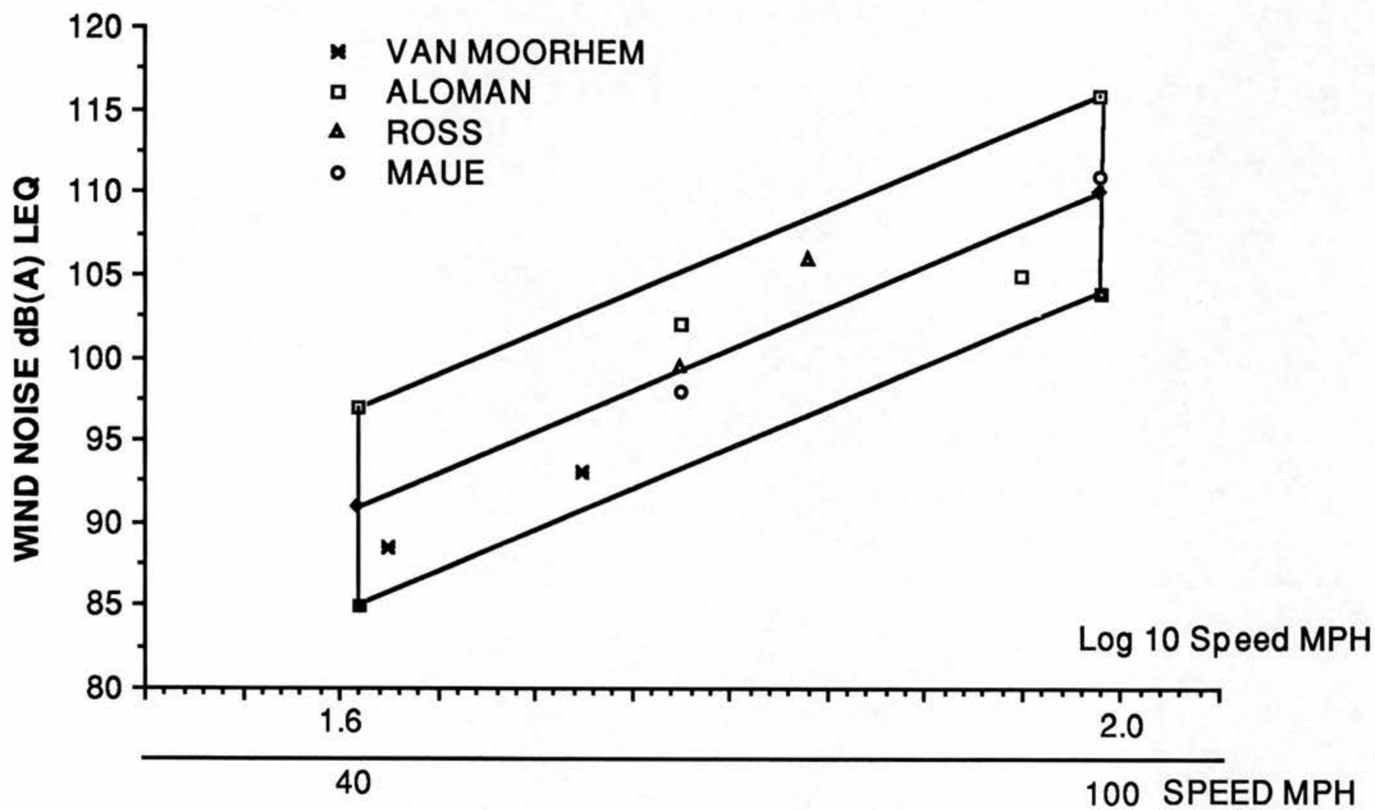


FIGURE 2.8 AVERAGE NOISE PLOT WITH 95% CONFIDENCE INTERVALS AND PREVIOUS RESULTS.



3.Source of wind noise

Our flow visualisation work shows smooth flow adherent to the majority of the helmet until it reaches the back of the helmet where a large horseshoe shaped area of turbulence and separation occurs: "the wake". There is also a fair amount of turbulent flow generated by the chin piece of the helmet and flowing along the inferior surface (Figure 2-9). With the addition of the demerara sugar there is a similar flow pattern but a marked reduction (30%) in the size of the area of separation, as measured using the paraffin dye method, indicating the creation of a turbulent boundary layer.

The sound measurements are shown in Table 2-5. They show that, in causing a turbulent boundary layer to form around the helmet, the application of sugar leads to a significant increase in the sound levels which then approach those measured on the road. Interestingly there is no significant difference in the standard and sugar coated helmet's sound levels when measured on the road despite the significant difference in the wind tunnel.

FIGURE 2.9 AIRFLOW PATTERN AROUND MOTORCYCLE HELMET (SMOKE IN WIND TUNNEL) COURTESY OF D. NASH.

TABLE 2.5 SOUND LEVELS OF AGV 3000 HELMET

@ 90 mph (MEAN +1SD dB(A)

		TEST SITE	
	Wind tunnel	Open road	
MODIFICATION			
Standard	92 (2)	106.5 (3.2)	t =8.1 P<0.01
Sugar coated	103 (2.5)	107 (3)	NS
	t =6.1 P<0.05	NS	

DISCUSSION OF RESULTS

A frequency analysis of wind noise at various speeds has shown a consistent pattern of low frequency noise with its maximal A-weighted energy centered on 500Hz. This is important when one considers that at these low frequencies (125-1000 Hz) a "typical" motorcycle crash helmet offers no effective sound attenuation and often demonstrates resonance at 500Hz. For this reason one can assume that the measured intra-helmet sound levels are closely representative of the generated wind noise.

On the basis of our wind tunnel work it would appear that a turbulent boundary layer is the major sound source; a previously unreported finding. This conclusion is based on the production of noise levels not statistically different to those recorded on the open road by "tripping" the boundary layer from laminar to turbulent early in its course. In this situation, the boundary layer exists as a thin layer of air (0-10mm) lying between the free stream airflow and the helmet shell. When laminar it can be regarded as infinitely multilayered with each layer moving at increasing speed, from stationary in the layer adjacent to the helmet shell, to free stream velocity in the layer adjacent to the free stream airflow. When turbulent it can be regarded as a thin layer of air adjacent to the helmet shell in which there are random and diffuse pressure changes which increase with increasing velocity of the free stream airflow. The "Reynolds number" (Re) is designed to give some measure of the likelihood of turbulence in the boundary layer and is given by the formula:

$$Re = pvl/\mu$$

where p is air density (Kg/m^3), v is velocity of free stream airflow (m/s), l is the length of the helmet from front to back (m) and μ is air viscosity (Kg/m). Turbulence in the boundary layer is more likely when the Reynolds number is high, when the surface over which there is flow (helmet shell) is rough and if there is turbulence in the free stream airflow. For the motorcyclist, with calculated Reynolds numbers for flow conditions around a helmet ranging from 0.75 to 1.5 x 10^6 and the almost certain turbulence of the airflow striking the front face of the helmet after its passage over the nose of the motorcycle, a turbulent boundary layer could be predicted from basic fluid dynamic theory (Douglas, 1980). This finding also demonstrates the flaws in using a laminar flow wind tunnel for helmet noise work and indicates the need for turbulent flow conditions.

The results presented here for the wind noise levels in a motorcycle crash helmet are not new. In fact there is considerable overlap of these results and previously performed work as shown in Fig 2-8. We have shown that at speeds above 45mph (20.5m/s) a rider is exposed to sufficient noise to be at risk of noise-induced hearing loss. As a helmet is a legal requirement in this country, the bareheaded investigation was done largely out of curiosity. Although our method of obtaining "bareheaded" sound levels seems somewhat unnatural, our figures are in close agreement with those reported by Van Moorhem (1981) which were measured directly at the rider's ear. This lends some validity to this technique. Certainly, the noise levels and consequently the risk of noise damage appear significantly greater. This finding may be related to the inverse square law whereby the wearing of a helmet "lifts" the turbulent sound source 3-4cm from the ear with a consequent reduction in the noise levels, and perhaps also to the smoother surface offered by the outer shell.

What is particularly noteworthy about this study however, is that despite varying riding conditions, it has failed to show any major influences, other than vehicle speed, on the measured noise levels for the motorcyclist, although there were small but statistically significant differences between different types of crash helmet. (This excludes the bareheaded results which have little practical relevance in the UK.) In fact a range of less than 4dB covered all mean values at all speeds (Table 2-3). On the basis of these results wind noise appears to be a common and similar problem for all motorcyclists, regardless of helmet type or machine ridden, with the mean sound levels, at any speed, predictable from the equation:

$$WN = 13.5 + 49.\log_{10}V$$

where WN is wind noise in dB(A) Leq and V is vehicle speed (mph). There are 95% confidence intervals of +/-6dB.

At this point it is worth considering some sources of error. We have already seen that the reproducibility for the same set of test conditions is good with an error of less than 1dB. Although there is a potential 10% error in the motorcycle speedometer reading, this is likely to be a systematic error, and the use of experienced motorcyclists should minimise this problem by their ability to maintain a constant speed. There are small but significant differences in the sound attenuation values of various helmets. These are of the same order as the differences between the sound levels recorded for different helmets (2-5dB) and certainly well within the error inherent in any subjectively based test technique (3-5dB). Finally, the largest source of error is the random changes in wind speed and atmospheric conditions that occur in the real world. Observed differences as large as 5dB for the same set of test parameters measured on different days were seen.

With this in mind, the small but significant differences between different helmets are probably just a statistical quirk and there are, probably, no "real world" differences between currently available motorcycle helmets, certainly as regards noise levels. A spread of 12dB for the 95% C.I. of the average noise plot seems large in acoustic terms but is probably representative of the total potential error of this test technique when used in the real world. Regardless of these minor apparent differences, at speeds above 45mph (20.5m/s), the rider will be exposed to excessive and relatively similar wind noise levels regardless of which helmet he wears or which motorcycle he rides.

CONCLUSIONS

1. Motorcyclists are exposed to excessive and potentially harmful wind noise levels when riding at speeds of greater than 40mph (17m/s) regardless of their helmet choice.
2. The source of this noise appears to be a turbulent boundary layer.
3. As currently designed motorcycle helmets offer no useful attenuation against this low frequency sound although they do reduce sound levels when compared to wearing no helmet.

CHAPTER 3

THE EFFECTS OF WIND NOISE ON MOTORCYCLISTS' HEARING

INTRODUCTION

If there is abundant evidence of excessive wind noise when riding, there is certainly a paucity of evidence regarding its effects on the hearing of motorcyclists. It is obviously important to ascertain the occurrence of any adverse effects as this will strengthen any argument for remedial action. This chapter aims to achieve that objective by looking at both the long and short term effects of this noise exposure.

METHODS AND MATERIALS

1. Long-term effects

Motorcyclists were invited to attend for audiometric assessment at a number of test sites: Plymouth, Bristol, Brierly Hill and at Donington Park race track. A mobile test facility was used at the latter location but fixed audiology facilities existed at the base hospitals at all other locations.

A screening process was undertaken for all prospective subjects. A brief telephone screen was first exercised to exclude previous ear disease and occupational noise exposure. Succesful candidates were then invited to attend the audiometric facility. At this stage a thorough clinical history was taken to identify any previous ear disease, severe systemic illness or head injury. Any person with such a history was excluded. Also excluded was anyone who had a history of "significant" alternative recreational or occupational noise exposure.

"Significant" is a rather nebulous term but for these examples would be deemed to have occurred if the subject was required to wear hearing protection at work or if he used firearms more than twice in any year.

Clinical examination and tympanometry were then performed with further exclusions for subjects with abnormal findings. The aim was to recruit subjects who were well in all respects and whose only "significant" noise exposure was motorcycling. It was hoped that by such screening the test group could be compared to an age and sex matched "otologically normal" control group.

After this screening process, the remaining subjects were questioned with regard to their motorcycling history. As the work reported in chapter 2 demonstrated that the type of helmet worn and machine ridden are relatively unimportant as regards noise levels, these were not asked for. Instead riders were asked their age, occupation (or usual occupation if unemployed), number of years of riding experience and average number of miles per year ridden. These riders were also asked whether they were regular users of earplugs. The first 90 riders recruited were also asked if they had ever suffered any tinnitus after riding, as an indicator of any temporary threshold shift.

Manual pure-tone audiograms for both air- and bone-conduction were then performed as recommended by the BSA and BAOL (Anon., 1981). (Air-conduction was performed at the following frequencies: 0.25, 0.5, 1, 2, 4, 6 and 8kHz; Bone-conduction at: 0.5, 1, 2 and 4kHz)
Subjects with air-bone gaps of greater than 10dB at 4kHz and 5dB at any other frequency, and therefore indicative of some conductive hearing loss, were excluded from further analysis. Some degree of air-bone gap can be found with "normal" hearing; our figures are stricter than other groups (Coles et al, 1991; Lightfoot and

Hughes, 1993) and were chosen to avoid any possibility of conductive hearing loss confounding the data.

To avoid the presence of any temporary threshold shift, subjects were asked not to ride for the 24 hours prior to audiometry.

This audiometric data was analysed using a case control design at the MRC Institute of Hearing Research in Nottingham. An appropriate control group was obtained from the MRC National Study of Hearing (NSH) (Davis, 1989). The NSH data was compared to the motorcyclists as a whole group and then broken down into Racers, Police riders and "Leisure" riders. Models were fitted in turn to each of the dependent variables, better and worse hearing ears at each frequency, with independent variables, age as a covariate, and each of the above grouping factors in turn. A normal distribution error structure was presumed. In essence the model was a case control analysis to look at the statistical effect of wind noise from motorcycling as measured by hearing thresholds at each audiometric frequency. The statistical model corrects for age (from 0-50 years) by the provision of a factor which was the same for both test and control samples (e.g. 0.1dB/year at 0.5kHz). The NSH data is taken as the baseline (hearing at age 0) and the motorcyclists' models are compared to this. Any differences are noted as an additional factor which represents an increase or decrease in hearing threshold at each frequency. The significance of this "correction factor" was assessed by analysis of variance and the two-sample t-test. Results were assumed to be significant when $P<0.05$.

The tympanometers used were an Electromedics and a GSI 33. The audiometers were either a Graystad GSI 16 (Lucas Grason-Stadler, Milford, NH, USA) or a Kamplex AD 27 (Interacoustics AS, Assens, Denmark) both of which complied with BS 5966 (1980) and were regularly calibrated to BS 2497 (1988) for air-conduction and BS 6950 (1988) for bone-conduction. The background noise levels in the static test rooms met the requirements specified in BS 6655 (1986). Although the mobile audiometric facility did not quite meet these stringent requirements, it certainly satisfied the slightly less demanding but still acceptable standards described by Robinson (King,1992).

2. Short-term effects

A large proportion of the first 90 riders recruited for the hearing survey part of this study admitted to tinnitus following prolonged riding. This was felt to represent temporary threshold shift occuring after what would certainly be excessive noise exposure. We felt it important to have some idea of the magnitude of this TTS and therefore performed the following investigation.

Eighteen experienced motorcyclists, all with hearing thresholds of better than 20dB(HL) at all standard audiometric frequencies, were asked to undertake a standard test route of approximately 80 miles at a fairly constant 80mph to give a total riding time of 1 hour. A manual pure-tone audiogram was performed immediately prior to the test journey and again starting within 2 minutes of their return from the test run. The audiometrician was "blind" to the initial audiogram. The change in audiometric threshold represents the temporary threshold shift and was assessed statistically with a paired t-test.

RESULTS

1. Long-term effects

Over 400 motorcyclists offered themselves for inclusion in the study, many of whom were declined at the first telephone screen due to previous noise exposure or ear disease. Unfortunately accurate figures for subjects declined at this stage are unavailable. Thirty five subjects were excluded on the basis of significant previous noise exposure in their history and 18 on the basis of abnormal findings on tympanometry and audiometry (Asymetrical hearing loss in 2 and excessive air-bone gaps in 16). A total of 285 subjects survived the total screening process and were submitted for statistical comparison with the NSH database. The mean age was 35 years (SD:9.8). Fourteen (5%) were women. For the purposes of analysis against the NSH data it was felt to be appropriate to further exclude all subjects over the age of 50 and all women, leaving a study group of 246 men with a mean age of 33 years and riding experience of 13.5 years. The majority of subjects were in non-manual occupations (85%, n=210), 29 (12%) were manual workers and in 7 (3%) this data was unrecorded. Their riding histories are shown in Table 3-1. For comparison, the NSH control group of 182 came from a total group of 522, having excluded 154 with excessive air-bone gaps and a further 186 with previous noise exposure.

Persistent tinnitus was found in 12 out of the first 90 motorcyclists (13%). Worsening of this tinnitus or the temporary occurence of tinnitus after prolonged riding was found in 65 riders (72%). This usually meant at least 1 hour of prolonged high speed riding.

The results of the audiometric analysis are shown for the "better hearing" ear in Table 3-2 and for the "worse hearing" ear in Table 3-3. A positive "correction" factor for motorcyclists represents a worsening of hearing threshold. The standard errors for each parameter are shown in brackets. It can be seen that the hearing of all motorcyclists and sub-groups is significantly worse than the controls at 0.25, 0.5, 1 and 2kHz, but this is most marked for the police motorcyclists. This result is independent of age.

2. Short-term effects

Some degree of temporary threshold shift occurred in all test subjects after 1 hour of relatively high speed riding. The pooled data is shown in tabular form in Table 3-4 and graphically in Figure 3-1. TTS was most marked at the low/middle audiometric frequencies with the mean maximal TTS occurring at 1kHz.

TABLE 3.1 RIDING HISTORY OF MOTORCYCLISTS
MEAN VALUES (+ 1SD)

GROUP	AGE	RIDING EXPERIENCE	MILES/YEAR ($X10^3$)
ALL MOTORCYCLISTS	33 (7.6)	13.5 (6.9)	10 (8.5)
LIESURE	34 (7.7)	14.4 (7.1)	9.5 (8.5)
RACERS	29 (5.9)	10.9 (5.6)	N/A
POLICE	39 (6.7)	17.4 (6.7)	15.5 (5.3)

TABLE 3.2 MODEL FOR HEARING THRESHOLDS FOR BETTER EAR (STANDARD ERROR)

FREQUENCY (KHz)	.25	.5	1	2	4	6	8
NSH VS ALL MOTORCYCLISTS							
GRAND MEAN (FOR AGE 0)	5.7 (1.33)	0.9 (1.30)	-2.3 (1.16)	-2.8 (1.50)	-6.3 (2.13)	-0.1 (2.52)	-6.5 (2.43)
AGE CORRECTION (dB PER YEAR)	0.1 (0.04)	0.1 (0.04)	0.2 (0.04)	0.2 (0.05)	0.5 (0.07)	0.6 (0.08)	0.6 (0.08)
CORRECTION FACTOR FOR MOTORCYCLISTS	2.0 (0.74)	3.7 (0.72)	3.6 (0.64)	1.9 (0.83)	0.0NS (1.18)	-2.5NS (1.40)	-0.6NS (1.35)
NSH VS 3 MOTORCYCLIST GROUPS							
GRAND MEAN (FOR AGE 0)	5.9 (1.36)	0.9 (1.32)	-2.2 (1.18)	-2.9 (1.53)	-6.4 (2.17)	0.1 (2.56)	-6.0 (2.46)
AGE CORRECTION (dB PER YEAR)	0.1 (0.04)	0.1 0.04)	0.2 (0.04)	0.2 (0.05)	0.5 (0.07)	0.6 (0.08)	0.6 (0.08)
CORRECTION FACTOR							
LEISURE (N=159)	1.9 (0.86)	3.5 (0.83)	3.3 (0.74)	1.3NS (0.96)	-0.6NS (1.36)	-3.4NS (1.61)	-1.6NS (1.55)
RACERS (N=73)	1.9NS (1.12)	4.0 (1.09)	3.6 (0.97)	2.7 (1.26)	0.7NS (1.78)	-1.8NS (2.11)	-0.1NS (2.02)
POLICE (N=14)	4.7 (2.39)	4.5 (2.33)	5.9 (2.08)	4.5 (2.69)	2.7NS (3.82)	4.5NS (4.52)	9.8 (4.34)

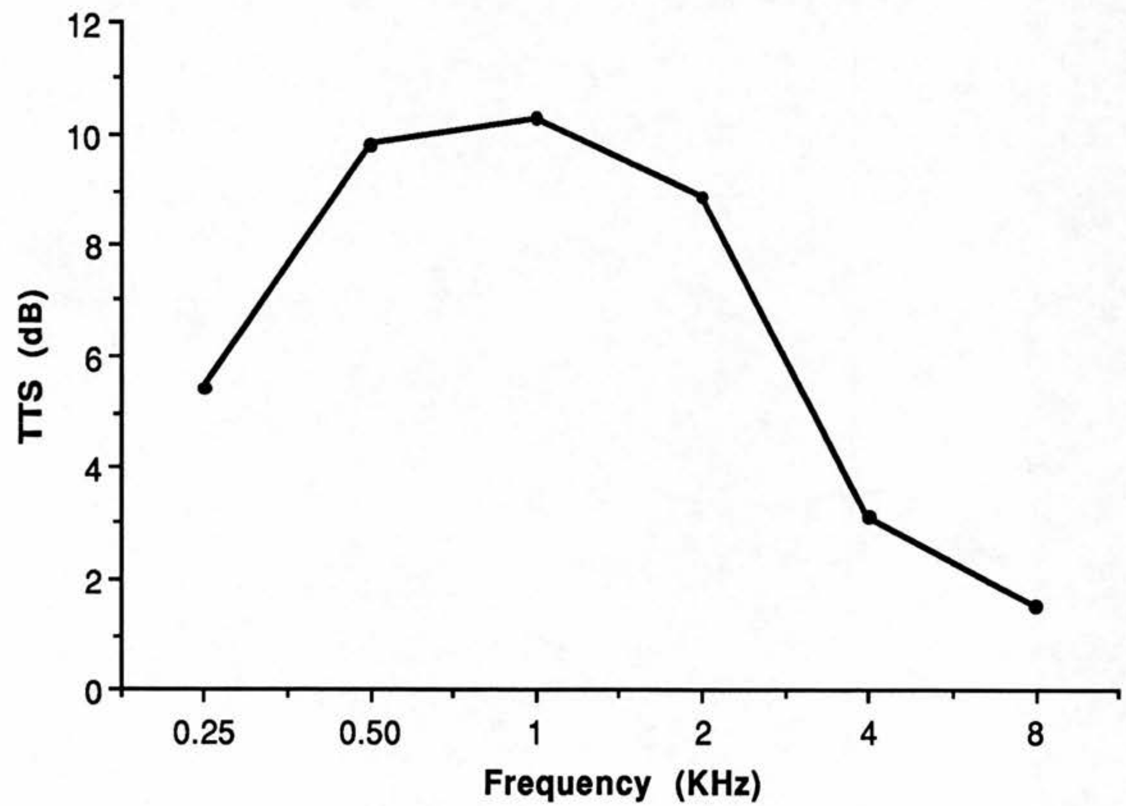
TABLE 3.3 MODEL FOR HEARING THRESHOLDS FOR WORSE EAR (STANDARD ERROR)

FREQUENCY (KHz)	.25	.5	1	2	4	6	8
NSH VS ALL MOTORCYCLISTS							
GRAND MEAN (FOR AGE 0)	6.0 (1.28)	3.0 (1.23)	-0.4 (1.26)	-1.4 (1.67)	-1.2 (2.64)	1.3 (2.93)	-4.0 (2.98)
AGE CORRECTION (dB PER YEAR)	0.1 (0.04)	0.1 (0.04)	0.2 (0.04)	0.3 (0.05)	0.6 (0.08)	0.7 (0.09)	0.6 (0.09)
CORRECTION FACTOR FOR MOTORCYCLISTS	2.8 (0.71)	3.4 (0.69)	3.1 (0.70)	2.1 (0.93)	-0.2NS (1.46)	-2..9NS (1.63)	-2.5NS (1.66)
NSH VS 3 MOTORCYCLIST GROUPS							
GRAND MEAN (FOR AGE 0)	6.3 (1.30)	3.3 (1.26)	-0.4 (1.29)	-1.8 (1.70)	-1.8 (2.68)	1.6 (2.98)	-3.4 (3.03)
AGE CORRECTION (dB PER YEAR)	0.1 (0.04)	0.1 (0.04)	0.2 (0.04)	0.3 (0.05)	0.6 (0.09)	0.7 (0.09)	0.6 (0.10)
CORRECTION FACTOR							
LEISURE (N=159)	3.1 (0.82)	3.5 (0.79)	2.9 (0.81)	1.5NS (1.07)	-1.6NS (1.69)	-3.5NS (1.88)	-3.2NS (1.91)
RACERS (N=73)	1.7NS (1.07)	2.7 (1.03)	3.2 (1.06)	3.6 (1.40)	2.3NS (2.21)	-2.7NS (2.46)	-2.8NS (2.49)
POLICE (N=14)	5.2 (2.30)	6.1 (2.21)	5.1 (2.27)	0.9NS (2.99)	0.6NS (4.73)	3.1NS (5.26)	8.0NS (5.34)

TABLE 3.4 TEMPORY THRESHOLD SHIFT IN MOTORCYCLISTS (18 SUBJECTS; 80MPH FOR 1 HOUR)

AUDIOMETRIC FREQUENCY (Hz)	0.25	0.5	1	2	4	8
MEAN THRESHOLD BEFORE (dBHL)	8.6	5.8	5.7	3.9	6.2	8.6
	(5.0)	(4.4)	(4.3)	(4.8)	(6.6)	(6.2)
MEAN THRESHOLD AFTER (dBHL) (SD)	14.0	15.6	16	12.8	9.3	10.1
	(6.4)	(4.7)	(6.0)	(5.9)	(6.3)	(7.2)
MEAN T.T.S. (dB)	5.4	9.8	10.3	8.9	3.1	1.5
P VALUE	0.0002	0.0000	0.0000	0.000	0.49	0.34

FIGURE 3.1 TEMPORARY THRESHOLD SHIFT AFTER MOTORCYCLING



DISCUSSION OF RESULTS

On the basis of the results presented in this chapter, it would appear that the noise exposure from motorcycling results in both short- and long-term adverse effects on hearing. We have demonstrated significant TTS, which many motorcyclists (72%) are aware of as tinnitus after longer journeys, and significant PTS when compared to an appropriate control group.

This study is not the first to demonstrate a permanent hearing loss in motorcyclists (Fletcher and Gross, 1977; Jongepier and Van der Weerd, 1989). It is however the first study that has used appropriate and well documented controls (in this case from the NSH), and standard and accepted statistical analysis. This group is also the largest study group to date, and has been thoroughly screened to remove all other potential confounding factors, such as co-existent otological pathology and alternative noise exposure. As such, these results probably represent the first reliable and generally applicable assessment of the long-term effects of motorcycling on hearing.

It is interesting that the predominant hearing loss occured at 0.5 and 1kHz. One of the first concerns about this low frequency hearing loss is that it may represent masking of auditory threshold by environmental noise. This is unlikely given the relative improvement in thresholds at 0.25kHz and the results of the temporary threshold shift experiment where the maximal TTS occurred at the same audiometric frequencies. These frequencies are half to one octave above the relatively narrow, A-weighted "centre" frequency of wind noise. This lends further support to the hypothesis that "wind noise" is the predominant damaging noise source for motorcyclists and, that relatively narrow tonal bands of noise can lead to "atypical" noise-induced hearing loss outside the "classic" 3-6kHz dip (Alberti, 1987; Bernabei, 1953; Knight, 1963).

It may still be possible that this loss in fact represents some residual TTS despite our efforts to avoid this by asking subjects to avoid any noise exposure, particularly motorcycling, for the 24 hours prior to testing. A similar worry, again with a low-frequency hearing loss, has been previously reported for naval flight-deck personnel where there was a slight improvement in hearing thresholds with the passage of quite prolonged periods of time (Knight and Coles, 1966). Serial audiometry, or a longer break from motorcycling, might have helped elucidate this point but was, unfortunately, logistically impossible. However, an examination of the data does show that the maximal PTS tended to occur at 0.5kHz whereas the maximal TTS was at 1kHz, perhaps indicating the occurence of a different process. This would also support the contention that, until this point can be definitively decided, it is probably reasonable to assume some degree of truly permanent hearing loss. Regardless, there is no doubt that wind noise exposure is having tangible adverse effects on the hearing of motorcyclists.

It is also noteworthy that the hearing loss is greatest for the sub-group of police motorcyclists and least for "leisure" riders, with the racers falling in between. Most recreational riders ride for a relatively short time each day, often less than half an hour and usually in rush hour traffic on their way to and from work, thus keeping speeds down. Longer trips occur on a very intermittent basis. As for the racers, although their speeds are very high, they rarely spend more than 45 minutes on the motorcycle at any one time and usually less than 2 hours in total for any one day. In addition their riding is usually restricted to 3 days around a race meeting for each week. For both of these sub-groups this intermittent noise exposure allows plentiful time for audiological recovery. The police motorcyclists however, spend many hours on their machines each day and do this for a full working week. It is therefore inevitable that their noise exposure will be greatest and their hearing loss worst. This hypothesis is to some extent supported by the significantly greater annual mileage of the police riders. These results must be viewed with a little caution given that they are based on relatively small numbers. However a trend is apparent that invites further investigation with larger numbers. The findings of this study taken together are a strong and immediate argument for some form of remedial action.

CONCLUSIONS

Noise exposure from motorcycling results in:

1. Significant temporary threshold shift, maximal at 1kHz, after only 1 hour of relatively high speed riding.
2. Significant permanent hearing loss at 0.5 and 1kHz.

CHAPTER 4

AWARENESS AND ATTITUDES OF MOTORCYCLISTS TO NOISE

INTRODUCTION

Having established that motorcyclists are exposed to excessive noise levels which produce real rather than potential adverse effects on riders' hearing it would seem appropriate to take some form of remedial action. However, I believe that any such action is at risk of being "pie in the sky" unless the views of the target group are first taken into account. This part of the project was therefore undertaken in an effort to discover what motorcyclists know about the risks of excessive noise exposure from motorcycling, means of prevention and attitudes towards this.

MATERIALS AND METHODS

A structured questionaire was used to interview randomly selected motorcyclists at two separate race meetings in Liverpool and near Bath, during the summer of 1992. Motorcyclists were selected from the ranks of both racers and spectators. An abbreviated version of the questions asked is shown with the results in Table 4-1.

RESULTS

The interview results are sumarised in Table 4-1 and represent the data from interviews with 124 motorcyclists. Based on this study group, the "typical" motorcyclist appears to be male (96%), with a median age of 30 years (range 17-60) and a median riding experience of 10 years (range 1-43). Although he is well aware of the dangers of excessive noise and the existence and purpose of earplugs, he does not equate this problem with riding a motorcyle. Indeed only 16% of this group were regular users of earplugs when riding.

On a more reassuring note 74% of riders expressed a willingness to use earplugs if they thought there was a real risk to their hearing. Not surprisingly only 1 rider indicated that he would stop riding to protect his hearing.

Many riders were under the impression that their crash helmet already provides adequate hearing protection. When told this was not the case 76% of riders thought it should. Most would be prepared to pay more for this option.
For both earplugs and intra-helmet ear protection a total of 25 riders (20%) expressed concern about the possible interference with warning signal perception.

TABLE 4.1 RESULTS OF NOISE AWARENESS SURVEY

QUESTION	PERCENTAGE ANSWERING YES (n = 124)
1. IS RIDING A MOTORCYCLE NOISY	38% (47)
2. CAN NOISE DAMAGE HEARING	99% (122)
3. KNOWLEDGE OF EAR PROTECTORS EARPLUGS - 91% EARMUFFS - 16% OTHER - <1%	91% (113)
4. DO YOU WEAR EARPLUGS	16% (20)
5. WOULD YOU WEAR EARPLUGS IF YOU KNEW OF A RISK TO HEARING	74% (92)
6. DO YOU KNOW WHERE TO OBTAIN EARPLUGS	74% (92) CORRECT RESPONSE
7. HOW MUCH WOULD YOU PAY	88% (108) <£10
8. DOES A HELMET PROVIDE ADAQUETE HEARING PROTECTION?	76% (94)
9. IF NOT SHOULD IT?	76% (94)
10. WOULD YOU PAY MORE?	59% (73)

DISCUSSION OF RESULTS

Motorcyclists attending motorcycle race meetings may not be strictly representative of motorcyclists in general, although the age and sex distribution of this group is very similar to that of the group in chapter 3. They are however, likely to represent the interested and even "dedicated" rider. It is this sub-group in particular who could be expected to continue riding for many years and would thus exposed to the greatest risk of hearing damage; their views are therefore important.

It would seem that as a group motorcyclists are well aware of the problems of excessive noise exposure but do not equate this problem with motorcycling. However, they do appear to be willing to take precautions if a real risk can be shown to exist, and are even prepared to put their hands in their pockets to do this. This is particularly encouraging as these interviews were conducted very early in the project, before the motorcycle media had identified and reported any of this work and while most motorcyclists would still be quite cynical of such "critical" questioning. If truly representative, these results imply that with appropriate intervention and education remedial action can be instituted and should be successful.

CONCLUSIONS

1. Overall awareness of the problems of excessive noise exposure from wind noise when motorcycling is low.

2. Motorcyclists appear willing to take appropriate remedial action.

3. Concern exists about possible adverse effects of ear protection on warning signal detection.

CHAPTER 5

HEARING PROTECTION FOR MOTORCYCLISTS

INTRODUCTION

Having established a need for some form of remedial action, and with the ideal solution unknown, some form of personal hearing protection seems an obvious first choice. Earmuffs are obviously impractical and as currently designed a motorcycle crash helmet provides no useful attenuation against the low frequency wind noise. It would therefore seem that the only realistic choice of personal hearing protection for motorcyclists is earplugs. But which ones and how effective are they? The aim of this chapter was to answer these questions.

METHODS

The study was conducted in two parts. The first was required to establish which earplugs should be assessed in the second part. The second part was a more formal assessment of the function and performance of earplugs to be used by motorcyclists.

1. A random survey of 40 chemists was undertaken in Plymouth, Bristol, Birmingham, Edinburgh and Liverpool to see which types of earplugs were easily available to the public.
Based on the results of this section, two types of earplugs were chosen for section 2. Although freely available, wax earplugs were deemed unsuitable for motorcyclists on the grounds of their tendency to pick up dirt, break up with use and generally rather fiddly nature. It was also felt that some motorcyclists may be aware of the existence of personalised earplugs and that a representative personally moulded earplug should also be included for testing. As the results presented in chapter 4 showed that very few motorcyclists would be prepared to pay more than £10 for earplugs, no earplugs costing more than this would be considered for testing in section 2. It was felt that as most audiology departments already provide moulded 'plugs at reasonable cost (approximately £10) for ear occlusion whilst swimming, these would prove to be the cheapest and most readily available of the personalised earplugs. Hence the choice of the "silisoft" earplugs.

2a. 13 subjects with normal hearing thresholds (<20dB at all frequencies) were used to test 3 types of earplug. The plugs were tested for sound attenuation using an "insertion loss" technique similar to that described by the American Standard of 1957 (ASA, 1957). In essence the subject was asked to sit in a sound proof room, 1 metre

from a single Graystad loudspeaker driven by a GSI 16 audiometer. Pure tones were produced at the frequencies of 250, 500 1000, 2000, 4000 and 6000 Hertz and a free field audiogram obtained by the method of limits. This procedure was repeated for each earplug both with and without the subject's crash helmet in place. With the earplug (with or without the helmet) in place, the threshold obtained will be worse by an amount that corresponds to the "insertion loss", or attenuation score of the test item. The tests were performed in random order and the subjects were asked to fit the earplugs themselves. The "silisoft" plug was tested after removing and replacing the earplug, to break the initial material insertion seal.
The subjects were also asked to score the earplugs for comfort and acceptability from 1 for good to 5 for bad after a short period of use.

2b. The efficacy of the "best" earplug was then tested by examining its effects on temporary threshold shift in a similar fashion to the method used in Chapter 3. Ten experienced motorcyclists were asked to undertake a standard test route of approximately 80 miles at a fairly constant 80mph to give a total riding time of 1 hour. A manual pure-tone audiogram was performed immediately prior to the test journey and again starting within 2 minutes of their return from the test run. The audiometrician was "blind" to the initial audiogram. The ten subjects were asked to perform the test run on two occasions; once with and once without the optimal earplugs chosen from section 2a in place. Both runs were undertaken in dry and relatively windless riding conditions. None of the ten subject riders were habitual wearers of earplugs.

Statistical analysis was performed using the Wilcoxon paired, two-sample "t" and chi-squared tests.

RESULTS

1. The results for this section are shown in Table 5-1. Earplugs were unavailable in 4 shops visited. The soft yellow foam earplugs (EARfit) were almost universally available and were significantly more often available than their nearest rival, the AQUAfit (both Cabot Safety Ltd) (x^2=15.2, 1df, $p<0.001$).

2. The mean scores and standard deviation for earplug attenuation are shown in Table 5-2. Although our technique gives consistently poorer figures for low frequency attenuation than those obtained by the manufacturer using the current British Standard: BS 5108(1991), these differences are not statistically significant. In addition there are no significant differences in the performance of the 3 types of earplugs tested.
The results for the attenuation of earplug and helmet together are again shown as mean and 1 standard deviation in Table 5-3. Again there are no significant differences in performance between the 3 earplugs. Of interest is the consistently poorer performance of all 3 types of 'plug at 500Hz with the crash helmet in place. This is shown graphically for the EARfit plug in Figure 5-1 and is attributed to the phenomena of helmet resonance previously described in chapter 2.

The subjective comfort scores were significantly different with the EARfit scoring a median of 2 (Range 1-3), AQUAfit a median of 3 (Range 2-4) and the silisoft scoring 4 (Range 3-5). The EARfit plug was felt to be significantly the most comfortable (Wilcoxon paired test: $p<0.01$).

TABLE 5.1 AVAILABILITY OF EARPLUGS (40 CHEMIST'S SHOPS)

EARPLUG	AVAILABILITY (%)
EARfit	36 (90%)
AQUAfit	20 (50%)
Earex	8 (2 0 %)
Antiphones	1 (2.5%)

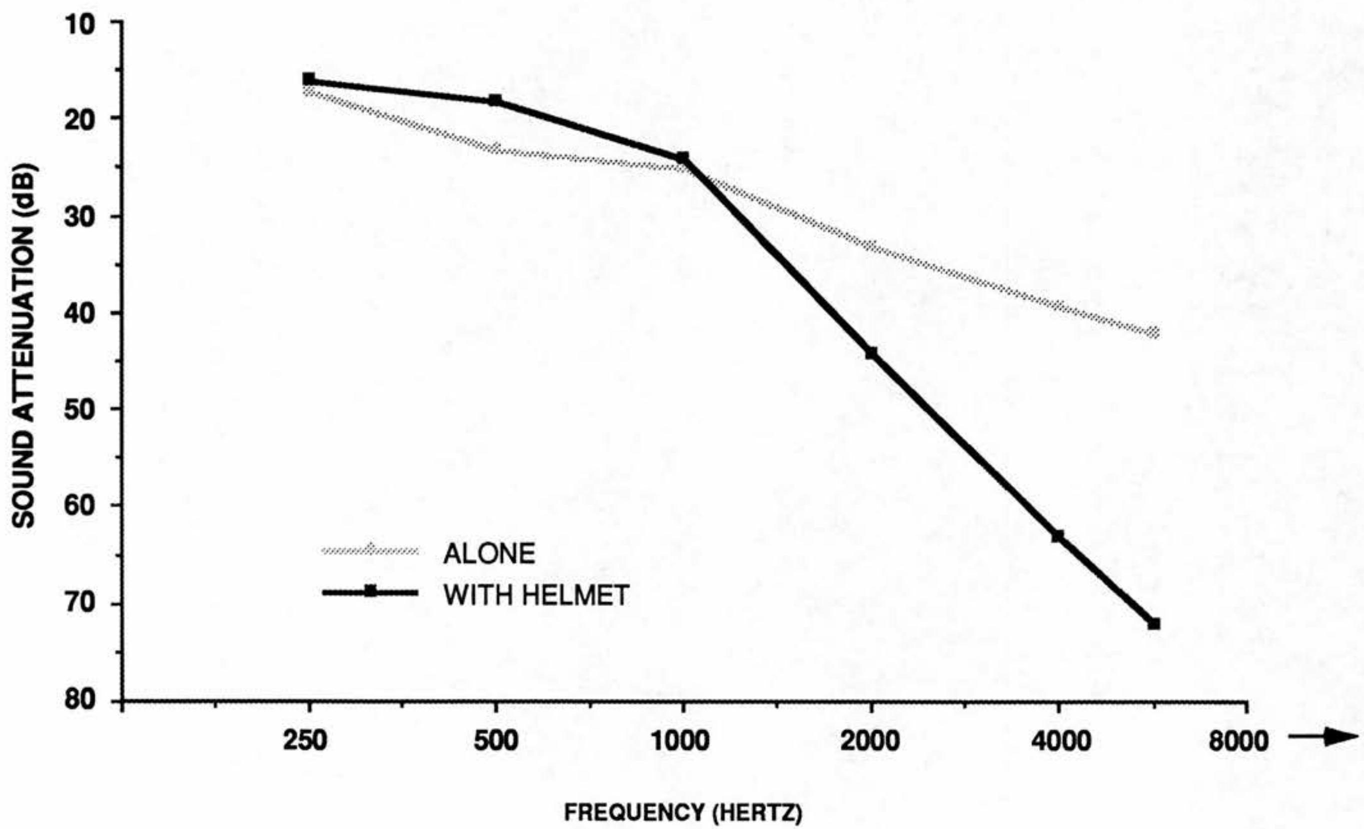
TABLE 5.2 MEAN SOUND ATTENUATION OF EARPLUGS ALONE
(Scores in dB with 1 Standard Deviation)

	FREQUENCY (Hertz)					
	250	500	1000	2000	4000	6000
AQUAfit	15.8 (5.7)	20.8 (8.4)	19.2 (8.9)	26.2 (9.4)	35 (11.9)	40.4 (12.7)
EARfit	17.3 (3.9)	22.7 (8.6)	25 (8.9)	31.9 (11.5)	39.2 (12.9)	41.5 (8.3)
Silisoft	13.5 (6.9)	18.8 (9.2)	18.0 (7.8)	29.2 (10.6)	34.6 (7.8)	38.8 (12.4)

TABLE 5.3 MEAN SOUND ATTENUATION OF EARPLUGS AND HELMET
(Scores in dB with 1 Standard Deviation)

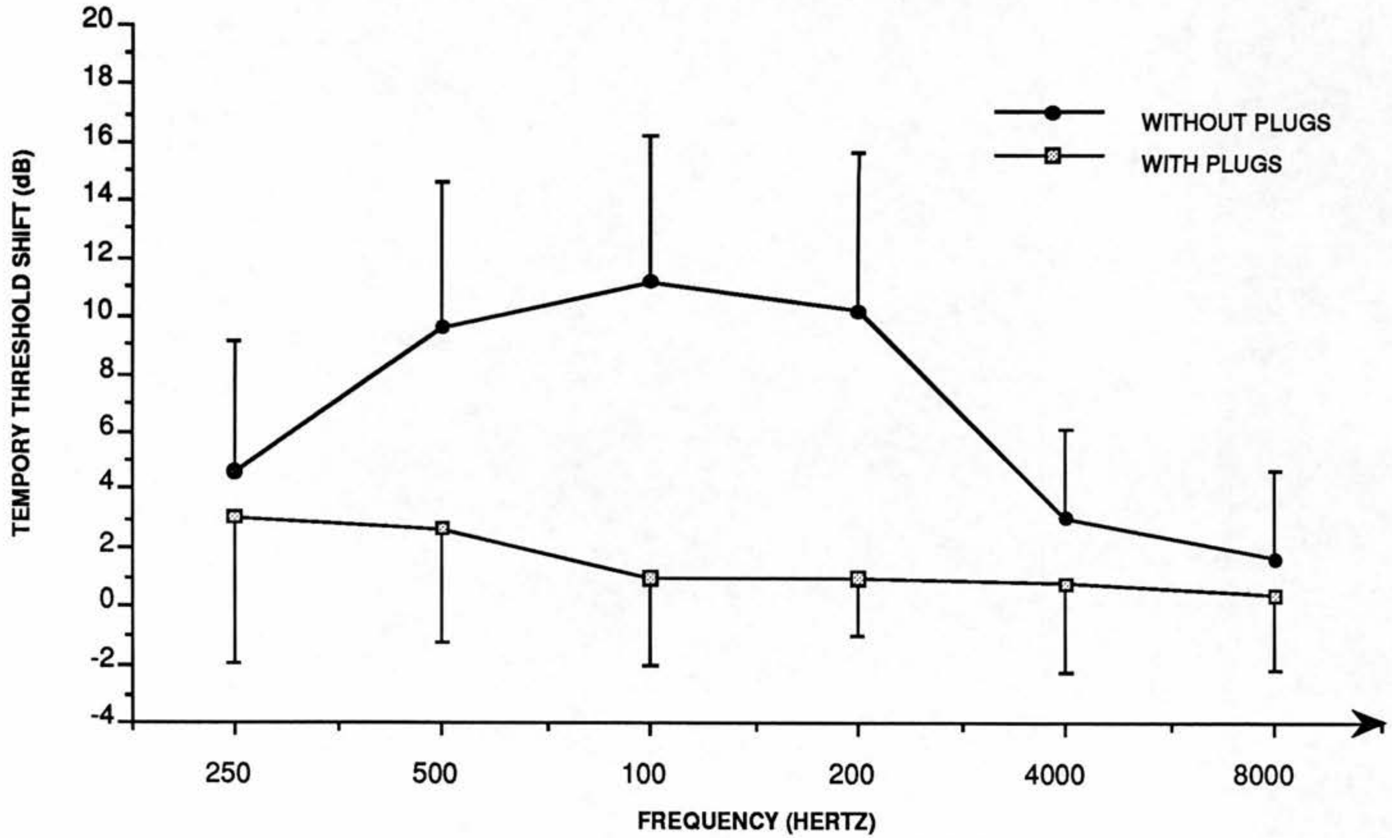
	FREQUENCY (Hertz)					
	250	500	1000	2000	4000	6000
AQUAfit	15.8	17.3	18.5	38.8	48.5	60.4
	(5.3)	(5.3)	(7.7)	(11.9)	(10.7)	(10.7)
EARfit	16.1	18.0	23.8	43.8	63.5	72.3
	(4.2)	(8.0)	(11.4)	(10.6)	(8.5))	(13.3)
Silisoft	13.8	15.8	21.1	41.9	60.8	62.7
	(7.9)	(9.3)	(7.9)	(12.8)	(9.3)	(13.2)

FIGURE 5.1 MEAN ATTENUATION SCORES OF SOFT YELLOW FOAM EARPLUGS



2b. The mean results and standard deviation for temporary threshold shift both with and without earplugs are shown graphically in Figure 5-2. The maximal TTS again occurred around 1kHz. The lesser TTS occurring at 500, 1000 and 2000 Hertz with earplugs in place are all significant at the 1% level (t = 2.8, 7.7 & 7.5 respectively).

FIGURE 5.2 MEAN VALUES OF TEMPORY THRESHOLD SHIFT FOLLOWING ONE HOUR'S RIDING AT 80mph (& 1 S.D.)



DISCUSSION OF RESULTS

This study has shown that soft yellow, closed-cell, foam earplugs (EARfit, Cabot Safety Ltd, UK) are an effective, comfortable, cheap and readily available solution to the problem of wind noise exposure from motorcycling.

The survey of chemist's shops was interesting in that it revealed that the soft yellow foam plugs were stocked by most chemists visited. This would imply that it is the only earplug that is realistically available to the general and motorcycling public, and certainly the cheapest at about 50 pence per pair. Additionally, in our survey of motorcyclists, described in chapter 4, the soft yellow foam earplug was the most frequently cited. Arguably at this point we could have restricted our further analysis to this 'plug alone. However, we felt this to be somewhat inappropriate and consequently sought out the other relatively easily available alternatives for comparison.

The use of a now out of date test procedure to investigate earplug attenuation might be criticised. However, there have been a number of reports where this technique has been compared to a more modern standard and no significant differences found (Martin, 1977). Interestingly our technique recorded consistently lower values than more recent laboratory standard (BS5108:Part 1:1991) for the same types of earplug. The reason for this is almost certainly due to the self-fitting of the earplugs by the subjects and their lack of prior training on the test technique, and is supported by several reports demonstrating that the "real world" scores for any hearing protector are significantly worse than the corresponding idealistic "laboratory" score, usually by about 10-15dB (Berger, 1983; Alberti, 1982). This performance reduction is usually due to poor fitting and/or damage to the ear protector. Both these occurrences often relate to the comfort of the device to be worn. For this reason the importance of assessing the comfort of these earplugs cannot be overstressed: if they are not comfortable they will not be worn (Tengling, 1982).

The use of temporary threshold shift (TTS) is not an ideal way to test the efficacy of earplugs. A better method would be a longitudinal survey looking at the permanent threshold shift in two groups of motorcyclists, one using earplugs and the other not. However this is rarely feasible in any survey of noise damage and is certainly not feasible with the requirement for an immediate solution. In addition there is an ethical dilemma as to whether one could allow a group of riders to ride with unprotected ears in the knowledge of excessive noise levels and real risk of hearing loss. In these situations recourse is often taken to the phenomena of TTS. There is no doubt that an association does exist between TTS and PTS but unfortunately this is not sufficient to allow clinical predictions to be made. It would thus seem reasonable to assume that if an ear protector can abolish the occurrence of TTS, as ours did, it is likely to be having some beneficial effect on the potential PTS (Nixon, 1982). Finally, as our interest is primarily with a real world setting, so as to provide a feasible and practical rather than theoretical solution, we feel our techniques were entirely justified.

CONCLUSIONS

1. All earplugs seem to offer similar sound attenuation at low frequencies (approx. 15-20dB(A) at 250-1000Hz).

2. The ideal earplug for the motorcyclist on the grounds of cost, comfort and availability is the soft, yellow, closed-cell foam type (EARfit, Cabot Safety Ltd, UK).

3. These earplugs can abolish the temporary threshold shift associated with 1 hour of high speed riding.

CHAPTER 6

WARNING SIGNAL DETECTION BY MOTORCYCLISTS

INTRODUCTION

Although earplugs are undoubtably efficacious and there is general willingness amongst motorcyclists to use them if required, a sizeable proportion are unhappy about this from the point of view of possible impairment of warning signal detection (chapter 4). Indeed this was also a common concern amongst many of the non-motorcycling individuals who took an interest in this project. For this reason we felt it important to investigate warning signal detection for the motorcyclist and the effect upon this of wearing hearing protection, in this case earplugs.

This study divided into 2 parts. First, to establish the acoustic environment of the motorcyclist, both with and without a helmet, with increasing speed, and secondly, to investigate warning signal detection in this variable acoustic environment.

MATERIALS AND METHODS

ACOUSTIC ENVIRONMENT

The term "wind noise" (WN) has been used to describe the aerodynamic generation of noise by turbulent airflow around the motorcyclists' head. However, in this chapter, this term will be taken to mean all background sounds heard by the rider regardless of whether they are due to wind noise, machine noise, or a combination of the two. The relationship between WN and speed, from 40 to 100mph, for both the helmeted and bareheaded rider has been investigated in chapter 2. The same technique was used to establish sound levels from 0 to 40mph. The miniature microphone was secured in the rider's concha under the helmet or in the prosthetic ear for the bareheaded equivalent and sound levels were then measured for 2 minutes on six occasions at speeds of 0, 10, 20 and 30mph. The helmet used for this section was a Driver Alien 2. These results were then combined with the data from chapter 2 and the mean values for all speeds from 0 to 100mph were then plotted against $\log_{10}$ speed(mph).

In addition, the sounds at each 10mph increment were recorded onto magnetic tape and subject to a frequency analysis, using a Quest model 1800 with OB300 third octave filter.

SIGNAL RECOGNITION AND DETECTION

The noise/speed plots obtained in the previous section were used to choose the representative character and level of WN to act as background masking noise for the subsequent signal detection experiment. Four road traffic sounds felt to be of importance to motorcyclists were also recorded onto magnetic tape and subject to third octave frequency analysis.

The signals selected were:
1. Car horn.
2. Two-tone siren.
3. Pelican crossing bleep.
4. "Traffic noise" (Recorded sound of passing traffic)

These sounds were transferred into a Commodore Amiga A500 computer and stored digitally using "Prosound Gold", a sound sampling software packgage (Stephens, 1988). Each sound was sampled, trimmed and looped so that on playback from the computer memory, it could be presented indefinitely with no acoustic variation in the signal quality. The saved samples were all loaded into a software program, "MED Version 3.0" (Kinnunen, 1991), on the Amiga A500. This is a fourtrack edit/playback system that acted as the signal generator for the audiometer. The stereo outputs of the computer were then individually connected to the right and left channels of a two channel Kamplex AC4 audiometer. The signals from the two channels were mixed electronically, amplified by an Eagle PA200 single channel amplifier and reproduced through a GSI loudspeaker stack. The signal present and attenuator circuits of the audiometer were used to control the audio signal produced by the computer. The playback level of each sample was adjusted in MED 3.0 so that, at a preset amplifier gain setting, the levels of background WN or test signal measured by a sound level meter at the subject's shoulder was the same as the audiometer attenuator dial settings in dB(A). The audiometer/amplifier/loudspeaker system had a maximum output of 95dB(A) and a linearity better than 1dB over the dynamic range 60-90dB(A). The audiometer attenuator had stepsizes of 1,2 and 5dB.

Nineteen volunteer subjects, 9 women and 10 men with a median age of 17 years (range 16-28) and pure-tone thresholds better than 20dB(HL) were invited onto the study. They were asked to sit individually in a sound-proof room (BS 6655, 1986) and listen for the signal noises presented in varying background WN, for 3 different riding conditions: bareheaded, with helmet, and with a helmet and earplugs. Soft yellow foam earplugs (EARfit, Cabot Safety Ltd, UK) were chosen as our test earplug on the basis of the results presented in chapter 5. The volume and character of the background WN was selected so as to be appropriate for that particular speed and riding condition, as demonstrated in Fig. 6-1. For example at 20mph the background noise for the bareheaded rider would be 95dB(A) of predominantly wind noise and 75dB(A) of predominantly vehicle noise for the corresponding test with the helmet, plus or minus earplugs, in place. The quietest level at which the warning signal was consistently detected (masked threshold) was recorded as the minimum detection level (MDL) and was established using a modified method of limits.

To avoid the effects of any temporary threshold shift, the subjects were first tested wearing a new pair of earplugs in addition to the helmet, then the helmet alone and finally bareheaded. The order of presentation of the test signals was randomised. Each set of 3 tests took about 40 minutes to complete.

As a supplementary experiment subjects were also asked to identify the warning signals during signal detection experiments. The subjects listened for the signals presented in a random order in each of the background WN levels used in the helmet tests, at a signal:noise ratio of 1:1, and were asked to identify the signal. This task was only performed with a crash helmet in place with or without earplugs.

The chi-squared and Student's "t" tests were used for statistical analysis.

RESULTS

ACOUSTIC ENVIRONMENT

The mean sound levels for both the helmeted and bareheaded rider are shown in Table 6-1 and Figure 6-1. It can be seen that 3 distinct zones exist for both noise plots which are remarkably parallel above 10mph. Frequency analysis shows that at low speeds the vehicle noise is dominant and the rate of background noise increase is modest (<5dB(A) per doubling of speed). At higher speeds wind noise is dominant and the rate of WN increase is much greater (16dB(A) per doubling of speed). Between these two regions is a transitional zone where both sound sources provide similar contributions. The sound levels for the bareheaded rider are consistently 18dB(A) greater than for the helmeted rider, once above 10mph.

SIGNAL RECOGNITION AND DETECTION

The sound levels and character as defined in Figure 6-1 were used to select appropriate masking sounds (from our recorded database) to represent "equivalent speeds" for the differing riding conditions and consequently all results will be presented in terms of "equivalent speeds" and not absolute background noise levels.

SIGNAL RECOGNITION

The third-octave band frequency analysis of wind noise and some of the chosen warning signals are shown in Figure 6-2. It can be seen that these all display slightly different "centre" frequencies. In addition they also have characteristic time histories which contribute to their identification which will not be discussed further. Signal recognition amongst our subjects was consistently good regardless of the presence of earplugs and is shown in Table 6-2. The recognition of "traffic noise" tended to be poorer than for the other 3 signals but these differences were not statistically significant (x^2 = 0.013, 3df).

TABLE 6.1 SOUND LEVEL FOR MOTORCYCLISTS WITH SPEED [MEAN + 1SD dB(A)]

Speed (mph)	Log 10	Noise levels (dB(A))	
		Barehead	**Helmet**
0	-	76.5 (1.5)	71.5 (1.6)
10	1.00	85.5 (2.0)	74.0 (2.0)
20	1.30	92.0 (1.9)	77.1 (1.7)
30	1.48	104.0 (1.9)	83.3 (1.0)
40	1.60	107.1 (1.1)	90.7 (0.4)
50	1.70	112.5 (2.6)	96 (2.0)
60	1.78	117.1 (2.3)	101.2 (1.7)
80	1.90	124.1 (2.3)	108.6 (1.1)
100	2.00	130.6 (3.1)	113.0 (1.3)

FIGURE 6.1 **MEAN SOUND LEVELS FOR HELMETED AND BAREHEAD RIDERS WITH SPEED**

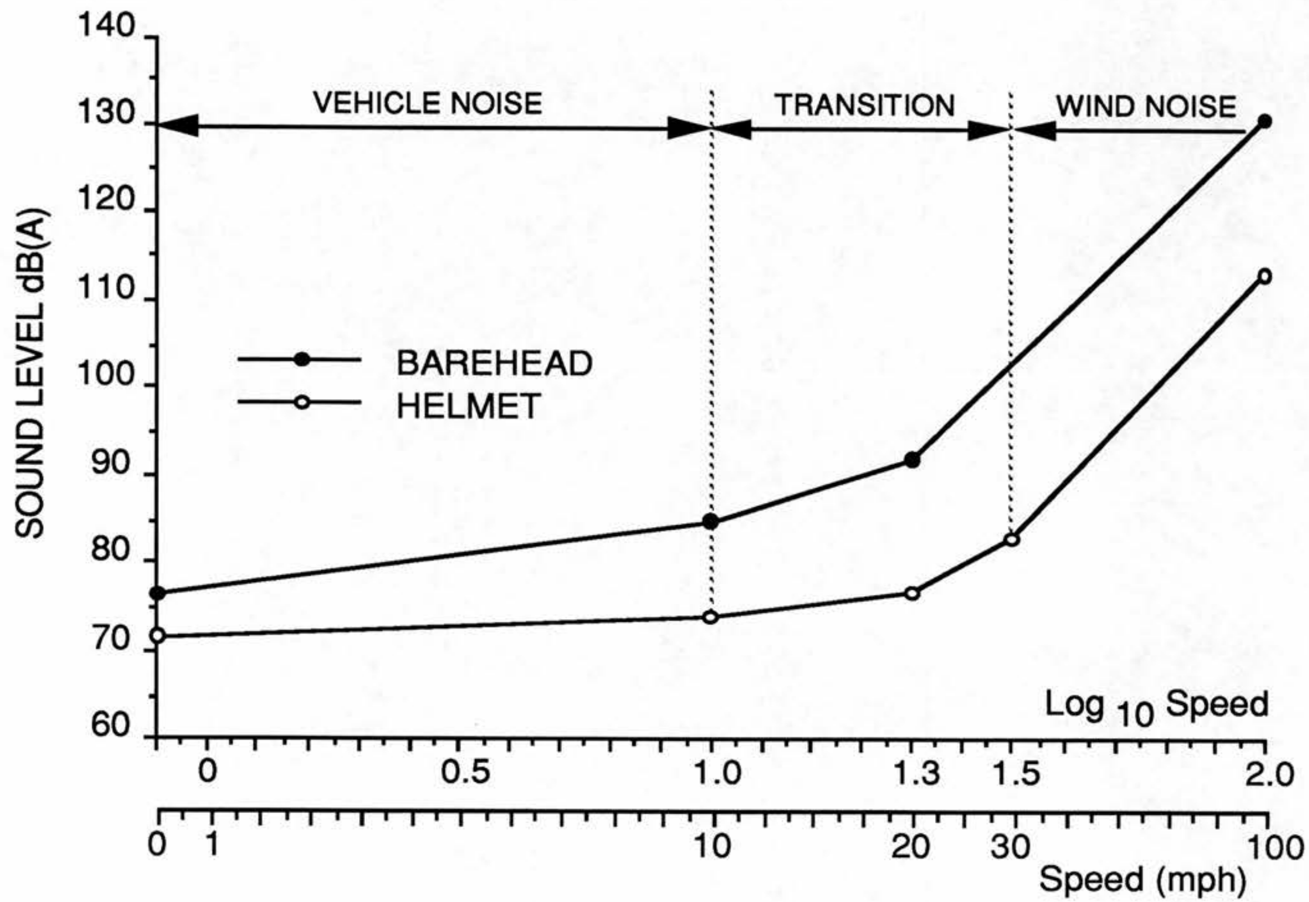


FIGURE 6.2

THIRD OCTAVE FREQUENCY ANALYSIS OF WIND NOISE AND WARNING SIGNALS

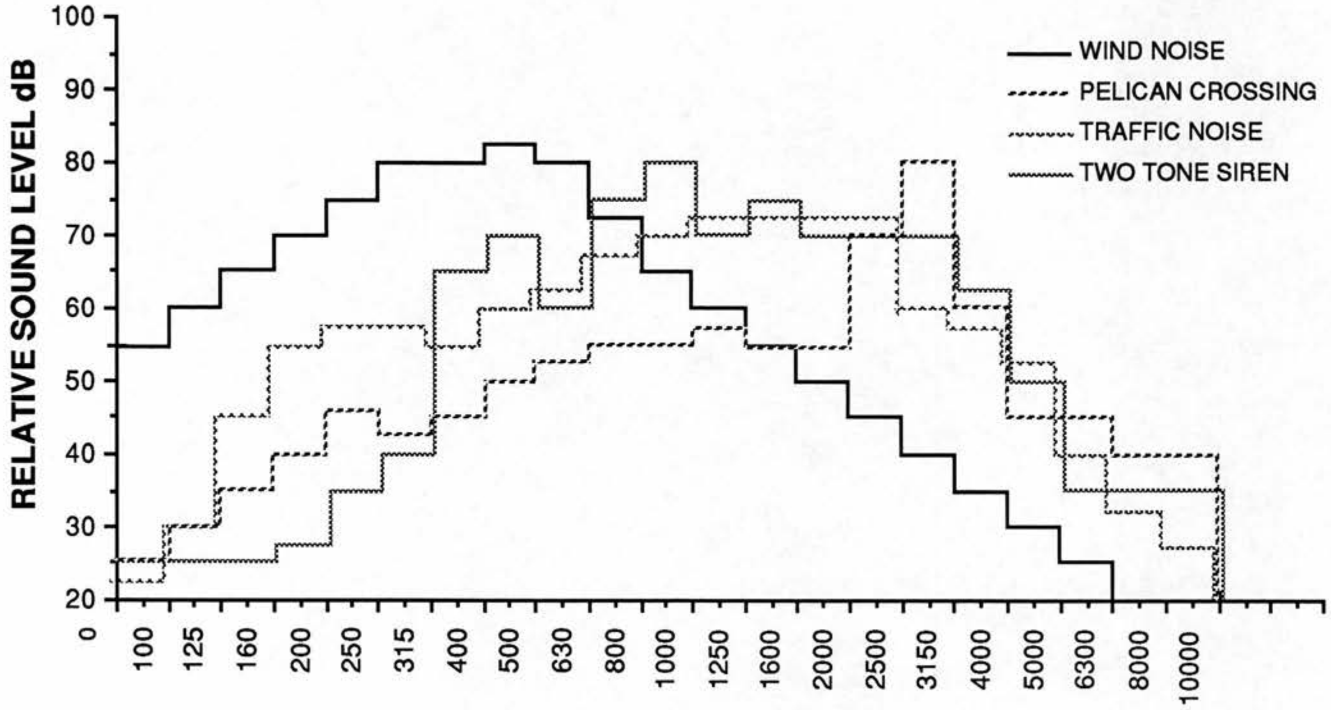


TABLE 6.2 SIGNAL RECOGNITION FOR WARNING SIGNALS IN BACKGROUND NOISE

Signal	Correct Identification	
	Helmet (n)	**Helmet + Earplugs(n)**
Car Horn	96%(29)	100%(30)
Pelican Crossing	100%(30)	100%(30)
Two Tone Siren	100%(30)	96%(29)
Traffic noise	73%(22)	80%(24)

SIGNAL DETECTION

The results for the minimum detection levels (MDL) of the 4 warning signals are shown numerically in Table 6-3, and graphically in figures 6-3, 6-4, 6-5 and 6-6. These results show that at speeds of 30mph or less MDLs are lowest when wearing a crash helmet without earplugs. This is true even when stationary. Once above 30mph, the MDLs are lowest with a helmet and earplugs. For all speeds greater than 0mph, the MDLs are consistently poorest for the bareheaded subject. The exception to this is for the "pelican crossing" signal which has a major high frequency component and is heard worst at standstill with earplugs in place.

Figures 6-3 to 6-6 also seem to show that the rate of increase in MDL with speed appears to be less with a helmet and earplugs than for a helmet alone for all 4 warning signals.

The statistical significance of these differences is also shown in Table 6-3.

TABLE 6.3 MINIMUM DETECTION LEVELS AT 'EQUIVALENT SPEEDS' (MEAN & 1SD dB(A)

Signal	Speed	Barehead	Significance of difference	Helmet	Significance of difference	Helmet + plug
Car horn	0	53(2.6)	$P < 0.01$	50(2.6)	$P < 0.001$	56(3.0)
	20	78(6.2)	$P < 0.001$	53(4.0)	$P < 0.001$	58(3.6)
	30	-		65(4.0)	NS	64(3.1)
	40	-		75(3.3)	$P < 0.01$	71(2.3)
	50	-		83(3.5)	$P < 0.001$	77(4.1)
Pelican crossing	0	39(1.5)	$P < 0.01$	36(3.6)	$P < 0.001$	52(5.3)
	20	68(4.6)	$P < 0.001$	41(5.0)	$P < 0.001$	52(4.2)
	30	-		51(4.0)	$P < 0.001$	56(4.4)
	40	-		62(5.4)	NS	62(4.8)
	50	-		70(6.4)	NS	68(5.3)
Two-tone siren	0	52(2.8)	$P < 0.001$	46(3.9)	$P < 0.001$	54(1.6)
	20	79(2.5)	$P < 0.001$	51(4.0)	$P < 0.01$	56(4.4)
	30	-		63(4.6)	NS	63(2.3)
	40	-		73(4.0)	$P < 0.01$	69(3.3)
	50	-		81(4.1)	$P < 0.001$	77(2.9)
Traffic noise	0	62(2.6)	$P < 0.001$	57(2.8)	$P < 0.01$	61(2.1)
	20	87(1.6)	$P < 0.001$	59(2.8)	$P < 0.001$	65(3.0)
	30	-		69(4.9)	$P < 0.05$	72(3.0)
	40	-		77(4.0)	NS	77(2.9)
	50	-		81(3.5)	$P < 0.05$	85(4.0)

NS,not significant

FIGURE 6.3 MEAN MINIMUM DETECTION LEVELS FOR TRAFFIC NOISE IN "EQUIVALENT" BACKGROUND WIND NOISE.

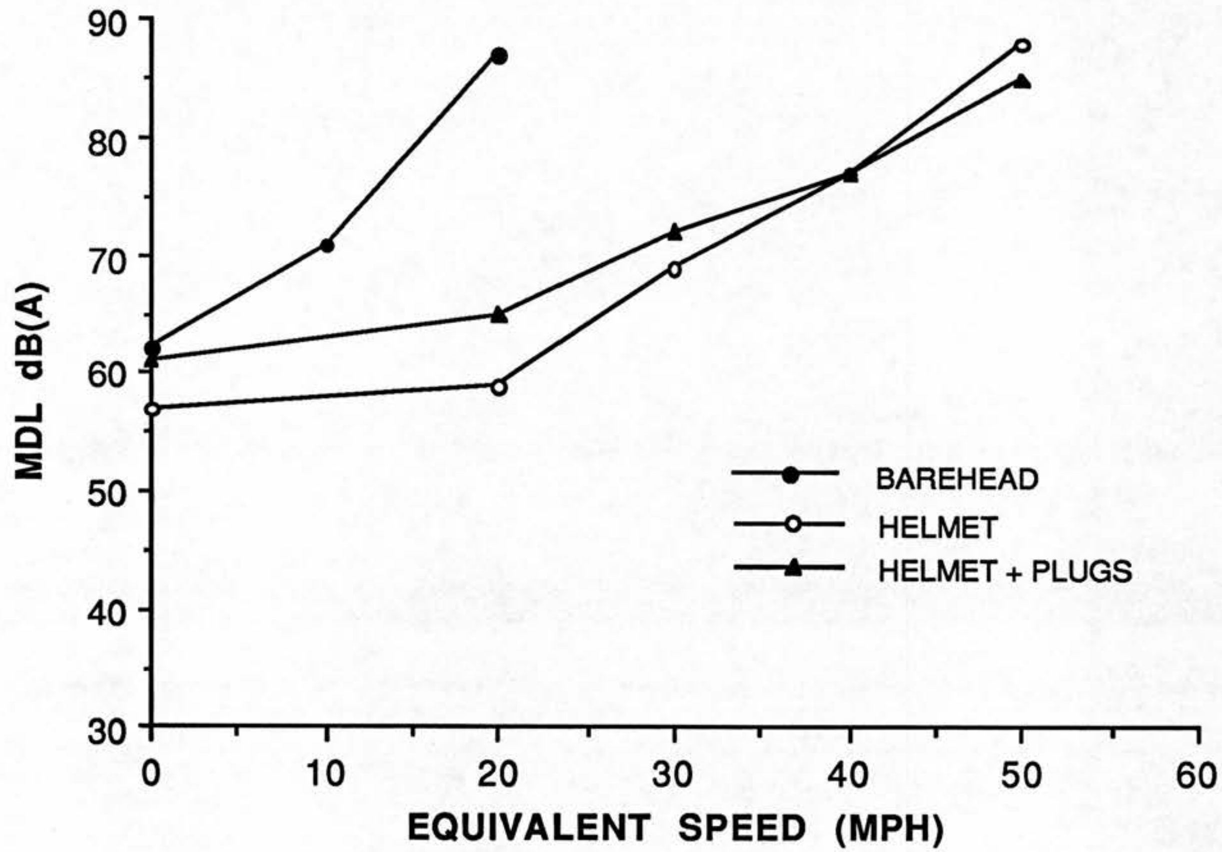


FIGURE 6.4 MEAN MINIMUM DETECTION LEVELS FOR PELICAN CROSSING IN "EQUIVALENT" BACKGROUND WIND NOISE.

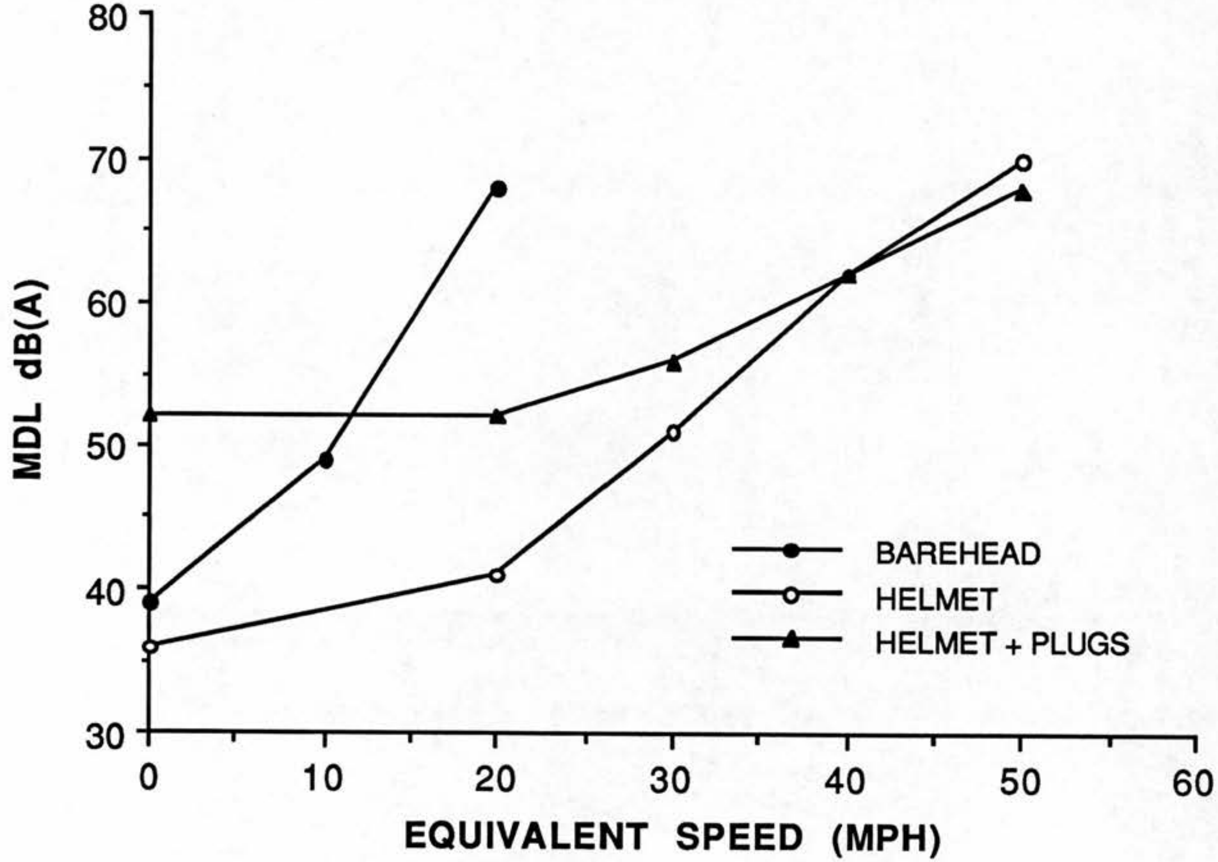


FIGURE 6.5 MEAN MINIMUM DETECTION LEVELS FOR CAR HORN IN "EQUIVALENT" BACKGROUND WIND NOISE.

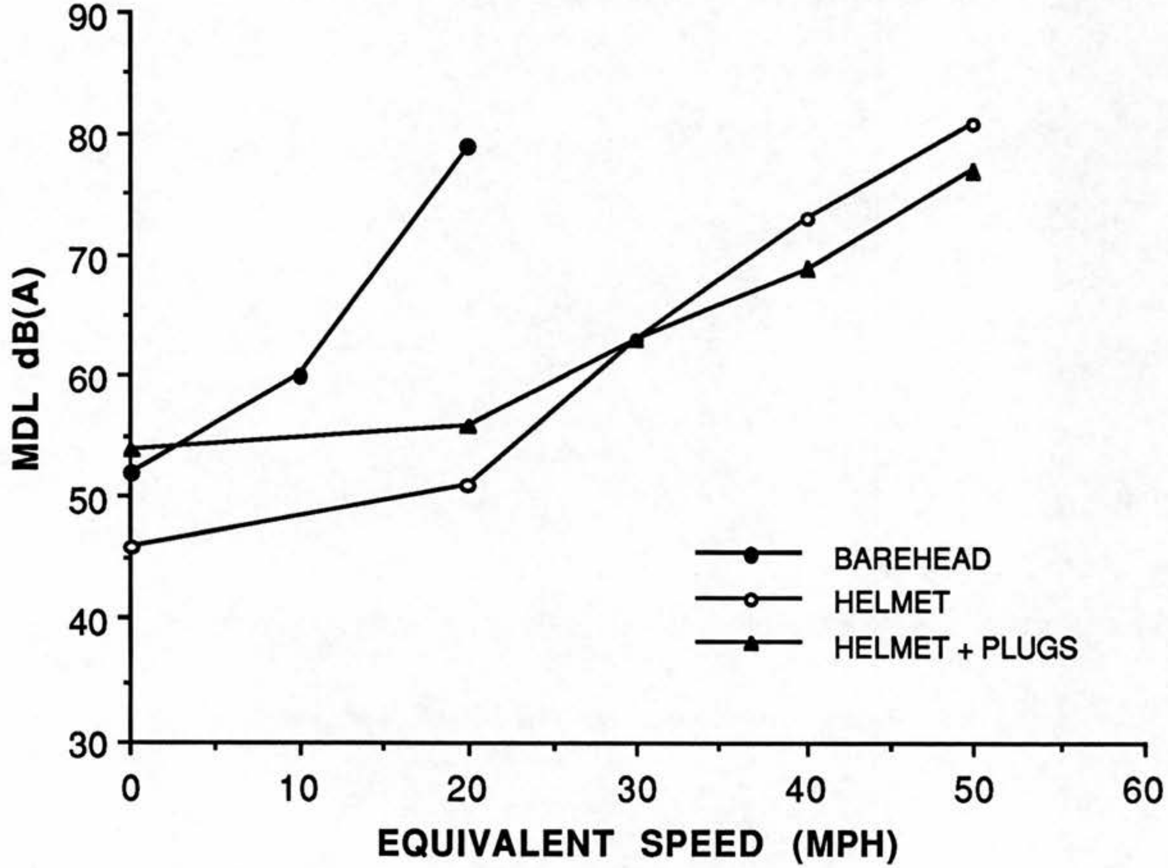
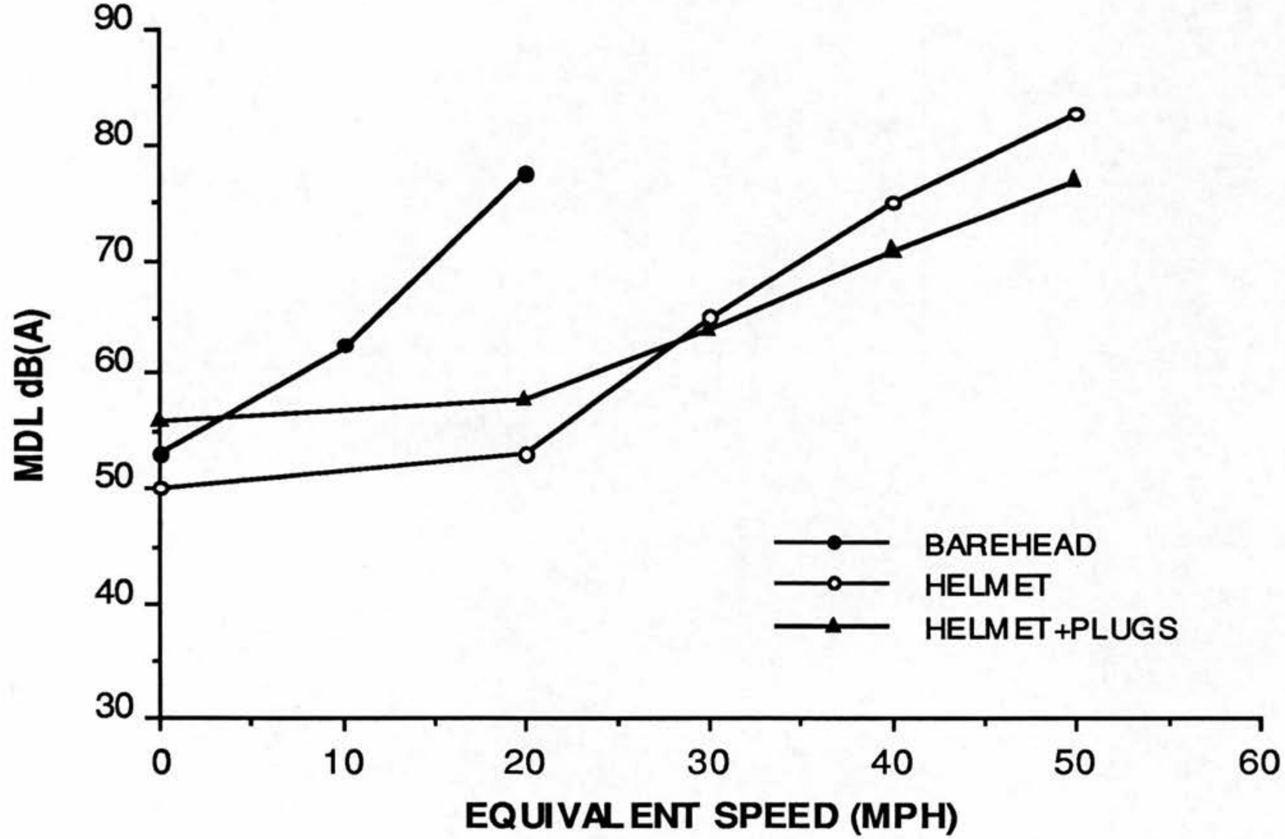


FIGURE 6.6 MEAN MINIMUM DETECTION LEVELS FOR TWO TONE SIREN IN "EQUIVALENT" BACKGROUND WIND NOISE.



DISCUSSION OF RESULTS

This section has shown that the acoustic environment of the motorcyclist is not constant but varies in both character and volume, in a relatively predictable fashion, with speed.
We already know that at higher speeds (>40mph) wind noise is the dominant sound source. At lower speeds (<10mph), vehicle noise with its slightly higher frequency spectrum is dominant. Between these speeds is the variable "transition zone" where both vehicle noise and wind noise contribute. The precise speed at which transition occurs depends on several factors such as whether a helmet is being worn and how loud is the vehicle. Transition will occur earlier with no helmet and with a quiet motorcycle, and later with a helmet and a noisy motorcycle.

The main task of this chapter was to examine the effect of wearing earplugs on the detection of warning signals for the British (helmet wearing) motorcyclist. In this regard it has clearly shown that at higher speeds, with higher background WN levels, the use of earplugs does not impair warning signal recognition or detectability and in fact actually reduces thresholds for signal detection, certainly in the normal hearing individual.

It is unfortunate that the maximum output of our test system (95dB(A)) limited our maximum "equivalent speed" to 50mph for the helmeted rider; examination of figures 6-3 to 6-6 seems to suggest that the improved MDLs for the 4 warning signals with helmet and earplugs should become even more pronounced with increasing speed.
Despite this criticism, the results are in agreement with previous industrial research where signal and speech discrimination seem to improve with ear protection in the presence of increasing background noise (Berger, 1980; Wilkins and Martin, 1982).

As expected from previous work (Binnington, 1993) the average MDLs were lowest when the "centre" frequency of the warning signal was furthest from the "centre" frequency of the background noise. Consequently the MDLs were highest for "traffic noise" and lowest for the pelican crossing. The difference was less obvious with earplugs in place and reflects the impressive high frequency attenuation of a helmet and earplugs together (chapter 5).

CONCLUSIONS

1. The acoustic environment of the motorcyclist varies in both character and volume in a relatively predictable fashion with speed.

2. At speeds of 30mph or less, signal detectability is best with a helmet alone.

3. At speeds of 40mph or more, signal detectability is best with a helmet and earplugs.

CHAPTER 7

TWO SOLUTIONS TO THE PROBLEM OF NOISE EXPOSURE FOR MOTORCYCLISTS

INTRODUCTION

We have presented unequivocal evidence that motorcyclists are regularly exposed to excessive noise levels when they ride (Chapter 2) and that this noise exposure has significant adverse effects on hearing in both the short and long term (Chapter 3). Currently, the only practicable form of hearing protection is earplugs, with the soft yellow, closed-cell foam type (EARfit, Cabot Safety Ltd) as the optimal choice on the grounds of cost, comfort and ease of availability (Chapter 5), without compromising the riders ability to detect warning signals at higher speed (Chapter 6).

Unfortunately the level of awareness to this problem is low; less than 20% of motorcyclists regularly use earplugs and most are under the mistaken impression that their current helmet provides adequate hearing protection (chapter 4).

This chapter therefore details two possible solutions to this problem:

1. An antecedent behavioural modification strategy to increase awareness and the use of earplugs.
2. The design and development of a "quiet" motorcycle crash helmet.

METHODS

1. Earplugs

Subjects were recruited from the consecutive customers of a large motorcycle accessory dealer (Hein Gericke, Bristol), where they were offered an advice sheet (Appendix 7-1: at the end of this chapter) and a free pair of earplugs (EARfit, Cabot Safety Ltd) at the time of purchase of a new helmet. All customers held full motorcycle driving licences and were current riders. The date, names, addresses and contact telephone numbers were noted and details of any potential subjects who declined the offer of earplugs were recorded at that time. The recruitment period was from January to April 1993.

The subjects were contacted by telephone, 3-4 months following their recruitment and interviewed with regard to their use of earplugs. The results for this group, in terms of earplug useage both before and after the intervention, were statistically compared with both a retrospective (Chapter 4) and a prospective control group, drawn from regular riders at a local motorcycle club. Earplug useage was considered positive only if the subject expressed an intention to buy or had already bought further earplugs.

2. Helmets

A number of aerodynamic and sound-proofing design modifications were made to a motorcycle crash helmet in an effort to achieve intra-helmet sound levels that were significantly lower than typical current helmet noise levels.

To achieve this, measured wind noise levels had to fall outside (below) the 95% confidence intervals of our previously described "noise plot" (Chapter 2).

Noise measurements were made at the ear using a Quest M-28 multiple memory noise-logging dosimeter and 8mm omnidirectional microphone using the method previously described in Chapter 2. Sound measurements for each modification were made at least 6 times at the 2 test speeds of 50 and 80mph.

The modifications followed 2 lines:

1. "aerodynamic", with the aim of modifying the turbulent airflow around the helmet. This was done by the following means:

a. drilling holes in the helmet shell

b. fitting a sharp nose cone to the helmet to make it more "streamlined"

c. fitting a neck-piece to seal off the lower free edge of the helmet around the neck.

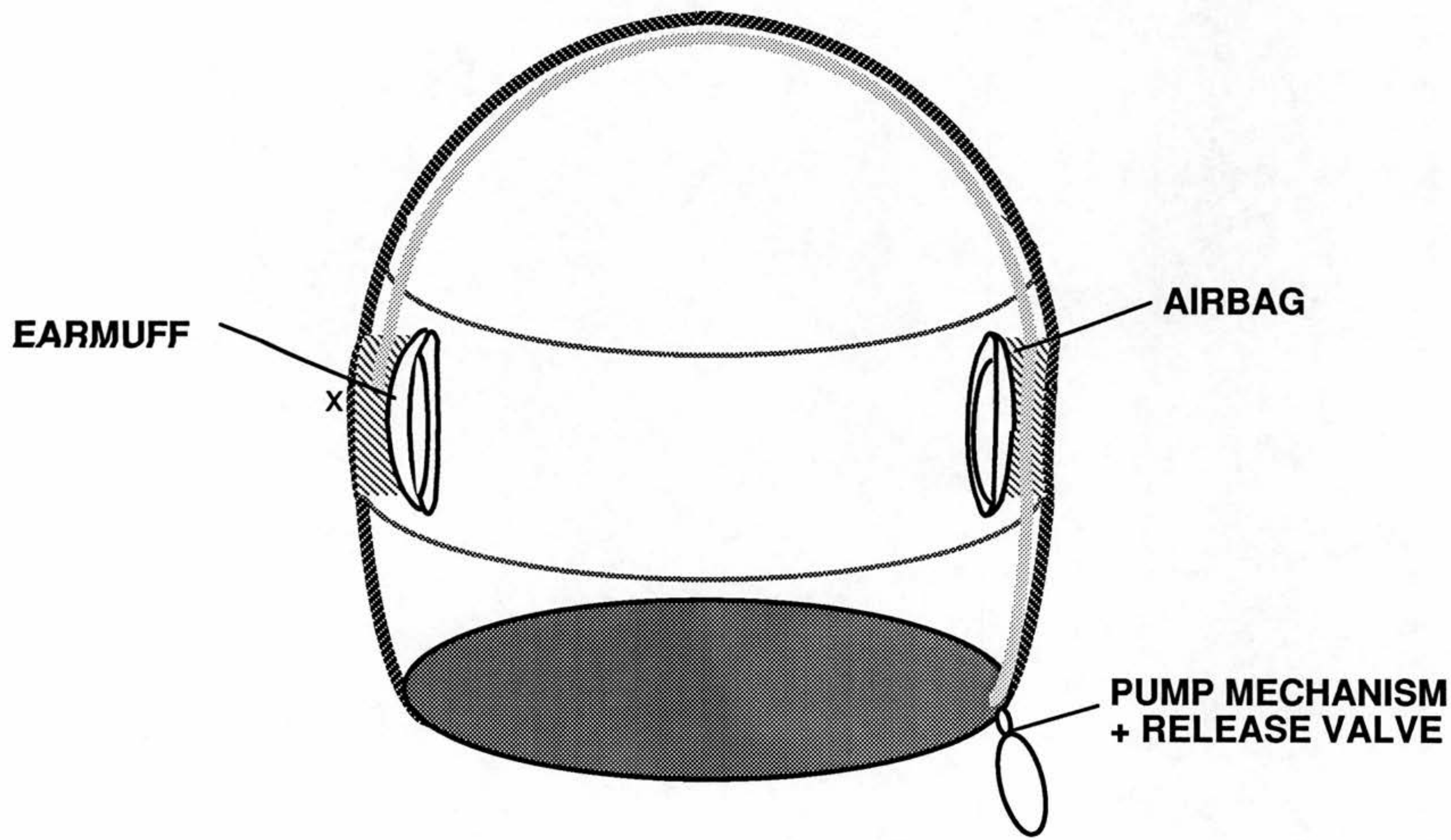
2. Accept the noise levels at source and try to improve the attenuation characteristics of the helmet, by

a. "double glazing" the helmet by the provision of a second larger shell overlying the true helmet shell

b. incorporate earmuffs under the original helmet shell. This modification was subsequently altered to include a pneumatic pump device to "push" the earmuffs medially against the head after the helmet had been fitted on the rider's head, and released prior to removal (Figure 7-1). This section cannot really be described as a "scientific" experiment but more as a gradual evolution in helmet development and design.

Statistical analysis was performed using the unpaired "t" and chi-squared tests.

FIGURE 7.1 SCHEMATIC DIAGRAM OF MODIFIED MOTORCYCLE CRASH HELMET.



RESULTS

1. Earplugs

Forty eight riders were recruited to the study. No-one declined the offer of earplugs and an advice sheet. 7 riders were excluded form the final analysis: 3 were uncontactable on the telephone numbers given, 3 had given up motorcycling in the intervening period and 1 subject turned out to be a pillion rider (passenger) only. The last 4 individuals all offered positive attitudes towards the use of earplugs. The median age of the remaining 41 subjects was 28 years (range 21-52), with a median riding experience of 10 years (range 1-35). The majority, 36 (88%), were male.

There was a significant improvement in the rate of earplug useage in this group, following the intervention (83%), when compared to their prior useage rate (27%) and that of the two control groups (25 & 16%). This is shown in Table 7-1.

The reasons given by the 7 riders who would not continue to use earplugs were: ear infections (presumably otitis externa) in 3, another 3 felt they were too awkward and fiddly to use and 1 just "couldn't cope". All the subjects tried them at least once and all felt there was a marked reduction in noise levels.

Two other frequent comments by the whole study group were:

1. that riders were aware of less tinnitus and fatigue after a long journey with earplugs in place, and
2. that despite the benefits of earplugs, ear protection ought to be provided by the helmet.

2. Helmets

The wind noise levels of the various helmet modifications at 50 and 80mph are documented in Table 7-2, as are our known "standard means" for these speeds, and are shown graphically in relation to our previously reported "average noise plot" in Figure 7-2. It can be seen that the only modification that achieved a significant reduction in noise levels was the inclusion of earmuffs, with pneumatic control system, under the helmet shell.

TABLE 7.1 RATE OF EARPLUG USE FOR VARIOUS GROUPS

	PERCENTAGE USING PLUGS (N)	
RETROSPECTIVE CONTROLS (N=124)	16%	(20)
PROSPECTIVE CONTROLS (N=60)	25%	(15)
STUDY GROUP (N=41)		
PRE-INTERVENTION	27%	(9)*
POST-INTERVENTION	83%	(30)*

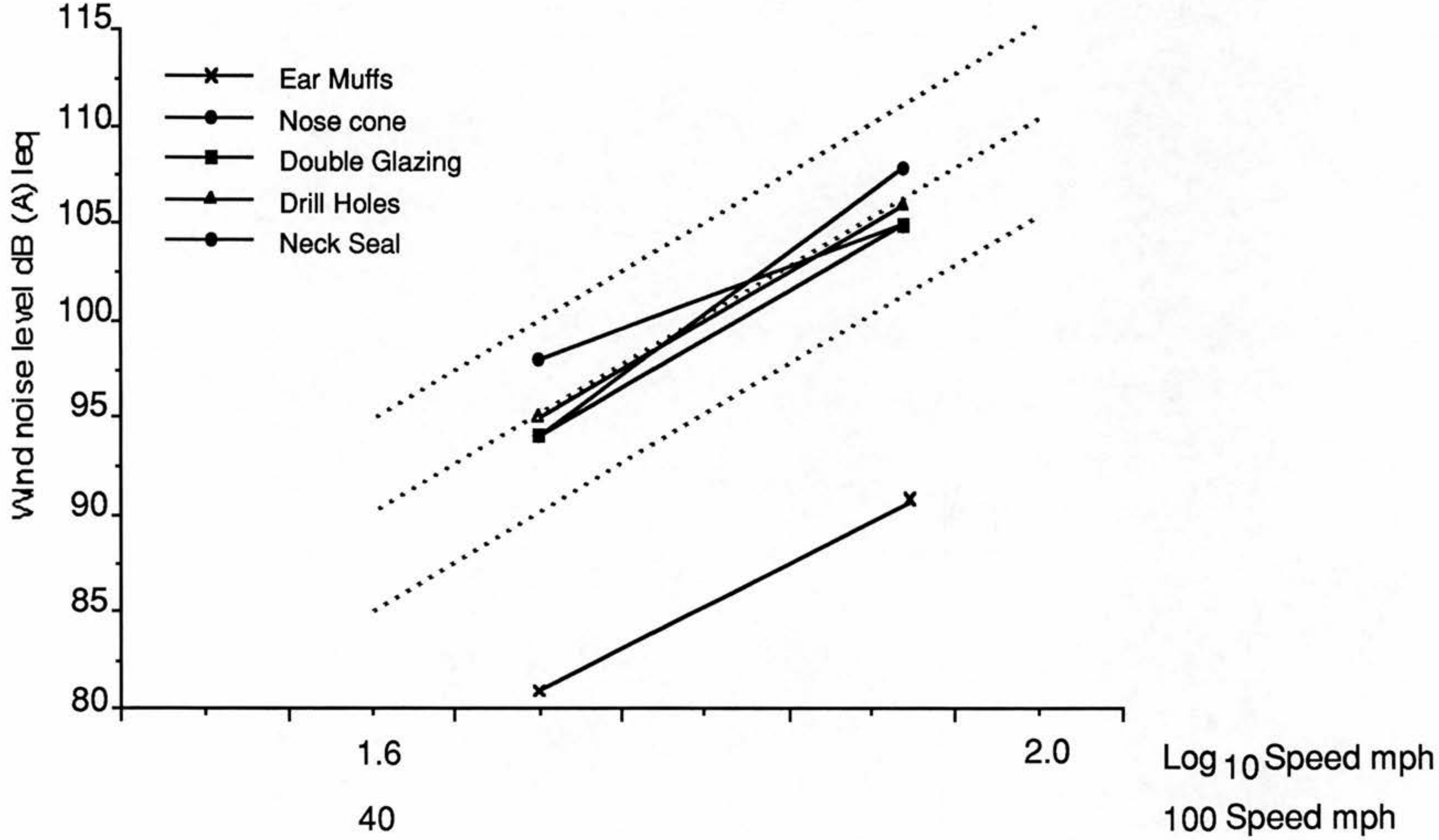
* X^2 =21.7, $p<0.001$

TABLE 7.2 AT EAR WIND NOISE LEVELS WITH MODIFIED HELMETS

MODIFICATION	NOISE LEVEL dB (A) Leq (± 1SD)		SIGNIFICANCE
	22 m/s (50 mph)	36 m/s (80 mph)	
Drill Holes	95 (3.2)	106 (3.0)	NS
Nose Cone	94 (2.5)	105 (2.9)	NS
Neck Seal	98 (2.7)	105 (3.1)	NS
" Double Glazing"	94 (3.0)	108 (2.2)	NS
Ear Muffs	81 (2.8) *	91 (2.6) *	P<0.001
Known "Standard"	95 (3.0)	107 (3.0)	

* = COMPARISON AGAINST KNOWN "STANDARD".

FIGURE 7.2 WIND NOISE LEVELS OF MODIFIED HELMETS DISPLAYED ON "AVERAGE NOISE PLOT".



DISCUSSION OF RESULTS

This study has shown that the provision of earplugs at the point of sale of a motorcycle helmet with an advice sheet can significantly increase the rate of earplug use. This despite efforts to be as conservative as possible by only counting those who intended to buy or had already bought earplugs as "converts".

The earplugs need not necessarily be provided with a crash helmet but there were good reasons why we chose this route. Prompting strategies such as this one have been shown to work best when provided in close proximity to the site of the desired response, in this case the donning of a (new) helmet and with minimal "cost", in terms of effort involved, in undertaking this response, hopefully accomplished by providing a free pair of earplugs (Wogalter, 1989; Lefebure, 1988; Druce and Carter, 1988). In addition a crash helmet is the only legal requirement, in terms of clothing, for motorcycling, as well as being a perishable item. As such it must be replaced periodically and rarely with "second hand models". Thus all of the "at risk" population should eventually come into contact with our message.

A telephone interview is not an ideal way to establish an exact rate of earplug use and it may be argued that we were told only what we wanted to hear; a flaw of any interview based technique. However we have no reason to believe the answers received were not truthful especially in the light of the many associated positive comments on the virtues of earplugs. In addition these results should be representative of motorcyclists in general given the marked similarities of this study group to all previous study groups in terms of age, sex and riding experience (Chapters 3,4).

Finally, it is worth noting that 3 (7%) of our study group could not use earplugs as a result of what were presumed to be ear infections. This is much higher than the average quoted figure for ear infections in industry of 2% (Berger, 1985). If representative, this equates to a sizeable proportion of motorcyclists who would be unable to use this form of ear protection regardless of their motivation.

The lack of success with a variety of aerodynamic helmet modifications could probably be predicted from fluid dynamic theory. With the noise source as the turbulent boundary layer adjacent to the helmet shell (Chapter 2) and the unfavourable aerodynamic conditions in this region due mainly to the excessive turbulence in the free stream airflow after its passage around the front of the motorcycle, improvements were always unlikely. Not to mention the inevitable safety constraints on outer helmet shape. Consequently, some form of sound attenuation always seemed more likely to succeed and, as suspected, the inclusion of earmuffs under the helmet shell did lead to a significant improvement in noise levels, a finding previously reported by Iho and Johanson (1983). The addition of the pneumatic control system though is a significant advantage. It allows improved fitting and acts as a simple "on/off" switch. This method has the added attractions of being simple, relatively cheap and involves only minimal alterations to the helmet interior. It might also allow the housing of a small loudspeaker for an intercom or entertaiment system.

CONCLUSIONS

1. Providing earplugs and a noise advice sheet with every new helmet can significantly increase the earplug useage rate.
2. Relatively simple helmet modifications can be made which effect a significant reduction in "at ear" wind noise levels.

APPENDIX 7-1

PROTECT YOUR EARS!

1. Excessive noise levels can damage your hearing

2. High speed riding on a motorcycle (50mph plus) causes excessive "wind noise"

3. Wearing earplugs can protect against this problem, particularly if worn on all LONGER HIGH SPEED RUNS.

4. Earplugs will NOT upset your ability to hear problems with the engine or surrounding warning signals.

NOTES

These earplugs have been provided to allow you to protect your hearing. They need not be worn around town as the noise levels are relatively low. They are a good idea and a sensible precaution on any high speed run where noise levels are known to be excessively high.

If they become lost or worn-out, replacements can be easily and cheaply obtained from any large chemist and some major sports shops.

CHAPTER 8

DISCUSSION AND CONCLUSIONS

DISCUSSION

The problem of airflow generated noise has only relatively recently been recognised and this mainly in connection with aeronautics, and in particular, jet aircraft (Lighthill, 1952; Richards, 1968). One of the main concerns in this field has been the levels and source of noise within the aircraft fuselage. Research in this field has demonstrated that a turbulent boundary layer is a significant sound source, that this sound is predominantly low frequency in nature and increases by approximately 16dB per doubling of speed at sub-sonic velocities (Hay, 1964; Maestrello, 1965; Richards, 1968). It would appear that improving cabin wall attenuation is the most efficient method of reducing interior sound levels (Hay, 1964).

Our work on the source and levels of wind noise, described in chapter 2, has shown that a turbulent boundary layer is also the sound source for motorcyclists, a previously unreported finding. Indeed, our results also display a 16dB(A) increase in sound levels per doubling of vehicle speed. Furthermore, with essential safety constraints on outer helmet shape and the unfavourable aerodynamic conditions around the riders head, one could predict that minor differences in helmet shape and aerodynamics would be unlikely to alter wind noise levels. This was in fact confirmed experimentally in chapters 2 & 7.

Although previous workers have described similar sound levels, this work is the first to recognise the ubiquitous nature of the problem for motorcyclists. It would appear that noise levels are essentially similar for all riders, regardless of machine ridden or helmet worn, and (currently) depend almost exclusively on vehicle speed.

Of particular importance, this work is the first to adequately demonstrate adverse effects as a consequence of this noise exposure. We have shown a significant hearing loss in motorcyclists when compared to suitable controls. We have also identified significant temporary threshold shift after only 1 hour of high speed riding and a corresponding subjective complaint of tinnitus. There are also other frequent, often non-specific and extra-auditory, complaints from riders of fatigue, headaches and even disequilibrium after prolonged high speed riding. Similar extra-auditory symptoms have been described in industry and elsewhere (Berger, 1981; Godlee, 1991). All these adverse effects are a strong argument for remedial action. In addition, for the group of professional riders, there is also the medico-legal consideration of occupational hearing loss for their employer. To some extent the risk of personal injury is covered within the contracts of the racers. For the dispatch rider, as most are self-employed, the responsibility for personal protection is on the individual. However, for the police rider, this remains a potential issue and is a further argument for hearing protection.

At the start of this project, overall awareness to this problem amongst motorcyclists was low as described in chapter 4. However, a number of (motorcycle) journalists became aware of our work and several reports were published (Moto Grand Prix, 1992; BIKE, 1992 & 1993a; Performance Bikes, 1992 & 1993; Motorcycle News, 1992 & 1993b). This led to some colourful literary debate (Brouwer, 1993; McCombe, 1993) and a tangible increase in public awareness (BIKE, 1993b). There is no doubt however, that motorcyclists are willing (chapter 2), perhaps even keen, to adopt some type of hearing protection. (This factor may well have accounted for the (non-significant) increase in earplug usage rate seen when comparing the retrospective and prospective control groups in chapter 7.) Given the results of the previously described aeronautic research and the finding of minimal helmet attenuation (chapter 2), some form of attenuating device, either earplugs or integral helmet attenuation, appeared to offer a suitable solution.

This work has thoroughly analysed the role of earplugs in this regard and found them to be efficacious in terms of preventing TTS (chapter 5), relatively safe in terms of signal detection (chapter 6) and generally acceptable and beneficial in terms of increased usage and improved general well being after riding (chapter 7).
Integral helmet attenuation has also been investigated and a simple system of pneumatically operated earmuffs inside the helmet shell has been developed with significant reductions in "at-ear" wind noise levels (chapter 7), also demonstrating efficacy. With regard to safety, this system also works by sound attenuation so there is no reason to suppose that its effects on warning signal detection will be any different to those of earplugs. Indeed this system has the added advantage of the pneumatic "on/off" switch. This allows the removal of any attenuating effects at low speeds in town and a consequent improvement in signal detection (signal detection being best without earplugs at low speeds: chapter 6). This may be of particular importance given that the majority of motorcycle accidents occur in town and at speeds of less than 40mph (Wilson, 1992). Having said that, the overall contribution of external auditory cues to road safety for motorcyclists, and motorists in general, remains to be established.
As for acceptability, there can be little doubt that the motorcycling public are now more aware of this problem than ever before and are anxious for some kind of solution. A helmet is a costly piece of protective equipment and not surprisingly becomes a natural focus

for attention. The comments of our subjects in chapters 4 and 7, and recent correspondence in a number of motorcycle journals (Bike 1993b), speak volumes in this regard.

There can be no doubt that either solution would be effective in reducing the noise exposure of motorcyclists. However, only the earplug option could be immediately instituted. Unfortunately this option demands the cooperation of motorcyclists, not all of whom can or will use earplugs and, as with any behaviour changing strategy, many who start will not persist, particularly in the field of hearing protection where the long-term benefits are not immediately obvious (Lofgreen, 1982). This solution would also require co-operation from the U.K. motorcycle industry, who would be admitting, by implication, that their products (helmets) are less than perfect. Although eminently feasible, it is therefore unlikely that this solution would achieve widespread success.

Integral helmet protection is a much more attractive proposition for several reasons. It would make for a more "ideal" helmet which should have strong commercial appeal as a positive selling point. The earmuff should reduce the risks of ear infections associated with earplugs and could be developed to house a small communication device, either for entertainment for the social rider or radio-linkage for the police or dispatch rider. Finally, as wearing a crash helmet is a legal requirement to ride, incorporated ear protection would remove the need for any behaviour change or cooperation from the motorcyclist, and if all helmets were designed this way (perhaps as a result of a change in design standards), it might ultimately ensure that 100% of riders were protected.

Unfortunately any new helmet design must pass appropriate British and European safety standards which our current model has not. To produce a helmet that meets these standards takes both time and money for research, development and testing. Consequently, for this idea to have a realistic chance of success, the involvement of an established dealer/manufacturer is required. Our belief in this system, and the importance of remedial action for this problem, led to a patent application on the modified helmet design. A number of manufacturers and importers have been approached with the results of this work and this design. At the time of writing 2 European helmet manufacturers have committed themselves under "letters of confidence" to further evaluation and assessment of this idea with a view to developing a commercial product.

Despite this apparent success, there are other areas that still require investigation and evaluation. A more detailed analysis of the sound source might profitably be undertaken. With better understanding of this, improvements in sound levels at source may still be possible. Other forms of sound reduction exist: Active noise reduction (ANR) is a system that uses a small micro-computer to monitor the background noise and produces a similar sound that is exactly out of phase with the original sound: anti-noise. This has the effect of reducing the "at ear" noise levels. This technique has been successful in the aeronautic and military fields and there is no reason to suppose that it could not be successful for motorcyclists, although cost is a potentially limiting factor. Finally, the importance of auditory cues for the vehicle user remains to be established. Further work is obviously required.

Motorcycling is more than simply a mode of transport; it is a great source of pleasure for many and even a way of life for some. Like all of life's pleasures it is not without its price and risks, many of which are unavoidable. We hope that the practical results of this work will allow one area of potential risk to be avoided while at the same time improving the quality and pleasures of this enjoyable and exhilarating activity.

CONCLUSIONS

1. Motorcyclists are exposed to excessive, turbulent airflow generated, noise levels when riding.

2. This exposure leads to both short- and long-term hearing damage.

3. In general motorcyclists have a low awareness to this problem.

4. Earplugs provide an efficacious method of combating this problem with no adverse effects on warning signal detection.

5. Earplug usage can be increased by providing earplugs and an advice sheet at the point of sale of new helmets.

6. Relatively simple helmet modifications can lead to a significant reduction in "at ear" wind noise levels and appears to be an ideal solution awaiting further commercial development.

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