Role of Driver Hearing in Commercial Motor Vehicle Operation: An Evaluation of the FHWA Hearing Requirement

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(ABSTRACT)

The Federal Highway Administration (FHWA) currently requires that all persons seeking a commercial driver's license for interstate commerce possess a certain minimal level of hearing. After an extensive literature review on topics related to hearing and driving, a human factors engineering approach was used to evaluate the appropriateness of this hearing requirement, the methods currently specified to test drivers' hearing, and the appropriate hearing levels required. Task analysis, audiometry, dosimetry, in-cab noise measurements, and analytical prediction of both speech intelligibility and masked thresholds were all used in performing the evaluation. One of the methods currently used to test truck driver hearing, the forced-whisper test, was also evaluated in a laboratory experiment in order to compare its effectiveness to that of standard pure-tone audiometry.

Results indicated that there are truck driving tasks which require the use of hearing, that truck drivers may be suffering permanent hearing loss as a result of driving, that team drivers may be approaching a 100% OSHA noise dose over 24 hours, and that truck-cab noise severely compromises the intelligibility of live and CB speech, as well as the audibility of most internal and external warning signals. The forced whisper experiment demonstrated that there is significant variability in the sound pressure level of whispers produced using this technique (in the words, word types, and trials main effects). The test *was* found to be repeatable for a group of listeners with good hearing, but was found to have only a weak relationship to the results of pure-tone audiometry for a group of 21 subjects with hearing levels ranging from good to very poor. Several truck cab and warning signal design changes, as well as regulatory changes, were recommended based on the overall results of this evaluation.

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CHAPTER 1: INTRODUCTION

The Federal Highway Administration (FHWA) currently requires that commercial vehicle operators (CVOs) have a specific level of hearing in order to obtain or renew a commercial driver's license (CDL) for interstate commerce (Federal Highway Administration, 1994). However, there is little empirical evidence for the validity of the current hearing level requirement (Songer, LaPorte, Palmer, Lave, Talbott, Gibson, and Austin, 1992). In fact, there are anecdotal reports of hearing-impaired and deaf drivers who have had long accident-free careers (Petersen, 1978). On the other hand, civilian drivers assume that if it becomes necessary to alert a CVO of their presence due to a "blind spot" (an area where the CVO cannot visually detect an adjacent vehicle if one is present), that the CVO will hear their automobile horn. A deaf or hearing-impaired driver would be unlikely to hear a car horn under this situation, and the civilian driver does not usually have another option for alerting the CVO. Also, most emergency vehicles rely on both auditory and visual warning signals to make their presence known. So while it may be unclear whether CVOs actually need to hear in order to drive safely, *there are many situations in which it is assumed that CVOs are able to hear; lawmakers, driving instructors, and even highway engineers/designers make this assumption.*

Another consideration is the design of truck-cab interiors. Truck cabs have changed tremendously in recent years, and will continue to change, not only with the advent of Intelligent Transportation Systems (ITS), but also as drivers continue to demand more comfortable and quieter cabs. Many recently introduced and proposed ITS displays rely on concurrent auditory and visual signals, taking advantage of a concept known as cross-modal time-sharing (Wickens, 1992). Cross-modal time-sharing is intended to provide the operator with redundant modes for obtaining information, especially under conditions of high workload. Underlying this theory of display design is the assumption that the operator is unimpaired in all sensory modalities, so that if the visual channel is overloaded, the operator will have no trouble obtaining the information from the alternative (usually auditory) channel. Since the commercial vehicle operator already works under conditions of high visual workload, some researchers are advocating purely auditory ITS displays in order to avoid further visual loading (Micheal, 1995b). As the commercial vehicle cab becomes more complex, more auditory displays will likely be added to the cab, based on the current FHWA hearing requirement and the resulting assumption that the operator is not hearing-impaired.

There is also evidence that deaf and hearing-impaired individuals are capable of developing compensatory mechanisms, especially when the deafness or impairment occurs early in life. If deaf and hearing-impaired individuals are able to safely operate commercial vehicles through the use of compensatory mechanisms, they should not be prevented from obtaining a CDL, and the FHWA hearing requirement should be eliminated or relaxed. However, if the ability to hear auditory ITS displays becomes a critical requirement for safe driving, then perhaps the current standard should be retained, or even tightened. Furthermore, drivers may not be able to develop compensatory mechanisms for purely auditory displays. Finally, some have argued that the cab of the commercial motor vehicle is so noisy that the driver is virtually hearing-impaired, and that an actual impairment should not prevent a person from obtaining a CDL (Federal Highway Administration, 1976a). These are all issues which have not heretofore been adequately researched.

The research presented herein represents an attempt to determine whether the current FHWA hearing requirement for commercial vehicle operators is justified, to ascertain the level of hearing necessary to operate a commercial vehicle safely, and to determine whether such requirements will be necessary in the future. The primary research tool used for making this determination was a detailed task analysis, consisting of literature review, subject matter expert (SME) interviews, job observations, and questionnaires. Some form of hearing requirement is justified if there are found to be driving tasks which are safety-critical and which are also dependent on hearing, with no compensatory mechanism or display available for the hearing-impaired driver. If this is found to be the case, the level of hearing required would then need to be quantified. Literature review, task analysis, and noise exposure measurements were used to develop audibility predictions for the truck-driving task. Current FHWA requirements allow medical examiners the option of testing CVO hearing by either a forced-whisper test or an audiometric test measured at three frequencies. There have been questions raised about the validity of the forced-whisper test (King, 1953), and about the relevance of either test to truck driving tasks (Songer et al., 1992). The forced-whisper test was analyzed both by literature review and by an experiment to more accurately assess the validity of this test.

CHAPTER 2: LITERATURE REVIEW

FHWA Hearing Requirements

Substance of the requirements. The Federal Highway Administration (FHWA) has established physical qualifications for persons operating vehicles in interstate commerce (Federal Highway Administration, 1994). The hearing requirement reads:

> A person is physically qualified to drive a motor vehicle if that person … [this part contains a list of impairments which disqualify a driver from obtaining a CDL, including diabetes, epilepsy, and visual impairments] … First perceives a forced-whispered voice in the better ear at not less than 5 feet with or without the use of a hearing aid or, if tested by use of an audiometric device, does not have an average hearing loss in the better ear greater than 40 decibels at 500 Hz, 1,000 Hz, and 2,000 Hz with or without a hearing aid when the audiometric device is calibrated to American National Standard (formerly ASA Standard) Z24.5-1951. [Authors' notes: 1) ANSI Z24.5-1951 has been superseded by ANSI S3.6-1969. 2) Decibels, abbreviated as dB, roughly correspond to what people perceive as volume, while frequency, Hz, roughly corresponds to the perception of pitch.] (Federal Highway Administration, 1994, pp. 640-641).

Disregarding for a moment the issue of whether the hearing requirement should be retained, there are several problems with the substance of this paragraph. The first problem is the inherent subjectivity of the forced-whisper test as pointed out by King (1953). A medical examiner's certificate is all that is required to prove that the hearing requirement has been met; examination by an audiologist is not required. This means that general practitioners and family practitioners are performing these forced-whisper tests as part of the biennial Department of Transportation (DOT) physical examination. Many practitioners have different ideas as to what constitutes a forced whisper (King, 1953). While consistent results have been obtained when a single trained audiologist performed forced-whisper tests on several different subjects (Macphee, Crowther, and McAlpine, 1988), large variations (8-16 dB) have been observed between multiple trained otologists (King, 1953). The second problem is that if the test is designed to test for speech intelligibility, as indicated by the use of the forced-whisper test, the audiometric test does not cover the entire range of frequencies that are critical to the understanding of human speech (approximately 500-4,000 Hz). A third problem is in the wording of the phrase "average hearing loss … greater than 40 decibels." This is inappropriate terminology, because all audiometric decibel values are weighted by frequency and are termed either dBHL (decibel hearing level) or dBHTL (decibel hearing threshold level) (Ward, 1986). A hearing loss, on the other hand, refers to an individual's loss of hearing over time. A driver with an original audiogram showing an average hearing level of 20 dBHL over the three frequencies of interest could make a strong argument that a 40 dB loss would not occur until the hearing level at these frequencies averaged 60 dBHL. Finally, an audiometric test cannot be given with a hearing aid in place (Songer et al., 1992). Regardless of the outcome of this study, at the very least there should be some change in the wording of this rule.

The FHWA (Federal Highway Administration, 1976a) was petitioned by the State of Wisconsin in 1976 to relax its hearing requirements and to allow deaf drivers to operate in interstate commerce. The petition was denied based on a review of the available literature and invited comments from interested persons. Though the literature cited in the decision is now 20-30 years old, not much of substance has been added to it, and so it will be reviewed here as the rationale for the current requirement.

Research cited in the FHWA decision. Henderson and Burg (1973) studied the role of vision and audition in truck and bus driving. In studying truck driving tasks requiring hearing, they found that the most critical hearing tasks occurred prior to driving, in the pre-trip inspection. They concluded that drivers capable of hearing critical noises during the pre-trip inspection would have no trouble hearing other important noises during the driving task. Henderson and Burg (1973) recommended that hearing requirements be based on the intensity and spectral composition of the auditory stimuli of interest in the relatively quiet environment (of the pre-trip inspection). The authors then performed audiograms on 236 commercial vehicle operators (including bus drivers), and tried to correlate hearing level with a complete accident history for each driver. In this case, greater hearing loss was associated with a better driving record. Since the drivers were all qualified commercial drivers, the range of hearing loss was fairly narrow, and no conclusions were reached as to whether this trend would extend to higher levels of hearing loss if empirically tested. Also, since hearing loss is correlated with age, it could be that it was simply the older drivers (thus more experienced) who had the greater hearing loss, but also the best driving records. The authors did make a recommendation that the then-current standard not be relaxed for the purpose of collecting such data, given the potential risk for increased accidents.

Finesilver (1962) reported on a comparison of the driving records of deaf drivers and hearing drivers in Colorado, showing that deaf drivers have better driving records than hearing drivers. Though Finesilver (1962) was very supportive of deaf drivers and provided anecdotal evidence to indicate that deaf drivers are the safest drivers on the road, there were several flaws with his study. The first was the manner in which the driving records were obtained. The records of 100 deaf drivers were obtained from individuals attending a special course of the Denver Driving Improvement School. Finesilver described these students as alert, responsive, and enthusiastic. In fact, this group of deaf drivers had requested that a special course be developed for deaf drivers. The driving records of the hearing population were taken at random from state records. No mention was made of how many of the normal-hearing drivers had attended the Denver Driving Improvement School. It is quite probable that the deaf drivers who self-presented for a driver improvement course would be more conscientious drivers than either a random sample of deaf drivers or a random sample of hearing drivers. Another problem was that the average age of the deaf drivers was greater than that of the hearing drivers, which could also impact the results. Finally, no consideration was given to driving exposure (miles driven per month or year) or type of driving (such as rural versus urban driving). There could easily have been large differences in the amount and type of driving experiences between the deaf and hearing drivers in this sample. This study used only self-reported deaf drivers and drivers with minimal hearing for the deaf group, but made no attempt to quantify the hearing level of the hearing drivers, some of whom undoubtedly had a certain degree of hearing impairment. Though Finesilver's conclusions were totally supportive of deaf drivers, his report did not add anything to the empirical data concerning the hearing requirements of drivers in general, and did not address commercial vehicle operations at all.

Coppin and Peck (1963) performed a study of totally deaf drivers in California. Names of deaf persons were obtained through an organization composed of deaf people. The driving records of 721 of these deaf persons were then obtained for a specific three-year period. These driving records were compared with the driving records of 94,935 non-deaf drivers for a different three-year period. No attempt was made to determine the hearing level of the non-deaf drivers, some of whom were undoubtedly hearing-impaired to some degree. Deaf and non-deaf drivers were compared on gender, age, annual mileage, occupation, and area of residence. Significant differences were found for annual mileage (deaf drivers drove more miles), occupation (deaf drivers were concentrated in the skilled and semi-skilled jobs and professions, and underrepresented in the executive and clerical categories), and age (deaf drivers were older). The driving records of both groups were then compared. Deaf drivers were found to have a significantly higher number of accidents (1.78 times as many as the non-deaf drivers) and convictions (1.26

times as many as the non-deaf drivers). No conclusion was reached as to possible causes for the differences, since the samples differed so greatly on other variables. Some problems with this study include the use of a sample belonging to a deaf organization which may not be representative of the entire deaf population, the failure to obtain the hearing levels of the non-deaf drivers, the fact that different time periods were used for the driving records of the deaf and non-deaf drivers, and the failure to control for confounding variables such as annual mileage and occupation.

Subsequently, Coppin and Peck (1964) attempted to correct some of the flaws of their previous study by matching a sample of totally deaf drivers with non-deaf drivers on several important variables. A total of 453 deaf drivers were matched with 453 non-deaf drivers on gender, age, annual mileage, and occupation. There were still significant differences in area of residence with all of the non-deaf drivers living in the San Francisco or Los Angeles areas. An analysis of this difference showed that deaf males who lived in the urbanized San Francisco or Los Angeles areas had a significantly higher number of accidents and conviction points than deaf males living in other areas of the state. No such difference was found for deaf females. For this reason, only the driving records of those deaf males residing in Los Angeles or San Francisco were considered further, while all of the records for deaf females were included. The final sample size was 170 males and 140 females for both the deaf and non-deaf groups. The driving records for both groups were obtained for the same three-year period. For conviction points, deaf drivers did not differ significantly from non-deaf drivers, regardless of gender. For accidents, deaf male drivers still had 1.8 times as many accidents as non-deaf male drivers, while deaf female drivers did not differ significantly from non-deaf female drivers. Due to the matching process used, the authors felt confident in attributing the greater number of accidents to deafness, but several serious flaws remained in this study. For one thing, all of the non-deaf drivers were from the L.A. or S.F. areas, and these drivers could differ significantly from non-deaf drivers from the other areas of the state. Also, the hearing levels of the non-deaf drivers were not obtained. Hearing loss is a continuum, and this study compared one end of the continuum to the rest of the continuum, instead of to the other end of the continuum (totally non-hearing-impaired drivers). If hearing loss impacts driving, then a correlation should exist between the level of hearing loss and the driving record. No analysis of this type was made. Still, this study did provide an indication that there may be some relationship between hearing loss and driving performance.

Cook (1974) compared the driving records of 81 hearing-impaired drivers with those of 100 non-hearing-impaired drivers (all lived in Wisconsin). The hearing-impaired drivers were all alumni of educational programs for the hearing impaired in Wisconsin. Their driving records were obtained, but their level of hearing impairment was not reported. The sample was matched by age, but not by any other variable. In comparing driving points lost, there was no significant difference between the two groups. When the data were broken down by type of incident, the hearing-impaired drivers were found to have 1.82 times the number of accidents as the non-hearing-impaired drivers (a result very similar to that found in both Coppin and Peck studies). This statistic included accidents resulting in a loss of points, as well as accidents not resulting in a loss of points. For violations not involving an accident, the hearing-impaired drivers were found to have fewer violations than the non-hearing-impaired drivers.

Cook (1974) speculated that these differences were attributable to deaf or hearing-impaired drivers being a very law-abiding group (thus the lower number of violations), but that they tended to get involved in more accidents because they must take their eyes off the road to communicate with passengers (either to lip-read or to read sign language). This study also contained several serious flaws. For one thing, drivers were matched only on age, leaving important variables such as gender, annual mileage, occupation, and area of residence unexplored. Another problem was the failure to correlate level of hearing impairment with accident or violation rate. If there is a relationship between hearing level and driving performance, it could show up as a linear or curvilinear relationship. The most striking aspect of this study is the close agreement between it and the two Coppin and Peck studies on the accident rate of deaf versus non-deaf drivers: 1.78 times as many accidents for deaf drivers in the Coppin and Peck (1963) study, 1.8 times as many accidents for male deaf drivers in the Coppin and Peck (1964) study, and 1.82 times as many accidents for the hearing-impaired in the Cook (1974) study. Despite the flaws in these studies, the close agreement among accident rates as compared to non-deaf or non-hearing-impaired drivers indicates that there may be some overall validity to these studies.

In rejecting the petition by the state of Wisconsin, the FHWA also referenced the comments made by parties supportive of relaxing the hearing requirement standard (Federal Highway Administration, 1976a). These comments fell into four categories:

1. Handicapped persons in general and deaf drivers in particular are able to compensate for their handicap.
2. Safe driving is almost totally dependent on visual acuity and alertness.
3. The current rule is discriminatory, especially in light of the fact that no state prohibits the deaf from operating automobiles.
4. Truck drivers are exposed to such high noise levels that they are virtually hearing-impaired, and that many warning signals are thus inaudible due to masking.

The FHWA concluded that the preponderance of evidence available indicated that hearing may play some role in safe driving, and that the previously mentioned studies adequately answered these comments. Given the potential for greater damage caused by accidents involving commercial vehicles as opposed to automobiles, and in the interest of public safety, the FHWA denied the petition of the State of Wisconsin.

Songer et al. (1992) were charged by the FHWA, Office of Motor Carriers with renewing the study of the role of hearing in commercial vehicle operations. Much had changed in the 16 years since the 1976 review. Interior noise levels had been reduced, making masking less of a problem, and more attention was being paid to the rights of the disabled, as exemplified by the passage of the Americans with Disabilities Act in 1990. Songer et al. (1992) performed an extensive literature review of driving and hearing, including the role of hearing in the driving task, noise levels in truck cabs, hearing loss in truck drivers, the relationship between hearing loss and accidents, hearing screening tests, and the existing hearing standards in place in several states and foreign countries. The authors then performed a risk analysis for relaxing the current standard, evaluated the current methods for testing driver hearing, and summarized a workshop on hearing disorders and commercial driving. No empirical research was conducted for this study.

Songer et al. (1992) felt that the literature review was inconclusive, and that research results to date neither proved nor disproved the hypothesis that hearing is required for safe driving of commercial vehicles. As for state regulations for *intrastate* commercial drivers, hearing-impaired drivers could obtain a CDL in 50-60% of the states, with most states following the federal guidelines, but some allowing waivers. (States are allowed to establish their own guidelines and regulations for commercial drivers who drive only within the state.) Screening for hearing impairment varied widely by state, with some drivers receiving no screening. Hearing regulations were also found to vary widely across countries.

In the risk analysis, Songer et al. (1992) projected the crash risk for a hearing-impaired driver to be between 0.7 and 2.0 times the rate of a normal hearing driver; this wide range is indicative of the general lack of definitive data on the accident rates for deaf drivers. The authors concluded that the current standard (Federal Highway Administration, 1994) is inadequate because of the inconclusiveness of studies relating to driving and hearing, hearing and job performance, and the inadequacy of the forced-whisper hearing test in screening out hearing-impaired drivers. (Note: This portion of the FHWA standard was last revised in 1990.) However, they did not feel confident in making any specific recommendations for changing the law, given the inconclusiveness of previous research. They did present four possible courses of action:

1. Have no regulations related to hearing impairment.
2. Keep the existing regulations.
3. Keep the existing regulations, but allow medical waivers.
4. Keep the existing regulations, but change the screening criteria so that only the pure-tone test is accepted and either:
   - allow medical waivers or
   - do not allow medical waivers (Songer et al., 1992, p. VI-6).

Given the inconclusiveness of the Songer et al. study, the FHWA invested in the research which led to this report as a means of answering the questions surrounding hearing and commercial vehicle operations more definitively.

Other Studies of the Driving Task and Hearing

In addition to the research cited by the FHWA in its 1976 response to the State of Wisconsin's petition, there have been many other studies of the relationship between hearing and driving. These articles have been prevalent in both the popular and scientific literature. Such articles tend to fall into two categories, hearing as it relates to aging and driving, and hearing and driving, regardless of age. Each will be reviewed briefly.

Hearing and driving. McFarland, Moore, and Warren (1955) provided a summary of early scientific research into the area of driving and hearing. They concluded that studies conducted prior to 1955 did not indicate any clear relationship between safe driving and hearing acuity. Commercial vehicle operations were considered in this report. McFarland et al. (1955) reported that at that time, the minimum standard for professional drivers under the Interstate Commerce Commission for hearing was not less than 10/20 in the better ear for conversational tones, without a hearing aid. As described by Newby

(1958), this means that the driver would have had to understand a conversational voice at 10 feet (it was assumed that a normal ear could hear such a voice at 20 feet). This method of measurement is outdated, but the prohibition of the use of a hearing aid seems to indicate that the standards have been relaxed somewhat in the intervening years. The authors also reported on the noise levels of various trucks, and recommended that these levels be reduced through the use of insulation, resilient mounting, and panel treatment (as has subsequently been done). The authors claimed that this would reduce driver fatigue but made no mention of the reduction in hearing loss that could also occur.

Elbel (1960) summarized several research studies on driving and hearing, many of them performed in Europe, and also found inconclusive results. Some studies reported a lower accident rate for deaf drivers, or a higher passing rate on drivers' examinations for deaf drivers, but Elbel pointed out that many of these studies were flawed, and so reached no conclusions about the relationship between hearing and driving. Norman (1962) also decried the lack of definitive research in this area, but concluded that hearing impairment would be a greater problem for a pedestrian than a driver. No research was cited to back up this opinion. Waller (1965), in a study of chronic medical conditions and traffic safety in California, did not even include hearing impairment or deafness as a chronic medical condition, although headaches and sinusitis were among the conditions that *were* included. Given the availability of the Coppin and Peck studies by this time, the lack of inclusion is puzzling, especially as these studies were also conducted in California. Perhaps the thorough coverage of the issue in the Coppin and Peck studies was felt to be adequate. Grattan and Jeffcoate (1968) also summarized the relationship between several medical conditions and driving. For hearing, they reported briefly on the Finesilver and the Coppin and Peck studies, which gave conflicting results, and thus no conclusions were presented.

Schein (1968), in a chapter on the deaf driver, appears to be biased in his opinion that deaf drivers should not be denied the privilege of driving. In reporting on the Coppin and Peck studies, he discounted the higher accident rates of deaf males, and cited the improvement in driving records from the first to the second study as indicative of deaf drivers having overall better driving records than non-deaf drivers, a conclusion Coppin and Peck (1964) never reached. Schein compared the driving records of deaf and non-deaf drivers in the Washington, D. C. area. All deaf drivers who had received a ticket or been involved in an accident in a three-year period were used in the sample, and compared to all non-deaf drivers. No mention was made of how the deafness of the drivers was determined. While the deaf drivers in this study had significantly fewer accidents than the non-deaf drivers, no attempt was made to control for gender, age, annual mileage, or occupation, and yet the failure to account for these factors was mentioned by Schein as a flaw of the first Coppin and Peck (1963) study. The data were presented in such abbreviated form that it is difficult to draw any conclusions from this study.

Burg, Stock, Light, and Douglass (1970) suggested that deaf individuals be licensed to drive commercial vehicles under the same restrictions recommended to state medical advisory boards for deaf drivers of private vehicles. The restriction consisted of having two outside mirrors in addition to the inside rearview mirror, and satisfactory completion of a course designed especially for the deaf driver. [Author's note: Most commercial truck cabs do not even make use of an inside rearview mirror, either because the cab does not have a rear window, or because when pulling a trailer, these mirrors are completely obstructed.] Burg et al. (1970) based this recommendation on the results of the Coppin and Peck (1963, 1964) studies, as well as the Schein (1968) study. Despite the methodological shortcomings of the Schein study, Burg et al. must have averaged the results of the studies, because they concluded that "In general, however, the deaf driver accident rate is approximately the same as that of the nondeaf driver" (Burg et al., 1970, pp. 289-290). In fact, in two of these studies deaf drivers had a significantly higher accident rate, and in the other, deaf drivers had a significantly lower accident rate. The authors recommended licensing deaf drivers for commercial vehicles under the restrictions mentioned earlier, despite noting that " … there is a scarcity of data which would either support or refute the capability of the deaf individual to drive such vehicles safely" (Burg et al., 1970, p. 290).

Henderson and Burg (1974), after completing the previously discussed work on vision and audition in bus and truck driving (Henderson and Burg, 1973), completed a second report on vision and audition in automobile and motorcycle driving. For automobile driving, they were unable to establish any tasks for which hearing is absolutely essential to safe performance. They noted that at the time, the noise levels inside many cars completely masked emergency warning tones, and in those situations where the masking was less severe (such as when a vehicle is stopped, or has a slow closing rate with another vehicle), the driver had more time to react, and that a deaf driver would thus have time to notice another vehicle visually and react appropriately. In the 22 years since this report was written, automobile interiors have become significantly quieter. However, the soundproofing used to accomplish this also attenuates external desirable sounds (in addition to such sources as engine and tire noise), and in so doing, reduces the audibility of emergency warning tones to the same or greater degree as did masking in the older, louder, automobiles. Also in the intervening years, automobile stereo equipment has become much more powerful, and some people play radios and tape decks at such levels that all but the loudest external sounds are masked. Henderson and Burg (1974) did not recommend auditory screening of applicants for driver's licenses, but did recommend standardizing warning signals at an optimal tone and level, reducing interior noise levels of vehicles, and reducing attenuation of warning signals by the vehicle (as discussed, these last two suggestions may be conflicting). For motorcycle drivers, they found that the noise level at the ear was so great as to mask all warning signals unless they were so close that it was too late to react. Henderson and Burg (1974) thus recommended against auditory screening of motorcycle driver's license applicants. This finding was supported by Van Moorhem, Shepherd, Magleby, and Torian (1981), who found that most auditory warnings are not particularly effective for motorcyclists riding at highway speeds.

Booher (1978) performed a survey of the research on the effects of visual and auditory impairment in driving performance. For commercial vehicle operators, Booher suggested that hearing may be necessary to hear engine noise, especially in congested urban areas, and to hear children in suburban areas. For automobile drivers, he concluded that there should be no impediment to obtaining a license, but recommended the use of outside mirrors and special training. One interesting compensatory tactic he recommended was for deaf drivers to have hearing passengers when driving in an unfamiliar area. However, this would require the deaf driver to remove their visual attention from the unfamiliar road to the passenger to obtain any necessary information, which seems perhaps more dangerous than navigating the unfamiliar area alone. Perhaps the intent was that the hearing passenger would only be used to ask for directions.

The National Highway Traffic Safety Administration (1980) prepared a booklet of guidelines for state medical advisory boards on functional aspects of driver impairment. Three medical classifications are used, and tractor-trailer drivers fall under Medical Category I. For hearing, drivers in Category I should not have any incapacitating hearing loss that would interfere with the ability to communicate, or that would present any special hazard in either cargo or passenger transport. The current FHWA hearing requirement was in place at this time, and was listed as an appendix to this document.

Lerner, Ratte, and Walker (1990) performed a review of the research on driver behavior at rail-highway crossings, including auditory aspects. Auditory cues were said to have the advantage of being detectable no matter which way the head is oriented, while for visual cues, the head must be pointed in the right direction and the eyes must be open (it is difficult to close the ears except with hearing protection devices). Lerner et al. (1990) also discussed the limitations of auditory warning signals for trains. The first drawback is that communities often object to loud noises such as train whistles, and in some cases have ordinances against them. Another problem is the effect of such loud warning devices on the persons who must listen to them most often, the engineers and other crew members. The auditory cue can also be attenuated by buildings, trees, and the vehicle itself, or be masked by noises internal or external to the vehicle. For these reasons, auditory warnings for trains were viewed as supplementary to visual warnings. The authors also repeated recommendations that truck drivers be informed of the unreliability of train horns in providing warning, and to roll down their windows and turn off radios when approaching an unguarded rail crossing (one with no physical barriers). Lerner et al. (1990) concluded that auditory cues have some value in warning drivers of approaching trains, even if only as a supplementary warning. This provides evidence of at least one concrete task for which hearing may be necessary for the safe operation of commercial vehicles.

Most recently, a study of commercial motor vehicle drivers' medical conditions and crash severity failed to include hearing impairment as a medical condition (Laberge-Nadeau, Dionne, Maag, Desjardins, Vanesse, and Ekoe, 1996). Only diabetes, coronary heart disease, hypertension, and binocular vision problems were considered in this study. Crashes of trucks whose drivers had binocular vision problems or hypertension were found to be more severe than those of healthy drivers. No reason was provided for the exclusion of hearing impairment as a medical condition.

The research on the relationship between driving and hearing has not advanced much in the last 30 years. The definitive study has yet to be conducted, but the two Coppin and Peck (1963; 1964) studies appear to be the most thorough and methodologically sound, despite their flaws. Emotions run high in this area due to the potential for discrimination against the deaf and hearing-impaired. Also, researchers have been reluctant to suggest eliminating the FHWA hearing requirement for commercial vehicle operators because of the potential risk to public safety should it turn out that hearing *is* essential for the safe operation of these vehicles. Recommending a change in the requirement is also fraught with economic and political implications. For example, while Songer et al. (1992) concluded that the forced-whisper test is probably not an effective screening device for truck drivers, they estimated that to force a switch to pure-tone audiometric testing could cost $247,500,000 the first year, and $123,750,000 per year thereafter (based on 5.5 million drivers receiving an initial audiogram at an average cost of $45, and having the audiogram repeated every two years). The persons expected to bear these costs would probably object strenuously to such a change. The importance of audition to safe driving is not as clear-cut an issue as is vision. People have operated vehicles with hearing impairment up to total deafness, with better or worse safety records than the non-hearing-impaired, depending on the study being referenced. No firm conclusions leading to a recommendation about the necessity and criteria of a hearing requirement for commercial vehicle operators can be drawn from this review of the literature on driving and hearing.

Hearing, aging, and driving. Another forum for the study of driving and hearing is in the area of aging. Hearing loss is known to increase with age, a phenomenon referred to as presbycusis (Weinstein, 1994). Hearing loss presently affects approximately 30% of persons over 65 years of age who are not institutionalized. Overall, 33% of those 65-74 years old, 45% of those 75-84 years old, and 62% of those over the age of 85 report a hearing problem (Weinstein, 1994). Besides presbycusis, other factors leading to increased hearing loss among the elderly include noise-induced hearing loss, metabolic conditions, vascular disease, senile dementia, and drug-induced hearing loss, since the elderly typically consume more medication than do other age groups (Weinstein, 1994). Since the elderly population tends to have such a high percentage of people with hearing loss, this would be an ideal situation in which to study the effect of hearing loss on driving. Unfortunately, the elderly also tend to have other age-related health problems, such as poor vision, reduced mobility, reduced reaction time, and reduced mental capacity, so it is difficult to attribute any increase in accident rate to any one factor.

In a study of driver behavior at rail-highway crossings, Lerner, Ratte, and Walker (1990) suggested that changes in auditory detection, along with other perceptual decrements associated with age, should cause older drivers to have more problems at rail-highway crossings. In a note in a journal for family physicians (Anonymous, 1987), physicians were advised to warn elderly patients of the decrements in vision and hearing that may accompany age, and to suggest the following methods to compensate for the loss of hearing: check mirrors more frequently, turn off the car radio (to diminish masking), use a hearing aid, and have hearing checked regularly.

More recent research has included hearing as one aspect of investigations into the accident rates of older drivers. McCloskey, Koepsell, Wolf, and Buchner (1994) performed a case-control study in which older drivers who had been in an accident in the previous two years were matched with other older drivers who had been accident-free. Several measures of sensory impairments were taken. Two controls were matched with every case on gender, age, and county of residence. The only increased risk factor found was that drivers who owned hearing aids and wore them while driving had 2.1 times the risk of an accident as other drivers, including drivers who were hearing-impaired but did not own a hearing aid, or drivers who owned a hearing aid but did not wear it while driving. The use of a hearing aid was self-reported, but medical records were available for many of the drivers, including pure-tone audiometry and speech reception thresholds. This number is very similar to that found in some of the previous studies (Cook, 1974; Coppin and Peck, 1963; Coppin and Peck, 1964). This risk was based on a further matching analysis that matched cases (only those who wore hearing aids while driving) and controls on race, education, miles driven, and the presence of a passenger, in addition to the matching previously described. The authors speculated that the hearing aid might actually interfere with the driving task in some way, which if true would have serious implications for the current FHWA requirements that truck drivers with hearing loss wear their hearing aids while driving. An example of such interference is that the wind from an open window blowing across a hearing aid microphone creates a roaring noise.

Foley, Wallace, and Eberhard (1995) also performed a well-designed study of risk factors for vehicle accidents among older drivers. This study used drivers in rural Iowa, and was part of a large-scale longitudinal health survey. Participants self-reported on the three hearing measures, which included "wears a hearing aid" (the question of wearing the hearing aid while driving was not asked), "cannot hear normal voice," and "has ringing in the ears." There was no increased risk for drivers self-reporting any of these hearing problems. The only increased risks were for drivers who were men, had back pain in the preceding twelve months, used non-steroidal anti-inflammatory drugs, or could recall less than three words on a delayed-recall memory test. The lack of significance for a relationship between hearing and driving could be attributed to the use of self-report, or to the fact that the question about the use of a hearing aid while driving was not asked, which was found to be significant in the McCloskey et al. (1994) study.

Many articles in the popular literature point out the decrease in auditory acuity that comes with age, provide checklists of warning signs, and provide tips for safe driving given reduced perception (Carney, 1989; Knepper, 1992; Lundy, 1992; Russell, 1995). This type of article tends to appear more frequently when there has been some well-publicized accident or incident involving an older driver. These articles serve some purpose in alerting the older driver or the families of older drivers to the fact that driving skills may decrease with age. However, these articles serve no real purpose in determining the importance of hearing for safe driving in an empirical sense.

That there is some decrement of hearing with age has been well-documented (Weinstein, 1994). Whether this decrement has an impact on the safe operation of commercial motor vehicles has not yet been determined. If commercial driving tasks are identified for which hearing is a critical part of the task, then the fact that hearing declines with age should be taken into consideration, and the FHWA hearing requirements might be revised to include provisions for age.

Effects of Occupational Noise Exposure

Noise and hearing loss. Approximately one-third of the 28 million people in the U. S. with hearing loss can attribute their loss to exposure to loud sounds, and more than 20 million are exposed on a regular basis to sounds loud enough to cause hearing loss (National Institutes of Health, 1990). Three types of hearing loss are generally attributed to excessive noise exposure: temporary threshold shift, noise-induced permanent threshold shift, and acoustic trauma (Jones, 1983). Temporary threshold shift (TTS) and noise-induced permanent threshold shift (also called NIPTS or noise-induced hearing loss) are the types that would be more likely to occur due to truck-cab noise exposure. A TTS of less than 25 dB over 8 hours is generally restored to normal after 16 hours off with no noise exposure (Jones, 1983), but continued exposure can produce a permanent shift. Of special concern for truck drivers is that many of them work 10 hours at a stretch, and then continue to work with less than 16 hours away from the job. Also, drivers who team-drive may be exposed to noise continuously, as they sleep and their partner drives. If truck-cab noise is found to cause a temporary threshold shift, drivers currently may not be provided with enough quiet time to recover from the TTS. Even minor TTS that would recover fully in an industrial setting may not be allowed time to recover in a truck driving setting.

Axelsson (1979) characterized noise-induced permanent hearing loss as a typically symmetric high-tone loss with a maximum at 4000 and 6000 Hz. Frequencies below 1500 Hz are not typically affected by noise, even after years of exposure. In general, there is a correlation between the length of exposure and the degree of hearing loss, although there is quite a bit of variability between people in their susceptibility to noise-induced hearing loss, as much as 30-50 dB with exposure to a given noise (National Institutes of Health, 1990). High frequencies, pure tones, and impulses increase the risk of hearing loss. More intense and longer-duration noise exposure tends to cause greater levels of hearing loss (National Institutes of Health, 1990). Other characteristics of noise-induced hearing loss include its slow development, irreversibility, and difficulty of self-detection until it reaches a severe level. This type of hearing loss can be measured and controlled, and prevention is the only therapy (Axelsson, 1979). The noise environment typically found to cause NIPTS is broadband industrial noise (Jones, 1983), such as that found in the truck cab. The relationship between TTS and NIPTS is not clear. Available evidence points to NIPTS as being more than just a cumulative effect of TTS (Jones, 1983). The cumulative effect of other factors such as presbycusis, non-occupational noise exposure, industrial chemicals, ototoxic drugs, and illness are hard to separate from the effects of occupational noise exposure (Jones, 1983). Despite these uncertainties, large-scale analyses have placed the threshold for hearing loss from long-term noise exposure at 80 dBA, with a 2 dB hearing loss for every 1 dB increase above 80 dBA (Jones, 1983). Noise levels less than 75 dBA are unlikely to cause permanent damage, even after years of exposure (National Institutes of Health, 1990).

Based on the findings that noise exposure causes hearing loss, the OSHA standards for noise were established in 1974 to protect U.S. workers from NIPTS (OSHA, 1990). Workers exposed to more than 90 dBA time-weighted average (the criterion level or permissible exposure limit) over an eight-hour shift are to be protected by means of administrative and engineering controls, or as a last resort, personal protective equipment. Workers exposed to more than 85 dBA (the action level) over an 8-hour shift are to be enrolled in a hearing conservation program. The hearing conservation program includes workplace monitoring, employee notification, audiometric testing, availability of hearing protection devices, a training program, and recordkeeping. Truck drivers are not protected by this OSHA guideline, but rather fall under the jurisdiction of the Office of Motor Carriers (OMC) of the FHWA (Songer et al., 1992). The current OMC regulation on interior truck-cab noise states that "the interior sound level at the driver's seating position of a motor vehicle must not exceed 90 dBA" when measured in a stationary test with all doors, windows, and vents closed and power accessories turned off (Federal Highway Administration, 1976b). These test conditions almost certainly produce lower readings than those encountered in real world driving. Also, even if the real world conditions are found to meet the 90 dBA requirement, this level is still sufficient to cause NIPTS, and potentially lead to widespread hearing loss among truck drivers.

Noise, hearing, and accidents. Kerr (1950) reported on the "accident proneness" of factory departments, or the tendency of certain factory departments to have more accidents than other departments. He attempted to determine the factors that could be contributing to this increased accident incidence. Forty variables were investigated, and only a few of these correlated significantly with accident rate. One significant factor was mean noise level, which was found to correlate significantly with accident frequency, though not with accident severity. Kerr was unable to determine from the results of this study whether the noise level caused the higher number of accidents, or whether the more hazardous operations also tended to be the more noisy operations.

Cohen (1973) studied the effect of noise on accident rates for workers exposed to high and low levels of noise. High-noise levels were considered to be those above 95 dBA, and low-noise levels were considered to be those below 80 dBA. A total of 520 workers worked in high-noise areas of two plants, and 514 worked in low-noise areas. Two manufacturing firms were studied, one large and one smaller (903 of the 1034 workers worked at the larger plant). Employee records were analyzed for a 5-year period prior to implementation of a hearing conservation program. For both plants, Cohen found that employees in the high-noise areas of the plant had significantly more accidents than workers in the low-noise areas of the plant. In order to research whether a reduction in noise exposure would cause a reduction in accidents, Cohen (1976) then examined the records of some of the same workers exposed to low and high levels of noise (>95 dBA and <80 dBA) for periods before and after implementation of the hearing conservation program. A total of 434 high-noise workers and 432 low-noise workers were studied; all worked at the same large manufacturing facility studied in the first report. The records of the same workers were compared for a two-year period preceding the implementation of the hearing conservation program, and for a two-year period after implementation of the hearing conservation program, with the one-year period of the implementation not considered in the data collection. In the two years after the hearing conservation program was instituted, workers from the high-noise areas of the plant showed significant reductions in accident rate as compared to workers in the low-noise group. Cohen was cautious in drawing conclusions from these studies, but taken together they provide compelling evidence of a relationship between noise exposure and accident rates.

Straub (1974) studied the effects of hearing loss on accidents. Twenty-six workers with bilateral hearing levels greater than 40 dBHL (averaged over 500, 1000, and 2000 Hz) were matched on the basis of sex, age, race, job operation, and accumulated service with 26 workers with bilateral hearing levels of less than 25 dBHL. There was no significant difference in the number of injuries for the hearing-impaired group. If noise is a cause of accidents as suggested by Kerr (1950), matching by job operation could be expected to show that hearing-impaired individuals would have fewer accidents, since they would not perceive the noise to be as great as the non-hearing-impaired workers, and any startle effect would be minimized for the hearing-impaired workers. Though the hearing-impaired group did have fewer injuries, the difference was not significant. The question of whether high-noise levels cause a greater number of accidents than do low-noise levels cannot be answered by the Straub study.

Finkelman, Zeitlin, Filippi, and Friend (1977) performed an empirical study of the effect of noise on the performance of a subsidiary task in which the primary task was driving. When performing both tasks in the presence of unpredictable bursts of white noise, drivers exhibited reduced accuracy but maintained speed (accuracy was measured by the number of pylons knocked over). In a real world driving environment, this would correlate with lane deviations or accidents. This research has implications for the effect of increasing complexity of the driving task in the modern truck cab. Much of the emerging Intelligent Transportation Systems (ITS) technology functions as a subsidiary task to which the driver must attend in addition to driving. Unexpected noises, such as those that may alert the driver to a mechanical problem, may cause the driver to become startled or swerve if they occur while the operator is attending to another ITS display. More research is needed in this area.

Schmidt, Royster, and Pearson (1980) reported on a study of job-related injuries in an industrial plant before and after the implementation of a hearing conservation program. For employees with 11 or more years of service, the injury rate declined significantly after the hearing conservation program was in place, with females showing a greater reduction than males. Workers in high-noise conditions were also compared to workers in low-noise conditions. The workers in the high-noise conditions were found to have significantly more injuries. Since many job related injuries are the result of accidents, this study provides some evidence that a reduction in noise exposure might cause a reduction in injuries, and by implication, accidents.

Wilkins and Acton (1982) reviewed many of the studies relating noise level to industrial accidents and concluded that there is a strong suggestion that noise may be a contributory factor in causing accidents. They suggested several possible mechanisms for this link. The first is that noise may cause workers to become inattentive. Another possible mechanism is masking, which may make it difficult or impossible for a worker to hear warning signals. Speech communication may also be masked, leading to misunderstandings and accidents. A third mechanism is a reported communication difficulty experienced by some persons wearing hearing protection devices, which tend to be used more often in high-noise environments. In general, this reduced communication is a perceptual artifact, except in persons with existing noise-induced hearing loss. The final mechanism discussed is the possibility that a noise-induced hearing loss caused by high-noise levels may itself cause an increase in accidents due to a decreased ability to hear warnings and speech communication. Evidence for such a link between industrial accidents and hearing-impaired workers is as inconclusive as the link between vehicular accidents and hearing-impaired drivers. Wilkins and Acton (1982) concluded that the overall evidence for a link between industrial noise and accident rate, although inconclusive, is strong enough that efforts should be made to reduce industrial noise levels whenever possible. Such action would have the added benefit of reducing the incidence of noise-induced hearing loss. They also recommended that engineering controls be given priority over the use of hearing protection devices.

Moll van Charante and Mulder (1990) examined the risk of industrial accidents in a shipyard as related to perceptual acuity. Measures of perceptual acuity included consumption of alcohol, work in high-noise environments, wearing of glasses, use of tranquilizers, and hearing loss. A case-control methodology was used, with cases being those persons who had experienced an occupational injury in the preceding 2 1/2 years. A hearing threshold level greater than 20 dBHL at 4000 Hz in the left ear, loud noise greater than 82 dBA, and alcohol consumption were all found to be significant predictors of accident rate. A hearing threshold level greater than 20 dBHL increased the risk of injury more than four times, and exposure to noise louder than 82 dBA doubled the risk of injury. As expected, hearing level and exposure to loud noise were found to interact, since noise exposure is known to cause hearing loss. The risk attributable to the combined effects of hearing level and noise exposure accounted for 43% of the total injuries. In a further analysis designed to account for the effect of postural instability on accidents, Moll van Charante, Snijders, and Mulder (1991) found no significant difference in posture control between cases and controls, either in silence or during exposure to excessive noise. They had postulated that the risk factors found in the previous study would have a significant impact on postural control, making cases more likely to slip, trip, or fall.

Based on the collective results of these studies, there seems to be some relationship between noise, hearing level, and industrial accident rates. The exact nature of the relationship and the mechanism which causes it remain unclear, and give rise to the following questions: Do accidents sometimes occur because of a startle reaction produced by a loud noise? If so, are the hearing-impaired safer in this type of environment? To what extent does loud noise mask warning signals, and is the masking greater for hearing-impaired workers? Perhaps communication ability is the key, or perhaps noisy environments tend to be unsafe environments in most cases, and removal of the noise would have no impact on the accident rate. Perhaps all of these mechanisms together act to affect accident rates. How does the wearing of hearing protection devices affect these mechanisms? No meta-analysis of these studies has been performed in order to answer these questions, and there are only strong hints that such a relationship exists.

Other extra-auditory effects of noise. Anticaglia and Cohen (1971) reviewed studies of the physiological extra-auditory effects of noise. They reported evidence that noise can affect the neurosensory processes, with unexpected impulse noise especially eliciting a startle reflex, which may lead to an increased risk of accidents. The startle reflex was found to be resistant to extinction, evidenced by the fact that experienced marksmen still exhibit the eyeblink portion of the startle reaction when firing their weapons. Exposure to high-noise levels has also been found to affect the visual field, color perception, and the sense of balance. However, the postural stability of shipyard workers was found not to be significantly impacted by exposure to loud noise (Moll van Charante et al., 1991). In the endocrine system, noise is thought to act as an environmental stressor, which causes a measurable release of adrenocortical, gonadal, and thyrotropic hormones. The cardiovascular system has been reported to respond to noise with vasoconstriction, fluctuations in arterial blood pressure, and alterations in some functions of the heart muscle. Vasoconstriction, especially, occurs at fairly low levels of noise exposure (beginning at about 70 dBA in the extremities), and increases with increasing noise intensity. Other reported effects of noise include reductions in salivary and digestive secretions and a general slowing of digestive functions. In a more recent study, high blood pressure was found to occur at the same rates in a noisy and a quiet industrial plant (Talbott, Helmkamp, Matthews, Kuller, Cottington, and Redmond, 1985). However, there was a strong relationship between severe noise-induced hearing loss and high blood pressure at both plants, suggesting that the same people may be susceptible to both conditions, or that the quieter plant may have been noisier in the past, and thus both groups were similarly exposed.

In the same study previously reviewed concerning the effect of noise on accident rates, Cohen (1973) also studied the effect of noise on other extra-auditory measures such as illness and absenteeism for workers exposed to high and low levels of noise. Employee records were analyzed for a 5-year period prior to implementation of a hearing conservation program. For the larger of the two plants studied, Cohen found that employees in the high-noise areas of the plant had significantly more diagnosed medical problems, discrete number of absences, and total number of days absent than workers in the low-noise areas of the plant. For the smaller plant, the only difference found was for number of discrete absences; high-noise workers had significantly more discrete absences than low-noise workers. In order to determine whether a reduction in noise exposure causes a reduction in extra-auditory problems for workers, Cohen (1976) then compared the pre- and post-hearing conservation program records of some of the same workers exposed to low and high levels of noise (>95 dBA and <80 dBA). A total of 434 high-noise workers and 432 low-noise workers were studied; all worked at the same large manufacturing facility studied in the first report. Four measures were taken in addition to accident rate: number of diagnosable medical problems, number of symptomatic complaints, number of discrete absences, and total number of days absent. Workers from the high-noise areas of the plant showed significant reductions in each of these measures except symptomatic complaints in the two-year period after implementation of the hearing conservation program. Workers in the low-noise group exhibited no significant reductions in any of these measures, but did show a significant unexplained increase in number of discrete absences and total number of days absent. Cohen was cautious in drawing conclusions from these studies, but taken together they provide compelling evidence of possible extra-auditory effects of noise exposure.

Ewertsen (1979) reported on the psychological effects of noise. The most common effect was said to be psychological irritation, but which is hard to define and measure. A study of 960 residents of high- and low-noise areas attempted to quantify some of the behavioral reactions to high-noise levels. Residents of the noisy area (477 people; traffic noise fluctuating between 69 and 78 dBA) were found to have significantly greater psychiatric medical consultations, use of sleeping medicine, use of tranquilizers, admission to mental hospitals, closed windows, isolation against noise, and change in position of rooms than residents of low-noise areas (483 people; traffic noise 51-63 dBA).

Lees, Romeril, and Wetherall (1980) performed a paired cohort study of 140 industrial workers. Half of the workers had been exposed to sound levels less than 85 dBA for 15 years, and half had been exposed to sound levels greater than 90 dBA for a period of from 3 to 15 years. Lees et al. (1980) did not find any evidence for increased absenteeism, headaches, or accidents among the group exposed to the higher noise levels. However, this study used a much smaller difference in the categorization of high- and low-noise levels than did other studies (see the Cohen studies, 1973 and 1976, where the categories were <80 dBA and >95 dBA). Here there is only a 5 dB difference between categories. Another problem with this study is that the low-noise workers had to have been exposed to low levels for 15 years, while the high-noise workers had to be exposed to high-noise levels for 3-15 years. Workers who were exposed to low levels of noise for 12 years, and then to higher levels for 3 years could easily have an overall noise exposure equal to or less than the same workers in the low-noise group. In other words, there could have been a significant amount of overlap between the low- and high-noise exposed groups in terms of their overall noise exposure. Due to this weakness in the experimental design, this study does not help answer the question of whether or not noise has extra-auditory effects on the worker.

Jones (1983) reviewed much of the literature on the extra-auditory effects of noise. Variable noise is characterized by level changes within a specified range, but which is seldom completely quiet, as found in the truck cab environment when upshifting or in city driving, when more shifting is required. One of the performance effects for variable noise is a slowing improvement on a learning task, with the effect becoming attenuated for well-practiced tasks. Overall, however, variable noise has been found to improve performance after a certain amount of exposure has occurred, especially for tasks requiring sustained attention (Jones, 1983). This would indicate that the variable noise in a truck cab would not be detrimental to the task of driving, which requires sustained attention. Continuous noise is loud and uninterrupted, such as that found when driving a truck on flat stretches of interstate for hours at a time with no need to shift gears. For vigilance tasks, such as detecting an oil pressure gauge warning light, the presence of continuous noise does not detract from detection of signals from a single source. But when the signals are coming from various sources, as can occur in a truck cab, various adverse effects are seen, such as failure to detect, slowed detection, and an increase in the number of false alarms (Jones, 1983). Signals in a truck cab, both visual and auditory, can come from the dashboard, the engine, the trailer, and the environment surrounding the truck. This would suggest that continuous truck cab noise may impair driver performance in vigilance tasks. Continuous noise has also been found to increase response time and errors, both of which could account for an increased risk of accidents in truck driving (Jones, 1983). Jones (1983) also reported that industrial workers have been reported to show improvements in productivity and a decreased number of errors while wearing hearing protection devices.

In addition to the effects of noise on hearing and accident rates, there is some evidence that noise can affect physiological functions, psychological functions, illness rates, and job performance. If truck driver noise exposure is excessive, drivers may be losing their hearing, which would be unfair in that they would then be prohibited from driving. Accident rates may be higher than they would be at lower noise levels, which would have an important impact on public safety. And drivers may be suffering physiologically and psychologically, which would have a negative impact on their long-term health. A review of truck-cab noise levels and truck-cab noise exposure will provide insight into the extent of the noise exposure problem for truck drivers.

Truck-Cab Noise

Measurements of truck-cab noise. In the early 1970's researchers began to take notice of truck-cab noise. Reports from 1970 until 1995 provide a fairly continuous record of changing interior truck-cab noise levels. All sound pressure levels (SPLs) discussed here will be reported in dBA for comparison purposes across studies. The dBA scale weights sound levels at different frequencies in a manner which approximates the frequency response of the human ear. The A-weighting tends to underrepresent the levels of low frequency sounds, which make up much of the energy encountered in truck-cab noise. However, these low frequency components are generally thought to be less harmful to the human ear in terms of hearing loss than are the high frequency components (Hessel, Heck, and McJilton, 1982). Furthermore, the ear is less sensitive to low frequency sounds than midrange (about 1000-4000 Hz) or high frequency (above about 4000 Hz) sounds. Due to the upward spread of masking, however, these low frequency components may result in a greater masking problem.

The earliest reference to truck-cab noise levels discovered in a search of the literature was that measured by Emme (1970) as reported in Henderson and Burg (1973). Measurements were taken on four commercial runs with different motors and makes of trucks. The results showed that under each of the four conditions studied, the truck-cab noise exceeded 100 dBA over 75% of the time. Morrison and Clarke (1972) performed several different types of interior truck-cab noise measurements in order to specify the correction factors for converting standardized stationary measurements into real-world figures. Several makes and models of trucks were tested. The exact means were not given, but from the graphs it appears that the sound level readings for the SAE J366 (SAE, 1988) test procedure averaged between 90 and 95 dBA, and the SPLs for the stationary acceleration test procedure averaged between 88 and 92 dBA. The stationary high idle test procedure produced an average SPL of between 89-93 dBA. In all cases, the noise level measured at the left ear was about 1 dB higher than the noise at the right ear. For the over-the-road tests, the readings were about 85-88 dBA. They concluded that the over the road tests showed significantly lower readings than the stationary tests. The work was said to be incomplete, but Morrison and Clarke predicted that the correction factor would be in the range of 3-5 dB (to be subtracted from the stationary test results to obtain the over the road values). Although the years of the trucks tested in these two studies were not specified, they were probably late 1960's models, based on the dates of publication of the two reports (1970 and 1972).

Reif, Moore, and Steevensz (1980) tested the noise levels of 58 commercial vehicles during normal long-distance operations. Model years ranged from 1968-1978 with 42 of the trucks in the 1974-1978 model year range. A wide range of makes and models were represented, and the trucks and drivers were obtained from a variety of long-haul trucking companies. For freeway driving, the L_{eq} averaged 88 dBA, for highway driving the L_{eq} averaged 86 dBA, and for city driving the L_{eq} averaged 84 dBA. In a follow-up analysis, Reif and Moore (1983) found that 40% of trucks were capable of exceeding the OSHA 90 dBA criterion level over a 10-hour shift, and 90% of trucks were capable of exceeding the 85 dBA action level. Worst case driving conditions were assumed (freeway driving, windows open, normal use of radio and CB radio, and 10-hour driving shift).

Hessel, Heck, and McJilton (1982) measured the noise levels in eight tractors under actual driving conditions. Model years ranged from 1973-1977, with three truck makes and two engine types represented. The measurements were made with a sound level meter with an attached octave-filter set, and for the first time, the truck-cab noise was analyzed by frequency, showing that the noise levels were considerably higher in the lower frequencies (below 125 Hz). As discussed earlier, A-weighted measurements (dBA) tend to underrepresent the lower frequencies, and Hessel et al. presented both the dBA and dBC levels. The dBA measurements averaged 83.4 and the dBC values averaged 102.2. This demonstrates the magnitude of the underrepresentation of the low frequency noise by the A-weighted measurements. The dBA levels calculated from dosimeter readouts averaged 88.6 dBA. They noted that the higher dosimeter levels probably occurred because the dosimeter was turned on during the entire driving time, while the sound level meter was only turned on when the standardized driving conditions had been reached.

Morrison (1993) measured the noise levels of four new truck cabs under ideal driving conditions (clear weather, constant speed, windows closed, and accessories off). Five minute A-weighted L_{eq} measurements were taken, and the results showed that sound levels varied from 74.3 dBA to 78.8 dBA. Spectral analysis was also performed, and showed that sound energy below 250 Hz was considerably greater than the higher frequency components. This was a substantial overall noise reduction compared to previous reports. The reduction may have been partly due to the idealized conditions, and to the fact that the trucks were new, but Morrison attributed most of the reduction as compared to 1970's era trucks to improved cab design, drive-train design, and passive noise control. The calculated OSHA noise dose was 0%, since all freeway measurements were below 80 dBA, and measurements below 80 dBA are not included in OSHA noise dose calculations. Dosimeters typically produce higher noise dose measurements than do sound level meters by about 2-3 dB, in addition to being more accurate (Royster, Berger, and Royster, 1986). Had a dosimeter been used for an entire work shift of driving these same vehicles, it is likely that the noise dose would have been greater than 0%.

Micheal (1995a) studied the noise levels of 6 new, 1995 model trucks with various cab configurations and engine types. In addition to standardized tests (SAE J366 and reverberation time measurements), more realistic driving conditions were tested. For these measurements, the window was partially rolled down and the radio was turned on to a comfortable level. Two constant speed measurements were taken under both the realistic and ideal (window up, radio off) conditions. Under ideal conditions, the noise level was 74.9 dBA, and for realistic conditions the level was 79.7 dBA. Micheal (1995a) also calculated a 0% OSHA noise dose for drivers of these trucks, even under the realistic conditions not tested in the Morrison (1993) study. He concluded that drivers' hearing was not threatened by the level of noise produced in currently manufactured trucks.

The fact that the trucks were new could have contributed to the quiet levels measured in these two studies, but the increase (if any) in noise as trucks get older has not been studied. The main factor for the low noise dose reported here may be that the noise was measured via real-time analyzer rather than with a dosimeter. A dosimeter measures the sound level over an entire work shift, and calculates the noise dose accordingly, but the dose reported was based on a five- minute measurement under constant speed conditions. Another difference between the readings reported in these studies and dosimetry is in the microphone placement (for Morrison and Michael, in the center of the cab, and for a dosimeter, on one shoulder of the driver, with the left shoulder probably providing a higher reading than the right shoulder). Therefore, the true noise dose for drivers of these vehicles under real-world conditions would probably be greater than 0%.

van den Heever and Roets (1996) studied the noise exposure of truck drivers of two new South African trucks (the trucks tested were manufactured by MAN and Mercedes Benz). Measurements were made using dosimeters worn on the drivers' shirt collars. The dosimeters were set to reflect the South African safety standard of an 85 dBA threshold with a 3 dB exchange rate. The windows were open sometimes and closed at other times, apparently according to the driver's preference. Results showed that one brand of truck had an L_{eq} of 84.9 dBA, and the other brand had an L_{eq} of 85.8 dBA. These levels were close enough to 85 dBA that the authors concluded that the drivers of these brands of trucks should wear hearing protection devices while driving. The maximum levels (L_{max}) recorded were 118.5 dBA for one brand of truck, and 115.4 dBA for the other brand (these were attributed to door slams). No audiometric data were included in this report. These levels are significantly higher than the levels reported by Morrison (1993) and Micheal (1995a) for new trucks in the U.S.

There are several possible explanations for the higher levels reported by van den Heever and Roets (1996). Perhaps new trucks in South Africa are simply noisier than new trucks in the U.S. (neither of the South African brands are commonly driven in the U.S.). Only one brand of U.S. truck was studied in the Morrison and Micheal studies, and perhaps this brand is unusually quiet as compared to other trucks manufactured in the U.S. Finally, the measurements here were made using dosimeters worn for an entire work shift, whereas in the Morrison and Micheal studies they were made using real-time analyzers for 5-minute periods under ideal conditions. Perhaps these ideal conditions are not representative of the actual noise exposure in trucks, and the dosimeter-based measurements under real-world conditions offer a more accurate picture of actual exposure. Also, the South African safety standard is more strict than the OSHA standard, and the dosimeters integrated more of the noise than would a dosimeter set to reflect the OSHA standard.

Table 2.1 summarizes some of the measurements taken in truck cabs in road tests from the 1970's to the 1990's. Graphically, it can be seen from Figure 2.1 that truck-cab noise has dramatically decreased over the past twenty-five years. There are also anecdotal reports that as the trucks have become quieter, drivers are hearing noises they could not hear in the past (rattles and squeaks).

TABLE 2.1. Truck Cab Noise Measurements for On-Road Tests from Several Studies over a 25-Year Period

Study (year)	**Model years (# of trucks)**	**SPL in dBA**
Emme (1970) *	1960's era (4)	>100 dBA (75% of time)
Morrison & Clarke (1972) **	1960's era (16)	85-90 dBA
Hessel, Heck, & McJilton (1982) **, ***, ****	1972-1977 (8)	74-87 dBA
Reif & Moore (1983) **	1968-1978 (58)	85-90 dBA
Morrison (1993) ****	1993 (4)	<80 dBA
Micheal (1995a) ****	1995 (6)	<80 dBA
van den Heever & Roets (1996) ***	1995 (2)	>84 dBA

* - measurement device not specified; ** - sound level meter; *** - dosimeter; **** - spectrum analyzer

Note: The conditions under which the truck-cab noise was measured varied considerably from study to study.

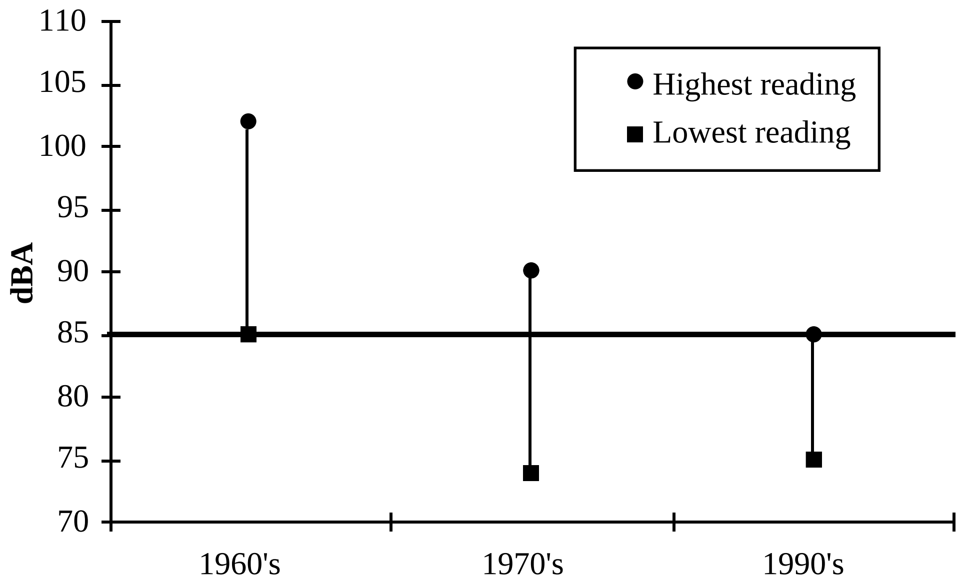

FIGURE 2.1. Trend for Interior Truck-Cab Noise from the 1960's to the 1990's
(OSHA Action Level of 85 dBA is represented by the solid line.)

Note: These SPLs were measured with various types of sound measuring equipment, and the conditions under which the truck-cab noise was measured also varied considerably from study to study. However, all measurements reflect L_{eq} or time-weighted averages, and do not represent maximum levels.

Noise exposure and hearing loss among truck drivers. If the noise levels in truck cabs exceed the OSHA action level, it would be expected that truck drivers would experience noise-induced hearing loss. Even when the noise levels began to drop in the 1970's, truck drivers were often exposed more than 8 hours per day, and often more than 10 hours per day (especially in driving with a partner, in which case the noise exposure is almost continuous, 24 hours a day). Even today, the effect of this continuous exposure has not been studied. Henderson and Burg (1973) measured the hearing levels of 128 truck drivers who averaged 15.4 years of truck driving experience. Average hearing loss for the better ear over the 500-8000 Hz range was 18.1 dB, with greater loss at the higher frequencies (they reported the findings in terms of hearing loss rather than hearing level, but did not indicate the comparison standard used to compute the loss). A notch indicative of noise-induced hearing loss occurred at the 6000 Hz frequency. All drivers possessed valid licenses, and so met the FHWA requirements for hearing. Henderson and Burg noted that the range of hearing loss was very narrow in their sample.

Nerbonne and Accardi (1975) also reported on noise-induced hearing loss in a truck driving population. A group of 81 drivers was found to have no factor other than exposure to truck driving which would contribute to a hearing loss (e.g., drivers over age 45 were excluded to eliminate the effect of presbycusis). Drivers were divided into three groups based on years of driving experience and their hearing levels examined. Mean hearing levels for the right ear were consistently better than for the left ear (the left ear is exposed to greater noise levels when the window is open), and there was a notch at 4000 Hz, indicative of noise-induced hearing loss. The main finding was a steady decrease in hearing level with driving experience. A comparison with data on non-noise exposed men showed that these truck drivers had a hearing threshold level 10-20 dB higher than their non-noise-exposed counterparts in the 250-4000 Hz range. The hearing level for men with 1-7 years driving experience was approximately 11.5 dBHL; for men with 8-14 years of driving experience, the mean hearing level was approximately 13 dBHL; for drivers with over 15 years experience, the mean hearing level was 16.2 dBHL. The authors concluded that noise exposure in trucks of that era was severe enough to cause some loss of hearing.

Kam (1980) studied the noise exposure levels of 20 truck drivers. Conditions for exposure measurement were kept as constant as possible across subjects. Pre- and post-workday audiograms were given to the drivers, and a 7.2 dB temporary threshold shift was reported, with a notch at 4000 Hz. The main finding from this study was that driving with the windows up reduced the sound level by about 20 dB as compared to driving with the windows completely down. The authors recommended the simple step of driving with the windows up to reduce noise exposure and possible hearing damage. In a health survey of professional drivers in Scandinavia, Backman (1983) reported that 13% of 633 male drivers had a hearing defect (arithmetic average of hearing level in the worse ear of more than 20 dBHL for 500, 1000, and 2000 Hz). Hearing defects increased for the older age groups, as would be expected from either noise-induced hearing loss or presbycusis. No conclusions were reached as to whether the hearing defects were caused by driving exposure.

Dufresne, Alleyne, and Reesal (1988) explored asymmetric hearing loss in truck drivers. The data for ten truck drivers showed a decidedly lower hearing level for the left ear (approximately 11 dB worse than the right ear). Over both ears, the average threshold level over the 250-8000 Hz range was approximately 46 dBHL. The left and right ears had a very similar profile, and both ears showed a notch at 4000 Hz. These drivers were taken from a sample of persons applying for Workers Compensation for job-related hearing loss, and thus could not be considered representative of truck drivers in general. The authors made no attempt to determine whether the loss was truly due to truck driving exposure, but noted that the 4000 Hz notch and the similar profiles of both ears, with the left ear being worse than the right, were indicative of a noise-induced hearing loss in which the left ear was more noise exposed than the right. They pointed out that this was consistent with driving a truck with the windows down and having the noise of rushing air closer to the left ear.

Lee, Chung, and Gannon (1981) approached the problem from a different direction. They studied speech discrimination in four groups of participants in different speech-to-noise ratios using recorded bus noise. Three of the groups were hearing-impaired, and they were tested both with and without their hearing aids. Two of the groups of hearing-impaired subjects would have passed the FHWA hearing requirements (they were hearing-impaired, but their main loss was at frequencies higher than 2000 Hz). All of the groups of hearing-impaired subjects performed significantly worse on the speech discrimination tests than did the normal hearing group. Use of a hearing aid did not improve the discrimination rate, and in some cases, it was significantly degraded by use of a hearing aid. One finding of this study was that frequencies above 2000 Hz are important for speech discrimination in noise and the authors recommended that the hearing requirements for commercial vehicle operators in Canada be modified to include some frequencies above 2000 Hz. Another finding was that those individuals with a severe hearing loss (worse than 40 dBHL averaged over 500, 1000, and 2000 Hz) performed significantly worse than the groups with mild or moderate hearing loss. This finding adds some support for keeping the 40 dB hearing level requirement for truck drivers. This study is relevant to the present study, because if speech communication is found to be an important task for truck drivers, then frequencies higher than 2000 Hz should also be tested; also, perhaps the use of hearing aids should not be mandated (if they do not improve speech discrimination in the noise levels found in trucks). The usefulness of hearing aids for detecting and discriminating other types of sounds, such as emergency vehicle sirens, in truck or bus noise has not been determined.

These studies indicate that there is evidence that noise exposure in truck cabs is related to hearing loss. Studies from other environments support this conclusion. For example, Fitzpatrick (1988) found that hearing loss among Army helicopter pilots was a function of noise exposure as measured by flying hours. However, most of the drivers in the studies reported here drove a large part of their careers in the older, noisier trucks representative of the 1960's through mid-1970's. To the authors' knowledge, there is no comprehensive audiometric database available in the open literature for drivers who have driven only the newer, quieter trucks. If the noise doses are truly as low as reported by Morrison (1993) and Micheal (1995a), then drivers who began their careers around 1980 or later would be expected to have very little noise-induced hearing loss caused by truck-cab noise. One important consideration is that many of the noise measurements reported have been taken under standardized conditions, usually either stationary or at a constant speed. In many cases, ideal conditions were used (windows up, accessories off). In some of the reports, noise doses were calculated based on these idealized conditions. Where noise doses were measured using dosimetry under real-world conditions, the noise doses reported have been much higher. This is logical, since the dosimeter is worn continuously during the driving shift. Dosimetry measurements of current U.S. trucks are needed to determine the true noise dose of truck drivers, and to determine whether this dose is high enough to cause a noise-induced hearing loss.

Forced-Whisper Test

The fact that the FHWA currently allows use of the forced-whisper test to test truck driver hearing implies that speech communication is essential for truck driving. In fact, the FHWA hearing requirements fall squarely into a Class B hearing level, which is defined as a slight handicap, average hearing threshold level in the better ear for 500, 1000, and 2000 Hz of not more than 40 dBHL, and which implies difficulty only with faint speech (Alpiner, 1987b). If difficulty with faint speech correlates with the exact hearing requirements for truck drivers, it seems logical that a forced-whisper test would be a reliable indicator of hearing handicap. As will be seen, however, the results of forced-whisper tests are extremely variable between testers, and may not correlate well with pure-tone audiometry. The forced-whisper test falls into a category of tests referred to as free-field voice tests (which also include tests using conversational voices and loud voices). Many of the forced-whisper experiments were performed as part of larger free-field voice experiments. Much of the research cited here will refer to the "free-field voice test," but where possible, the results pertaining specifically to the forced-whisper portion of the experiment will be separated from the overall results.

In 1953, King reported that free-field voice tests were widely used by otologists in routine practice (King, 1953). Two tests were described; one used a conversational voice and the other a whispered voice. King defined a whisper as the speech produced on expiration without the vibration of the vocal cords. A forced whisper, which is normally used, is produced by whispering with the residual air after expiration. However, King reported that there was some misunderstanding with the term "forced whisper," and that one book had described it as the whisper resulting "when one partially fills one's lungs and whispers as forcibly as possible." Advantages to the whisper test include elimination of pitch and tone variations and elimination of intensity variation within a single otologist's voice. Weaknesses of the test included lack of standardization, the inability to control the pitch and intensity of a whisper, the lack of control of ambient noise, and the different acoustic properties of test rooms.

Standardization variables include standardizing the definition of a forced whisper, the distance from the examiner to the patient, the masking technique to be used for the ear not being tested, and the test vocabulary to be used. For the purpose of his experiment, King used a whisper produced by residual air after expiration, a 20-foot distance, shielding of the patient's eyes to prevent lip-reading, tragal masking of the untested ear by an assistant (tragal masking involves using a finger to rub the tragus of the ear to create a masking sound), and a mix of meaningful words of high and low frequency of use. King then performed an experiment to test the variability between different examiners and within individual examiners. Four otologists who routinely performed the forced-whisper test participated in the study. The loudness of the whispers was measured in terms of the relative sound pressure level at 2.5 feet from the speaker. Within otologists, differences between the loudest word and the quietest word whispered ranged from 10-16 dB. Between otologists, the variability was just as great, ranging from 32-44 dB for the quietest word and 46-60 dB for the loudest word. Overall, words uttered in a forced whisper ranged from 32-60 dB. It was not reported whether the participants were male or female, but it can be assumed that all were male, given the date of this report.

Ambient noise also varies greatly from environment to environment. King measured the ambient noise in several rooms used for measuring hearing with the forced-whisper test, and reported levels ranging from 24-65 dB, with peaks in some of the rooms of over 70 dB. Acoustic properties of rooms were also variable, with time-to-decay of sound pressure level varying according to the furnishings and the wall, ceiling, and floor treatments used. At twenty feet, there was about a 7 dB difference in sound pressure level between two rooms of the same size with different wall, ceiling, and floor treatments.

All of the concerns raised by King in 1953 are still valid today regarding the FHWA hearing requirements. For drivers being examined using the forced-whisper method, the law requires detection of a forced-whispered voice at not less than 5 feet in the better ear, with or without the use of a hearing aid (Federal Highway Administration, 1994). No definition of forced whisper is given, and no standard is referenced [for audiometric measurements, ANSI Z24.5-1951 (now ANSI S3.6-1969) is provided for calibration purposes]. A specified distance between medical examiner and patient is given, but no provision is made for masking of the driver's eyes or untested ear. If tragal masking is to be used, then an assistant would be required due to the 5-foot distance between the medical examiner and patient, but this is not specified in the hearing requirement. The types of words to be tested are also not specified, and neither are the ambient noise and acoustic properties of the testing room. Given that most of these forced-whisper tests are occurring in a medical examiner's office during the biennial (every two years) DOT physical, variability is probably more pronounced than that described by King (1953). A wide variety of male and female medical examiners are performing the tests. These medical examiners are not typically audiologists, may have had no formal training on the forced-whisper procedure, and may even be using a procedure similar to that described by King (whisper as forcefully as possible). Masking of the patient's eyes and untested ear may or may not be performed. Different word lists may be used, or even a question, such as "How old are you?" may be used as the speech stimulus. This could lead to large differences between medical examiners, since sentences provide contextual clues that are not present in single words, digits, or letters. Ambient noise and acoustic properties of the examining rooms vary greatly depending on the size, furnishing, and room treatments. An experiment such as King's, performed today under real-world conditions, would probably reveal even greater variability in the intensity of the speech materials used in the forced-whisper test.

In an audiology text, Hinchcliffe (1981) mentioned the forced-whisper test and discussed the advantages and disadvantages of free-field voice tests. He concluded that many clinicians find such tests to be useful as screening tools despite their imprecision. In the case of the FHWA hearing requirement, the test is not being performed by audiometric clinicians, nor is it being used as a screening test. Instead, it is being used as a pass-fail test in the context of a physical examination. No mention is made of having the driver consult an audiologist upon failing the forced-whisper test (although one would hope that such a recommendation would be made, and that the medical examiner and driver would not rely upon the failure of the forced-whisper test to end a driver's career).

Swan and Browning (1985) reported on an experiment comparing the results of forced-whisper tests to audiometric tests. The authors evaluated 202 ears using the forced-whisper method; the experimenter (one of the authors) stood 2 feet behind the patient and whispered a combination of three letters and digits while masking the untested ear with tragal rubbing. When patients failed to repeat all three correctly, another three letter/digit combination was used. Patients were considered to have passed the test if they were able to repeat three of the possible six letters or digits correctly. The patient's hearing was then tested by audiometry at 500, 1000, and 2000 Hz. For patients with a hearing threshold level of 30 dBHL or less, the screening test produced a 13% false positive rate (13% of patients with a hearing level in this range had failed the forced-whisper test). For patients with a hearing level greater than 30 dBHL, the forced-whisper test was 100% accurate (all patients with hearing loss in this range had failed the forced-whisper test). The authors concluded that the forced-whisper test was a simple and effective screening methodology. But the study contained several flaws. The authors were the whisperers and were familiar with the forced-whisper technique. They did not specify whether the audiometry was performed manually or automatically, or if the audiometric test was performed blindly with regards to the results of the forced-whisper test. If the audiometry was performed manually, and the tester knew the results of the forced-whisper test, there was a potential for bias in the audiometric results. If the forced-whisper technique is to be demonstrated as an effective screening technique to be used by a wide variety of people, it needs to be validated using as the whisperers the same people who will be expected to use the technique in the field. Factors such as gender, age, and even the accent of the whisperer might affect the reliability of this tool as a screening technique. The possibility of inter-whisperer variability was not even addressed by Swan and Browning (1985).

In another text on clinical audiology, Browning (1986) recommended monaural free-field voice testing as a method of detecting hearing impairments and assessing the relative severity of the impairment. Detailed instructions are given for performing these tests. The patient must correctly repeat back 50% of what is spoken, and the voice level and distance from the ear at which this occurs is used to determine the level of hearing impairment. A whispered voice, a conversational voice, and a loud voice are presented at

2 feet and then 6 inches from the ear. Increasing loudness is commonly used, and the ear not being tested is masked by tragal rubbing. The test terminates when the patient answers 50% correctly at a particular voice and distance level. For the whisper test, Browning (1986) provided good evidence that individuals with thresholds greater than 30 dBHL will be unable to hear a whispered voice at 2 feet. This does not help much with the FHWA hearing requirement, except that if a true forced whisper is used at a distance of 5 feet, then it can be assumed that the driver who hears the forced whisper has a threshold less than 30 dBHL. No data were presented for distances greater than 2 feet. Browning's text is geared towards audiologists, however, and not toward family physicians or other medical examiners. Browning mentioned the difficulty of producing consistent whisper levels across audiologists, and within the same audiologist at different times, but concluded that the method is reliable in the hands of reasonably experienced audiologists. Since the FHWA does not require the hearing portion of the physical examination to be performed by an audiologist, no assumption can be made about the reliability of the tests being performed currently. Browning's guidelines indicate that if the FHWA were to retain the forced-whisper option, then a more standardized procedure such as that outlined in his textbook should be specified, along with the requirement that such a test be performed by an audiologist.

Macphee, Crowther, and McAlpine (1988) studied the use of a whispered voice test as a screening methodology for hearing impairment in elderly patients being admitted to a geriatric unit. Sixty-two patients were tested at their bedside by a geriatrician and an otolaryngologist (each patient received two independent tests). Tragal masking was used, and the tester stood behind the patient to occlude vision. A forced-whisper test at 6 inches and 2 feet and a conversational voice test at 6 inches and 2 feet were performed for each ear. The patient was required to repeat a set of three random numbers presented at each of these conditions. Pure tone audiometry was then performed blindly with regards to the voice test results. Hearing impairment for the purposes of this study was defined as a mean threshold at 500, 1000, and 2000 Hz greater than 30 dBHL. The voice testing between the two testers was concordant in 88% of all ears, and in 100% of all ears able to hear the whispered voice at 2 feet. Of the 38 ears that could hear a whispered voice at 2 feet, none had a hearing threshold greater than 30 dBHL. Of the 86 remaining ears that could not detect the forced whisper at 2 feet, only 7 had hearing thresholds less than 30 dBHL. All of the ears unable to detect the forced whisper at 6 inches were classified as hearing-impaired.

The conclusion drawn from this study was that the forced-whisper test is a reliable screening test for elderly patients who may benefit from the use of a hearing aid. The authors cited the excellent concordance of the geriatrician and otolaryngologist as evidence that non-specialist examiners can produce reliable results using this methodology. But several aspects of this study limit its generalizability to the present research. For example, the training of the geriatrician was not specified with regard to the forced-whisper test (either medical school training, or training for the purposes of this study). The vocal intensity levels of the two testers was not measured or reported, nor were the ambient noise levels of the bedside environments reported. Since only two testers were used, inter-tester variability was minimized. Most importantly, this test was being used as a screening test to determine whether elderly patients should be referred to an audiologist for possible fitting of a hearing aid. There was no public safety concern as to whether these elderly patients did or did not have a hearing loss, as might be the case with truck drivers. The main concern was with ease of communication for these elderly patients.

Browning, Swan, and Chew (1989) compared the results of free-field voice tests with audiometric testing. One of two clinicians tested 101 patients using the free-field voice test prior to performing any other examinations. Patients were required to repeat test words spoken in a forced whisper, conversational voice, or a loud voice at distances of 2 feet and 6 inches from the test ear. Test words were a random combination of three digits and letters, and the threshold was defined as the voice level and distance for which patients repeated two of three test words correctly for at least two tests. No differences were found between the clinicians in terms of the comparison of the free-field voice tests to the audiometric test, although the vocal intensity levels of the clinicians were not measured. The forced-whisper test at 2 feet had a sensitivity of 100% (no false negatives) and a specificity of 84% (16% false positives) for detecting hearing thresholds greater than 35 dBHL, where hearing level was measured as an arithmetic average of the hearing thresholds at 500, 1000, and 2000 Hz (the same three frequencies specified by the FHWA when audiometry is performed). Based on these results, the authors recommend this method for use by non-specialists to screen for hearing impairment. However, this study has a serious flaw in that the two clinicians who performed the forced-whisper test were the first two authors of the paper, and so were reporting on themselves as subjects to a certain degree. Both had performed prior research of this sort, and were familiar with the definition of and procedure for performing free-field voice tests. Before recommending this procedure to non-specialists, it would seem wise to perform a similar experiment with a number of non-specialists who have minimal training in the procedure, and compare those results with results of audiometric tests. The results of such an experiment might be quite different from those reported here.

Uhlmann, Rees, Psaty, and Duckert (1989) reported on the reliability and specificity of a number of auditory screening tests for older adults. One test used was the whisper test (the phrase "forced whisper" was never used, nor was "whisper" defined). A spoken voice test was also used. Patients received a battery of these screening tests from either an otolaryngologist or one of two audiologists. An audiometric test was then conducted in a separate session. Altogether, 62 ears were tested in this manner. To test for inter-observer reliability, the ears that were tested by the otolaryngologist were retested by one of the two audiologists. The whispered voice at 8 inches was found to be the most promising screening test, with 90% sensitivity (10% false negatives) and 78% specificity (22% false positives). The inter-observer reliability was also found to be good (0.67). The correlation of the whisper test to the audiometric test was significant at 7 frequencies between 250 and 8000 Hz. The spoken voice was found to be not sensitive enough to be used for screening. The authors noted that the reliability and validity of these tests may differ when performed by primary care physicians in primary care settings. They also noted that by giving the tests in a battery, knowledge of the results of earlier tests may have biased the results of later tests. They concluded that screening tests such as the whisper test need to be tested in clinical trials before they can be proved effective. Problems with the study not noted by the authors include the failure to define the whisper technique used, the failure to perform inter-observer reliability tests with different observers, and the fact that the patients were familiarized with the 15 word list before the test. Although Uhlmann et al. (1989) explored the reliability of the whisper test more fully than many other authors, this study does not answer the question of whether this test is reliable enough to be used as a widespread screening technique for hearing impairment.

Dempster and MacKenzie (1992) reported on the use of free-field voice tests in screening children for hearing impairment. They found that a forced-whisper test at 2 feet failed to detect one-fifth of the children with a hearing threshold greater than 25 dBHL (arithmetically averaged across 500, 1000, and 2000 Hz). This was in an ideal testing environment similar to those described in other studies. The authors noted that in non-specialist situations the results would probably be even poorer. They concluded that the free-field voice test was not an adequate screening device for children.

Carabellese, Appollonio, Rozzini, Bianchetti, Frisoni, Frattola, and Trabucchi (1993) used a free-field voice test to screen an elderly population for hearing impairment as part of a study on the effect of sensory impairment on the quality of life. The tester stood approximately 20 inches behind the person to be tested, and used a forced whisper. Three numbers were used as the testing words. The forced-whisper test was the only auditory screening that was performed (no audiometric measurements were taken). If participants wore hearing aids, they were allowed to use the aids while being tested. The authors mentioned that the forced-whisper test suffers from a lack of accuracy, and that problems have been reported with inter- and intra-observer variability, but concluded that the test was valid, reliable, and simple enough for use as a screening test. Despite the fact that they cited many of the studies reviewed here, the authors did not use a standardized version of the test, so voice intensity and distance were not varied. Also, the approximate hearing level corresponding to the forced-whisper test was not defined. This study did not evaluate the effectiveness of the forced-whisper test as a screening technique, but rather assumed it was, and therefore used the test to define a hearing impairment.

Although several of these studies produced results indicating that the forced-whisper test is a valid and reliable screening test when only one or two people perform the whispers, there has been no research indicating the validity and reliability of this method when used by many different clinicians in the field. For the truck driver DOT physical examinations, the tests are being performed by thousands of different medical examiners. There are no data on how reliable and valid this test might be when performed under such conditions. Pure tone audiometry has become the standard method for describing auditory sensitivity (Yantis, 1994). Many articles and textbooks of audiology do not even mention the forced-whisper test as a possible screening test for hearing impairment, and consequently, do not provide instructions for how to perform such a test (Alpiner, 1987a; Bess and Humes, 1990; Katz and Ivey, 1994; Morrill, 1986). When speech audiometry is mentioned in these texts, only audiometry using recorded voices presented through an audiometer is recommended (Bess and Humes, 1990; Katz and Ivey, 1994; Penrod, 1994). Free field voice tests or whisper tests are not presented as an option for obtaining speech reception thresholds. Other texts specifically recommend against using live voices for speech audiometry, since the voice production of the speaker can vary significantly between speakers and within the same speaker (Hood, 1981). If a live voice is to be used for speech audiometry, a monitored live voice is recommended, not a free-field voice (Penrod, 1994).

The Federal Aviation Administration (FAA) has recently moved away from use of a whisper test, specified merely as the " … ability to hear the whispered voice at a distance of at least 20 feet, 8 feet or 3 feet (depending on the class of medical certificate sought) with each ear separately" [Federal Aviation Administration, 1996b; Sections 67.13(c), 67.15(c), and 67.17(c)]. Alternatively, applicants for a first-class medical certificate could be tested by audiometry, by " … demonstrating a hearing acuity of at least 50 percent of normal in each ear throughout the effective speech and radio range as shown by a standard audiometer" [Federal Aviation Administration, 1996b; Section 67.13(c)]. The wording of this FAA requirement was even less specific than the current FHWA regulation. The new FAA regulations require applicants for any of the three classes of medical certificates to pass one of three more specific hearing tests:

1. Demonstrate an ability to hear an average conversational voice in a quiet room, using both ears, at a distance of 6 feet from the examiner, with the back turned to the examiner.
2. Demonstrate an acceptable understanding of speech as determined by audiometric speech discrimination testing to a score of at least 70 percent obtained in one ear or in a sound field environment.
3. Provide acceptable results of pure tone audiometric testing of unaided hearing acuity according to the following table of worst acceptable thresholds, using the calibration standards of the American National Standards Institute, 1969:

Frequency (Hz)	**Better ear (dBHL)**	**Poorer ear (dBHL)**
500	35	35
1000	30	50
2000	30	50
3000	40	60

[Federal Aviation Administration, 1996a; Sections 67.105(a), 67.205(a), and 67.305(a)].

In changing the regulations, the FAA made the choice of tests more consistent with standard audiometric practice, and codified those tests which more accurately assess communication ability. The free-field voice test recommended is still somewhat vague in methodology, and subject to all of the problems discussed earlier in connection with free-field voice tests (standardization of a conversational voice, identifying the vocabulary to be used, and defining a "quiet room"). The other two tests are well-defined enough that they should provide an accurate and objective test of pilots' communication ability.

For identification of those with hearing impairment, the American-Speech-Language Hearing Association (1985) recommends the use of pure-tone audiometry and if possible, acoustic immitance screening to detect middle ear problems. If only pure-tone audiometry is used, the frequencies to be tested include 500, 1000, 2000, and 4000 Hz. The use of speech materials is specifically discouraged, because procedures using speech materials fail to identify individuals with hearing impairment in the frequency range above 500 Hz (American Speech-Language-Hearing Association, 1985). In a draft of guidelines for identifying hearing impairment for adults and the elderly, the American Speech-Language-Hearing Association (1989) recommended using case history, visual inspection, and a pure-tone screening test. No mention was made of using voice tests as a screening technique. One possible underlying reason for the overwhelming recommendation of audiometry for auditory screening and hearing impairment measurement is that OSHA requires an audiometric screening program for all workplaces for which the noise level exceeds the action level of 85 dBA for an 8-hour work shift (OSHA, 1990). OSHA mandates that a precise hearing history be kept for all employees exposed to these levels, and the free-field voice tests do not allow for this level of precision. Audiometers have become more widely available, and there are many people who are trained in their use, so the practice of less precise and objective methods has come into disfavor.

Research Direction

The preceding discussion of literature makes it clear that there are many questions remaining to be answered about the FHWA truck driver hearing requirement. To date, a definitive, empirical study of this issue has not been performed. The present research attempts to answer many of the questions concerning truck driver hearing, noise exposure, and hearing-critical driving tasks. A unified experimental method was developed to tie together as many of these questions as possible. Figure 2.2 identifies many of the questions that have been raised about the FHWA hearing requirement and outlines the research methods used to answer these questions in the research program described herein. Each of the experimental methods and results is fully described in the following sections of this report.

Is the FHWA Hearing Requirement Necessary?

Elements of Research Project Designed to Answer This Question:

Are there truck driving tasks which require the use of hearing?
Literature review, subject matter expert interviews.

If so, which tasks are they? Task analysis (questionnaires, job observation).

How noisy are trucks? Spectral analysis of truck noise.

What is the noise dose being received by truck drivers? Dosimetry.

Is the truck driving task damaging drivers' hearing? Audiometric examinations.

What is the hearing level for a sample of truck drivers? Audiometric examinations.

At what level do the drivers need to be able to hear to detect the sounds associated with these tasks? Audibility predictions.

At what level should the hearing requirement be set? Audibility predictions.

Is the forced whisper test a viable test of hearing? Literature review, forced whisper experiments.

FIGURE 2.2. Research Elements Designed to Answer Specific Questions about the FHWA Hearing Requirement (questions followed by elements)

CHAPTER 3: TASK ANALYSIS

Introduction

Task analysis is a formal human factors methodology for describing and analyzing the performance demands on the human element of a system (Drury, Paramore, Cott, Grey, and Corlett, 1987). A task analysis describes the performance required by humans so that human and machine may operate optimally in a unified system. One use of task analysis is to determine whether humans are capable of performing the specified task. In this study, the objectives were to first identify whether any commercial truck driving tasks require the use of hearing, and if so, to determine whether truck driving is a hearing-critical job based on the criticality of those tasks.

Drury et al. (1987) described the four phases of task analysis, and these were followed for this study in order to provide a systematic means of data collection. The first phase of a task analysis is system discrimination and analysis, in which the intent is preliminary task identification. For this study, a system functional analysis was used to identify major truck driving functions. These functions were then broken down into tasks which may require the use of hearing. The next step was to produce a task description task list. The task list was verified by outside experts (other transportation researchers and truck drivers). This led to a detailed task description. The third phase was descriptive data collection, which can be done by documentation review, questionnaire survey, interviews, and observation. All of these methods were used in the task analysis, and the final result is a comprehensive list of all truck driving tasks for which hearing is required. The final phase is to determine whether the task analysis can be used for other types of analysis. The truck driving task analysis should prove useful in developing personnel selection criteria and measures, or in revising the current FHWA hearing standards. Though there are several other references for task analytic procedures (see Fleishman and Quaintance, 1984, for a comprehensive review of task description), the Drury et al. (1987) method was used here, as it provides a more systematic approach.

Background and Prior Task Analytic Research

Several researchers over the years have performed task analyses of commercial vehicle operations. These will be briefly reviewed here so that task analytic methods used by others may be explored. Haddon (1972) was interested in classifying motor vehicle crashes. He developed a matrix with event phases on one axis (pre-event, event, post-event, and results), and factors along the other axis (human, vehicle and equipment, and environment). The event phases he developed could be used to provide a rough description of driving phases, such as pre-trip activities, driving activities, and post-trip activities. However, this breakdown was not really detailed enough or function-specific enough to be appropriate for the current study.

Henderson and Burg (1973), in a study of vision and audition in truck and bus driving, performed the first real task analysis of truck driving tasks requiring hearing. They elected to break tasks into several categories based on the nature and purpose of the stimuli and on the environmental conditions surrounding the driver. The stimuli categories were warning/attention getting, feedback, identifiable other sounds, and non-identifiable other sounds. The environmental conditions were high noise, low noise, and quiet. A 3x4 matrix was then constructed with these categories along the axes. Tasks could then be fitted into this matrix, and assigned a rating of 1-3, in which a 3 represented those behaviors that absolutely depend on detection of auditory stimuli. Criticality scores and importance ratings could then be obtained for each task. The authors followed up the design of this conceptual framework with interviews and discussions with truck and bus drivers. At the time this study was conducted, the noise inside truck cabs routinely exceeded 100 dBA (Emme, 1970), and external noises were difficult to hear during operation. Most drivers reported that external sounds would be difficult to hear, but that they listened for engine sounds, both to know when to shift and to detect malfunctions. Henderson and Burg (1973) then performed job observations of the truck driving task to confirm previous results. No external sounds were observed during this observation phase of the task analysis. Though a task analysis was undertaken, no specific tasks were listed for the categories described. Henderson and Burg (1973) provided the first framework for classifying hearing tasks in commercial vehicle operations, but did not apparently collect or classify any tasks.

Moe, Kelley, and Farlow (1973) conducted an extensive truck and bus driver task analysis. Task descriptions developed for passenger car drivers were extended to bus and truck drivers by interviews conducted with drivers. The preliminary outline of tasks was then reviewed by 6 experts, resulting in a reorganized and rewritten task list. The tasks were organized into 6 functional categories: preoperative procedures, routine driving tasks, special driving tasks, driving emergencies, hooking up doubles (specific to truck driving), and carrying passengers (specific to bus driving). A total of 383 truck driving tasks were identified (note that in this task analysis, all tasks were considered, not just those involving hearing). For the truck driving tasks, 37 experts then each evaluated 75 randomly selected task statements according to high, medium, or low criticality. Items were assigned a rating of 1-5 X's according to the criticality ratings, with 5 X's being most critical. This method resulted in the most complete truck driving task analysis to date, and has been used by other researchers approaching this problem.

Rabideau and Young (1973) studied safety critical behaviors during truck driving by means of formal task analysis. Since the focus was on safety critical behaviors, only those that occurred during the route driving section were included, so many tasks such as pre-trip inspections were not considered. The development of the task list was not well-described. Rather than dividing the tasks by function, the authors decided to use information categories. Information categories included: task identification, display, required decisions, controls, control activation, control action, and feedback. Characteristic errors were also identified. This research was considered incomplete and was preliminary to further work done by Young and Rabideau (1974) in specifying a model for truck-cab design. In this later paper, the task analysis process is described in more detail. The completed task list was validated by interviews with truck drivers and by activity sampling (randomly spaced segments of job observation). Despite the fairly thorough description of the process used to conduct the task analysis, the full task analysis was not presented. The examples provided are not complete enough to be of use, but the methodology used, especially in validating the results of the task analysis, appears to be consistent with that outlined in Drury et al. (1987).

Boyar, Couts, Joshi, and Klein (1985) performed an analysis of preventable accidents in which they attempted to assign causes to such accidents. The study was focused on motor carriers, and so is very applicable to the present research. Since this study was geared toward preventable accidents, most of the causation codes were assigned to the "driver" category, rather than the vehicle, highway system, environment, or miscellaneous categories. For example, weather itself was never considered to be the cause for an accident. Rather, the driver was considered to have failed to allow for adverse weather conditions. Of the 36 driver fault categories, none of them directly referred to the failure of the driver to hear a signal. For example, if a truck was hit by a train due to failure to hear the train whistle, it would probably be assigned to the "inattentive," "failure to obey traffic control signal," "failure to obey traffic sign," "reckless," or "careless/erratic driving" categories of driver fault. Although this report provides an excellent description of the types and causes of commercial motor vehicle accidents, it adds nothing to the literature on those driver tasks requiring the use of hearing. Had categories for "failure to hear warning signal" and "failure to hear mechanical problem" been included, this report could have proved very useful in determining the importance of hearing to safe driving.

Michon (1985) reviewed a number of models of driver behavior, including task analysis. He made a persuasive argument for going away from behavioral models of driver behavior and embracing cognitive models of driver behavior. Michon (1985) viewed a thorough, systematic task analysis as the first step toward either model, though he did not perform a driving task analysis or provide detail on how to perform one. Based on the driving task under consideration, he gave examples of productions, in the form of if-then statements, which the driver must complete in order to achieve the goal. Michon's work rests on the assumption that a detailed task analysis for the task of interest is already in hand. This approach would be useful for analyzing safety critical tasks in more detail and for specifying the cognitive processes required for task completion, but provides no clear guidance on task analysis.

For the work performed in this study, the task analysis performed by Micheal (1995b) is probably most relevant. One reason is that the work is recent, and also includes Intelligent Transportation Systems (ITS) considerations. Micheal (1995) was also interested in auditory and visual driving tasks, and prepared his task analysis with these perceptual modes in mind. Finally, his work was centered around commercial vehicles, making it very relevant to the present study. His method involved a literature review, including much of the same research cited above. The Moe et al. (1973) study was felt to be the most complete truck driving task analysis available, and so he used that task list, but Micheal limited the task list by including only those tasks for which hearing or vision could be deemed to play a role. Micheal kept the criticality ratings used by Moe et al. (1-5, with 5 being most critical). Finally, he presented the list to several truck driving experts, and asked them to update it, keeping in mind the ITS and other new technology that exists in many truck cabs today. The result was an updated list of truck driving tasks which require the use of hearing or vision, and which are ranked by criticality to safe driving. This list was used as a starting point for the current study. Micheal's final task list is broken down into several functional categories, including primary task, display monitoring, control activation, shifting/double clutching, steering, braking, and comfort-related tasks.

Several researchers have approached the development of ITS technologies and designs from a task analytic point of view. Stene (1991) performed a task analysis of intersections for the PROMETHEUS project. Stene used a task classification in which driving is divided into strategic tasks, navigation tasks, road tasks, traffic tasks, and maneuvering tasks. Tasks are placed into the correct category, and then driver information needs can be specified for each task. Driver workload can then be predicted or lessened for complex situations. Lee and Raby (1994) proposed using a network analysis to guide the task analysis of ITS systems. Network analysis allows a quantitative analysis of the information flows that link system functions, and this can be used to guide the task analysis for complex systems. Traditional methods of task analysis consider each task separately, with little consideration given to the interactions among system components or tasks. Network analysis is said to allow for analysis of these interactions. Alm, Sviden, and Waern (1994) proposed using a cognitive integration of ITS functions based on the driver's tasks. They hypothesized that failure to do this will result in driver distraction when interfacing with ITS systems while driving. None of these three studies provides much guidance for developing a commercial vehicle task analysis, but they serve as a reminder that ITS systems which may become more integrated into the truck cab of the future will likely result in a different level of workload for the driver (higher or lower, depending on how well the system is designed), and that ITS tasks may interact with other driving tasks in complex ways.

The most recent work on the task analysis of truck driving tasks is that published by the National Highway Traffic Safety Administration (1996b; 1996c). This work provides an excellent review of task analysis literature (most of which has been described above), and includes many different types of task listings. This work was not published until after the subject matter expert interviews were completed and the task analysis questionnaire prepared, but a review of all of the task analyses contained within the report indicate that no new tasks would have been added to the interview questions or questionnaires. Since the overall purpose of the National Highway Traffic Safety Administration (1996a) study was to assess how new, ITS equipment might interfere with or add to driver workload, most of the task analysis was slanted away from hearing and audition and towards visual tasks. Although this study is a useful guide to task analysis in commercial vehicle operations, it is of limited utility for the current study.

Methods

As mentioned above, the task analysis presented herein follows the methodology described by Drury et al. (1987). The four phases are:

1. System description and analysis
2. Task description task list
3. Descriptive data collection
4. Applications analysis

Each phase is described, along with the method used to accomplish the work. Drury et al. describe this approach as being top-down, meaning that more detail is obtained at each level than the one before.

System description and analysis. The system of interest is the commercial vehicle and the driver, especially those parts of the vehicle/driver interface that may require the use of hearing. For this study, the first division of truck driving tasks has been made with the decision to focus on those tasks requiring hearing. This implies that there are other truck driving tasks which require the use of vision, touch, and smell (although perhaps not taste). Hearing, or audition, is a perceptual sense. The human auditory system is always open and ready to receive input, except in the cases of deafness, masking noise, or the use of hearing protection devices. When the auditory system is in this open phase, it is constantly receiving input, even when the person may not be aware of noise or signals. In the case of a truck cab, there is noise present whenever the engine is turned on and running.

In identifying those tasks requiring the use of hearing or audition, the focus is upon noises that may occur before and during the driving task, and many of these noises may be unpredictable in time (mechanical noises, for instance). The use of a timeline approach (such as an operational sequence diagram) to task analysis is not possible under these conditions, since the noises or signals of interest may occur at any time. Although the driving task itself is continuous, no two segments of driving are alike, unlike an assembly line, where the same actions are repeated over and over. The presence of other vehicles, adverse weather, and different loads ensure that the truck driving task is constantly changing. The dynamic nature of truck driving thus rules out the use of a sequential task description format and subtask analysis. These constraints dictate that the task analysis take the form of a task list, not constrained in time, but rather broken down into multiple functional categories. The system functional analysis was thus used as the next task breakdown (all system functions which may require the use of hearing were identified).

Several functional classification schemes have been used in previous truck driving task analyses. One way to categorize tasks is to break them down into perceptions, discriminations, decisions, control actions, and communications (Drury et al., 1987). Three of these categories have the potential to require hearing: perceptions (was the noise heard?), discriminations (what was the noise heard?), and communications (listening to another person). In reviewing the task analysis performed by Micheal, those tasks he classified as auditory seemed to fit reasonably into a modification of the categories suggested by Drury et al. Truck driving hearing tasks can thus be placed into the following functional categories:

1. Communication
2. Detection of mechanical problems (perception and discrimination)
3. Detection of internal warning signals (perception and discrimination)
4. Detection of external warning signals (perception and discrimination)
5. Primary driving task noises (perception and discrimination of noises other than those in functional categories 2-4, above)

This is the functional classification scheme used for the remainder of the task analysis.

Task description task list. The second step was the development of a task description task list. Tasks identified by Micheal (1995b) as having an auditory component were used as a starting point for the rest of the task analysis procedures. These tasks are listed in Table 3.1, divided into the functional categories listed above. The tasks listed for external warning signals were not present in the Micheal (1995b) task analysis, but were added based on some of the other task analyses reviewed.

Descriptive data collection: Documentation review. As described by Drury et al. (1987), there are four methods of obtaining the information needed to complete the detailed task analysis. All four methods were used in this study. The first method is documentation review. The literature already cited was used to flesh out the task list shown in Table 3.1. The task list was then shown to several transportation researchers, who were asked to add more items to the list. Four researchers, all considered to be veteran scientists in human factors aspects of transportation, were used to review this version of the task list.

TABLE 3.1. Task List of Commercial Vehicle Tasks Requiring the Use of Hearing (adapted from Micheal, 1995b)

Category	**Task description**
Primary driving task	Maintain required forward motion and path within posted speed limit Shift gears Accelerate Use clutch Use brakes
Communication	CB radio Cellular phone
Detection of mechanical problems	Air pressure Sliding 5th wheel Brakes
Detection of internal warning signals	Oil pressure Oil temperature Tachometer Fuel level Alarm clock Cellular phone
Detection of external warning signals	Emergency vehicle sirens Other tractor-trailer horns Automobile horns Train whistles Backup warning alarm of other vehicles

Descriptive data collection: Structured interviews of subject matter experts. The second method of data collection is to conduct interviews with subject matter experts. The task list resulting from the documentation review, Table 3.1, was used as a starting point to form a set of interview questions, and the interview questions were again reviewed by the same four transportation researchers to check for inconsistencies or omissions. Personal interviews were then conducted with 11 subject matter experts (SMEs) in the area of commercial vehicle operations. A complete description of the interview process used can be found in Chapter 4 of this document. Transcriptions of each interview were reviewed for additional tasks to add to the questionnaire. When interviews began producing little fresh information (as happened after 10 or so interviews), the interview phase of data collection was suspended. All of the interviews were compiled into a master document for easy reference, and this master document was then used to compile a questionnaire (presented as Appendix A) for wide distribution. As can be seen from the task lists contained in the final questionnaire, the tasks originally delineated by Micheal (1995b) were greatly expanded upon and presented at a much higher level of detail as a result of the refinement process described above. A complete report of the SME interviews can be found in Lee, Robinson, and Casali (1996), a Virginia Tech technical report prepared as part of the FHWA research program.

Descriptive data collection: Job observations. In order to verify that the task list compiled by the interviews was complete, ten job observations were made. Job observations consisted of the experimenter riding in a truck for several hours with a driver performing his normal routine. It was expected that these job observations would be sufficient to verify the results of the interviews. The driver's permission was obtained through use of an informed consent form. The experimenter attempted to be aware of all noises that were heard during the driving task. Related tasks, such as pre-trip inspections, making deliveries, and use of a weigh station were also observed. The experimenter took notes during the observation. After completion of the job observation, the driver was thanked for his participation. The experimenter notes were then used to verify the results of the interviews. Only two unusual noises were observed during the approximately 160 hours of job observations. One ambulance siren was heard briefly, and a rattling noise was heard which turned out to be a loose side mirror which was subsequently tightened. Both of these types of noises were already included in the questionnaires at this point, so the job observations did not result in any new tasks being added.

Descriptive data collection: Questionnaires. Based on the original task list, the interview text, the interview results, and the job observations, a questionnaire was prepared listing all tasks identified as having an auditory component. The questionnaire was designed to obtain information about the importance of each task to safe driving, and the importance of hearing to completion of each task. This questionnaire was reviewed by several transportation researchers, truck drivers, and truck mechanics. After review and revision, it was distributed to 80 truck drivers. Booths at rest areas and truck stops were used for questionnaire distribution. The driver was compensated for his or her time after returning the questionnaire (drivers could choose between a souvenir and monetary compensation). The questionnaire was designed to take no more than an average of 30 minutes to complete, and actual completion time ranged between 20 and 25 minutes.

The final form of the questionnaire is shown in Appendix A. An example of the task analysis format is shown in Table 3.2. Each task analysis item was rated on a five-point scale for importance of the task to safe driving, as well as the importance of hearing to completion of the task. In this way, tasks could be ranked, and those with the largest hearing component that are also safety-critical could be determined. The questionnaire was designed using the procedures recommended by Bourque and Fielder (1995) to assure that questions were non-biased and that a high response rate was achieved. Quantitative data analysis of the completed questionnaires was possible, using the methods outlined in the data analysis section, below.

TABLE 3.2. Example of Questionnaire Format Used in Completing the Task Analysis

Please rate the importance of each of the following driving tasks to safe driving (Column 1), and then rate the importance of hearing to the completion of that task (Column 2), where 1 = Very Unimportant, 2 = Unimportant, 3 = Unsure, 4 = Important, and 5 = Very Important. Circle the choice that best corresponds to your opinion.

	Column 1 Importance of task to safe driving	**Column 2** Importance of hearing to completion of task
Pre-trip inspection	1 2 3 4 5	1 2 3 4 5
Braking	1 2 3 4 5	1 2 3 4 5
Backing up to a loading dock	1 2 3 4 5	1 2 3 4 5
Merging into traffic	1 2 3 4 5	1 2 3 4 5
Detection of engine problems	1 2 3 4 5	1 2 3 4 5
Communicating with the dispatcher	1 2 3 4 5	1 2 3 4 5

Data Analysis

The questionnaire was evaluated on three levels. The first level of evaluation was to determine the adequacy of the sample population and the sampling procedure. The sample should be representative of the population of interest, and should be chosen in a random manner (Weisberg and Bowen, 1977). In order to determine whether the final sample of 80 was representative of the truck driver population, comparisons were attempted for certain population characteristics. Driver characteristics that might influence the answers given in the questionnaire are age, gender, and years of driving experience. If a random sampling technique is used, the sample should match the population on the distribution of these characteristics within a few percentage points. In order to perform a truly random sample, however, all members of the population of interest need to be known and listed (Weisberg and Bowen, 1977), and each has to have an equal chance of being selected, and this was not possible for truck drivers. Instead, the sampling technique approached randomness with questionnaires being distributed at truck stops and rest areas (a sample of opportunity). After all questionnaires were returned, the population characteristics for gender were obtained through census data and the sample was compared to the population on this characteristic (population data on age and years of experience were not available). Comparing the percentage of female drivers in the sample (4%) to the percentage of female drivers in the overall truck driving population (6%), it appears that the sample is representative of the population, at least with respect to gender. Since no census data were available addressing age or years of experience, the only alternative was an examination of the descriptive statistics (mean, range, and standard deviation) for these variables. Based on this examination, the sample was judged to be representative of the population with respect to age and years of experience (see discussion in the Results section, below).

The next area of evaluation was the determination of the quality of the questionnaire. This was determined through validity and reliability testing (Litwin, 1995). If a questionnaire is well-constructed, following the guidelines set forth in such sources as Weisberg and Bowen (1977) and Bourque and Fielder (1995), it is more likely that the survey will be found to be reliable and valid. Face validity is present if the questionnaire appears (to the population of interest) to measure what it is supposed to measure. Content validity is present if a panel of experts agree that the questionnaire items seem sound. The overall construct tested by this questionnaire was truck driver opinion on the importance of hearing to safe truck driving. The face validity and content validity of the questionnaire were tested during the subject matter expert interviews, by review of the questionnaire by other researchers, and by using specific experts to evaluate certain parts of the questionnaire (such as using mechanics for the mechanical failure questions). Other types of validity, such as criterion and construct validity, were not measured during the course of this experiment, since there are no other instruments available which are designed to measure the same construct. Other instruments would be needed so that the instruments could be compared to measure these types of validity.

For the purposes of this experiment, reliability was examined using the technique described by Litwin (1995). Internal consistency is the measure of how well several items in a survey vary together in a sample. It is applied to groups of items that are thought to measure different aspects of the same concept. In this questionnaire, since the task analysis items had a numerical component, and their corresponding items in the mechanical failures section had an alphabetic code, the actual internal consistency was reported by percentage rather than as a coefficient alpha.

The final phase of data analysis was the actual reporting of the answers to the questionnaire. These were analyzed as outlined in Weisberg and Bowen (1977). First, the statistics for each variable are reported in terms of means, standard deviations, and criterion matching. Relationships between groups of items were then explored by analyzing differences in distributions and means.

Results

The first level of evaluation was to determine the adequacy of the sample population and the sampling procedure**.** The sampling technique approached randomness, with drivers electing to fill out the questionnaire after reading a poster at a rest area or truck stop. Twenty of the drivers were solicited at a rest area on a north/south interstate highway in the eastern U.S., while the other 60 drivers were obtained at a truck stop right at the intersection of east/west and north/south interstate highways. It was hoped that this sampling technique would allow drivers from all parts of the country to participate in the study. The only demographic statistic for which comparison data was available was gender. In 1990 (Equal Employment Opportunity Commission, 1990), 6% of truck drivers were female, while for this questionnaire, 4% of respondents were female (77 males and 3 females filled out the questionnaires). The gender representation was thus fairly close to the population statistic. Despite a comprehensive search of several databases, no comparison data were found for age or years of experience. The age variable seemed fairly well-distributed, with a mean of 42.2 years, a range of 21-64 years, and a standard deviation of 9.95 years. Likewise, the years of experience variable also seemed well-distributed, with a mean of 14.2 years, a range of 0-40 years, and a standard deviation of 10.22 years. There were 2 trainees among the respondents, as well as one driver who had recently retired. Overall, the drivers who responded to the questionnaire were fairly representative of truck drivers nationwide.

Internal consistency is the measure of how well several items in a survey vary together in a sample. In this questionnaire, most of the related items could not be compared directly, as one question had a numeric answer and the corresponding question had an alphabetic answer. For example, in the task analysis section, the driver would be asked to rate the importance of hearing a mechanical problem on a 5-point scale. In the mechanical problems section, the driver would be asked how they detected the same mechanical problem (such as by vision or hearing). Thus the consistency was simply tallied, i.e., how many drivers gave consistent answers to the same questions presented in different ways? There were a total of 7 question pairs such as this distributed throughout the questionnaire, and each will be discussed.

The first question pair had to do with loudness and noise exposure. Near the beginning of the questionnaire, drivers were asked whether they thought it was loud in their trucks, and at the end of the questionnaire, they were asked whether they were concerned with their noise exposure in the truck. Only 52 of the 80 drivers answered these 2 questions the same way (65% consistent, $r = 0.344$). The trend was for drivers to report that they did not think their trucks were loud (beginning of survey), but to say that they were concerned with their noise exposure in the truck by the end of the survey. One plausible explanation for this result is that by the time drivers had answered many questions about noise and hearing, their opinion had shifted towards thinking their trucks were louder.

There were four question pairs dealing with mechanical problems. For detection of low oil, 31 drivers gave consistent answers between the task analysis and mechanical problems sections (39% consistent). For detection of high engine temperature, 29 drivers responded consistently in the two sections (36% consistent). For a tire blowout, 62 drivers were consistent (78% consistency), while for a load shift, 30 drivers were consistent (38% consistency). Another question pair dealt with trains approaching a crossing. For these questions, 48 drivers gave consistent answers (60% consistency). For emergency vehicle detection, 55 drivers gave consistent responses (69% consistency). Internal consistency varied considerably, which can probably be attributed to the way these questions were written and positioned within the questionnaire.

A further check of internal consistency was made with drivers' responses to the first two questions (is hearing important for the safe operation of commercial vehicles; is hearing necessary for the safe operation of commercial vehicles) as compared to their mean hearing importance ratings in the task analysis section of the questionnaire. Drivers who answered that hearing was both important *and* necessary had a mean hearing importance rating over all tasks of 4.05 out of 5 (N = 72). Drivers who answered no to one or both of these questions had a mean hearing importance rating of 3.49 (N = 8). So drivers appeared to be consistent in that if they first expressed the opinion that hearing was either not important or not necessary for the safe operation of commercial vehicles, they followed this opinion up by underrating the importance of hearing to specific driving tasks by 14%.

The questionnaire data are presented in full as Appendix B. The task analysis questions were subjected to a power analysis which demonstrated 95% confidence that all of the sample means were within +/- 10% of the population mean. For developing the final list of hearing-critical tasks, two criteria were used. First, a task was not considered to be driving-critical unless over 50% of the drivers classified it as either "important " or "very important." All of the tasks in the questionnaire met this criterion, due to the extensive SME interviews which went into the questionnaire and the expert reviews of the questionnaire as it was being written and revised. The next criterion was that a task was not considered hearing-critical unless over 50% of the drivers said that hearing was either "important " or "very important" to the completion of the task. Three of the tasks failed to meet this criterion (detection of fluid problems, detection of a car approaching from behind, and detection of high gearbox temperature). The final list of hearing-critical tasks, broken down by functional categories, is shown in Table 3.3. A further breakdown was possible for mechanical problems, due to the extensive mechanical problems section of the questionnaire. For these, hearing was said to be critical to detection of the mechanical problem if drivers responded that hearing was the first or second most common way of detecting that problem. Only 24 of 50 mechanical problems met this criterion, and they are presented in Table 3.4. A total of 44 critical driving incidents involving hearing were self-reported by 33 drivers, and these fell into 8 categories: blown out tires (9 incidents reported); engine noises, external mechanical noises (8 incidents reported); air leaks, hiss (6 incidents reported); CB or live voice warning of accident or other situation (6 incidents reported); emergency vehicles, sirens (5 incidents reported); railroad crossings, train whistles (4 incidents reported); automobile or truck horns (4 incidents reported); and load shifts (2 incidents reported). A full description of critical incidents is given in Appendix B.

Discussion

The quality of questionnaire completion was high. Despite the length of the questionnaire, drivers took their time and filled them out completely. This was evidenced by the fact that 33 drivers (41%) took the time to answer the question about critical incidents, which required a self-formulated answer. Approximately 10% of the drivers who passed by the "advertisement" poster filled out a questionnaire. Many drivers expressed an interest in participating, but were unable to do so because of time or schedule constraints. Only one driver expressed a negative opinion of the questionnaire after completing it, and his comment was simply that the questionnaire was too long. Although the internal consistency was not as high as had been hoped, there was a high level of agreement about the task analysis answers, as evidenced by the fact that for all but three of the questions, over 50% of the drivers rated the task importance and hearing importance as a 4 or 5 (important or very important). There were many other valuable sections of the questionnaire which are not directly relevant to the task analysis (sections on hearing loss, noisy hobbies and occupations, and truck accessories, for example). These have been analyzed and provide valuable input into other areas of this report. Overall, the questionnaire provided the first detailed task analysis of CVO tasks which are hearing-critical. *Based on the number of commercial driving tasks identified as hearing-critical, and on the number of critical incidents reported, a serious argument can be made that commercial truck driving should be classified as a hearing-critical job.*

Applications analysis. The task descriptive data collected during the previous three stages of task analysis (system description and analysis, task description task list, and descriptive data collection) can also be used for a variety of further types of analysis (Drury et al., 1987). For this research, one of the goals is to establish whether the current FHWA hearing requirements should be modified. Since tasks were identified which are both safety-critical and require the use of hearing, then some criterion for CVO hearing will need to be determined. This will lead to personnel selection criteria and measures, as described by Drury et al. (1987). With input from the task analysis, other elements of the overall research effort were used to determine a hearing criterion.

TABLE 3.3 Final List of Hearing-Critical CVO Driving Tasks

Routine driving tasks:
Pre-trip inspection
Maneuvering in light city traffic
Maneuvering in heavy city traffic
Maneuvering in light highway traffic
Maneuvering in heavy highway traffic
Maneuvering in light rural traffic
Upshifting
Downshifting
Detecting missed gears
Turning
Braking
Accelerating
Passing another vehicle
Being passed by another vehicle
Parking
Emergency stopping
Backing up to a loading dock
Going through a weigh station (while listening for non-verbal signals)
Entering and exiting limited access highways, including weigh stations, rest stops, and on/off ramps
Merging into traffic
Negotiating upgrades
Negotiating downgrades
Communication:
Making deliveries
Backing up to a loading dock
Weigh station communications
Communicating with the dispatcher
Listening to the CB radio, radio, or tape deck
Communicating with other drivers on the CB

TABLE 3.3. (continued) Final List of Hearing-Critical CVO Driving Tasks

Detection of mechanical problems:

- Tire blowout
- Other tire/wheel problems
- Pre-trip inspections
- Engine
- Transmission/drivetrain
- Suspension
- Air pressure problems
- Problem with trailer
- Load shift

Detection of internal (inside cab) warning signals:

- Low oil pressure
- High oil temperature
- Low water
- Low air pressure
- Engine temperature

Detection of external (outside cab) warning signals:

- Detection of approaching trains
- Detection of emergency vehicles
- Detection of automobile horns
- Detection of truck horns
- Detection of a car in the blind spot
- Detection of a car coming up on the **left** side
- Detection of a car coming up on the **right** side
- Detection of pedestrians, animals, and other unmarked road hazards
- Detection of rumble strips
- Detection of lane deviation
- Detection of lane edge bumps

TABLE 3.4. Final List of Hearing-Critical CVO Mechanical Problems

Engine

- Adjustment or tune-up needed
- Bad injector
- Problem with turbocharger
- Loose, worn, or broken belts
- Engine temperature high
- Problem with water pump

Drive train

- Clutch problem
- Transmission problem
- Drive line, drive shaft
- Universal joint
- Differential problem
- Axle problem

Brakes

- None

Air system

- Total loss of air pressure
- Slow leak in air lines or fittings
- Compressor problem
- Air tank problem
- Bad gauge
- Bad warning buzzer
- Air pressure too high

Tires and wheels

- Tire blowout
- Bad wheel bearing

Trailer

- Air coupling problem
- Problem with Reefer (refrigeration) unit

Electrical system

- Problem with alternator

CHAPTER 4: OPERATOR/SUBJECT MATTER EXPERT SURVEY

Introduction

The second method of data collection for task analysis (as described in Chapter 3 of this report) is to conduct interviews with subject matter experts (SMEs). The task list which resulted from the documentation review described in Chapter 3 was used to form a set of interview questions, and the interview questions were again reviewed by the same four transportation researchers to check for inconsistencies or omissions. Personal interviews were then conducted with 11 SMEs in the area of commercial vehicle operations. All of the SMEs were male, due to the high prevalence of males in this occupation. An attempt was made to obtain a mix of SMEs in regard to driving experience, current job, and vehicle type. The SME panel included drivers with long-haul, intermediate, and short-haul experience, dispatchers with driving experience, driving instructors, and driving supervisors. No SME had less than 7 years of driving experience. The SMEs had experience with several types of trucks, including straight trucks, tractor-trailers (conventional, refrigerated, and tandem), tank trucks, and flatbeds. The overall mix of the SME panel thus provided a balance of experiences to ensure that tasks particular to one type of truck or one type of driving were not neglected.

Procedures

Potential SMEs were contacted by phone and asked for an appointment. Interviews were conducted at the SME's place of employment. The SME was asked to read a description of the interview process, and to sign an informed consent form upon agreeing to participate. The SME was asked for permission to audiotape the interview to reduce the interview time. All of the participants agreed to this. Audiotaping had additional advantages in that it enabled the entire interview process to proceed more smoothly, as well as allowing the interviewer to focus on asking the questions and make more frequent eye contact with the SME being interviewed. A personal stereo cassette recorder was used to make the recordings. The interview questions were reviewed by the interviewer several times before the first interview so that the process was smooth, without the need for frequent referrals to the interview text. At the beginning of the interview, and at several points during the interview, the SME was reassured that the tape was completely confidential, and was encouraged to freely express his opinion on all questions. Each interview took from 40 minutes to 1 hour. At the completion of the interview the SME was thanked for participating and compensated for his time.

Analysis

After the interview was complete, the tape was copy-protected and transcribed. After each tape was transcribed, it was reviewed for additional tasks to add to the questionnaire. When interviews began producing little fresh information (as happened after 10 or so interviews), the interview phase of data collection was suspended. All of the interviews were compiled into a master document for easy reference, and this master document was then used to compile a questionnaire for wide distribution. A complete report of the SME interviews including all eleven transcriptions can be found in Lee, Robinson, and Casali (1996).

Results

Summary of responses. Table 4.1 provides demographic statistics of the drivers interviewed. Following this table is a summary of the interview responses. For each question, the number of drivers responding in each way is reported. Due to the nature of the interview, questions were sometimes inadvertently omitted from an interview, and this is reported where it occurred. Reading this summary provides background information on the opinions of subject matter experts as regards truck driver hearing. For some questions, there seems to be a consensus answer to the question, while in other cases, the SMEs were divided as to their opinions.

TABLE 4.1. Demographic Attributes of Subject Matter Experts

Attribute	Statistic
Number of drivers interviewed	11 (all were male)
Age, mean	51.4 years
Age, range	28 - 76 years
Driving experience, mean	21.5 years
Driving experience, range	7 - 55 years
Related experience, mean	5.3 years
Miles driven per week, mean	2,372
Miles per week, range	40 - 5,500

Background information:

- **Age -** mean age, 51.4 years
- **Gender -** 11 subject matter experts, all were male
- **Truck driving experience, in years -** mean experience, 21.5 years
    - **Miles driven per week -** mean miles per week, 2,372
- **Related experience, in years (driving instructor, dispatcher, supervisor) -** mean related experience, 5.3 years

1. Start with some general questions:

- **Do you feel that hearing is important for the safe operation of commercial vehicles?**
  "Yes" response by all eleven SMEs.
- **Why or why not?**
  All eleven SMEs cited the need to be aware of what is going on in the environment around the truck, and several mentioned the need to be aware of what was going on within the truck, such as mechanical problems.
- **If you feel it is important, do you feel that it is also necessary?**
  "Yes" response by eight SMEs; three gave qualified answers, saying that there may be exceptions to the rule, that drivers may be at a disadvantage without good hearing, or that they could not answer fairly, since they were not deaf.

- **Do you feel that it is loud *inside* your truck (or trucks in general, if you are no longer driving)?**

  "No" response by one SME; ten gave qualified answers, saying that either some trucks are loud and some are not, or that trucks used to be loud, but that they are much quieter now. There was a general consensus that new trucks being built today are not loud.
- **Do you use the radio, CB, or other audio devices while driving? Which devices do you use? What percent of time are they in use?**

  "No" response by two SMEs who did not have radios available. The other nine SMEs used the radio, CB, tape deck, or all three. For most of the drivers, at least one device was on the majority of the time. The AM/FM radio was used the most, followed by the CB and the tape deck.
- **Do you drive with the windows down? What percent of time do you drive with the windows down, by season?**

  All of the drivers reported driving with the windows down some of the time, especially in trucks with no air conditioning. The percentage of time that the window was down varied by season. Other reasons for driving with the window down were to get fresh air and to pull cigarette smoke out of the cab. Only one driver mentioned (in a negative way) the rushing sound associated with having the window down.
- **Are there other sources of noise in your truck?**

  "No" response by nine SMEs; two SMEs stated that older trucks get rattles.
- **Air brakes, Jake brake?**

  Four drivers reported that their trucks did not have Jake brakes. The seven who had trucks with Jake brakes stated that they made some noise, but not much. One driver indicated that the Jake brakes got louder as the truck got older.
- **Are you concerned about your noise exposure in the truck?**

  "No" response by nine SMEs; two SMEs indicated that they used to be concerned in the older trucks, and one of these indicated that he got earaches from the older trucks. Neither of these drivers tried using hearing protection devices to protect themselves from the noise.

2. <u>Ask some specific questions about tasks:</u>

- **Can you name specific examples of driving tasks for which you feel hearing is important or necessary, or for which you feel that hearing increases driving safety?**

Common answers were: to hear other vehicles, to hear car horns, to listen for mechanical problems, to hear train whistles, to hear emergency vehicles, to communicate, and to hear forklifts and conveyors.

3. Depending on their answer to number 2, prompt them with specific scenarios (memory joggers):

- **What about for pre-trip inspections?**
  Two drivers said hearing was not important for this task. Two drivers said they listen to the horn to make sure it works. Seven drivers mentioned the need to listen for air leaks while doing a pre-trip inspection of the braking system.
- **City driving?**
  Ten SMEs said that hearing was important in city driving due to the large volume of traffic and the increased number of emergency vehicles. Several mentioned the need to turn down the radio and crack the window when entering a congested area. One driver said hearing was not important when driving in the city.
- **Highway driving?**
  Eight SMEs said that hearing was important in this situation, mainly in listening for other vehicles when passing or being passed. One driver said that vision is more important than hearing in this situation [Authors' note: Vision is generally acknowledged to be more important than hearing in almost every driving situation]. The question was inadvertently left out in two interviews.
- **Rural driving?**
  "Yes" response by seven SMEs, and a "no" response by four SMEs.
- **Shifting? Upshifting vs. downshifting? Missed gears?**
  Two drivers reported that they did not use hearing to shift (they had automatic transmissions or used the tachometer), and nine reported that they did (they listened to the level of the r.p.m.'s to tell them when to shift). Other sounds mentioned were the sound of an incorrectly performed double clutch and the sound of a clutch slipping.
- **Steering?**
  Six SMEs reported that mechanical problems with the steering could be detected with hearing. Several mentioned a "popping" or "cracking" noise that occurs when the steering is about to go out. One mentioned that you could hear when the steering fluid was getting low. Five drivers said hearing was not important for steering.

- **Turning?**
  Eight drivers indicated that at least some degree of hearing was necessary when turning, to listen for mechanical problems, pedestrians, cars that are in the blind spot, or vehicles that do not realize the turning radius required by these trucks. Three drivers said hearing was not important in turning.
- **Braking?**
  Six SMEs indicated that hearing was important in listening for air leaks and other brake problems while five indicated that hearing is not necessary in braking (some of them indicated that gauges provide the necessary information).
- **Accelerating?**
  Six drivers stressed the need to listen to the r.p.m.'s when accelerating, while five drivers said that hearing is not important in acceleration.
- **Passing? Being passed?**
  Nine drivers indicated that hearing was important for these tasks, to hear the horns of other vehicles, especially when they are in the blind spot. Some drivers mentioned that they could sometimes hear mechanical problems with their own or another vehicle more clearly in a passing situation. One driver said that hearing is not necessary in a passing situation, and the question was inadvertently omitted from one interview.
- **Parking?**
  Six SMEs said that hearing is important in parking, primarily to hear other vehicles. Five said that it was not important.
- **Emergency stopping?**
  Seven drivers indicated that they would be listening for things such as other vehicles, mechanical problems, or load shifts when making an emergency stop. Four drivers indicated that in an emergency stop, they would be stopping no matter what kind of noise they heard, so hearing was not important.
- **Tire blowout?**
  All eleven SMEs stated that this was very important. Some indicated that they could also feel a blowout, some said they could only hear it, and others said that it depended on which axle the tire was on.
- **Making deliveries?**
  All eleven SMEs stated that hearing played some role when making deliveries. The reasons given included communication of delivery instructions, listening for back-up alarms, and listening for a person who may be helping the driver back in.

- **Backing into a loading dock?**
  Eight drivers stated that hearing was important for backing into a loading dock, mostly for listening for directions from a helper. Three drivers said that it wasn't important in this situation. Most drivers said that they preferred to back themselves in (no help), and most indicated that voice and hand signals are both used when help is given.
- **Weigh stations?**
  Ten SMEs indicated that they use their hearing when going through a weigh station. These drivers stated that weigh stations have intercoms through which the scale master can tell the driver to pull around back and bring his paperwork inside (if overloaded). One driver said that the scale personnel assume you can hear them, and another driver said that he always rolled the windows down so he could hear the intercom if necessary. One driver who drove local routes stated that he did not use a weigh station.
- **Communicating with the dispatcher?**
  Several of the drivers indicated that many companies have gone to a computer and satellite based dispatching system, so that the driver does not have to talk directly to a dispatcher any more. Eight drivers said that there are still times when the driver needs to talk to a dispatcher by phone; some companies use cellular phones extensively, and small companies rely more on normal phone communications. Two drivers indicated that because of the technology, hearing was not necessary in communicating with the dispatcher, and the question was inadvertently left out of one interview.
- **Listening to the CB radio or a radio or tape deck?**
  Seven drivers indicated that they used the CB for safety purposes at times, and that hearing was required to use the CB. One driver indicated that he did not use the CB, and the other radio was not important to driving. The question was inadvertently left out of three interviews.
- **Entering and exiting limited access highways, including weigh stations, rest stops, and on/off ramps?**
  Eight SMEs indicated that they used hearing in this situation to listen for vehicles in the blind spot and for the sound of the load shifting. Three SMEs indicated that hearing was not important in this situation.
- **Detection of pedestrians, animals, and other unmarked road hazards?**
  "Yes" response by six SMEs, especially to hear pedestrians; "no" response by five SMEs.

- **Driving in wind, rain, snow, and sleet?**
  Six drivers indicated that hearing was important in this situation, to hear the wind level or to hear the intensity of the rain or sleet. Five drivers indicated that hearing was not used in this situation.
- **Detection of increased trailer sway?**
  Eight drivers responded that trailer sway was detected mostly by feeling, with some visual aspects. Three drivers indicated that this question was not applicable to them because of the type of truck they drove.
- **Negotiating upgrades and downgrades?**
  Five drivers indicated that they use hearing to listen for engine sounds in this situation, to know when to shift. Five drivers said they do not use their hearing in this situation. The question was inadvertently omitted for one driver.
- **What about using the trailer hand brake for downgrades?**
  After the first two SMEs indicated that this practice was forbidden, the question was dropped from the interview.
- **Detection of mechanical problems?**
  Nine drivers stated that hearing was very important in the detection of mechanical problems, while one driver stated that all mechanical problems should be caught during the pre-trip inspection. The question was inadvertently omitted for one driver.
- **Detection of approaching trains?**
  Nine SMEs said that hearing is important in detecting trains, while one said that it is only important in rural areas. One driver said that hearing is not important for this task.
- **Are trains detected by whistles, horns, or bells?**
  Seven of these drivers indicated that the train's horn or whistle is detected from a further distance than are the crossing bells, two indicated that the bells were easier to detect, and one said that both were audible.
- **Detection of emergency vehicles?**
  Eight of the SMEs indicated that hearing is very important in detecting emergency vehicles. Two said that vision is more important in this situation. One SME said that sirens can be heard more easily in the city, but that on the Interstate, emergency vehicles are more easily seen first. Of the drivers who said that hearing was important for this task, most said that they had no trouble hearing sirens within their truck cabs.

- **Detection of automobile horns?**
  All eleven SMEs indicated that hearing is important in being able to detect automobile horns. Several of them expressed the opinion that the horns are often hard to hear, and may need to be made more powerful.
- **Detection of truck horns?**
  Ten of the drivers indicated that the air horn present on most commercial vehicles is important to hear, and that they have no problem hearing them. One driver indicated that the horns are difficult to hear. Several drivers mentioned that the air horn is a way for drivers to communicate when the CB radio is not being used for some reason.
- **What about when a car is in your blind spot?**
  Nine drivers said that it is important to be able to hear when a car in the blind spot blows its horn, with one of these drivers expressing the opinion that there should not be much of a blind spot anymore with all of the mirrors available. One driver said that hearing is not important in this situation. Most of the drivers said that they thought most automobile drivers assumed that truck drivers would be able to hear their horns. The question was inadvertently left out of one interview.
- **Use of a radar detector?**
  The first five drivers indicated that this question made them uncomfortable, so it was dropped from later interviews. These five indicated that when such devices were legal, there was both a light and a buzzer associated with a detection.

4. Ask questions to get information about the detection of mechanical problems. Wait for answer to first question, then use memory joggers:

- **In your experience, what is the most common method for detecting mechanical problems?**
  Six of the SMEs gave no direct response to this question. Three said that hearing was the most important sense in detecting mechanical problems, and two said that all of the senses are important, it just depends on the problem.
- **Vibration?**
  Problems with the tires, wheel bearings, universal joint, drive shaft, front-end alignment, engine mounting bolt, brakes, and engine.
- **Smell?**
  Brakes overheating or on fire, electrical shorts, oil dripping on the engine, wheel bearing overheating, tire overheating, belt problems, and gear box overheating.

- **Mechanical noise?**
  Problems with the rods, the transmission, the gears, air leak, the engine knocking, rear axle, reefer unit, power steering, low oil, broken fan belt, engine problems, drive shaft problems, and fuel injector.
- **Warning lights on the dashboard?**
  Low oil pressure, low water, engine temperature, low air pressure, battery charge, anti-lock braking system. Apparently there are a lot of warning lights available, and some trucks have more than others. The most common appear to be the first four listed.
- **Audible warning alarms?**
  Most of the drivers indicated that for all of the warning lights on their trucks, there is also an accompanying buzzer.
- **Differing handling characteristics?**
  Problem with steering, tie rod end going bad, load shift, low air pressure, bad roads, tire getting low, tire blowout, front-end alignment, tractor and trailer alignment, or a broken spring.
- **What problems or problem types are detectable by what methods?**
  This question did not generate any useful responses, and was dropped after the first few interviews.
- **If sound is used as a cue for any of these problems, are there corresponding non-auditory cues which could be detected by hearing-impaired drivers?**
  No useful responses generated.
- **If not, can you think of ways to design displays to alert hearing-impaired drivers to problems? For example, what about a display that adjusted to the current sound level, and could be adjusted to compensate for mildly hearing impaired drivers?**
  No useful responses generated.
- **Do you detect center lane deviations by the sound of the marker bumps, or by the vibration they cause? Do you detect edge of road lane deviations by the sound of the edge marker bumps, or by the vibration they cause?**
  These questions were combined in the later interviews, since the answer seemed to be the same in the first few interviews. The answers were evenly divided, with four SMEs stating that they could feel and hear these markers equally, four stating that they could feel these markers more than hear them, and three stating that they could hear them more than feel them.

5. Ask questions that will prompt thought about ITS technology. Wait for answer to first question, then use memory joggers:

- **Have you heard of IVHS, ITS, or smart road technology?**
  Only two drivers responded in a positive manner to these questions. The other nine had either not heard of these terms, or had only heard of them in terms of a local project of which they had very little concrete knowledge. Due to the lack of good responses, the list below was mentioned to all SMEs, but only to get their opinion on the potential usefulness of each.
- **What kinds of things come to mind when you hear these terms?**
  The two drivers who had heard of ITS indicated that they had envisioned things such as a heads-up map on the windshield, sensors in the highway to detect speeders, computers at weigh stations that could detect more than just weight (things such as the number of hours driven), computers with maps, and a coordinated traffic flow system (traffic lights coordinated with sensors in the road).
- **Do you think that any of the following new technologies will either increase or decrease the importance of hearing in the driving task: (Note: Only the answers of those SMEs who voiced an opinion about a technology are presented below)**
- **Motorist service information?**
  Five SMEs has an opinion on this technology. One thought it would be too distracting and three thought it might be somewhat useful, although all four of these mentioned that the information is available in book form presently. One SME indicated that his company already presented this information via computer.
- **Real time routing information?**
  Two SMEs thought this information would be useful if presented on a screen, either as map or text instructions, while two SMEs thought it would be useful if presented auditorially (they thought a map would be too distracting). One of the SMEs indicated that his company already provided text-based routing information via computer.
- **Trip recorders?**
  Five SMEs were aware of these devices. Analog versions have been around for decades. They indicated that these devices have a bad reputation with the drivers, and that the driver does not interact with the system (the company reads it when the driver returns).

- **Crash recorders?**

  Four drivers thought that a crash recorder similar to that used by airlines would be a useful new technology. One driver thought it should contain voice data as well as mechanical information.
- **On-board diagnostic equipment?**

  Four of the drivers thought it would be good to have more detailed diagnostic information about the mechanical condition of their trucks.
- **Weigh-in-motion?**

  Six of the drivers were aware of systems in existence now, with bypass lanes in some weigh stations. One driver indicated that it would be desirable not to have to leave the Interstate to get weighed, so that traffic would not back up.
- **Automated toll collection?**

  Three drivers thought that this technology would be good, or were aware of such systems in use now.
- **Collision avoidance systems?**

  Seven SMEs were either aware of current collision avoidance systems, or thought that they would be a good idea. Of the SMEs who had experienced these systems, they were of the opinion that they worked well.
- **Fitness-for-duty testing?**

  Three drivers thought this would be a good idea. Most drivers made some association between the DOT physical and random drug screens and this technology, and did not seem to grasp the purpose of fitness-for-duty testing.
- **For each technology, ask what role they think hearing will play in the use of the technology.**

  Due to scarcity of knowledge about these technologies, this question was not asked.
- **For each technology, rate the importance of the technology to the driving task (Important, Unsure, Unimportant).**

  This question was not asked after the first two interviews for the reason cited above.
- **Would drivers be likely to disable the technology, if they could?**

  All eleven SMEs answered this question. Nine thought that drivers would be likely to disable the technology, especially if they perceived that it was interfering with their ability to make a living. Several SMEs knew of cases in which drivers had managed to disable some technology in the truck. Two SMEs thought that drivers would not be likely to disable these technologies.

6. Try to find out how they are more likely to detect train whistles, horns, and bells, emergency vehicles, sirens, and automobile horns.

- **How do you first detect the following events? Do you first hear it, see it, or detect it by some other means? Does detection method differ by time of day?**
  At this point three of the drivers indicated that they performed most of their driving in the daytime, and could not report on day/night differences.
- **Train approaching crossing?**
  Four SMEs indicated that sound was the most important method of detecting trains, regardless of circumstances. Three thought vision was most important, night or day. Four thought that it depended on the circumstances (day/night, city/rural area, environment).
- **Police car?**
  Seven SMEs thought that the method of detection varies by day/night, city/Interstate, etc. Two thought hearing is more important all the time, while two thought that vision is more important all the time.
- **Ambulance?**
  All eleven indicated that the method of detection is nearly the same for ambulances as for police cars.
- **Fire truck?**
  All eleven indicated that the method of detection is nearly the same for fire trucks as for police cars.
- **Automobile that is trying to get your attention?**
  Nine SMEs indicated that detection of an automobile trying to get your attention varies by city/Interstate, day/night, or the method being used by the automobile driver (flashing the lights versus blowing the horn). One SME indicated that vision is used at all times, and one SME indicated that hearing is used at all times.

7. Try to get some insight into the role of hearing in critical driving incidents:

- **Can you think of any particular examples in which you feel that hearing played an important role in a critical driving situation, either because you could not hear something, or because you did hear something? Describe each incident fully, including type of sound, time of day, type of truck being driven, weather, and traffic density. If possible, have them draw a sketch of each incident. Obtain the outcome of the incident.**
  Freely volunteered stories included: A driver heard a funny noise and pulled over to check it out. A valve stem had come out of one of his tires and the air was rushing

out. The driver felt the tire would have caught on fire if he had not heard the noise. Another driver reported coming upon a train track unexpectedly and hearing the train whistle at the last second. He was able to stop in time, but if he had not heard the whistle, he felt he would have been involved in an accident.

<u>Memory joggers (examples of critical incidents):</u>

- **Blown tire?**
  Ten of the eleven SMEs had experienced blown tires, and all ten indicated that they were able to hear the blowout before they felt it. Some of them mentioned that a tire that has blown out or gone flat can catch on fire if it is not detected and changed quickly. One SME had not experienced a blowout.
- **Load shift?**
  Seven drivers had experienced load shifts of one type or another. Of these, three reported that they had heard some noise associated with the shift, although all three indicated that feeling also played a role. Four drivers said that they only felt the shift, and did not hear anything.
- **Involvement in an accident?**
  Although several reported having had one or more accidents, none of the SMEs felt that the accidents were caused by a failure to hear something.
- **Avoidance of an accident?**
  Five drivers reported that they had avoided accidents due to hearing a noise such as an automobile horn, a train whistle, or a backup alarm. In addition, nearly all drivers had reported being alerted of a vehicle in their blind spot by a car horn (earlier in the interview).
- **Severe mechanical problems?**
  Five of the drivers reported having been alerted to severe mechanical problems by a noise. Problems included: bad wheel bearing, loose drive line, broken drive shaft, severe engine problems, and bad fuel pump.
- **Ambulance behind you that you didn't hear?**
  Four drivers reported having been startled by an ambulance that was behind them but that they did not hear. One of these four drivers reported being issued a ticket for failing to yield the right of way to an emergency vehicle that he did not hear.
- **Traffic violation?**
  The only one mentioned was the one cited above for failing to yield to an emergency vehicle.

- **Brake failure ?**

  No driver reported brake failure as a result of failure to hear, but one driver mentioned that he had caught minor air leaks by hearing them, and another mentioned that a buzzer warns the driver when the air is low, so hearing could play a role in preventing brake failures.
- **Skidding due to braking quickly?**

  No drivers reported any incidents of this type due to hearing or failure to hear.
- **Skidding due to fast cornering?**

  Same as above.

8. Hearing loss history

- **Do you have any hearing loss (also ask about other noise exposure, especially long-term occupations such as military service, mechanic, lumber industry and hobbies such as hunting)?**

  None of the drivers reported having a known hearing loss. Several were aware of other drivers who had hearing loss and were required to wear hearing aids while driving. Noisy hobbies surveyed included: attendance at car races, using a chainsaw, hunting, and officiating college basketball games. None of the SMEs reported wearing hearing protection devices while participating in noisy hobbies. Noisy occupations and work environments included: military, police officer, planer operator in a sawmill, brick yard, textile plant, jack hammer operator, granite quarry, and oil fields. Most SMEs reported having worn hearing protection devices as required when working in noisy occupations.

- **What type of truck do you drive (have you driven)? What were the years and makes of these trucks? If more than one type, how many years did you drive each type? Try to estimate the percentage, if possible.**

  Drivers did not do well at estimating the percentage of time and number of years that different trucks were driven. The following is a list of the specific truck models and model years mentioned by the drivers:

  > Freightliner - 1994, 1995, 1996; International - 1972, 1995, 1996; White - 1939, 1955, 1984; Mack - 1968, 1990; Peterbilt - 1980; Kenworth - 1972; Chevrolet - 1979, 1989; Volvo - 1987; and Ford - 1970, 1972, 1974, 1980.

CHAPTER 5: AUDIOMETRY, DOSIMETRY, NOISE SPECTRAL MEASUREMENTS, AND AUDIBILITY PREDICTIONS

Audiometry

Method. Ten drivers participated in the audiometry study. Each driver drove a different truck on a commercial-type run lasting 8-18 hours. Each driver underwent audiometric testing before and after the end of the workday. The drivers were all male with ages ranging from 23-47 years ($\bar{x}$ = 34.3 yrs.). All drivers met the FHWA hearing requirement based on the pre-trip audiogram (an average hearing level of no more than 40 dBHL at 500, 1000, and 2000 Hz in the better ear), and all possessed current commercial driver's licenses. Commercial driving experience ranged from 1.5-24 years ($\bar{x}$ = 10.5 yrs.). The drivers averaged 2400 miles per week in the form of several 500-800 mile trips each week. Almost all of the drivers reported being actively involved in noisy non-occupational hobbies such as hunting, wood-working, and motorsport attendance. Some of the drivers had also previously been exposed to potentially harmful levels of occupational noise in other jobs. The drivers consented to all aspects of the experiment, and were compensated for their participation.

Pre-work audiograms were also available for another population of 20 drivers from a previous study; this resulted in a pool of 30 drivers for investigation of noise-induced permanent threshold shift (NIPTS). For the pool of 30 drivers, the mean age was 35.2 years and the mean driving experience was 9.0 years. All 30 drivers were male.

A total of ten trucks was used in the study. Two trucking companies agreed to participate, but due to fleet buying, only three makes of trucks were available for this experiment. All of the truck cabs were conventional (as opposed to cab-over) and all had standard sleeper-berth cabs (as opposed to the deluxe sleeper-berth models sometimes used for cross-country trips). The curtains to the sleeper compartment were kept open during all but one of the trips. Although the trucks were from three homogenous manufacturer groups, the cargo, weight, and mileage variables demonstrated considerable randomness. The characteristics of these trucks are more fully described later in the section on "Noise Spectral Measurements."

Apparatus. Audiometry was performed with a portable Beltone Model 119 pure-tone audiometer. Circumaural earphone enclosures were used to provide added attenuation of ambient noise. The audiometer was calibrated before the first audiograms were performed.

Procedure. The drivers were selected by the trucking companies. The experimenter met with the driver at the beginning of the trip, explained the experiment, and asked the driver to read and sign an informed consent form. Audiograms were performed in a quiet room at the driver's place of work. The ambient noise level of the room was measured with a RION SA-27 one-third octave-band analyzer with a 1/2 inch microphone to ensure the ambient noise level was within OSHA specifications for field audiometry (OSHA, 1990). A modified Hughson-Westlake procedure was used to determine the hearing threshold of the drivers at 9 frequencies from 125-8000 Hz. The right ear was tested first followed by the left ear, with the entire test requiring 15-20 minutes. The truck trips began as soon as all of the audiometric measurements were complete and the dosimeter was activated (see section on "Dosimetry," later in the report). The drivers then worked a normal driving shift. At the end of the trip the experimenter performed another audiometric examination following the same procedures used for the pre-workday test, including measuring the ambient noise level. Due to equipment warm-up time, the post-workday audiograms were performed from 15-25 minutes after the end of the driving shift.

Results. The ambient noise levels for the audiometric testing were for the most part well within the OSHA guidelines (OSHA, 1990), probably due to the time of day (early morning and late night). For three of the post-workday tests, the ambient noise level at a single frequency exceeded that specified by OSHA. OSHA specifies that the ambient noise level shall not exceed 40 dB at 500 Hz; for one of these post-workday tests, the 500 Hz level was 44.5 dB, and for another it was 41.2 dB. For another of the post-workday tests, the ambient noise level at 1000 Hz measured 47.5 dB, while OSHA specifies a maximum of 40 dB at 1000 Hz. All of the other tests met the levels specified by OSHA. Surprisingly, given the generally noisy nature of truck depots, the ambient noise levels were found to be acceptable. Table 5.1 summarizes the ambient noise levels for the audiometric testing.

TABLE 5.1. Mean Ambient Noise Levels (in dB) for Audiometric Measurements

Frequency (Hz)	OSHA Level (dB)	Mean Level (pre-workday)	Mean Level (post-workday)
500	40	30.1	31.3
1000	40	29.8	31.8
2000	47	30.4	30.4
4000	57	28.6	26.9
8000	62	27.3	26.5

A paired two-sample *t*-test was used to compare the pre- and post-workday audiograms for each ear at each frequency. For the left ear, there were no significant differences between the pre- and post-workday audiograms. For the right ear, there was one frequency at which the post-workday audiogram produced a *lower* reading (thus better hearing). At 4000 Hz, the TTS registered -3.0 dB [*p (one-tailed)* = 0.012]. For the rest of the frequencies at the right ear, there were no significant differences between the pre- and post-workday audiograms. Left and right ear results are displayed graphically in Figures 5.1 and 5.2, respectively. Table 5.2 provides the actual mean pre- and post-workday audiometric readings for each ear by frequency.

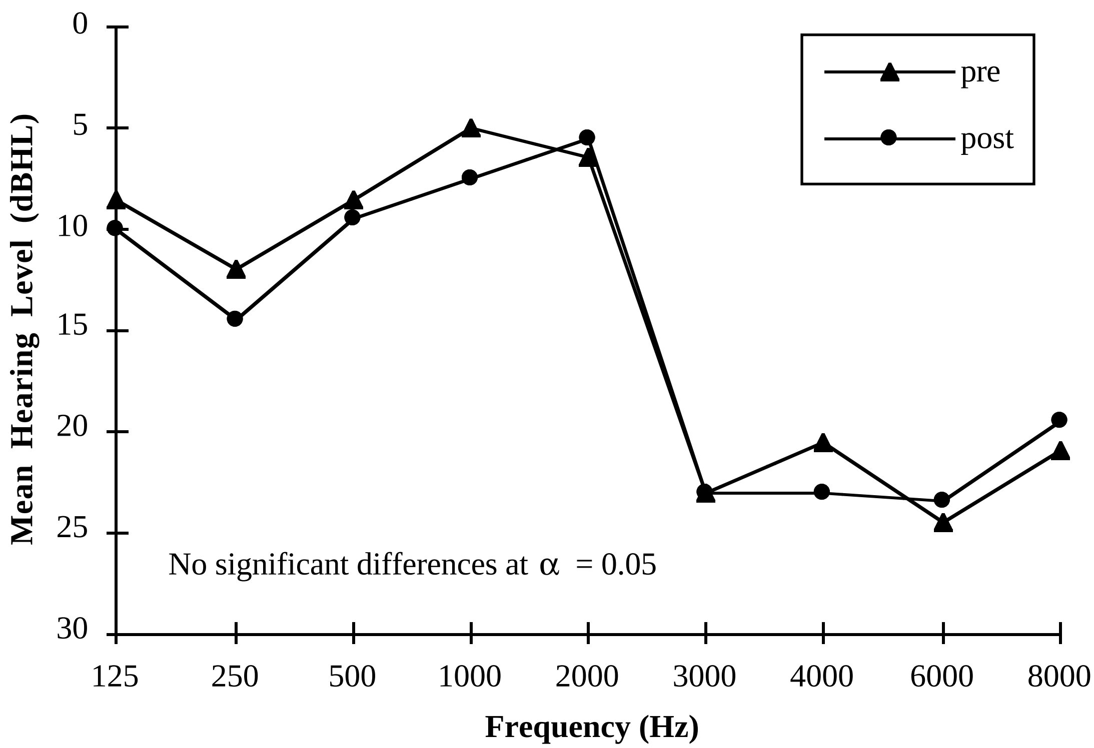

FIGURE 5.1. Mean Pre- and Post-Workday Audiograms for Ten Drivers, Left Ears (no significant differences at $\alpha = 0.05$)

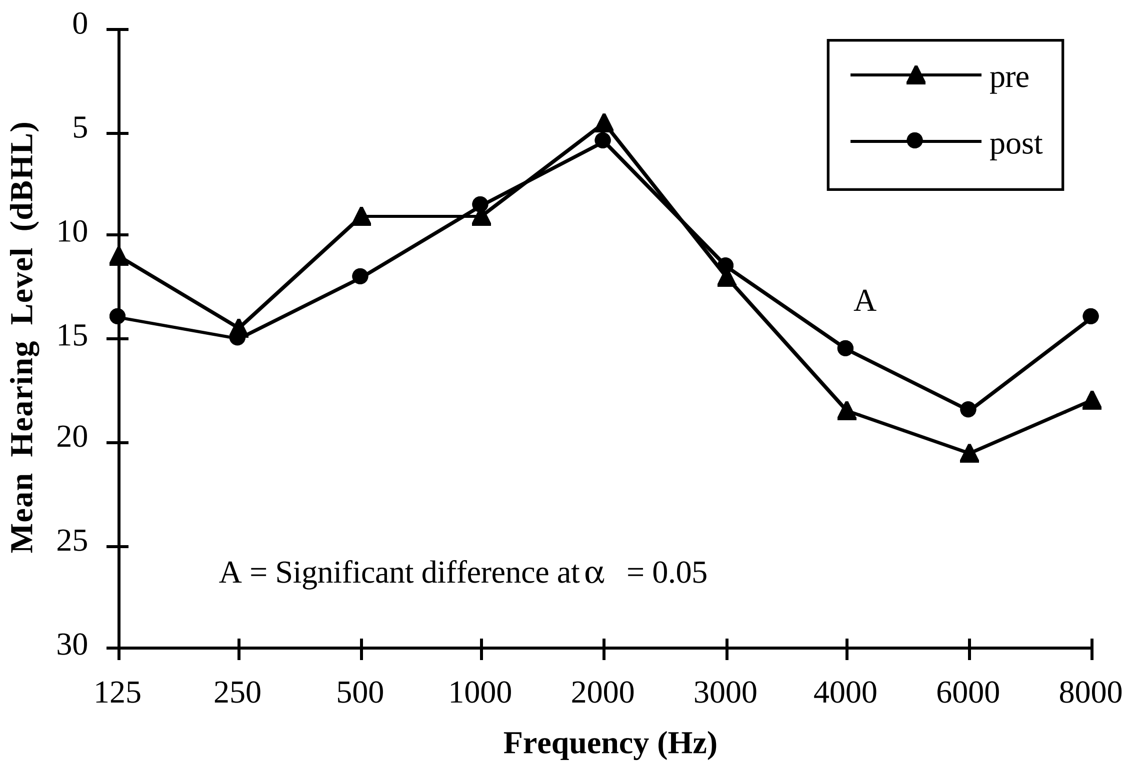

FIGURE 5.2. Mean Pre- and Post-Workday Audiograms for Ten Drivers, Right Ears (point marked with an 'A' is significantly different at $\alpha = 0.05$)

In Figure 5.3, the average pre-workday audiogram for thirty truck drivers (the 10 drivers from this study plus 20 additional drivers who participated in other studies) is shown superimposed on a graph of the hearing level for 35 year-old non-noise-exposed males (the mean age of the thirty truck drivers in this sample was 35.2 years). This was done for comparitive purposes to see if this sample of truck drivers exhibited hearing levels greater than would be expected for non-noise-exposed males (and have thus suffered a noise-induced permanent threshold shift or NIPTS). The NIPTS data for each frequency are presented in Table 5.3.

TABLE 5.2. Pre- and Post-Workday Audiometric Results, dBHL

	Right Ear					Left Ear				
Frequency	**pre-**	**post-**	**TTS**	***p***	***t*, df**	**pre-**	**post-**	**TTS**	***p***	***t*, df**
125	11.0	14.0	3.0	0.06	-1.77, 9	8.5	10.0	1.5	0.27	-0.63, 9
250	14.5	15.0	0.5	0.42	-0.21, 9	12.0	14.5	2.5	0.18	-0.96, 9
500	9.0	12.0	3.0	0.13	-1.20, 9	8.5	9.5	1.0	0.35	-0.41, 9
1000	9.0	8.5	-0.5	0.36	0.36, 9	5.0	7.5	2.5	0.11	-1.34, 9
2000	4.5	5.5	1.0	0.28	-0.61, 9	6.5	5.5	-1.0	0.25	0.69, 9
3000	12.0	11.5	-0.5	0.39	0.29, 9	23.0	23.0	0.0	0.50	0.00, 9
4000	18.5	15.5	-3.0	0.01	2.71, 9	20.5	23.0	2.5	0.21	-0.90, 9
6000	20.5	18.5	-2.0	0.08	1.50, 9	24.5	23.5	-1.0	0.36	0.36, 9
8000	18.0	14.0	-4.0	0.06	1.71, 9	21.0	19.5	-1.5	0.22	0.82, 9

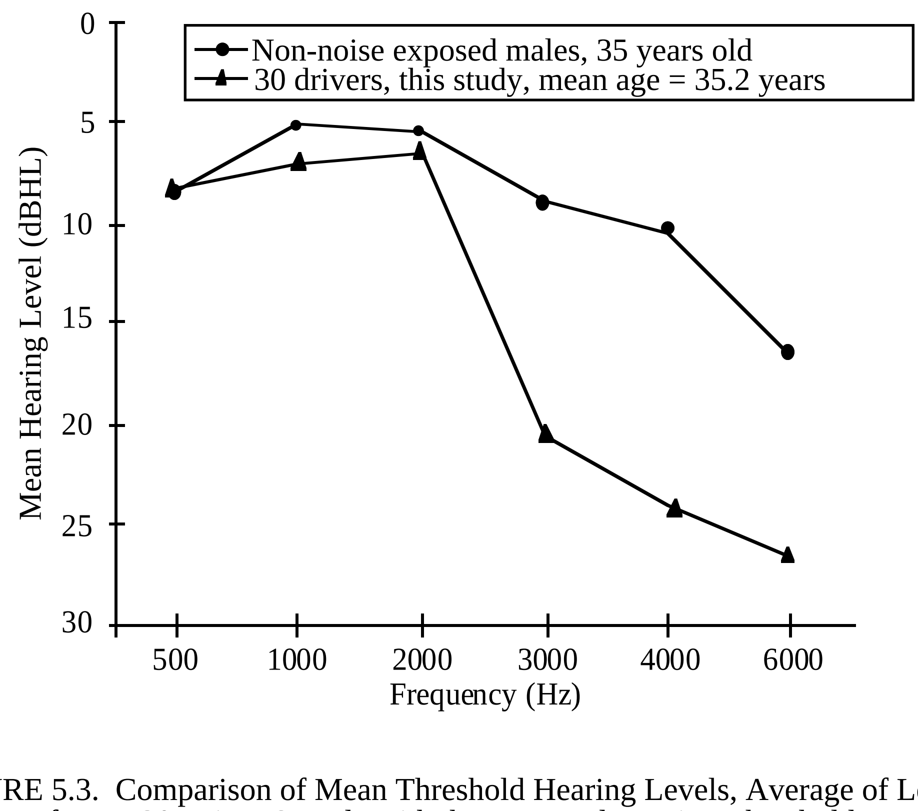

FIGURE 5.3. Comparison of Mean Threshold Hearing Levels, Average of Left and Right Ears, from a 30 Driver Sample with the Expected Hearing Threshold Levels for 35 Year-Old Non-Noise-Exposed Males in an Industrialized Society (from Ward, 1986). Mean driving experience for sample = 9.0 years.

TABLE 5.3. Mean Hearing Level (dBHL) for 30 Truck Drivers

Frequency (Hz)	30 Male Drivers dBHL	Non-Exposed Males, dBHL	Difference dB
500	8.2	8.5	-0.3
1000	7.1	5.3	1.8
2000	6.6	5.5	1.1
3000	20.5	9.0	11.5
4000	24.0	10.5	13.5
6000	26.5	16.5	10.0

Note: Non-exposed levels from Ward (1986).

Discussion. Based on the results of this study, there is no indication that current trucks of similar makes and mileage levels as those discussed herein are causing TTS among truck drivers. Due to the scheduling requirements of the trips, drivers were given little notice of participation, and were not able to control their pre-audiogram noise-exposure. The drivers could have been exposed to gunfire noise, loud music, and other noisy hobbies within a few hours of the pre-trip audiogram, thus resulting in a pre-elevated hearing threshold level. The 15-25 minute delay between the end of the shift and the audiometric test could also have played a role in the non-TTS finding. Laboratory TTS testing is usually done within 2 minutes after the noise exposure ends, and before recovery can occur. However, in field testing such as this, unavoidable delays of up to 25 minutes are not uncommon (Karlovich, 1988). A final factor contributing to the lack of TTS is that the drivers were allowed to set their own schedules for breaks and refueling. These rest breaks probably allowed sufficient recovery time for any TTS that might show up with continuous exposure to these noise levels.

Based on Figure 5.3 and Table 5.3, there is a permanent threshold shift, very likely a noise-induced permanent threshold shift, among the sample of truck drivers studied herein, especially at 3000, 4000, and 6000 Hz (three frequencies not required to be tested by the FHWA). Notches at these higher frequencies tend to be indicative of noise-induced hearing loss. Also, the 3000 and 4000 Hz frequencies are critical to the understanding of speech. Axelsson (1979) characterized noise-induced permanent hearing loss as a typically symmetric high-tone loss with a maximum at 4000 and 6000 Hz, with frequencies below 1500 Hz not typically affected by noise, even after years of exposure; this characterization is in agreement with the findings of this research. The suspected NIPTS reported herein for 30 male drivers is in close agreement with previous reports of truck driver hearing loss (Backman, 1983; Henderson and Burg, 1973;

Nerbonne and Accardi, 1975), lending support to the idea that truck-cab noise is continuing to cause hearing loss, even among drivers of 1990's model trucks.

However, because of the prevalence of noisy hobbies and previous industrial exposures, no conclusions can be drawn as to how much, if any, of the reported loss can actually be attributed to truck-cab noise exposure. Some of the supplementary questions on the task analysis questionnaire indicated that truck drivers in general tend to participate in noisy hobbies and to have had previous occupational noise exposure. In fact, 84% of the 80-driver sample who completed questionnaires reported at least one noisy hobby, and 85% reported at least one noisy previous occupation. Table 5.4 presents some of these findings. This prevalence of non-truck driving noise exposure has not been reported in the literature previously, but should be taken into consideration whenever truck driver audiometry is reported.

Conclusions. This sample of 10 drivers did not demonstrate any evidence of TTS while driving this particular sample of trucks. Although the larger sample of 30 drivers appears to have suffered a significant NIPTS, it cannot be determined whether the hearing loss was the result of the noise exposure while driving a truck or from other noise exposures (either noisy hobbies or other noisy occupations). The high prevalence of non-driving noise exposure is a serious confounding factor which makes any analysis of truck driver audiometry difficult. Whether or not the NIPTS was caused by truck driving, the frequencies at which the NIPTS occurred are not the same frequencies required to be tested by the FHWA, so even larger NIPTSs at these frequencies would not result in the loss of the CDL for this sample of truck drivers.

TABLE 5.4. Some Common Noisy Hobbies and Previous Occupations for a Sample of 80 Truck Drivers

Category	**Percent Reporting Participation**
Hobbies:	
Hunting	51%
Yard work (mowing, blowers, etc.)	51%
Attendance or participation in motor sports	49%
Other shooting (target, skeet, etc.)	40%
Shop work (wood/metal working, etc.)	38%
Recreational vehicles (ATVs, motorcycles, etc.)	33%
Farming	4%
Music	3%
Other	3%
1 or more noisy hobbies	**84%**
3 or more noisy hobbies	**50%**
Occupations (previous):	
Military	48%
Automobile repair	39%
Machine shop	28%
Lumber mill	16%
Quarry, mining, oil rig	9%
Factory	9%
Drop forge/die press	3%
Farming	3%
Boiler operator	1%
Other	6%
1 or more previous noisy occupations	**85%**
3 or more previous noisy occupations	**24%**

Dosimetry

Method. The same ten drivers participated in the dosimetry study as in the audiometry study. Each driver wore a Quest M-27 noise logging dosimeter with the microphone clipped to the right shoulder of his shirt. The drivers consented to all aspects of the experiment, and were compensated for their participation. The dosimeter was calibrated to 94 dB at 1000 Hz before and after each use, and was set to calculate the OSHA noise dose with a 5 dB exchange rate. (Although commercial vehicle operators are not covered by OSHA noise exposure regulations, the OSHA regulations do provide the best available metric for evaluating the risk of hearing loss due to noise exposure, regardless of the noise source.) The dosimeter was turned on and attached to the driver's belt and shoulder immediately following the audiometric testing. The dosimeter was left running during all stoppages (such as to refuel, eat, or have paperwork signed) except that it was paused and removed while the driver was sleeping. At the end of the trip, the dosimeter was turned off and removed. For nine of the trips, a dosimeter was also placed in the sleeper-berth compartment, with the microphone placed slightly above the pillow, where the driver's head would be if he were sleeping. The sleeper-berth dosimeter was also left running during all stoppages (such as to refuel, eat, or have paperwork signed), and it was also paused and removed while the driver was sleeping. For eight of the nine sleeper-berth measurements, the curtains were left open and the sleeper-berth radio speakers were turned off, while for one trip, the curtains were closed but the speakers were left turned on.

Results. Dosimetry results showed that all of the 8-hour noise doses measured were less than 50%, and would thus be allowed under the OSHA regulations [although the trucking industry is not presently required to follow OSHA guidelines (Songer et al., 1992)]. A 50% dose represents the OSHA action level, or the level at which a hearing conservation program must be put into place in industry. A 100% dose represents the OSHA criterion level, or the level at which administrative or engineering controls must be instituted to bring the dose below 100%. Noise doses were also calculated (projected) for 10- and 24-hour exposure durations for each truck. Drivers are allowed to drive up to 10 hours without taking a break (Federal Highway Administration, 1995), and those driving in teams may be exposed to similar noise levels up to 24 hours per day, although some of this time is usually spent in the sleeper berth. The three noise dose measurements and the L_{eq} measurements are presented in Table 5.5 for each truck/driver combination. Trucks

5 and 9 slightly exceeded a 100% noise dose for 24 hours, while the rest of the trucks were below a 100% noise dose even when considering a 24-hour time frame, with three trucks measuring less than a 50% dose over 24 hours. The L_{eq} of the truck-cab noise as also measured by dosimeter ranged from 78.7 dBA to 83.9 dBA, with a mean of 81.6 dBA.

TABLE 5.5. Noise Doses and L_{eq} for the 10 Truck/Driver Combinations Reported in This Study

Truck/Driver Number	**8-Hour Dose**	**10-Hour Dose**	**24-Hour Dose**	**L_{eq} (dBA)**
1	7.9%	9.8%	23.6%	78.7
2	12.4%	15.5%	37.2%	79.8
3	22.3%	27.8%	66.8%	82.0
4	22.0%	27.5%	66.0%	81.5
5	34.6%	43.3%	103.9%	83.9
6	27.5%	34.4%	82.6%	81.9
7	31.1%	38.9%	93.4%	83.2
8	32.6%	40.8%	97.8%	82.9
9	36.0%	45.0%	107.9%	83.6
10	9.4%	11.8%	28.2%	78.9
Mean	**23.6%**	**29.5%**	**70.7%**	**81.6**

Note: 8-hour dose measured; 10 and 24-hour doses calculated, based on 8-hour measured doses.

The sleeper-berth doses were much lower than the front seat doses. In all cases, the 24-hour dose was less than 10%, and in all but one case, less than 3%. Since drivers usually sleep for 5 or 10 hours, Table 5.6 provides these noise doses as well as the 24-hour sleeper-berth dose. Table 5.6 also provides the L_{eq} measurements for the sleeper berth for each truck/driver combination. The L_{eq}s were also much lower for the sleeper berths, ranging from 73.4-75.2 dBA, with a mean of 74.4 dBA.

Some sample calculations are provided for 24-hour doses for drivers following different driving/sleeping patterns. A mean 24-hour dose for a driver who follows the rules of service requirements for a 24-hour period with a 10-5-9 driving-sleeping pattern, and who spends non-driving time in the sleeper berth would be as follows: the first 10 hours of driving would constitute a 29.5% dose (mean 10-hour dose for these 10 trucks); the next

5 hours would accumulate a dose of 0.2% in the sleeper berth; the final 9 hours of driving would accumulate an additional dose of 26.6%, for a 24-hour dose of 56.3% (slightly above the OSHA action limit). A similar calculation for the worst-case scenario (truck 9 for the driving dose and truck 10 for the sleeper-berth dose) would result in a 24-hour dose of 87% (45% + 1.5% + 40.5%), which is approaching the OSHA criterion level. On the other hand, a driver who followed a 10-10-4 driving-sleeping pattern would have a mean dose of 41.8% (29.5% + 0.5% + 11.8%) and a worst-case dose of 65.9% (45% + 2.9% + 18%). By maximizing time spent in the sleeper berth, a driver can significantly reduce the 24-hour noise dose, and may even be able to bring the dose below the OSHA action level. These calculations are for team drivers; single drivers would be expected to have lower 24-hour doses, since their non-driving time would be spent in the sleeper berth with the truck idling or turned off, which would result in a much lower noise dose.

TABLE 5.6. Noise Doses and L_{eq} for the 9 Sleeper Berths Reported in This Study

Truck/Driver Number	5-Hour Dose	10-Hour Dose	24-Hour Dose	L_{eq} (dBA)
1	0.5%	0.9%	2.3%	74.5
3	<0.1%	0.1%	0.2%	73.9
4	<0.1%	<0.1%	0.1%	73.8
5	<0.1%	0.1%	0.1%	74.6
6	0.0%	0.0%	0.0%	73.4
7	<0.1%	0.1%	0.2%	74.2
8	<0.1%	0.1%	0.2%	75.2
9	<0.1%	0.1%	0.1%	74.7
10	1.5%	2.9%	7.0%	75.1
Mean	**0.2%**	**0.5%**	**1.1%**	**74.4**

Note: All doses calculated, based on 8-hour measured doses. The curtains were open and speakers off for all trucks except truck 10, for which the curtains were closed and the speakers left on.

The lower noise level in the sleeper berth can be explained by two factors. First, the sleeper berth is further away from the primary noise source (the engine). Second, the sleeper berth typically contains a greater proportion of absorptive materials than does the cab area. The mattress, pillow, bed coverings, and even the wall surface in the sleeper berth are all more absorptive than many of the materials found in the cab area, and collectively, they provide some sound transmission loss as well. For example, as to reflection, the cab area has a lot of glass surface area, which is highly reflective of noise, while a typical sleeper berth contains very little glass.

The dosimeter also provides true peak sound pressure level readings. These ranged from 120.7-130.8 dBA for the cab, and from 120.7-126.7 dBA for the sleeper berth. These measurements are only slightly above the van den Heever and Roets (1996) L_{max} readings of 115.4-118.5 dBA for South African trucks, which they attributed to door slams. In the current study, the timing of the peak readings also seemed to correlate with door slams.

Discussion. The 8-hour and projected 10-hour noise doses experienced by the truck drivers in the study were not excessive as gauged against OSHA requirements for general industry. The drivers were allowed to set their own schedules for breaks and refueling. This probably helped keep the noise dose within acceptable limits, since the dosimeter was kept running during all but sleeping breaks. However, team drivers who spend most of their non-driving time in the cab rather than the sleeper berth might be exposed to levels which exceed the action level, and in some cases, the criterion level, over a 24-hour period. Team drivers who spend non-driving time in the sleeper berth could easily exceed the OSHA action level over a 24-hour period, as shown by three of the four example dose calculations. Even drivers who follow a 10-10-4 driving-sleeping pattern can approach or exceed the OSHA action level over a 24-hour period. So although the sleeper berth is much quieter than the cab, the 24-hour dose will still often exceed the OSHA action level of 50%. If the trucking industry were subject to OSHA regulations, a hearing conservation program might be ordered put into place based on these findings. For single drivers, the time spent in the sleeper berth would probably result in a noise dose of 0% (see engine idle noise level discussion in Noise Spectral Measurements section, later in the report), so that the 24-hour noise dose would be somewhat lower for these drivers. The noise doses were measured with rest breaks, meal breaks, and refueling breaks included, so they represent realistic predictions of actual truck trip noise doses. Also adding realism to the noise doses is the fact that in 8 out of 10 cases, these doses were measured on fairly high mileage vehicles.

Conclusions. For these 10 trucks, the 24-hour noise doses often exceeded the OSHA action level, even with sleeper-berth time included. Maximizing time spent in the sleeper berth helps reduce the 24-hour dose, and probably also provides additional recovery time for any TTS that may be occurring. Team drivers should be encouraged to spend the maximum amount of time possible in the sleeper berth in order to reduce their total noise exposure. For single drivers, the dose should be somewhat lower, and of less concern. Even if single drivers spend non-driving time in the cab, the lower noise levels during engine idling will result in lower noise doses than for team drivers.

Noise Spectral Measurements

Trucks. Nine trucks were evaluated for this part of the study. Two trucking companies agreed to participate, but due to fleet buying, only three makes of trucks were available for this experiment. One vehicle was a 1997 Volvo VN with a Volvo VE DIZ-425HP engine and 2400 miles on the odometer. Two of the vehicles were Kenworths (a 1992 model with a Caterpillar 425 engine and 240,000 miles and a 1993 model with a Caterpillar 3406 engine and 365,000 miles). The other 6 trucks were all 1994 Internationals with Detroit 60 Series engines; each had approximately 250,000 miles. All of the truck cabs were conventional (as opposed to cab-over) and all had standard sleeper-berth cabs (as opposed to the deluxe sleeper-berth models sometimes used for cross-country trips). The curtains to the sleeper compartment were kept open during all but one of the trips. All trucks pulled box trailers, some with refrigeration units that were in use during the trip. Several of the trailers had canvas tops. Cargo included mulch, dry goods, paper, and produce. During some portions of the trips the trailer was loaded and at other times the trailer was empty. As a consequence, vehicle weight varied greatly. To recapitulate, although the trucks were from three homogenous manufacturer groups, the cargo, weight, and mileage variables demonstrated considerable randomness.

Apparatus. Truck-cab noise was measured under real world conditions using a RION SA-27 one-third octave band analyzer. The 1/2 inch microphone/preamplifier assembly was suspended from the truck cab ceiling using a custom stabilizing fixture. The microphone was placed at the driver's ear level, approximately 26 cm to the right of the driver's right ear. The placement of the microphone is shown in Figure 5.4. The spectrum analyzer was calibrated to 94 dB at 1000 Hz before and after each use with a RION NC-73 calibrator. The spectrum analyzer was set for dB(linear), slow (1s) response, and L_{eq} with a 5-second integration time. Since the measurements were taken for 30 minutes at a time, there were 360 samples for each one-third octave band for each condition. These data were stored in the spectrum analyzer's memory and then transferred to a laptop computer between measurements.

FIGURE 5.4. Placement of Microphone in Truck Cab

Procedures. Noise measurements were taken as described by Micheal (1995a). A 1/2 inch microphone was suspended from the ceiling of the truck cab using the same equipment used by Morrison and Casali (1994) and Micheal (1995a). Thirty-minute L_{eq} measurements were taken under 8 conditions (all possible combinations of windows up or down, ventilation on or off, and radios on or off). These measurements were taken at near-constant highway speeds of approximately 65 miles per hour. The experimenter asked the driver to turn radios on and off, open and close windows, and turn ventilation on and off as the experimental protocol required. The driver was then allowed to adjust the level of these items to his personal preferences. A normal level of conversation between the driver and experimenter was maintained during the data collection periods in order to add further realism to the measurements. The experimenter collected the noise data and transferred them to the laptop computer after each 30-minute measurement.

Additional data were also collected as time and circumstances permitted. For four of the trucks, engine idle measurements were also taken. These measurements were made with the windows open and closed, for periods ranging from 4.5 to 30 minutes per condition. The analyzer's settings and microphone placement were as described previously. One-third octave band measurements were also obtained in the sleeper berths of 2 trucks, for periods ranging from 15-30 minutes per condition. Conditions explored for sleeper-berth measurements were curtain open or closed and radio on or off. The microphone was suspended above the pillow, slightly above the driver's head position if he were sleeping. Analyzer settings were unchanged.

Results. After the trip was completed, the truck-cab noise data were transferred to a desktop computer and the data transformed into 30 minute equivalent sound pressure levels (L_{eq}s) using Equation (5.1) for sound pressure levels obtained over discrete intervals of time (Earshen, 1986):

$$L_{eq} = 10\log\left[\frac{1}{T}\sum_{i=1}^{N}\left(10^{L_{Fi}/10}t_i\right)\right] \quad \textbf{(5.1)}$$

where T is the observation time, i is the i_{th} interval, N is the total number of intervals, t_i is the duration of the i_{th} observation interval, and L_{Fi} is the linear sound level during t_i. The resulting spectra were then weighted and summed to obtain broadband SPLs in dB(linear), dBA, and dBC, using Equation (5.2) (Ostergaard, 1986):

$$L_{pt} = 10\log_{10}\left[\sum_{i=1}^{N}10^{L_{pi}/10}\right] \quad \textbf{(5.2)}$$

where L_{pt} is the total SPL in decibels of the N frequency bands and L_{pi} represents the individual sound pressure levels (SPLs) to be added. The one-third octave band levels for each condition and the mean over all eight conditions are shown in Table 5.7. Mean spectra for all 9 trucks for each condition are presented in Figures 5.5 (a-h). A summary of the engine idle measurements can be found in Table 5.8, while a summary of sleeper-berth measurements can be found in Table 5.9. An analysis of variance for L_{eq} in dB(linear), dBA, and dBC was conducted on the three factors (windows up or down, ventilation on or off, and radios on or off). None of the factors or interactions proved significant at $\alpha = 0.05$. Table 5.10 presents the mean SPLs for each factor.

Discussion. The mean A-weighted L_{eq} across all trucks for all conditions was calculated to be 89.1 dBA, which is just below the OSHA permissible exposure level of 90 dBA for an eight-hour period. This is significantly higher then the SPLs reported by Morrison and Casali (1994) and Micheal (1995a). However, the analyzer measurements for this study were taken when the truck was proceeding at full speed, and so do not take into account the effect of rest periods and time spent away from the noise. The dosimeter readings obtained for this study more accurately reflect the truck driver's true noise exposure over an entire work shift including meal breaks, refueling stops, and rest breaks, and these were all below 85 dBA, with a mean L_{eq} of 81.6 dBA (they were also in close agreement with the van den Heever and Roets 1996 dosimetry results). The lack of a statistically significant increase in noise level with radios on, windows down, or ventilation on demonstrates that under all conditions, the major source of truck-cab noise is from the engine, and any efforts at noise control should begin there.

The mean engine idle L_{eq} of 68.2 dBA is well within a range considered safe for human hearing, so time spent either in the cab or sleeper berth while the engine is idling should not be of concern in terms of hearing damage. The sleeper-berth noise as measured under highway speed conditions was substantially less than the truck cab noise (81.6 dBA for the sleeper berth as opposed to 89.1 dBA for the truck cab), again emphasizing that time spent in the sleeper berth minimizes noise exposure.

TABLE 5.7. One-Third Octave Band Levels for Each Driving Condition, dB(linear)

Frequency (Hz)	WD V0 R0	WD V0 R1	WD V1 R0	WD V1 R1	WU V0 R0	WU V0 R1	WU V1 R0	WU V1 R1	Mean
25	89.4	89.3	89.6	89.2	89.0	89.2	88.9	88.7	89.2
31.5	90.7	90.5	90.8	90.8	90.9	90.9	90.8	90.7	90.8
40	90.0	89.9	90.0	90.0	89.9	89.7	89.4	89.8	89.8
50	89.0	88.9	89.1	89.3	88.8	88.4	88.3	88.5	88.8
63	88.3	88.4	88.6	88.8	88.1	88.1	87.6	87.7	88.2
80	87.5	87.7	88.0	88.0	87.9	87.6	87.3	87.4	87.7
100	86.8	87.1	87.1	87.3	86.6	86.5	86.1	86.2	86.7
125	86.0	86.2	86.3	86.4	85.3	85.5	84.9	85.1	85.7
160	84.7	85.1	85.0	85.4	83.9	84.2	83.5	83.9	84.5
200	83.4	84.3	83.8	84.6	82.5	83.2	82.0	82.7	83.3
250	82.2	83.1	82.6	83.3	81.5	82.1	81.0	81.6	82.2
315	81.2	82.1	81.6	82.4	80.3	81.3	79.9	80.7	81.2
400	80.3	81.3	80.6	81.4	79.5	80.3	79.0	79.8	80.3
500	80.5	81.9	80.8	81.8	79.8	81.4	79.5	80.6	80.8
630	80.0	81.1	80.3	81.1	79.1	80.2	78.8	79.8	80.1
800	79.7	80.7	80.0	81.0	78.6	79.8	78.4	79.3	79.7
1000	78.7	80.0	79.0	80.0	77.3	79.1	77.1	78.2	78.7
1250	78.1	79.6	78.4	79.4	76.6	78.5	76.3	77.5	78.1
1600	77.2	78.9	77.5	78.6	75.6	77.8	75.4	76.7	77.2
2000	76.6	78.7	76.9	78.3	75.0	77.5	74.7	76.4	76.8
2500	75.7	77.6	75.9	77.4	73.9	76.3	73.7	75.2	75.7
3150	74.9	76.7	75.2	76.6	72.9	75.0	72.8	74.0	74.8
4000	73.9	75.7	74.2	75.6	71.7	73.7	71.6	72.9	73.7
5000	72.6	74.2	72.9	74.2	70.2	72.2	70.0	71.4	72.2
6300	70.8	72.5	71.1	72.4	68.3	70.1	68.1	69.5	70.4
8000	71.0	72.4	71.3	72.5	68.5	70.1	68.4	69.7	70.5
10000	70.3	71.7	70.5	71.8	67.5	69.1	67.5	68.8	69.6
12500	67.6	69.5	67.9	69.6	64.5	66.3	64.3	66.5	67.0
16000	66.3	68.2	66.5	68.3	62.9	64.6	62.7	64.9	65.5
20000	64.6	66.7	64.9	66.8	60.9	62.7	60.7	63.1	63.8
dB(linear)	**98.9**	**99.1**	**99.1**	**99.3**	**98.8**	**98.9**	**98.4**	**98.6**	**98.9**
dBA	**89.0**	**90.4**	**89.3**	**90.3**	**87.9**	**89.4**	**87.6**	**88.6**	**89.1**
dBC	**97.6**	**97.9**	**97.8**	**98.1**	**97.4**	**97.5**	**97.0**	**97.2**	**97.5**

Note - WD = Windows down; WU = Windows up; V0 = Ventilation off; V1 = Ventilation on; R0 = Radios off; R1 = Radios on.

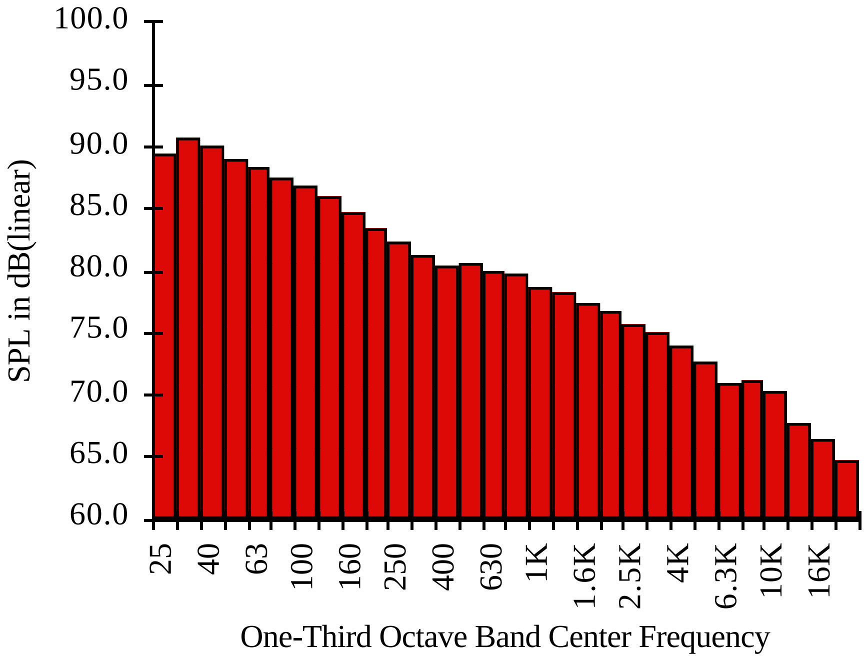

FIGURE 5.5a. Mean One-Third Octave Band Levels of Nine Trucks, Windows Down, Ventilation Off, Radios Off Condition (Broadband SPL = 98.9 dB(linear), 89.0 dBA)

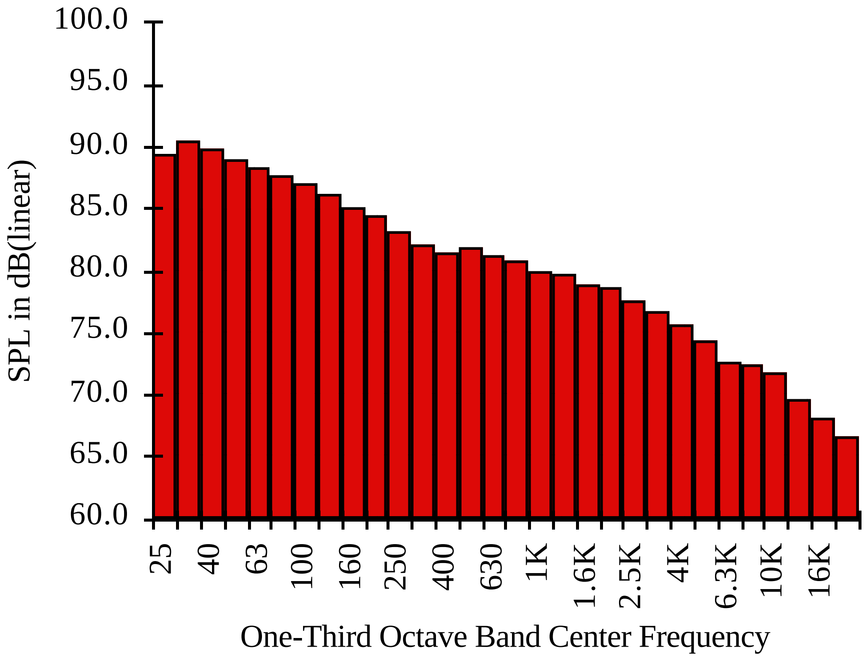

FIGURE 5.5b. Mean One-Third Octave Band Levels of Nine Trucks, Windows Down, Ventilation Off, Radios On Condition (Broadband SPL = 99.1 dB(linear), 90.4 dBA)

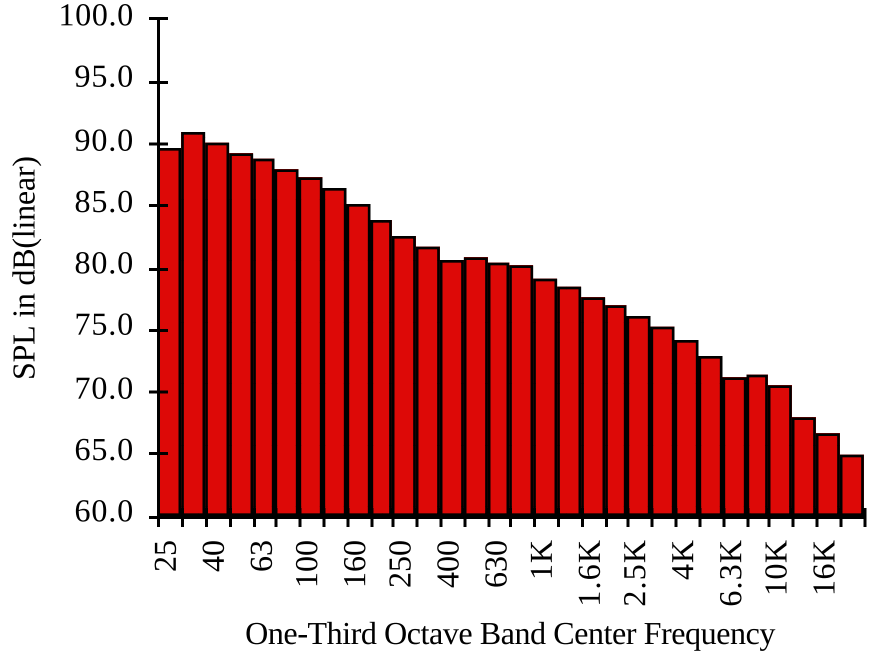

FIGURE 5.5c. Mean One-Third Octave Band Levels of Nine Trucks, Windows Down, Ventilation On, Radios Off Condition (Broadband SPL = 99.1 dB(linear), 89.3 dBA)

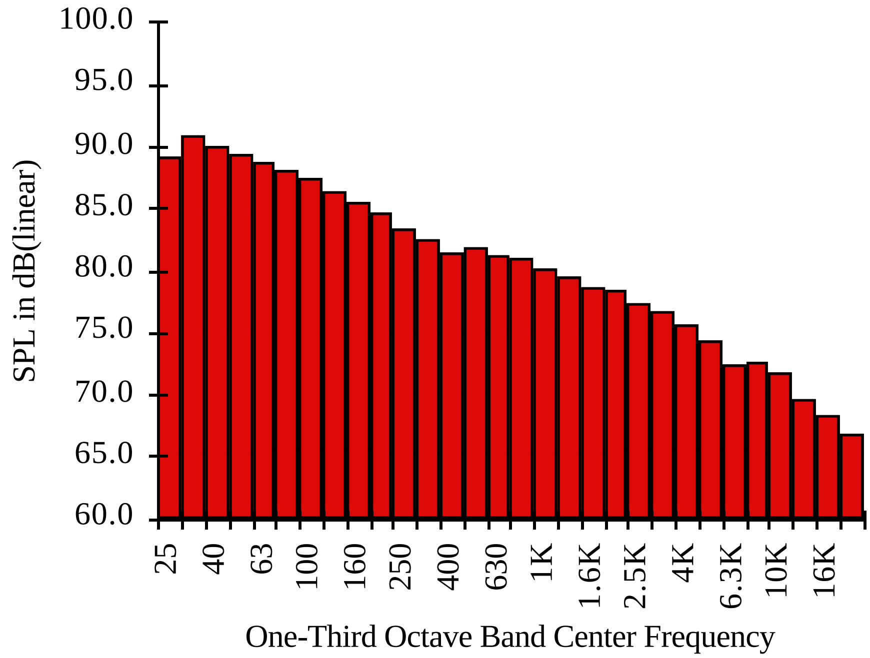

FIGURE 5.5d. Mean One-Third Octave Band Levels of Nine Trucks, Windows Down, Ventilation On, Radios On Condition (Broadband SPL = 99.3 dB(linear), 90.3 dBA)

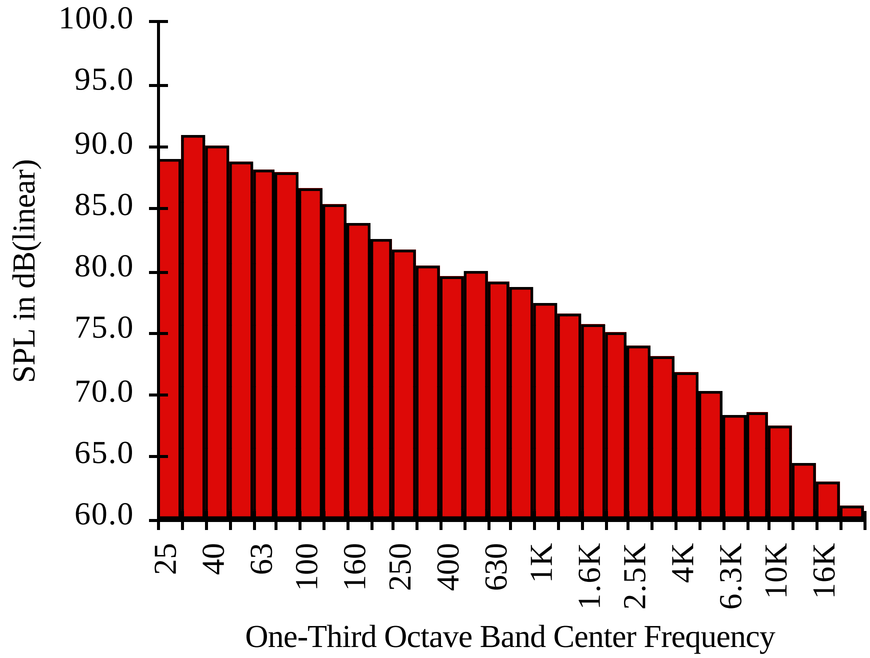

FIGURE 5.5e. Mean One-Third Octave Band Levels of Nine Trucks, Windows Up, Ventilation Off, Radios Off Condition (Broadband SPL = 98.8 dB(linear), 87.9 dBA)

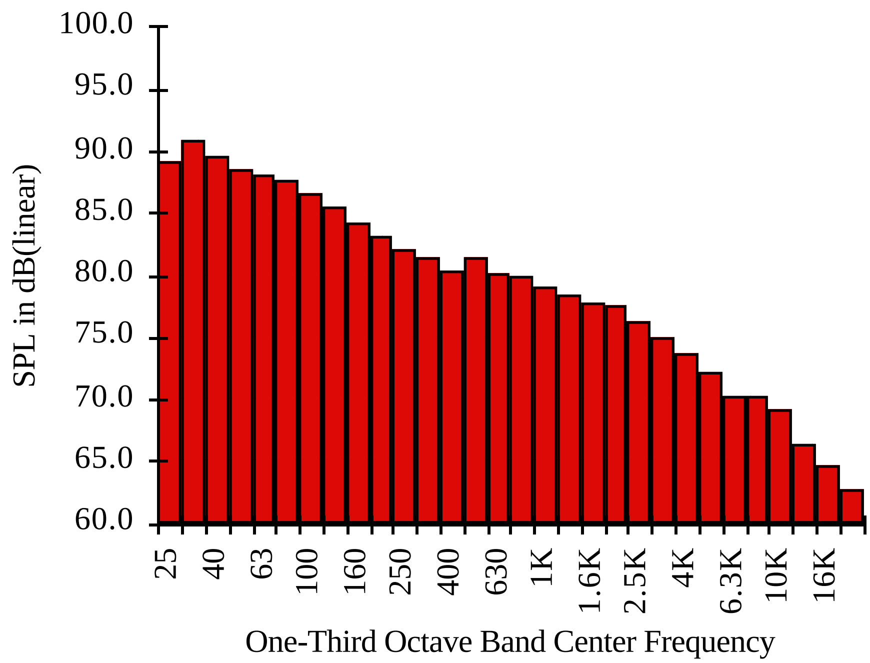

FIGURE 5.5f. Mean One-Third Octave Band Levels of Nine Trucks, Windows Up, Ventilation Off, Radios On Condition (Broadband SPL = 98.9 dB(linear), 89.4 dBA)

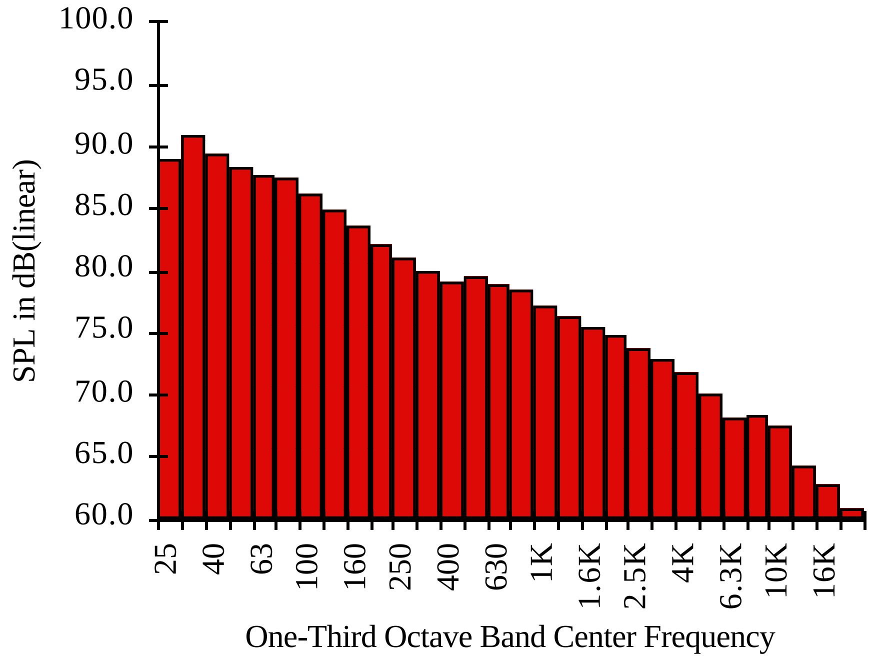

FIGURE 5.5g. Mean One-Third Octave Band Levels of Nine Trucks, Windows Up, Ventilation On, Radios Off Condition (Broadband SPL = 98.4 dB(linear), 87.6 dBA)

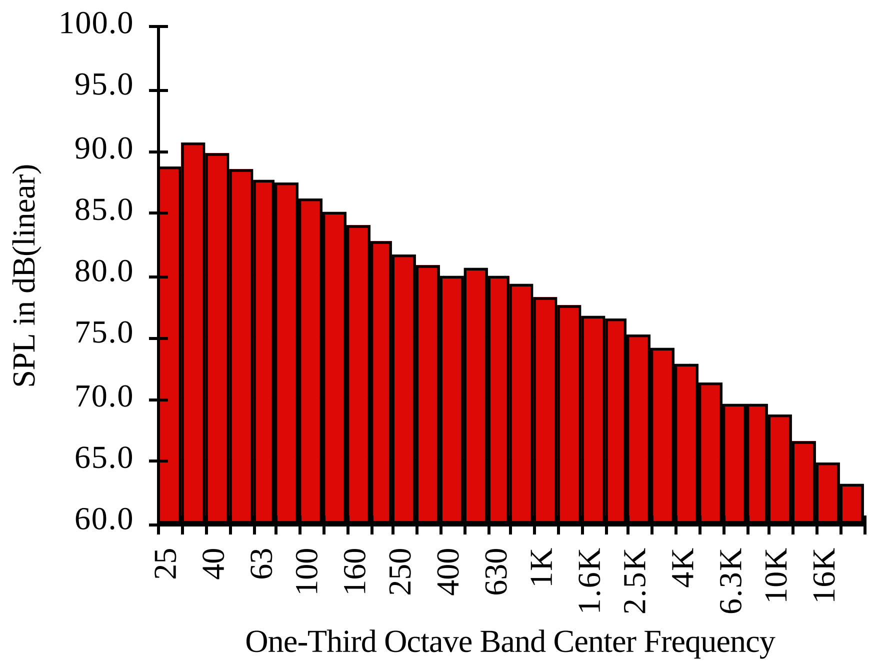

FIGURE 5.5h. Mean One-Third Octave Band Levels of Nine Trucks, Windows Up, Ventilation On, Radios On Condition (Broadband SPL = 98.6 dB(linear), 88.6 dBA)

TABLE 5.8. One-Third Octave Band Levels for Engine Idle Conditions, dB(linear)

Frequency (Hz)	Windows Up	Windows Down	Mean
25	77.9	78.0	78.0
31.5	79.7	80.1	79.9
40	77.3	81.0	79.2
50	78.0	77.8	77.9
63	78.2	78.6	78.4
80	75.0	73.9	74.5
100	72.8	72.1	72.5
125	68.1	67.7	67.9
160	63.7	62.5	63.1
200	63.8	61.1	62.5
250	62.2	59.6	60.9
315	60.9	59.0	60.0
400	60.2	58.7	59.5
500	61.0	60.2	60.6
630	60.7	60.8	60.8
800	60.0	59.7	59.9
1000	60.1	59.8	60.0
1250	57.1	56.7	56.9
1600	55.3	55.5	55.4
2000	53.2	53.6	53.4
2500	51.4	51.6	51.5
3150	48.8	50.1	49.5
4000	46.5	47.8	47.2
5000	44.4	45.0	44.7
6300	42.5	42.3	42.4
8000	40.2	40.0	40.1
10000	39.3	39.1	39.2
12500	38.0	36.5	37.3
16000	36.0	34.2	35.1
20000	32.9	31.4	32.2
dB(linear)	**86.1**	**86.8**	**86.5**
dBA	**68.4**	**68.0**	**68.2**

TABLE 5.9. One-Third Octave Band Levels for Sleeper-Berth Conditions, dB(linear)

Frequency (Hz)	**Curtain open, radios off**	**Curtain open, radios on**	**Curtain closed, radios off**	**Curtain closed, radios on**	**Mean**
25	90.9	90.5	85.0	87.1	88.4
31.5	91.2	90.7	85.7	86.9	88.6
40	92.2	92.0	87.6	87.5	89.8
50	89.5	90.9	84.1	83.9	87.1
63	89.8	90.7	85.1	84.5	87.5
80	90.4	90.6	86.8	86.1	88.5
100	89.3	89.8	84.0	83.2	86.6
125	87.5	88.5	85.1	84.4	86.4
160	86.0	86.9	78.5	77.7	82.3
200	84.3	85.5	70.9	72.6	78.3
250	82.8	84.0	68.9	70.1	76.5
315	81.7	83.0	66.2	68.3	74.8
400	80.3	81.5	64.9	66.9	73.4
500	80.1	81.3	64.4	66.7	73.1
630	78.6	79.9	62.0	65.4	71.5
800	78.0	79.3	59.9	62.5	69.9
1000	76.7	78.0	57.8	60.8	68.3
1250	75.9	77.2	56.8	60.1	67.5
1600	74.6	75.9	55.4	58.8	66.2
2000	74.2	75.5	55.0	58.4	65.8
2500	73.1	74.5	53.8	57.1	64.6
3150	72.3	73.6	53.3	56.4	63.9
4000	71.3	72.7	52.6	55.5	63.0
5000	69.9	71.2	51.1	54.0	61.6
6300	67.1	68.5	49.1	51.7	59.1
8000	67.9	69.2	50.1	52.7	60.0
10000	67.1	68.3	49.3	51.9	59.2
12500	62.3	64.4	33.9	38.0	49.7
16000	60.8	62.9	32.2	35.9	48.0
20000	57.9	60.2	28.6	32.2	44.7
dB(linear)	**100.1**	**100.5**	**94.8**	**94.9**	**97.6**
dBA	**87.6**	**88.8**	**74.6**	**75.3**	**81.6**

TABLE 5.10. Mean Sound Pressure Levels for Each Factor

Factor	**Condition**	**Mean SPL dB(linear)**	**Mean SPL dBA**	**Mean SPL dBC**
Windows	Down	99.1	89.7	97.8
	Up	98.6	88.4	97.3
Ventilation	Off	98.9	89.2	97.6
	On	98.8	88.9	97.5
Radios	Off	98.8	88.4	97.4
	On	99.0	89.7	97.7

Note - No significant differences found at $\alpha = 0.05$ using an analysis of variance.

Another important observation regarding the sleeper berth is that the broadband A-weighted SPL was 13.3 dB lower with the curtains closed than with the curtains open, regardless of whether or not the radios were on, so drivers should be advised to close the curtains whenever they are in the sleeper berth to further reduce noise exposure. The sleeper-berth L_{eq}s as measured by analyzer were higher than those measured with the dosimeter, but the same reasoning holds as for the cab measurements — all readings made using the analyzer were taken when the truck was proceeding at full speed, so these readings do not take into account the effect of rest periods and time spent away from the noise, while the dosimeter readings do take these periods into account. Previous studies in which dosimeter readings were higher than analyzer readings only included driving time, and did not include any non-driving time in the dose calculations (Hessel et al., 1982; van den Heever and Roets, 1996). Figure 5.6 compares the noise levels measured during this study to other noise measurements taken over a 30-year period. As can be seen, the noise levels reported here are not as low as some recent studies performed under idealized conditions, but still show a substantial decrease over the last 30 years.

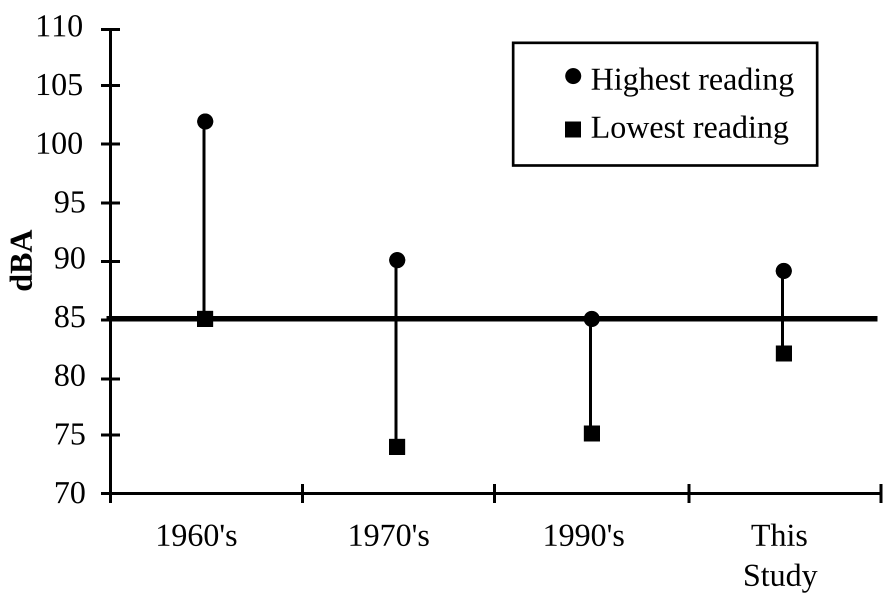

FIGURE 5.6. Trend for Interior Truck-Cab Noise from the 1960's to the 1990's, Including this Study (OSHA Action Level of 85 dBA is represented by the solid line.)

Conclusions. It is important to note that measurements reported herein were taken under real-world conditions: these were actual commercial runs, the trucks were both loaded and unloaded, the vehicles were fairly high-mileage, 1990's vintage trucks in regular use, the drivers were allowed to adjust conditions to their personal preferences, a normal amount of conversation was allowed, and the drivers were allowed to set the schedule for rest breaks. Heretofore, such real-world data have not been readily available. To this extent, the SPLs reported probably more accurately reflect the levels being experienced in commercial vehicles than many previous studies in which the trucks were new and/or unloaded and/or driven in a standardized manner. The mean L_{eq} of 89.1 dBA measured by spectrum analyzer warrants concern, as it is very near the OSHA criteria level of 90 dBA for an 8-hour shift. For many of the trucks in this study, driving at highway speeds without a break for eight hours would result in an OSHA noise dose of over 100%. However, the lower levels measured by dosimeter are probably more reflective of the drivers' true exposure, due to the realistic manner in which these measurements were obtained (including rest breaks, etc.). Any time spent in the truck while it is idling can be considered safe from a noise perspective. Again, drivers should be encouraged to maximize time spent in the sleeper berth (with the curtains closed) when they are not driving in order to minimize their daily noise exposure.

Audibility Predictions

Articulation Index. The Articulation Index (AI), described in ANSI S3.5-1969 (ANSI, 1969), "American National Standard Methods for the Calculation of the Articulation Index," provides a method of predicting the intelligibility of speech given a certain speech spectrum and continuous noise level. The methodology has been validated for male talkers, but not for female talkers or children. Given that approximately 94% of truck drivers are male (Equal Employment Opportunity Commission, 1990), the AI appears to offer a reasonable tool for determining the speech intelligibility of communications in the truck cab.

In order to use this method, the masking noise (in this case, truck-cab noise) is measured in one-third octave bands. The speech levels are either taken from a table of the ideal speech spectrum for male voices or are measured directly. The difference between the band pressure level of the speech peaks and the band pressure level of the noise is calculated, and the resulting values are multiplied by weighting factors for each one-third octave band according to that band's importance to speech intelligibility. The weighting factors also help account for the upward spread of masking. The resulting weighted values are added, and the resulting sum is referred to as the Articulation Index. The AI can vary from 0.0 to 1.0, with higher values representing greater intelligibility. Figure 5.7 shows the relationship of the calculated AI to the intelligibility scores for sentences the first time they are presented to a listener.

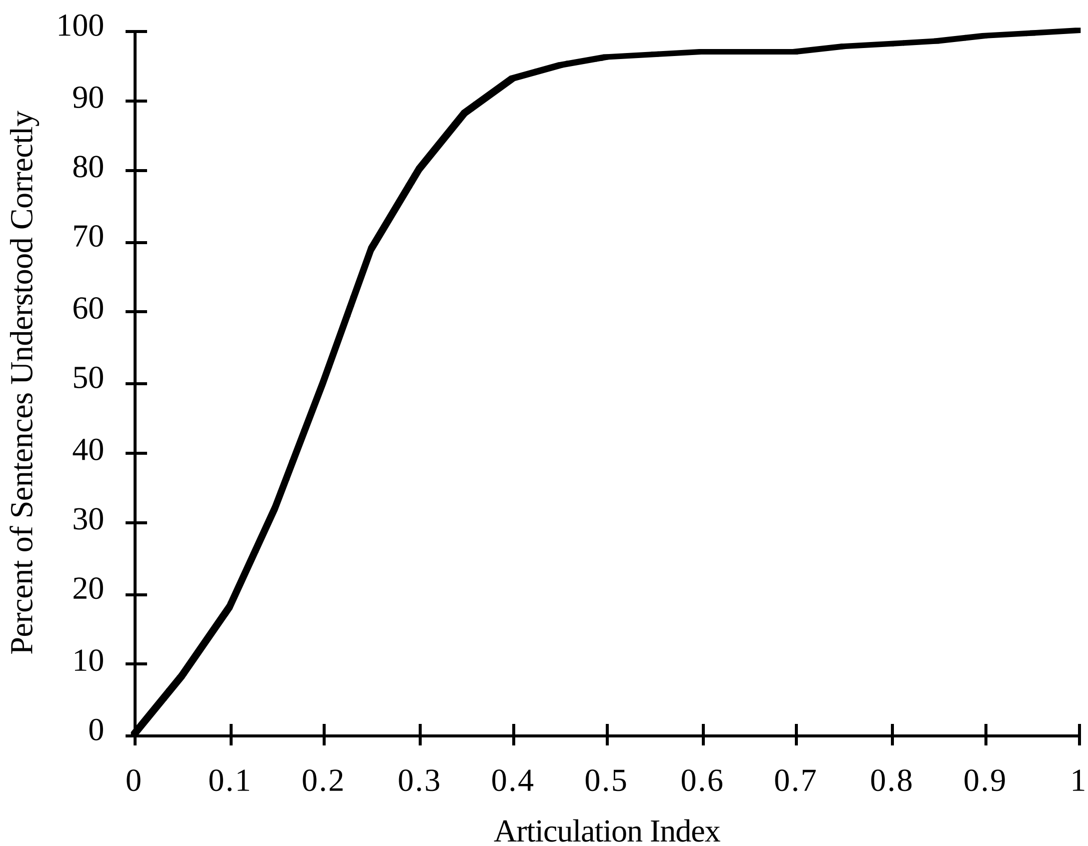

FIGURE 5.7. Relationship Between AI and Sentences First Presented to Listeners (from ANSI S3.5-1969)

Few studies have calculated an Articulation Index for speech intelligibility in truck-cab noise. Morrison and Casali (1993) calculated an AI for synthesized (computer-produced) speech in truck-cab noise at different speech to noise ratios (S/N ratios), although ANSI S3.5-(1969) was written before synthesized speech was in common use, and therefore was not designed with this application in mind. Using the modified rhyme test (MRT) as the experimental paradigm, the highest intelligibility score achieved empirically for synthesized speech in truck-cab noise was just 72% at a speech-to-noise ratio (S/N) of 15 dB. When background speech noise such as that produced by a CB or stereo was added, the intelligibility dropped to less than 60%. The results were even worse for individuals suffering from a mild hearing loss. In contrast, using the AI to predict the intelligibility of real speech under the same noise conditions resulted in intelligibility exceeding 90% in all cases (Morrison and Casali, 1993), indicating that this analytic measure was not a good predictor of the actual intelligibility of synthesized speech in heavy vehicle noise. The major reason synthesized speech is so much less intelligible in noise is that even the best speech synthesizers available are not capable of accurately reproducing the subtleties of real human speech.

Micheal (1995a) also calculated the AI for several new trucks based on his own noise level measurements, but used only one speech spectrum: the ideal male voice spectrum presented in ANSI S3.5-1969 at a long-term SPL of 65 dB. The highest AI value calculated was 0.0318, and the typical AI was 0.0055. All AI calculations corresponded to very poor intelligibility ratings of less than 10%. Micheal's calculations were most applicable to a male seated in the passenger seat and speaking to the driver in a normal voice at 65 dB. Under these conditions, very little of what was being said would be intelligible. This scenario is unrealistic, however, since an increase in the speaker's vocal effort is reflexive when background noise levels increase. Micheal (1995a) did not make any further effort to calculate AI values for more realistic speech levels.

Currently there are two primary types of speech communication in truck cabs. The first is the speech communication that occurs over the CB radio and the second is the personal communication between two drivers who drive as a team. These were the conditions investigated herein. The problem was approached from two directions: "What vocal effort/radio output level is required for reliable communication in the various truck cab noise conditions?" and "What level of intelligibility can be achieved at *maximum* sustainable vocal effort/radio output level in the noisiest conditions?"

For personal, face-to-face communication, it was assumed that the shape of the voice spectrum would not differ significantly from the ideal male spectrum provided in ANSI S3.5-1969 and shown in Figure 5.8. Although the shape of the spectrum was retained, the broadband spectrum level could be as loud as 88 dB (a loud shout) to provide adequate intelligibility (Kryter, 1972). For the CB radio, actual measurements of frequency response characteristics were performed for 5 CB radios in the Auditory

Systems Laboratory at Virginia Tech, using the protocol detailed in Appendix C. The mean frequency response characteristics are found in Table 5.11. An upper level of 90 dB(linear) for the CB radio was assumed as the highest level of undistorted speech possible from a loudspeaker. When performing AI calculations, loudspeaker output levels greater than 90 dB are penalized for the distortion that begins to occur at such levels (ANSI, 1969).

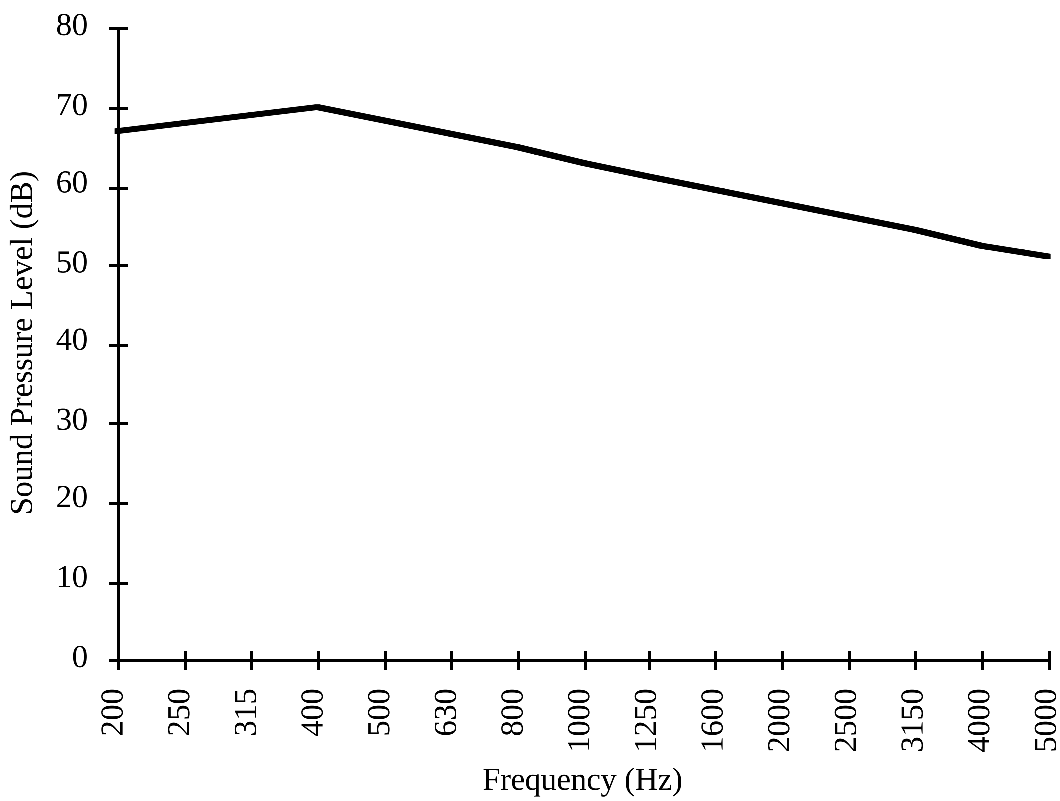

FIGURE 5.8. Idealized Speech Peaks - Male Voices, for Long Term RMS Level of 65 dB (adapted from ANSI S3.5-1969)

The acoustic profile of the truck-cab noise (the masking noise) was already available for use, based on the spectral measurements described earlier. The quietest and noisiest spectral profile for each of the eight truck-cab noise conditions was used for the AI calculations, so that a wide range of listening conditions would be represented. A decision was also made to use an 80% intelligibility score for sentences first presented to listeners as a criterion level for adequate truck cab communication. This is the most common form of speech heard in truck cabs, and corresponds to an AI of 0.30 (see Figure

5.7). With all of the necessary variables in hand, the speech level output required to achieve an AI of 0.30 for both the CB and live speech was calculated for all 16 conditions (both the noisiest and the quietest example for each of the 8 original truck-cab noise driving conditions), using the procedures specified in ANSI S3.5-1969. An AI of 0.30 was possible within the limits of 88 dB(linear) for live speech (per Kryter, 1972) and 90 dB(linear) for undistorted CB speech only for the 8 quietest conditions. For the 8 noisiest conditions, these constraints were violated, so the actual maximum achievable AIs were also calculated for these conditions. The results of these calculations are given in Table 5.12 for live speech and in Table 5.13 for CB speech.

TABLE 5.11. Mean Frequency Response Characteristics of 18 CB Radio Combinations

Frequency (Hz)	Mean CB Frequency Response (dB)
25	-10.5
31.5	-17.8
40	-28.1
50	-29.9
63	-33.7
80	-36.9
100	-38.1
125	-47.6
160	-45.0
200	-43.8
250	-35.3
315	-21.7
400	-9.7
500	-1.0
630	3.0
800	3.6
1000	3.2
1250	3.1
1600	1.5
2000	-0.7
2500	-2.4
3150	-8.2
4000	-15.2
5000	-28.5
6300	-40.8
8000	-43.6
10000	-44.7
12500	-41.8
16000	-37.2
20000	-32.7

TABLE 5.12. Summary of AI Calculations for Live Speech, Sentences First Presented to Listeners

Condition	Calculated AI	Intelligibility	Speech Level Required dB(linear)
Quietest Conditions			
WDV0R0	0.30	80%	82.1
WDV0R1	0.30	80%	88.5
WDV1R0	0.30	80%	83.4
WDV1R1	0.30	80%	87.4
WUV0R0	0.30	80%	71.8
WUV0R1	0.30	80%	82.8
WUV1R0	0.30	80%	71.8
WUV1R1	0.30	80%	76.4
Noisiest Conditions			
WDV0R0	0.30	80%	93.1
WDV0R1	0.30	80%	93.1
WDV1R0	0.30	80%	93.1
WDV1R1	0.30	80%	94.1
WUV0R0	0.30	80%	94.2
WUV0R1	0.30	80%	94.1
WUV1R0	0.30	80%	93.4
WUV1R1	0.30	80%	93.1
Noisiest Conditions	**Achievable AI**	**Achievable Intelligibility**	**Achievable Speech Level, dB(linear)***
WDV0R0	0.14	28%	88.0
WDV0R1	0.10	18%	88.0
WDV1R0	0.09	16%	88.0
WDV1R1	0.11	19%	88.0
WUV0R0	0.10	18%	88.0
WUV0R1	0.11	19%	88.0
WUV1R0	0.13	25%	88.0
WUV1R1	0.14	28%	88.0

Note: WD = Windows down; WU = Windows up; V0 = Ventilation off; V1 = Ventilation on; R0 = Radios off; R1 = Radios on.

***** per Kryter, 1972

TABLE 5.13. Summary of AI Calculations for CB Speech, Sentences First Presented to Listeners

Condition	Calculated AI	Intelligibility	Speech Level Required dB(linear)
Quietest Conditions			
WDV0R0	0.30	80%	82.6
WDV0R1	0.30	80%	89.3
WDV1R0	0.30	80%	84.0
WDV1R1	0.30	80%	88.0
WUV0R0	0.30	80%	73.0
WUV0R1	0.30	80%	84.4
WUV1R0	0.30	80%	73.0
WUV1R1	0.30	80%	77.8
Noisiest Conditions			
WDV0R0	0.30	80%	93.5
WDV0R1	0.30	80%	93.5
WDV1R0	0.30	80%	93.5
WDV1R1	0.30	80%	94.6
WUV0R0	0.30	80%	94.8
WUV0R1	0.30	80%	94.7
WUV1R0	0.30	80%	94.0
WUV1R1	0.30	80%	93.5
Noisiest Conditions	**Achievable AI**	**Achievable Intelligibility**	**Achievable Speech Level, dB(linear)**
WDV0R0	0.21	50%	90.0
WDV0R1	0.18	46%	90.0
WDV1R0	0.17	44%	90.0
WDV1R1	0.19	49%	90.0
WUV0R0	0.18	46%	90.0
WUV0R1	0.19	49%	90.0
WUV1R0	0.21	50%	90.0
WUV1R1	0.22	53%	90.0

Note: WD = Windows down; WU = Windows up; V0 = Ventilation off; V1 = Ventilation on; R0 = Radios off; R1 = Radios on.

The results showed that suitably reliable communication is possible in some of the noise conditions, while at other times, even at extreme vocal efforts/sound levels, only very low AIs are achievable. Under the noisiest conditions, vocal efforts for live speech would need to be at an unsustainable level (in the range of 93-94 dB) for reliable communication. Likewise, CB radio loudspeaker volume would need to be in the range of 93-95 dB, which would likely result in distortion and which would itself degrade communication. For live speech in the noisier conditions, the achievable AI ranged from 0.09-0.14, corresponding to intelligibility scores of 16-28%. For CB speech under the noisiest conditions, the achievable AI ranged from 0.17-0.22, corresponding to intelligibility scores of 44-53%. The results of these AI calculations were verified by observation. The experimenter noted that during some of the conditions, for some of the trucks, it was possible to carry on a conversation in a normal voice, while at other times adequate communication was impossible even with a raised or shouted voice. The truck driver often had to turn down the radio momentarily to make himself understood. *Overall, the truck cab environments studied herein are not conducive to good speech communication, whether the speech emanates from a CB radio or as live vocal efforts.*

Masked threshold of warning signals. One of the most widely accepted methods for determining the audibility of non-speech auditory displays, alarms and/or warnings in noise is outlined in ISO 7731-1986(E), "Danger Signals for Work Places–Auditory Danger Signals" (ISO, 1986). The procedure for calculating the masked threshold of a signal in noise, using one-third octave band analysis, is as follows:

Step 1: Starting at the lowest one-third octave band level available, the masked threshold (L_{T1}) for a signal in that band is:

$$L_{T1} = L_{N1},$$

where L_{N1} is the noise level measured in the one-third octave band in question.

Step 2: For each successive one-third octave band, n, the masked threshold (L_{Tn}) is the noise level in that band or the masked threshold in the preceding band, less a constant, whichever is *greater*:

$$L_{Tn} = \max(L_{Nn} ; L_{Tn-1} - C),$$

C = 2.5 dB for one-third octave band data.

As can be seen, masked thresholds depend solely on noise level. Once the masked thresholds are determined, the signals' spectra are compared to these masked thresholds to determine: a) if signals presented at known or prescribed levels are audible in these noise conditions and b) the levels at which these signals must be presented to be audible in these conditions. If one or more of the one-third octave band levels of the signal exceed the masked threshold level calculated for a particular noise condition (preferably in the frequency range from 300 to 3000 Hz), then the signal should be audible if being listened for attentively. To ensure audibility under adverse conditions (i.e., periods of high workload or inattention) the Standard recommends that the signal levels exceed the masked threshold levels by 13 dB (when the predictions are based on one-third octave band analyses). The Standard also requires that the hearing ability of the listener be taken into account, as must the attenuation of hearing protectors (in this case, the truck cab acts as a type of hearing protector in attenuating external sounds), but no guidelines are presented for doing so. It is usually assumed that if the signal levels are above the listeners' hearing threshold levels, then the signal should be audible. For HPDs, actual listening tests are suggested. The signals of interest can either be measured directly or known signal spectra can be used.

Warning signals commonly used to alert truck drivers include intentional in-cab auditory displays (e.g., a buzzer indicating a mechanical failure), sirens, train horns, and back-up alarms (see the Task Analysis section of this report for a complete discussion of hearing-critical truck driving tasks). To determine the audibility of such signals in truck-cab noise, the spectra of several warning signals were obtained. These spectra were obtained either from previously published material, or were measured directly using the RION SA-27 one-third octave-band analyzer. The 14 signals used in the audibility analysis were a train whistle at two distances, an emergency vehicle siren at two distances, a backup alarm at two distances, and 8 in-cab signals intended to warn or inform the driver. The acoustic profile of the truck-cab noise was already available from the measurements described earlier. These spectra were used to determine the masked threshold for each of the 14 signals in 18 noise conditions (the quietest and the noisiest example for each of the 8 truck-noise driving conditions, and the 2 engine-idle conditions). The engine idle conditions were felt to be important, since trucks are often stopped or moving very slowly when the driver is listening for some of these signals (such as at a railway crossing, loading dock, or stop light). The masked thresholds for each noise condition are presented in Table 5.14 and Table 5.15 for the quiet and noisy driving conditions, respectively, while Table 5.16 presents the masked thresholds for the engine idle conditions.

The attenuation of the truck cab was also considered for those signals originating outside the cab (i.e., the backup alarm, siren, and train horn). Appendix D presents the details of how the attenuation was determined by the insertion loss method. The insertion loss at each one-third octave band provided a correction factor for that band, shown in Table 5.17. For example, the insertion loss of the truck cab with the windows open was subtracted from the signal spectra when calculating the masked threshold for windows-open conditions. Likewise, the insertion loss of the truck cab with the windows closed was subtracted from the signal spectra when calculating the masked threshold for windows closed conditions.

TABLE 5.14. Masked Thresholds (in dB) Calculated per ISO 7731-1986(E) for Quietest of Each of 8 Listening Conditions

Frequency (Hz)	WD V0 R0	WD V0 R1	WD V1 R0	WD V1 R1	WU V0 R0	WU V0 R1	WU V1 R0	WU V1 R1
315	75.5	79.8	76.2	79.1	70.3	77.3	69.5	72.6
400	73.5	78.9	74.3	77.3	68.9	74.9	67.5	70.4
500	73.3	81.0	74.1	79.0	68.6	80.2	67.8	72.8
630	73.5	79.4	74.4	77.9	67.3	77.7	66.8	71.2
800	71.6	78.0	73.1	77.0	65.2	75.2	65.1	68.7
1000	69.9	77.3	71.4	76.3	62.7	73.1	62.6	66.2
1250	69.3	75.8	70.8	74.7	60.2	70.6	60.1	63.7
1600	68.1	75.0	69.5	73.8	57.7	71.4	57.6	63.1
2000	67.2	75.0	69.0	73.0	56.0	70.5	55.9	62.8
2500	66.2	73.6	67.9	72.0	54.8	68.5	54.8	60.3
3150	65.2	72.0	67.1	70.6	52.3	66.0	52.5	57.8
4000	64.3	70.7	66.2	69.7	49.8	63.5	50.2	55.3
5000	63.1	69.4	65.0	68.4	47.3	61.0	47.7	52.8

Note: WD = Windows down; WU = Windows up; V0 = Ventilation off; V1 = Ventilation on; R0 = Radios off; R1 = Radios on.

TABLE 5.15. Masked Thresholds (in dB) Calculated per ISO 7731-1986(E) for Noisiest of Each of 8 Listening Conditions

Frequency (Hz)	WD V0 R0	WD V0 R1	WD V1 R0	WD V1 R1	WU V0 R0	WU V0 R1	WU V1 R0	WU V1 R1
315	83.8	84.8	84.7	84.2	83.8	83.7	83.1	83.5
400	82.6	83.4	83.9	83.0	83.0	82.8	82.3	82.3
500	82.9	83.5	83.9	83.1	83.6	83.3	83.1	82.6
630	82.1	82.9	84.0	82.5	83.8	83.3	82.4	81.9
800	82.0	82.9	83.8	82.9	83.4	83.2	82.5	82.0
1000	81.2	82.1	82.6	82.1	82.2	82.0	81.8	80.9
1250	80.5	81.5	82.3	81.8	81.9	81.5	80.9	80.3
1600	79.3	80.7	81.7	81.0	81.2	80.9	79.9	79.3
2000	79.1	81.2	80.9	80.5	80.3	80.3	79.5	79.4
2500	78.1	80.1	80.0	79.2	79.3	79.4	78.3	78.2
3150	77.4	79.4	79.5	78.8	78.7	78.8	77.8	77.4
4000	76.4	78.5	78.4	77.6	77.6	77.6	76.7	76.5
5000	75.1	77.0	77.0	76.4	76.1	76.1	75.4	75.1

Note: WD = Windows down; WU = Windows up; V0 = Ventilation off; V1 = Ventilation on; R0 = Radios off; R1 = Radios on.

TABLE 5.16. Masked Thresholds (in dB) Calculated per ISO 7731-1986(E) for Engine Idle Conditions

Frequency (Hz)	Windows Up	Windows Down
315	60.9	61.1
400	60.2	58.7
500	61.0	60.2
630	60.7	60.8
800	60.0	59.7
1000	60.1	59.8
1250	57.6	57.3
1600	55.3	55.5
2000	53.2	53.6
2500	51.4	51.6
3150	48.9	50.1
4000	46.5	47.8
5000	44.4	45.3

TABLE 5.17. Insertion Loss (in dB) for Truck Cabs, Windows Down and Windows Up

Frequency (Hz)	IL, Windows Down	IL, Windows Up
315	5.8	27.5
400	11.2	31.9
500	9.5	31.1
630	11.1	30.4
800	7.8	27.7
1000	10.7	28.6
1250	11.1	32.9
1600	13.6	31.5
2000	7.7	26.2
2500	9.2	29.6
3150	10.4	32.0
4000	7.9	34.2
5000	11.5	37.2

Note for Tables 5.14 - 5.17: The one-third octave bands from 300-3000 Hz are critical for the audibility calculations per ISO 7731-1986(E), although frequencies up to 5000 Hz were considered in this analysis.

The methods presented in ISO 7731-1986(E) were then used to compare the acoustic profile of each warning signal (with the external signals adjusted for the attenuation of the truck cab) to the masked threshold for each noise condition to determine whether the signals were likely to be heard. The range of frequencies considered for the ISO 7731-1986(E) audibility analysis was extended up to the 5000 Hz band, as it became obvious that many of the signals had energy above 3000 Hz, but below 5000 Hz. In all cases, the signal levels were checked to determine at which bands, if any, the signal exceeded the masked threshold by 13 dB and at which bands, if any, the signal exceeded the masked threshold by less than 13 dB. The matrices presented in Tables 5.18 and 5.19 indicate which signals exceeded the masked threshold by 13 dB or more in at least one of the one-third octave-bands of interest (Table 5.18) and which signals exceeded the masked thresholds by less than 13 dB (Table 5.19). Examples of the actual numerical differences for the train horn in each noise condition appears in Appendix E. The complete set of tables (all signals, all conditions) can be found in Robinson, Casali, and Lee (1997).

Backup alarm. The one-third octave-band spectrum of a typical backup alarm had been measured previously by personnel from the Auditory Systems Laboratory. The alarm type was a Target Tech Model 112, and the original measurement was made 23 feet away from and directly in line with the alarm. The inverse distance law for sound (sound pressure decreases in inverse proportion to the square of the distance from the source) was then used to calculate the sound pressure level at 70 feet from the alarm. The 23-foot distance was believed to be typical of the distance from the truck cab to a forklift or other device operating alongside the truck. The 70-foot distance was believed to represent the distance from the truck cab to a forklift or other device directly behind a truck with a sleeper berth and a standard length trailer. The effective (adjusted for the attenuation of the truck cab) signal levels for the backup alarm at each distance for both the windows-up and windows-down conditions are shown in Table 5.20. For each of these four signal conditions, the backup alarm's spectrum was compared to the masked thresholds for each of the 18 noise conditions.

In none of the conditions or distances did the backup alarm exceed the masked threshold by 13 dB or more. At 23 feet, the backup alarm did exceed the masked threshold by less than 13 dB in the 800, 1250, 2500, and 4000 Hz bands in the engine idle, windows open condition, and in the 800 and 1250 bands in the quietest windows down, ventilation off, radios off driving condition. At 70 feet, the backup alarm exceeded the masked threshold in the 800 and 1250 Hz bands only for the engine idle, windows open condition, but by less than 13 dB. An examination of the effective signal spectra and the degree by which the signal exceeded the masked threshold revealed the frequencies most important for audibility of the backup alarm are 800 and 1250 Hz (primary) and 2500 and 4000 Hz (secondary). Overall, the backup alarm was found to have very poor audibility in the noise conditions studied herein.

TABLE 5.18. Matrix Showing Which Signals Exceed Masked Threshold by *at Least 13 dB** for Which Conditions in at Least One 1/3 Octave Band Between 315 and 5000 Hz

Signal / **Noise Condition**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Quietest														
WDV0R0	--	--	+	--	--	--	--	--	--	--	--	--	+	+
WDV0R1	--	--	--	--	--	--	--	--	--	--	--	--	--	--
WDV1R0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
WDV1R1	--	--	--	--	--	--	--	--	--	--	--	--	--	--
WUV0R0	--	--	--	--	--	--	+	+	+	--	+	+	+	+
WUV0R1	--	--	--	--	--	--	--	--	--	--	--	--	+	+
WUV1R0	--	--	--	--	--	--	+	+	+	--	+	+	+	+
WUV1R1	--	--	--	--	--	--	--	--	+	--	--	+	+	+
Noisiest														
WDV0R0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
WDV0R1	--	--	--	--	--	--	--	--	--	--	--	--	--	--
WDV1R0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
WDV1R1	--	--	--	--	--	--	--	--	--	--	--	--	--	--
WUV0R0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
WUV0R1	--	--	--	--	--	--	--	--	--	--	--	--	--	--
WUV1R0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
WUV1R1	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Idle														
Windows Down	--	--	+	--	--	--	+	+	+	--	+	+	+	+
Idle														
Windows Up	--	--	--	--	--	--	+	+	+	--	+	+	+	+

Note: + denotes that signal exceeds masked threshold by at least 13 dB for this condition. 1 = Backup alarm, 23 ft.; 2 = Backup alarm, 70 ft.; 3 = Siren, 66 ft.; 4 = Siren, 330 ft.; 5 = Train horn, 660 ft.; 6 = Train horn, 1320 ft.; 7 = All-purpose #1; 8 = All-purpose #2; 9 = All-purpose #3; 10 = Turn signal #1; 11 = Turn signal #2; 12 = Turn signal #3; 13 = Differential lock; 14 = Fifth Wheel. Actual signals are described in the text.

* - per ISO 7731-1986(E) guidelines.

TABLE 5.19. Matrix Showing Which Signals Exceed Masked Threshold by *Less Than 13 dB** in Which Conditions in at Least One 1/3 Octave Band Between 315 and 5000 Hz

Signal / **Noise Condition**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Quietest														
WDV0R0	+	--	+	--	--	--	--	+	+	--	--	+	+	+
WDV0R1	--	--	+	--	--	--	--	--	--	--	--	--	+	+
WDV1R0	--	--	+	--	--	--	--	+	+	--	--	+	+	+
WDV1R1	--	--	+	--	--	--	--	--	+	--	--	--	+	+
WUV0R0	--	--	--	--	--	--	+	+	+	+	+	+	+	+
WUV0R1	--	--	--	--	--	--	+	+	+	--	--	+	+	+
WUV1R0	--	--	--	--	--	--	+	+	+	+	+	+	+	+
WUV1R1	--	--	--	--	--	--	+	+	+	--	+	+	+	+
Noisiest														
WDV0R0	--	--	+	--	--	--	--	--	--	--	--	--	+	+
WDV0R1	--	--	+	--	--	--	--	--	--	--	--	--	--	--
WDV1R0	--	--	+	--	--	--	--	--	--	--	--	--	--	--
WDV1R1	--	--	+	--	--	--	--	--	--	--	--	--	+	+
WUV0R0	--	--	--	--	--	--	--	--	--	--	--	--	+	+
WUV0R1	--	--	--	--	--	--	--	--	--	--	--	--	+	+
WUV1R0	--	--	--	--	--	--	--	--	--	--	--	--	+	+
WUV1R1	--	--	--	--	--	--	--	--	--	--	--	--	+	+
Idle														
Windows Down	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Idle														
Windows Up	--	--	+	--	--	--	+	+	+	+	+	+	+	+

Note: + denotes that signal exceeds masked threshold but by less than 13 dB for this condition. 1 = Backup alarm, 23 ft.; 2 = Backup alarm, 70 ft.; 3 = Siren, 66 ft.; 4 = Siren, 330 ft.; 5 = Train horn, 660 ft.; 6 = Train horn, 1320 ft.; 7 = All-purpose #1; 8 = All-purpose #2; 9 = All-purpose #3; 10 = Turn signal #1; 11 = Turn signal #2; 12 = Turn signal #3; 13 = Differential lock; 14 = Fifth Wheel. Actual signals are described in the text.

* - per ISO 7731-1986(E) guidelines.

TABLE 5.20. Effective Signal Spectra (in dB) for the Backup Alarm (Band Level Minus Insertion Loss) for 23 ft. and 70 ft. Distances

Frequency (Hz)	**23 ft. Windows Down**	**23 ft. Windows Up**	**70 ft. Windows Down**	**70 ft. Windows Up**
315	52.7	31	43.0	21.3
400	47.1	26.4	37.4	16.7
500	50	28.4	40.3	18.7
630	46.2	26.9	36.5	17.2
800	**71.7**	51.8	**62.0**	42.1
1000	49.3	31.4	39.6	21.7
1250	**69.4**	47.6	**59.7**	37.9
1600	50.4	32.5	40.7	22.8
2000	48.9	30.4	39.2	20.7
2500	**59.8**	39.4	50.1	29.7
3150	46.6	25	36.9	15.3
4000	**53.1**	26.8	43.4	17.1
5000	37.2	11.5	27.5	1.8

Bold indicates that signal exceeds the masked threshold at this frequency for at least one of 18 conditions (see text for details).

Emergency vehicle siren. The one-third octave-band spectrum of a typical emergency vehicle siren had also been measured previously by personnel from the Auditory Systems Laboratory. Spectral measurements on a Federal Signal "yelp"-type siren were made at distances of 66 and 330 feet directly in front of the vehicle. The 66-foot distance was felt to represent a typical distance from the truck cab to an emergency vehicle directly behind a truck with a sleeper berth and a standard length trailer. The 330-foot distance was selected to allow the driver from 15-45 seconds to react if he/she heard the siren at that distance, depending of course on closing speed. The 15-second allowance assumed a worst case closing speed between the emergency vehicle and truck of 15 miles per hour. Effective signal spectra for the siren were calculated just as they were for the backup alarm and appear in Table 5.21.

The siren exceed the masked threshold by 13 dB or more in at least one of the one-third octave bands of interest for only two conditions (the engine idle, windows open condition and the quietest windows down, ventilation off, radios off driving condition) at the 66-foot distance, but not for any conditions at the 330-foot distance. This finding was corroborated by anecdotal reports and job observations in that some drivers reported being surprised to see an emergency vehicle passing them when they had not heard the siren as the vehicle approached. The siren exceeded the masked threshold by less than 13 dB at 66 feet for 10 of the 18 conditions at 800 Hz, and in the engine idle, windows open condition at 4000 Hz. At the 330-foot distance, the siren exceeded the masked threshold for only the engine idle, windows open condition at 1250 Hz. The three frequencies which appear to affect audibility of the siren to the greatest degree are 800 and 1250 Hz (primary) and 1600, 2500, and 4000 Hz (secondary). Although none of these frequencies are required to be tested by the FHWA, many of them fall within the range of the FHWA test frequencies. As with the backup alarm, the siren exhibited poor audibility characteristics for most truck noise conditions.

TABLE 5.21. Effective Signal Spectra (in dB) for the Siren (Band Level Minus Insertion Loss) for 66 ft. and 330 ft. Distances

Frequency (Hz)	66 ft. Windows Down	66 ft. Windows Up	330 ft. Windows Down	330 ft. Windows Up
315	37.2	15.5	31.2	9.5
400	32.6	11.9	26.2	5.5
500	36	14.4	27.5	5.9
630	33.1	13.8	27.5	8.2
800	**84.3**	**64.4**	56.2	36.3
1000	55.4	37.5	55.1	37.2
1250	34	12.2	**64.4**	42.6
1600	47.3	29.4	51.1	33.2
2000	39.8	21.3	34.7	16.2
2500	50.7	30.3	42.4	22
3150	41.9	20.3	35.6	14
4000	**51.4**	25.1	34.4	8.1
5000	40.5	14.8	25.4	-0.3

Bold indicates that signal exceeds the masked threshold at this frequency for at least one of 18 conditions (see text for details).

Train horn. The one-third octave-band spectral profile of a typical train horn was also measured for purposes of determining its audibility in truck noise. The horn tested was a 5-horn configuration, with 2 horns pointing to the front and three to the back. The horn was mounted on the side of the locomotive, near the top of the cab. The measurements were made at distances of 660 feet (1/8 mile) directly in front of and behind the locomotive. Two measurements were made from each direction and the results averaged to produce a mean spectral profile for a train horn at this distance. The inverse distance law was then used to calculate the sound pressure level at 1320 feet (1/4 mile) from the train.

A time study was performed to determine the length of time necessary for trucks to clear a typical rail-highway crossing. Measurements were obtained for the time required for each of 28 trucks to completely clear a distance equivalent to a double rail-highway crossing (one with 2 tracks) while starting from a full stop. The mean time to clear such a crossing was 10.4 seconds, while 95% of the trucks would be able to clear the crossing in 14.3 seconds. In 10 seconds, a train traveling at 45 m.p.h. (the speed limit for coal trains) would travel 651 feet (approximately 1/8 mile). In 15 seconds, a train traveling at 60 m.p.h. (the speed limit for freight trains) would travel 1320 feet (1/4 mile). The 1/8 and 1/4 mile distances thus represent the minimum safe distances at which the locomotive horn must be heard to allow the truck driver time to clear the crossing under the conditions stated above. These distances were felt to be representative of real-world listening conditions for truck drivers at rail-highway crossings. Coincidentally, 1320 feet is also the distance from the rail-highway crossing to the whistle post, the point at which the train first begins blowing the horn, and thus the first opportunity the driver would have to hear the horn (Mortimer, 1994). The effective signal levels for the train horn appear in Table 5.22.

In none of the conditions at either distance did the train horn exceed the masked threshold by 13 dB or more. The inability of truck drivers to hear train horns has been previously reported in the literature. Lerner et al. (1990) recommended that truck drivers be informed of the unreliability of train horns in providing warning, and advised to roll down their windows and turn off radios when approaching unguarded rail crossings (those with no physical barriers). Interestingly, the masked threshold was exceeded, but by less than 13 dB, at both the 1/8 and 1/4 mile distances for the engine idle, windows open condition in one or more of the one-third octave bands of interest. Given that drivers are often at their most attentive when stopped at a railroad crossing listening for a train horn, a train horn which exceeds the masked threshold is more likely to be heard than many other signals (such as sirens) to which the driver is not likely to be attending closely. This assumes, of course, that the driver does indeed bring the truck to a complete stop at the rail crossing, rolls the windows down, and turns off all noise producing accessories (radios, ventilation fans, etc.). Since train horns produce broadband sounds, all of the bands from 315 Hz through 3150 Hz are important in determining their audibility. This range includes all three of the test frequencies mentioned in the FHWA hearing level requirements (Federal Highway Administration, 1994).

TABLE 5.22. Effective Signal Spectra (in dB) for the Train Horn (Band Level Minus Insertion Loss) for 660 ft. and 1320 ft. Distances

Frequency (Hz)	660 ft. Windows Down	660 ft. Windows Up	1320 ft. Windows Down	1320 ft. Windows Up
315	**69.1**	47.4	**63.0**	41.3
400	**60.2**	39.5	54.2	33.5
500	**63.6**	42.0	57.5	35.9
630	**67.6**	48.3	**61.6**	42.3
800	**65.1**	45.2	59.1	39.2
1000	**59.9**	42.0	53.9	36.0
1250	**61.2**	39.4	55.1	33.3
1600	52.9	35.0	46.9	29.0
2000	**59.0**	40.5	53.0	34.5
2500	**57.0**	36.6	51.0	30.6
3150	**51.6**	30.0	45.6	24.0
4000	46.9	20.6	40.9	14.6
5000	40.0	14.3	34.0	8.3

Bold indicates that signal exceeds the masked threshold at this frequency for at least one of 18 conditions (see text for details).

In-cab signals. Measurements were also performed for eight in-cab auditory signals. These were obtained in three different truck cabs: a '97 Volvo VNL64T with a sleeper cab, a '97 Volvo WIATTES with no sleeper cab, and a '97 Volvo WXLL with a garbage truck cab. Two signals were measured in each of these cabs. The first was an all-purpose signal used to indicate low air pressure, low oil pressure, and high engine temperature, as well as other types of mechanical failures. These all-purpose signals varied slightly across the three cab types with two of these signals being tonal in nature and the third signal being more broadband. The all-purpose signal could only be measured with the truck idling, and measurements were also taken of the idle noise for each truck so that the difference between the idle noise and the truck noise could be analyzed. The second signal measured in all three cabs was the turn signal activation indicator (since trucks make wide turns, it is important for automobile safety that these signals not be left on inadvertently). Again, the signal varied somewhat between the three cabs. For the turn signal indicator, it was possible to measure the signal with the engine turned off. In one cab, two additional signals were also measured with the engine turned off — the differential lock activation indicator and the 5th wheel activation indicator, both of which sounded like compressed air escaping through the in-dash ventilation ducts. Insertion loss was not considered for the eight interior signals since the sounds originate within the truck cab rather than from outside the cab. In all cases, the levels were measured with the microphone at or near the driver's head position. The spectra for all eight of the interior signals are presented in Table 5.23. For the all-purpose signals, only those frequencies for which the signal exceeded the idle noise by at least 12 dB are represented, although in all three cases, the primary frequency, 4000 Hz, exceeded the background (idle) noise by more than 15 dB, as per ISO 7779-1988(E) (ISO, 1988).

TABLE 5.23. Interior Signal Levels (in dB)

Frequency (Hz)	All-Purpose #1	All-Purpose #2	All-Purpose #3	Turn Signal #1	Turn Signal #2	Turn Signal #3	Diff. Lock	5th Wheel
315	-----	-----	-----	51.9	47.4	44.4	**59.9**	**55.7**
400	-----	-----	-----	40.8	49.7	44.2	**63.2**	**58.5**
500	-----	-----	-----	42.3	54.2	40.2	**65.5**	**59.5**
630	-----	-----	-----	38.8	44.0	41.3	**63.5**	**64.3**
800	-----	-----	-----	39.0	39.0	34.8	**70.5**	**70.1**
1000	-----	-----	-----	41.8	38.6	38.6	**68.8**	**66.1**
1250	-----	-----	-----	35.7	38.8	34.9	**66.3**	**66.7**
1600	-----	-----	-----	35.0	46.4	46.7	**68.9**	**70.5**
2000	-----	**66.5**	-----	49.5	**59.3**	**61.3**	**72.3**	**70.0**
2500	-----	-----	**65.7**	35.6	46.0	45.0	**77.4**	**74.3**
3150	44.2	-----	**65.7**	38.0	**52.7**	49.0	**77.1**	**76.0**
4000	**63.8**	**67.2**	**70.1**	**51.0**	**63.3**	**69.3**	**77.4**	**76.8**
5000	-----	-----	**65.3**	36.0	**45.6**	**50.5**	**76.8**	**77.0**

Bold indicates that signal exceeds the masked threshold at this frequency for at least one of 18 conditions (see text for details).

The two tonal all-purpose signals (#1 and #2) exceeded the masked threshold by 13 dB or more in one or more of the one-third octave bands considered in four of the quietest conditions (the idle conditions with windows up and down and the two quietest windows up, radios off driving conditions). Both of these signals contained much of their energy in the 4000 Hz band, with additional energy for signal #1 in the 3150 Hz band and for signal #2 in the 2000 Hz band. All-purpose signal #3 exceeded the masked threshold by 13 dB or more in at least one one-third octave band in five of the eighteen conditions (the same four conditions as #1 and #2, as well as the quietest windows up, ventilation on, radios on condition). All-purpose signals #1 and #2 exceeded the masked threshold by less than 13 dB in six and eight of the eighteen noise conditions respectively, while the broadband signal (#3) did so in ten of the eighteen conditions, all in multiple frequency bands from 2500 Hz to 5000 Hz. (See Table 5.19 for more detail.) For all three all-purpose signals, 4000 Hz was the dominant frequency. The tonal signals (#1 and #2) also contained substantial peaks at 2000 Hz and 3150 Hz, while the broadband signal (#3) contained substantial energy from 2500 to 5000 Hz.

One of the turn signals (#1 in Table 5.23) did not exceed the masked threshold by 13 dB in any one-third octave band for any of the noise conditions, while the other two did so in only four (#2) and five (#3) of the eighteen noise conditions respectively (see Table 5.18). In each case, the turn signal contained most of its energy in the 4000 Hz band. Although turn signal #1 never exceeded the masked threshold by 13 dB for any condition, it exceeded the masked threshold by less than 13 dB for four of eighteen noise conditions, but only at 4000 Hz. Turn signal #2 did so for 5 conditions while turn signal #3 did so for eight of eighteen conditions (at several frequencies above 2000 Hz in both cases).

The differential lock activation indicator and the 5th wheel activation indicator were very similar broadband sounds containing substantial energy in most of the bands from 400 to 5000 Hz. Both signals exceeded the masked threshold by at least 13 dB in several one-third octave bands for 7 of the 18 noise conditions. Furthermore, both signals exceeded the masked threshold, but by less than 13 dB, in 16 of the 18 conditions. (See Table 5.19 for more detail.)

Discussion. A quick look at Table 5.18 reveals that signals rarely exceeded the masked threshold by the 13 dB recommended by ISO 7731-1986(E), and never in the noisier conditions. The masked threshold was exceeded to some degree less than 13 dB in fewer than half of all possible combinations of signals/conditions (Table 5.19). Again, the noisier driving conditions had very few signals which exceeded masked threshold. *Overall, this analysis shows that for these noise conditions, for these signals, there is generally a very poor probability of most signals being heard.* The one condition for which the masked threshold was exceeded for all signals was the engine idle, windows open condition. As discussed earlier, this is a condition under which truck drivers are often at their most attentive, especially when stopped at a rail-highway crossing or an intersection. Another factor which stands out from the audibility analysis is the fact that many of the internal signals have primary frequencies above 3000 Hz (specifically the all-purpose signals and the turn signal indicator). The warning signal design guidelines presented in ISO 7731-1986(E) are intended to increase audibility, and this Standard recommends that warning signals contain primary energy in the 300-3000 Hz range.

Hearing level requirements. In the past, when truck cab interior noise levels were higher, many sounds originating outside the cab were masked by the noise produced by the truck. Although this is still happening to some degree, especially in the noisier conditions reported herein, the attenuation of the truck cab now seems to be playing a larger role in reducing the audibility of these signals (while at the same time, reducing the noise exposure hazard to the operator's hearing). Many of the techniques manufacturers have used to make truck cabs quieter, such as greater use of insulation and sound absorptive materials, have also increased the cabs' attenuation of external sounds, including intentional and incidental warning signals. This reduction of exterior noise (see Table 5.17), especially with windows closed, had a large impact on the masked thresholds calculated for these external sounds. As manufacturers have striven to make the cab quieter, safer, and more comfortable for the driver, the sound level of external signals has remained unchanged, with the result that these signals are as difficult to detect today as they were 15 years ago when the greater problem was the masking noise inside the cab. Although the level of such exterior signals are not under the control of the truck manufacturers, interior signals are under the manufacturers' direct control. Manufacturers can manipulate the level, spectral, and temporal characteristics of interior signals to overcome the adverse sound environment inside truck cabs.

Masked threshold predictions based on ISO 7731-1986(E) are, and are intended to be, conservative. They are meant to apply to a large and diverse population, a wide variety of signals, and incorporate a substantial safety margin. [The reader is encouraged to review the brief discussion of the conservative nature of predicting masked thresholds in Robinson et al. (1997), Appendix F.] The question intended to be addressed by the Standard is: "At what level must a signal be presented to be audible in a given noise environment?" Once a threshold is determined for a signal, a safety factor (13 dB when the calculations are based on one-third octave-band analyses such as those described herein) is added to this masked threshold to account for such factors as the hearing level of the listeners, inattention, and response criteria. In this respect, the Standard serves as a design tool. The Standard can also be used as an evaluation tool, to determine if one or more specific alarms are audible in specific noise environments. It is in this respect that the Standard has been utilized in the preceding discussions.

A question not directly addressed by this or any other standard is: What hearing level must the listener possess to actually hear the signal in the noise environment? Although ISO 7731 does state explicitly that hearing-impaired individuals are to be considered in the predictions, it falls short of suggesting how this might be accomplished other than requiring actual listening tests when necessary (a highly impractical solution for this sort of research). Therefore, a different approach must be attempted.

There are two possible ways to approach the problem. First, establish the hearing level necessary to hear the signals as they occur in the environment, regardless of the presence of any masking noise produced by the truck. The rationale for this approach is that, since these levels represent the levels at which the signals occur naturally, if the listener cannot hear them in "relative quiet," then he/she could never hope to hear them in the presence of masking noise. The analytical method to be used for this approach is as follows:

1. Determine the band levels for each of the signals (for each distance from the source of the signal, where applicable).
2. Determine, for each individual signal at each distance, which one-third octave band(s) contain most of the signal's energy. The levels in these bands represent the various signals' *thresholds of audibility*. A functional definition of an auditory threshold is the sound pressure level at which the stimulus is *just audible* to an individual listening intently for it in the specified conditions. However, a signal presented at its threshold of audibility would only be detected between 50% and 75% of the time even under ideal conditions. To ensure audibility under less than ideal conditions (e.g., inattention), a signal must be presented at some level above its auditory threshold. The usual recommendation is to increase the signal level by 10 to 15 dB (Sorkin, 1987; Wilkins and Martin, 1978), while for one-third octave-band analyses, ISO 7731-1986(E) suggests adding 13 dB to the signal's threshold.
3. To enable the band levels in Step 2 to represent signal levels that can easily be detected most of the time, even under conditions of inattention, subtract 13 dB from these levels and let the resulting levels represent the signals' *true thresholds of audibility.*
4. Convert these *true thresholds of audibility* from dB sound pressure level to dB hearing level (dBHL) using the minimum audible field (MAF) conversions contained in ISO 226-1961(E), 1961. This would then represent the minimum hearing threshold level that would enable an individual (in his/her better ear) to reliably detect the signal in the absence of any masking noise or in noise whose spectrum was at or below his/her hearing threshold at the relevant frequencies. These calculations are presented in Table 5.24.

TABLE 5.24. Hearing Levels Required for Detecting Warning Signals in Quiet

Signal	Important Frequencies for Audibility (Hz)	Band Level at Each Frequency (dB)	Threshold of Audibility (Band Level minus 13 dB)	Hearing Level Required, dBHL (Thr. of Aud. minus MAF)
Backup Alarm (23 ft.)	800	79.5	66.5	62.1
	1250	80.5	67.5	63.6
	2500	69.0	56.0	57.2
	4000	61.0	48.0	51.9
Backup Alarm (70 ft.)	800	69.8	56.8	52.4
	1250	70.8	57.8	53.9
	2500	59.3	46.3	47.5
	4000	51.3	38.3	42.2
Siren (66 ft.)	800	92.1	79.1	74.7
	1600	60.9	47.9	45.3
	2500	59.9	46.9	48.1
	4000	59.3	46.3	50.2
Siren (330 ft.)	1250	75.5	62.5	58.6
	2500	51.6	38.6	39.8
Train Horn (660 ft.)	315	74.9	61.9	52.5
	400	71.4	58.4	51.2
	500	73.1	60.1	54.1
	630	78.7	65.7	60.5
	800	72.9	59.9	55.5
	1000	70.6	57.6	53.4
	1250	72.3	59.3	55.4
	1600	66.5	53.5	50.9
	2000	66.7	53.7	52.7
	2500	66.2	53.2	54.4
	3150	62.0	49.0	51.9
Train Horn (1320 ft.)	315	68.8	55.8	46.4
	400	65.4	52.4	45.2
	500	67.0	54.0	48.0
	630	72.7	59.7	54.5
	800	66.9	53.9	49.5
	1000	64.6	51.6	47.4
	1250	66.2	53.2	49.3
	1600	60.5	47.5	44.9
	2000	60.7	47.7	46.7
	2500	60.2	47.2	48.4
	3150	56.0	43.0	45.9

Note: Table continued on next page. Differences in the siren spectra at the two distances may be a measurement artifact caused by ground reflectance or environmental absorption.

TABLE 5.24 (Cont.). Hearing Levels Required for Detecting Warning Signals in Quiet

Signal	**Important Frequencies for Audibility (Hz)**	**Band Level at Each Frequency (dB)**	**Threshold of Audibility (Band Level minus 13 dB)**	**Hearing Level Required, dBHL (Thr. of Aud. minus MAF)**
All-purpose #1	3150	44.2	31.2	34.1
	4000	63.8	50.8	54.7
All-purpose #2	2000	66.5	53.5	52.5
	4000	67.2	54.2	58.1
All-purpose #3	2500	65.7	52.7	53.9
	3150	65.7	52.7	55.6
	4000	70.1	57.1	61.0
	5000	65.3	52.3	53.4
Turn Signal #1	4000	51.0	38.0	41.9
Turn Signal #2	2000	59.3	46.3	45.3
	3150	52.7	39.7	42.6
	4000	63.3	50.3	54.2
Turn Signal #3	2000	61.3	58.3	57.3
	4000	69.3	56.3	60.2
Differential Lock	400	63.2	50.2	43.0
	500	65.5	52.5	46.5
	630	63.5	50.5	45.3
	800	70.5	57.5	53.1
	1000	68.8	55.8	51.6
	1250	66.3	53.3	49.4
	1600	68.9	55.9	53.3
	2000	72.3	59.3	58.3
	2500	77.4	64.4	65.6
	3150	77.1	64.1	67.0
	4000	77.4	64.4	68.3
	5000	76.8	63.8	64.9
5th Wheel	400	58.5	45.5	38.3
	500	59.5	46.5	40.5
	630	64.3	51.3	46.1
	800	70.1	57.1	52.7
	1000	66.1	53.1	48.9
	1250	66.7	53.7	49.8
	1600	70.5	57.5	54.9
	2000	70.0	57.0	56.0
	2500	74.3	61.3	62.5
	3150	76.0	63.0	65.9
	4000	76.8	63.8	67.7
	5000	77.0	64.0	65.1

A second (and slightly more conservative approach) would be to base the hearing requirement on the masked threshold calculated for the quietest of the eighteen noise conditions investigated (engine idle, windows open for the external signals and engine idle, windows closed for the interior signals, since these conditions provided the greatest chance of audibility for these signals). For this approach, the rationale is that this condition is representative of situations where the truck might be stopped at a traffic light, railroad crossing, or loading dock, and the driver would need to be able to hear the siren of an approaching emergency vehicle, the backup alarm on a truck or forklift, or the horn of an approaching train. The "quietest" condition was chosen since, as before, if the driver cannot hear the relevant signal in the quietest of the truck noise conditions, he/she would have no hope of hearing it under noisier conditions. The procedures are similar to those outlined above, except that the levels in Step 1 now represent the masked threshold levels of the signals in the quietest noise condition, rather than the band levels as measured in the environment. Another difference is that in using the masked thresholds for the quietest condition as a starting point, the distances for the external signals do not matter, unless they affect the primary frequency (as is the case for the emergency vehicle siren).

Given the conservative nature of the ISO masked threshold predictions, the signals at these levels would exhibit greater audibility than if they were at their true masked thresholds (as determined empirically), but would probably not be detected 100% of the time. Subtracting 13 dB from the bands containing most of the signals' energy and converting to dBHL results in an estimate of the minimum allowable hearing levels to hear the signals in the quietest noise condition measured. These results are shown in Table 5.25. Note that in this table the signal bandwidths for signals represented more than once in the previous table (Table 5.24) have been combined and are not listed separately, because for this approach, it is not necessary to know the spectral levels for a specific distance or individual alarm, but simply the bandwidth of the signals for the general case or across a class of alarms (such as all-purpose signals). Recall that the hearing level requirements in this approach are based on the masked threshold for the quietest noise condition, and not on the actual signal levels.

TABLE 5.25. Hearing Level Required to Hear Signals in Quietest Condition (Engine Idle, Windows Open for Signals 1-3 and Engine Idle, Windows Closed for Signals 4-7)

Signal	Important Frequencies for Audibility (Hz)	Masked Threshold at this Frequency (dB)	Threshold of Audibility (MT minus 13 dB)	Hearing Level Required, dBHL (Thr. of Aud. minus MAF)
1. Backup Alarm	800	59.7	46.7	42.3
	1250	57.3	44.3	40.4
	2500	51.6	38.6	39.8
	4000	47.8	34.8	38.7
2. Siren	800	59.7	46.7	42.3
	1250	57.3	44.3	40.4
	1600	55.5	42.5	39.9
	2500	51.6	38.6	39.8
	4000	47.8	34.8	38.7
3. Train Horn	315	61.1	48.1	38.7
	400	58.7	45.7	38.5
	500	60.2	47.2	41.2
	630	60.8	47.8	42.6
	800	59.7	46.7	42.3
	1000	59.8	46.8	42.6
	1250	57.3	44.3	40.4
	1600	55.5	42.5	39.9
	2000	53.6	40.6	39.6
	2500	51.6	38.6	39.8
	3150	50.1	37.1	40.0
4. All-purpose	2000	53.2	40.2	39.2
	2500	51.4	38.4	39.6
	3150	48.9	35.9	38.8
	4000	46.5	33.5	37.4
	5000	44.4	31.4	32.5

Note: Table continued on next page.

TABLE 5.25 (Cont.). Hearing Level Required to Hear Signals in Quietest Condition (Engine Idle, Windows Open for Signals 1-3 and Engine Idle, Windows Closed for Signals 4-7)

Signal	Important Frequencies for Audibility (Hz)	Masked Threshold at this Frequency (dB)	Threshold of Audibility (MT minus 13 dB)	Hearing Level Required, dBHL (Thr. of Aud. minus MAF)
5. Turn Signal	2000	53.2	40.2	39.2
	3150	48.9	35.9	38.8
	4000	46.5	33.5	37.4
6. Differential Lock	400	60.2	47.2	40.0
	500	61.0	48.0	42.0
	630	60.7	47.7	42.5
	800	60.0	47.0	42.6
	1000	60.1	47.1	42.9
	1250	57.6	44.6	40.7
	1600	55.3	42.3	39.7
	2000	53.2	40.2	39.2
	2500	51.4	38.4	39.6
	3150	48.9	35.9	38.8
	4000	46.5	33.5	37.4
	5000	44.4	31.4	32.5
7. Fifth Wheel	400	60.2	47.2	40.0
	500	61.0	48.0	42.0
	630	60.7	47.7	42.5
	800	60.0	47.0	42.6
	1000	60.1	47.1	42.9
	1250	57.6	44.6	40.7
	1600	55.3	42.3	39.7
	2000	53.2	40.2	39.2
	2500	51.4	38.4	39.6
	3150	48.9	35.9	38.8
	4000	46.5	33.5	37.4
	5000	44.4	31.4	32.5

In establishing a hearing requirement, the question of bandwidth must be addressed in conjunction with the problem of establishing the minimum suggested hearing levels. (As used for the remainder of this discussion, "minimum suggested hearing level" means the least amount of hearing that would allow a driver to hear the signals, even though numerically, it represents the maximum hearing level in dBHL.) While several of the signals (train horn, differential lock and 5th wheel indicators) investigated are broadband sounds having energy fairly evenly distributed across a wide range of frequencies from 315 or 400 Hz to 4000 and 5000 Hz, others were of a tonal nature or had multiple tonal components (all-purpose alarms, siren). As implied in the ISO Standard, it is not absolutely necessary to hear all of the signal, but is important to hear the signal components in at least one band that contains much of the signal energy. An individual possessing sufficiently good hearing in one or more of the bands represented by the tonal signals should also be able to hear the broadband signals. The bandwidth containing all of the components of the tonal signals extends from 800 Hz (backup alarm and siren) at the low-frequency end to 4000 Hz (turn indicators and all-purpose signals) at the high-frequency end. This bandwidth is somewhat narrower than that represented by the broadband signals alone. It is therefore likely that an individual possessing adequate hearing in this range of frequencies would be able to hear all of the alarms represented.

However, an important question remains unanswered: what exactly is "hearing well enough?" or in other words, "What should the audiometric requirement be?" The answer depends on which of the two approaches is used. In the case where the signals are being listened for in "quiet," that is, as they were measured in the environment, the conservative approach would be to use the minimum hearing level for each band across all of the signals and conditions examined. These minimum suggested hearing levels for listening in "quiet" are shown in the second column of Table 5.26. For the approach based on the masked threshold levels of the quietest noise condition, the hearing threshold levels depend only on the masked threshold levels and do not directly depend on the signal levels. Rather, the signals' spectra are important only for identifying those bands that are critical for detecting the signals. The minimum suggested hearing levels for listening in noise are shown in the third column of Table 5.26. Remarkably, the two approaches provide very similar answers, with few differences greater than 5 dB. Another notable characteristic of this comparison is that the dBHL values also tend to cluster around 40 dBHL, which is the average level required by the FHWA for 500, 1000, and 2000 Hz.

TABLE 5.26. Suggested Minimum Hearing Levels for Detecting Warning Signals

1/3 Octave Band Center Frequency (Hz)	Minimum Suggested Hearing Level (listening in "quiet") (dBHL)	Minimum Suggested Hearing Level (listening in noise) (dBHL)
800	49.5	42.6
1000	47.4	42.9
1250	49.3	40.7
1600	44.9	39.9
2000	45.3	39.6
2500	39.8	39.8
3150	34.1	40.0
4000	41.9	38.7

CHAPTER 6: COMPARISON OF THE FORCED WHISPER TEST TO PURE-TONE AUDIOMETRY

Introduction

In order to answer the questions raised by the previous research on the forced whisper technique (as described in Chapter 1), an experiment in four parts was conducted. In the first part, family practice physicians were informally interviewed as to their experience in performing the forced-whisper test. The second experiment attempted to quantify the variability of forced whispers from a variety of whisperers with similar forced-whisper training as that reported by the physicians. This was an attempt to verify the results of King (1953). The third experiment attempted to quantify the test-retest reliability for the same whisperer and listener. In this experiment, an attempt was made to replicate real-world conditions (several physicians testing several patients), which has not been done before. Finally, the forced-whisper results were compared to the results of pure-tone audiometry to determine whether there is a correlation between audiometric tests and forced-whisper tests. This was an attempt to replicate the results found in most of the forced-whisper literature described previously.

Survey of Physicians

In order to get a baseline idea of the training and experience of physicians in performing the forced-whisper test, 7 family practice physicians were informally surveyed. Family practice physicians were used because they are representative of the general type of physician that a driver might seek out to obtain the biannual DOT physical. The questions used appear in Table 6.1. The results of the survey were used to develop the training for the whisperers participating in the other parts of the experiment. The physicians surveyed were either known to the experimenter, or known to a physician known to the experimenter, in order to gain their cooperation and trust.

TABLE 6.1. Questions Used in a Survey of Family Practice Physicians

Survey questions for Family Practice Physicians:

Information: The Auditory Systems Laboratory of the Virginia Tech Department of Industrial and Systems Engineering is conducting an experiment concerning a screening test known as the forced-whisper test. If you could answer the following very short questionnaire, it would extremely helpful to us. The survey is only this single page, and should take only 5-10 minutes to complete. Three other physicians besides yourself are being asked to complete this questionnaire. Thank you in advance for your help.

Instructions: Please just answer the questions below as quickly as possible, relying totally on your memory (do not refer to books or articles or ask other physicians). Your answers will remain totally anonymous, and are to be used only as a guideline for training subjects to perform the forced-whisper test for an experiment. If you have any questions, feel free to call Suzie Lee at 540-231-9086.

1. Have you performed the biannual physical examinations of truck drivers required by the Department of Transportation? ____________
2. How many of these examinations would you estimate that you perform in a year? ____________
3. How do you perform the hearing test required as part of this physical examination? ____
4. Have you ever heard of the forced-whisper test? ____________
5. If so, how would you define the forced-whisper test? ____________ ____
6. Do you formally perform the forced-whisper test? ____________
   a. How far away do you stand when performing the forced-whisper test? ____________
   b. Do you mask the patient's eyes when performing the test? ____________
   c. Do you mask the ear not being tested? How? ____________ ____
   d. What words or sentences do you normally use to test? ____________ ____
   e. Have you ever failed a driver based on the results of a forced-whisper test? ____________
7. Have you ever just estimated a driver's hearing level based on the rest of the examination?_______
8. Were you formally trained to perform the forced-whisper test? ____________
9. Was the forced-whisper test taught in medical school, in your memory? ____________
   a. If so, did you practice performing the test? ____________
   b. Was a certain level of proficiency or consistency on this test required to be demonstrated as part of your work in any course? _____________

Based on the results of the truck driver task analysis questionnaire, it was suspected that the forced whisper test is not being performed in the manner prescribed by the FHWA (see Appendix B). Of 80 truck drivers surveyed, 11% reported never having had a hearing test. Only 76% of drivers who reported having had a hearing test at all reported being tested within the past 24 months. Fourteen percent of those who reported having had a hearing test reported that their most recent hearing test was a forced-whisper test. From these reports, it seems as though truck driver hearing levels are being screened rather informally in some cases. Physicians may be judging driver hearing based on the rest of the physical examination, and the driver's communication ability as perceived during this examination. Indeed, the results of the physician survey bear out this hypothesis, and also highlight the fact that physicians are not performing the forced-whisper test in the specified manner (a true forced-whisper voice at 5 feet).

Table 6.2 presents the results of the survey. Of the 7 physicians who completed the survey, there was wide discrepancy in knowledge of and training in the forced-whisper method. As can be seen, although all physicians reported performing the biannual physical examinations, only 1 of 7 specified the whisper test when first asked how the hearing portion of the test is administered. The ticking watch/rubbing fingers method mentioned by two physicians is an older screening test similar to the forced-whisper test, but is not mentioned in the FHWA hearing requirement. Although 5 of 7 reported having heard of the forced-whisper test, none defined the "forced" part of the technique. Three reported performing the test at least occasionally, but none of these three reported the correct distance (five feet), instead performing the test at distances ranging from 1-2 feet. And although none reported masking the patient's eyes explicitly, 3 of 4 defined the whisper as being done out of the patient's line of sight (a detail not specified by the FHWA).

Only 2 of 4 physicians reported masking the ear not being tested, and each of the four reported using different words or phrases for testing. None of these 4 had ever failed a driver based on the results of the forced-whisper test. Only one of 7 acknowledged formal training in the forced-whisper technique, although 3 of 7 reported that it was taught in medical school. Only one of these three reported practicing the test in medical school, and no one reported that a proficiency in this test was a requirement of any medical school course.

TABLE 6.2. Results of a Survey of Family Practice Physicians

1. Have you performed the biannual physical examinations of truck drivers required by the Department of Transportation? **Yes, 7 of 7**

2. How many of these examinations would you estimate that you perform in a year? **3; 5; 6; 10-15 (2); 20; 25**

3. How do you perform the hearing test required as part of this physical examination? **Whisper test (1 of 7); Spoken voice (1 of 7); Audiometry (2 of 7); Ticking watch or rubbing fingers (2 of 7); Normal conversation (1 of 7)**

4. Have you ever heard of the forced-whisper test? **Yes, 5 of 7; No, 2 of 7**

5. If so, how would you define the forced-whisper test? **Stand behind patient and whisper; whispering commands behind patient; stand next to patient out of field of view and whisper; whispering into side of ear being tested and asking patient to repeat; see if patient can hear a "loud" whisper in each ear**

6. Do you formally perform the forced-whisper test? **Yes, 2 of 7; No, 4 of 7; Occasionally, 1 of 7**

    a. How far away do you stand when performing the forced-whisper test? **12 inches, 18 inches, 2 feet, 1 physician each**

    b. Do you mask the patient's eyes when performing the test? **No, 4 of 4; although 3 of 4 specified that test is done out of sight of patient**

    c. Do you mask the ear not being tested? How? **Yes, 2 of 4, with hand (1), patient does (1); No, 2 of 4**

    d. What words or sentences do you normally use to test? **Raise your hand; "number nine"; Tennessee, Virginia, Maryland; What is your name?**

    e. Have you ever failed a driver based on the results of a forced-whisper test? **No (4 of 4)**

7. Have you ever just estimated a driver's hearing level based on the rest of the examination? **Yes, 3 of 7; No, 4 of 7**

8. Were you formally trained to perform the forced-whisper test? **Yes, 1 of 7; No, 6 of 7**

9. Was the forced-whisper test taught in medical school, in your memory? **Yes, 3 of 7; No, 3 of 7; Maybe, 1 of 7**

    a. If so, did you practice performing the test? **Yes, 1 of 3; No, 2 of 3**

    b. Was a certain level of proficiency or consistency on this test required to be demonstrated as part of your work in any course? **No, 3 of 3**

Based on the results of this informal survey, there seems to be widely varying exposure to and knowledge of the forced-whisper test, and in no case does the physician seem to be aware of the specific requirements of the FHWA hearing requirement. For example, the two physicians who reported knowing nothing of the test were the ones who reported using the ticking watch/rubbing fingers method. The other five reported using the forced-whisper test at least occasionally or in the past, and none appeared to know the correct distance. No one seemed to be aware of the "forced" nature of the whisper to be used. The test words were not standardized, and 3 of the 7 reported occasionally estimating the hearing level based on the rest of the examination. Overall, the results of the physician survey support the aforementioned conjecture based on the driver task analysis questionnaire, that is: *the forced-whisper test is being performed informally and incorrectly, when it is performed at all.*

Variability of Forced-Whisper Intensity Within and Between Whisperers

Rationale. The first question that comes to mind with any free-field voice test such as the forced-whisper experiment is "Are the voice levels consistent enough to make the test meaningful?" To this end, an experiment was designed to answer this question for a highly controlled laboratory environment (and thus assuming that any variation would be even greater under real-world conditions).

Experimental design. There were three independent variables for this part of the experiment. The first was gender (a between-subjects variable with two levels). The second independent variable was word type, a within-subjects variable with three levels. Three types of words were tested, and each type had 10 different words nested within it. One set of words consisted of the ten digits (zero, one, ..., nine). Another set consisted of ten letters of the alphabet containing a mixture of sounds (the set of "a, c, e, f, h, i, l, o, r, u" was chosen, since it contains five vowels, five consonants, and minimal repetition of end sounds). The third set consisted of ten spondees. Spondees are two-syllable words with an equal stress on both syllables, such as baseball or cowboy (Katz and Ivey, 1994). Spondees are said to rise rapidly in intelligibility when intensity increases even slightly. For this reason they are considered ideal for determining speech thresholds. The spondees used were taken from a standard list published in audiology texts (duckpond, headlight, inkwell, whitewash, eardrum, schoolboy, greyhound, birthday, mousetrap, and pancake). These three word types were chosen because they represent all of the word types reported as test words in forced-whisper experiments to date. They were also thought to be more likely to represent the words physicians are currently using to perform the forced-whisper test, although the results of the physician survey did not bear this out. The third independent variable, also within-subjects, was trials, as each participant was asked to repeat each word three times. The dependent measure for this experiment was the rms sound pressure level of the forced-whisper words, and it was measured in dBA. The experimental design is depicted graphically in Figure 6.1.

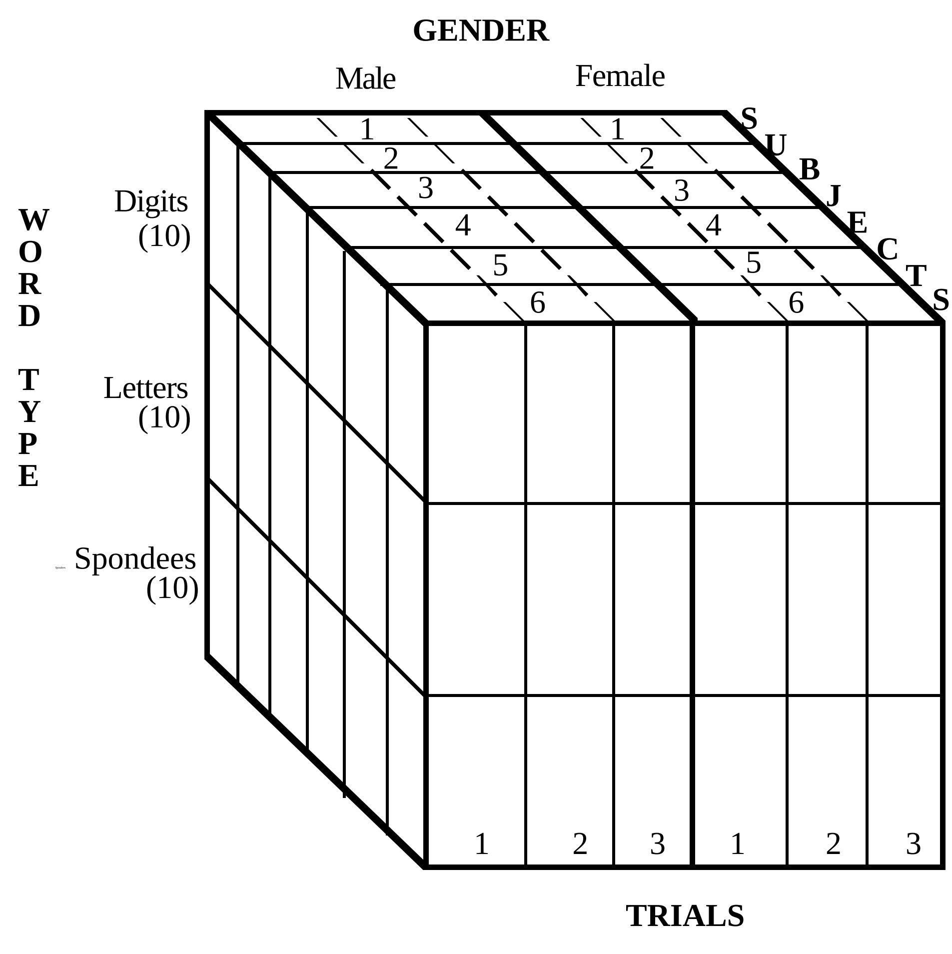

FIGURE 6.1. Experimental Design for the Forced-Whisper Variability Experiment

Procedure. Six males and six females were recruited to utter the forced whispers. The mean age of the participants was 27.4 years, with a minimum age of 23, to more closely represent the minimum age for practicing medical examiners such as nurses and physicians. Most were graduate students, again in an effort to replicate the professional status of medical examiners. All were non-smokers so that the effect of smoking on voice level was not a confounding factor. All were native English speakers, to reduce the possible confounding effect of accent on vocal intensity. Participants were screened for known respiratory problems such as colds, pneumonia, laryngitis, asthma, and bronchitis, which could also affect vocal intensity.

Before beginning the experiment, participants read and signed an informed consent form. The participants were trained on the technique of the forced whisper as much as was deemed necessary based on the survey of physicians. Participants were asked to read a one-page sheet of instructions defining and describing the forced-whisper technique. The experimenter then demonstrated the technique, after which the participant practiced the technique a few times. At this point, the participant was taken into the anechoic chamber in the Auditory Systems Laboratory for further practice under experimental conditions.

The whisperer was positioned so that his or her mouth was 5 feet away from a microphone positioned at the ear level of a 50th percentile standing male (160 cm from the floor). Whisperers stood on an anti-fatigue rubber mat while performing the forced whispers. The words to be whispered were presented via a timed Powerpoint presentation. A practice set of 9 words (3 of each type) was used to familiarize the whisperer with the word types and technique. Some whisperers required a second practice session before data collection could begin. The experimenter listened during the practice session and provided feedback as to perceived compliance with the forced whisper technique as well as overall consistency. The data collection phase began once the participant and whisperer were satisfied that the technique was mastered. Note that this amount of instruction and practice was at least as extensive as the training reported by physicians in the survey, and in many cases, the training for this experiment was more extensive.

Once the training was complete, the experimenter offered the whisperer a break, if desired. The data collection was broken into three 20-minute sessions with a 5 minute break between each one. During each session, the 30 words were presented on a laptop computer via a timed Powerpoint presentation. Spacer slides were inserted between each word. The spacer slide stayed up for 20 seconds, then the word slide appeared for 20 seconds. Once the word slide appeared, the whisperer had 20 seconds to exhale completely and say the word. Most whisperers completed this process in 8-12 seconds, and then had about 30 seconds of rest before the next word appeared. Although the same 30 words were used in each of the three trials, the order was varied for each trial. The screening, practice, data collection, and breaks added up to approximately 90 minutes per experimental session. Participants were compensated for their time at the conclusion of the experimental session.

Equipment and data collection. The anechoic room in the Auditory Systems Laboratory was used as the experimental environment. In pilot testing, it was discovered that the ambient noise levels in the other available laboratory rooms were too high to allow for detection of the very low sound pressure levels produced by the forced whisper technique. The ambient noise level of the anechoic chamber was measured to be between 10 and 15 dBA. A RION SA-27 one-third octave band spectrum analyzer with a 1/2 inch microphone/preamplifier assembly was used to collect the data, and was positioned as described earlier. The spectrum analyzer was calibrated to 94 dB at 1000 Hz before and after each use with a RION NC-73 calibrator. The spectrum analyzer was set for dB(A), fast (0.1s) response, and L_{eq} with a 1-second integration time. Data were collected in octave bands, rather than 1/3 octave bands, since only the broadband sound pressure level was of interest. This setting was found to be best for measuring the sound pressure level of short words, after some trial and error. The A-weighting scale was chosen since it provided the best sensitivity for these very low sound pressure levels which were also concentrated in the mid-frequency range of approximately 500-2000 Hz. The analyzer was used in STORE mode, meaning that each 1- second integration was stored in a separate memory location. The experimenter was seated in a chair to the right of the whisperer, and started the data collection when the word came up on screen, pausing the data collection after each word was whispered. The memory storage location of each word was marked on a checksheet for use in the data reduction phase. During the 5-minute break between trial sessions, the data were downloaded into the same laptop computer used to present the words.

Data analysis. The raw data were opened in a spreadsheet, and the broadband A-weighted sound pressure level for each word was picked out, using the memory storage location notes as guides (so that a cough would not be interpreted as a word, for example). In some cases, the word was broken over 2 storage locations, and in this case a log sum formula was used to combine the SPLs into a single value. Descriptive statistics (mean, standard deviation, and range) were calculated for each subject, gender, trial, word, and word type, as well for the grand sums. The data were analyzed using the SAS statistical package (the ANOVA procedure).

Results. The grand mean SPL across all words, subjects, and trials was 29.2 dBA, with a standard deviation of 8.1 dBA. Table 6.3 presents the descriptive statistics for subjects and gender, while Table 6.4 presents trials and word type. The words themselves are presented in Table 6.5. As can be seen, the minimum SPL across all subjects, words, and trials was 10.1 dBA, while the maximum was 49.6 dBA, for a grand range of 39.5 dB. The means across gender were very close, 28.8 for males and 29.6 for females.

The ANOVA summary table for the experiment is presented in Table 6.6. Using α = 0.05 as the criterion, the main effects of word type ($F_{2,20} = 4.84$, $p = 0.0193$) and trials ($F_{2,20} = 3.78$, $p = 0.0405$) were significant, as well as the nested effect of words/word type ($F_{27,270} = 4.31$, $p < 0.0001$). The main effect of gender was not significant. There were no significant interactions.

For the main effect of trials, a Duncan Multiple Range Test at $\alpha = 0.05$ showed trial 1 to be significantly higher in intensity (30.15 dBA), as compared to trials 2 and 3, which were not significantly different from one another (28.91 and 28.43 dBA, respectively). Figure 6.2 displays the comparisons for the main effect of trials. For the main effect of word type, the Duncan Multiple Range Test at $\alpha = 0.05$ showed spondees to be significantly higher in intensity (29.97 dBA), as compared to digits (28.68 dBA) and letters (28.85 dBA), which did not differ significantly from one another. These values are displayed graphically in Figure 6.3.

For words/word type, there were 4 overlapping groupings of words with significant differences from other groups of words. The largest of these groups, the C group (as shown in Figure 6.4), contained 26 of the 30 words, meaning that 87% of the words did not differ significantly from one another in SPL. The B group contained 25 words, the A group contained 24 words, and the D group contained 12 words. The only words not included in the C group were e (significantly quieter than the words in group C), and schoolboy, r, and i (significantly louder than the words in group C).

Since subjects seemed to show a large degree of variability in the SPL of the forced whispers, a one-way analysis of variance was performed with subjects as the independent variable (subjects could not be tested within the main ANOVA, since it was used as an error term). The ANOVA summary table for subjects is presented in Table 6.7. Using α = 0.05 as the criterion, the subjects variable was significant ($F_{11,1068}$ = 173.884, p = 0.0001). A Duncan Multiple Range Test at α = 0.05 showed some degree of overlap between subjects, which mostly occurred in pairs, as shown in Figure 6.4.

TABLE 6.3. Descriptive Statistics Summary Table for the Forced-Whisper Variability Experiment, Subjects and Gender (all SPL values in dBA)

Subject	**Gender**	**Age**	**Mean SPL**	**Std. Dev.**	**Min. Value**	**Max. Value**	**Range**
Subject 1	M	24	26.8	4.6	15.5	35.9	20.4
Subject 2	M	27	29.6	4.7	22.1	39.5	17.4
Subject 3	M	26	26.0	6.5	10.1	39.0	28.9
Subject 4	F	31	21.1	5.5	12.9	32.7	19.8
Subject 5	F	23	35.5	5.1	24.6	44.0	19.4
Subject 6	F	31	29.5	3.8	17.8	37.3	19.6
Subject 7	M	25	31.2	5.1	18.3	41.8	23.5
Subject 8	M	28	22.1	6.7	10.9	41.5	30.6
Subject 9	F	29	17.4	2.9	12.2	28.8	16.6
Subject 10	F	32	34.6	4.8	24.5	49.6	25.1
Subject 11	F	28	39.3	3.7	25.1	46.4	21.3
Subject 12	M	25	36.9	3.5	29.2	44.9	15.7
Male	6	25.8	28.8	7.0	10.1	44.9	34.8
Female	6	29.0	29.6	9.1	12.2	49.6	37.4
Grand Mean	**12**	**27.4**	**29.2**	**8.1**	**10.1**	**49.6**	**39.5**

TABLE 6.4. Descriptive Statistics Summary Table for the Forced-Whisper Variability Experiment, Trials and Word Types (all SPL values in dBA)

Trials	**Mean SPL**	**Std. Dev.**	**Min. Value**	**Max. Value**	**Range**
Trial 1	30.2	7.7	12.9	49.6	36.7
Trial 2	28.9	8.1	10.9	44.8	33.9
Trial 3	28.4	8.4	10.1	45.0	34.9
Mean	**29.2**	**8.1**	**10.1**	**49.6**	**39.5**

Word Type	**Mean SPL**	**Std. Dev.**	**Min. Value**	**Max. Value**	**Range**
Digits	28.7	8.1	11.2	45.3	34.1
Letters	28.9	8.2	10.1	49.6	39.5
Spondees	30.0	8.0	13.0	44.8	31.8
Mean	**29.2**	**8.1**	**10.1**	**49.6**	**39.5**

TABLE 6.5. Descriptive Statistics Summary Table for the Forced-Whisper Variability Experiment, Individual Words (all SPL values in dBA)

Word	**Mean SPL**	**Std. Dev.**	**Range**
zero	29.7	7.7	27.5
one	28.2	8.2	29.5
two	26.7	6.9	25.3
three	26.5	7.7	28.8
four	28.4	8.7	28.2
five	29.9	8.6	31.5
six	29.9	9.2	30.6
seven	30.5	7.7	27.7
eight	28.0	7.6	26.5
nine	28.9	8.0	30.2
a	26.7	7.0	28.9
c	29.3	8.2	27.8
e	24.4	7.5	26.4
f	27.5	8.4	28.6
h	28.4	8.0	27.0
i	32.7	8.2	32.5
l	30.3	7.5	36.7
o	30.8	8.4	31.4
r	31.5	7.9	29.2
u	27.0	8.0	30.9
greyhound	30.2	8.6	27.6
schoolboy	31.4	6.9	24.1
inkwell	30.2	7.9	29.7
whitewash	31.0	9.0	31.4
pancake	28.5	6.6	21.0
mousetrap	31.0	8.5	30.0
eardrum	30.1	8.4	27.6
headlight	29.3	8.4	25.7
birthday	28.4	8.2	28.4
duckpond	29.7	8.0	31.8
Grand Mean	**29.2**	**8.1**	**28.8**

TABLE 6.6. ANOVA Summary Table for the Forced-Whisper Variability Experiment (mixed factor, partially hierarchical design)

Source of Variation	**df**	**SS**	**MS**	**F value**	***p* value***
Between					
Gender (G)	1	169.219	169.219	0.0037	0.9525
Subjects / Gender (S/G)	10	45288.168	45288.168		
Within					
Trials (T)	2	569.078	284.539	3.7788	**0.0405**
T x G	2	48.807	24.404	0.3241	0.7269
T x S/G	20	1505.978	75.299		
Word Type (WT)	2	351.826	175.913	4.8428	**0.0193**
WT x G	2	17.342	8.671	0.2387	0.7899
WT x S/G	20	726.496	36.325		
Words (W) / WT	27	3037.039	112.483	4.3089	**<0.0001**
W/WT x G	27	846.131	31.338	1.2005	0.2320
W/WT x S/G	270	7048.410	26.105		
Trials (T) x WT	4	67.471	16.868	1.0832	0.3777
T x WT x G	4	16.385	4.096	0.2630	0.8999
T x WT x S/G	40	622.864	15.572		
T x W/WT	54	1123.694	20.809	1.3399	0.0641
T x W/WT x G	54	951.958	17.629	1.1267	0.2563
T x W/WT x G x S/G	540	8449.139	15.647		
Totals	**1079**	**70840.003**			

***Bold** indicates significance at $p < 0.05$

TABLE 6.7. ANOVA Summary Table for the Subject Variable

Source of Variation	**df**	**SS**	**MS**	**F value**	***p* value***
Between					
Subjects	11	45457.387	4132.490	173.88	**0.0001**
Error	1068	25382.617	23.766		
Totals	**1079**	**70840.003**			

***Bold** indicates significance at $p < 0.05$

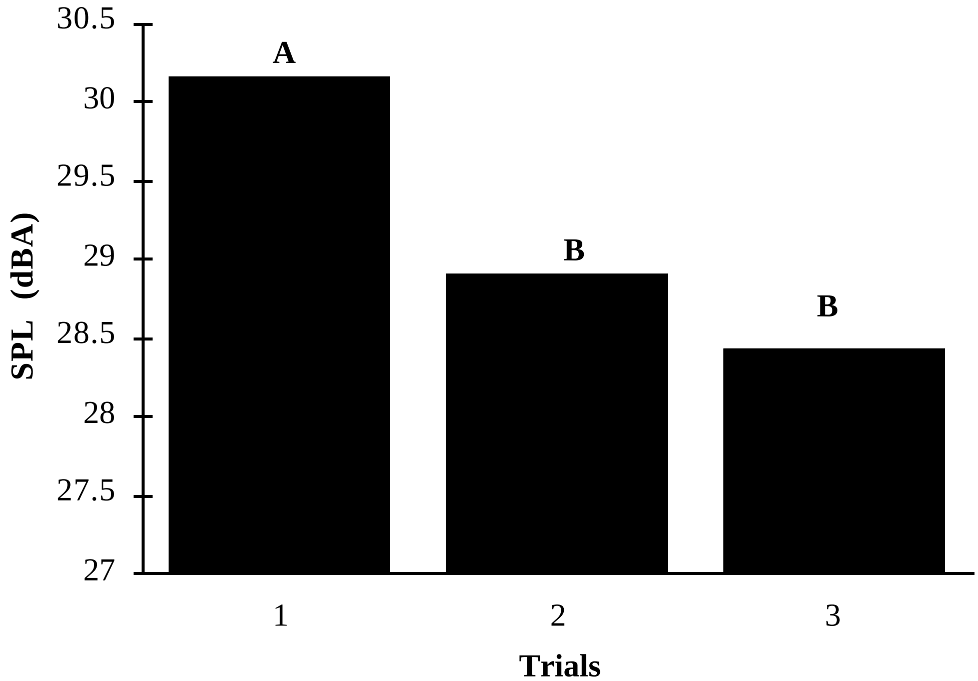

FIGURE 6.2. Main Effect of Trials (points marked with different letters are significantly different using a Duncan Multiple Range Test at $\alpha =$ 0.05).

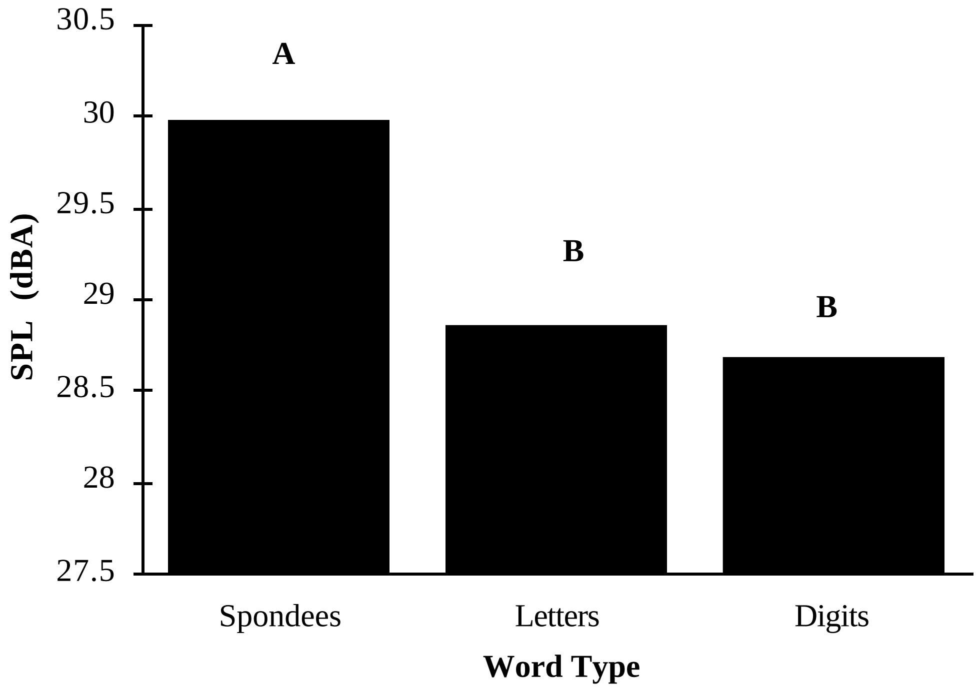

FIGURE 6.3. Main Effect of Word Type (points marked with different letters are significantly different using a Duncan Multiple Range Test at $\alpha = 0.05$)

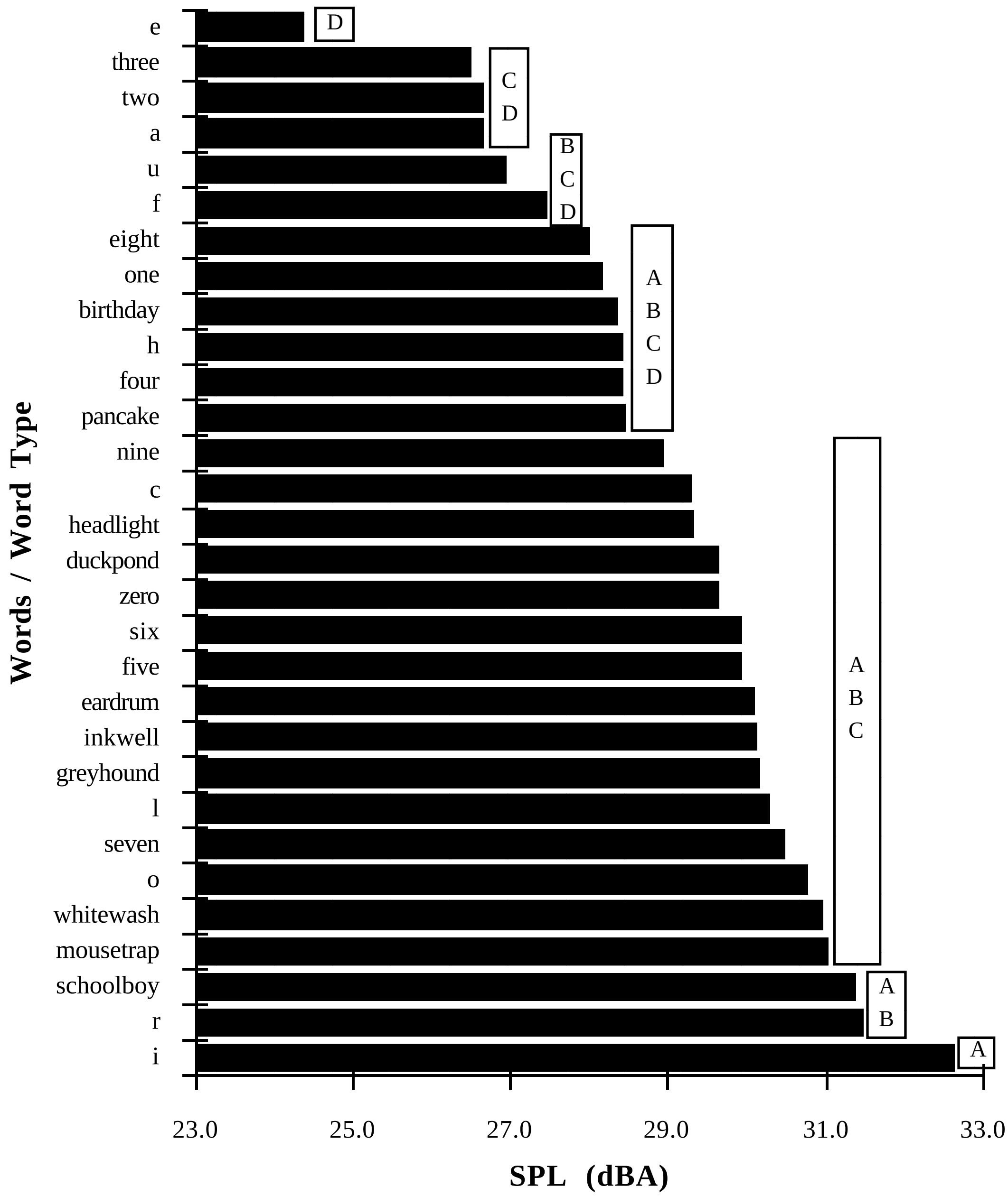

FIGURE 6.4. Main Effect of Words/Word Type (points marked with the same letter are not significantly different using a Duncan Multiple Range Test at $\alpha = 0.05$)

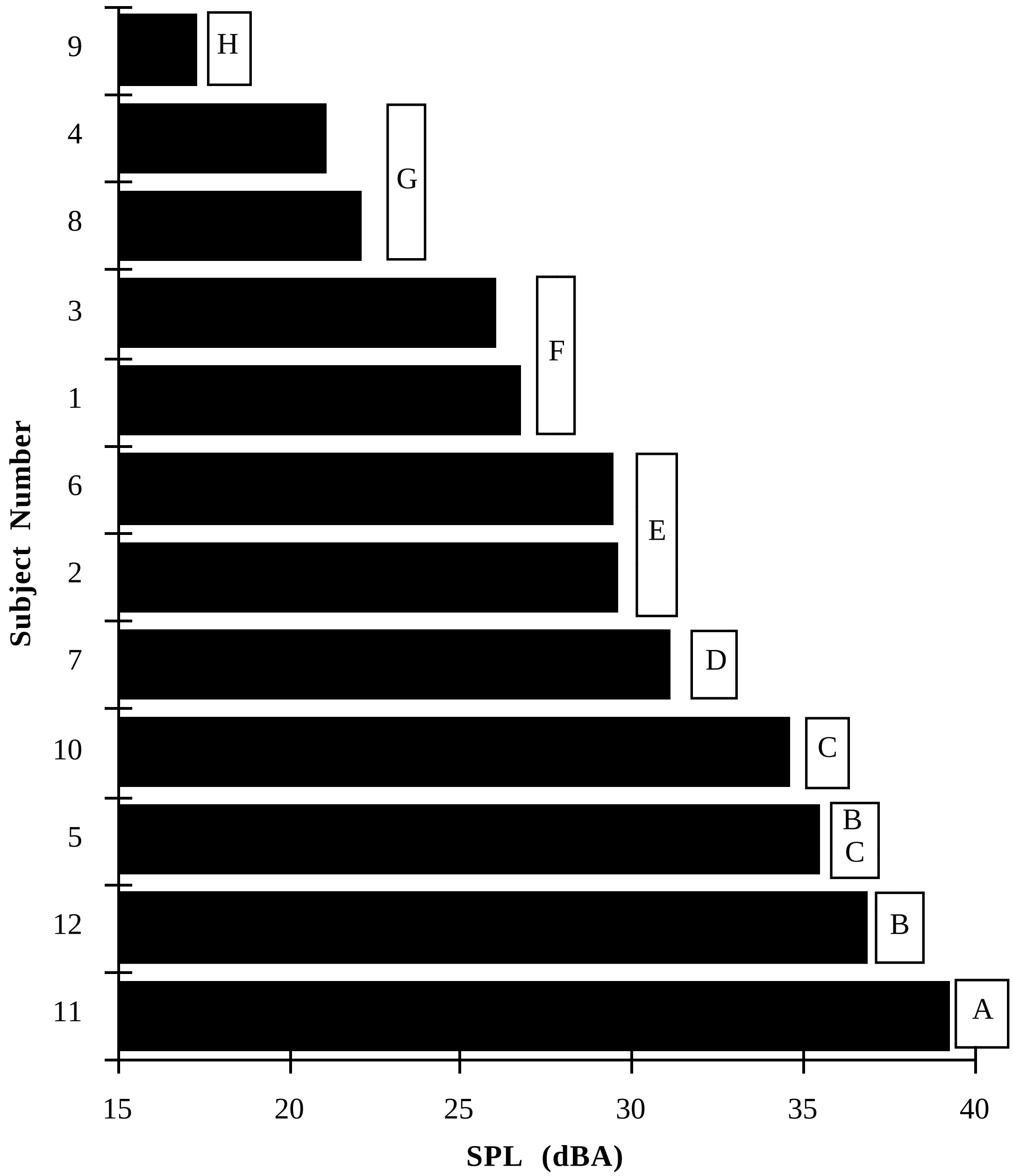

FIGURE 6.5. Subjects Variable (points marked with the same letter are not significantly different using a Duncan Multiple Range Test at $\alpha = 0.05$)

Discussion. The main effect of trials was significant, in that the vocal intensity for the first trial was greater than for the subsequent two trials. There are two explanations for this difference: a learning (or practice) effect, and a fatigue effect. If fatigue were the cause, one might expect that there would also be greater variation (as measured by standard deviation) in the latter two trials, whereas if there was a practice effect, the opposite might be true, and the standard deviation might decrease in the latter two trials, as whisperers gained more control over the whispering technique. In fact, the standard deviation increased throughout the trials, increasing from 7.7 dB in the first trial to 8.1 and 8.4 dB in the second and third trials, respectively, indicating that fatigue may be the cause for the significance of the trials main effect. In future experiments of the forced-whisper test, rest breaks of longer than five minutes should be provided, or fewer words should be tested in the overall session. From a practical standpoint, this also indicates that in training for the forced whisper test, most whisperers will be able to achieve low variability without excessive practice.

For the main effect of word type, spondees produced a higher SPL than letters or digits. This is probably due to the two-syllable nature of spondees, as compared to the single-syllable letters and digits (with the exception of zero and seven). As a result, the one-second integration period was nearly completely filled with sound for a spondee, while there was some dead time when a letter or digit was whispered. While spondees are said to increase rapidly in intelligibility with minimal increases in vocal intensity, they do not seem well-suited for the forced-whisper test. Because the whisperer is using only residual air, long words are difficult to complete using this technique. Nearly all of the whisperers expressed concern that it was difficult to articulate the spondees with the forced whisper technique, especially some of the longer ones such as schoolboy, greyhound, and mousetrap. In fact, the end of the spondee was often cut off as the whisperer simply ran out of air. And as will be seen in the subsequent two experiments, spondees exhibited lower intelligibility in forced-whisper testing involving a listener. For these reasons, spondees are not well-suited as test materials for the forced-whisper test.

For the words themselves, most of the variation is probably due to the different lengths of the words, especially as discussed previously in relation to spondees, as well as the different sounds required to articulate the word. For example, the words a, eight, and h are all in the lower one-third of SPL ranking, and all contain the short *a* sound. In choosing words to use as test materials, some consideration should also be given to low variability. The twelve letters and digits (disregarding spondees for the aforementioned reasons) with the lowest variability include (in ascending order): two, a, e, l, eight, zero, seven, three, r, u, h, and nine. Of these, e and r are significantly different in SPL from the others, as described above (see Figure 6.4). This leaves a set of ten digits and letters with low variability, which do not differ significantly in SPL, and which are easy to articulate using the forced-whisper technique. Based on the results of this experiment, a recommended list of forced-whisper test words would thus be: two, a, l, eight, zero, seven, three, u, h, and nine.

Perhaps the most important finding for this experiment is the large degree of variation in sound pressure level between subjects. The experiment described herein provided very standardized conditions for performing the forced whisper vocal technique. Subjects fell within a fairly narrow age range, all were non-smokers with no known respiratory problems, and all were native English speakers. All received the same training, performed the test under the same acoustic conditions, and were tested using the same words. Despite these tight experimental controls, there was significant variation in the vocal intensity of the forced whispers. Under real-world conditions, with wide variations in age, lung capacity, accent, test words, and acoustic environment, the amount of variation would almost certainly be even larger. *On the basis of variability in measured sound pressure levels among live forced whispers, therefore, the forced-whisper test would seem to be a highly subjective method of screening or testing hearing.*

Test-Retest Reliability of Forced-Whisper Test

Rationale. Although empirical testing of the vocal intensity of the forced whisper showed wide variation, it is still possible that, as used in practice, the forced whisper test might prove to be a valid testing or screening technique. For this reason, an experiment was designed to measure the test-retest reliability of the forced whisper technique, using live whisperers and listeners.

Subjects. Two males and two females were recruited as whisperers for this experiment. The data for the whisperers in the first experiment were examined to find those whisperers with the least variability (as measured by standard deviation) and who had means closest to the grand mean across all subjects. One of the whisperers chosen in this manner declined to participate in this second experiment, so the next best candidate was recruited. These whisperers had the advantage of already being trained in this vocal technique, and being well-practiced in the words to be used. Twelve listeners were also recruited, six males and six females. The listeners were all screened using pure-tone audiometry, and all had pure-tone average (PTA) hearing levels of better than 20 dBHL measured over 500, 1000, and 2000 Hz in each ear. Three listeners were assigned to each whisperer without regard to gender-matching so that there were twelve whisperer-listener pairs. Each listener was tested two times using a live forced-whisper test, at a minimum of one week apart, in order to test the reliability of a single whisperer with a single listener over time. Each ear was tested in both the test and the retest, and the pass/fail data for each ear was recorded, for a total of 24 ears tested two times apiece.

Procedure. After reading and signing an informed consent form, the whisperer was screened via a pure-tone audiometry test. If the subject passed the screening test, a whisperer/listener session was scheduled. All forced-whisper tests were performed in Room 519N of the Auditory Systems Lab, a room with similar acoustic characteristics to those of a physician's office. Subjects and listeners received different instruction sheets informing them of specific aspects of the test. For example, listeners were advised as to the three *types* of words for which they would be listening, while whisperers were reminded of the definition and technique for the forced whisper.

The best method for masking the ear not being tested was determined through pre-testing. The two choices investigated were tragal masking or a soft foam earplug. Swan (1989) found tragal rubbing to be more effective then the Bárány noise-box in masking the untested ear in a forced-whisper test. Swan defined tragal rubbing as occlusion of the meatus by finger tip pressure and then rotation of the finger tip to create a noise in the ear. In testing, both the experimenter and listener found the tragal masking technique to be uncomfortable and distracting, so the earplug was used. Although some listeners also found the earplug to be uncomfortable, none reported it to be distracting.

The eighteen words from Experiment 1 with the least variability across whisperers were chosen for use in these tests, six from each category of digits, letters, and spondees. Words were organized into three-word sets, with each set containing one word of each type. The same 18 words were reorganized into different sets for use in the retests. The sets are presented in Table 6.8.

TABLE 6.8. Words Used for the Forced-Whisper Test-Retest Experiment

Test:	
Right Ear	**Left Ear**
Group 1	**Group 1**
h	pancake
five	a
headlight	two
Group 2	**Group 2**
schoolboy	seven
eight	r
u	birthday
Group 3	**Group 3**
nine	l
e	duckpond
inkwell	three
Retest:	
Right Ear	**Left Ear**
Group 1	**Group 1**
two	headlight
l	e
duckpond	nine
Group 2	**Group 2**
pancake	u
seven	inkwell
a	five
Group 3	**Group 3**
three	eight
birthday	h
r	schoolboy

After reading the instructions and having the soft foam earplug inserted into the ear not being tested, the whisperer and listener were instructed to stand at marked positions five feet apart (the experimental layout is shown in Figure 6.6). The listener was positioned with his or her back to the whisperer in order to avoid any possibility of lip-reading. Listeners were asked to write down the set of three test words presented by the whisperer (it took approximately 30 seconds to present the 3 words, since the whisperer had to inhale and then exhale completely after each word). If the listener understood two of three words correctly, they were considered to have passed the test for that ear, and the other ear was then tested in the same manner. Listeners had three chances to pass the test for each ear (each chance consisting of a different three word set as shown in Table 6.8), and the test terminated at any point in which the listener was able to write down two of the three words in the set correctly (spelling was not considered important, e.g., 'see' for the letter 'c' was accepted). For each ear tested, a pass/fail mark (at trial 1, 2, or 3) was recorded as the dependent measure. Each test took approximately 10 minutes to complete. Whisperers and listeners were compensated for their time at the end of each experimental session.

After a period of time ranging from 7-41 days, the same listener/whisperer pair returned to the laboratory for a retest session, which was identical to the first session, except that different word sets were used.

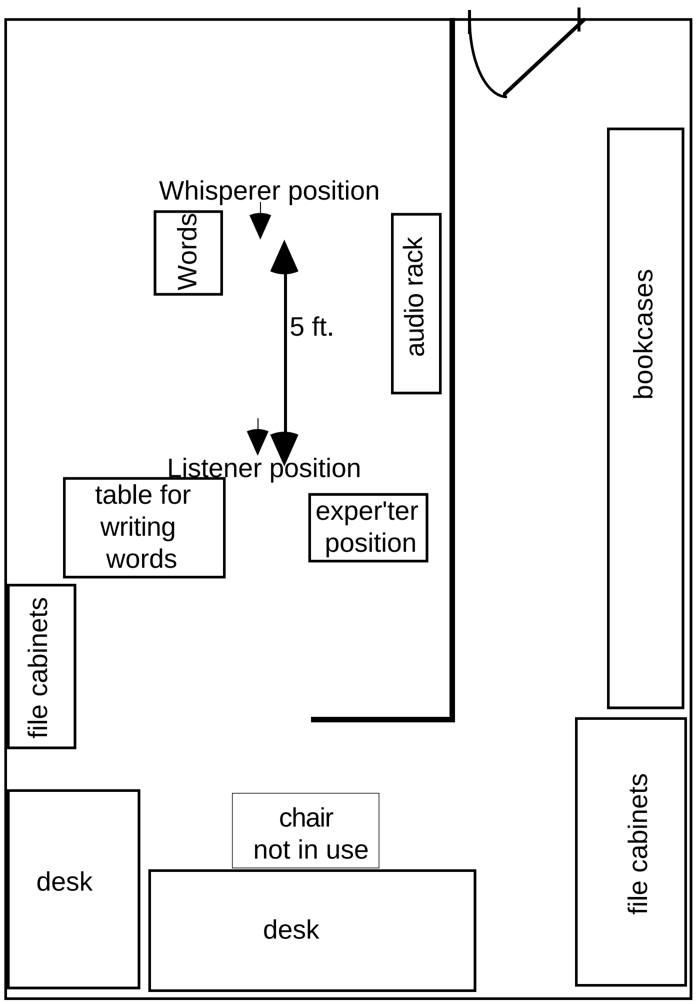

FIGURE 6.6. Experimental Layout for the Forced-Whisper Test-Retest Reliability Experiment (Room 519N Whittemore Hall)

Data analysis. Pass/fail results were compared for the test and the retest. For listeners who passed the test, notes were taken on whether they passed on the first, second, or third try, and also whether they passed with all three words correct, or just two of three. Passing on the first trial with all 3 words correct was assigned a score of 6, passing on the first trial with 2 of 3 correct was assigned a score of 5, passing on the second trial with all three words correct was assigned a score of 4, and so on, down to 0, which would signify not passing the test at all. Significant differences in the results of the test and retest were evaluated using a paired *t*-test.

Results. The demographic data for the whisperers and listeners is presented in Table 6.9. Due mostly to the fairly low hearing levels (i.e., normal or near-normal hearing) of the listeners, all listeners were able to pass the test. Some subjects passed on the first trial, with perfect scores, while others passed only on the second trial, or with 2 out of 3 scores. For the retest, most subjects were also able to pass within 2 trials, although some again had perfect scores and some had 2 of 3 scores. Table 6.10 presents the results of the test and retest for all whisperer/listener pairs, while scores are presented graphically in Figure 6.7.

The *t*-tests (the "paired two-sample for means" *t*-test procedure was used) showed no significant differences between the test and retest. For the right ear, the mean score for the test was 5.6, while it dropped to 5.3 for the retest, a difference which was not significant at $\alpha = 0.05$ ($t = 0.6724$, p two-tailed = 0.52). For the left ear, there was a larger difference in scores, 5.4 for the test and 4.7 for the retest, but the difference was still not significant ($t = 1.9$, p two-tailed = 0.0820). Since neither ear showed significance, the left and right ears were pooled to increase the sample size (and thus the statistical power). For the pooled sample, the mean for the test was 5.5, while it was 5.0 for the retest, a difference which was still not significant ($t = 1.8127$, p two-tailed = 0.0830).

TABLE 6.9. Demographic Data for the Whisperers and Listeners for the Test-Retest Forced Whisper Experiment

Whisperer Listeners	Age	Gender	Listener PTA R	Listener PTA L	Mean SPL from Experiment 1
1	27	M			29.6
1	33	F	6.7	1.7	
2	35	F	3.3	1.7	
3	23	M	-3.3	-6.7	
2	24	M			26.8
4	27	F	0.0	8.3	
5	20	F	-3.3	-1.7	
6	43	F	8.3	6.7	
3	32	F			34.6
7	32	M	0.0	-3.3	
8	25	M	10.0	10.0	
9	23	M	0.0	5.0	
4	31	F			29.5
10	20	M	-1.7	-5.0	
11	22	M	0.0	-8.3	
12	27	F	6.7	5.0	
Mean	**29**	**2M2F**			**30.1**
	28	**6M6F**	**2.2**	**1.1**	

TABLE 6.10. Results of the Forced-Whisper Test-Retest Experiment

Whisperer Listeners	Right Ear Test	Right Ear Retest	Left Ear Test	Left Ear Retest	Days Between Tests
1					
1	6	5	5	4	34
2	6	5	5	5	29
3	6	6	5	5	22
2					
4	6	6	6	4	29
5	6	3	4	3	24
6	6	5	5	6	24
3					
7	6	6	6	5	41
8	6	5	6	5	7
9	5	5	6	5	35
4					
10	6	6	6	6	19
11	4	6	5	6	19
12	4	6	6	2	15
Mean	**5.6**	**5.3**	**5.4**	**4.7**	**24.8**

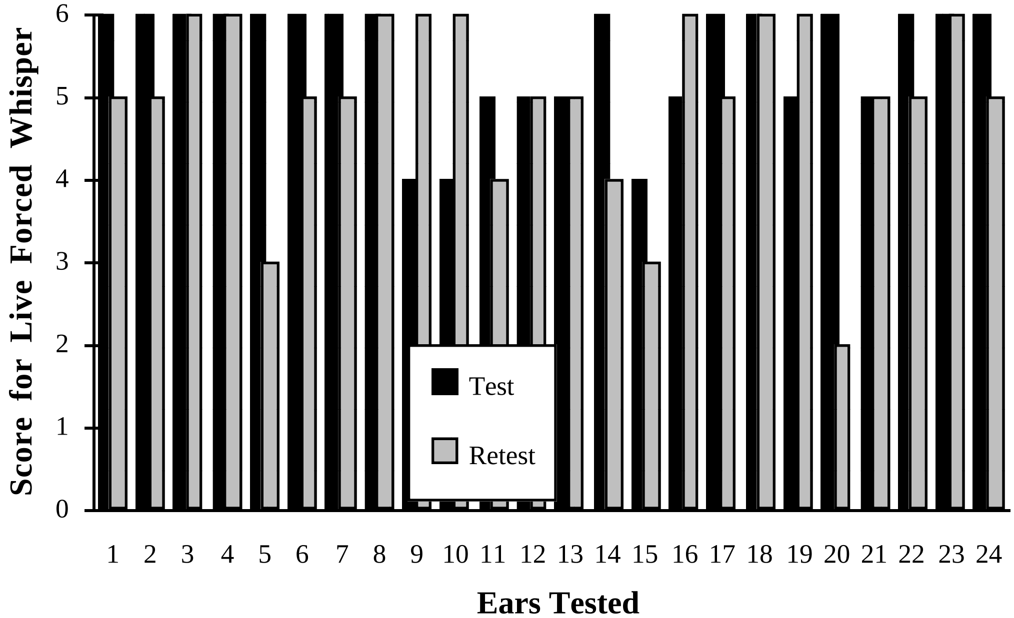

FIGURE 6.7. Test-Retest Scores for the Live Forced Whisper Experiment

Discussion. Overall, there were no significant findings from the test-retest experiment. Listeners with good hearing levels were able to pass the test under standardized conditions with minimal problems, and were also able to pass the retest with similar scores. Since the highest PTA hearing level in this experiment was 10.0 dBHL, it cannot be inferred that the same findings would have resulted for persons exhibiting higher PTA hearing levels. *Overall, for subjects with this level of hearing and under these standardized conditions, the forced whisper test appears to be repeatable for given pairs of whisperers and listeners.*

Of interest is that when a word was missed, it was usually the spondee. In the first experiment, whisperers commented that spondees were more difficult to whisper using the forced-whisper technique, with the result that the end of the word was often cut off. In this experiment, the same phenomenon most likely made the spondees less intelligible. In addition, listeners were only advised as to the *types* of words that would be presented. Two of the word types, digits and letters, were from a limited set (10 and 26, respectively), while the spondees were derived from a much larger set. So although spondees are usually said to have higher intelligibility, in the case of the forced-whisper test, with no prior review of the word list, they appear to exhibit lower intelligibility, and so perhaps should not be recommended for use in this test.

The acoustic environment was quite different for this experiment than for the first one. The room had reverberant qualities not present in the anechoic chamber used in the first experiment, and the ambient noise level was as much as 20 dB higher (approximately 11-13 dBA broadband for the anechoic chamber and 29-31 dBA broadband for Room 519N). From the observation of the experimenter, it seemed as though the live whispers were louder than those produced in the anechoic chamber. The Lombard Reflex (a reflexive increase in vocal intensity in the presence of noise) could account for this perceived increase. In order to test this hypothesis, the most consistent whisperer (in terms of low standard deviation and proximity to the grand mean) from the first experiment was recruited to force whisper 9 words in Room 519N, under the same conditions as for this experiment, but with the SPL measured in the same way as for the first experiment. Results showed that her vocal intensity increased approximately 6.6 dB over the first experiment in the presence of the ambient noise in Room 519N, although the variation for this whisperer was still low, with a standard deviation of 1.8 dB . This lends credence to the theory that all of the forced whispers for this experiment, although performed by the most consistent whisperers from the first experiment, were louder as a result of the Lombard Reflex. An alternative theory for the louder whispers (as perceived and measured) in Room 519N is that in the anechoic chamber, much of the sound may have been absorbed before reaching the microphone at 5 feet, and so a whisper of the same intensity in the anechoic chamber and Room 519N might have produced greatly differing measured SPLs at five feet.

A final note on procedure: for this test, both the listener and whisperer had immediate feedback of results. Both knew if the listener had passed the test, because the test terminated as soon as the listener could identify 2 of 3 words correctly. This may have had the unintended effect of having the whisperer increase vocal effort, albeit unconsciously, in an effort to make certain that the listener passed the test. Although from the standpoint of the experimenter no such increase was perceived, this does not mean that this phenomenon did not occur. In future tests of this sort, it would be better to have all three word sets whispered, and provide no knowledge of results until after tests and retests for both ears were complete. This would diminish the chance of such a phenomenon occurring.

Relationship of Forced-Whisper Test to Pure-Tone Audiometry

Rationale. Since the FHWA requires that truck driver hearing be tested by either the forced-whisper test or by pure-tone audiometry at three frequencies, an experiment was designed to evaluate whether there is any relationship between the two tests. The experiment was designed in such a way that both false positive/false negative rates and a regression model could be extracted from the data. A recorded forced-whispered voice was used for this experiment, to keep the conditions as consistent as possible across subjects.

Subjects. Twenty-one listeners were recruited for this experiment, with varying degrees of hearing loss from fairly severe (one subject wore a hearing aid) to fairly good. Subjects were recruited without regard to gender (13 females and 8 males). A few of the normal-hearing subjects from the second experiment also participated in this experiment (different word lists were used for this experiment to avoid any confounding effect). Listeners underwent an audiometric screening test at nine frequencies prior to participating in the experiment. This allowed subjects to be placed into three hearing level categories, based on hearing in the worse ear, in order to ensure that a fairly even number of subjects for each hearing category were represented in the experiment. The proposed categories of < 20 dBHL, < 40 dBHL, and ≥ 40 dBHL PTA were found to be too restrictive, as subjects with hearing levels greater than 20 dBHL PTA were unable to hear the fairly faint forced-whisper recording. The three categories were thus adjusted downward, to 1) -10 to 5 dBHL PTA, 2) >5 to 15 dBHL PTA, and 3) > 15 dBHL PTA. The final subject count was 8 listeners in group 1, 7 in group 2, and 6 in group 3, reflecting the generally difficult nature of finding subjects with moderate levels of hearing loss. Original plans called for subjects to be recruited from audiology patients, but with the revised categories of hearing loss this would have resulted in many or all of Group 3 being unable to hear the whispered words. There were thus a total of 42 ears available for testing and analysis.

From the first experiment, the most consistent whisperer (in terms of low standard deviation and proximity to the grand mean) was recruited to record nine forced-whisper words (3 sets of three words each). The nine words with least variability for this subject were selected as the test words. The subject was re-instructed in the forced-whisper technique, and instructed to be as consistent as possible in making the recordings.

Equipment. A SONY TCD-D10 PROII digital tape recorder was used to make the recording. The microphone was an Audio-Technica ATM10 omnidirectional fixed-charge condenser microphone, using the right channel of the DAT recorder. A windscreen was used, since the subject had to stand very close (1 inch) to the microphone to make the recordings. The recordings were made in the anechoic chamber, in order to use the quietest possible acoustic environment. The SPLs of the whispered words were measured in the same way as for experiment 1 to ensure that the words were of the same overall intensity as for that experiment. The words were played back at an SPL $\pm$ 1 dB from the SPLs of the mean for the first experiment (29.2 dBA). The output of the sound equipment was checked daily and adjusted if necessary to keep it within this range.

Procedure. After classifying subjects based on the three hearing categories, they received a forced-whisper test presented by loudspeaker from a shelf-top stereo system connected to the SONY DAT recorder. Listeners received instruction on the three types of words to be listened for, and a soft foam earplug was used to mask the ear not being tested. The tests were conducted in Room 519N, the same room as was used for experiment 2. The experimental setup is depicted in Figure 6.8. The listener began the test at 5 feet from the loudspeaker, and listened to a set of 3 forced-whisper words from that distance. The listener then wrote down the words heard, if any. If two of three words were heard correctly, the test terminated for that ear. Although the FHWA hearing requirement specifies that the test be performed at 5 feet, the physician survey indicated that the test is usually performed from *no more than 2 feet* in practice. For this reason, if the listener was unable to pass the test at 5 feet, the test was repeated at 1-foot increments (at 4, 3, and 2 feet), terminating when the listener passed the test (or failed to pass the test at the 2 foot minimum distance). Adding these distances also allowed for a more meaningful regression analysis. The second ear was then tested in the same manner, using a different set of three words.

Data analysis. The pass/fail results of the forced-whisper test were placed into contingency tables based on various hearing levels and passing distances, in order to determine whether a particular combination provided high levels of specificity and low false positive/false negative rates. A Chi-Square test of independence was also performed for each contingency table. A regression analysis was then used to determine if there is a linear relationship between hearing level as measured by audiometry and passing a forced-whisper test at various distances. Regression analysis was used to compare the pass/fail rate to the PTA of 500, 1000, and 2000 Hz (PTA3), to the PTA of 500, 1000, 2000, and 4000 Hz (PTA4), and to the PTA of all 9 frequencies from 125-8000 Hz (PTA9).

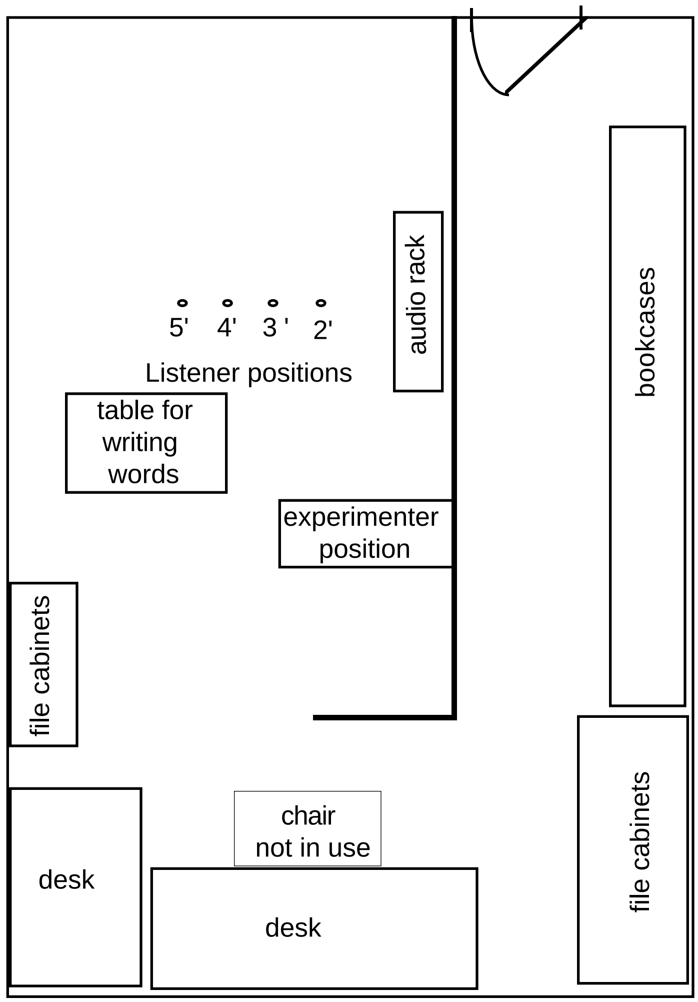

FIGURE 6.8. Experimental Layout for the Recorded Voice Forced-Whisper Experiment (Room 519N Whittemore Hall)

Results. The demographic data for the 3 groups of listeners is provided in Table 6.11. Note that the subjects in groups 2 and 3 were considerably older, on average, than those in group 1. The PTA3, PTA4, and PTA9 hearing levels for the three groups are represented graphically in Figure 6.9.

Six contingency tables were developed in a manner similar to signal detection theory. For medical tests, the term Sensitivity means the same thing as Hit (the person has a hearing loss, and they fail the test), Specificity is the same as a Correct Rejection (the person does not have a hearing impairment, and they pass the test), False Positive is the same as False Alarm (the person does not have a hearing loss, but they fail the test), and False Negative is the same as Miss (the person has a hearing loss, but they pass the test)(Browning et al., 1989).

The first set of 3 tables was based on the assumption that only the 5-foot distance is valid for the forced whisper test. Three levels of hearing were tested this way: one with a 40 dBHL PTA criterion, one with a 20 dBHL criterion, and one with a 10 dBHL criterion. The results are presented in Table 6.12, and clearly show that this test, as presented under these conditions, is extremely conservative. In the tables, the top left quadrant represents specificity at 32.5%, the top right quadrant is false positive at 67.5%, the lower left is false negative at 0%, and the lower right corner is sensitivity at 100% (representing only two ears, however). The specificity improved considerably (to 46.4%) at the 10 dBHL criterion, but not enough to make this a valid screening test, even for a 10 dB hearing level.

When a passing score at 2 feet or better is considered, the numbers improve almost to acceptable levels (Table 6.13). The specificity for a 40 dBHL is 62.5%, and improves to 73.5% for a 20 dBHL and 82.1% for a 10 dBHL. So a forced whisper test performed under these (highly standardized) conditions at 2 feet is a good predictor of a 10 dBHL (not very useful in terms of the FHWA hearing requirement).

The Chi-Square test of independence provides a method of testing the cells of a contingency table for deviation from the expected frequency for each cell, under the assumption that the expected frequency would be equal to the observed frequency if the two measures (distance and dBHL) were independent. For five of the six tables there were cells with expected counts less than 5, for which occurrence the χ^2 test is not recommended. For the 2 feet, 10 dBHL table, however, the expected counts were all greater than 5, and thus the test could be employed ($\chi^2 = 17.838$, $p < 0.001$). This significance indicates a lack of independence between the hearing level ($\leq$ 10 dBHL or > 10 dBHL) and passing or failing the forced whisper test at 2 feet or more, a relationship which was expected.

TABLE 6.11. Demographic and Hearing Level Data for the Listeners in the Recorded Voice Forced-Whisper Experiment

Group 1 -10 to 5 dBHL PTA worse ear	**Age**	**Gender**	**Right Ear PTA3**	**Right Ear PTA4**	**Right Ear PTA9**	**Left Ear PTA3**	**Left Ear PTA4**	**Left Ear PTA9**
1	20	F	-3.3	-2.5	-0.6	-1.7	-2.5	2.8
2	35	F	3.3	5.0	5.0	1.7	0.0	2.2
3	32	M	0.0	2.5	5.6	-3.3	-1.3	1.7
4	22	M	0.0	0.0	2.2	-8.3	-7.5	-3.3
5	22	F	1.7	2.5	1.7	1.7	1.3	-2.2
6	23	M	-3.3	-1.3	0.6	-6.7	-5.0	0.0
7	20	M	-1.7	-1.3	2.8	-5.0	-5.0	1.7
8	21	F	-1.7	0.0	3.9	-1.7	-2.5	1.1
Mean	**24.9**		**-0.6**	**0.6**	**2.6**	**-2.9**	**-2.8**	**0.5**

Group 2 >5 to 15 dBHL PTA worse ear	**Age**	**Gender**	**Right Ear PTA3**	**Right Ear PTA4**	**Right Ear PTA9**	**Left Ear PTA3**	**Left Ear PTA4**	**Left Ear PTA9**
1	43	F	8.3	6.3	7.2	6.7	5.0	7.8
2	24	F	6.7	6.3	6.7	3.3	2.5	5.0
3	27	F	6.7	6.3	3.3	5.0	3.8	2.2
4	42	F	10.0	8.8	10.0	11.7	11.3	10.6
5	25	M	10.0	12.5	11.7	10.0	12.5	11.1
6	53	M	8.3	21.3	32.8	11.7	18.8	18.3
7	59	M	13.3	21.3	18.3	15.0	17.5	19.4
Mean	**39.0**		**9.0**	**11.8**	**12.9**	**9.0**	**10.2**	**10.6**

Group 3 >15 dBHL PTA worse ear	**Age**	**Gender**	**Right Ear PTA3**	**Right Ear PTA4**	**Right Ear PTA9**	**Left Ear PTA3**	**Left Ear PTA4**	**Left Ear PTA9**
1	24	F	31.7	28.8	23.9	33.3	28.8	25.0
2	43	F	33.3	33.8	24.4	31.7	33.8	22.2
3	25	M	30.0	37.5	40.0	10.0	20.0	25.6
4	26	F	6.7	5.0	6.1	48.3	46.3	48.3
5	41	F	20.0	20.0	16.7	16.7	13.8	11.1
6	65	F	51.7	48.8	47.2	36.7	36.3	34.4
Mean	**37.3**		**28.9**	**29.0**	**26.4**	**29.4**	**29.8**	**27.8**

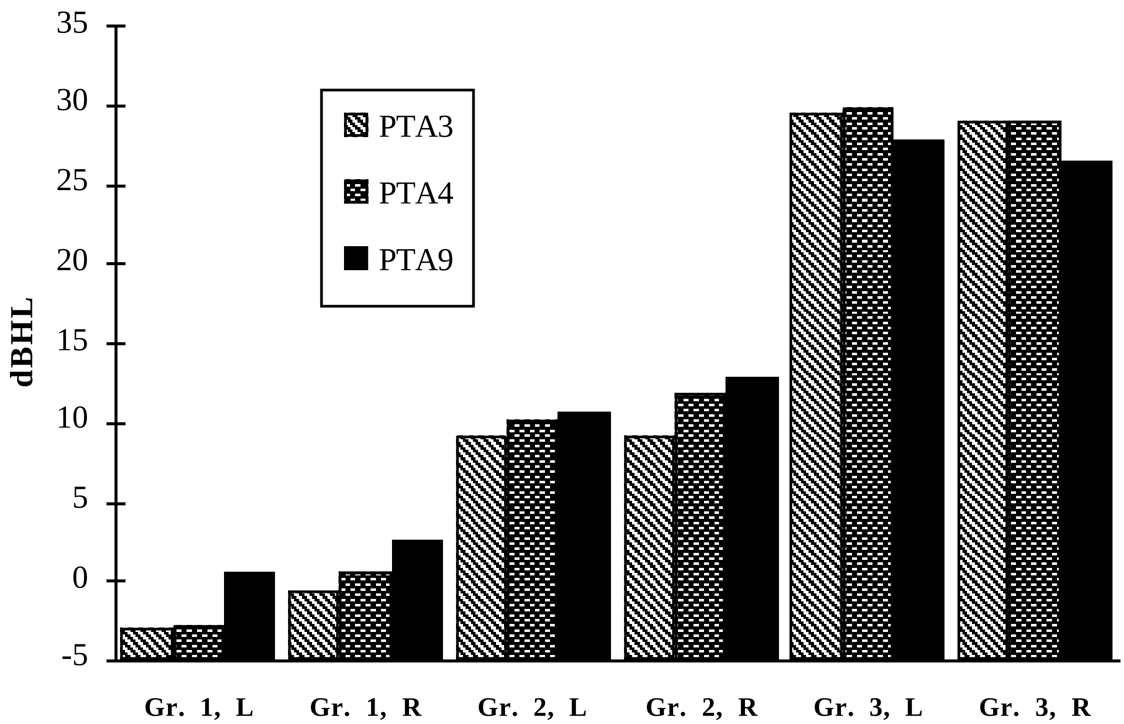

FIGURE 6.9. Mean Pure-tone Hearing Levels for Left and Right Ears for Three Categories of Hearing Level

TABLE 6.12. Contingency Tables for 5' Pass Distance

40 dBHL Criterion	# of subj.	Pass	Fail
HL ≤ 40dB	40	13 (32.5%)	27 (67.5%)
HL > 40dB	2	0 (0.0%)	2 (100.0%)

20 dBHL Criterion	# of subj.	Pass	Fail
HL ≤ 20dB	34	13 (38.2%)	21 (61.8%)
HL > 20dB	8	0 (0.0%)	8 (100.0%)

10 dBHL Criterion	# of subj.	Pass	Fail
HL ≤ 10dB	28	13 (46.4%)	15 (53.6%)
HL > 10dB	14	0 (0.0%)	14 (100.0%)

TABLE 6.13. Contingency Tables for 2' or Better Pass Distance

40 dBHL Criterion	# of subj.	Pass	Fail
HL ≤ 40dB	40	25 (62.5%)	15 (37.5%)
HL > 40dB	2	0 (0.0%)	2 (100.0%)

20 dBHL Criterion	# of subj.	Pass	Fail
HL ≤ 20dB	34	25 (73.5%)	9 (26.5%)
HL > 20dB	8	0 (0.0%)	8 (100.0%)

10 dBHL Criterion	# of subj.	Pass	Fail
HL ≤ 10dB	28	23 (82.1%)	5 (17.9%)
HL > 10dB	14	2 (14.3%)	12 (85.7%)

Since passing distance data were also available, linear regression models were developed for the PTA3, PTA4, and PTA9 averages. For PTA3, the model had an R^2 of 0.5126, and a p-value of < 0.001. The fitted model is:

$$\text{Pass Distance} = 3.532 - (0.106 * \text{PTA3})$$

The scatterplot with fitted line is shown in Figure 6.10. Note that the R^2 value is relatively low and the fitted line has a lot of outliers.

For PTA4 the fit was better, with an R^2 of 0.5949 and a p-value of < 0.001. The fitted model for PTA4 is:

$$\text{Pass Distance} = 3.737 - (0.114 * \text{PTA4})$$

The scatterplot with fitted line for the PTA4 model is shown in Figure 6.11. Despite the fact that this model provides a better fit, it is still not adequate for predicting the pass distance. Note that the fitted line crosses the x-axis at about 34 dBHL, while no one with worse than about 13 dBHL PTA4 passed the test, even at two feet.

For PTA9 the fit fell between the other two, with an R^2 of 0.5537 and a p-value of < 0.001. The fitted model for PTA9 (scatterplot is shown in Figure 6.12) is:

$$\text{Pass Distance} = 3.894 - (0.122 * \text{PTA9})$$

Again, the fit for this model is inadequate.

Upon inspection, the scatterplots for all three models suggest that a non-linear relationship may be at work. The most logical relationship, and one which seems to fit the pattern of the scatterplots, is based on the function $y = 1/x^2$, since SPL is inversely related to the square of the distance from the sound source (the inverse distance law for sound states that sound pressure decreases in inverse proportion to the square of the distance from the source). Several transformations using this and similar functions, however, failed to improve the fit, and in many cases, the fit was made much worse by the transformation. It is possible that a true non-linear approach would yield an improved model, but such an analysis fell beyond the scope of this project.

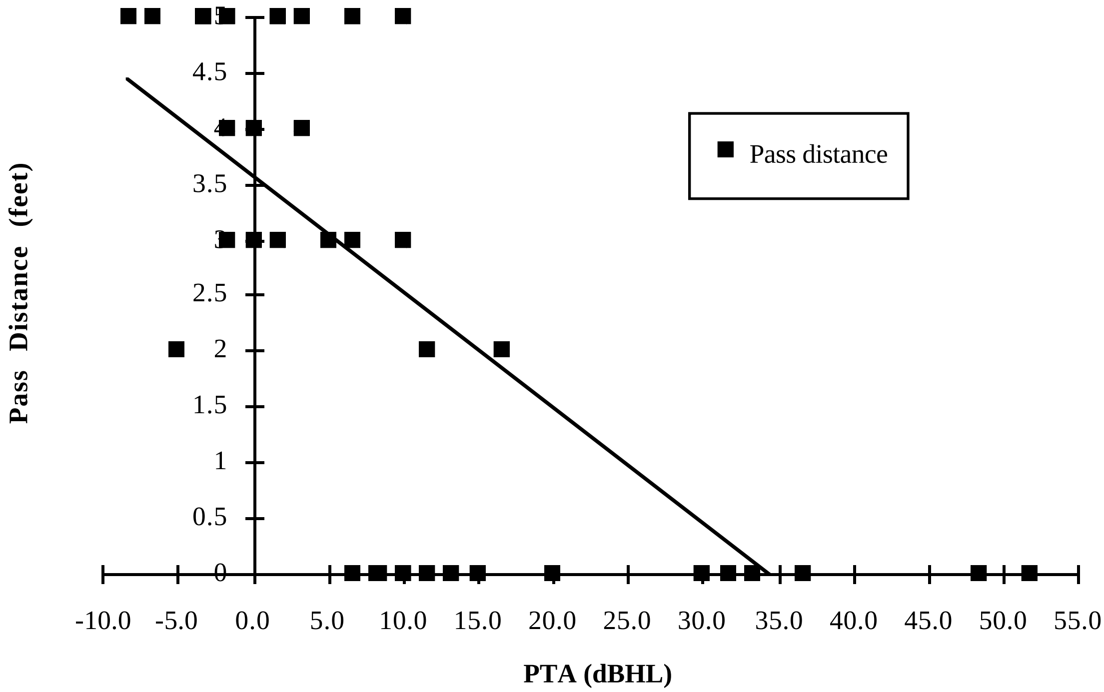

FIGURE 6.10. Scatterplot and Fitted Line for Regression Model for PTA3 (.5K, 1K, 2K) Pass Distance

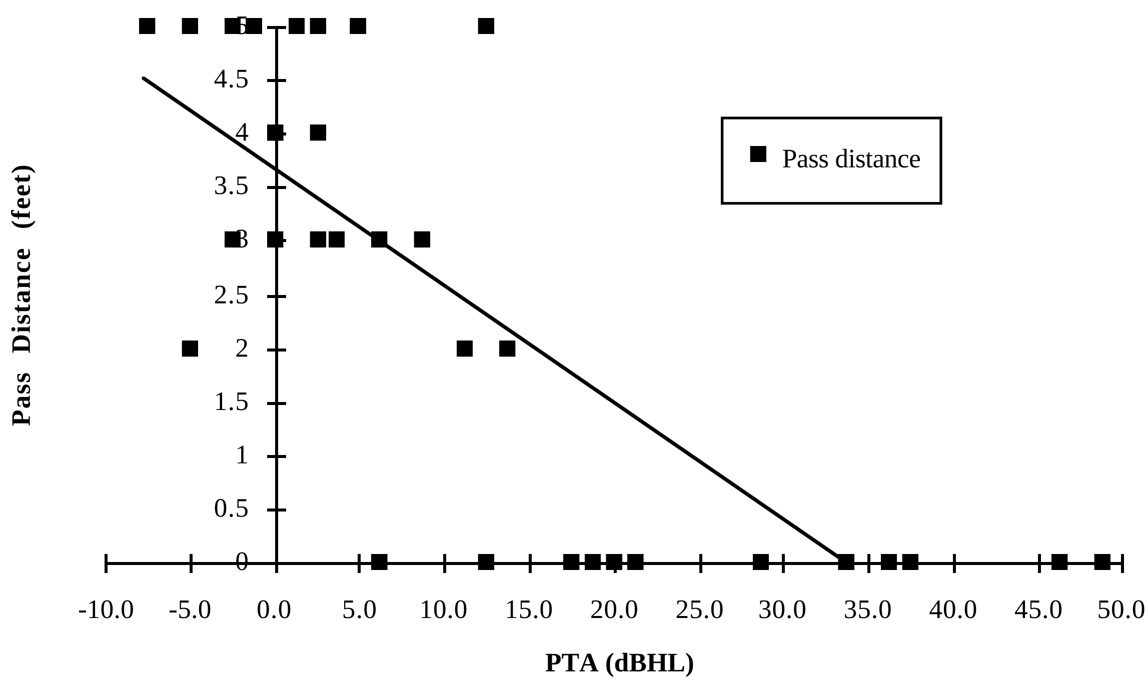

FIGURE 6.11 Scatterplot and Fitted Line for Regression Model for PTA4 (.5K, 1K, 2K, 4K) Pass Distance

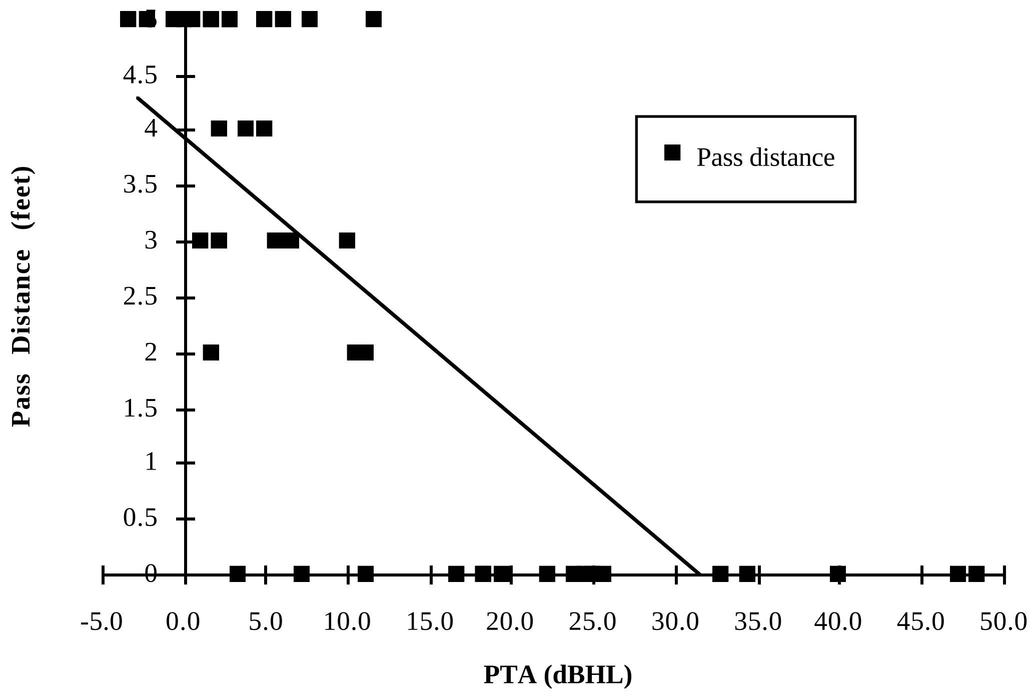

FIGURE 6.12. Scatterplot and Fitted Line for Regression Model for PTA9 (125, 250, .5K, 1K, 2K, 3K, 4K, 6K, 8K) Pass Distance

Discussion. Due to the effort made to play the whispers at a level equal to the mean across subjects for the first experiment, the SPL for these recorded forced whispers was very low. This may have caused the data to appear to be more conservative (as demonstrated by the contingency tables) than would be the case under real-world conditions. As discussed previously, under the ambient noise levels present in the testing room, live whisperers would probably have used louder whispers due to the Lombard effect, and the same would also probably be true for real-life testing in a physician's examining room. As a matter of fact, the ambient noise level of the testing room was very close to the overall SPL of the forced-whisper recorded voice at 5 feet, possibly resulting in a high degree of masking. However, this experiment provided as controlled a test as is possible by using of a high-fidelity recorded voice, and also by having all listeners presented with the same signals. Given this level of control, the failure to find better fitted models is disappointing, but illustrates the subjective nature of the forced-whisper test in general. Also, there may be a non-linear relationship between these two tests which was not uncovered by the linear regression approach. *Overall, this test* *indicates a very weak relationship between the forced-whisper test, as conducted under very standardized conditions, and standard audiometric testing, providing further proof that the forced-whisper test is inadequate for the purpose intended by the FHWA.*

As a matter of interest, the FHWA allows the forced whisper test to be conducted with hearing aids in place. One of the subjects in group 3 wore a hearing aid in one ear, and for this subject, the forced-whisper portion of the test was performed both with and without the hearing aid. She was unable to pass the test at 2 feet even with the hearing aid set to a normal level. By audiometric examination, this same subject would have been eligible for a commercial driver's license for interstate commerce, as her PTA 3 in the better (non-hearing aid) ear was 36.7 dBHL. If the forced-whisper test is retained in its current form by the FHWA, further study of the use and effect of hearing aids would be beneficial.

Conclusions on Forced-Whisper Test

Overall, the five methods used herein to evaluate the forced-whisper test indicate that the test is outdated, is not being used as specified by the FHWA, has high variability in the SPL of whispers, and has only a weak relationship to the standard pure-tone audiometric test. The literature review indicated that the forced-whisper test was more widely used and taught in the past, when audiometers were not as widely available. Free-field voice tests of any sort, for any purpose, are specifically discouraged from use in many recent audiology textbooks, due to their subjective nature. The informal survey of family practice physicians indicated that some had never heard of the forced whisper test, some were using it without any formal training in the technique, and that none of the seven surveyed were using it as prescribed by the FHWA, especially in regards to the 5-foot distance.

The variability experiment demonstrated a high degree of variability in the SPL of forced whispers, between words, word types, and trials, and perhaps most significantly, between subjects, despite a high degree of control over experimental conditions. Under real-world conditions, this variability would be even greater, meaning that the test as administered does not provide a standardized method of testing driver hearing. This is especially true given the widely varying forced-whisper test methods described in the physician survey. The test-retest experiment demonstrated that, for subjects with a fairly narrow range of good hearing, the test does seem repeatable under laboratory conditions. The forced-whisper test shows only a weak relationship to the results of a pure-tone audiometry test. At the SPLs used in the final experiment, the forced-whisper test appears to be a marginally viable diagnostic tool only at 2 feet, and even then, only for diagnosing a hearing level less than 10 dBHL PTA. *The evidence is conclusive that the forced-whisper test is not being administered as specified by the FHWA, and that even if it were, it is an inadequate test of truck driver hearing, especially given the ease and availability of the pure-tone audiometric examination.*

CHAPTER 7: RECAPITULATION

Literature Review

Hearing and the driving task. Despite a large number of studies and reports, the research on the relationship between driving and hearing has not advanced much in the last 30 years. The definitive study on this topic has yet to be conducted, but the two Coppin and Peck (1963; 1964) studies appear to be the most thorough and methodologically sound, despite the number of years that have passed since these studies were undertaken. Coppin and Peck (1963; 1964) found an elevated risk of vehicle accidents for male deaf drivers as compared to normal-hearing drivers, although no such elevation of risk level was found for female deaf drivers. Emotions run high in this area due to the potential for discrimination against the deaf and hearing-impaired. Since there has been an FHWA hearing requirement for 40 years or more, there is a definite lack of empirical research on the accident rate for deaf or hearing-impaired drivers of commercial vehicles. As a result, researchers have been reluctant to suggest eliminating the FHWA hearing requirement for commercial vehicle operators because of the potential risk to public safety should it turn out that hearing *is* essential for the safe operation of these vehicles.

The importance of audition to safe driving is not as clear-cut an issue as is vision. People have operated private vehicles with hearing impairment up to total deafness, with better or worse safety records than the non-hearing-impaired, depending on the study being referenced. Another factor requiring consideration is the well-documented decrement of hearing with age. Any impact this decrement might have on the safe operation of commercial motor vehicles has yet to be determined. No firm conclusions could be reached from the review of the literature on driving and hearing.

Recommending a change in the requirement is also fraught with economic and political implications. For example, while Songer et al. (1992) concluded that the forced-whisper test is probably not an effective screening device for truck drivers, they estimated that to force a switch to pure-tone audiometric testing could cost $247,500,000 the first year, and $123,750,000 per year thereafter (based on 5.5 million drivers receiving an initial audiogram at an average cost of $45, and having the audiogram repeated every two years). The persons expected to bear these costs would probably object strenuously to such a change. The financial burden might not be as heavy as has been suggested, given that of the 80 drivers who completed the task analysis questionnaires, 42 reported having had a pure-tone audiometric test within the past 24 months, 11 reported having had a whisper test within the past 24 months, and 2 reported having had both types of hearing tests within the past 24 months. Sixteen drivers were not aware of having had any hearing test within the past 24 months. Taken with the fact that 2 of 7 physicians reported testing driver hearing with audiometry, this suggests that the audiometric test is already in fairly widespread use for the biennial DOT physical, and thus the economic impact of requiring pure-tone audiometric testing would not be as great as has been predicted.

Noise and hearing loss. Approximately one-third of the 28 million people in the U. S. with hearing loss can attribute their loss to exposure to loud sounds, and more than 20 million are exposed on a regular basis to sounds loud enough to cause hearing loss (National Institutes of Health, 1990). Three types of hearing loss are generally attributed to excessive noise exposure: temporary threshold shift, noise-induced permanent threshold shift, and acoustic trauma (Jones, 1983). Of these, temporary threshold shift (TTS) and noise-induced permanent threshold shift (also called NIPTS or noise-induced hearing loss) are the types that would be more likely to occur due to truck-cab noise exposure. Truck drivers are not protected by the OSHA guideline which sets limits on daily industrial noise exposure, but rather fall under the jurisdiction of the Office of Motor Carriers (OMC) of the FHWA. The current OMC regulation on interior truck-cab noise states that "the interior sound level at the driver's seating position of a motor vehicle must not exceed 90 dBA" when measured in a stationary test with all doors, windows, and vents closed and power accessories turned off (Federal Highway Administration, 1976b). These test conditions almost certainly produce lower readings than those encountered in real world driving. Even real world conditions found to meet the 90 dBA OMC requirement are still sufficient to cause NIPTS and potentially cause widespread hearing loss among truck drivers. If truck driver noise exposure is found to be excessive, drivers may very well be losing their hearing, which would be unfair (a sort of "Catch-22") in that they would then be prohibited from driving (if the hearing loss was in the same frequency range required to be tested by the FHWA).

Other effects of noise. Based on the results of several studies, there appears to be a relationship between noise, hearing level, and industrial accident rates. The exact nature of the relationship and the mechanism which causes it remain unclear. If such a mechanism exists, it might also occur during truck driving, which could mean that the truck noise itself has some effect on accident rates; in other words, accident rates may be higher than they would be at lower noise levels, which would have an important impact on public safety. To the authors' knowledge, however, no study of this issue has been undertaken. In addition to the effects of noise on hearing and accident rates, there is some evidence that noise can affect physiological functions, psychological functions, illness rates, and job performance. Truck-cab noise may be causing drivers physiological and psychological suffering, which could have a negative impact on their long-term health and on their career.

Truck-cab noise levels and truck driver hearing loss. Truck-cab noise levels as reported over the past twenty-five years have shown a dramatic decrease. Despite this decline, several studies indicate that noise exposure in truck cabs is related to hearing loss. Most of the drivers in these studies drove a large part of their careers in the older, noisier trucks representative of the 1960's through mid-1970's. To the authors' knowledge, there is no comprehensive audiometric database available in the open literature for drivers who have driven only the newer, quieter trucks. If current noise doses are truly as low as recent reports indicate (Morrison, 1993; Micheal, 1995a), then drivers who began their careers around 1980 or later would be expected to have very little noise-induced hearing loss caused by truck-cab noise. One important consideration is that many of these recent noise measurements have been taken under standardized conditions, usually either stationary or at a constant speed. In many cases, ideal conditions were used (windows up, accessories off). In some of the reports, noise doses were calculated based on these idealized conditions.

Forced-whisper test. Although many studies have produced results indicating that the forced-whisper test is a valid and reliable screening test when only one or two people perform the whispers, there has been no research indicating the validity and reliability of this method when used by many different clinicians in the field. For the truck driver DOT physical examinations, the tests are being performed by thousands of different medical examiners. There are no data on how reliable and valid this test might be when performed under such conditions.

Pure tone audiometry has become the standard method for describing auditory sensitivity (Yantis, 1994). Many articles and textbooks of audiology do not even mention the forced-whisper test as a possible screening test for hearing impairment, and consequently, do not provide instructions for how to perform such a test (Alpiner, 1987a; Bess and Humes, 1990; Katz and Ivey, 1994; Morrill, 1986). When speech audiometry is mentioned in these texts, only audiometry using recorded voices presented through an audiometer is recommended (Bess and Humes, 1990; Katz and Ivey, 1994; Penrod, 1994). Free field voice tests or whisper tests are not presented as an option for obtaining the speech reception thresholds. Other texts specifically recommend against using live voices for speech audiometry, since the voice production of the speaker can vary significantly between speakers and within the same speaker (Hood, 1981). If a live voice is to be used for speech audiometry, a monitored live voice is recommended, not a free-field voice (Penrod, 1994).

For identification of those with hearing impairment, the American-Speech-Language Hearing Association (1985) recommends the use of pure-tone audiometry and if possible, acoustic immitance screening to detect middle ear problems. If only pure-tone audiometry is used, the frequencies to be tested include 500, 1000, 2000, and 4000 Hz. The use of speech materials is specifically discouraged, because procedures using speech materials fail to identify individuals with hearing impairment in the frequency range above 500 Hz (American Speech-Language-Hearing Association, 1985). In a draft of guidelines for identifying hearing impairment for adults and the elderly, the American Speech-Language-Hearing Association (1989) recommended using case history, visual inspection, and a pure-tone screening test. No mention was made of using voice tests as a screening technique. As audiometers have become more widely available and more people have become trained in their use, less precise and objective methods such as the forced-whisper test have come into disfavor.

Task Analysis

A structured approach was used for the task analysis. An extensive literature review of truck driving task analysis was followed by subject matter expert interviews and job observations, and the effort culminated with an extensive task analysis questionnaire. Transportation experts reviewed the interview questions and task analysis questionnaire at every stage of development. Of the 80 drivers who completed questionnaires, there was a high level of agreement about the task analysis answers, as evidenced by the fact that for all but three of the questions, over 50% of the drivers rated the task importance and hearing importance as a 4 or 5 (important or very important). The questionnaire provided the first detailed task analysis of hearing-critical CVO tasks. *Based on the number of commercial driving tasks identified as hearing-critical, and on the number of critical incidents reported, a serious argument can be made that commercial truck driving should be classified as a hearing-critical job.*

Subject Matter Expert Interviews

The subjects matter expert (SME) interviews were used as an important preliminary step for the Task Analysis. These interviews provided valuable input for the development of the task analysis questionnaire. *The consensus opinion of the 11 SMEs was that there are many truck driving tasks which require the use of hearing.*

Audiometry, Dosimetry, Noise Spectral Measurements, and Audibility Predictions

Audiometry. Based on the results of the pre- and post-workday audiometric measurements of 10 drivers, there is no indication that current trucks of similar makes and mileage levels as those studied here are causing TTS among truck drivers. Due to the scheduling requirements of the trips, drivers were given little notice of participation, and were not able to control their pre-audiogram noise-exposure, which could have caused an elevated pre-test threshold shift. The 15-25 minute delay between the end of the shift and the audiometric test could also have played a role in the non-TTS finding. A final factor contributing to the lack of TTS is that the drivers were allowed to set their own schedules for breaks and refueling. These rest breaks probably allowed sufficient recovery time for any TTS that might show up with continuous exposure to these noise levels.

Based on the pre-work audiograms of a sample of 30 drivers (compared to audiograms of a non-noise exposed population of the same gender and age group), there did appear to be a noise-induced permanent threshold shift, especially at 3000, 4000, and 6000 Hz (three frequencies not required to be tested by the FHWA). Notches at these higher frequencies tend to be indicative of noise-induced hearing loss. The NIPTS reported for these 30 male drivers is also in close agreement with previous reports of truck driver hearing loss (Backman, 1983; Henderson and Burg, 1973; Nerbonne and Accardi, 1975), lending support to the idea that truck-cab noise is continuing to cause hearing loss, even among drivers of 1990's model trucks. However, because of the prevalence of noisy hobbies and previous industrial exposures for these 30 drivers, no conclusions can be drawn as to how much, if any, of the reported loss can be attributed to truck-cab noise. Some of the supplementary questions on the task analysis questionnaire indicated that truck drivers in general tend to participate in noisy hobbies and to have had previous occupational noise exposure (84% of the 80-driver sample who completed questionnaires reported at least one noisy hobby, and 85% reported at least one noisy previous occupation). This high prevalence of non-truck driving noise exposure for truck drivers has not been reported in the literature previously, but should be taken into consideration whenever truck driver audiometry is reported.

Dosimetry. The 8-hour and projected 10-hour noise doses experienced by the truck drivers in this study were not excessive. The drivers were allowed to set their own schedules for breaks and refueling. This probably helped keep the noise dose within acceptable limits, since the dosimeter was kept running during all but sleeping breaks. However, team drivers who spend most of their non-driving time in the cab rather than the sleeper berth might be exposed to levels which exceed the OSHA action level of a 50% noise dose, and in some cases, the OSHA criterion level of a 100% noise dose, over a 24-hour period. Team drivers who spend non-driving time in the sleeper berth could also easily exceed the action level over a 24-hour period. Even drivers who follow a 10-10-4 driving-sleeping pattern (10 hours of driving followed by 10 hours in the sleeper berth followed by 4 more hours of driving) during a given 24-hour period can approach or exceed the OSHA action level over that 24-hour period. So although the sleeper berth is much quieter than the cab, the 24-hour dose will still often exceed the OSHA action level of 50%. For single drivers, the sleeper berth noise dose would probably be 0%, so that the 24-hour noise dose would be somewhat lower for these drivers. The noise doses were measured with rest breaks, meal breaks, and refueling breaks included, so they represent realistic predictions of actual truck trip noise doses. Also adding realism to the noise doses is the fact that in 8 out of 10 cases, these doses were measured on fairly high mileage vehicles.

Noise spectral measurements. The noise spectral measurements revealed that truck-cab noise is primarily low-frequency in nature, with most energy concentrated below 315 Hz. The mean A-weighted L_{eq} across all trucks for the highway-speed driving conditions was calculated to be 89.1 dBA, which is just below the OSHA permissible exposure level of 90 dBA for an eight-hour period. This is significantly higher then the SPLs reported by Morrison and Casali (1994) and Micheal (1995). However, the dosimeter readings obtained for this study more accurately reflect the truck driver's true noise exposure over an entire work shift including meal breaks, refueling stops, and rest breaks, and these were all below 85 dBA, with a mean L_{eq} of 81.6 dBA (which is also in close agreement with the van den Heever and Roets 1996 dosimetry results). The lack of a statistically significant increase in noise level with radios on, windows down, or ventilation on demonstrates that under all conditions, the major source of truck-cab noise is from the engine/drivetrain, and any efforts at noise control should begin there. The mean engine idle L_{eq} of 68.2 dBA is well within a range considered safe for human hearing, so time spent either in the cab or sleeper berth while the engine is idling should not be of concern in terms of hearing damage. The sleeper-berth noise as measured under highway-speed driving conditions was substantially less than the truck cab noise (81.6 dBA for the sleeper berth as opposed to 89.1 dBA for the truck cab), again emphasizing that time spent in the sleeper berth minimizes noise exposure.

Audibility predictions. The Articulation Index (AI) results showed that suitably reliable communication (80% intelligibility for sentences first presented to listeners) is possible in some of the noise conditions, while at other times, even at extreme vocal efforts/sound levels, only very low AIs are achievable. Under the noisiest conditions, vocal efforts for live speech would need to be at an unsustainable level for reliable communication. Likewise, CB radio loudspeaker volume would need to be in the range of 93-95 dB, which would likely result in distortion (which would itself degrade communication). For live speech in the noisiest conditions, the achievable AI ranged from 0.09-0.14, corresponding to intelligibility scores of 16-28%, while for CB speech under the noisiest conditions, the achievable AI ranged from 0.17-0.22, corresponding to intelligibility scores of 44-53%. *These intelligibility scores for the noisier conditions are unacceptably low, leading to the overall conclusion that the truck cab environments studied for this report are not conducive to good speech communication.*

The audibility analyses performed for warning signals [as per ISO 7731-1986(E)] showed that these signals rarely exceeded the masked threshold by the recommended 13 dB, and never in the noisier conditions. The masked threshold was exceeded to some degree less than 13 dB in fewer than half of all possible combinations of signals/conditions, and again, the noisier driving conditions had very few signals which exceeded masked threshold. *Overall, the analysis showed that for these noise conditions, for these signals, there is a very poor probability that most signals will be heard.* The one condition for which the masked threshold was exceeded for all signals was the engine idle, windows open condition. This is a condition under which truck drivers are often at their most attentive, especially when stopped at a rail-highway crossing or an intersection. Another notable finding of the audibility analysis is the fact that many of the interior signals have primary frequencies above 3000 Hz (specifically the all-purpose signals and the turn signal indicator), while the warning signal design guidelines presented in ISO 7731-1986(E) recommend that warning signals contain primary energy in the 300-3000 Hz range.

In establishing a hearing requirement, the question of bandwidth must be addressed in conjunction with the question dealing with minimum suggested hearing levels. An individual possessing sufficiently good hearing in one or more of the bands represented by the tonal signals should not have any difficulty hearing the broadband signals. The bandwidth containing all of the components of the tonal signals extended from 800 Hz (backup alarm and siren) at the low-frequency end of the range to 4000 Hz (turn indicators and all-purpose signals) at the high-frequency end. This bandwidth is somewhat narrower than that represented by the broadband signals alone. It is therefore likely that an individual who possesses good hearing in this range of frequencies will be able to hear all of the alarms represented.

The question to be answered is thus that of how well a driver must hear in order to detect these signals, and the answer depends on how the hearing level requirements are set. In the case where the signals are being listened for in "quiet," that is, as they were measured in the environment, the conservative approach is to use the minimum hearing level for each band across all of the signals and conditions examined. For the approach based on the masked threshold levels for the quietest noise condition, the hearing threshold levels depend only on the masked threshold levels and do not directly depend on specific signal levels. In this case, the signals' spectra specify only the bands that are important for detecting the signals. Remarkably, the two approaches provide very similar answers, with few differences greater than 5 dB. Another notable characteristic of this comparison is that the hearing levels also tend to cluster around 40 dBHL, which is the average level required by the FHWA for 500, 1000, and 2000 Hz. Frequencies up to 4000 Hz were investigated only because some of the in-cab signals had their peak energy concentrated at 4000 Hz. If these in-cab auditory displays had been designed so that their peak energy was in the range from 1000 Hz to 2000 Hz [falling within the guidelines of ISO 7731-1986(E)], then the bandwidth required for signal detection would have been contained in the range of audiometric frequencies currently specified by the FHWA recommendations for audiometric testing.

Relationship of Forced-Whisper Test to Pure-Tone Audiometry

Overall, the five methods used herein to evaluate the forced-whisper test indicate that the test is outdated, is not being used as specified by the FHWA, has high variability in the SPL of whispers, and has only a weak relationship to the standard pure-tone audiometric test. The literature review indicated that the forced-whisper test was more widely used and taught in the past, when audiometers were not as widely available. Free-field voice tests of any sort, for any purpose, are specifically discouraged from use in many recent audiology textbooks, due to their subjective nature. The informal survey of family practice physicians indicated that some had never heard of the forced whisper test, some were using it without any formal training in the technique, and that none of the seven surveyed were using it as prescribed by the FHWA, especially in regards to the 5-foot distance.

The variability experiment demonstrated a high degree of variability in the SPL of forced whispers, between words, word types, and trials, and perhaps most significantly, between subjects, despite a high degree of control over experimental conditions. Under real-world conditions, this variability would be even greater, meaning that the test as administered does not provide a standardized method of testing driver hearing. This is especially true given the widely varying forced-whisper test methods described in the physician survey. The test-retest experiment demonstrated that, for subjects with a fairly narrow range of good hearing, the test does seem repeatable under laboratory conditions. The forced-whisper test shows only a weak relationship to the results of a pure-tone audiometry test. At the SPLs used in the final experiment, the forced-whisper test appears to be a marginally viable diagnostic tool only at 2 feet, and even then, only for diagnosing a hearing level less than 10 dBHL PTA. *The evidence is conclusive that the forced-whisper test is not being administered as specified by the FHWA, and that even if it were, it is an inadequate test of truck driver hearing, especially given the ease and availability of the pure-tone audiometric examination.*

CHAPTER 8: CONCLUSIONS

The questions raised near the beginning of this report are reiterated in Figure 8.1, below. The research conducted and summarized in this report provides answers to most of these questions. Each will be addressed in turn, to determine what conclusions can be reached about the role of hearing in CVO truck driving.

Is the FHWA Hearing Requirement Necessary?

Elements of Research Project Designed to Answer This Question:

Are there truck driving tasks which require the use of hearing? Literature review, subject matter expert interviews.

If so, which tasks are they? Task analysis (questionnaires, job observation).

How noisy are trucks? Spectral analysis of truck noise.

What is the noise dose being received by truck drivers? Dosimetry.

Is the truck driving task damaging drivers' hearing? Audiometric examinations.

What is the hearing level for a sample of truck drivers? Audiometric examinations.

At what level do the drivers need to be able to hear to detect the sounds associated with these tasks? Audibility predictions.

At what level should the hearing requirement be set? Audibility predictions.

Is the forced whisper test a viable test of hearing? Literature review, forced whisper experiments.

FIGURE 8.1. Research Elements Designed to Answer Specific Questions about the FHWA Hearing Requirement

Are There Truck Driving Tasks Which Require the Use of Hearing?

A review of the literature was conducted to develop a list of potential tasks which were then presented to a group of subject matter experts (SMEs). The consensus of the SMEs was that there *are* many tasks for which truck drivers are required to use their hearing. Examples include, but are not limited to, communication (both interpersonal and via CB radio or telephone), detection of internal and external warning signals, and detection of mechanical problems (such as a tire blowout). Tables 3.3 and 3.4 and Appendix B contain specific tasks which were identified through the task analysis process.

If So, Which Tasks Are They?

Having established with some certainty that there are tasks for which truck drivers rely on their hearing, job observations and questionnaires were used to determine precisely which tasks these are. A comprehensive list of tasks was developed, including mechanical problems which can be detected by hearing. The conclusion of this section of the report was that truck driving should be classified as a hearing-critical job, and that some form of hearing test should be used to screen drivers with respect to their ability to hear the signals and noises identified as part of these tasks. In addition, drivers identified many critical incidents for which hearing played a role. Many of these incidents involved avoidance of an accident because the driver heard a sound (such as a car horn from a vehicle in the truck driver' blind spot when the truck driver was attempting to change lanes). Again, Tables 3.3 and 3.4 and Appendix B contain specific tasks and critical incidents which were identified through the task analysis process.

Is the FHWA Hearing Requirement Necessary?

Considering the collective data discussed herein, it is quite clear that the answer to this question is a definite "Yes." Furthermore, some modification of the current requirement is needed, as will be discussed below. This research has identified many truck driving tasks which require the use of hearing. Many examples of critical incidents involving the use of hearing were also obtained. The consensus of both the subject matter experts and the drivers completing questionnaires was that hearing is both important and necessary for the safe operation of commercial vehicles. Given that there are tasks and signals for which truck drivers must listen, a hearing requirement becomes the only way to ensure that commercial vehicle operators are able to safely complete these tasks. Answers to many of the following questions will reiterate this point.

How Noisy are Trucks?

The mean L_{eq} of 89.1 dBA (as measured by the real-time analyzer for highway-speed driving conditions) is loud enough to warrant concern for truck driver hearing loss (when compared to the OSHA permissible exposure limit of 90 dBA for 8 hours for industrial exposure). At these levels, truck-cab noise is also loud enough to mask both intentional and incidental warning signals, originating from both inside and outside the truck cab. Of further concern is that noise at these levels impedes effective communication in the truck cab, both face-to-face communication and CB communication.

What is the Noise Dose Being Received by Truck Drivers?

The 8- and 10-hour noise doses experienced by the drivers in this study were not great enough to put them at risk of excessive hearing damage, again as referenced to the OSHA guidelines. However, it must be remembered that the OSHA guidelines are not intended to prevent hearing loss, but are only intended to limit the loss so that over a working lifetime, the worker does not suffer substantial loss of the ability to communicate. Truck driving is different from industrial noise exposure in that drivers are often in the work environment for 24 hours a day for days at a time. Calculations showed that drivers under these circumstances would almost always be exposed to OSHA 24-hour noise doses in excess of 50%, often approaching 100% (the OSHA permissible exposure limit). Single drivers and local drivers are probably not at risk of excessive hearing damage, but team drivers may be, and should be advised to spend as much non-driving time as possible in the sleeper berth with the curtains closed, to minimize their noise exposure.

Is the Truck Driving Task Damaging Drivers' Hearing?

As stated above, the OSHA guidelines for industry are not intended to prevent hearing loss, but rather to limit it. The 30-driver sample of truck drivers showed a suspected noise-induced permanent threshold shift (NIPTS) at three of the higher frequencies (3000, 4000, and 6000 Hz) which are usually associated with such a shift. However, this finding was confounded by the apparent tendency of truck drivers to have other non-truck driving noise exposure (either leisure or previous occupational exposure). Unless a sample of truck drivers can be found who have not had any noise exposure other than that from truck driving, it will be difficult to answer this question with more certainty. One interesting observation is that even if it is found that truck-driving noise exposure causes NIPTS, the affected frequencies are not currently required to be tested by the FHWA, so the hearing loss would not be likely to result in the loss of the CDL for this sample of drivers. There was no evidence of a temporary threshold shift due to truck-driving noise exposure, probably because of the field techniques used.

What is the Hearing Level for a Sample of Truck Drivers?

For the three frequencies required to be tested by the FHWA if an audiometric test is used (500, 1000, and 2000 Hz), the 30-driver sample had a mean level of 7.3 dBHL for both ears (as compared to 40 dBHL in the better ear for the FHWA requirements). When 3000, 4000, and 6000 Hz were added in, the mean level rose to 15.5 dBHL. This sample of drivers would have no trouble passing the hearing requirement of the DOT physical, even though they appeared to have suffered a NIPTS at the higher frequencies.

At What Levels Do Drivers Need to Hear to Detect These Sounds ?

Based on the calculations performed for detection of the warning signals under both quiet and quiet truck noise conditions, the minimum hearing levels are in the range of 35-50 dBHL for the frequencies between 800 and 4000 Hz for the detection of these signals at their current levels and spectral characteristics.

At What Level Should the Hearing Requirement be Set?

Given that a driver's ability to hear the signals is a matter of public safety, the more conservative of the two approaches discussed earlier should be used in setting the levels for the pure-tone audiometry hearing requirement. If a driver cannot hear the signals of interest under the quietest of the truck-cab noise conditions, then he/she has no hope of hearing them under the noisier conditions. Setting the hearing level at 13 dB below the masked threshold of the quietest noise condition provides reasonable assurance that drivers who possess this level of hearing will be able to detect these signals. As discussed previously, the quietest conditions were the engine idle conditions, under which the driver is often at his/her most attentive, such as at a rail-highway crossing or at an intersection.

Audiometric readings are usually measured in increments of 5 dB, so the suggested level for each frequency needs to be rounded to the nearest 5 dB, to take advantage of the measurement resolution available with most contemporary audiometers. If the same frequencies were to be retained (500, 1000, and 2000 Hz), the levels should be set at 45 dBHL for 500 Hz (based on the suggested minimum level of the nearest frequency, 800 Hz, of 42.6 dBHL), 45 dBHL for 1000 Hz (based on the suggested minimum level for 1000 Hz of 42.9 dBHL), and 40 dBHL for 2000 Hz (based on the suggested minimum level for 2000 Hz of 39.6 dBHL). If 3000 Hz were to be added to the requirement (e.g., the FAA now requires 3000 Hz to be tested), the level should be set at 40 dBHL (based on the suggested minimum level of the nearest frequency, 3150 Hz, of 40.0 dBHL). Since many of the in-cab signals contained their peak energy in the 4000 Hz band, this frequency should also be considered for adoption into the requirement, and should be set at 40 dBHL (based on the suggested minimum level of 38.7 dBHL at 4000 Hz). These levels should be set as a numerical *maximum* for the better ear for each pure-tone frequency, since using an average (as is now done) would mean that a driver with a severe hearing impairment at one of these frequencies would not be able to detect signals whose primary energy was contained in that band. Adding 3000 and 4000 Hz to the audiometric testing requirement would have the added benefit of testing at the frequencies most critical to speech intelligibility. As hearing degenerates in the 3000-4000 Hz range, the listener's ability to detect and distinguish voiced and non-voiced consonants (the speech components most critical to intelligibility) degrades, resulting in a reduced ability to understand speech.

Is the Forced Whisper Test a Viable Test of Hearing?

Based on the extensive review of the literature, it appears that the forced-whisper test is not considered reliable or valid except by four to five researchers, and the research reported by these authors contains many serious flaws. Before the present experiments, a truly unbiased, comprehensive study of the validity and reliability of the forced-whisper test had not been attempted for the past 54 years, during which time the field of audiology has made great strides. The FAA has recently moved away from a whisper test for pilots. Textbooks and professional organizations discourage the use of free-field voice tests (such as the forced-whisper test) as screening tests for hearing. The empirical research conducted and reported herein provides further evidence that the method (as defined by the FHWA) is subjective, is not being properly administered, produces an unacceptable amount of variation between whisperers even under tightly controlled laboratory conditions, and has only a weak relationship to the results of pure-tone audiometric testing. For these reasons, the forced-whisper test must be considered an outdated mode of screening truck drivers for hearing damage/hearing loss. If there is to be a hearing requirement for truck drivers, it should be based on objective audiometric methods, recommendations for which are made in the next chapter.

CHAPTER 9: RECOMMENDATIONS

Recommendations for Truck-Cab Noise Reduction

Truck-cab noise, although it has decreased in the past 25 years, is still unacceptably high for many reasons. First of all, the mean L_{eq} is very near the OSHA permissible exposure limit of 90 dBA for 8 hours. Second, the truck-cab noise degrades communication in the truck cab to unacceptable levels under many conditions. Third, the noise levels often mask both interior and exterior warning signals, thus impacting public safety. For these reasons, manufacturers should continue to make every effort to decrease truck-cab noise levels in future models. Personal communication with engineers at a large truck-assembly plant indicate that at least some new trucks arriving on the market in 1998 will be measurably quieter than current models. Since it will take several years to replace the current fleet of noisier trucks which are already on the road, this noise reduction effort should be undertaken by all manufacturers as quickly as possible. Since this is a public health concern (both for the driver and the general public), features which help reduce truck-cab noise should be offered not only on the deluxe models, but should instead become standard features. Manufacturers should also take care to ensure that in the process of making the truck cab quieter, they do not attenuate external warning signals to an unacceptable degree. Every effort should be made to isolate and reduce the transmission of noise from the engine to the cab area without compromising the driver's ability to hear external warning signals such as train horns, sirens, and backup alarms.

In-Cab Warning Signal Design Recommendations

Truck manufacturers should adhere to the warning signal design recommendations appearing in the literature (Patterson, 1982; Sorkin, 1987; ISO, 1986). These sources suggest that warning and advisory signals should contain their primary energy in the frequency range from 700 to 3000 Hz to ensure that individuals suffering from a noise-induced hearing loss are still able to hear the signals. (Noise-induced hearing loss first appears at 4000 and 6000 Hz, and progresses to the lower frequencies as the loss becomes more severe). All three of the all-purpose in-cab alarms tested in this research effort had their primary frequency component in the one-third octave band centered at 4000 Hz, as did all three turn signals tested. Although the turn signals had secondary components at

2000 Hz, their levels were 2 to 8 dB less than the primary component's levels. This is particularly important since the examination of drivers' audiograms reported herein indicate that the truck driving population may indeed suffer from a noise-induced hearing loss. (For the purposes of this discussion, it is irrelevant whether or not the loss is occupation-related; it is only relevant that the loss exists.) If in-cab auditory displays were designed so that their peak energy was in the 1000-2000 Hz frequency range, the probability of individuals suffering substantial high-frequency hearing loss detecting the signals would be maximized.

It would appear, based on measurements performed, direct observations, and interviews, that it is common for truck manufacturers to equip their trucks with all-purpose alarms that are used to notify the driver of malfunctions and/or critical engine conditions. Within a specific truck, different alarm functions may be represented by a single alarm with only its period differing from function to function. Although this practice is acceptable when the number of alarm functions is small, as the number of alarm functions increases the contrast between their associated alarms or displays must be more pronounced. This issue will become more critical as new technologies are introduced (e.g., Intelligent Transportation Systems). Manufacturers must begin to address this issue now so as to avoid the potential for driver confusion, and thus delayed reaction time, when presented with a warning signal which could have one of many meanings.

Many of the current in-cab auditory displays are inaudible or only marginally audible in any but the quietest noise conditions. This problem should be addressed from two perspectives, by reducing the noise level in the cab and/or by increasing the presentation levels of the signals. Either approach would accomplish the desired effect. However, there may be a practical limit to the truck manufacturers' ability to reduce the noise levels in the truck cab. Also, if the output levels of the auditory displays are increased so that they are easily audible in the noisiest conditions, they may be excessively loud for the quieter conditions, potentially causing a startle effect that could lead to an accident. An alternative would be the use of noise-sensing circuits that adjust the alarms' output levels as the noise level changes, always attempting to maintain a desired signal-to-noise ratio. Some manufacturers of aftermarket backup alarms equip their alarms with such circuits. Truck manufacturers should investigate this technology as a potential solution to the inaudibility of in-cab alarms.

Recommendation of an Appropriate Hearing Test for Truck Drivers

Recommended hearing test to be used. At this time, lacking any evidence that the forced-whisper test correlates with appropriate hearing level requirements, further use of this test cannot be advocated. This leaves pure-tone audiometry as the only viable choice. As discussed previously, it appears based on the questionnaire results that as many as half of all drivers are already receiving this type of test, often as part of their physical examination, and thus the additional cost would be much less than projected by Songer et al. (1992). Audiometers are available that can be operated in a quiet office by a nurse, aide, or other medical examiner with limited, but careful, training.

Pure-tone audiometric frequencies to be tested. The range of frequencies to be tested should be, at a minimum, from 500 Hz to 4000 Hz (specifically, 500, 1000, 2000, 3000, and 4000 Hz). The upper end of this range was set at 4000 Hz since contemporary in-cab warning signals contain most of their energy in the 4000 Hz frequency band. If these in-cab warnings were to be redesigned so that most of their energy was contained in the 1000-2000 Hz range (falling within the recommendations of Patterson, 1982; Sorkin, 1987; and ISO, 1986), then the upper end of the hearing test range could be lowered to 2000 Hz, assuming that other important signals continue to fall below this frequency. As it is, some drivers who meet the current hearing requirement (being tested only at 500, 1000, and 2000 Hz) will not be able to hear existing in-cab warning signals, even under the quietest conditions, due to noise-induced permanent threshold shift at 4000 Hz.

Minimum recommended pure-tone audiometric hearing-threshold levels. Table 9.1 presents the minimum recommended levels for the better ear for the frequencies between 500 and 4000 Hz. These are based on the more conservative hearing level at 13 dB below the masked threshold of the quietest noise condition, as discussed previously. Again, it must be emphasized that these should be the *minimum* hearing level requirement for each test frequency (although a numeric maximum), and that an arithmetic average should not be used.

TABLE 9.1. Final Minimum Hearing Level Recommendations

Audiometric Frequency (Hz)	Minimum Level for Listening in Noise (from Table 5.26)	Final Minimum Hearing Level Recommendation for the Better Ear
500	42.6 dBHL at 800 Hz	45 dBHL
1000	42.9 dBHL at 1000 Hz	45 dBHL
2000	39.6 dBHL at 2000 Hz	40 dBHL
3000	40.0 dBHL at 3150 Hz	40 dBHL
4000	38.7 dBHL at 4000 Hz	40 dBHL

Recommendations for Further Research

Development of an audiometric database for truck drivers. One area which this research project identified as a true need for future studies of this sort is a comprehensive audiometric database of truck drivers. The high proportion of drivers engaging in noisy hobbies and previous occupations makes it difficult to say with any certainty whether truck drivers are suffering hearing loss as a result of their driving activities or as a result of other noisy activities. The database study should be large enough in scale that the effect of such non-driving exposure can be accounted for in the statistical analysis. In conjunction with this audiometric database study, a study of truck-cab noise should be conducted every two to three years to determine whether truck-cab noise is increasing or decreasing, so that this can also be taken into account when analyzing the audiometric results.

Temporary threshold shift laboratory experiment. In order to prevent some of the confounding that occurred in the present study, especially as regards performing TTS studies under field conditions, an experiment using laboratory produced truck noise would be valuable. Drivers could perform a simulated driving task for up to 10 hours at a time, with limited time away from noise, and their hearing levels could be checked periodically to determine whether a TTS is produced given the levels of truck noise reported herein.

Further analysis of the forced-whisper test. In order to answer some of the questions raised by this research on the forced-whisper test, further forced-whisper experiments might prove valuable. Such research should only be conducted if the test continues in use as a diagnostic tool for truck driver hearing. Possible experiments include: 1) further analysis of test-retest results, using subjects with a wider range of hearing loss than was possible in the current study; 2) further comparisons of the forced whisper results to pure-tone audiometry, perhaps using a louder forced-whisper than in this study, and using a larger number of ears; and 3) a larger study of the use of the forced whisper test with hearing aids in place.

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APPENDIX A

CVO Hearing Requirements
Task Analysis Questionnaire

Instructions:

Please fill out the enclosed questionnaire as completely and accurately as possible. If you no longer drive a commercial motor vehicle, answer all questions as if they pertain to your most recent driving job. Your answers will remain strictly confidential, and your name will not be associated with your answers in any way. Please contact Suzanne Lee @ 540-231-9086 if you have any questions about this questionnaire.

Background information:

Age: ________

Gender: ________

Truck driving experience, in years: ________ years

Miles driven per week:

Now: ________ miles/week

At maximum: ________ miles/week

Related experience, in years (such as driving instructor, dispatcher, supervisor):

________ years

1. Do you feel that hearing is important for the safe operation of commercial vehicles?

   ☐ Yes ☐ No

2. If you feel it is important, do you feel that it is also necessary?

   ☐ Yes ☐ No

3. Do you feel that it is loud *inside* your truck?

   ☐ Yes ☐ No

4. Do you sometimes drive with the windows down?

   ☐ Yes ☐ No

   If yes, how often?

   ☐ Always ☐ Often ☐ Seldom

5. Which of the following devices do you use while in the truck? What percent of the time are they in use?

   ☐ CB radio ________%
   ☐ Private band radio ________%
   ☐ AM/FM radio ________%
   ☐ Tape deck ________%
   ☐ CD player ________%
   ☐ Television ________%
   ☐ Other audio devices (list) ____________________ ________%
   ____________________ ________%

6. Do you have any known hearing loss? ☐ Yes ☐ No

If yes, how would you categorize the loss?

☐ slight ☐ moderate ☐ severe ☐ total

Have you had a hearing test? ☐ Yes ☐ No

When was your last hearing test? ____________________

What type of test was it?

☐ Audiometric (headphones) ☐ Whisper test ☐ Other __________

What was the result? ____

Do you own a hearing aid? ☐ Yes ☐ No

Do you wear a hearing aid while driving your truck? ☐ Yes ☐ No

Do you wear a hearing aid when not driving your truck? ☐ Yes ☐ No

7. Check any of the following hobbies you have been involved in:

☐ participation in or live attendance at car races, tractor pulls, etc.
☐ hunting
☐ target shooting, skeet shooting, etc.
☐ woodworking, metal working
☐ using a chainsaw, gas-powered trimmer, gas-powered snow-blower
☐ riding an all-terrain vehicle or snowmobile
☐ other noisy hobbies ____

8. Check any of the following occupations you have pursued:

☐ military ☐ lumber or furniture industry
☐ boiler operator ☐ quarry operations
☐ machine shop ☐ automobile or truck repair
☐ other noisy occupations ____

9. Do you currently wear any sort of hearing protection device when you are exposed to noise:

At work? ☐ Yes ☐ No

In leisure activities? ☐ Yes ☐ No

Type worn ☐ Earmuffs ☐ Earplugs

Brand/model worn (if known) ________________________________

10. What type of truck do you currently drive most often (make, model, and year)?

____

Make Model Year

<u>Questionnaire:</u>

Please rate the importance of each of the following driving tasks to safe driving (Column 1), and then rate the importance of hearing to the completion of that task (Column 2), where:

<u>1 = Very Unimportant, 2 = Unimportant, 3 = Unsure, 4 = Important, and 5 = Very Important</u>. Circle the choice that best corresponds to your opinion.

	Column 1 Importance of <u>task</u> to safe driving	Column 2 Importance of <u>hearing</u> to completion of task
Routine driving tasks:		
Pre-trip inspection	1 2 3 4 5	1 2 3 4 5
Maneuvering in light city traffic	1 2 3 4 5	1 2 3 4 5
Maneuvering in heavy city traffic	1 2 3 4 5	1 2 3 4 5
Maneuvering in light hwy. traffic	1 2 3 4 5	1 2 3 4 5
Maneuvering in heavy hwy. traffic	1 2 3 4 5	1 2 3 4 5
Maneuvering in light rural traffic	1 2 3 4 5	1 2 3 4 5
Upshifting	1 2 3 4 5	1 2 3 4 5
Downshifting	1 2 3 4 5	1 2 3 4 5
Detecting missed gears	1 2 3 4 5	1 2 3 4 5
Turning	1 2 3 4 5	1 2 3 4 5
Braking	1 2 3 4 5	1 2 3 4 5
Accelerating	1 2 3 4 5	1 2 3 4 5
Passing another vehicle	1 2 3 4 5	1 2 3 4 5
Being passed by another vehicle	1 2 3 4 5	1 2 3 4 5
Parking	1 2 3 4 5	1 2 3 4 5
Emergency stopping	1 2 3 4 5	1 2 3 4 5
Backing up to a loading dock	1 2 3 4 5	1 2 3 4 5
Going through a weigh station	1 2 3 4 5	1 2 3 4 5
Entering and exiting limited access highways, including:		
Weigh stations	1 2 3 4 5	1 2 3 4 5
Rest stops	1 2 3 4 5	1 2 3 4 5
On/off ramps	1 2 3 4 5	1 2 3 4 5
Merging into traffic	1 2 3 4 5	1 2 3 4 5
Negotiating upgrades	1 2 3 4 5	1 2 3 4 5
Negotiating downgrades	1 2 3 4 5	1 2 3 4 5

Questionnaire, continued:

1 = Very Unimportant, 2 = Unimportant, 3 = Unsure, 4 = Important, and 5 = Very Important. Circle the choice that best corresponds to your opinion.

	Column 1 Importance of task to safe driving	Column 2 Importance of hearing to completion of task
Communication:		
Making deliveries	1 2 3 4 5	1 2 3 4 5
Backing up to a loading dock	1 2 3 4 5	1 2 3 4 5
Weigh station communications	1 2 3 4 5	1 2 3 4 5
Communicating with the dispatcher	1 2 3 4 5	1 2 3 4 5
Listening to the CB radio, radio, or tape deck	1 2 3 4 5	1 2 3 4 5
Communicating with other drivers on the CB	1 2 3 4 5	1 2 3 4 5
Detection of mechanical problems:		
Tire blowout	1 2 3 4 5	1 2 3 4 5
Other tire/wheel problems	1 2 3 4 5	1 2 3 4 5
Pre-trip inspections	1 2 3 4 5	1 2 3 4 5
Engine	1 2 3 4 5	1 2 3 4 5
Transmission/drivetrain	1 2 3 4 5	1 2 3 4 5
Suspension	1 2 3 4 5	1 2 3 4 5
Air pressure problems	1 2 3 4 5	1 2 3 4 5
Fluid problems	1 2 3 4 5	1 2 3 4 5
Problem with trailer	1 2 3 4 5	1 2 3 4 5
Load shift	1 2 3 4 5	1 2 3 4 5
Detection of internal (inside cab) warning signals:		
Low oil pressure	1 2 3 4 5	1 2 3 4 5
High oil temperature	1 2 3 4 5	1 2 3 4 5
Low water	1 2 3 4 5	1 2 3 4 5
Low air pressure	1 2 3 4 5	1 2 3 4 5
Gearbox temperature	1 2 3 4 5	1 2 3 4 5
Engine temperature	1 2 3 4 5	1 2 3 4 5

<u>Questionnaire, continued:</u>

<u>1 = Very Unimportant, 2 = Unimportant, 3 = Unsure, 4 = Important, and 5 = Very Important</u>. Circle the choice that best corresponds to your opinion.

	Column 1 Importance of <u>task</u> to safe driving	Column 2 Importance of <u>hearing</u> to completion of task
Detection of external (outside cab) warning signals:		
Detection of approaching trains	1 2 3 4 5	1 2 3 4 5
Detection of emergency vehicles	1 2 3 4 5	1 2 3 4 5
Detection of automobile horns	1 2 3 4 5	1 2 3 4 5
Detection of truck horns	1 2 3 4 5	1 2 3 4 5
Detection of a car in your blind spot	1 2 3 4 5	1 2 3 4 5
Detection of a car approaching from behind	1 2 3 4 5	1 2 3 4 5
Detection of a car coming up on your **left** side	1 2 3 4 5	1 2 3 4 5
Detection of a car coming up on your **right** side	1 2 3 4 5	1 2 3 4 5
Detection of pedestrians, animals, and other unmarked road hazards	1 2 3 4 5	1 2 3 4 5
Detection of rumble strips	1 2 3 4 5	1 2 3 4 5
Detection of lane deviation	1 2 3 4 5	1 2 3 4 5
Detection of lane edge bumps	1 2 3 4 5	1 2 3 4 5

<u>New technology:</u>
Are any of the following new technologies included in your truck cab? If so, is there a sound or hearing component of the technology?

<u>Have available or use?</u>	**<u>Hearing component?</u>**	
☐ Cellular phone	☐ Yes	☐ No
☐ GPS (Global positioning system)	☐ Yes	☐ No
☐ Computer interface with main office	☐ Yes	☐ No
☐ Electronic navigation aid	☐ Yes	☐ No
☐ Regional traffic flow system (Ex.-Advantage I-75)	☐ Yes	☐ No
☐ Collision avoidance system	☐ Yes	☐ No
☐ Electronic trip recorder	☐ Yes	☐ No
☐ Automated toll collection/payment	☐ Yes	☐ No
☐ MayDay system for emergencies	☐ Yes	☐ No
☐ Drowsiness detection system	☐ Yes	☐ No

Mechanical Problems:

When the following mechanical problems are encountered, how do you first detect their occurrence?

Circle V for Visual, H for Hearing, S for Smell, F for Feel or Handling, O for Other, or NA for Not Applicable

Engine

Loss of coolant/low coolant	V H S F O NA
Low oil	V H S F O NA
Adjustment or tune-up needed	V H S F O NA
Bad injector	V H S F O NA
Problem with turbo charger	V H S F O NA
Loose, worn, or broken belts	V H S F O NA
Engine temperature high	V H S F O NA
Dirty air or fuel filter	V H S F O NA
Problem with water pump	V H S F O NA
Loose engine mount	V H S F O NA

Drive train

Clutch problem	V H S F O NA
Transmission problem	V H S F O NA
Tie rod end worn out	V H S F O NA
Drag link problem	V H S F O NA
Drive line, drive shaft	V H S F O NA
Universal joint	V H S F O NA
Differential problem	V H S F O NA
Axle problem	V H S F O NA

Brakes

Overheating	V H S F O NA
Worn brake pads	V H S F O NA
Warped or cracked drums	V H S F O NA
Brake cam bearings worn	V H S F O NA
Problem with slack adjusters	V H S F O NA

Air system

Total loss of air pressure	V H S F O NA
Slow leak in air lines or fittings	V H S F O NA
Water or oil in air line	V H S F O NA
Compressor problem	V H S F O NA
Air tank problem	V H S F O NA
Bad gauge	V H S F O NA
Bad warning buzzer	V H S F O NA
Air pressure too high	V H S F O NA

Mechanical Problems, continued:
When the following mechanical problems are encountered, how do you first detect their occurrence?
Circle V for Visual, H for Hearing, S for Smell, F for Feel or Handling, O for Other, or NA for Not Applicable

Tires and wheels

Tire blowout	**V H S F O NA**
Flat tire - no blowout	**V H S F O NA**
Worn tires/flat spot on tire	**V H S F O NA**
Bad wheel bearing	**V H S F O NA**
Bent rims	**V H S F O NA**
Loose lug nuts	**V H S F O NA**

Trailer

Loss of trailer brakes	**V H S F O NA**
Load shift	**V H S F O NA**
Air coupling problem	**V H S F O NA**
5th wheel problem	**V H S F O NA**
Tandem/sliding system problem	**V H S F O NA**
Landing gear/dolly problem	**V H S F O NA**
Problem with Reefer unit	**V H S F O NA**

Electrical system

Lights burned out	**V H S F O NA**
Problem with alternator	**V H S F O NA**
Bad battery	**V H S F O NA**
Short circuit in lighting system	**V H S F O NA**
Worn wires	**V H S F O NA**

Emergency vehicles and trains:
How do you first detect the following events? Do you first hear it (H) or see it (S)? Does the detection method differ by time of day?

	Night		Day	
Train approaching crossing	**H**	**S**	**H**	**S**
Police car	**H**	**S**	**H**	**S**
Ambulance	**H**	**S**	**H**	**S**
Fire truck	**H**	**S**	**H**	**S**

Are you concerned about your noise exposure in the truck?

☐ Yes ☐ No

Critical driving incidents:
Can you think of any particular examples in which you feel that your hearing played an important role in a critical driving situation, either because you could not hear something, or because you did hear something? If so, please describe each incident as fully as possible. Some examples of critical driving incidents are: tire blowout, load shift, involvement in an accident, avoidance of an accident, severe mechanical problems, ambulance behind you that you didn't hear, traffic violation, and brake failure. (Use back of sheet if more room is needed.)

Incident 1:

Incident 2:

Incident 3:

APPENDIX B

CVO Hearing Requirements Task Analysis Questionnaire
Summary of Answers Received (80 questionnaires)

<u>Background information:</u>

Age (years):
Mean = 42.23; s.d. = 9.95; range = 21 - 64; N = 80

Gender:
male = 77 (96.2%); female = 3 (3.8%); N = 80; national avg. = 6% female (1990 census)

Truck driving experience (years):
Mean = 14.24; s.d. = 10.22; range = 0 - 40; N = 80

Miles/week, now: Mean = 2598.5; s.d. = 766.7; range = 0-5000; N = 77

Miles/week, max.: Mean = 3199.3; s.d. = 1030.9; range = 41-6800; N = 78

Related experience (years) (such as driving instructor, dispatcher, supervisor):
Mean = 2.79; s.d. = 4.75; range = 0 - 25; N = 80

1. Do you feel that hearing is important for the safe operation of commercial vehicles?
Yes = 77 (96%) No = 3 (4%)

2. If you feel it is important, do you feel that it is also necessary?
Yes = 73 (91%) No = 7 (9%)

3. Do you feel that it is loud *inside* your truck?
Yes = 31 (39%) No = 48 (61%)

4. Do you sometimes drive with the windows down?
Yes = 69 (86%) No = 11 (14%)

If yes, how often?
Always = 7 (10%) Often = 34 (51%) Seldom = 26 (39%)

5. Which of the following devices do you use while in the truck? What percent of the time are they in use?

CB radio used by 95% of drivers; in use 66% of time by these drivers.
Private band radio used by 6% of drivers; in use 28% of time by these drivers.
AM/FM radio used by 89% of drivers; in use 54% of time by these drivers.
Tape deck used by 58% of drivers; in use 29% of time by these drivers.
CD player used by 10% of drivers; in use 35% of time by these drivers.
Television used by 46% of drivers; in use 14% of time by these drivers (many wrote that TV was only in use when they were stopped).
Other audio devices (list): None listed

6. Do you have any known hearing loss?
Yes = 26 (33%)   No = 52 (67%)

If yes, how would you categorize the loss?
slight = 16 (64%)   moderate = 8 (32%)   severe = 1 (4%)   total = 0

Have you had a hearing test?
Yes = 71 (89%)   No = 9 (11%)

When was your last hearing test?
Mean = 29.8 months
Within 24 months = 52 (76%)   More than 24 months = 16 (24%)

What type of test was it?
Audiometric = 57 (83%)   Whisper test = 10 (14%)
Both = 2 (3%)   Other = 1 (1%) (type not specified)

What was the result?
Many did not answer this. Of those who did, most wrote "pass", "good", or "OK", while some specified high frequency loss.

Do you own a hearing aid?
Yes = 3 (4%)   No = 74 (96%)

Do you wear a hearing aid while driving your truck?
Yes = 1 (1%)   No = 76 (99%)

Do you wear a hearing aid when not driving your truck?
Yes = 2 (3%)   No = 75 (97%)

7. Check any of the following hobbies you have been involved in:

Motor sports:	39 (49%)
Hunting:	41 (51%)
Other shooting:	32 (40%)
Shop work (woodworking, metal working):	27 (34%)
Yard work (chainsaw, gas-powered trimmer, etc.):	40 (50%)
All-terrain vehicle or snowmobile:	23 (29%)
Other noisy hobbies:	

Farming equipment:	3 (4%)
Motorcycles:	3 (4%)
Mechanics:	3 (4%)
Loud music:	2 (3%)
Mowers:	1 (1%)
Movies:	1 (1%)
Flying:	1 (1%)

8. Check any of the following occupations you have pursued:

Military:	38 (48%)
Boiler operator:	1 (1%)
Machine shop:	22 (28%)
Lumber or furniture industry:	13 (16%)
Quarry operations:	5 (6%)
Automobile or truck repair:	31 (39%)

Other noisy occupations:

Factory:	7 (9%)
Drop forge/die press:	2 (3%)
Farming:	2 (3%)
Heavy equipment:	2 (3%)
Welder:	1 (1%)
Oil rig:	1 (1%)
Mining:	1 (1%)
Airlines:	1 (1%)
Restaurant:	1 (1%)

9. Do you currently wear any sort of hearing protection device when you are exposed to noise:

At work?

Yes = 13 (17%) No = 64 (83%)

In leisure activities?

Yes = 17 (23%) No = 58 (77%)

Type worn:

Earmuffs = 6 (23%) Earplugs = 16 (62%) Both = 4 (15%)

Brand/model worn (if known):

Two drivers specified yellow foam plugs.

10. What type of truck do you currently drive most often (make, model, and year)?

Make:

Freightliner = 31 (39%)	International = 15 (19%)	Kenworth = 12 (15%)
Peterbilt = 9 (11%)	Volvo = 6 (8%)	White = 2 (3%)
Mack = 1 (1%)	Ford = 1 (1%)	Chevrolet = 1 (1%)
Hiwo = 1 (1%)	Recently retired = 1 (1%)	

Model:

Many drivers did not answer this question, and the answers that were given were not very specific. Some answered with the configuration (cabover, conventional), while only a few provided the true make of the truck.

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Year:

1987 = 2 (3%)	1989 = 3 (4%)	1990 = 3 (4%)
1991 = 1 (1%)	1992 = 7 (9%)	1993 = 2 (3%)
1994 = 10 (13%)	1995 = 19 (24%)	1996 = 18 (23%)
1997 = 14 (18%)		

Questionnaire:
Please rate the importance of each of the following driving tasks to safe driving, and then rate the importance of hearing to the completion of that task, where:
1 = Very Unimportant, 2 = Unimportant, 3 = Unsure, 4 = Important, and 5 = Very Important.

Routine driving tasks:	**Mean**	**s.d.**	**% rating task a 4 or 5**
Pre-trip inspection:			
Task importance	4.8	0.582	97.5%
Hearing importance	3.7	1.306	66.3%
Maneuvering in light city traffic:			
Task importance	4.6	0.608	93.8%
Hearing importance	4.2	0.909	83.8%
Maneuvering in heavy city traffic:			
Task importance	4.9	0.460	97.5%
Hearing importance	4.5	0.860	86.3%
Maneuvering in light highway traffic:			
Task importance	4.4	0.669	92.5%
Hearing importance	4.0	0.974	73.8%
Maneuvering in heavy highway traffic:			
Task importance	4.7	0.552	98.8%
Hearing importance	4.3	0.901	81.3%
Maneuvering in light rural traffic:			
Task importance	4.3	0.807	82.5%
Hearing importance	3.9	1.045	70.0%
Upshifting:			
Task importance	4.4	0.783	88.8%
Hearing importance	4.1	0.984	81.3%
Downshifting:			
Task importance	4.3	0.854	88.8%
Hearing importance	4.1	1.052	78.8%
Detecting missed gears:			
Task importance	4.2	1.095	81.3%
Hearing importance	4.1	1.219	73.8%
Turning:			
Task importance	4.5	0.749	92.5%
Hearing importance	3.8	1.190	62.5%
Braking:			
Task importance	4.5	0.762	95.0%
Hearing importance	3.8	1.185	65.0%
Accelerating:			
Task importance	4.2	0.986	82.5%
Hearing importance	3.8	1.272	70.0%
Passing another vehicle:			
Task importance	4.5	0.818	86.3%
Hearing importance	3.9	1.219	70.0%
Being passed by another vehicle:			
Task importance	4.3	0.856	83.8%
Hearing importance	3.7	1.242	65.0%

Routine driving tasks:	Mean	s.d.	% rating task a 4 or 5
Parking:			
Task importance	4.4	0.900	88.8%
Hearing importance	3.9	1.319	67.5%
Emergency stopping:			
Task importance	4.5	1.041	87.5%
Hearing importance	3.9	1.313	70.0%
Backing up to a loading dock:			
Task importance	4.4	0.916	88.8%
Hearing importance	4.1	1.177	72.5%
Going through a weigh station:			
Task importance	4.2	1.219	78.8%
Hearing importance	4.3	1.171	82.5%
Entering and exiting limited access highways, including:			
Weigh stations:			
Task importance	4.4	0.920	82.5%
Hearing importance	4.2	1.140	80.0%
Rest stops:			
Task importance	4.1	0.993	73.8%
Hearing importance	3.7	1.252	57.5%
On/off ramps:			
Task importance	4.3	0.979	82.5%
Hearing importance	3.8	1.282	66.3%
Merging into traffic:			
Task importance	4.6	0.727	90.0%
Hearing importance	4.0	1.154	73.8%
Negotiating upgrades:			
Task importance	4.3	0.834	82.5%
Hearing importance	3.7	1.171	63.8%
Negotiating downgrades:			
Task importance	4.5	0.696	90.0%
Hearing importance	3.9	1.136	67.5%

Communication:			
Making deliveries:			
Task importance	4.2	0.937	80.0%
Hearing importance	4.2	1.094	78.8%
Backing up to a loading dock:			
Task importance	4.3	0.881	86.3%
Hearing importance	4.1	1.133	72.5%
Weigh station communications:			
Task importance	4.4	0.892	83.8%
Hearing importance	4.6	0.694	91.3%
Communicating with the dispatcher:			
Task importance	4.3	1.071	81.3%
Hearing importance	4.6	0.804	88.8%
Listening to the CB radio, radio, or tape deck:			
Task importance	3.4	1.262	51.3%
Hearing importance	3.6	1.269	55.0%

Communication:	**Mean**	**s.d.**	**% rating task a 4 or 5**
Communicating with other drivers on the CB:			
Task importance	3.8	1.136	70.0%
Hearing importance	3.9	1.144	67.5%

Detection of mechanical problems:

Tire blowout:			
Task importance	4.7	0.693	93.8%
Hearing importance	4.6	0.843	88.8%
Other tire/wheel problems:			
Task importance	4.7	0.610	92.5%
Hearing importance	4.4	1.019	80.0%
Pre-trip inspections:			
Task importance	4.6	0.833	91.3%
Hearing importance	4.1	1.202	76.3%
Engine:			
Task importance	4.6	0.653	91.3%
Hearing importance	4.6	0.613	90.0%
Transmission/drivetrain:			
Task importance	4.6	0.638	92.5%
Hearing importance	4.6	0.695	90.0%
Suspension:			
Task importance	4.4	0.815	82.5%
Hearing importance	4.2	1.014	77.5%
Air pressure problems:			
Task importance	4.6	0.762	87.5%
Hearing importance	4.4	0.997	78.8%
Fluid problems:			
Task importance	4.4	0.919	80.0%
Hearing importance	3.5	1.339	48.8%
Problem with trailer:			
Task importance	4.5	0.824	86.3%
Hearing importance	4.1	1.129	70.0%
Load shift:			
Task importance	4.7	0.753	86.3%
Hearing importance	4.1	1.340	71.3%

Detection of internal (inside cab) warning signals:

Low oil pressure:			
Task importance	4.5	0.982	82.5%
Hearing importance	3.9	1.336	63.8%
High oil temperature:			
Task importance	4.4	0.990	81.3%
Hearing importance	3.8	1.373	63.8%
Low water:			
Task importance	4.4	1.006	82.5%
Hearing importance	3.9	1.402	65.0%
Low air pressure:			
Task importance	4.6	0.833	88.8%
Hearing importance	4.3	1.133	78.8%

Detection of internal (inside cab) warning signals:	**Mean**	**s.d.**	**% rating task a 4 or 5**
Gearbox temperature:			
Task importance	4.2	1.053	75.0%
Hearing importance	3.4	1.376	47.5%
Engine temperature:			
Task importance	4.4	0.981	81.3%
Hearing importance	3.7	1.374	58.8%

Detection of external (outside cab) warning signals:

Detection of approaching trains:			
Task importance	4.8	0.710	95.0%
Hearing importance	4.6	0.880	90.0%
Detection of emergency vehicles:			
Task importance	4.8	0.563	93.8%
Hearing importance	4.7	0.635	95.0%
Detection of automobile horns:			
Task importance	4.5	0.904	83.8%
Hearing importance	4.5	0.874	88.8%
Detection of truck horns:			
Task importance	4.6	0.777	88.8%
Hearing importance	4.6	0.886	90.0%
Detection of a car in your blind spot:			
Task importance	4.7	0.715	88.8%
Hearing importance	3.7	1.336	58.8%
Detection of a car approaching from behind:			
Task importance	4.2	1.116	75.0%
Hearing importance	3.3	1.413	45.0%
Detection of a car coming up on your **left** side:			
Task importance	4.3	1.022	77.5%
Hearing importance	3.4	1.392	53.8%
Detection of a car coming up on your **right** side:			
Task importance	4.4	1.017	82.5%
Hearing importance	3.6	1.408	58.8%
Detection of pedestrians, animals, and other unmarked road hazards:			
Task importance	4.5	0.945	85.0%
Hearing importance	3.5	1.413	53.8%
Detection of rumble strips:			
Task importance	4.2	1.031	77.5%
Hearing importance	3.8	1.313	63.8%
Detection of lane deviation:			
Task importance	4.4	0.855	87.5%
Hearing importance	3.6	1.365	56.3%
Detection of lane edge bumps:			
Task importance	4.4	0.855	87.5%
Hearing importance	3.7	1.356	63.8%

New technology:

Are any of the following new technologies included in your truck cab? If so, is there a sound or hearing component of the technology?

Item:	In truck or use?		Hearing component?	
Cellular phone:	25	(31%)	25	(100%)
GPS (Global positioning system):	10	(13%)	5	(50%)
Computer interface w/ main office:	24	(30%)	20	(83%)
Electronic navigation aid:	1	(1%)	1	(100%)
Regional traffic flow system:	0	(0%)	0	(0%)
Collision avoidance system:	1	(1%)	1	(100%)
Electronic trip recorder:	8	(10%)	5	(63%)
Automated toll collection/payment:	5	(6%)	1	(20%)
MayDay system for emergencies:	7	(9%)	3	(43%)
Drowsiness detection system:	2	(3%)	2	(100%)

Mechanical Problems:

When the following mechanical problems are encountered, how do you first detect their occurrence? (Multiple answers were allowed, so percentages sometimes add up to more than 100%.)

V=Visual, H=Hearing, S=Smell, F=Feel or Handling, O=Other

Engine	**V**	**H**	**S**	**F**	**O**
Loss of coolant/low coolant:	70%	15%	25%	1%	3%
Low oil:	85%	10%	1%	1%	3%
Adjustment or tune-up needed:	11%	55%	1%	33%	3%
Bad injector:	11	54%	0%	38%	1%
Problem with turbo charger:	14%	68%	1%	30%	3%
Loose, worn, or broken belts:	58%	35%	11%	16%	6%
Engine temperature high:	80%	15%	15%	4%	3%
Dirty air or fuel filter:	46%	10%	4%	38%	6%
Problem with water pump:	54%	34%	14%	8%	6%
Loose engine mount:	34%	29%	1%	50%	5%

Drive train	**V**	**H**	**S**	**F**	**O**
Clutch problem:	9%	18%	8%	78%	1%
Transmission problem:	9%	34%	1%	68%	1%
Tie rod end worn out:	31%	6%	1%	69%	1%
Drag link problem:	30%	10%	1%	61%	5%
Drive line, drive shaft:	21%	26%	1%	66%	1%
Universal joint:	20%	34%	1%	65%	1%
Differential problem:	18%	39%	1%	61%	1%
Axle problem:	18%	33%	4%	59%	3%

Brakes	**V**	**H**	**S**	**F**	**O**
Overheating:	44%	9%	65%	10%	1%
Worn brake pads:	59%	19%	11%	28%	3%
Warped or cracked drums:	70%	10%	1%	18%	5%
Brake cam bearings worn:	59%	9%	5%	30%	6%
Problem with slack adjusters:	56%	5%	1%	41%	5%

Air system	V	H	S	F	O
Total loss of air pressure:	49%	56%	3%	21%	5%
Slow leak in air lines or fittings:	16%	78%	3%	10%	4%
Water or oil in air line:	53%	6%	9%	23%	8%
Compressor problem:	34%	55%	6%	10%	5%
Air tank problem:	40%	51%	1%	10%	8%
Bad gauge:	81%	6%	4%	3%	4%
Bad warning buzzer:	35%	65%	4%	4%	6%
Air pressure too high:	80%	18%	4%	4%	1%

Tires and wheels	V	H	S	F	O
Tire blowout:	24%	78%	4%	36%	3%
Flat tire - no blowout:	46%	24%	3%	56%	4%
Worn tires/flat spot on tire:	56%	21%	3%	41%	4%
Bad wheel bearing:	24%	43%	13%	39%	9%
Bent rims:	70%	6%	4%	38%	3%
Loose lug nuts:	71%	13%	5%	31%	1%

Trailer	V	H	S	F	O
Loss of trailer brakes:	15%	11%	3%	78%	3%
Load shift:	35%	16%	0%	74%	0%
Air coupling problem:	38%	60%	4%	15%	1%
5th wheel problem:	64%	15%	1%	43%	0%
Tandem/sliding system problem:	66%	9%	1%	30%	4%
Landing gear/dolly problem:	75%	1%	1%	25%	4%
Problem with Reefer unit:	49%	46%	4%	8%	1%

Electrical system	V	H	S	F	O
Lights burned out:	93%	0%	8%	3%	1%
Problem with alternator:	85%	16%	8%	4%	4%
Bad battery:	71%	9%	11%	4%	11%
Short circuit in lighting system:	81%	4%	16%	1%	4%
Worn wires:	84%	1%	15%	4%	5%

Emergency vehicles and trains:
How do you first detect the following events? Do you first hear it (H) or see it (S)? Does the detection method differ by time of day?

Train approaching crossing:

Night:	H = 32 (41%)	S = 43 (54%)	Both = 4 (5%)
Day:	H = 29 (38%)	S = 44 (58%)	Both = 3 (4%)

Police car:

Night:	H = 27 (34%)	S = 47 (59%)	Both = 5 (6%)
Day:	H = 31 (41%)	S = 40 (53%)	Both = 5 (7%)

Ambulance:

Night:	H = 28 (35%)	S = 44 (56%)	Both = 7 (9%)
Day:	H = 37 (49%)	S = 33 (43%)	Both = 6 (8%)

Fire truck:

Night:	H = 30 (38%)	S = 43 (54%)	Both = 6 (8%)
Day:	H = 40 (53%)	S = 31 (41%)	Both = 5 (7%)

Are you concerned about your noise exposure in the truck?

Yes = 44 (56%)　　No = 34 (44%)

<u>Critical driving incidents:</u>
Can you think of any particular examples in which you feel that your hearing played an important role in a critical driving situation, either because you could not hear something, or because you did hear something? If so, please describe each incident as fully as possible. Some examples of critical driving incidents are: tire blowout, load shift, involvement in an accident, avoidance of an accident, severe mechanical problems, ambulance behind you that you didn't hear, traffic violation, and brake failure.

There were a total of 44 critical incidents reported by 33 drivers. All incidents are transcribed directly from the drivers' descriptions on the questionnaires. The breakdown by categories was developed during the data analysis, when it became apparent that there were a few categories into which all of the answers could be fitted.

Blown out tires (9):

- Blown and low tires.
- Numerous flat and blown tires.
- Tire blew out: My tire blew out and there was a civilian car beside me, I pulled to the right sharply to avoid the tire hitting the car (good hearing, seeing, reacting).
- Blow out.
- I have had 4 or 5 tire blowouts.
- Heard trailer tire blow.
- In Houston, I heard tire blow, had two tandems blow at once. Other times I had one flat tire, but never heard it go.
- I had left steering tire to blow out on inside lane. Nobody was hurt, just the truck.
- Tire blows out, when you have the CB going and the FM with the windows up and the AC on it is hard to tell sometimes.

Engine noises, external mechanical noises (8):

- Can hear any difference in motor noise.
- Was driving a car one time and realized the truck driver behind me was having trouble with the Jake brake so I got out of the way because I knew he was having trouble slowing down.
- Backing into a loading dock, if you can't hear well you can back into another trailer, hit a parked car, hit a dock too hard, causing damage to rear of trailer or dock.
- Car carrier. I often roll down window and turn off radio and listen for chains dragging.
- Universal joint rattling, had repaired before broke down.
- Turning left off exit ramp. After starting turn, heard crash on my blind side. After investigating (2 cars had collided), I pulled to side to assist.
- I had an engine overheat while I was sleeping. The warning buzzer got me up so I didn't hurt my engine.
- Lost a front wheel bearing left side. Heard it when it started to disintegrate and slowed down to about 10 mph going from I64 in Virginia over to Staunton VA.

Air leaks (hiss) (6):

- Lost air line on trailer; did not hear; found out when brakes needed; no accident.
- Hearing the air hiss when checking the trailer brake operational readiness. If there is a hiss there is a leak in the air pressure system.
- If the windshield wiper activation knob is not turned completely to the off position, one will hear a hiss from the dashboard - air leak.
- Heard air leak in air bag suspension system.
- Glad hand not properly put on - air leak.
- Thought I heard air leaking so I slowed down to about 40 mph and sure enough front steering tire went down.

CB or live voice warning of accident or other situation (6):
- CB radio warned of accident ahead giving me more time to slow and warn other traffic, thus reducing possible further rigs involved.
- I would hate to have lost my hearing and not be allowed to drive anymore, but hearing just the CB radio is very important. I don't like listening to the damn thing because about 25-40% of the drivers are real jerks, but you are aware of all driving situations on and off the road by someone with a CB. Many a time's I've been aware of the (or almost all the time) situation well before it's at hand.
- Co-driver yelled that car was starting to "fishtail" ahead of me. I was able to swerve to avoid serious accident. If I had not reacted in time, the accident would have been much worse.
- Was coming off a mountain in Pa. when I turned on my CB and I heard about an accident that was about 1 mile ahead of me. If I didn't turn on my CB and hear about it I would have been going too fast to stop in time and I might not have been here today to write this.
- I was traveling south on I 81 and was fixing to come over a hill at about 65 miles/hr when I heard on the CB that there was a truck jackknifing just on the other side of the hill, so I slowed down. If I had not heard it on the CB I would be part of another statistic.
- When another driver tells you on the CB it is clear to change lanes.

Emergency vehicles (sirens) (5):
- I have heard ambulance and police cars and sirens coming up behind me.
- I heard an ambulance coming on the freeway and was able to get out of his way without a collision.
- Lots of times you're going down the road, you hear sirens, then you look in your mirror, or you will see them first.
- Couldn't hear ambulance approaching intersection until it was too close.
- Traffic violation, didn't see in time. (Author's note - This incident was not described fully enough, but seemed to fit best here. It was the only situation that came to mind which would involve a traffic violation for not seeing something in time, and presumably not hearing it, either.)

Railroad crossings (train whistles) (4):
- I have heard trains approaching unmarked crossings before I have seen them.
- Crossing guard at RR crossing didn't work. Started across. Looked and saw nothing coming. 2 trucks went before me then I heard a horn, still didn't see anything. Stopped and waited and an Amtrak train came around the bend from the blind side. Could have been a bad mess if I had not heard it.
- I heard a train at a crossing and was able to stop. The warning lights were out.
- Approaching RR crossing, signals failed. Heard train before crossing.

Automobile or truck horns (4)
- Barely heard the horn blowing of a car on the right side of the truck blind side as I slowly made preparations to change lanes to the right.
- Car horns.
- A run-away truck down a mountain. I heard his horn before I saw him and was able to get out of his way.
- Car in my blind spot honking to let me know he was there.

Load shifts (2):
- Load shift.
- Load shift I heard once.

APPENDIX C

Method Used for Measuring Frequency Response Characteristics of CB Radios

Equipment:

- Larson-Davis LD-3100 real-time analyzer, set for one-third OB L_{eq} measurements, 30 seconds
- Measurement microphone - Larson-Davis 1/2" free-field microphone, Model 2540, Serial no. 1453
- Pre-amplifier - Larson-Davis 1/2" pre-amplifier, Model 900B, Serial no. 2394
- Acoustic calibrator - Brüel & Kjær Type 4230, 94 dB, 1000 Hz
- 5 CB radios, marked A-E, set to send/receive on Channel 40, squelch OFF
    - A - Cobra 25 LTD WX Classic
    - B - Radio Shack TRC-464
    - C - Realistic TRC-427
    - D - Midland 77-099
    - E - Radio Shack TRC-443
- Power supply units for radios
- Antenna, antenna cable, for radios
- Source of pink noise (Norwegian Electronics PC controlled 828); Noise Level Attenuation - -5 dB; 25 dB - OFF; Noise type - Pink; Chopping - OFF; level - 90 dB +/- 1.5 dB.

Protocol:

The noise level and spectrum of the pink noise in the reverberant chamber (containing the transmitting radio) was set at approximately 90 dB (measured at the "subject's head center position") and measured five times. The average of these measurements was used for the transmitting spectrum in the final frequency response calculations. The free-field microphone was used for these measurements, and it was positioned in the same location as the microphone of the CB radios. One radio was set up in the anechoic chamber (the receiving radio). The other radio was set up in the reverberant chamber (the transmitting radio). The microphone of the transmitting radio was keyed using rubber bands, being careful not to obstruct the microphone itself. Pink noise was then transmitted to the receiving radio. The noise level and spectrum of the pink noise at the receiving radio was then measured. The volume control on the receiving CB was set to approximately 90 dB (+/- 1.5 dB). After the volume was set, five measurements were made to more closely approximate the "mean" frequency response for that particular pair of radios. The measurement microphone was placed 6.5" from the center of the speaker of the receiving CB, perpendicular to and facing the front plane of the speaker. The readings for each measurement were printed out immediately after the measurement was taken, and the sending/receiving radio combination was noted on the printout. The measurement microphone was calibrated before the first measurements were taken in each room. Frequency response measurements were performed in this manner for each of the following 18 sending/receiving radio combinations:

Transmitting Radio:		Receiving Radio:
A	---------->	B
A	---------->	C
A	---------->	E
B	---------->	A
B	---------->	C
B	---------->	E
C	--------->	A
C	---------->	B
C	---------->	D
C	---------->	E
D	---------->	A
D	---------->	B
D	---------->	C
D	---------->	E
E	---------->	A
E	---------->	B
E	---------->	C
E	---------->	D

Note: Radio D developed a reception problem halfway through the experiment, and was unable to receive noise from radios A and B.

Analysis:
The one-third OB spectra of the pink noise were entered into a spreadsheet, averaged, and the resulting spectrum adjusted slightly so that the broadband RMS level was exactly 90 dB. The one-third OB spectra for each combination were then entered and averaged, and the resulting receiving radio spectrum was adjusted slightly up or down until the broadband RMS level was also exactly 90 dB. The difference in level at each one-third OB center frequency between the noise at the sending radio and the noise at the receiving radio was then calculated as the frequency response for that combination. The frequency responses for all 18 combinations were plotted, and proved to be extremely consistent across combinations. Since they were so consistent, the average frequency response for all 18 combinations was then used to adjust the ideal speech spectrum used in the subsequent calculations of the Articulation Index as required by ANSI S3.5-1969, paragraph 4.2.1.1.

Performed by:
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APPENDIX D

Volvo Truck Cab Insertion Loss Measurements

1997 Volvo truck cab with sleeper berth, Model VN, with Volvo VE DIZ-425HP engine
Microphone positioned at 26.5" above driver's seat pan, 15.5" to right of driver's right ear, hung by shock cords from cab interior supports

Measurement equipment:
- RION SA-27 one-third OB real-time analyzer, 30 sec. L_{eq}, flat (linear) weighting, 1 sec. (slow) response
- RION NH-17 1/2" microphone and UC-53 1/2" pre-amplifier with foam windscreen on microphone.
- RION NC-73 calibrator
- Tall Radio Shack microphone stand for out of truck measurement
- Stanley 12' tape measure

Audio equipment:
- Yamaha GE-60 graphic equalizer, pink noise on, equalizer flat
- NAD 1020B stereo pre-amplifier, set to mono
- NAD 2200 stereo power amplifier
- Infinity RS 6b speakers (2)
- Metal speaker stands (2)
- Wooden speaker stands (2)

Computer equipment:
- Gateway 2000 laptop with Pentium processor
- RION Transfer Program, cable

Protocol:
All measurements took place at the loading dock of Whittemore Hall, May 22, 1997, 11:45 am -12:15 pm. The weather was fair and warm, with no precipitation. The truck engine was turned off for all measurements. The speakers were placed on stands with the bottom of the speakers approximately 72" from the ground so that the center of the speaker was at the approximate height of the microphone. The front face of the speakers was approximately 24" from the truck's front tires, and the speakers were slightly to the front of the front axles, with the face of the speakers angled towards the microphone. Pink noise was played as loud as the audio system gain would allow. The first measurement was pink noise with the windows up. The next measurement was pink noise with the windows down. The third measurement was ambient noise, windows up. The final measurement was pink noise with the truck removed, and the microphone placed at 93" above ground, in the same position relative to the speakers as it had been in the truck cab. In all cases, the measurement was stopped and redone if noisy trucks, motorcycles, etc. drove by. Immediately after each measurement was taken, the data were transferred to the computer using the RION transfer program.

Calibration:
- Prior to truck measurements - 93.9 dB at 1000 Hz
- After truck measurements - 93.9 dB at 1000 Hz
- Prior to out-of-truck measurement - 93.8 dB at 1000 Hz
- After out-of-truck measurement - 93.5 dB at 1000 Hz

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APPENDIX E

Tables of Masked Threshold Minus Effective Signal Level for 18 Noise Conditions for Train Horn

TABLE E1
Train Horn for Engine Idle, Windows Up Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	60.9	47.4	-13.6	41.3	-19.6
400	60.2	39.5	-20.7	33.5	-26.7
500	61.0	42.0	-19.0	35.9	-25.0
630	60.7	48.3	-12.4	42.3	-18.4
800	60.0	45.2	-14.8	39.2	-20.8
1000	60.1	42.0	-18.1	36.0	-24.2
1250	57.6	39.4	-18.3	33.3	-24.3
1600	55.3	35.0	-20.3	29.0	-26.4
2000	53.2	40.5	-12.8	34.5	-18.8
2500	51.4	36.6	-14.8	30.6	-20.8
3150	48.9	30.0	-18.9	24.0	-24.9
4000	46.5	20.6	-25.9	14.6	-32.0
5000	44.4	14.3	-30.1	8.3	-36.1

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E2
Train Horn for Engine Idle, Windows Down Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	61.1	69.1	**7.9**	63.0	**1.9**
400	58.7	60.2	**1.5**	54.2	-4.5
500	60.2	63.6	**3.4**	57.5	-2.6
630	60.8	67.6	**6.8**	61.6	**0.8**
800	59.7	65.1	**5.3**	59.1	-0.7
1000	59.8	59.9	**0.1**	53.9	-5.9
1250	57.3	61.2	**3.9**	55.1	-2.2
1600	55.5	52.9	-2.6	46.9	-8.6
2000	53.6	59.0	**5.4**	53.0	-0.6
2500	51.6	57.0	**5.4**	51.0	-0.6
3150	50.1	51.6	**1.5**	45.6	-4.5
4000	47.8	46.9	-0.9	40.9	-7.0
5000	45.3	40.0	-5.3	34.0	-11.4

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E3
Train Horn for Quietest Windows Down, Ventilation Off, Radio Off Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	75.5	69.1	-6.5	63.0	-12.5
400	73.5	60.2	-13.3	54.2	-19.3
500	73.3	63.6	-9.8	57.5	-15.8
630	73.5	67.6	-5.9	61.6	-11.9
800	71.6	65.1	-6.5	59.1	-12.5
1000	69.9	59.9	-10.0	53.9	-16.0
1250	69.3	61.2	-8.2	55.1	-14.2
1600	68.1	52.9	-15.2	46.9	-21.2
2000	67.2	59.0	-8.2	53.0	-14.2
2500	66.2	57.0	-9.2	51.0	-15.2
3150	65.2	51.6	-13.6	45.6	-19.6
4000	64.3	46.9	-17.4	40.9	-23.4
5000	63.1	40.0	-23.1	34.0	-29.1

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E4
Train Horn for Quietest Windows Down, Ventilation Off, Radio On Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	79.8	69.1	-10.8	63.0	-16.8
400	78.9	60.2	-18.7	54.2	-24.7
500	81.0	63.6	-17.5	57.5	-23.5
630	79.4	67.6	-11.8	61.6	-17.8
800	78.0	65.1	-12.9	59.1	-18.9
1000	77.3	59.9	-17.4	53.9	-23.4
1250	75.8	61.2	-14.7	55.1	-20.7
1600	75.0	52.9	-22.1	46.9	-28.1
2000	75.0	59.0	-16.0	53.0	-22.0
2500	73.6	57.0	-16.6	51.0	-22.6
3150	72.0	51.6	-20.4	45.6	-26.4
4000	70.7	46.9	-23.8	40.9	-29.8
5000	69.4	40.0	-29.4	34.0	-35.4

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E5
Train Horn for Quietest Windows Down, Ventilation On, Radio Off Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	79.8	69.1	-7.2	63.0	-13.2
400	78.9	60.2	-14.1	54.2	-20.1
500	81.0	63.6	-10.6	57.5	-16.6
630	79.4	67.6	-6.8	61.6	-12.8
800	78.0	65.1	-8.0	59.1	-14.0
1000	77.3	59.9	-11.5	53.9	-17.5
1250	75.8	61.2	-9.7	55.1	-15.7
1600	75.0	52.9	-16.6	46.9	-22.7
2000	75.0	59.0	-10.0	53.0	-16.0
2500	73.6	57.0	-11.0	51.0	-17.0
3150	72.0	51.6	-15.5	45.6	-21.5
4000	70.7	46.9	-19.3	40.9	-25.4
5000	69.4	40.0	-25.0	34.0	-31.0

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E6
Train Horn for Quietest Windows Down, Ventilation On, Radio On Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	79.1	69.1	-10.0	63.0	-16.0
400	77.3	60.2	-17.1	54.2	-23.1
500	79.0	63.6	-15.4	57.5	-21.4
630	77.9	67.6	-10.3	61.6	-16.3
800	77.0	65.1	-12.0	59.1	-18.0
1000	76.3	59.9	-16.4	53.9	-22.5
1250	74.7	61.2	-13.5	55.1	-19.5
1600	73.8	52.9	-20.9	46.9	-26.9
2000	73.0	59.0	-14.1	53.0	-20.1
2500	72.0	57.0	-15.0	51.0	-21.0
3150	70.6	51.6	-19.1	45.6	-25.1
4000	69.7	46.9	-22.8	40.9	-28.8
5000	68.4	40.0	-28.4	34.0	-34.4

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E7

Train Horn for Quietest Windows Up, Ventilation Off, Radio Off Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	70.3	47.4	-22.9	41.3	-28.9
400	68.9	39.5	-29.4	33.5	-35.4
500	68.6	42.0	-26.7	35.9	-32.7
630	67.3	48.3	-19.0	42.3	-25.0
800	65.2	45.2	-20.0	39.2	-26.1
1000	62.7	42.0	-20.7	36.0	-26.8
1250	60.2	39.4	-20.9	33.3	-26.9
1600	57.7	35.0	-22.7	29.0	-28.7
2000	56.0	40.5	-15.5	34.5	-21.5
2500	54.8	36.6	-18.2	30.6	-24.2
3150	52.3	30.0	-22.4	24.0	-28.4
4000	49.8	20.6	-29.2	14.6	-35.2
5000	47.3	14.3	-33.0	8.3	-39.0

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E8

Train Horn for Quietest Windows Up, Ventilation Off, Radio On Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	77.3	47.4	-29.9	41.3	-35.9
400	74.9	39.5	-35.4	33.5	-41.4
500	80.2	42.0	-38.2	35.9	-44.2
630	77.7	48.3	-29.4	42.3	-35.4
800	75.2	45.2	-30.0	39.2	-36.0
1000	73.1	42.0	-31.1	36.0	-37.1
1250	70.6	39.4	-31.2	33.3	-37.2
1600	71.4	35.0	-36.4	29.0	-42.4
2000	70.5	40.5	-30.0	34.5	-36.1
2500	68.5	36.6	-32.0	30.6	-38.0
3150	66.0	30.0	-36.1	24.0	-42.1
4000	63.5	20.6	-42.9	14.6	-49.0
5000	61.0	14.3	-46.7	8.3	-52.8

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E9

Train Horn for Quietest Windows Up, Ventilation On, Radio Off Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	69.5	47.4	-22.1	41.3	-28.2
400	67.5	39.5	-28.0	33.5	-34.1
500	67.8	42.0	-25.8	35.9	-31.9
630	66.8	48.3	-18.5	42.3	-24.6
800	65.1	45.2	-20.0	39.2	-26.0
1000	62.6	42.0	-20.7	36.0	-26.7
1250	60.1	39.4	-20.8	33.3	-26.8
1600	57.6	35.0	-22.6	29.0	-28.7
2000	55.9	40.5	-15.4	34.5	-21.5
2500	54.8	36.6	-18.2	30.6	-24.2
3150	52.5	30.0	-22.5	24.0	-28.5
4000	50.2	20.6	-29.6	14.6	-35.6
5000	47.7	14.3	-33.4	8.3	-39.4

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E10

Train Horn for Quietest Windows Up, Ventilation On, Radio On Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	72.6	47.4	-25.3	41.3	-31.3
400	70.4	39.5	-30.9	33.5	-36.9
500	72.8	42.0	-30.9	35.9	-36.9
630	71.2	48.3	-22.9	42.3	-28.9
800	68.7	45.2	-23.5	39.2	-29.5
1000	66.2	42.0	-24.2	36.0	-30.2
1250	63.7	39.4	-24.4	33.3	-30.4
1600	63.1	35.0	-28.1	29.0	-34.1
2000	62.8	40.5	-22.3	34.5	-28.3
2500	60.3	36.6	-23.7	30.6	-29.7
3150	57.8	30.0	-27.8	24.0	-33.8
4000	55.3	20.6	-34.7	14.6	-40.7
5000	52.8	14.3	-38.5	8.3	-44.5

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E11

Train Horn for Noisiest Windows Down, Ventilation Off, Radio Off Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	83.8	69.1	-14.7	63.0	-20.8
400	82.6	60.2	-22.4	54.2	-28.4
500	82.9	63.6	-19.3	57.5	-25.3
630	82.1	67.6	-14.5	61.6	-20.5
800	82.0	65.1	-16.9	59.1	-22.9
1000	81.2	59.9	-21.3	53.9	-27.3
1250	80.5	61.2	-19.4	55.1	-25.4
1600	79.3	52.9	-26.4	46.9	-32.4
2000	79.1	59.0	-20.1	53.0	-26.1
2500	78.1	57.0	-21.1	51.0	-27.2
3150	77.4	51.6	-25.8	45.6	-31.9
4000	76.4	46.9	-29.5	40.9	-35.5
5000	75.1	40.0	-35.1	34.0	-41.1

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E12

Train Horn for Noisiest Windows Down, Ventilation Off, Radio On Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	84.8	69.1	-15.7	63.0	-21.7
400	83.4	60.2	-23.2	54.2	-29.2
500	83.5	63.6	-20.0	57.5	-26.0
630	82.9	67.6	-15.3	61.6	-21.3
800	82.9	65.1	-17.9	59.1	-23.9
1000	82.1	59.9	-22.2	53.9	-28.2
1250	81.5	61.2	-20.3	55.1	-26.4
1600	80.7	52.9	-27.8	46.9	-33.9
2000	81.2	59.0	-22.2	53.0	-28.2
2500	80.1	57.0	-23.1	51.0	-29.1
3150	79.4	51.6	-27.9	45.6	-33.9
4000	78.5	46.9	-31.6	40.9	-37.6
5000	77.0	40.0	-37.0	34.0	-43.0

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E13

Train Horn for Noisiest Windows Down, Ventilation On, Radio Off Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	84.7	69.1	-15.7	63.0	-21.7
400	83.9	60.2	-23.7	54.2	-29.8
500	83.9	63.6	-20.3	57.5	-26.4
630	84.0	67.6	-16.4	61.6	-22.4
800	83.8	65.1	-18.7	59.1	-24.7
1000	82.6	59.9	-22.7	53.9	-28.7
1250	82.3	61.2	-21.1	55.1	-27.1
1600	81.7	52.9	-28.8	46.9	-34.9
2000	80.9	59.0	-22.0	53.0	-28.0
2500	80.0	57.0	-23.0	51.0	-29.0
3150	79.5	51.6	-27.9	45.6	-33.9
4000	78.4	46.9	-31.5	40.9	-37.6
5000	77.0	40.0	-37.0	34.0	-43.1

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E14

Train Horn for Noisiest Windows Down, Ventilation On, Radio On Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	84.2	69.1	-15.1	63.0	-21.2
400	83.0	60.2	-22.8	54.2	-28.8
500	83.1	63.6	-19.5	57.5	-25.6
630	82.5	67.6	-14.9	61.6	-20.9
800	82.9	65.1	-17.8	59.1	-23.8
1000	82.1	59.9	-22.3	53.9	-28.3
1250	81.8	61.2	-20.7	55.1	-26.7
1600	81.0	52.9	-28.1	46.9	-34.1
2000	80.5	59.0	-21.6	53.0	-27.6
2500	79.2	57.0	-22.3	51.0	-28.3
3150	78.8	51.6	-27.3	45.6	-33.3
4000	77.6	46.9	-30.7	40.9	-36.7
5000	76.4	40.0	-36.4	34.0	-42.4

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E15
Train Horn for Noisiest Windows Up, Ventilation Off, Radio Off Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	83.8	47.4	-36.5	41.3	-42.5
400	83.0	39.5	-43.5	33.5	-49.6
500	83.6	42.0	-41.7	35.9	-47.7
630	83.8	48.3	-35.5	42.3	-41.5
800	83.4	45.2	-38.2	39.2	-44.2
1000	82.2	42.0	-40.2	36.0	-46.2
1250	81.9	39.4	-42.5	33.3	-48.5
1600	81.2	35.0	-46.2	29.0	-52.2
2000	80.3	40.5	-39.8	34.5	-45.8
2500	79.3	36.6	-42.8	30.6	-48.8
3150	78.7	30.0	-48.7	24.0	-54.7
4000	77.6	20.6	-57.0	14.6	-63.0
5000	76.1	14.3	-61.8	8.3	-67.9

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E16
Train Horn for Noisiest Windows Up, Ventilation Off, Radio On Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	83.7	47.4	-36.3	41.3	-42.4
400	82.8	39.5	-43.3	33.5	-49.4
500	83.3	42.0	-41.3	35.9	-47.4
630	83.3	48.3	-35.0	42.3	-41.0
800	83.2	45.2	-38.0	39.2	-44.0
1000	82.0	42.0	-40.1	36.0	-46.1
1250	81.5	39.4	-42.2	33.3	-48.2
1600	80.9	35.0	-45.9	29.0	-52.0
2000	80.3	40.5	-39.8	34.5	-45.8
2500	79.4	36.6	-42.8	30.6	-48.8
3150	78.8	30.0	-48.8	24.0	-54.8
4000	77.6	20.6	-57.0	14.6	-63.0
5000	76.1	14.3	-61.8	8.3	-67.9

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E17
Train Horn for Noisiest Windows Up, Ventilation On, Radio Off Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	83.1	47.4	-35.8	41.3	-41.8
400	82.3	39.5	-42.8	33.5	-48.9
500	83.1	42.0	-41.1	35.9	-47.2
630	82.4	48.3	-34.1	42.3	-40.1
800	82.5	45.2	-37.3	39.2	-43.3
1000	81.8	42.0	-39.8	36.0	-45.8
1250	80.9	39.4	-41.6	33.3	-47.6
1600	79.9	35.0	-44.9	29.0	-50.9
2000	79.5	40.5	-39.0	34.5	-45.0
2500	78.3	36.6	-41.8	30.6	-47.8
3150	77.8	30.0	-47.8	24.0	-53.8
4000	76.7	20.6	-56.1	14.6	-62.1
5000	75.4	14.3	-61.1	8.3	-67.1

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

TABLE E18
Train Horn for Noisiest Windows Up, Ventilation On, Radio On Condition

Freq. (Hz)	Masked Threshold (dB)	Train Horn 660' Effective Signal	Eff. Signal Minus Masked Threshold	Train Horn 1320' Effective Signal	Eff. Signal Minus Masked Threshold
315	83.5	47.4	-36.1	41.3	-42.2
400	82.3	39.5	-42.8	33.5	-48.8
500	82.6	42.0	-40.6	35.9	-46.6
630	81.9	48.3	-33.6	42.3	-39.6
800	82.0	45.2	-36.9	39.2	-42.9
1000	80.9	42.0	-39.0	36.0	-45.0
1250	80.3	39.4	-40.9	33.3	-46.9
1600	79.3	35.0	-44.3	29.0	-50.3
2000	79.4	40.5	-38.9	34.5	-45.0
2500	78.2	36.6	-41.6	30.6	-47.6
3150	77.4	30.0	-47.4	24.0	-53.4
4000	76.5	20.6	-55.9	14.6	-61.9
5000	75.1	14.3	-60.8	8.3	-66.8

Bold indicates that signal exceeds the masked threshold at this frequency for this condition.

SUZANNE E. LEE

Suzanne Lee was born and spent her childhood years in Louisiana. She obtained a B.A. in English Literature from Louisiana Sate University in 1980. After that, Ms. Lee worked in industry for several years, spending time in the coffee, lumber, and chemical manufacturing industries. From 1990-1993 she worked as an industrial engineering aide for Hercules, Inc., at the Radford Army Ammunition Plant in Radford, Virginia. In 1993 she returned to school, and in 1995 she obtained an M.S. in safety engineering from the Department of Industrial and Systems Engineering at Virginia Tech. Her research topic for her master's thesis was the psychophysics of team lifting. For one semester during her master's tenure she served as a graduate teaching assistant for ISE 3614, Introduction to Human Factors Engineering. After completing her master's degree, Ms. Lee joined the Auditory Systems Laboratory, and from 1996-1998 she conducted the research project outlined in this dissertation. During this time she also participated in several other research projects involving audiometry and hearing protection devices. Ms. Lee is an active member of the Human Factors and Ergonomics Society, as well as the Institute of Industrial Engineers. She has lived with her family in Blacksburg, Virginia for the past 12 years. Her daughter attends the Blacksburg New School, where Suzanne has served as Secretary (2 years) and Vice-President (1 year). Suzanne has also been active in civic affairs, serving on the Town of Blacksburg's Arbor Day Committee for three years. Suzanne enjoys reading, camping, hiking, and playing soccer.