U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**

www.nhtsa.gov

DOT HS 811 496 October 2011

Quieter Cars and the Safety of Blind Pedestrians, Phase 2: Development of Potential Specifications for Vehicle Countermeasure Sounds

Final Report

APA Format Reference:
Hastings, A., Pollard, J. K., Garay-Vega, L., Stearns, M. D., & Guthy, C. (2011, October). *Quieter Cars and the Safety of Blind Pedestrians, Phase 2: Development of Potential Specifications for Vehicle Countermeasure Sounds*. (Report No. DOT HS 811 496). Washington, DC: National Highway Traffic Safety Administration.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank) DOT HS 811 496	2. REPORT DATE October 2011	3. REPORT TYPE AND DATES COVERED Final Report: April 2010 to April 2011

4. TITLE AND SUBTITLE
Quieter Cars and the Safety of Blind Pedestrians, Phase 2: Development of Potential Specifications for Vehicle Countermeasure Sounds

5. FUNDING NUMBERS
HS59A3

6. AUTHOR(S)
Dr. Aaron Hastings, John K. Pollard, Dr. Lisandra Garay-Vega, Dr. Mary D. Stearns, and Catherine Guthy

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Research and Innovative Technology Administration
John A. Volpe National Transportation Systems Center
Cambridge, MA 02142

8. PERFORMING ORGANIZATION REPORT NUMBER
DOT-VNTSC-NHTSA-11-04

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
National Highway Traffic Safety Administration
Human Factors Engineering Integration Division
Vehicle Safety Research Office, NVS-331
Washington, DC 20590

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

This document is available to the public through the National Technical Information Service www.ntis.gov

12b. DISTRIBUTION CODE

13. ABSTRACT This project performed research to support the development of potential specifications for vehicle sounds, (i.e., audible countermeasures) to be used in vehicles while operating in electric mode in specific low speed conditions. The purpose of the synthetic vehicle sound is to alert pedestrians, including blind pedestrians, of vehicle presence and operation. The project developed various options and approaches to specify vehicle sounds that could be used to provide information at least equivalent to the cues provided by ICE vehicles, including speed change. Acoustic data from a sample of ICE vehicles was used to determine the sound levels at which synthetic vehicle sounds, developed as countermeasures, could be set. Psychoacoustic models and human-subject testing were used to explore issues of detectability, masking, and recognition of ICE-like and alternative sound countermeasures. Data were used to develop potential options that could be pursued to develop specifications for synthetic vehicle sounds. Project results indicate that vehicle detectability could potentially be met through various options including: recording(s) of actual ICE sounds; synthesized ICE-equivalent sounds; alternative, non-ICE-like sounds designed for detectability; and a hybrid of the options listed above.

14. SUBJECT TERMS
Electric vehicle, pedestrians, acoustic measurement, auditory detectability

15. NUMBER OF PAGES
156

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18298-102

ACKNOWLEDGMENTS

The authors of this report are, *Dr. Aaron Hastings, John K. Pollard, Dr. Lisandra Garay-Vega, Dr. Mary D. Stearns, and Catherine Guthy* of the John A. Volpe National Transportation Systems Center (Volpe Center), Research and Innovative Technology Administration, United States Department of Transportation.

Special appreciation is due to the National Highway Traffic Safety Administration, including *Tim Johnson*, director of the Office of Human-Vehicle Performance Research and *Stephen Beretzky*, project lead in the Human Factors/Engineering Integration Division.

Special thanks to *Steven Rothstein*, president of the Perkins School for the Blind, Watertown, Massachusetts, for the recommendations provided in terms of recruitment, transportation, and logistics for the human-subject experiments. We acknowledge *Kim Charlson*, Director of the Perkins Braille & Talking Book Library, who helped us distribute recruitment information.

We thank *Arthur O'Neill*, vice president of the Carroll Center for the Blind, Newton, Massachusetts, for his willingness to collaborate in this research. We would like to thank *Rabih Dow*, director of the Carroll Center's Residential Rehabilitation Training Program. We acknowledge the work of Joe Kolb, Heather Platt, and Naomi Zabot. These orientation and mobility instructors provided valuable information while demonstrating the various walking and listening situations typical for pedestrians who are blind.

Megan Robertson, director of orientation and mobility department, Massachusetts Commission for the Blind, and *Bob Hachey, president,* Bay State Council of the Blind for distributing recruitment information.

The authors appreciate the feedback and information exchange with researchers and representatives of several organizations including: Alliance of Automobile Manufacturers; American Council of the Blind; American Foundation for the Blind; Association of International Automobile Manufacturers; Environmental Protection Agency; International Organization for Standardization; Japan Automobile Manufacturers Association; National Federation of the Blind; Society of Automotive Engineers; and Unites Nations Economic Commission for Europe, Word Forum for Harmonization of Vehicle Regulation.

The authors acknowledge Volpe Center team members who made valuable contributions to this study.

Finally, the authors extend special appreciation to the volunteers who participated in the human-subject experiments.

LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of variance
AASHTO	American Association of State Highway and Transportation Officials
AVAS	Approaching Vehicle Audible System
CANbus	Controller Area Network bus
dB	Decibel
dB(A)	A-weighted decibel level
DSP	Digital signal processer
EPA	Environmental Protection Agency
ERB	Equivalent Rectangular Bandwidths
EVs	Electric vehicles
GPS	Global positioning system
HEVs	Hybrid-electric vehicles
ICE	Internal combustion engine
IRB	Institutional Review Board
$\mathbf{L_{Aeq\ 1/2\ sec}}$	A-weighted ½-second equivalent sound pressure level
$\mathbf{L_{AF(max)}}$	Max A-weighted SPL fast time weighting over each ½-second interval
$\mathbf{L_{AF(min)}}$	Min A-weighted SPL fast time weighting over each ½-second interval
$\mathbf{L_{Zeq,\ 1/2\ sec}}$	Un-weighted ½-second equivalent sound pressure level
LD824	Larson Davis Model 824
MLIT	Ministry of Land, Infrastructure, Transport and Tourism
mph	Miles per hour
NCSA	National Center for Statistics and Analysis
NHTSA	National Highway Traffic Safety Administration
OEM	Original equipment manufacturer
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SLM	Sound level meter
SPL	Sound pressure level
SUV	Sport Utility Vehicle
USDOT	United States Department of Transportation
Volpe Center	Volpe National Transportation Systems Center
VRTC	Vehicle Research Test Center, NHTSA

ACOUSTIC DEFINITIONS

Acoustics	Science of sounds. Includes sound production, transmission and effects.
Ambient Noise	Composite of sound from many sources near and far at a given place.
Audiometer	Device used to measure hearing sensitivity as a function of frequency.
Detection	In acoustics, determination of the presence of an acoustic signal.
Frequency	For a sine wave, the number of periods occurring in 1 second.
Loudness	Attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from soft to loud.
Pitch	Attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from low to high.
Pure Tone	Line spectrum that consists of a signal at a single frequency.
Sound Pressure Level	Level of a sound in decibels relative to an internationally defined reference level.
Spectrum	Description of the resolution of a signal into components, each of different frequency.
Timbre	Catch-all term for every other attribute of a sound except its steady-state amplitude and pitch. These include the relative proportions of tonal and random components, the shape of the spectral plot, the rise and decay times, amplitude and frequency modulations, etc. Enables listeners to judge that two non-identical sounds (similarly presented and having the same loudness and pitch) are dissimilar, e.g. two different musical instruments playing the same note at the same loudness.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Executive Summary

PURPOSE

This report documents research conducted to identify potential methods of developing specification for vehicle sounds (audible countermeasures), for use in electric vehicles (EV), plug-in hybrid electric vehicles (PHEV) or hybrid electric vehicles (HEV) operating in electric mode. The research focused on developing objective specifications for detectability using sound pressure levels (SPLs) and spectral profile characteristics. The feasibility of objectively specifying other aspects of sound quality for the purpose of predicting recognizability was explored.

This research was funded by the National Highway and Traffic Safety Administration's (NHTSA) Office of Human-Vehicle Performance Research and is a follow-on to NHTSA's Phase 1 research, which initially studied the issue of Quieter Cars.   The Volpe National Transportation Systems Center (Volpe Center) of the U.S. Department of Transportation's Research and Innovative Technology Administration (RITA) completed this research under an Inter-Agency Agreement (IAA) with NHTSA.

Acoustic countermeasures should alert pedestrians, including blind pedestrians, of vehicle presence and operation, and provide alerting information at least equivalent to the cues provided by internal combustion engine (ICE) vehicles. Based on this premise, acoustic data acquired from a sample of ICE vehicles were used to determine the sound levels at which ICE-like synthetic vehicle sounds, developed as countermeasures, could be set. Acoustic measurement included overall A-weighted sound levels and one-third octave band data. Draft specifications for ICE-equivalent sounds are based on the mean sound level of all trials for a given operating mode.

Acoustic measurements were collected for the following vehicle operating modes:

- Low speed pass-by forward at 6, 10, 15 and 20 mph;
- Low speed pass-by reverse at 6 mph;
- Acceleration (from 0 to 10 mph);
- Idle; and
- Start-up.

Ten vehicles from model years 2000 to 2009 were measured in a quiet residential environment for these operating modes.

Psychoacoustic models and human-subject testing were used to explore issues of detectability, masking, and recognition of ICE-like and alternative sound countermeasures. Human-subject testing was conducted to compare countermeasure sounds in a representative urban-ambient noise condition; a semi-controlled environment with an overall A-weighted sound level of approximately 58 to 61 dB(A). The metric of performance for the human-subject testing was the distance at which these sound sources were detected and recognized as a vehicle. Countermeasure sounds were evaluated for 6 mph forward pass-by at two sound pressure levels within the range of typical ICE vehicles (i.e., 59.5 and 63.5 dB(A)). A qualitative and quantitative description of these sounds is provided in this report.

The countermeasure systems evaluated included:

- Sounds produced by vehicles with integrated countermeasures rented from manufacturers; and
- Sounds produced by prototype countermeasure systems rented from manufacturers, and played back by loudspeakers temporarily mounted on HEVs rented separately.

A total of nine sounds were evaluated (labeled A1, A2, A5, B, C, D, E1, E3, and E4). The sounds included ICE-like sounds, alternative sounds designed according to psychoacoustic principles, and sounds that combine alternative sounds with some ICE-like components. In addition to the countermeasures sounds, an ICE vehicle, that produced 60 dB(A) in the 6 mph pass-by test, was included in the study as a baseline for comparison purposes. The ICE vehicle was labeled system 'R'.

RESULTS

A summary for the acoustic measurements of the ten ICE vehicles is given in Table ES-1, along with the ambient level for reference. Here the average overall A-weighted level ($L_{Aeq,\ ½\ sec}$) is given for each operating mode. These levels are interpreted as the minimum acceptable level for countermeasure sounds for the specified operating mode. One-third octave band levels for ICE vehicles are also documented in this report.

Table ES-1. Minimum Overall A-weighted Level ($L_{Aeq,\ ½\ sec}$) by Vehicle Operation

Vehicle Operation	**$L_{Aeq,\ 1/2\ sec,}$ dB(A)**
6 mph, Reverse	58.4
6 mph, Forward	61.1
10 mph, Forward	63.6
15 mph, Forward	68.1
20 mph, Forward	70.2
Acceleration from 0 to 10 mph	66.7
Start-up	70.7
Idle	55.2
Ambient	58.4

Moore's Loudness model was used to explore whether ICE vehicle sounds would be perceived in the presence of a given ambient sound level. According to the model, all ICE vehicles included in the acoustic measurements would be detectable at the point of closest approach. Frequency components between 1600 and 5000 Hz one-third octave bands would be more detectable due to strong signal strength and relatively low ambient levels in this range. Frequency components less than 500 Hz would have been less (or not at all) detectable due, in part, to ambient levels typically being high below 500 Hz. During testing tonal components emitted by two ICE vehicles would be particularly detectable, according to the model.

Human-subject testing was conducted to examine various sounds at two playback levels in an urban ambient condition. Table ES-2 shows the mean detection distances for the sounds evaluated in the human-subject studies; sounds at the top of the list can be described as alternative sounds designed according to psychoacoustic principles and sounds at the end of the list can be described as ICE-like sounds with only the fundamental combustion noise or otherwise lacking in the qualities that support detectability. The lower and upper sound levels evaluated in the human-subject test were 59.5 and 63.5 dB(A) respectively. The two sound pressure levels of the playback were selected represent most of the range of SPL values for the 10 ICE vehicles recorded in the 6-mph-pass-by tests, and to approximately bracket the 61 dB(A) mean of those tests. An ICE vehicle that produced 60 dB(A) in the 6 mph pass-by test was used as a reference in the evaluation.

Table ES-2. Mean Detection Distance (in Feet) for all Countermeasure Sounds at two Amplitudes and for the Reference ICE Vehicle

Sound Number	Average Detection Distance (feet) for amplitude equal 59.5 dB(A)	Average Detection Distance (feet) for amplitude equal 63.5 dB(A)
E4	72	85
A2	57	77
E3	52	70
A5	50	47
ICE vehicle, 60 dB(A)	41	NA
A1	35	44
C	32	41
E1	30	32
B	20	25
D	19	NA

In general, synthetic sounds that resemble those of an ICE vehicle produce similar detection distances as actual ICE vehicles. In some instances, synthetic sounds designed according to psychoacoustic principles can produce double the detection distances at slightly lower overall sound levels. Synthetic sounds that contain only the fundamental component of combustion noise, but lack the harmonics and other high-frequency noises (fans, gears, etc.) of an actual ICE were relatively ineffective, i.e., their detection distances were only about half those of an ICE.

DISCUSSION

The most important components of a sound to alert pedestrians of an approaching vehicle under conditions of urban ambient noise generally lie in the frequency range of 300 to 5,000 Hz. Much of the acoustic power emitted by ICEs lies in the range below 300 Hz, but it is not necessary to reproduce these sounds, since they are usually masked by the ambient, and because they do not provide good directional cues. Sounds above 5,000 Hz are generally at much lower levels, so that they are not as important for detection, and maybe inaudible to persons with high-frequency hearing loss.

The literature of auditory warnings and the psychoacoustic models show that for a warning sound to be detected, it is necessary that it contain some components (one-third-octave bands), preferably 4 or more, that exceed the corresponding bands in the ambient noise. Detectability of countermeasure sounds can be specified through various options, such as:

- Recording(s) of Actual ICE Sounds (Option A).
    1. Defined by overall A-weighted levels.
    2. Defined by one-third octave band average spectra.
    3. Defined by one-third octave band minima spectra.
    4. Combinations of the above.
- Synthesized ICE-Equivalent Sounds (Option B).
    1. Defined by overall A-weighted levels.
    2. Defined by one-third octave band average spectra.
    3. Defined by one-third octave band minima spectra.
    4. Combinations of the above.
- Alternative, non ICE-like Sounds Designed for Detectability (Option C).
- Hybrid of options listed above (Option D).

Countermeasure sounds could be based on recordings of actual ICE vehicles made at various speeds and under various operating conditions and selected by the processor to correspond to a given vehicle’s operation at each moment while operating below 20 mph (Option A).

A second alternative is to allow the sounds to be generated by a digital signal processor chip programmed to emulate the sounds of an ICE, at least in the 300 to 5000 Hz range (Option B). This alternative would permit a wider range of sounds and would still ensure that countermeasure sounds resemble ICE sounds.

Sounds designed for maximum detectability at a given sound-pressure level follow certain well-known principles described in this report (Option C). Finally, as a fourth option, digital signal processors can simultaneously create both sounds that resemble ICE noise and sounds that embody special characteristics to enhance detection (Option D). The two types of sounds can be blended in any proportion, with both components being pitch shifted according to vehicle speed.

USE OF OBJECTIVE VERSUS SUBJECTIVE CRITERIA FOR DETECTION AND RECOGNITION

For the reasons given in the Phase 1 report [DOT HS 811 304] on this research, the Phase 2 work focused initially on the following idea. The lack of *detectability* of quieter cars could be remediated if they are fitted with synthetic sound generators that emulate the sound of typical ICEs and that future specifications for the vehicle sounds can be specified in terms of objectively measured parameters– namely, overall sound output as measured by the SAE J2889-1 procedure together with spectral distribution specifications for the minimum amount of sound level in one-third-octave bands. However, *recognizability* is a different matter. Most sounds, and sounds as complex as those emitted by an ICE, have numerous properties in addition to loudness and spectral distribution that affect human perception. Among these properties are rise time, decay time, repetition rates, variations in pitch and loudness, and phase relations among various components of the sound. It can be demonstrated, for example, that changes in these properties can render a sound unrecognizable even though loudness and spectral distribution are unchanged by playing a recording of the sound backwards. There are no established quantitative metrics for many qualities of a sound that a person might use for recognition.

Some of the prototype sounds that were tested in this research were synthesized to resemble ICE sounds, while others were not. Some sounds, were comprised of entirely synthetic, non-ICE sounds generated by a digital-signal-processor (DSP), and demonstrated that, in some instances, it is possible to achieve significantly better detection distances, at the same sound level (as measured by the SAE 2889-1 draft procedure), compared with ICE-like sounds. Sounds constructed according to established principles for auditory warnings were recognized on first hearing in the human-subject tests when they were played at a level approximately equal to or higher than the ambient noise level. These sounds lack the low-frequency, fundamental combustion noise of an ICE, which allows them to be played through small, well-sealed speakers similar to those used in back-up warning devices. Given these advantages, there is likely to be an industry preference for use of entirely synthetic sounds. However, an objective specification for non-ICE-like sounds is more difficult to develop than one for synthetic sound generators that emulate the sound of typical ICEs. This former approach could result in a wider variety of sounds, some of which might be not recognized as a vehicle or which might be perceived as annoying. Most of the sounds offered for testing by manufacturers were chosen through a jurying process.

1. INTRODUCTION

1.1 Background

HEVs are two times more likely than ICE vehicles to be in a pedestrian crash where the vehicle is backing out, slowing/stopping, starting in traffic, and, entering or leaving a parking space/driveway. The vehicles involved in such crashes are likely to be moving at low speeds where the difference between the sounds emitted by HEVs and ICEs is substantial. The crash incidence rate for the combined set of maneuvers is 1.2 percent and 0.6 percent for HEVs and ICE vehicles respectively and the difference is statistically significant. The analysis, conducted by NCSA, uses a small sample (8,387 HEVs and 559,703 ICE vehicles) and does not intend to provide national estimates (Hanna, 2009).

A reduction in the sound emitted by vehicles operating at low speeds and in electric mode may have implications for all pedestrians; however pedestrians who are blind may be particularly affected because they depend almost entirely on auditory cues to navigate. Groups representing people who are blind have expressed concern about the lack of sound emitted by HEVs (Maurer, 2008).

Previous research by NHTSA (Phase 1) documented the acoustic characteristics of ICE and HEVs and evaluated the auditory detectability of these vehicles. Acoustic measurements were obtained for the following operating conditions: backing out at 5 mph; slowing from 20 to 10 mph; approaching at a constant low speed; accelerating from a stop; and idle. Acoustic measurements for vehicles approaching at low speeds (6 mph and 10 mph) and moderate speeds (20 mph, 30 mph, 40 mph) were used to document how the overall sound level for ICE vehicles and their HEV twins differ as a function of vehicle speed. Human-subject studies examined the auditory detectability of ICE vehicles and HEVs (operated in electric mode) for two ambient sound levels. Three operating conditions used for the human-subject studies were: vehicle backing out at 5 mph; vehicle slowing from 20 to 10 mph; and vehicle approaching at a constant speed (6 mph). The study also identified countermeasure concepts from literature reviews. (Garay-Vega, Hastings, Pollard, Zuschlag, and Stearns, 2010).

The results of NHTSA (Phase 1) shows that the overall sound levels for the HEVs tested are noticeably lower at low speeds than for the ICE vehicles tested (Garay-Vega, et al., 2010). Considering the results of acoustic measurements and human subject data, countermeasures are only needed when vehicles are operated at speeds generally less than 10 to 20 mph where tire noise is not dominant (Garay-Vega, et al., 2010; Japanese Automobile Standard Internationalization Centre, 2009). On average, participants took significantly longer to detect vehicles operating in electric mode than the ICE counterparts. These results are consistent with studies at the University of California Irvine (Rosenblum, 2008) and Western Michigan University (Wall Emerson, unpublished) as well as studies conducted by the Japanese Automobile Standards Internationalization Centre (JASIC). Response time to detect a target vehicle varies by vehicle operating condition, ambient sound level, and vehicle type (i.e., ICE versus HEV in EV mode) (Garay-Vega, et al., 2010).

At the present time, synthetic vehicle sounds appear to be the only countermeasure that is useful in providing relevant sound cues needed by pedestrians. Relevant sound cues provide information about vehicle presence, speed, and rate of change in speed. Considering the results of previous studies, such sounds are only needed when vehicles are operated at low speeds (generally less than 10-20 mph) (Garay-Vega, et. al, 2010; Japanese Automobile Standard Internationalization Centre, 2009) and possibly when stationary. The characteristic sound of an ICE vehicle being started is also desired as it is often the first cue of the presence of a potential threat, for example, in a parking lot. The sound of a vehicle accelerating from stop, for example at a traffic signal, provides relevant cues about the state of the traffic flow and is also considered important.

Groups representing people who are blind have expressed a preference for sound(s) that will be recognized as that of an approaching vehicle so that it will be intuitive for all pedestrians (Goodes, Bai, & Meyer, 2009; Maurer, 2008).

1.2 Research Purpose

The purpose of this research was to develop potential specifications for vehicle sounds (i.e., audible countermeasures) to be used in vehicles while operating in electric mode in specific low speed conditions. The specifications include quantitative specifications for sound levels and spectral profiles for detectability. The feasibility of objectively specifying other aspects of sound quality for the purpose of predicting recognizability of the synthetic sounds was explored.

1.3 Research Objectives

The following objectives were established to meet the goal of the research:

- Determine the distribution of the sound levels of typical ICE vehicles in the operating modes of concern;
- Develop detectability specifications for vehicle sounds;
- Conduct human-subject testing to measure the detectability and recognizability of synthetic vehicle sounds; and
- Determine feasibility of an objective specification test (or develop alternative evaluation procedure).

1.4 Technical Approach

Acoustic data acquired from a sample of ICE vehicles were used to determine the sound levels at which ICE-like synthetic vehicle sounds, developed as countermeasures, would be set. Measurements include overall sound levels and one-third octave band data. Draft specifications were based on the mean sound level of all trials for a given operating mode.

Vehicle operations were identified from various sources including: NHTSA crash data analysis; previous research by NHTSA (Phase 1 of this research program); concerns expressed by representatives of the blind community; and feedback from subject matter experts.

Acoustic measurements are collected for the following vehicle operating modes:

- Low speed pass-by forward at 6, 10, 15 and 20 mph;
- Low speed pass-by reverse at 6 mph;
- Acceleration (from 0 to 10 mph);
- Idle; and
- Start-up.

One of the operating modes, deceleration from 20 to 10 mph (as if to turn right), that was tested in Phase 1 of this program could not be included in the Phase 2 study. Deceleration from 20 to 10 mph (as if to turn right) was not included in Phase 2 because a location of sufficient length to test vehicle deceleration was not readily available. In addition, to conduct a valid test of the detectability of decelerations with real vehicles, it would be necessary to limit the number of subjects being tested to only one or two in a single experimental session, so that they would be exposed to essentially the same auditory content. Conducting numerous additional sessions, or extending session durations to approximately six hours so that deceleration could be included was inadvisable for reasons of cost, timeliness of project completion, and the health and comfort of the subjects. Start-up operation was not tested in Phase I but such sounds were measured in Phase 2. The ability of human subjects to detect and recognize startup, idle, and 0-to-10-mph acceleration sounds was recorded during the first experimental session.

Draft specifications were then refined using information from psychoacoustic model(s) and human-subject testing. Psychoacoustic model(s) and human-subject testing were used to explore issues of detectability, masking, and recognition of alternative sound countermeasures. Figure 1 shows a flow diagram of the technical approach used to develop potential specifications for synthetic vehicle sounds. A summary of findings, discussion of alternative approaches to specify vehicle sounds for quieter cars, and recommendations for future work in the area are included in this report.

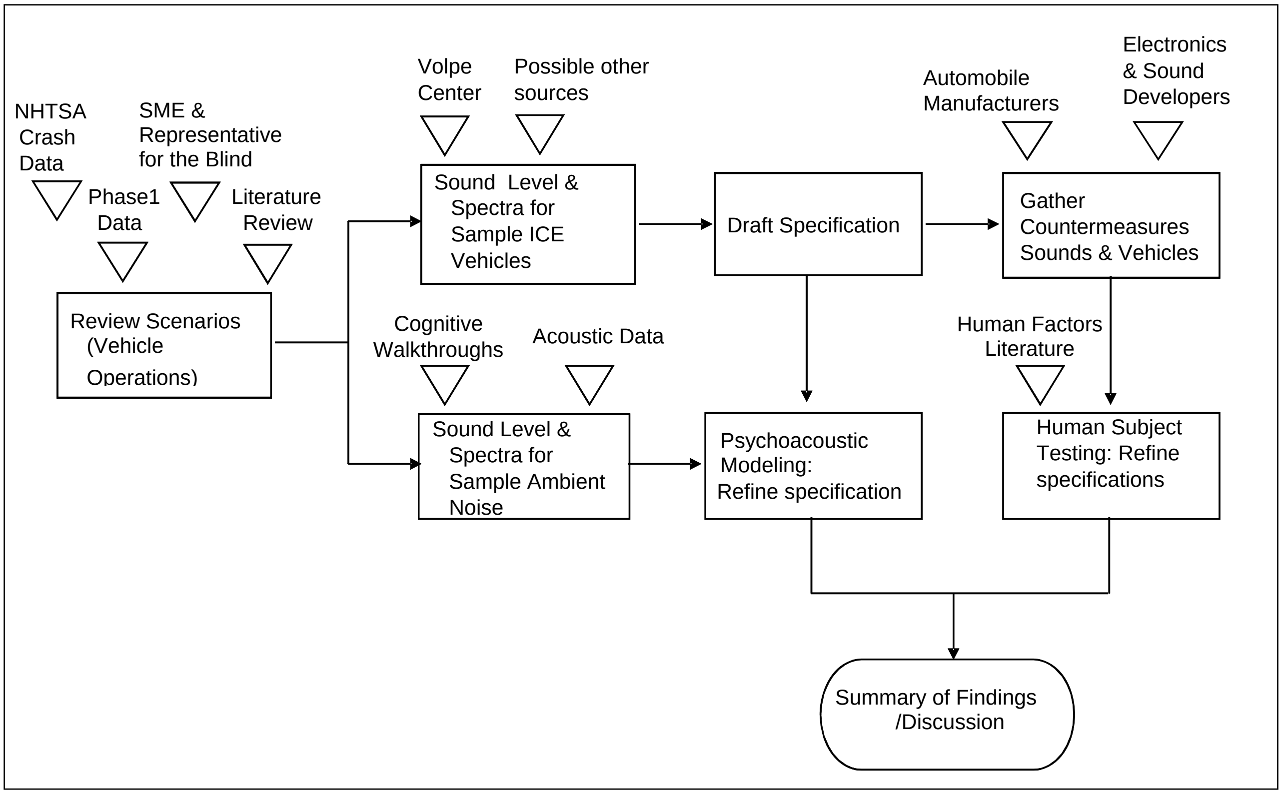


Figure 1. Technical Approach to Develop Potential Specifications for Vehicle Sounds

1.5 Outreach

NHTSA and the Volpe Center have taken an active role in connecting with various public and private entities and seeking their input concerning this research. These entities include:

- Alliance of Automobile Manufacturers;
- American Council of the Blind;
- American Foundation for the Blind;
- Association of International Automobile Manufacturers;
- International Organization for Standardization;
- International Organization of Motor Vehicle Manufacturers;
- Japan Automobile Manufacturers Association;
- Massachusetts Commission for the Blind;
- National Federation of the Blind;
- Perkins School for the Blind;
- Society of Automotive Engineers;
- The Carroll Center for the Blind;

- United Nations Economic Commission for Europe, World Forum for Harmonization of Vehicle Regulation; and
- U.S. Environmental Protection Agency.

NHTSA also has a docket to facilitate information exchange with the public.

1.6 Report Organization

- Chapter 2 includes background information.
- Chapter 3 discusses the pedestrian-vehicle scenarios and vehicle operating considered in the evaluation.
- Chapter 4 describes acoustic measurements of ICE vehicles, countermeasure sounds, and ambient sounds.
- Chapter 5 discusses the acoustic analysis of ICE vehicles, including preliminary specifications, as well as acoustic analysis of countermeasures and ambient sounds.
- Chapter 5 discusses the acoustic characteristics of ICE vehicles and ambient sounds.
- Chapter 6 focuses on psychoacoustic models used to explore issues of detectability, masking of ICE vehicles and alternative sound countermeasures.
- Chapter 7 describes human-subject testing used to explore issues of detectability and recognition of alternative sound countermeasures.
- Chapter 8 presents a discussion of potential specifications for sounds for quieter cars.
- Chapter 9 includes a summary of findings and considerations for future research.

2. BACKGROUND

2.1 Audible Cues for Pedestrians

The acoustic countermeasure should alert pedestrians, including blind pedestrians, of vehicle presence and operation. The audible countermeasure sounds should provide information equivalent to the information provided by ICE vehicles, including speed change. This report documents research conducted to identify potential methods to specify levels and spectral content for vehicle sounds to be used as countermeasures on quieter cars. For the purpose of this report, countermeasure sounds would apply to vehicles operating in electric only mode while operating in the specified conditions.

2.2 Detection Distance

Detection distance is the distance between the pedestrian and the vehicle at the time the vehicle was detected. Detection distance is the performance metric used in this report to evaluate the relative effectiveness of potential countermeasure sounds. The needed detection distance is computed from the vehicle speed and the pedestrian response time. For a vehicle approaching at a given speed, the larger the average detection distance the greater the likelihood that pedestrians will avoid conflict with that vehicle.

Stopping sight distance is the distance that enables a vehicle traveling at or near the design speed to stop before reaching a stationary object in its path. The stopping sight distance has two components: brake reaction and braking distance. Brake reaction is the distance traveled from the time the driver detects an object to the instant the driver applies the brakes. The recommended design criterion for brake reaction time (American Association of State Highway and Transportation Officials, AASHTO) is 2.5 seconds. A 2.5-second brake reaction time for stopping situations considers the capabilities of most drivers, including older drivers. Braking distance refers to the distance needed to stop the vehicle once the drivers applied the brakes, and depends on vehicle speed, deceleration rate, and roadway grade (AASHTO, 2004). For example, the stopping sight distance for a vehicle approaching at 6 mph is 25.5 ft (assuming brake reaction time of 2.5 s and a constant deceleration rate of 11.2 ft/s^2). The vehicle would travel approximately 22.5 ft while the driver reacts, plus need another 3.5 ft to decelerate the vehicle. In this example, the pedestrian must detect the vehicle (and respond) when the vehicle is at least 25.5 ft away in order to avoid a potential collision. Table 1 shows stopping sight distance as a function of vehicle speed and driver reaction time. Stopping sight distance can be compared with detection distances to assess the relative effectiveness of countermeasure sounds.

Table 1. Stopping Sight Distance as a Function of Vehicle Speed and Driver Reaction Time

Vehicle Speed	Driver Reaction Time = 1 sec	Driver Reaction Time = 1.5 sec	Driver Reaction Time = 2 sec	Driver Reaction Time = 2.5 sec
6 mph	12.3 ft	16.7 ft	21.1 ft	25.5 ft
10 mph	24.3 ft	31.6 ft	39.0 ft	46.3 ft
15 mph	43.6 ft	54.6 ft	65.7 ft	76.7 ft
20 mph	67.7 ft	82.4 ft	97.1 ft	111.8 ft

2.3 Masking Effect

Masking is the process by which the auditory threshold for one sound is raised by the presence of another (masking) sound. A sound signal is most easily masked by a sound having components close to those of the signal. In a very quiet rural or suburban environment, vehicles operating in pure electric mode at low speeds can often be detected by their tire noise, for example, the clicks produced by pebbles lodged in the tread. However at the levels of ambient noise that are typically present in commercial areas of suburbs, and certainly of cities, ambient noise masks low-speed tire noise. Pedestrians derive audible cues of vehicle approach primarily from ICE noise, once the ambient noise level rises above 45 dB(A). ICE noise provides useful cues at ambient levels up to roughly 75 dB(A), although there is no sharp transition from safe detectability conditions to unsafe ones, but rather a gradual one marked by increasing risk for the blind pedestrian. Blind pedestrians try to avoid crossing streets in the presence of very high levels of ambient noise without assistance from a sighted person, service animal, or a traffic control signal with audible indications.

The issue of masking was explored in this study using psychoacoustic models (Section 6).

2.4 Overview of International Activities

2.4.1 Japan

In 2009, the MLIT of Japan assembled a committee to study the issue of the quietness of HEVs. The committee concluded that an Approaching Vehicle Audible System (AVAS) was a realistic alternative for pedestrians who are blind or visually impaired. Several studies were conducted on the issue (MLIT and JASIC, 2010).

In 2010, MLIT announced guidelines for AVAS based on the recommendations of the study committee. Although several vehicles were considered in the initial scope, MLIT concluded that AVAS shall be installed only on HEVs that can run on electric motors, EVs and fuel-cell vehicles. In terms of activation condition, the MLIT recommends that AVAS automatically generate sound at least in a speed range from the start of a vehicle until reaching 20 km/h and when moving in reverse. The AVAS would not be required when a vehicle is stopped. The system may include a switch to temporarily halt the operation of the AVAS. The reason for including a pause switch is because they believe that the system is not needed in expressways where there are no pedestrians and to reduce other issues such drivers deliberately increasing vehicle speed in order to stop the AVAS (MLIT and JASIC, 2010).

The MLIT includes the following guidelines for the type and volume for the sound generator system (MLIT and JASIC, 2010):

- "The sound shall be continuous sound associating motor vehicles running condition."
- "Siren, chime, bells, melody, horns sounds, animals, insects, and sound of natural phenomenon such as wave, wind, river current, etc., are not allowed."
- "The sounds generated shall be automatically altered in volume or tone depending on the vehicle speed for easier recognition of the move of the vehicle."
- "Sound volume shall not exceed a level of the sound generated when vehicles driven by internal combustion only run at speed of 20 km/h."

The use of add-on devices, generating sound continuously for 5 seconds or longer, have been approved in order to increase AVAS penetration. MLIT will look into social acceptability and verification of technology implementation issues before moving from a voluntary process to a mandate (MLIT and JASIC, 2010).

2.4.2 United Nations

UNECE World Forum for Harmonization of Vehicle Regulation has an informal group on Quiet Road Transport Vehicles (QRTV). The objective if the QRTV is to…"Determine the viability of 'quiet vehicle' audible acoustic signaling techniques and the potential need for their global harmonization." The QRTV's program plan includes: review the available research; determine human factors needed for pedestrians; develop technical performance parameters for vehicles based on human factors needs; determine audible sound characteristics and ways to convey desired vehicle performance information to pedestrians; and determine technical and economical feasibility of potential audible warning techniques (GRB Quiet Road Transport Vehicles, 2010).

2.4.3 US: Pedestrian Safety Enhancement Act 2010

The Pedestrian Safety Enhancement Act of 2010 (Public Law 111-373) was signed into law on January 4th, 2011. The Act directs the Secretary of Transportation to study and establish a motor vehicle safety standard that provides for a means of alerting blind and other pedestrians of motor vehicle operation. The goal is to promulgate a motor vehicle safety standard by establishing performance requirements for an alert sound that allows blind and other pedestrians to reasonably detect a nearby electric or hybrid electric vehicle. The law will apply to new electric and hybrid electric vehicles. The alert sound shall not require activation by the driver or the pedestrian, and shall allow pedestrians to reasonably detect an EV or HEV in critical operating scenarios such as constant speed, accelerating, or decelerating (Public Law 111-373, 2011).

3. VEHICLE OPERATING MODES

Vehicle operations were identified from various sources including: NHTSA crash data analysis; previous research by NHTSA (Phase 1 of this research program); concerns expressed by representatives of the blind community; and feedback from subject matter experts in orientation and mobility for individuals who are blind. Vehicle operations are described in this section.

3.1 Vehicle Approaching at Low Speed (forward)

One of the strategies used by pedestrians who are blind is to cross when the road is quiet. The technique assumes that a vehicle is loud enough to be heard far enough away to determine that it is safe to proceed when masking sounds are not excessive and no other vehicles are detected. A quieter vehicle approaching at low speed may not be detected until it is too close to the pedestrian. The scenario includes a pedestrian standing on the curb waiting to cross a street or pathway where there may be vehicles approaching at low speed from the right or left. The task is to detect a vehicle that would affect the decision about when to start across the street. Low speed operation refers to speeds below 20 mph.

3.2 Vehicle Approaching at Low Speed (reverse)

Some HEVs can use the electric motor as the sole source of propulsion for low speeds operation and this is particularly true when the batteries are fully charged. There is a concern that HEVs, in electric mode, may not be detectable when backing out. The scenario includes a pedestrian walking along a sidewalk with driveways on the left or right. The task is to detect a vehicle backing out of a driveway at 6 mph.

3.3 Vehicle Traveling in Parallel and Slowing (deceleration)

The sound characteristics of a vehicle slowing in the parallel street helps pedestrians, blind pedestrians in particular, to identify vehicles that may turn into their crossing path. The scenario includes a pedestrian trying to decide when to start crossing the street, there is a surge of parallel traffic on the immediate left. The task is to detect the presence of a vehicle in the parallel street and then distinguish between a vehicle traveling straight through the intersection at 20 mph and a vehicle decelerating from 20 mph to 10 mph as if to turn right into the pedestrian path.

3.4 Vehicle Accelerating from a Stop

A vehicle operating in electric mode may not be heard during initial acceleration. The sound characteristics of a vehicle accelerating from a stop provide important cues for pedestrians. For example, a vehicle accelerating from stop in the parallel street indicates that the perpendicular traffic does not have the right of way and thus a crossing opportunity may be available. Pedestrians may initiate their crossing as soon as they detect the surge of parallel traffic or may delay the decision to make sure traffic is moving straight through the intersection and not turning into their path. A significant delay in detecting the surge of parallel traffic may reduce the chance to complete a crossing within the designated walking interval. Another example includes a vehicle accelerating from a stopped position while coming out of a side street, parking lane, or driveway. In actual ICE vehicles, sounds of acceleration from a stationary position are much louder than 6-mph constant-speed pass-by. They were immediately detected and recognized by all participants in the human-subject test when played at their original volume, or even several dB lower.

3.5 Vehicle Stationary: Idle

Pedestrians who are blind use the sound characteristics of vehicles idling to establish alignment and to avoid veering into traffic while crossing a street. The sound characteristics of vehicle idling in the far lane gives cues about the width of the road (number of lanes), conveying information about the distance to walk, and the time required to cross the road. There is a concern that a vehicle operating in electric mode may not be detected when it is stationary and idling. There is a potential safety issue at intersections or parking lots when a vehicle starts moving at the same time the pedestrian enters the conflicting path. Idle sounds in current ICEs are often difficult to perceive in urban ambient.

3.6 Vehicle Starting-Up

The characteristic sound of a vehicle being started is often the first indication of a potential threat for blind pedestrians, for example, in a parking lot, parking lane, or driveway. In actual ICE vehicles, startup sounds are relatively loud and there is no doubt that such sounds would be immediately detected.

3.7 Phase 2 Data Collection by Vehicle Operation

Table 2 shows each vehicle operation along with an indication of whether we collected acoustic measurements and/or human subject data as part of this research.

Table 2. Data Collection by Vehicle Operation

Vehicle Operation	Acoustic Measurements	Subjective Response
Low speed forward	Yes (6, 10, 15, and 20 mph)	Yes (6 mph)
Low speed reverse	Yes (6 mph)	None
Slowing from 20 mph to 10 mph	None	None
Accelerating from 0 to 10 mph	Yes	Some
Idle	Yes	Some
Start up	Yes	Some

4. ACOUSTIC MEASUREMENT OF VEHICLES AND AMBIENT SOUNDS

4.1 Purpose

Acoustic measurements were conducted for ICE vehicles, ambient conditions, and prototype countermeasure sounds. Sound pressure levels and spectra of the ICE vehicles were measured in order to establish preliminary specifications for minimum sound level and spectral characteristics for operating conditions simulating the operating modes described in Section 3. Ambient conditions were measured in order to correct for measured sound levels of both ICE and countermeasure data, as inputs to psychoacoustic models described in Section 6, and in order to determine a suitable level for the ambient conditions during human-subject testing described in Section 7.

4.2 Acoustic Measurements of ICE Vehicles

Ten vehicles from model years 2000 to 2009 were measured in a quiet residential environment for operating modes described in detail in Section 3.

4.2.1 Vehicle Measurement Site

The ICE vehicle measurement site was located in a quiet residential area, on Mason Street in Brookline, Massachusetts (Latitude / Longitude = 42.348165, -71.11248). A photo of the site and instrumentation setup is shown in Figure 2. This site was chosen for its low traffic volume; moderate ambient levels; low wind speeds; flat, clean asphalt pavement; and the presence of a large flat and open region for equipment setup. Except for the hour from 8:00 to 9:00 AM when students arrived at a local private school, the traffic in the area was sparse (typically 3 to 4 vehicles per hour). This was important in order to minimize noise contamination from other nearby roads. Mason Street itself was closed to through traffic during the measurements. Although not completely isolated, the ambient level in the area was low and representative of a quiet suburban area which may be encountered by pedestrians. There were typically more acoustic intrusions due to pedestrians during the measurements than vehicles. During measurements, the majority of the ambient noise was due to birds, insects, wind-induced noise in vegetation, and distant vehicles. The road surface consisted of bituminous asphalt in generally good shape (Figure 2). There were a few minor cracks in the road surface, which were easily avoided during measurements. The road surface was clean except for vegetative detritus from over-hanging tree limbs that was swept prior to measurements. The road was between a small, flat residential park on one side and three homes on the other side approximately 35 feet from the vehicle path. The close proximity of the homes to the measurement location was considered, however, because the microphones were typically within two feet of the vehicles at pass-by, it was expected that the direct sound would dominate the measurements. When analyzing the data, no evidence of sound reflected from the homes was found.

Figure 2. Vehicle Measurement Site for ICE Vehicles – Mason Street Brookline, Massachusetts

4.2.2 Vehicles Measured

Ten ICE vehicles with model years ranging from 2000 to 2009 were measured. Vehicles included seven mid-size vehicles, a pickup truck, a minivan, and a small SUV. Vehicles included American, Japanese, and European manufacturers. The vehicles are listed in Table 3. A full data set for the Solara was not obtainable due to a combination of low signal levels and high ambient levels during its scheduled measurement period. Vehicles were in good operating condition and did not generate sounds attributable to any type of defect. Tires had a tread depth considered sufficient for safe operation, even wear, and were representative of standard OEM tires. Volpe Center employees volunteered the vehicles for these measurements and thus represent a random sample of vehicles available in the public fleet.

Table 3. Internal Combustion Engine Vehicles Measured

Vehicle Year	Vehicle Make	Vehicle Model
2000	Nissan	Maxima
2003	Toyota	Tacoma
2003	SAAB	95
2004	Honda	Odyssey
2004	Mercury	Sable
2005	SAAB	93

Vehicle Year	Vehicle Make	Vehicle Model
2006	Toyota	Solara
2007	Mercury	Milan
2009	Nissan	Altima
2009	Toyota	RAV-4

4.2.3 Operating Modes

Acoustic measurements of ICE vehicles were collected for operating conditions that simulated the operating modes described in Section 3 with the exception of the deceleration mode. Deceleration was not measured because such measurements require a test location of sufficient length to allow a vehicle to accelerate to 20 mph, stabilize, and then slow to 10 mph. Such tests can be conducted only at a large facility (e.g., VRTC). The operating conditions tested were:

- Low speed pass-by forward at 6, 10, 15 and 20 mph;
- Low speed pass-by reverse at 6 mph;
- Acceleration (from 0 to 10 mph);
- Idle; and
- Start-up.

Acoustic metrics included minimum, average, and maximum A-weighted sound pressure levels and un-weighted one-third octave band levels between 12.5 Hz to 20,000 Hz. Each measurement was over a time interval of ½-second. Details of these metrics are given in Section 5.

4.2.4 Measurement Procedure

The preliminary specifications for these measurements were not to examine pedestrian perception, nor to make recordings for future analysis, but to make measurements in a format consistent with what would be expected for compliance testing. To this end, SAE-J2889-1 draft test procedure (Measurement of Minimum Noise Emitted by Road Vehicles, Revision 2009) provides an initial framework for assuring that the best signal-to-noise ratios are obtainable in a compliance testing format. SAE-J2889-1 Rev 2009 specifies an engineering method for measuring the minimum noise emission of road vehicles and considers two operating modes: stationary and 6.2 mph (10 km/h). This procedure does not include measurement of all the operating modes of concern nor does it include measurement of all metrics of interest for the current study, therefore, SAE-J2889-1 Rev 2009 was used as basis for the measurement procedure, but was modified as follows:

- Additional operating modes were measured: reverse at 6 mph; forward at 10, 15, and 20 mph; acceleration from stop; and start-up.
- Minimum, average, and maximum overall A-weighted sound pressure levels for each event were reported for the ½-second interval for which the vehicle was closest to the microphone line (for pass-by events) or for which the level was greatest (for start-up and idle).

- For pass-by and start-up measurements, un-weighted average one-third octave band sound levels for each event were reported for the ½-second interval for which the vehicle was closest to the microphone line (for pass-by events) or for which the level was greatest (for start-up events).
- SAE J2889-1 section 7.2.1 indicates that, "Before the measurements are started, the vehicle shall be brought to its normal operating conditions." This is the case for all operating modes except start-up, in which case, the vehicle will be positioned at PP' (see Figure 3) with the engine off prior to measurement.
- For the purposes of this measurement procedure, two measurements were sufficient rather than four. (SAE-J2889-1 calls for 4 repetitions of each measurement, however, the purpose of the SAE measurements is to obtain an estimate of a single vehicle's minimum level, while the purpose of measurements here is to obtain a distribution of levels. In this case, raw data is more useful and the estimate of the mean for individual vehicles is not critical.)
- When reporting original measurements, data were not averaged except for idle and ambient events. (Data were averaged during analysis when appropriate).

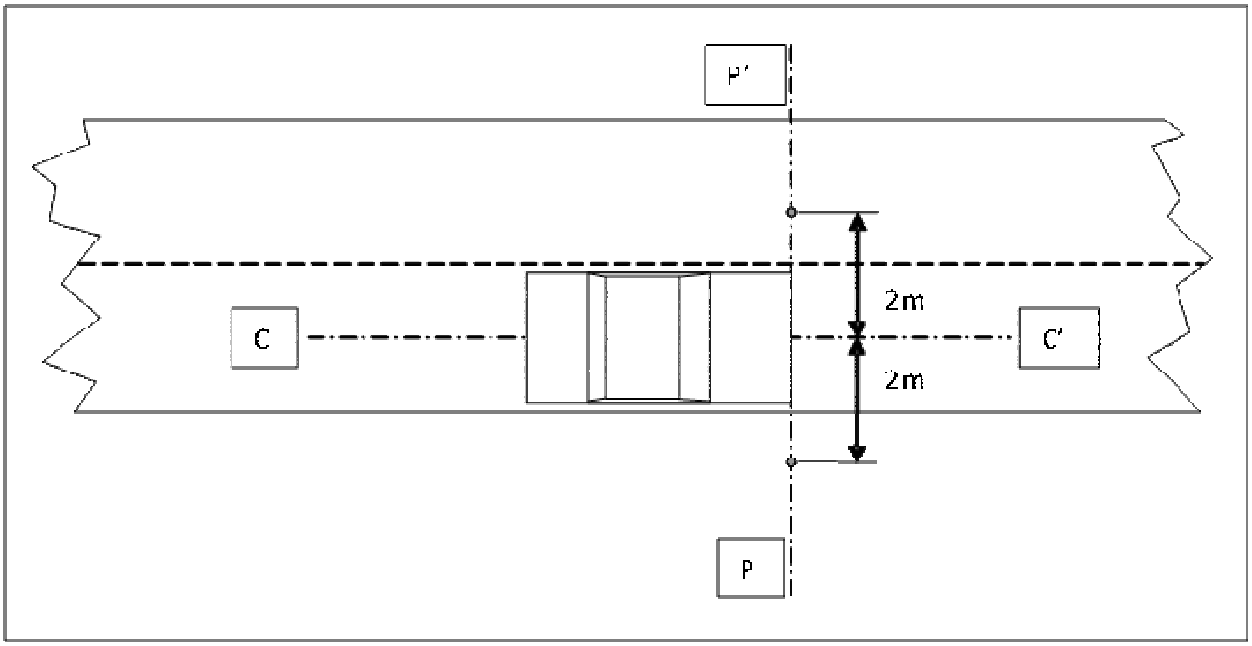


Figure 3. Microphone Line (PP') Relative to Vehicle Assuming Engine Mounted in Front of Vehicle. Vehicle Centerline is Labeled CC'

4.2.4.1 Measurement Protocol

Periodic ambient measurements were conducted in accordance with SAE J2889-1 section 6.3. The following steps were followed during an event:

- Initiated acoustic system;
- Continuously collected data every 1/2-second;
- Noted the maximum sound level displayed by the acoustic system;
- Noted any sounds heard from the measured vehicle, e.g. electric motor, engine, compressor, fan, tire noise, etc. Noted if the acoustic system indicated a minimum 3-dB rise and fall;
- Noted any potentially contaminating sounds;
- When possible, observed that wind speeds did not exceed the predetermined limit of 10 mph;
- Reset the “current” memory of the acoustic system in preparation for the next event; and
- Prepared the log sheets for the next event.

4.2.4.2 Low Speed Pass-by Reverse Measurement Procedure

- Vehicle accelerated to a constant specified speed.
- Target speed was 6 mph in reverse.
- Target speed was attained at least 1.5 seconds prior to passing PP’, the microphone line.
- Target speed was maintained within a tolerance of +/- 1 mph
- A minimum of 2 repetitions for this operating condition were measured for each vehicle. Any data that was clearly not representative of a typical vehicle, for example, dogs barking, leaf blowers, etc., was rejected.

4.2.4.3 Low Speed Pass-by Forward Measurement Procedure

- Vehicle accelerated to a constant specified speed.
- Target speeds included 6, 10, 15, and 20 mph in the forward direction
- Target speed was attained at least 1.5 seconds prior to passing PP’, the microphone line.
- Target speed was maintained within a tolerance of +/- 1 mph.
- A minimum of 2 repetitions for this operating condition were measured for each vehicle. Any data that was clearly not representative of a typical vehicle, for example, dogs barking, leaf blowers, etc., was rejected.

4.2.4.4 Acceleration from Stop Pass-by Measurement Procedure

- Vehicle started at rest at a distance of 30 meters from the microphone (as measured along the road) and then accelerated at a constant rate of 1 m/s^2 to a speed of 10 mph.
- The driver(s) attempted to accelerate at the same rate for each repetition.
- A minimum of 2 repetitions for this operating condition were measured for each vehicle. Any data that was clearly not representative of a typical vehicle, for example, dogs barking, leaf blowers, etc., were rejected.

4.2.4.5 Idle / Stationary Measurement Procedure

- Vehicle was started and remained at rest adjacent to the microphones.
- The measurement began after the vehicle came to steady state idle.
- The engine was running at idle, but all unnecessary accessory devices were off.
- A 1- minute measurement was conducted for each vehicle.

4.2.4.6 Start-up Measurement Procedure

- Starting with the vehicle off, the vehicle was turned on with the drive train in Park.
- A minimum of 2 repetitions for this operating condition were measured for each vehicle. Any data that was clearly not representative of a typical vehicle, for example, dogs barking, leaf blowers, etc., was rejected.

4.3 Measurement of Countermeasure Sounds

Prototype countermeasure sounds were rented/leased from various automotive manufacturers and vendors. The speaker systems for these countermeasure sounds were either installed inside the front grill or mounted on the hood, just above the front grill. The broadband sound levels during the human-subject testing of countermeasures were determined in a manner similar to that described in Section 4.2.4 for forward pass-by operations at 6 mph except that the measurement site was located on Potter Street, Cambridge, MA (Latitude / Longitude = 42.3647829, -71.085711). Because the ambient level here was about 58 to 60 dB(A), acoustic measurements of the one-third octave band spectra were not practical. Thus, alternative methods were used to determine the one-third octave band spectra for these sounds. Two methods were used: 1) for vehicles that could not be driven off of the Volpe Center campus, a direct electronic measurement was conducted, 2) for vehicles that could be driven off of the Volpe Center campus, the ICE vehicle measurement site was used.

4.3.1 Electronic Measurements

Since several of the vehicles were not road ready, they could not be driven to the ICE vehicle measurement site. Since the ambient at the Volpe Center site was too high to measure the countermeasure sounds without significant contamination by the ambient, the one-third octave band spectra of these sounds were determined by measuring the input voltage to the vehicle speaker due to the countermeasure sound by using an adapter to the sound level meter's pre-amplifier so that it could accept an electronic signal rather than an acoustic signal. Under these conditions measurements were made while the vehicles traveled at 6 mph.

4.3.2 Standard Acoustic Measurement

Two vehicles were road ready and could be driven to the ICE vehicle measurement site. For these two vehicles, 6 mph forward pass-by measurements were conducted as described in Section 4.2.4. Note, that both of these vehicles had the speaker systems internally mounted at inaccessible locations such that it was not practical to measure the countermeasure signals electronically. Because these were prototype systems provided by third parties, little modification could be done to the playback systems.

4.4 Acoustic Measurements of Ambient Levels

Ambient measurements were made for three purposes: 1) to determine if measured data were due to the vehicle or countermeasure sound, the noise (ambient), or both; 2) to determine appropriate levels for the ambient during countermeasure subject testing; and 3) to model the human perception of the signal, which uses both signal and ambient for inputs.

4.4.1 Ambient for ICE Vehicle Measurements

The ambient levels during ICE measurements were primarily of interest in order to make sure that the signal's acoustic characteristics were correctly estimated. However, the ambient levels during the ICE measurements were also used to predict human perception of the vehicle sounds. Psychoacoustic models are described in detail in Section 6. Ambient levels for the ICE measurement site were collected intermittently between vehicle operation events as described in Section 4.2.4.

4.4.2 Ambient for Countermeasure Measurements

The ambient levels during ICE measurements were only of interest in order to make sure that the best estimate of the signal's acoustic characteristics were correctly estimated. For standard acoustic measurements, ambient levels were determined the same as for the ICE measurement ambient. For direct electrical measurements, the ambient level was characterized by the instrument noise floor as determined by use of a "dummy" microphone, which simulates a microphone's load without otherwise contributing to the measurement.

4.4.3 Ambient for Countermeasure Subjective Testing

Prior to conducting the human subject countermeasure tests, typical ambient levels were determined in urban and suburban areas, along Centre Street in Newton, MA, which is typically used as the "final exam" route for orientation and mobility students at the Carroll Center for the Blind. These measurements were conducted at 17 locations near intersections with relatively high traffic volume and intersections removed from the main road. (A list of the intersections is included in Appendix A.1). The locations examined included signalized and stop-controlled intersections, one-way streets, and side streets or driveways. Walkthroughs were conducted with different orientation and mobility instructors; data were collected on different days of the week and time of day. The purpose of these measurements was to determine what a reasonable ambient level would be for the countermeasure human-subject testing.

Additionally, during the human-subject testing, the ambient sound was measured intermittently between test events as described in Section 4.2.4. These measurements were collected to support the analysis of human-subject testing of countermeasure sounds and for modeling human perception of both ICE vehicle sounds and prototype countermeasure sounds.

5. ACOUSTIC ANALYSIS

For the acoustic measurements presented in this report, ½-second intervals were measured continuously for several seconds for each event. Four metrics of the acoustic character of the event where considered during the acoustic analysis: 1) the un-weighted ½-second equivalent sound pressure level ($L_{Zeq,\,½\,sec}$), 2) the A-weighted ½-second equivalent sound pressure level ($L_{Aeq,\,½\,sec}$), 3) the maximum A-weighted sound pressure level using fast time weighting ($L_{AF,\,max}$) over each ½-second interval, and 4) the minimum A-weighted sound pressure level using fast time weighting ($L_{AF,\,min}$) over each ½-second interval. These metrics were determined for 1) the sum over all frequencies, 2) the sum over a band-limited spectrum, and 3) over each one-third octave band, for $L_{Aeq,\,½\,sec}$ only.

The un-weighted ½-second equivalent sound pressure level is defined as (IEC 61672-1, 2002):

$$\boldsymbol{L_{Zeq,\frac{1}{2}sec} = 20\ log_{10}\left\{\left[(1/T)\int_{t-T}^{t} p_Z^2(\zeta)d\zeta\right]^{1/2}/p_0\right\}}\ \textbf{dB}$$

where ζ is a dummy variable for the integration over time, T is the period of integration, $p_Z^2(\zeta)$ is the squared, un-weighted instantaneous sound pressure, and p_0 is the reference sound pressure.

Similarly, the A-weighted ½-second equivalent sound pressure level is defined as:

$$\boldsymbol{L_{Aeq,\frac{1}{2}sec} = 20\ log_{10}\left\{\left[(1/T)\int_{t-T}^{t} p_A^2(\zeta)d\zeta\right]^{1/2}/p_0\right\}}\ \textbf{dB(A)}$$

where $p_A^2(\zeta)$ is the squared, A-weighted instantaneous sound pressure. The maximum A-weighted sound pressure level using fast time weighting is determined by taking the maximum of the time-weighted sound pressure level given by:

$$\boldsymbol{L_{A\tau}(t) = 20\ log_{10}\left\{\left[(1/\tau)\int_{0}^{T} p_A^2(\zeta)e^{-(t-\zeta)/\tau}d\zeta\right]^{1/2}/p_0\right\}}\ \textbf{dB(A)}$$

Here τ is the time constant associated with the fast time weighting, 125 milliseconds, and *t* varies from 0 to T = ½-second. The minimum A-weighted sound pressure level using fast time weighting is determined by taking the minimum of the time-weighted sound pressure level of the above equation. Results are presented for the ½-second interval(s) that correspond to the vehicle's closest proximity to the microphone line. For pass-by, start-up, and acceleration events, this is a single ½-second interval. For idle events the average of multiple ½-second intervals are reported.

5.1 Acoustic Analysis of ICE Vehicles

This section provides an acoustic analysis of the ICE vehicles measured for the purposes of developing a preliminary specification for the minimum level of countermeasure sounds to be used in vehicles operating in electric only mode.

5.1.1 Overall A-weighted Sound Pressure Level Measurements

The original measured A-weighted levels, $L_{AF,min}$, $L_{Aeq,\ ½\ sec}$, and $L_{AF,max}$ at the microphone line are summarized for all trials, vehicle side (left/right), and operating modes for each vehicle in Table 4 to Table 6. At this point no corrections for ambient levels have been made. (Overall A-weighted uncorrected data are given for each event in Appendix A.2, Table 29 to Table 36). Table 4 summarizes the measured minimum level for each vehicle operation as well as the ambient measurements. The "Min($L_{AF,\ min}$)" column indicates the minimum of all $L_{AF,\ min}$ measurements (associated with the vehicle's closest proximity to the microphone line) for the specified operation. For example, the minimum $L_{AF,\ min}$ for the 6 mph, forward operation for all trials was 57.1 dB(A). Similarly the mean, maximum, and range for all trials are given in their respective columns. Table 5 summarizes the $L_{Aeq,\ ½\text{-}sec}$ metric in a similar fashion and Table 6 summarizes the $L_{AF,\ max}$ metric.

Table 4. Summary of Overall A-weighted Levels as Measured (not Corrected for Ambient Level at Microphone Line, $L_{AF\ ,min}$)

Vehicle Operation	**Minimum ($L_{AF,\ min}$)**	**Mean ($L_{AF,\ min}$)**	**Maximum ($L_{AF,\ min}$)**	**Range ($L_{AF,\ min}$)**
6 mph, Reverse	54.6	58.2	63.6	9.0
6 mph, Forward	57.1	60.7	63.8	6.7
10 mph, Forward	59.7	63.1	66.1	6.4
15 mph, Forward	62.2	67.0	69.9	7.7
20 mph, Forward	62.3	69.0	73.2	10.9
Acceleration	60.5	66.0	71.3	10.8
Start-up	46.1	65.0	75.6	29.5
Idle	52.2	55.5	59.9	7.7
Ambient	45.4	49.5	53.0	7.7

Table 5. Summary of Overall A-Weighted Levels as Measured (not Corrected for Ambient Level) at Microphone Line, $L_{Aeq\ ,1/2\ sec}$

Vehicle Operation	**Minimum ($L_{Aeq\ ,1/2\ sec}$)**	**Mean ($L_{Aeq\ ,1/2\ sec}$)**	**Maximum ($L_{Aeq\ ,1/2\ sec}$)**	**Range ($L_{Aeq\ ,1/2\ sec}$)**
6 mph, Reverse	54.9	58.7	64.8	9.9
6 mph, Forward	57.3	61.2	63.9	6.6
10 mph, Forward	60.0	64.1	66.4	6.4
15 mph, Forward	62.7	68.1	71.2	8.5
20 mph, Forward	63.6	70.2	73.9	10.3
Acceleration	60.8	66.7	72.9	12.1
Start-up	65.5	70.7	77.0	11.5
Idle	52.5	55.7	60.1	7.6
Ambient	46.2	50.0	53.4	7.2

Table 6. Summary of Overall A-Weighted Levels as Measured (not Corrected for Ambient Level) at Microphone Line, $L_{AF, max}$

Vehicle Operation	Minimum ($L_{AF, max}$)	Mean ($L_{AF, max}$)	Maximum ($L_{AF, max}$)	Range ($L_{AF, max}$)
6 mph, Reverse	55.2	59.0	65.5	10.3
6 mph, Forward	58.2	61.7	64.1	5.9
10 mph, Forward	60.9	64.1	66.7	5.8
15 mph, Forward	65.2	68.8	71.6	6.4
20 mph, Forward	64.8	71.0	74.3	9.5
Acceleration	61.2	67.2	73.6	12.4
Start-up	67.4	72.9	78.4	11.0
Idle	53.2	56.1	60.4	7.1
Ambient	47.1	50.8	54.0	6.9

The first question of interest is whether each metric provides unique information. In order to understand the uniqueness of each metric in characterizing ICE vehicles under the operating conditions specified, $L_{Aeq, ½\text{-sec}}$ data were compared with $L_{AF, max}$ in Figure 4, and with $L_{AF, min}$ in Figure 5. It can be seen that $L_{Aeq, ½\text{-sec}}$ and $L_{AF, max}$ are highly correlated, having coefficient of determination of 0.99. However considering Figure 5, it appears that $L_{Aeq, ½\text{-sec}}$ and $L_{AF, min}$ are not as highly correlated with a coefficient of determination of 0.80. Further examination revealed that the outliers (in the lower right corner) are all associated with the low values for $L_{AF, min}$ for start-up sounds. Since start-up events were very short, this is likely due to the $L_{AF, min}$ capturing ambient levels rather than the actual event. This indicates that $L_{AF, min}$ is not a desirable metric for quantifying the minimum sound level of start-ups. Removing these data from the comparison between $L_{Aeq, ½\text{-sec}}$ and $L_{AF, min}$ significantly improves the correlation, as can be seen in Figure 6, where the coefficient of determination increases to 0.99. The average differences between $L_{Aeq, ½\text{-sec}}$ and $L_{AF, max}$ were about 0.2 dB and the average differences between $L_{Aeq, ½\text{-sec}}$ and $L_{AF, min}$ (excluding start-up) were about 0.1 dB. Thus it was concluded that $L_{Aeq, ½\text{-sec}}$ provided a reasonable characterization of the acoustic character of all operations. Therefore, $L_{Aeq, ½\text{-sec}}$ is used for the remainder of the analysis.

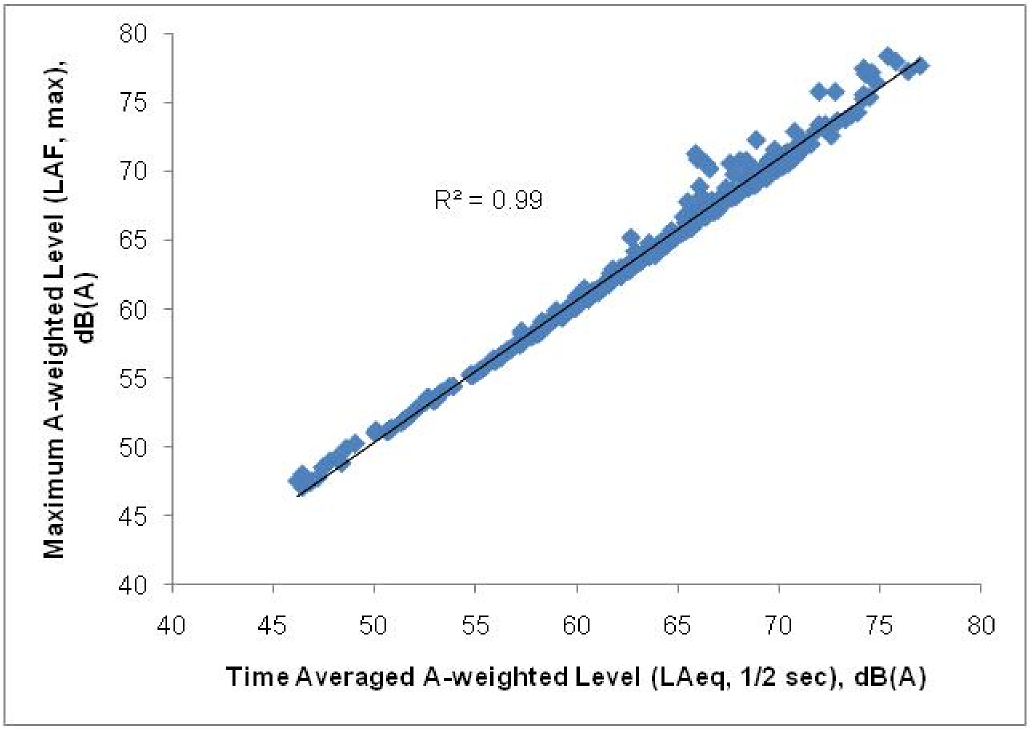


Figure 4. Correlation Between (not Corrected for Ambient Level) $L_{Aeq, 1/2 sec}$ and $L_{AF, max}$

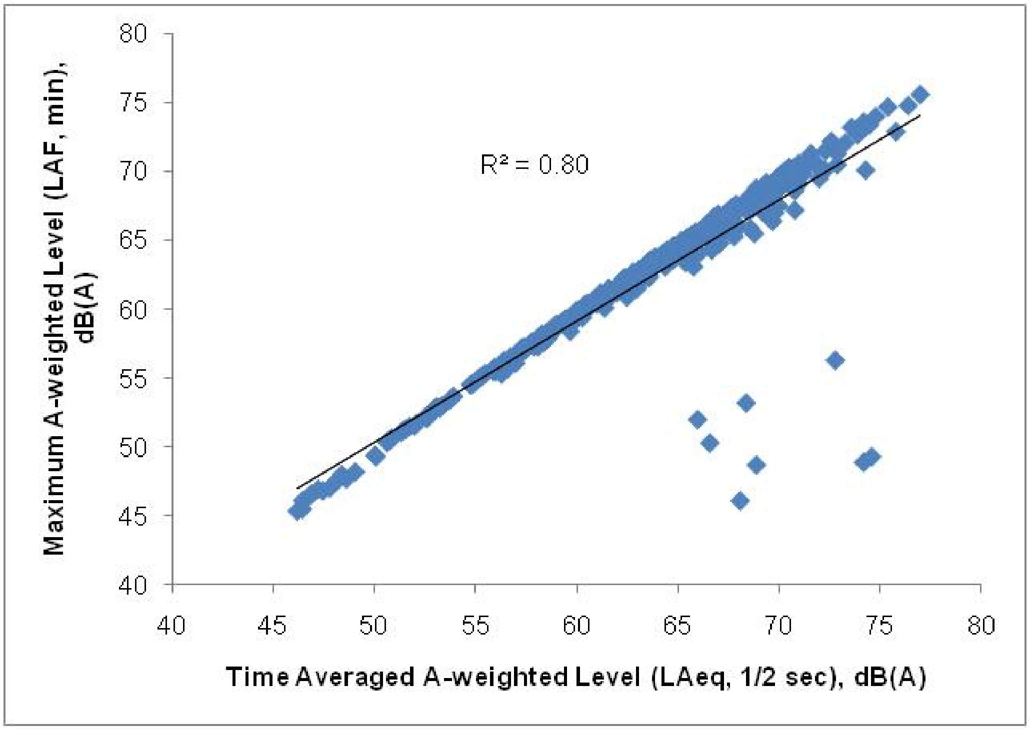


Figure 5. Correlation Between (not Corrected for Ambient Level) $L_{Aeq, 1/2 sec}$ and $L_{AF, min}$

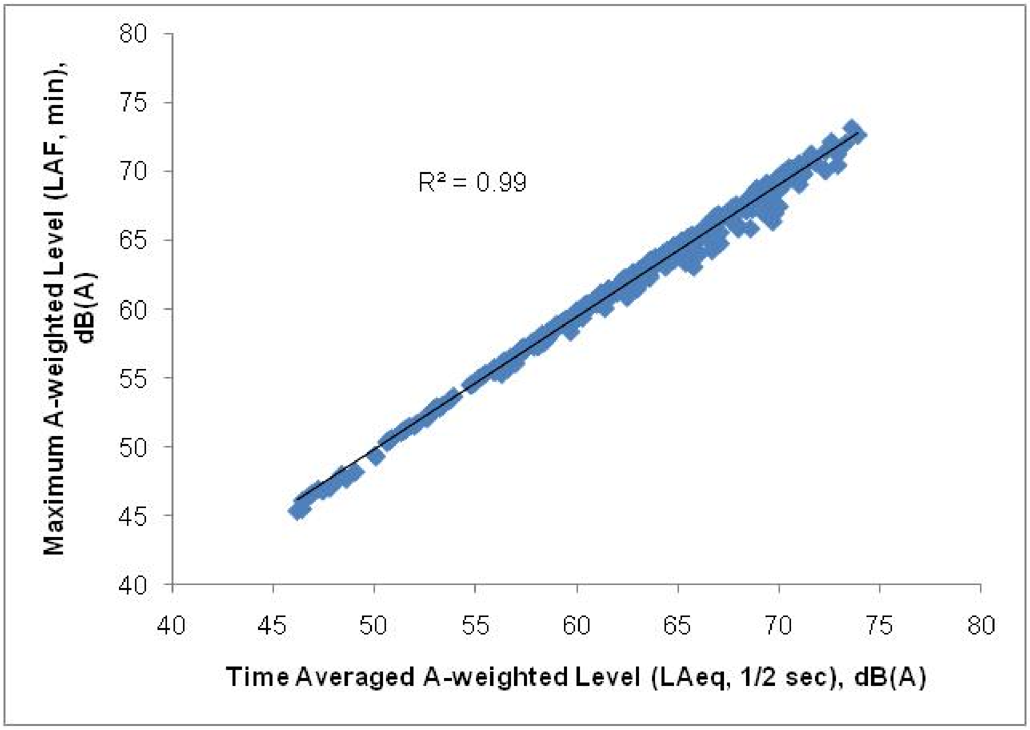


Figure 6. Correlation Between (not Corrected for Ambient Level) $L_{Aeq,\ 1,2\ sec}$ and $L_{AF,\ min}$ (Start-up Removed)

5.1.2 Determination of Frequency Range of Analysis

In this phase of the study, it was desired to measure ICE vehicles under ambient conditions that could be expected to be encountered by pedestrians. (In contrast to phase 1 of this study where it was desired to measure vehicles in the lowest ambient conditions possible.) These ambient conditions have sound levels which can effect the ability to measure the sound level of the ICE vehicles accurately. Therefore it was necessary to determine what portion of the measured sound was due predominantly to the measured vehicle and which portion was due predominantly to the ambient. It was expected that a frequency range that was due predominantly to the measured vehicle could be identified and that range would form the basis for further analysis. The frequency range was determined by comparing measurements of ICE vehicles with measurements of the ambient level during the measurements. Details of the measurement procedure are given in Section 4.2.4. In order to get an estimate that did not exclude any potential useful data, the ambient level for this comparison was set to the minimum in each third octave band for all ambient measurements during the ICE vehicle measurements. In this way, an estimate of the vehicle sound levels is conservatively high, that is, there is not a risk of underestimating the mininum level of the ICE vehicles.

In Figure 7, two operating modes (20 mph pass-by and Idle) are compared with the minimum ambient estimate. Here it can be seen that the ambient level is very close to the vehicle measured level below 100 Hz, making it impossible to accurately estimate the vehicle sound levels in this frequency range using the measured data. Therefore for further analysis of sound pressure levels, the data are band limited to include one-third octave bands from 100 Hz to 20 kHz. Typically, band limiting the data results in difference in the overall A-weighted level no greater than 0.1 dB.

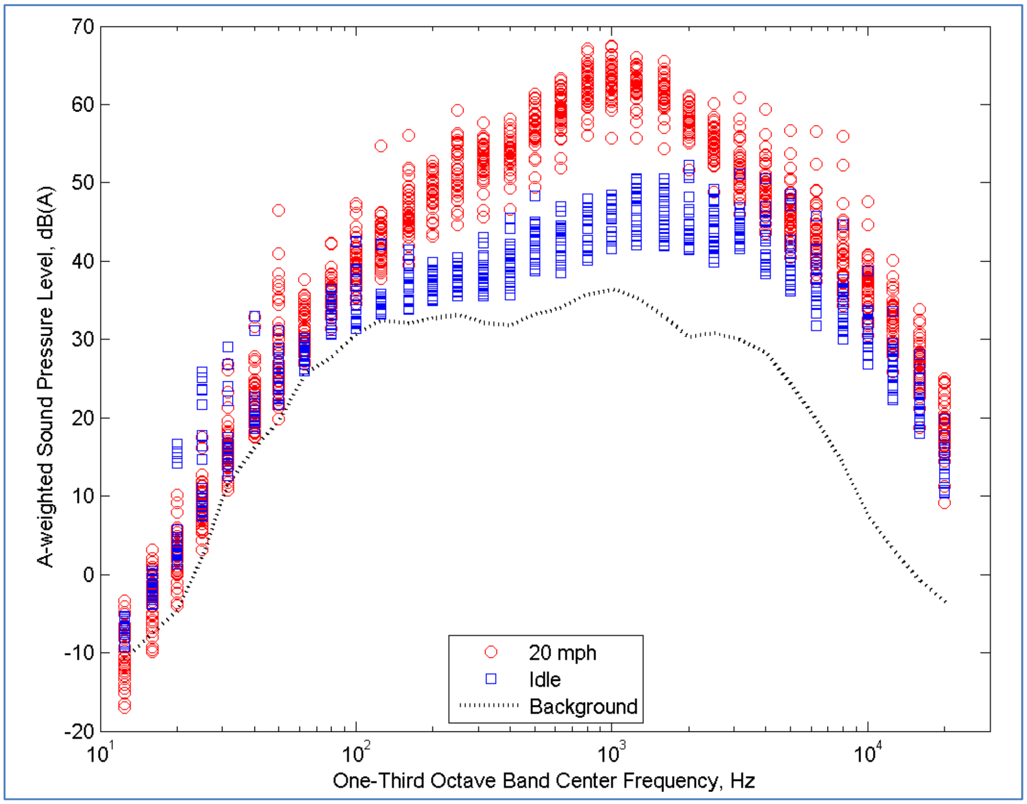


Figure 7. Comparison of Measured Levels of ICE Vehicles for two Operating Conditions (20 mph and Idle) With the Minimum Estimate of The Ambient Level. These Data for all Operating Conditions are Given in Appendix A-2.

5.1.3 $L_{Aeq,\ ½\ sec}$ Sound Pressure Levels Corrected for Ambient Level

SAE-J2889-1 Rev 2009 provides a method for correcting measured levels to account for ambient levels present during the measurement. This method operates on the overall level. Because third-octave band data is being analyzed for this report, corrections based on the overall level are not sufficient, therefore corrections were conducted in a manner similar to SAE-J2889-1 Rev 2009, but on a one-third octave band basis as follows: If the sound pressure level of the measured event in a specified one-third octave band is greater than or equal to 3 dB more than the ambient level for the specified one-third octave band, then the reported vehicle test condition sound pressure level shall be corrected according to:

$$L_{corrected} = 10\log_{10}\left\{\left(\mathrm{P}^2_{\mathrm{measured}} - \mathrm{P}^2_{\mathrm{ambient}}\right)/\mathrm{P}^2_{\mathrm{ref}}\right\}\ \mathrm{dB}$$

where, P_{ref} is 20 µPA.

If this criterion is not met, then the specified one-third octave band for the measured event is removed from further analysis. It is necessary to remove this data because “zeroing it out” or setting its level to the ambient will produce incorrect average results.

Once the individual one-third octave bands were corrected for the ambient level present during measurements, the broad band level was recomputed by summing the A-weighted one-third octave bands from 100 Hz to 20,000 Hz. The minimum, average, maximum, and range of $L_{Aeq,\ 1/2sec}$ are shown for the vehicles measured for each operating condition in Table 7. The difference between the corrected (and range limited) broad band levels and the original measured levels are shown in Table 8. Note that these differences are generally small, with an average difference of only -0.2 dB, that is, the corrected, band limited levels were on average about 0.2 dB lower than the original measured levels. This difference is small because most of the energy discounted was at low levels and low frequencies and therefore did not contribute significantly to the broad band level. However, these corrections were important so that low frequency one-third octave bands are correctly represented in the spectral specification in Section 5.1.4 as well as the psychoacoustic analysis in Section 6.

Table 7. Summary of ICE Measurements Using $L_{Aeq,\ ½\ sec}$ Adjusted for Ambient Level and Restricted to Frequency Range from 100 Hz to 20 kHz.

Vehicle Operation	**Minimum (L_{Aeq})**	**Mean (L_{Aeq})**	**Maximum (L_{Aeq})**	**Range (L_{Aeq})**
6 mph, Reverse	54.4	58.4	64.8	10.4
6 mph, Forward	57.2	61.1	63.8	6.6
10 mph, Forward	60.0	63.6	66.3	6.3
15 mph, Forward	62.8	68.1	71.1	8.2
20 mph, Forward	63.4	70.2	73.8	10.5
Acceleration	60.7	66.7	72.9	12.2
Start-up	65.3	70.7	77.0	11.7
Idle	51.6	55.2	59.9	8.4
Ambient	46.1	50.0	53.4	7.2

Table 8. Difference Between Corrected (and Range Limited) and Uncorrected Time Averaged Levels, $L_{Aeq,\ ½\ sec}$

Vehicle Operation	**Delta Minimum**	**Delta Mean**	**Delta Maximum**	**Delta Range**
6 mph, Reverse	-0.5	-0.3	0.0	0.5
6 mph, Forward	-0.1	-0.1	-0.1	0.0
10 mph, Forward	0.0	-0.5	-0.1	-0.1
15 mph, Forward	0.1	0.0	-0.1	-0.3
20 mph, Forward	-0.2	0.0	-0.1	0.2
Acceleration	-0.1	-0.1	0.0	0.1

Vehicle Operation	Delta Minimum	Delta Mean	Delta Maximum	Delta Range
Start-up	-0.2	0.0	0.0	0.2
Idle	-1.0	-0.5	-0.1	0.8
Ambient	-0.1	-0.1	0.0	0.1

5.1.4 Preliminary Specification for Detectability

The preliminary specification for countermeasure sounds is based on the supposition that typical ICE vehicles presently emit an acceptable amount of noise during low speed operations. These preliminary specifications represent the minimum overall A-weighted sound pressure level, and the minimum level in each one-third octave band for a countermeasure sound that simulates an ICE vehicle. Table 9 gives the preliminary specification for the broad band A-weighted sound pressure level for a vehicle generating a countermeasure sound. Figure 8 to Figure 15 show the corresponding A-weighted one-third octave band spectra. Based on the sounds we studied, each of these minima must be met in order to assure that the countermeasure sound emits sound at a level at least as great as the estimated typical ICE vehicle. Note that the logarithmic sum of the one-third octave bands do not equal the overall A-weighted sound pressure level requirement for a given operating mode. This is because the overall A-weighted sound pressure level is the average of the logarithmic sums while the sum of the one-third octave bands is a logarithmic sum of linear averages. That is, the order of the non-linear operator is not the same.

Table 9. Preliminary Specifications for Minimum Overall A-weighted Level ($L_{Aeq,\ ½\ sec}$) by Vehicle Operation

Vehicle Operation	$L_{Aeq,\ 1/2\ sec}$, dB(A)
6 mph, Reverse	58.4
6 mph, Forward	61.1
10 mph, Forward	63.6
15 mph, Forward	68.1
20 mph, Forward	70.2
Acceleration	66.7
Start-up	70.7
Idle	55.2
Ambient	58.4

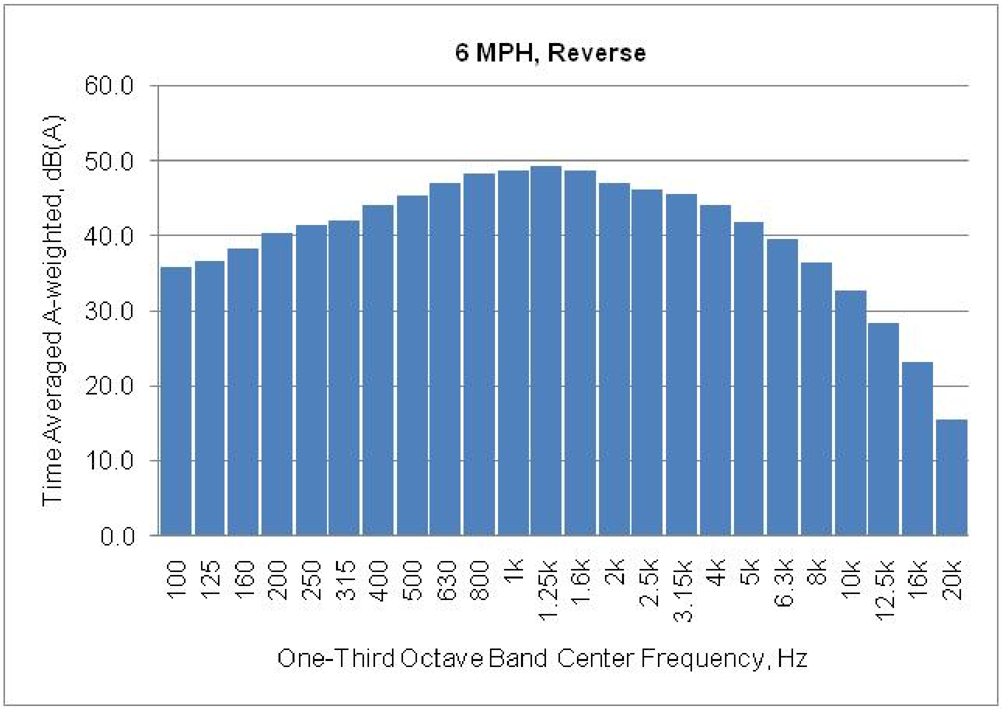


Figure 8. Minimum Level for Each One-Third Octave Band: 6 mph, Reverse.

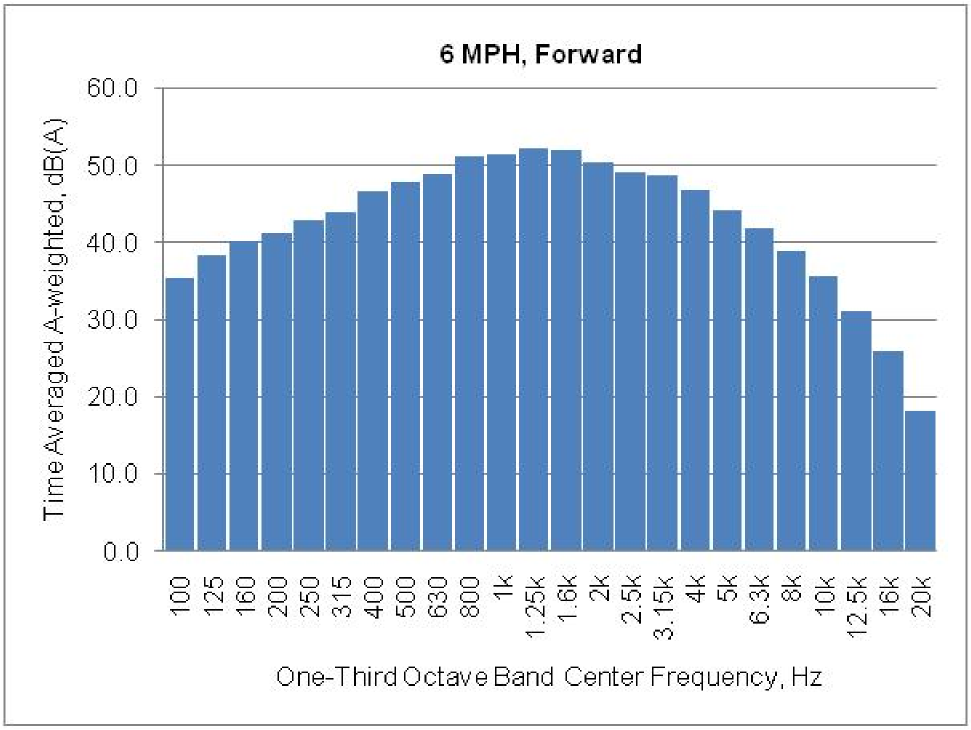


Figure 9. Minimum Level for Each One-Third Octave Band: 6 mph, Forward

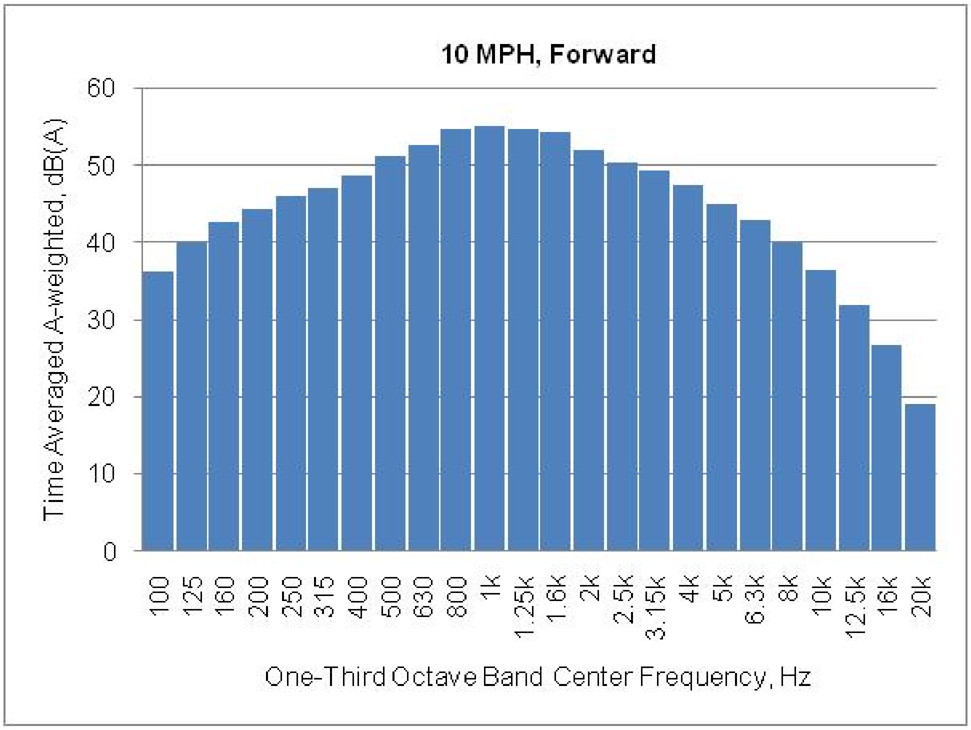


Figure 10. Minimum Level for Each One-Third Octave Band: 10 mph, Forward.

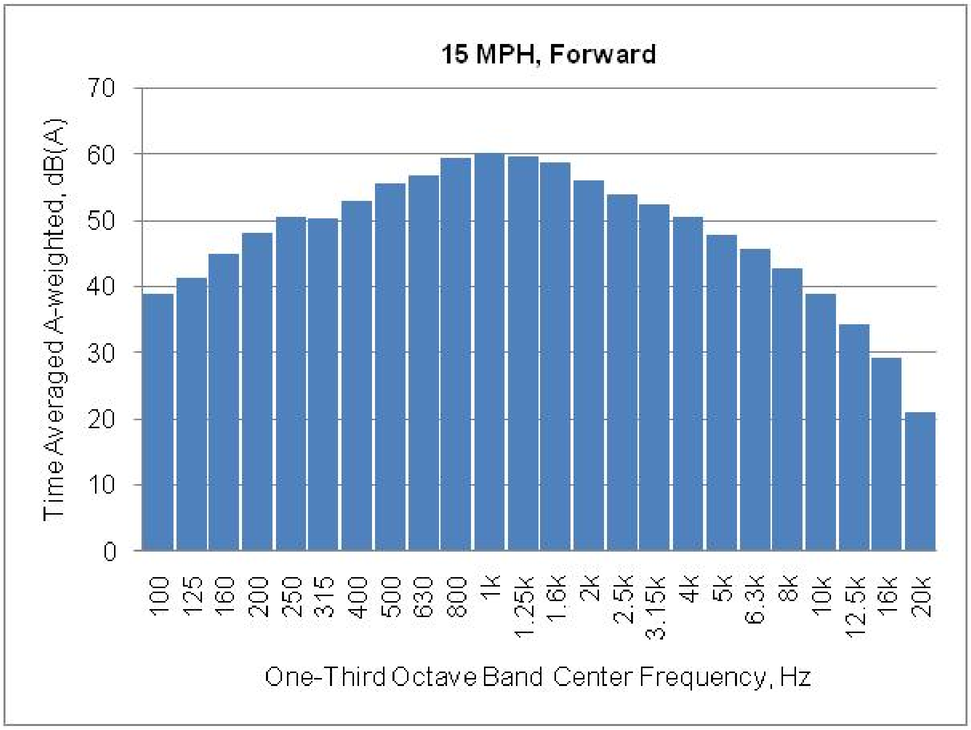


Figure 11. Minimum Level for Each One-Third Octave Band: 15 mph, Forward

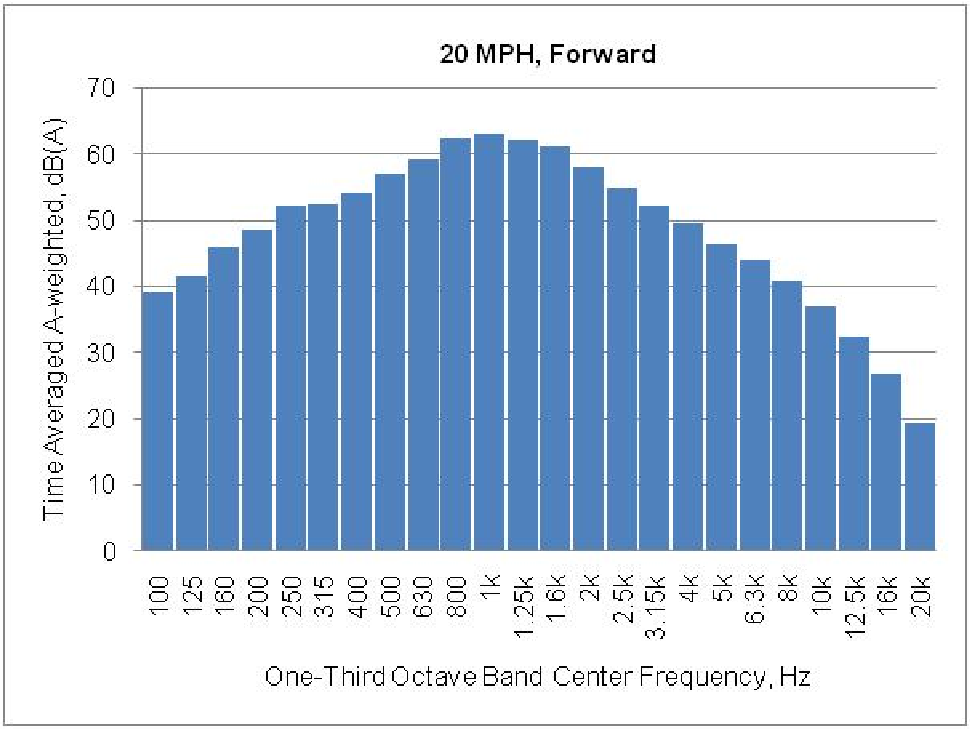


Figure 12. Minimum Level for Each One-Third Octave Band: 20 mph, Forward

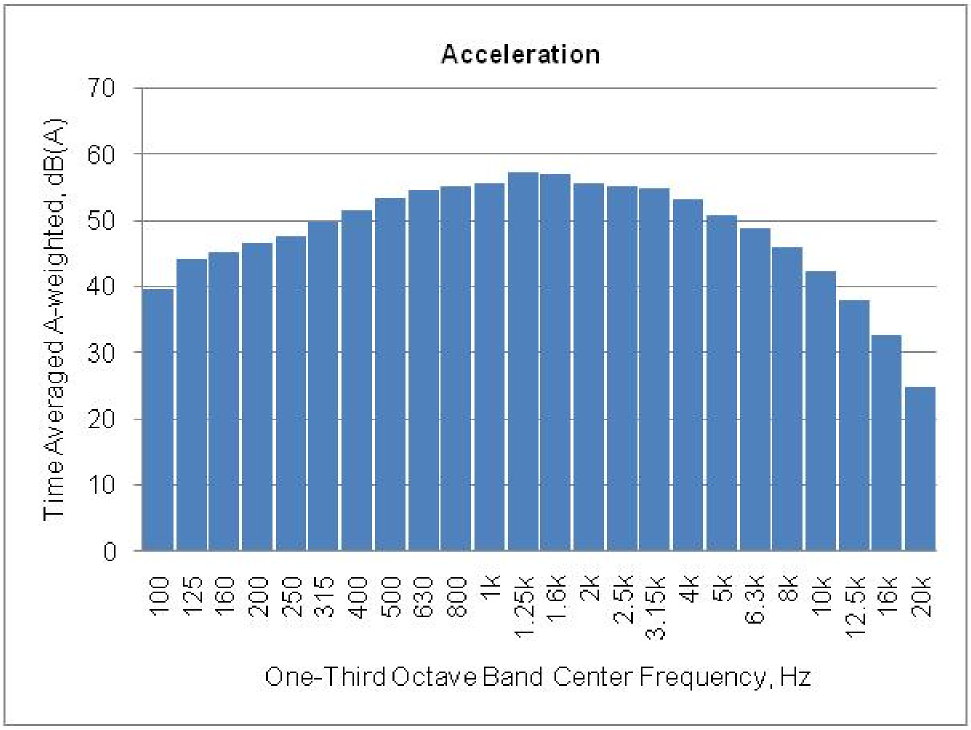


Figure 13. Minimum Level for Each One-Third Octave Band: Acceleration

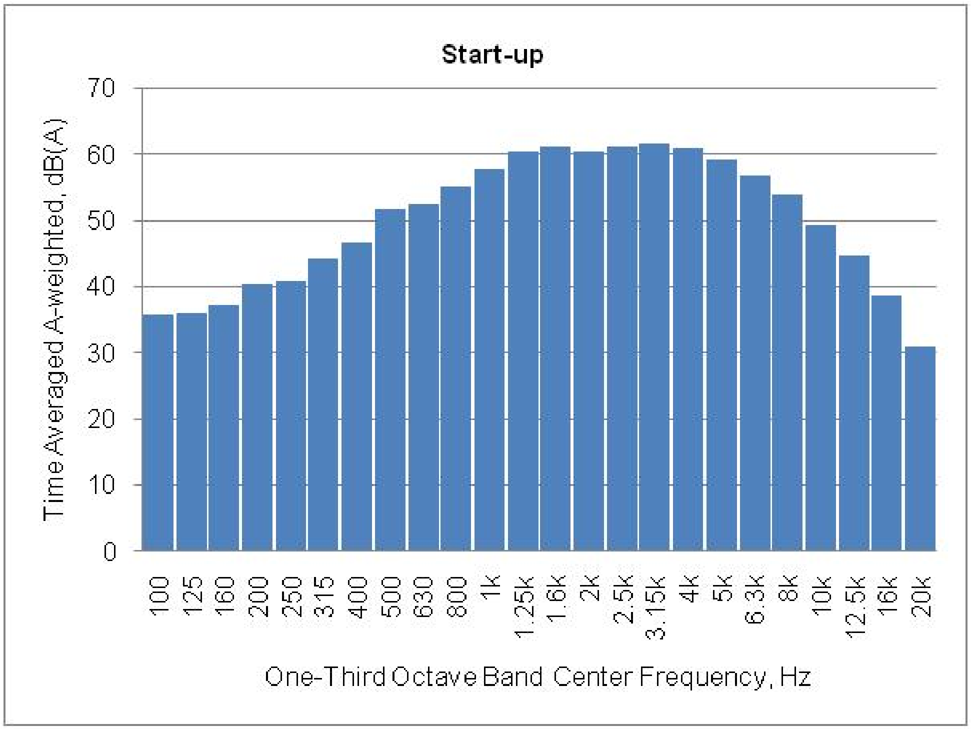


Figure 14. Minimum Level for Each One-Third Octave Band: Startup

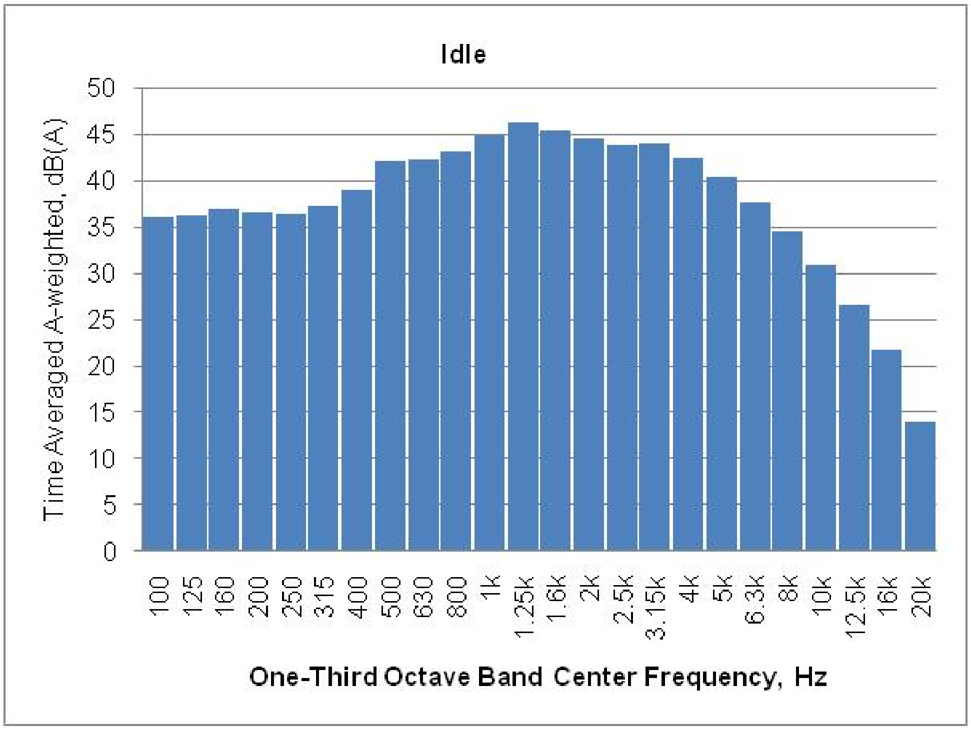


Figure 15. Minimum Level for Each One-Third Octave Band: Idle

5.2 Acoustic Analysis of Countermeasure Sounds

In addition to the ICE vehicles measured in order to develop a preliminary specification for detectability, a total of five countermeasure systems, capable of producing one or multiple sounds, were also measured. The systems are labeled A, B, C, D, and E and a total of nine sounds were evaluated: A1, A2, A5, B, C, D, E1, E3, and E4. These sounds were all intended to simulate 6 mph forward pass-by operations. As discussed in Section 4.3, two methods were used to measure these countermeasure sounds, 1) direct electrical measurements of the speaker input where these were accessible (A, B and E sounds), as well as 2) standard acoustical measurements, which were the only type available when access to the speaker was not possible (sounds C and D). Direct electrical recording permits an accurate spectral analysis of the synthetic sound generator output. However, if that is not available, any spectral analysis would necessarily be contaminated with tire noise and ambient noise. Because the post-processing of these two data sets was different from the sounds measured for ICE vehicles, results are reported separately. The acoustic analysis follows. (The human-subject evaluation of countermeasures is discussed in Section **7**)

5.2.1 $L_{Aeq, ½ sec}$ Sound Pressure Levels Corrected for Ambient Level – Electrical Measurement

For countermeasure sounds measured electrically, a single measurement was made for each sound, however, during countermeasure subjective testing, these sounds were adjusted to be played such that the broadband A-weighted level was one of two levels, 59.5 and 63.5 dB(A). Therefore, during this acoustic analysis, the electrically measured signals were adjusted to produce these same results. Because of the countermeasure designs themselves as well as the physical limitations of the speakers used, countermeasure sounds had very little low frequency content. Even though the electrical noise of the measurement system was very low, ranging between 3 and 24 dB(A) per octave band, the countermeasure signals were still typically too low to be measured, therefore, only the levels from 50 Hz to 20,000 Hz are presented here. Note that sound levels in lower frequency bands were still much lower than the existing ambient during the human subject testing, as will be discussed in greater detail later. Table 10 and Table 11 show the one-third octave band levels for each of the countermeasure sounds measured electrically with corrections for the instrument noise floor for this frequency range. For comparison with the ICE vehicle measurements, the band sums from 100 Hz to 20,000 Hz are also given.

Table 10. $L_{Aeq, ½ sec}$ Sound Pressure Levels Corrected for Ambient Level for Countermeasure Sounds Using Direct Electrical Measurement for low Playback Setting

1/3 Octave Band Center Frequency (Hz)	Sound A1	Sound A2	Sound A5	Sound B	Sound E1	Sound E3	Sound E4
100 to 20,000	59.6	59.6	59.6	58.7	59.1	59.6	59.5
50	3.3	-21.9	Below Ambient	48.3	22.8	28.6	0.8
63	11.9	-16.9	Below Ambient	37.7	32.1	21.5	6.0

80	28.5	-3.6	Below Ambient	16.8	51.0	31.5	11.6
100	40.4	11.9	Below Ambient	57.8	53.3	43.1	21.4
125	41.3	26.1	Below Ambient	51.1	56.0	36.4	33.8
160	45.1	40.7	-2.5	31.5	43.0	39.7	30.9
200	46.2	43.0	14.9	41.2	50.8	47.6	38.9
250	56.7	32.6	26.9	26.4	43.7	47.0	36.8
315	46.0	43.8	37.0	11.4	42.4	46.1	38.7
400	47.8	48.0	55.2	6.9	31.9	50.9	53.9
500	45.7	46.0	56.5	12.3	40.6	51.1	46.4
630	41.7	50.3	45.4	10.7	38.2	49.2	35.7
800	44.6	49.2	43.9	12.7	24.4	50.3	43.5
1k	42.4	47.6	41.7	0.0	34.5	48.7	40.1
1.25k	50.7	48.1	41.7	13.8	18.6	47.9	43.9
1.6k	39.3	50.9	43.4	15.2	29.7	47.6	41.7
2k	44.3	50.1	38.0	1.2	1.2	44.6	45.6
2.5k	24.9	50.0	29.6	1.3	1.3	42.7	56.7
3.15k	1.2	48.1	35.3	1.2	1.2	41.3	35.8
4k	1.0	42.8	27.8	1.0	1.0	39.3	21.6
5k	0.5	42.8	22.9	0.5	0.5	38.8	16.9
6.3k	-0.1	29.7	15.8	-0.1	-0.1	36.4	-0.1
8k	-1.1	-1.1	-1.1	-1.1	-1.1	32.0	-1.1
10k	-2.5	-2.5	-2.5	-2.5	-2.5	24.8	-2.5
12.5k	-4.3	-4.3	-4.3	-4.3	-4.3	17.9	-4.3
16k	-6.6	-6.6	-6.6	-6.6	-6.6	-6.6	-6.6
20k	-9.3	-9.3	-9.3	-9.3	-9.3	-9.3	-9.3

Table 11. $L_{\text{Aeq, ½ sec}}$ Sound Pressure Levels Corrected for Ambient Level for Countermeasure Sounds Using Direct Electrical Measurement for High Playback Setting

1/3 Octave Band Center Frequency (Hz)	Sound A1	Sound A2	Sound A5	Sound B	Sound E1	Sound E3	Sound E4
100 to 20,000	63.6	63.6	63.6	62.7	63.1	63.6	63.5
50	7.3	-16.9	Below Ambient	52.3	26.8	32.6	4.8
63	15.9	-11.2	Below Ambient	41.7	36.1	25.5	10.0

80	32.5	0.5	Below Ambient	20.8	55.0	35.5	15.6
100	44.4	15.9	-12.2	61.8	57.3	47.1	25.4
125	45.3	30.1	-5.4	55.1	60.0	40.4	37.8
160	49.1	44.7	2.7	35.5	47.0	43.7	34.9
200	50.2	47.0	19.0	45.2	54.8	51.6	42.9
250	60.7	36.6	30.9	30.4	47.7	51.0	40.8
315	50.0	47.8	41.0	16.3	46.4	50.1	42.7
400	51.8	52.0	59.2	12.6	35.9	54.9	57.9
500	49.7	50.0	60.5	16.8	44.6	55.1	50.4
630	45.7	54.3	49.4	15.7	42.2	53.2	39.7
800	48.6	53.2	47.9	17.7	28.5	54.3	47.5
1k	46.4	51.6	45.7	17.0	38.5	52.7	44.1
1.25k	54.7	52.1	45.7	18.9	23.0	51.9	47.9
1.6k	43.3	54.9	47.4	20.2	33.8	51.6	45.7
2k	48.3	54.1	42.0	21.0	1.2	48.6	49.6
2.5k	29.1	54.0	33.7	1.3	1.3	46.7	60.7
3.15k	1.2	52.1	39.3	1.2	1.2	45.3	39.9
4k	1.0	46.8	31.9	1.0	1.0	43.3	26.2
5k	0.5	46.8	27.2	0.5	0.5	42.8	22.0
6.3k	-0.1	33.8	21.2	-0.1	-0.1	40.4	19.3
8k	-1.1	15.2	-1.1	-1.1	-1.1	36.0	15.5
10k	-2.5	-2.5	-2.5	-2.5	-2.5	29.0	-2.5
12.5k	-4.3	-4.3	-4.3	-4.3	-4.3	22.5	-4.3
16k	-6.6	-6.6	-6.6	-6.6	-6.6	-6.6	-6.6
20k	-9.3	-9.3	-9.3	-9.3	-9.3	-9.3	-9.3

The data in Table 10 is also given in Figure 16, where it can easily be seen that only countermeasures ‘B’ and ‘E1’ had any significant low frequency content, and that the rest typically had significant content only above 100 to 200 Hz (here a component is considered significant if it is within 10 dB of neighboring one-third octave bands). This supports the further consideration of the frequency range from 100 to 20,000 Hz for analysis. Further, countermeasure sounds tended to have distinct peaks in their frequency spectra. Most had narrow-band components that were at least 10 dB higher than the neighboring content for a given countermeasure sound. For countermeasures ‘A2’ and ‘A5’, these narrow band components straddled two one-third octave bands, causing them to appear broader, however, this is an artifact of one-third octave band analysis. Countermeasures ‘B’ and ‘E1’ had the most relative low frequency content, countermeasures ‘A5’ and ‘E4’ had content that was centered in the mid-frequencies from 315 to 3150 Hz, and countermeasures ‘A2’ and ‘E3’ had the most broad band content.

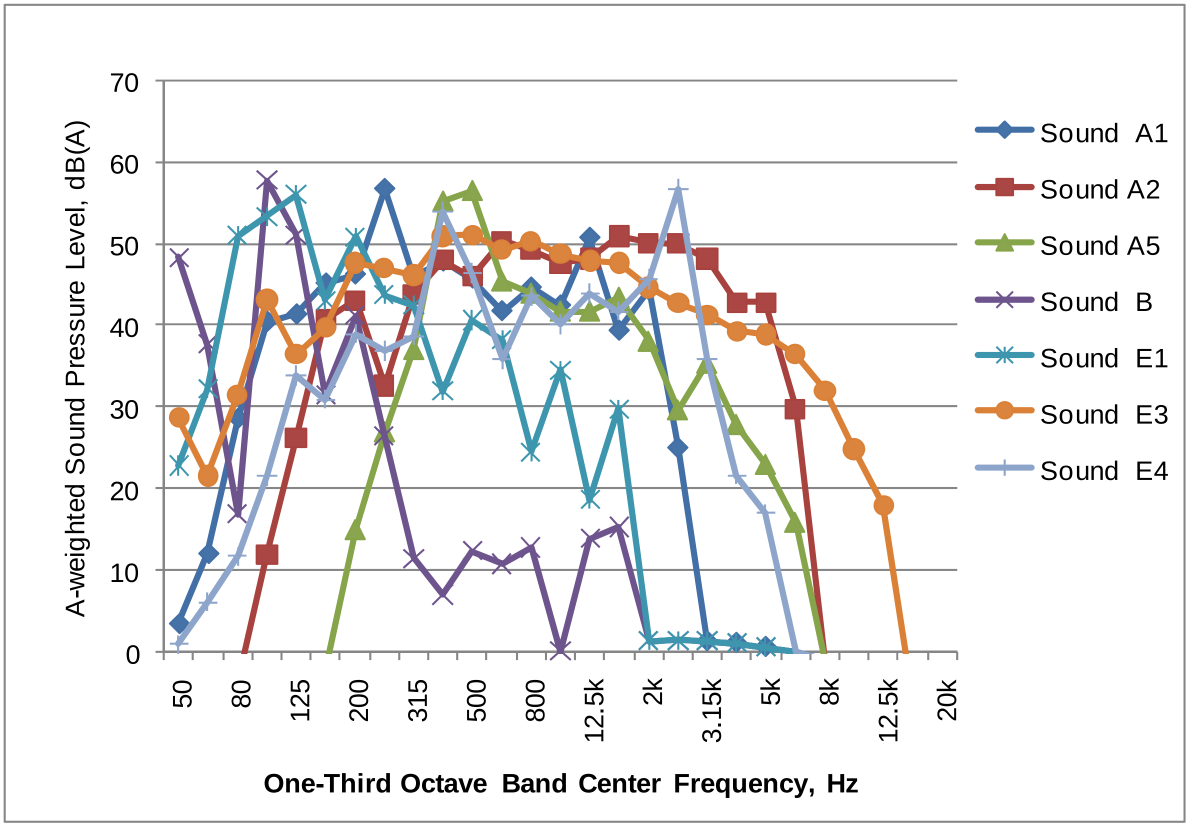


Figure 16. Countermeasure Sounds at Low Level, Nominal 59.5 dB(A). See Table 10 for Data Plotted

5.2.2 $L_{Aeq,\ ½\ sec}$ Sound Pressure Level Corrected for Ambient Level-Standard Measurement

The spectra and 100 to 20,000 Hz band sums are given for the two countermeasure systems measured at the ICE measurement site in Table 12. For both of these systems, the output level was not easily controllable. For system ‘D’, the maximum level was used, which could only achieve the lower level desired for the human-subject testing. For system ‘C’, the level was adjustable, with a small degree of uncertainty, and could be set to achieve the lower and higher levels desired for the human-subjects testing. A single level was used for this measurement, which targeted the higher level for human-subject testing. The measured level presented in Table 12 represents a single measurement, for each operation, and falls within the expected experimental error for the target level of 63.5 dB(A). Note, that neither reverse measurements (‘D’ or ‘C’) were used in the human-subject testing. These were measured simply to document the countermeasure sounds for both of these vehicles in reverse. Figure 17 shows these spectra. Note that below 200 Hz, the effect of the ambient at the measurement site made the measurement of the vehicle sounds uncertain and much of the data were rejected below this frequency, therefore this range is not shown in the figure. On the other hand the tonal rise around 3150 Hz is a reliable measurement. It appears that both countermeasure designers chose to emphasize this frequency range due to human hearing sensitivity at this frequency. The human auditory system is most sensitive at the threshold of hearing to sound between 1000 and 5000 Hz (Fletcher, H. and Munson, W. A. (1933). The developer of system ‘C’ indicated that part of their design for reverse was to increase the level coming from the front speaker so that the sound would be sufficiently loud while backing up. However, the measurement procedure used here was insensitive to the shielding effects of the vehicle since it focused on measuring the front of the vehicle. The measurement procedure could be adjusted so that the measurement references the rear of the vehicle for reverse operations.

Table 12. $L_{Aeq,\,½\,sec}$ Sound Pressure Levels Corrected for Ambient Level for Countermeasure Vehicles Using Traditional Measurement

1/3 Octave Band Center Frequency (Hz)	Sound C Forward	Sound C Reverse	Sound D Forward	Sound D Reverse
100 to 20 k	62.4	77.7	59.8	59.4
50	Below Ambient	Below Ambient	Below Ambient	Below Ambient
63	Below Ambient	30.4	Below Ambient	0.5
80	Below Ambient	4.5	Below Ambient	Below Ambient
100	Below Ambient	Below Ambient	7.7	7.2
125	Below Ambient	Below Ambient	Below Ambient	37.9
160	Below Ambient	10.9	Below Ambient	Below Ambient
200	39.4	35.6	36.6	40.1
250	44.4	38.0	42.6	44.9
315	46.3	39.4	41.4	46.8
400	48.6	41.9	39.0	42.1
500	54.4	50.7	40.4	42.0
630	57.5	51.5	44.3	44.1
800	53.3	46.5	46.6	44.9
1k	48.7	40.7	43.4	45.8
1.25k	44.4	46.7	43.3	47.0
1.6k	42.6	46.2	42.7	46.1
2k	44.9	76.2	56.9	54.0
2.5k	55.1	72.2	53.7	54.6
3.15k	42.5	52.2	36.6	39.0
4k	40.6	38.0	33.2	33.1
5k	37.1	31.5	43.1	32.4
6.3k	35.9	29.4	32.5	27.9
8k	38.1	13.1	30.0	25.7
10k	32.9	25.5	26.4	22.7
12.5k	24.1	19.0	24.1	20.7
16k	23.7	17.7	19.9	3.7
20k	17.8	15.1	-9.3	-9.3

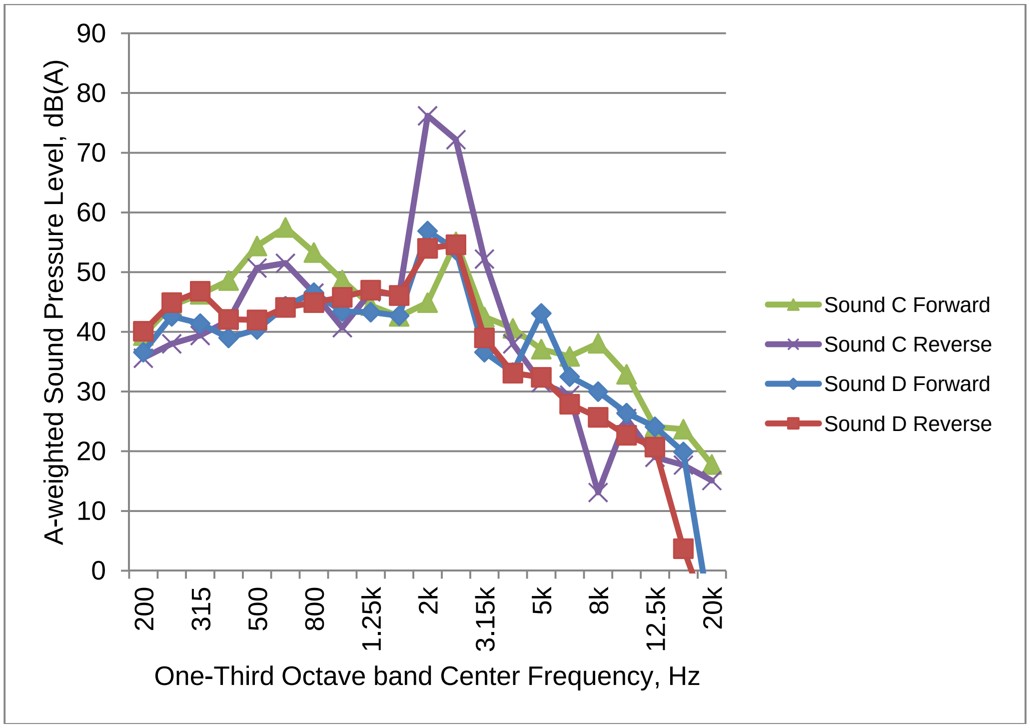


Figure 17. Countermeasure Sounds Measured at ICE Vehicle Measurement Site. See Table 12 for Data Plotted

5.2.3 Measurement of Vehicle Directivity

When evaluating detectability of sounds according to the levels measured with the orientation shown in Figure 3, it is important to consider that the level changes not only with distance but with the orientation between the vehicle and the subject. For example, if a sound radiates most effectively to the right of the vehicle, then the level will be greater to the right compared to, for example, the front of the vehicle. Therefore, detectability of a sound will depend not only on the measured level and the change due to distance, but will also depend on the relative change in level due to the orientation between the vehicle and the subject at the time of detection.

Directivity patterns describe the change in sound pressure level as a function of angular position relative to a reference line. Directivity measurements were made according to the layout shown in Figure 18. At each angle the sound pressure level of pink noise was measured at 6, 12, and 25 foot distances from the speaker. The results for each distance relative to the 0^o value for the distance are given in Table 13. This method requires a stationary vehicle and therefore could only be conducted on systems A, B, and E. Systems C and D could not be measured because their sounds could not be evaluated while the vehicles were stationary. These directivities represent the condition where a single external speaker was mounted on the front bumper. No directivity data is available for comparison with ICE vehicles at this time. These results are for context only and are not being used to suggest a preferred directivity pattern.

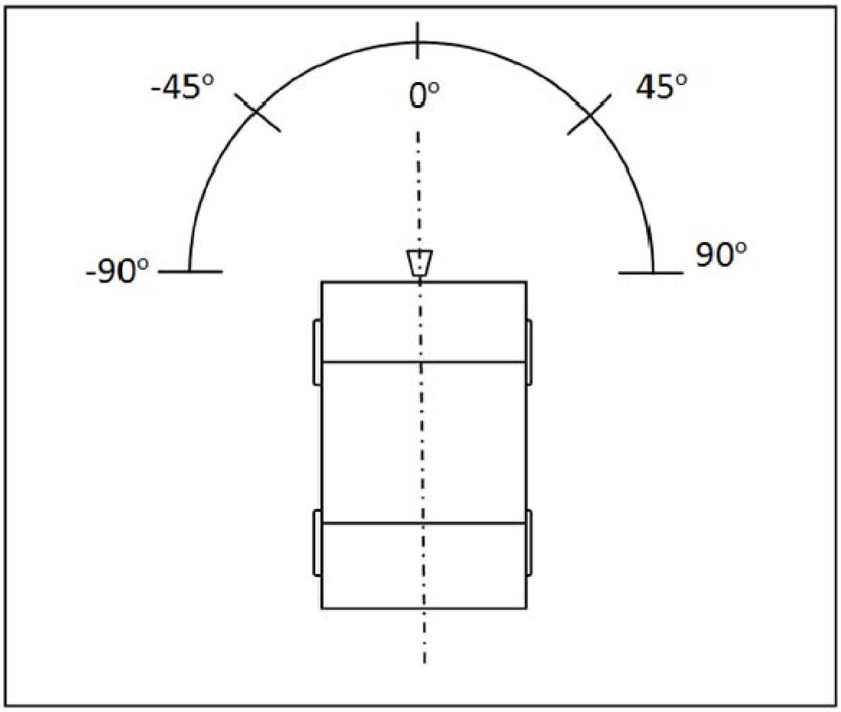


Figure 18. Measurement Diagram for Directivity Measurements. Reference Line is at 0°

Table 13. Attenuation, in dB, as a Function of Angle Relative to Vehicle Center Line for Three Distances From Speaker (6, 12, and 25 ft)

Angle Relative to Vehicle Centerline (degrees)	Attenuation 6 ft from speaker	Attenuation 12 ft from speaker	Attenuation 25 ft from speaker	Average Attenuation
-90	-7.9	-8.3	-8.3	-8.2
-45	-3.9	-2.9	-3.7	-3.5
0	0.0	0.0	0.0	0.0
45	-3.3	-3.6	-4.6	-3.8
90	-9.0	-9.2	-9.4	-9.2

The results indicate that for the systems evaluated, the difference in level for a subject directly in front of the speaker and one at a ninety degree angle to the speaker can be as high as 9 dB for the same distance. This result makes it unclear as to what sound pressure level the subject actually detects the vehicle, because the actual sound pressure level is a function of both distance and angle. Note however, that for any pass-by situation it is reasonable to expect a vehicle to be detected in the range between -45 to 45 degrees. In such cases the attenuation is significantly less, on the order of 3 dB.

5.3 Acoustic Analysis of Ambient Sounds

5.3.1 Ambient Levels during ICE Measurements-'Cottage Farm' Ambient

The primary purpose for these measurements was two-fold: 1) to determine corrections for measurements and 2) as an input to Psychoacoustic models. The corrections to measurements were discussed in Section 5.1.3. For these corrections, the minimum level for each one-third octave band was used. The ambient estimate used in the psychoacoustic models was derived from the minimum overall A-weighted level. Ambient levels for ICE measurements are summarized in Table 14 and Figure 19.

Table 14. Summary of Ambient Levels During ICE Measurements, A-weighted Level, dB(A)

1/3 Octave Band Center Frequency, Hz	Linear Average (1/3 Octave Band)	Min (Overall A-weighted)	Max (Overall A-weighted)	Min (1/3 Octave Band)	Max (1/3 Octave Band)
100 to 20k	49.6	46.1	53.4	45.3	54.7
100	34.6	30.7	34.1	30.7	38.4
125	35.5	32.4	36.8	32.4	42.1
160	36.1	32.1	37.9	32.0	41.5
200	36.9	32.7	37.9	32.7	41.2
250	36.5	33.9	38.1	33.1	40.7
315	36.5	32.5	37.6	32.1	41.5
400	36.0	31.9	38.1	31.8	39.7
500	36.7	33.6	39.8	33.1	41.1
630	38.2	34.4	41.7	34.0	42.2
800	40.2	36.0	46.1	35.8	46.1
1k	41.1	36.4	46.4	36.4	46.4
1.25k	40.0	35.3	45.1	35.3	45.1
1.6k	37.6	32.9	43.1	32.9	43.1
2k	34.7	30.3	37.8	30.3	37.8
2.5k	34.5	32.8	35.4	30.8	42.1
3.15k	35.5	36.9	37.1	30.0	39.6
4k	34.0	33.0	34.3	28.3	40.2
5k	29.0	25.0	29.8	24.3	32.8
6.3k	25.7	22.3	26.9	19.7	31.7
8k	20.2	16.6	22.4	14.1	24.2
10k	14.4	10.3	17.3	7.6	18.3

1/3 Octave Band Center Frequency, Hz	Linear Average (1/3 Octave Band)	Min (Overall A-weighted)	Max (Overall A-weighted)	Min (1/3 Octave Band)	Max (1/3 Octave Band)
12.5k	8.9	5.0	11.7	3.2	13.0
16k	3.1	0.7	5.6	-0.8	8.7
20k	-1.9	-3.1	-0.4	-3.5	2.0

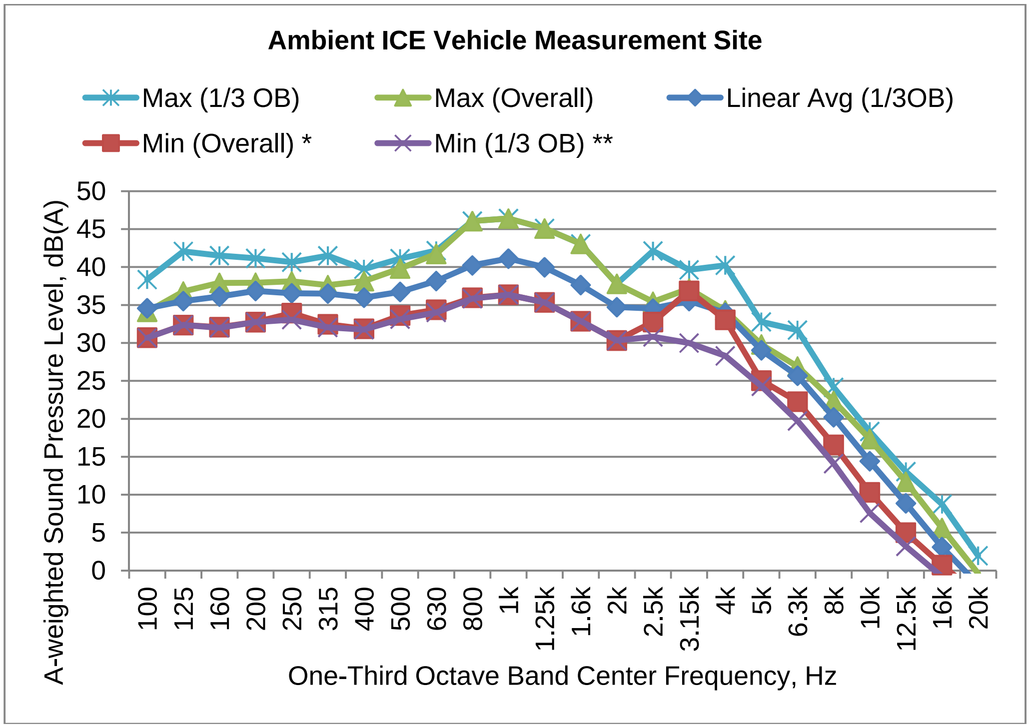


Figure 19. Five Measures of the Ambient at the ICE Vehicle Measurement Site. *The Minimum Overall Level Was Used for Psychoacoustic Computations. **The Minimum in One-Third Octave Band Was Used for Sound Pressure Level Corrections. Data are Repeated in Table 14

5.3.2 Ambient Levels Measured along Suburban Streets-‘Suburban’ Ambients

In order to determine what ambient levels would be reasonable for the human-subject testing, the ambient levels at several suburban intersections were measured and analyzed. The measurement locations were grouped into two categories: 1) busy intersections and 2) quiet back streets. A total of 17 sites over the course of three days were measured. The distribution of the one-half second equivalent A-weighted sound pressure levels are show in Figure 20. Here it can be seen that the average level of the quiet back street intersections was around 49 dB(A), the average level of the busy intersections was around 69 dB(A), and the average of the two was around 59 dB(A).

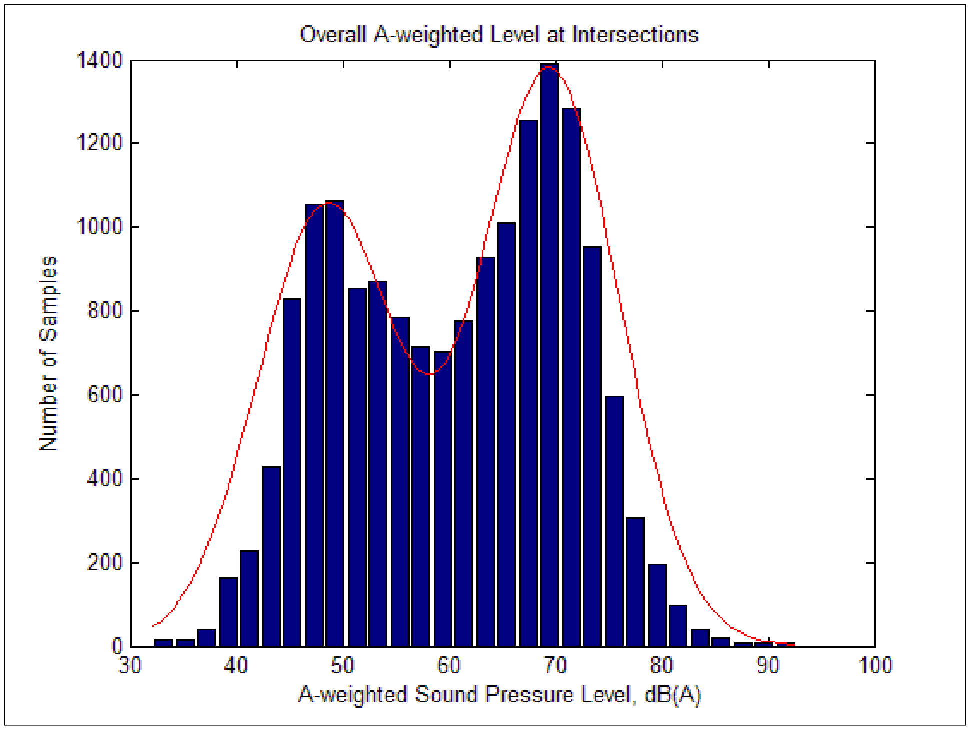


Figure 20. Ambient Level Distribution in Suburban Settings Including Both Light and Heavy Traffic

5.3.3 Ambient Level During Countermeasure Subjective Testing- ‘Countermeasure Test’ Ambient

Given the 20 dB range for typical sub-urban streets, it was necessary to establish at what ambient level the human-subject tests would be conducted. Because the highest ambient levels would likely mask all but the loudest countermeasure sounds, and since the lowest ambient levels would likely fail to mask all but the quietest countermeasure sounds, it was decided to target an ambient in the middle, that is around 59 dB(A). The site chosen was on the Volpe Center campus and had an ambient level that ranged from approximately 58 to 61 dB(A). At some points ambient levels were higher, but in general testing was halted to work around these times. The minimum, average, and maximum sound pressure levels for a sample period of the measured ambient are given in Figure 21 for August 14th. Similar results were obtained for the other days tested. An abridged version of the presented ambient spectrum was also used in psychoacoustic modeling. The abridged version is given in Table 15.

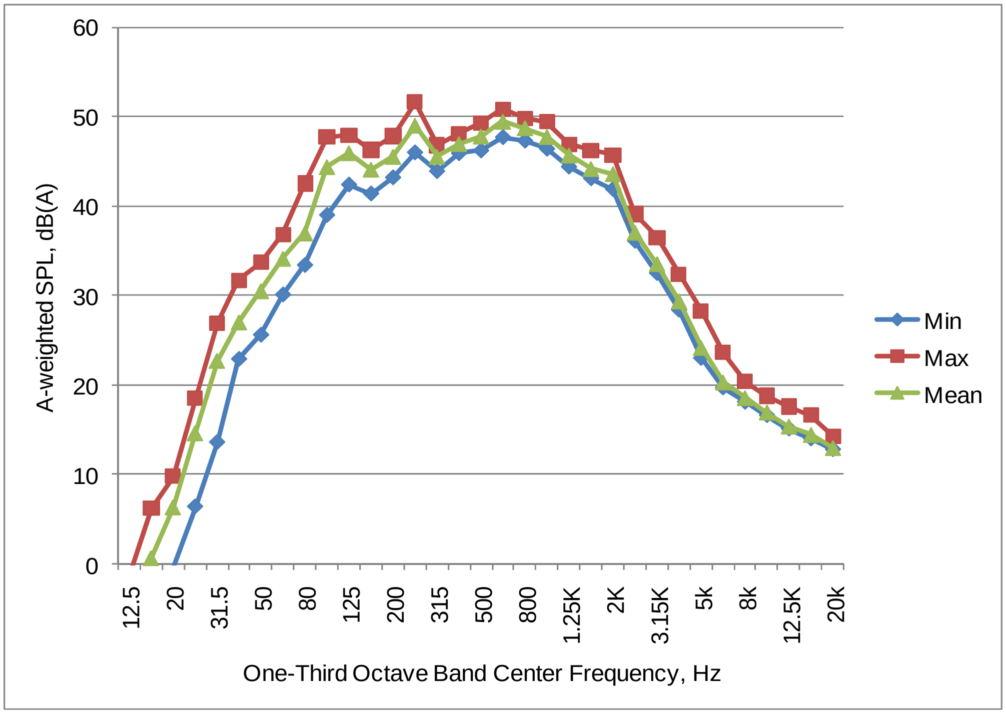


Figure 21. Sample Ambient Level During Countermeasure Testing on August 14th, 2010. Ambient Levels Ranged from 58 to 61 dB(A) During Testing

Table 15. Ambient Level During Countermeasure Testing Used for Computation of Psychoacoustic Metrics

1/3 Octave Band Center Frequency, Hz	SPL, dB(A)
50	30.5
63	34.1
80	37.0
100	44.4
125	46.0
160	44.1
200	45.5
250	49.0
315	45.5
400	47.0
500	47.8
630	49.5
800	48.7

1/3 Octave Band Center Frequency, Hz	SPL, dB(A)
1000	47.8
1250	45.7
1600	44.2
2000	43.6
2500	37.1
3150	33.5
4000	29.4
5000	24.2
6300	20.3
8000	18.5
10000	16.9
12500	15.4
16000	14.4
20000	13.0

The predominant sources of this ambient noise were the air-conditioning fans on the roofs of buildings about 400 feet west of the subject seating area. These were of essentially constant amplitude. Among the variable sources were direct wind noises, the rustling of tree leaves, and distant vehicles.

While the ambient noise produced by the air-conditioning fans varied by less than 1 dB (as measured by a monaural microphone) along the line of 28 seated subjects, it was clearly louder from the west than the east, when listened to subjectively. To confirm this, measurements were made using a binaural measurement system at the east end of the subject seating area. The ambient levels measured by the left (west) microphone were about 1.4 dB greater than the ambient levels measured by the right (east) microphone. The difference was even greater for frequencies from 800 to 20,000 Hz, where the average difference between the two sides was about 3.1 dB (see Figure 22). Thus, it is expected, because of the occlusion caused by the subject's head, that the effective ambient will be greater for subjects when they attempt to detect vehicles approaching from the west.

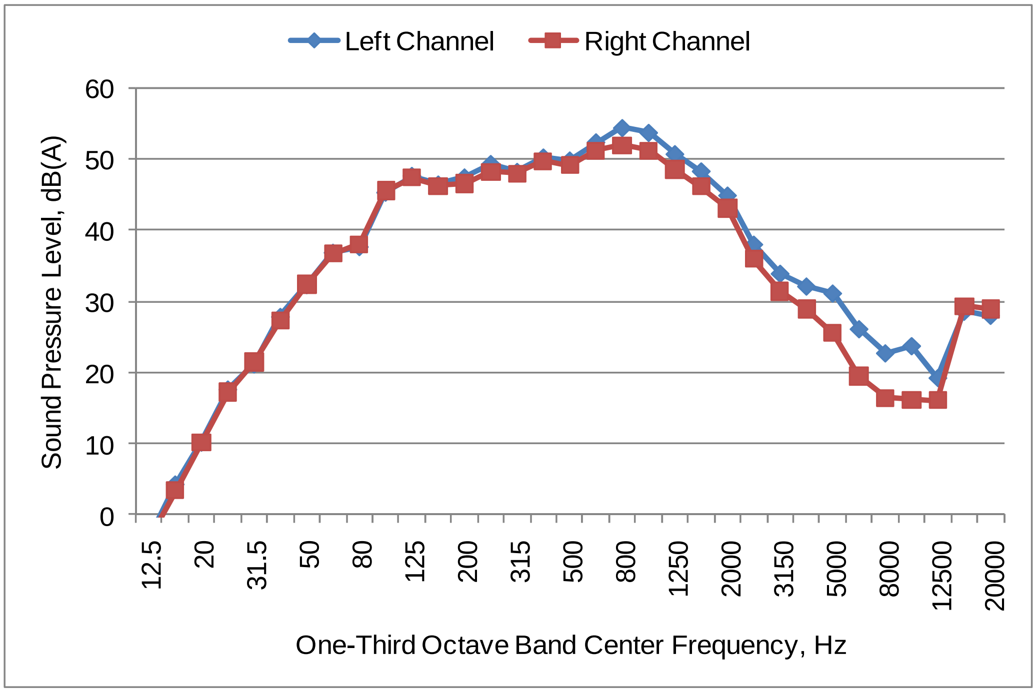


Figure 22. Comparison of Ambient Level for Left and Right Sides of Binaural Head During Countermeasure Testing

6. PSYCHOACOUSTIC ANALYSIS

Using the ICE and countermeasure signal data, several psychoacoustic models were applied in an effort to refine minimum specifications.

6.1 Comparison of Various Psychoacoustic Models for Two Sounds

Sound pressure level based metrics such as the A-weighted level provide a first estimate of the perceived loudness of a sound, however, these metrics fail to account for several factors that affect the perceived loudness including: 1) the level dependence on the frequency sensitivity, 2) level dependence on frequency selectivity, 3) frequency based masking effects, 4) pre- and post-masking, 5) co-modulation masking release, etc.

The level dependence on the frequency sensitivity refers to the fact that for the same change in sound pressure level for a low frequency sound and a high frequency sound, the low frequency sound will be perceived as increasing in loudness more than the high frequency sound. Sound pressure level frequency weightings such as A-, C-, and D-weighting account for this very roughly, however, these weighting functions are most appropriately chosen based on the overall level, and thus implicitly assume uniform spectral content.

The typical method of approximating frequency selectivity using sound pressure level metrics is to analyze the sound using one-third octave bands. These bands offer a very rough approximation of the human auditory system’s ability to analyze different frequencies of sounds separately. The actual shape and bandwidth of the auditory system’s frequency selectivity are more accurately related to the auditory tuning curves which are narrower for low levels and become broader with increased level (as well as with increased center frequency).

The human auditory system cannot completely separate frequency components. That is, the energy associated with a given frequency excites one region of the basilar membrane most effectively, but also excites neighboring regions to a lesser extent. (The basilar membrane is a membrane that attaches to the organ of Corti and together they are largely responsible for place based frequency selectivity.) Thus, a high energy component can prevent or reduce the perception of a lower energy component at a different frequency. That is, for example, an ambient with a high level of low frequency sound can mask a signal with components in a higher frequency range.

Other factors can also affect the perceived loudness of a sound to a lesser extent. For example, although not as strong, masking effects can be measured for sounds that happen either directly before or directly after the signal sound. Additionally, masking effects can be reduced by various processes such as, for example, co-modulation masking release. The key point here is that sound pressure level metrics offer a good first approximation to the perceived loudness of a sound, however, when it is desired to understand how quiet sounds are perceived in the presence of an ambient level, more refined models may provide additional guidance.

Several psychoacoustic models exist that relate sound pressure level data to either the perceived loudness of the signal or detectability/audibility. Loudness models include various versions of models proposed by Zwicker (Zwicker & Fastl, 1999; ISO 532-B; DIN 45 631) and Moore (Moore, 1993; ANSI S3.4-2007). Detectability models include Audibility (Fleming et al., 2005), Detect Sound (Zheng et al., 2007); Giguère et al., 2008), as well as Zwicker's loudness model with ambient (Kerber, S. & Fastl, 2008) and Moore's loudness model with ambient (Moore & Glasberg, 1997; Moore, Glasberg, and Bear, 1997). Both Zwicker's and Moore's loudness models address the first three factors mentioned above, and addressing these factors provides significant improvement on the modeling of perceived loudness. For detectability models, two approaches are taken. The Audibility model is more closely related to sound pressure level metrics, but provides a formal method to account for frequency selectivity using one-third octave bands, accounts for masking effects due to the ambient and the auditory system's internal noise, and accounts for a threshold which may need to be exceeded in order for a signal to be considered audible. Detect Sound and a version of Zwicker's loudness which accounts for the ambient both use loudness models (Detect Sound uses Moore's model) to compute the excitation due to both the ambient and the signal of interest, and then determine when the ambient no longer completely masks the signal. Note, Moore has also published a version of his model that takes into account the ambient, however, it is not known by the authors of this report, whether or not there is a minimum threshold. It is assumed that there is none, in which case, provided that a signal produced non-zero loudness in the presence of an ambient, it would be considered audible. A summary of the models discussed here is given in Table 16.

Table 16. Comparison of Psychoacoustic Models

Model	Type	Pros	Cons
Loudness (Zwicker)	Loudness	International Standard, Mature, Comprehensive	Output departs from standard concept of frequency
Loudness (Moore)	Loudness	International Standard, Mature, Comprehensive	Output departs from standard concept of frequency
Audibility	Detection	Simple to Compute, Simple to Understand and Explain	Does not include masking across one-third octave bands
Detect Sound	Detection	Simple Output	Does not give insight into why a signal may or may not be detected.
Loudness with Ambient (Zwicker)	Loudness / Detection	Most comprehensive model for detection, can be used to evaluate the growth of the loudness as the vehicle approaches	Not currently available in the public domain
Loudness with Ambient (Moore)	Loudness / Detection	Comprehensive, well documented model	Needs small additions in order to evaluate the growth of the loudness as the vehicle approaches

Of the available models Moore's loudness, with the ambient included, provides the most information for the perceived loudness and detectability of the signal. Therefore, Moore's loudness model with ambient included was used for the remainder of the psychoacoustic analysis.

6.2 Moore's Loudness with Ambient Associated with the Event Corresponding to the Maximum for ICE Vehicles

For each vehicle, the event with the maximum $L_{Aeq, ½ sec}$ at pass-by for each event was used to compute a specific loudness spectrum by using Moore's Loudness with Ambient for both the driver's side and the passenger's side. The driver side results are shown in Section 6.2.1 for the measured ambient condition, Cottage Farm Ambient. The driver side results are shown in Section 6.2.2 for the ambient condition present during countermeasure subject testing, Countermeasure Test Ambient. The purpose of considering both ambient conditions was to show the loudness of the measured vehicles in the presence of a realistic quiet and noisy ambient to understand how the ambient affects the perception of the sound to be detected. Results for the passenger side are given in Appendix A-2.

6.2.1 Cottage Farm Ambient

Figure 23 shows the perceived loudness of 10 ICE vehicles in the presence of the Cottage Farm Ambient. The abscissa is analogous to frequency, however the unit is Number of Equivalent Rectangular Bandwidths (ERBs). ERBs are a single value representation of the auditory filter bandwidth. The relationship between number of ERBs and frequency is given by:

$$Number\ of\ ERBs = 21.4\ log_{10}\left(\frac{4.37}{1000}f + 1\right)$$

At high number of ERBs, a small change in the number of ERBs corresponds to a large change in frequency. This is illustrated in Figure 24. To facilitate interpretation of these graphs, the number of ERBs and corresponding frequency are given in Table 17.

The ordinate is analogous to sound pressure level density. By integrating the specific loudness over the entire curve, the total loudness can be obtained. Because any non-zero specific loudness indicates a perceived loudness, any signal present in these graphs (with minima set to zero) is considered to be audible. In general both the ambient and the signal have non-zero specific loudness over at least part of the equivalent frequency range. This indicates that both the ambient and the signal are audible. In this case both the ambient and the signal vie for the subject's attention.

Tonal components can be seen as narrow peaks in Loudness spectra, such as those in Figure 25 for vehicle 1 at approximately 4 ERBs (123 Hz) and vehicle 3 at approximately 10 ERBs (442 Hz). These tonal components are most likely due directly to the combustion process, rather than the more broadband contributions from tire, gear, and other mechanical noise also present in the signal. With the exception of vehicle 7, all ICE vehicles were audible in the low ambient condition present at Cottage Farm. Although vehicle 7 was an ICE, it was extremely quiet and often did not exceed the ambient sufficiently to provide an accurate measurement.

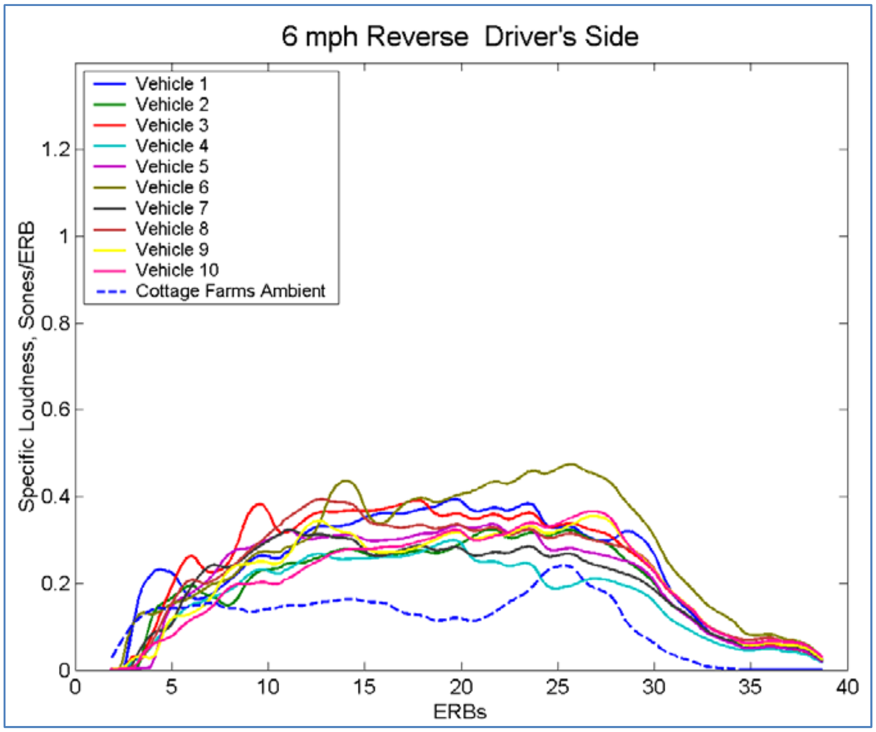


Figure 23. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Cottage Farm Ambient: 6 mph, Reverse, Driver's Side

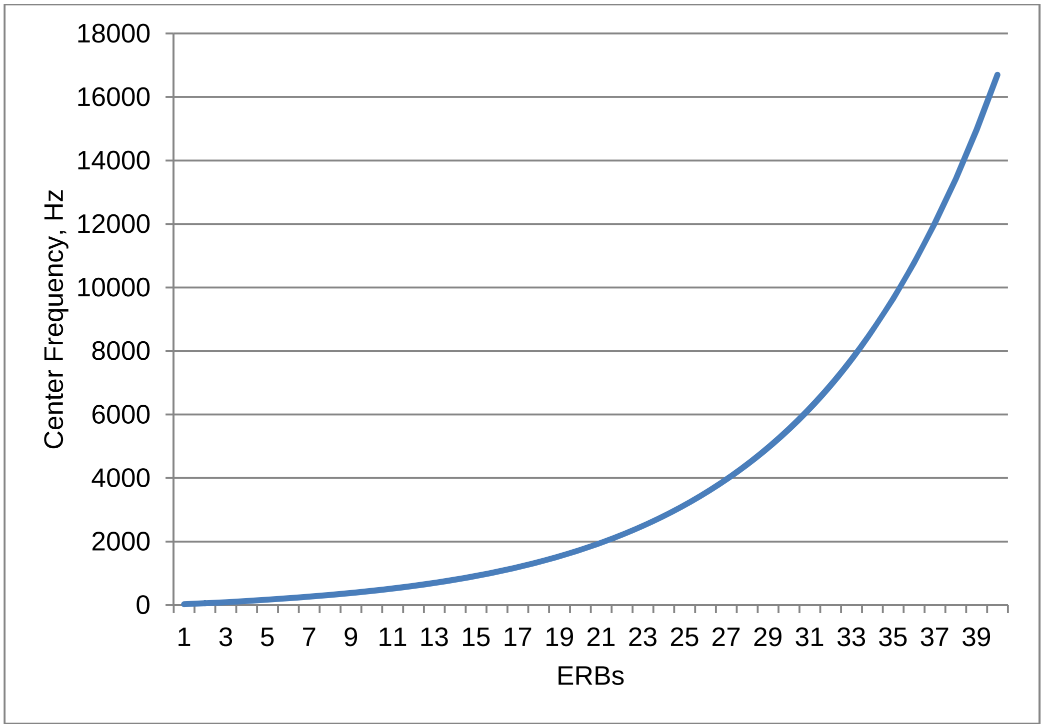


Figure 24. Relationship Between Number of ERBs and Frequency. See Table 17 for Data

Table 17. Number of ERBs and Corresponding Frequency, Hz

Number of ERBs	Frequency, Hz
1	26
2	55
3	87
4	123
5	163
6	208
7	257
8	312
9	374
10	442
11	519
12	603
13	698
14	803
15	921
16	1051
17	1196
18	1358
19	1539
20	1739
21	1739
22	1963
23	2212
24	2489
25	2798
26	3142
27	3525
28	3951
29	4426
30	4955
31	5544
32	6200
33	6930

Number of ERBs	Frequency, Hz
34	7743
35	8649
36	9657
37	10781
38	12031
39	13424
40	14975

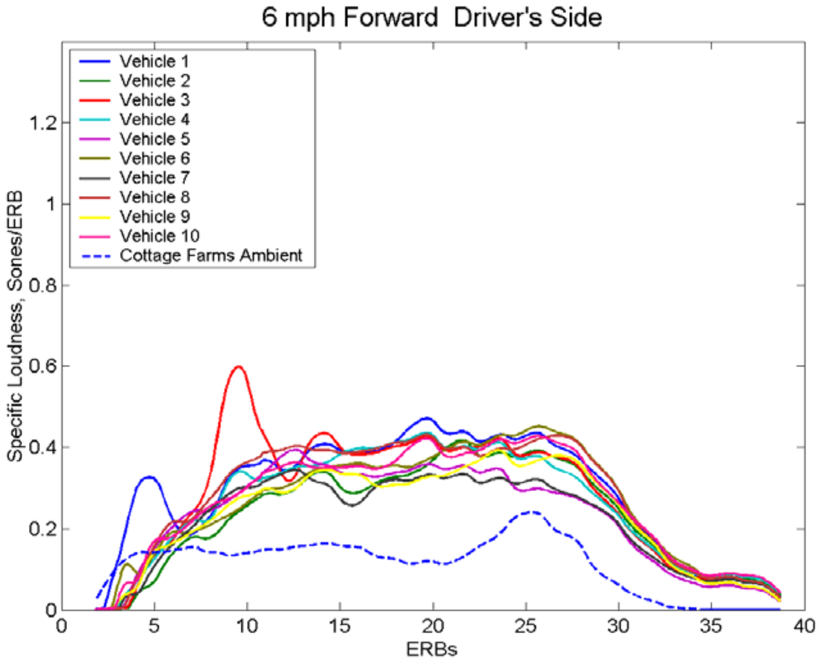


Figure 25. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Cottage Farm Ambient: 6 mph, Forward, Driver's Side (Driver Seat on the Right)

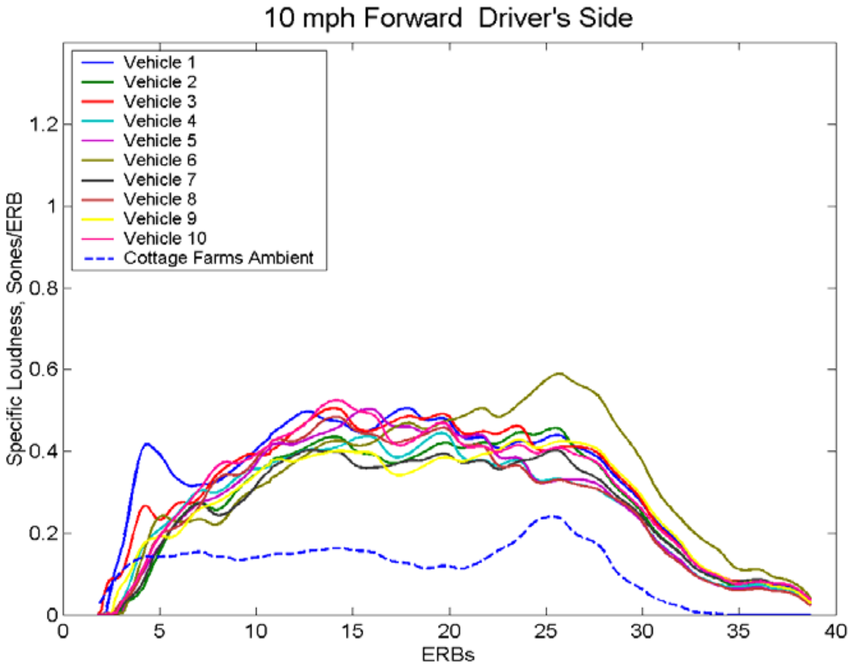


Figure 26. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Cottage Farm Ambient: 10 mph, Forward, Driver's Side

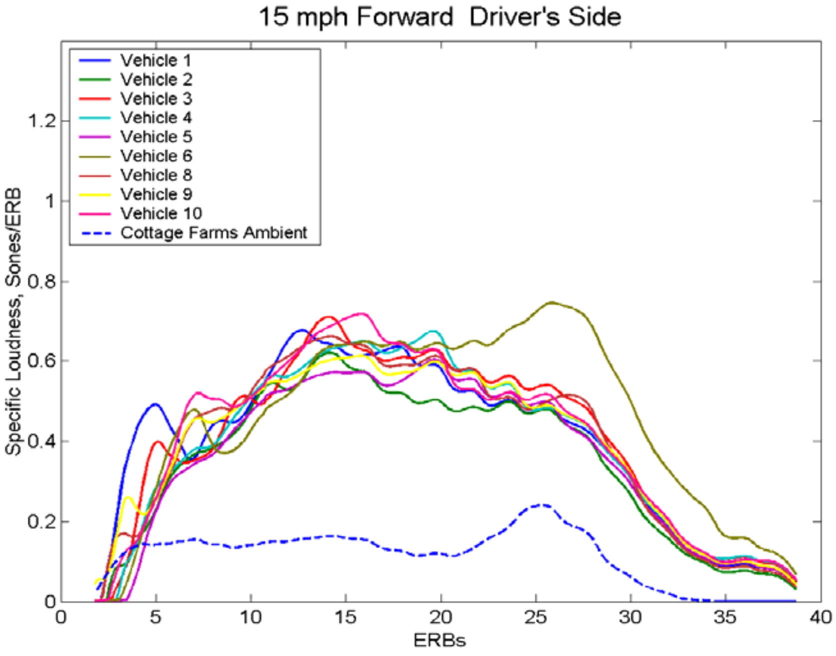


Figure 27. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Cottage Farm Ambient: 15 mph, Forward, Driver's Side

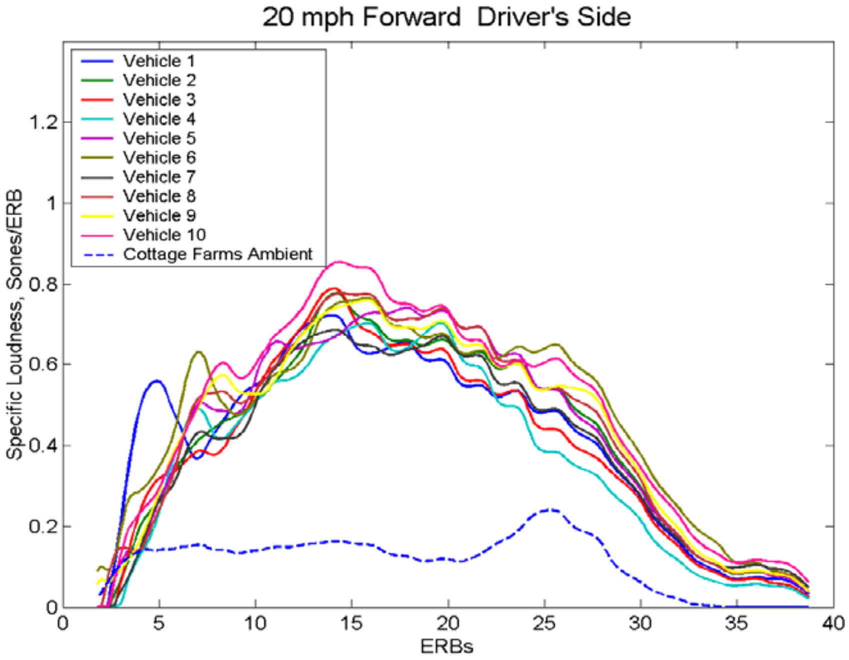


Figure 28. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Cottage Farm Ambient: 20 mph, Forward, Driver's Side

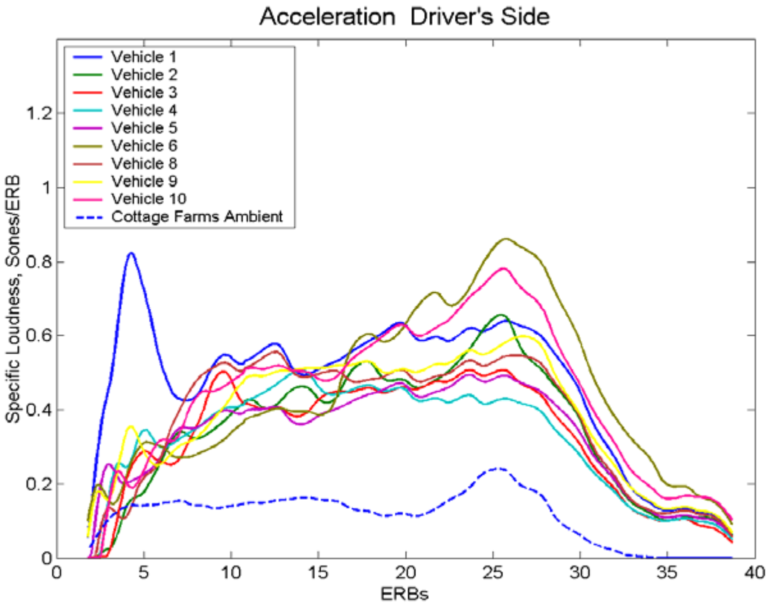


Figure 29. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Cottage Farm Ambient: Acceleration, Driver's Side

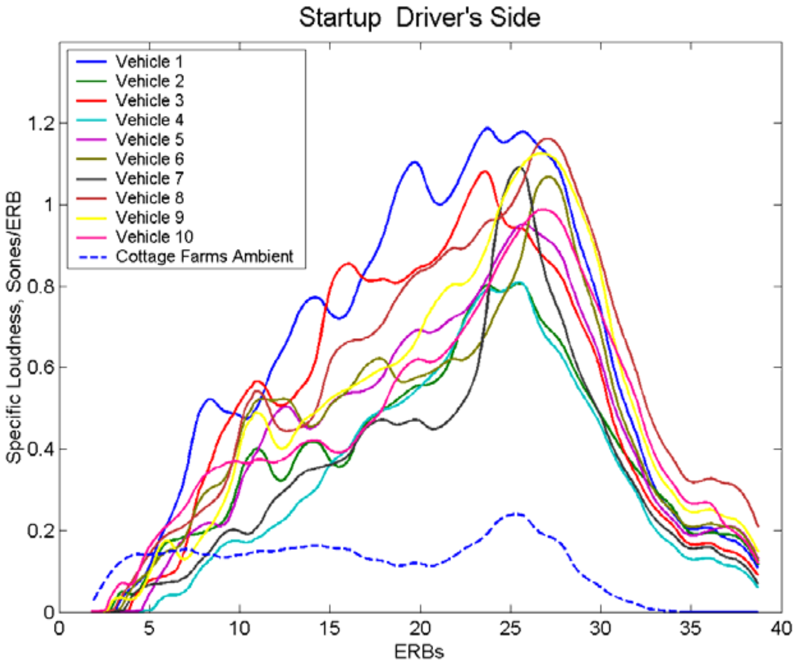


Figure 30. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Cottage Farm Ambient: Startup, Driver's Side

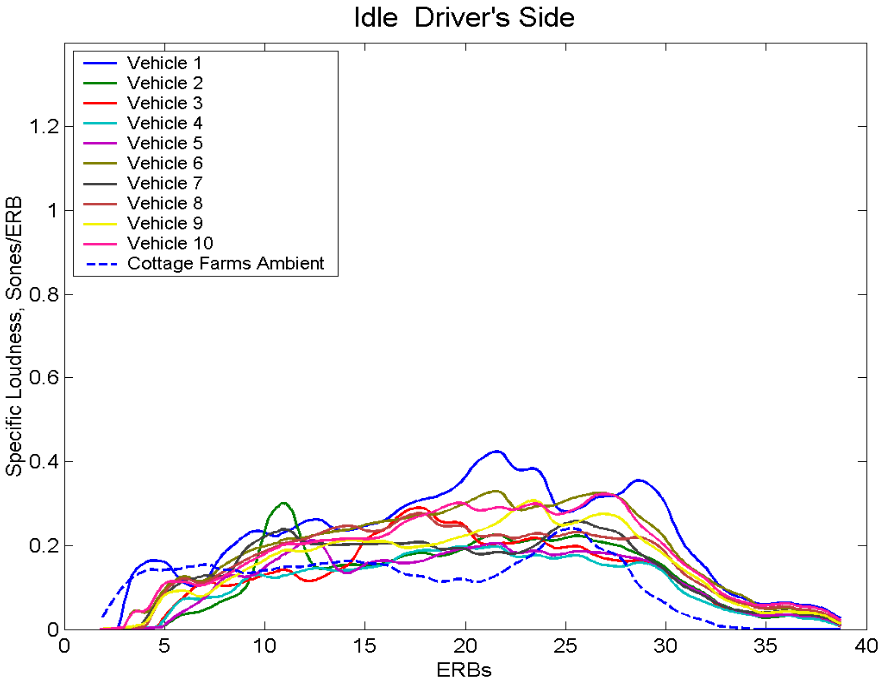


Figure 31. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Cottage Farm Ambient: Idle, Driver's Side

6.2.2 Countermeasure Test Ambient

The Cottage Farm ambient represents a condition where it is expected that typical ICE vehicles should be easily audible. The loudness model corroborates this and additionally shows low, mid, and high frequency components are audible. However, it is expected that pedestrians will need to detect vehicles in higher ambient levels. The Countermeasure Test Ambient was determined to have an overall level that was equivalent to the average of two typical ambient conditions encountered by pedestrians as discussed in Section 5.3.2. The masking effects of this ambient are much more pronounced. Even so, the loudness model predicts that the ICE vehicle will still be audible for all operating modes measured. However, low frequencies are much less detectable and in some cases not at all. See for example Figure 33 where only vehicle 1 has components (in this case a tonal component) audible below about 257 Hz. For idle, Figure 39, vehicles are generally not audible below 10 ERBs (442 Hz) and only become the dominant source somewhere between 20 to 25 ERBs (1739 to 2798 Hz).

These data show that for both ambient conditions the ICE vehicles are detectable when the vehicle is at its closest point to the microphone. These data do not answer the question, at what distance can the vehicles first be detected? This question is of interest for pass-by events. To answer this question, Loudness spectra for consecutive measurements as the vehicle approaches the microphone would need to be computed. This is beyond the scope of this study, but a sample illustration of the process for vehicles 1 and 7 is given in Section 6.3.

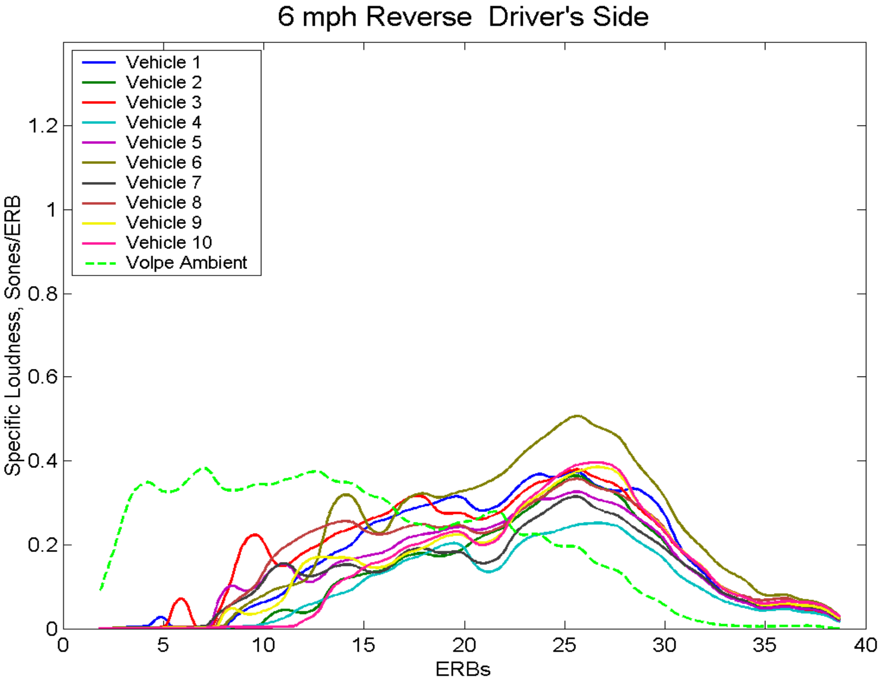


Figure 32. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Countermeasure Ambient: 6 mph, Reverse, Driver's Side

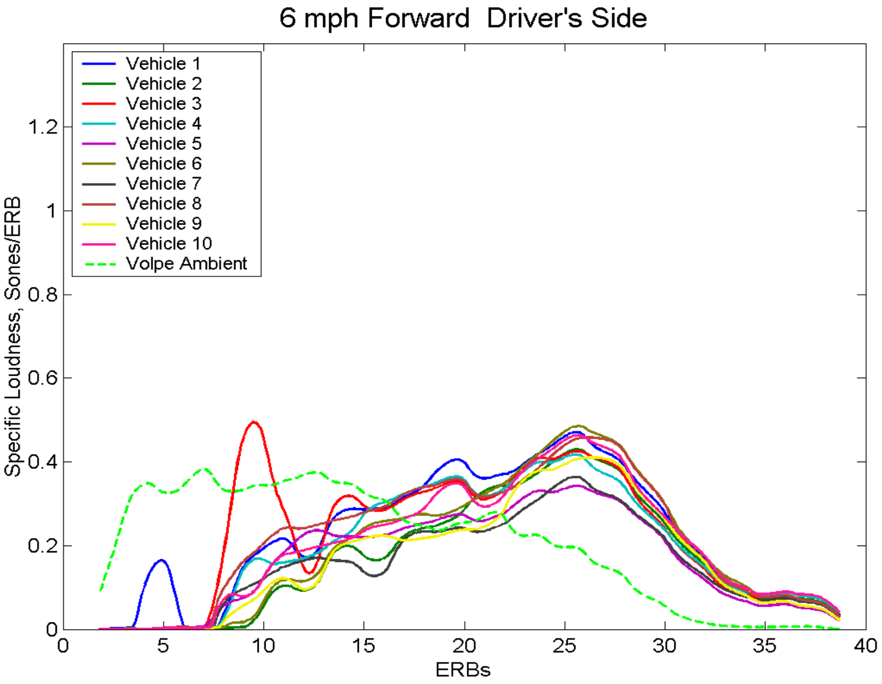


Figure 33. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Countermeasure Ambient: 6 mph, Forward, Driver's Side

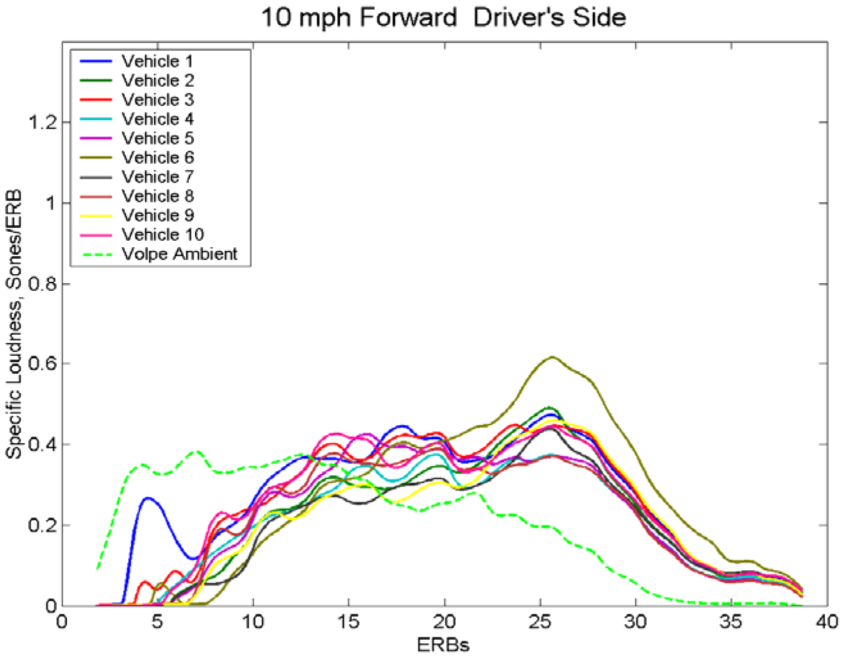


Figure 34. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Countermeasure Ambient: 10 mph, Forward, Driver's Side

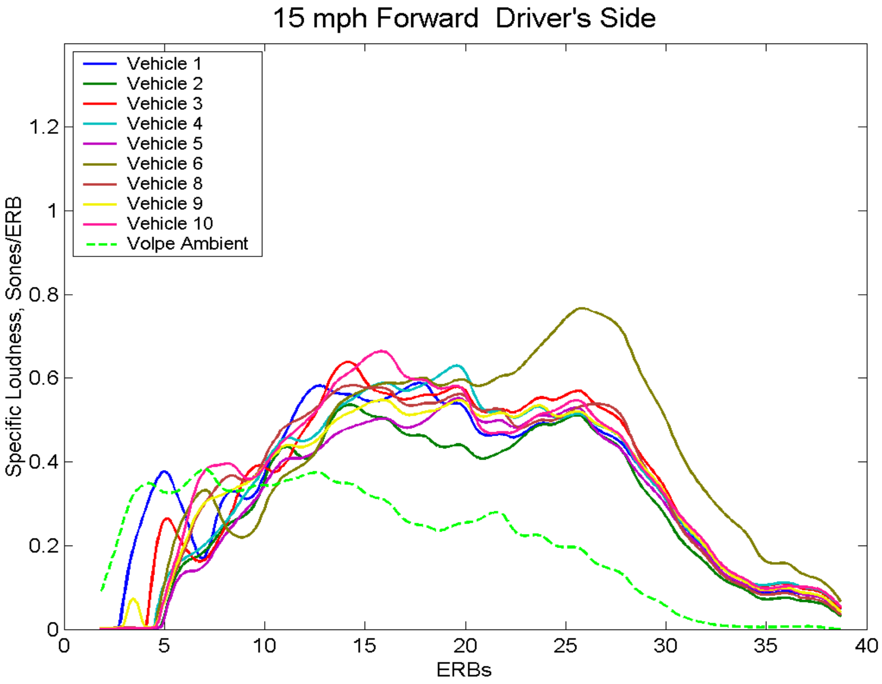


Figure 35. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Countermeasure Ambient: 15 mph, Forward, Driver's Side

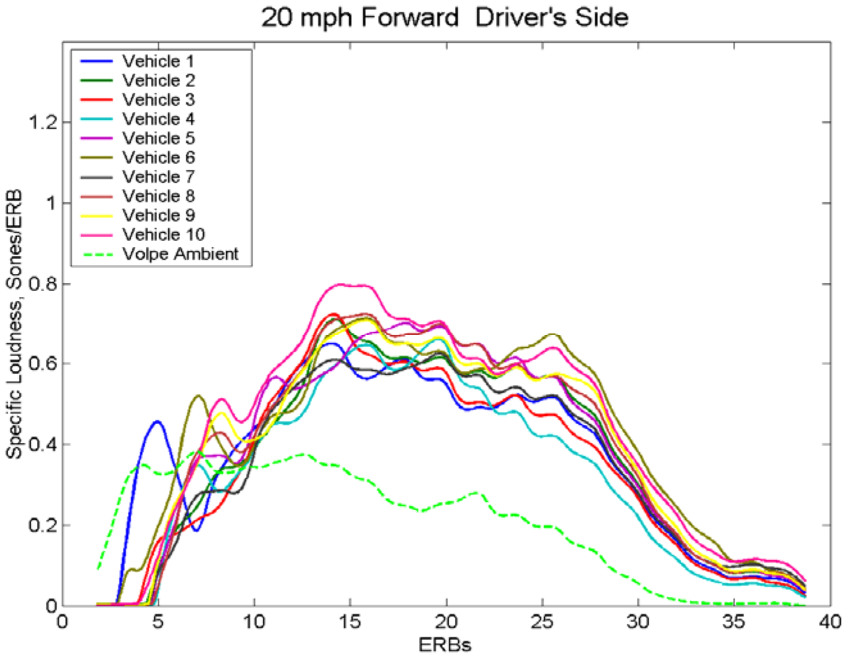


Figure 36. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Countermeasure Ambient: 20 mph, Forward, Driver's Side

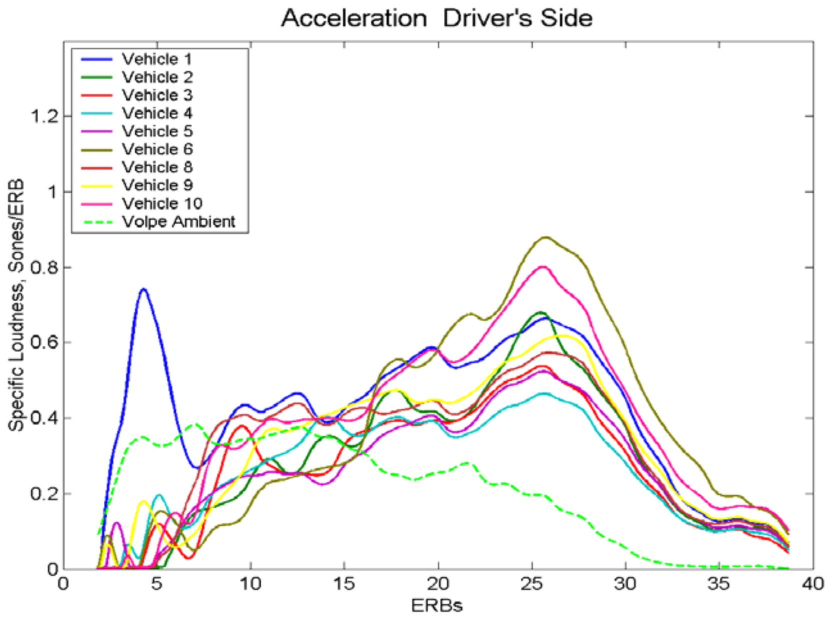


Figure 37. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Countermeasure Ambient: Acceleration, Driver's Side

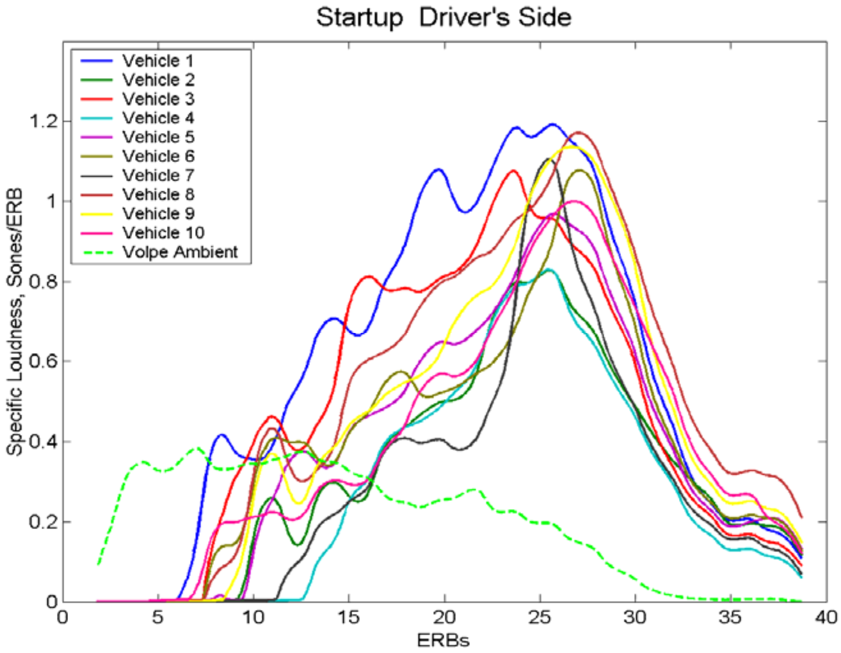


Figure 38. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Countermeasure Ambient: Startup, Driver's Side

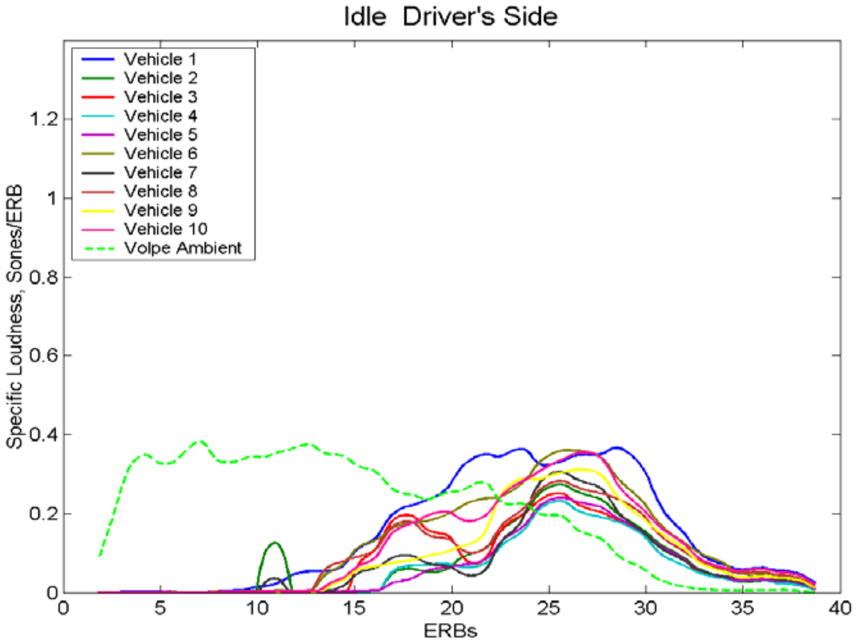


Figure 39. Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Countermeasure Ambient: Idle, Driver's Side

6.3 Moore's Loudness with Ambient Time History Associated with the Event Corresponding to the Maximum ICE Vehicles

Typically, as a vehicle approaches a subject it gets louder, and thus is easier to detect, provided that the sound emitted by the vehicle and the ambient sound level do not change. Examining how Loudness increases as a vehicle approaches can give insight as to when a vehicle can be detected and what the key components contributing to detection may or may not be. In order to evaluate the increase in the Loudness spectra as a vehicle approaches, Loudness spectra were computed for the quietest ICE, vehicle 7, and the loudest ICE, vehicle 1 (see Figure 40 to Figure 43). Loudness spectra were computed for both the Cottage Farm and Countermeasure Ambients for the 6 mph, forward operating condition. Due to data quality restrictions, the analysis was only conducted for the 5 seconds prior to pass-by. In all cases the loudness model indicates that at least some portion of the vehicles sound was audible during this entire period. Increase in Loudness was greater as the vehicle got closer to the microphone line, most likely due to the increased number of distance halving as the distance to the microphone got small. Also of interest, was the fact that the low frequency tonal component associated with vehicle 1 only becomes perceptible close to the microphone, even though the rest of vehicle 1's Loudness spectra indicates a more gradual growth. This may indicate that the tonal component is highly directional; for example it may be due to sound radiating out through the wheel well. This may indicate that directivity may need to be closely controlled if a tonal component is to be considered part of a countermeasure signal.

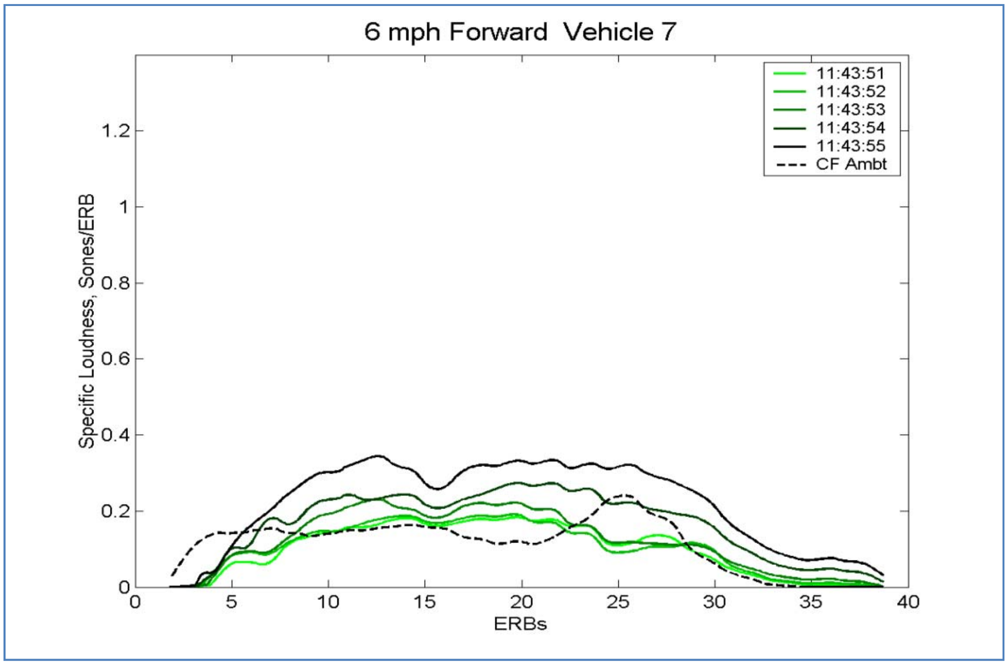


Figure 40. Growth of Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Cottage Farm Ambient: 6 mph, Forward, Driver's Side – Vehicle 7

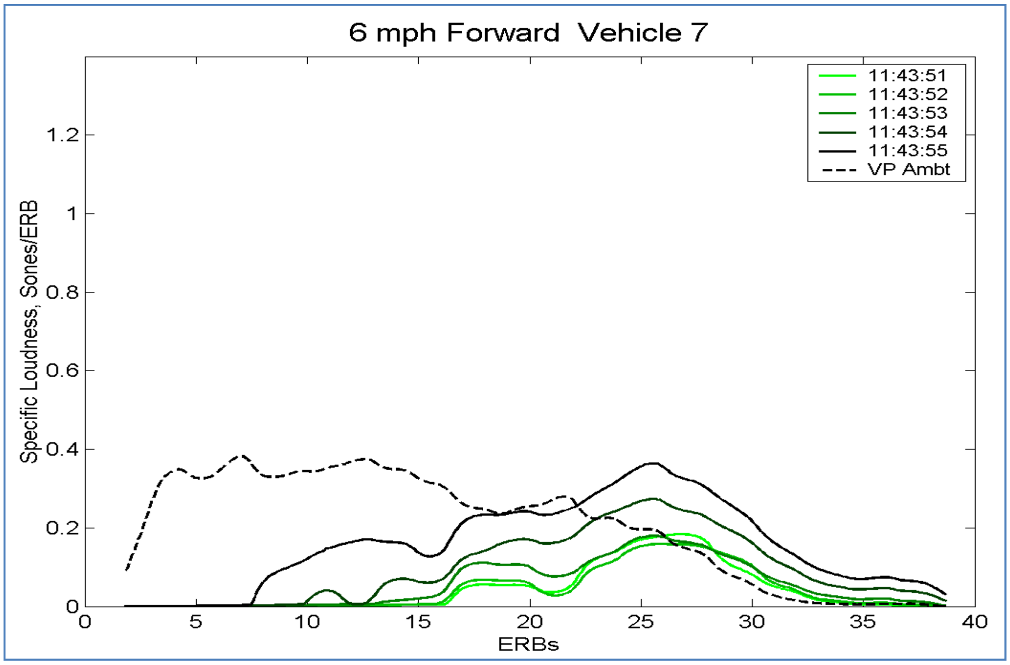


Figure 41. Growth of Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Countermeasure Ambient: 6 mph, Forward, Driver's Side – Vehicle 7

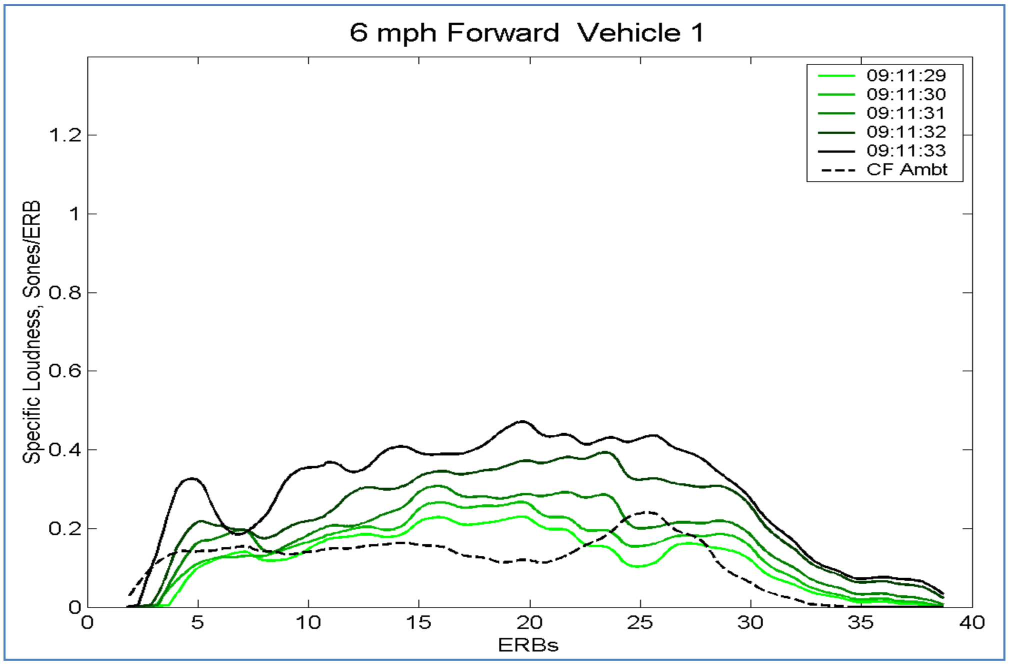


Figure 42. Growth of Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Cottage Farm Ambient: 6 mph, Forward, Driver's Side – Vehicle 1

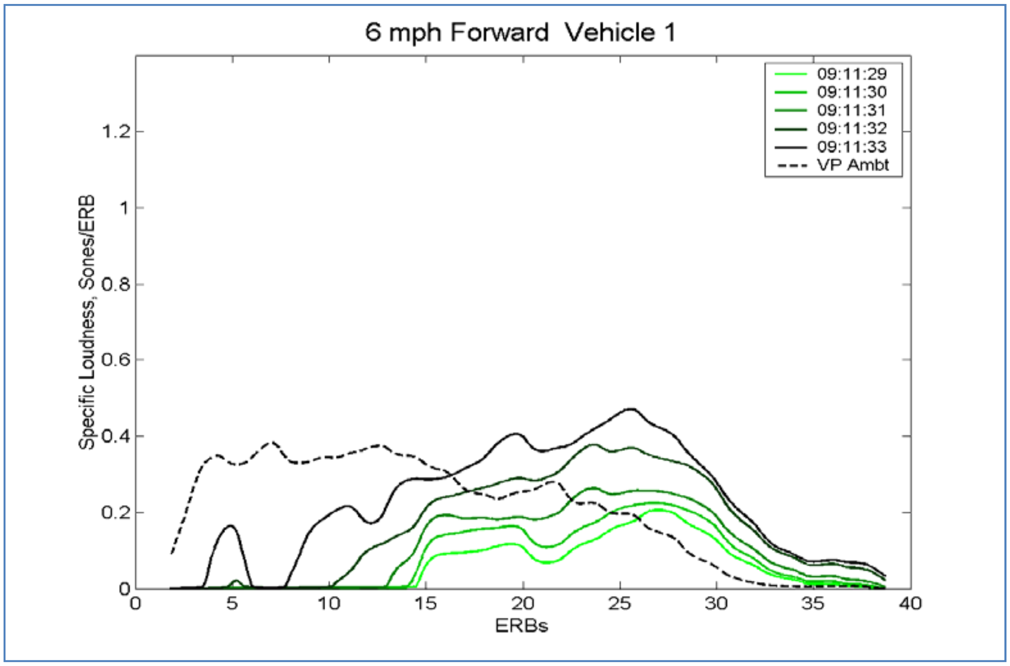


Figure 43. Growth of Specific Loudness of ICE Vehicle at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Countermeasure Ambient: 6 mph, Forward, Driver's Side – Vehicle 1

6.4 Moore’s Loudness with Ambient Associated with the Event Corresponding to the Maximum for Countermeasure Sounds

The Loudness spectra of the countermeasure signals are given for low, 59.5 dB(A) output levels in Figure 44 and for high output levels, 63.5 dB(A), in Figure 45. These spectra were only computed for the Countermeasure Ambient, 58.3 dB(A), as the purpose here is to provide potential explanation of countermeasure performance during the human-subject testing. One point to make here is that most of the countermeasure signals had strong tonal components. About half of the countermeasure sounds have tonal components below 2000 Hz, where the ambient was loud, and about half have tonal or broad band components above 2000 Hz, where the ambient was not as loud.

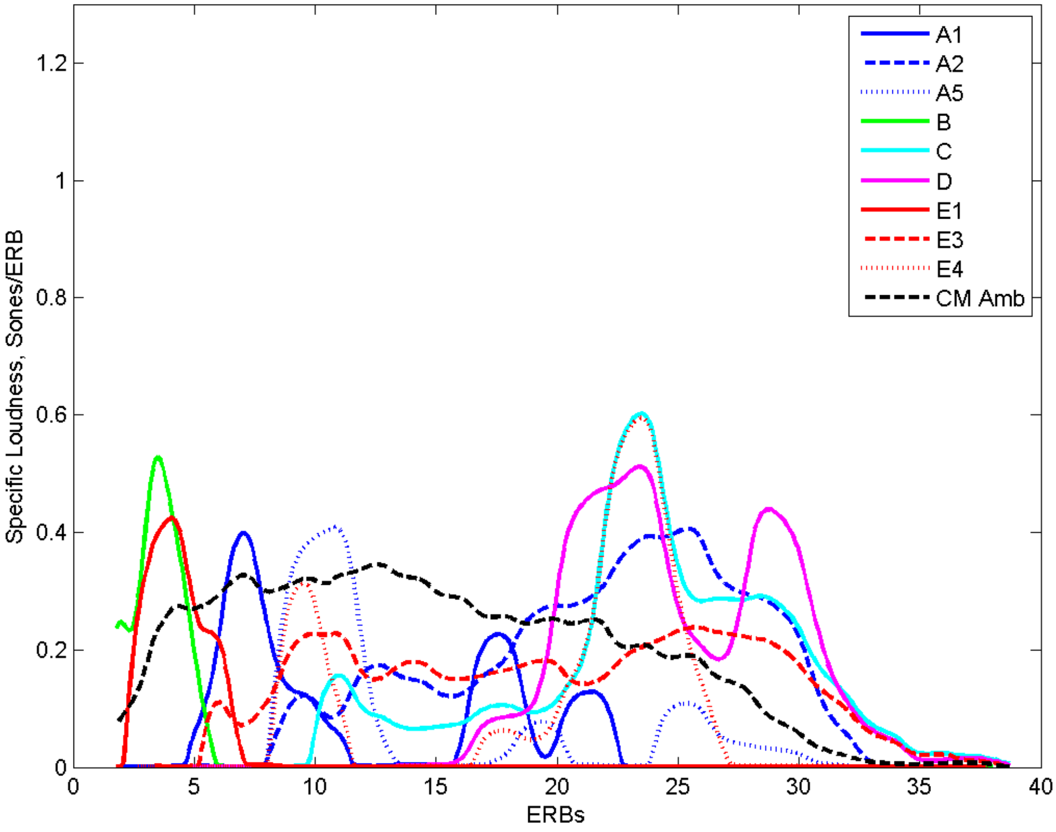


Figure 44. Specific Loudness of Countermeasure Sounds at Microphone Line According to Moore’s Loudness with Ambient in the Presence of the Countermeasure Ambient: Low Level, 59.5 dB(A)

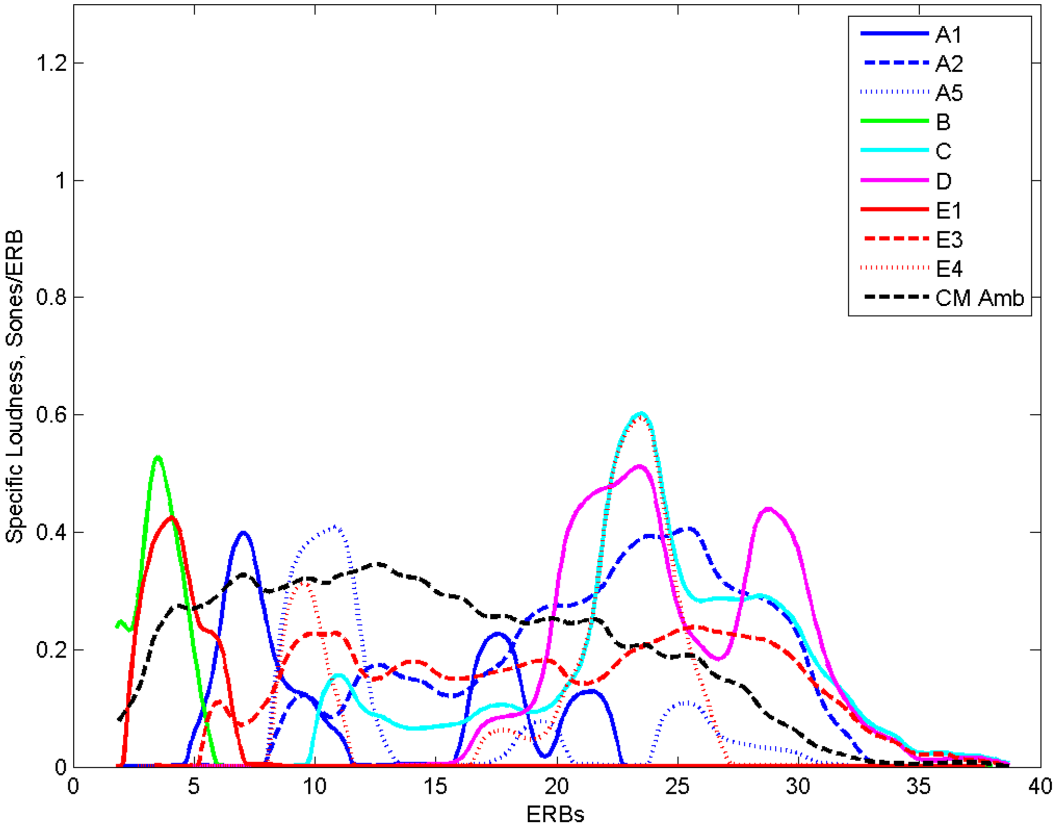


Figure 45. Specific Loudness of Countermeasure Sounds at Microphone Line According to Moore's Loudness with Ambient in the Presence of the Countermeasure Ambient: High Level, 63.5 dB(A)

6.5 Summary: Acoustic Analysis

- ICE Vehicle sounds are, on average, broad band in nature and do not have strong tonal components.
- According to Moore's Loudness model all vehicles were detectable at the point of closest approach.
- Frequency components less than 500 Hz were less (or not at all) detectable due, in part, to ambient levels typically being high below 500 Hz.
- Frequency components between 1600 and 5000 Hz were more detectable due to strong signal strength and relatively low ambient levels in this range.
- During testing tonal components emitted by two ICE vehicles were particularly detectable, according to the model.
- None of the existing models were designed to deal with moving sound sources.

7. EVALUATION OF COUNTERMEASURE SOUNDS

7.1 Purpose

Human-subject testing was conducted to compare alternative countermeasure sounds, in terms of the time and distance (when applicable) at which these sound sources were detected and recognized as a vehicle, in representative urban-ambient noise conditions. Countermeasure sounds were evaluated at two sound pressure levels typical of ICE vehicles at low speeds (i.e., 59.5 and 63.5 dB(A)). An ICE vehicle that produced 60 dB(A) in the 6 mph pass-by test was used as a reference in this evaluation.

7.2 Sound Characteristics to Improve Detectability

The following sound characteristics can improve detectability of a sound source (Stanton & Edworthy (Eds.) 1999):

- Pulsating quality with pulse widths of 100 to 200 msec.
- Inter-pulse intervals of about 150 msec.
- Fundamental tonal component in 150 to 1000 Hz range.
- At least three prominent harmonics in the 1 to 4 kHz range.
- Pitch shifting denoting vehicle speed change.

Some of the countermeasures evaluated in the human-subject studies have sound characteristics that could improve detectability when compared to ICE-equivalent sounds.

7.3 Countermeasure Evaluation Test Site

The evaluation of countermeasures took place in a parking lot located on the Volpe Center campus in Cambridge, Massachusetts. The test site has the acoustic characteristic of an urban area with a typical ambient noise level of approximately 58-61 dB(A). Ambient sound measurements at the test site were described in Section 5.3.3. Most of the ambient noise at the site was generated by fans on the roofs of buildings about 400 feet west of the test site, which resulted in a greater masking effect for vehicles approaching from the west (the “a-to-b” direction) than for the reverse. Figure 46 shows a photo of the test site. The test site has several characteristics essential for the conduct of the study. Vehicles that were not part of the study did not pass through the test site; all vehicular traffic was controlled by Volpe Center security guards. There was adequate approach distance for vehicles to get up to 6 mph speed before they became audible. An alternate route for test vehicles to go to the designated starting points while recharging their batteries was available. A large number of participants were seated next to each other and shaded from the sun. The road surface consisted of bituminous asphalt and was swept and washed down prior to each test session.

Figure 46. Test Site at the Volpe Center, Cambridge, Massachusetts

7.4 Countermeasure Sounds Evaluated

Countermeasure systems included HEVs, in electric mode, with sound generator systems, each of which generated one or multiple versions of ‘artificial engine noise’ or other sounds.

The countermeasure systems evaluated included:

- Sounds produced by vehicles with integrated countermeasures rented from manufacturers.
- Sounds produced by prototype countermeasure systems rented from manufacturers, and played back by loudspeakers temporarily mounted on HEVs rented separately.

Five vendors, motor vehicle manufacturers or suppliers of automotive electronics, agreed to rent prototypes of synthetic sound generators for EVs or HEVs to the government. All five systems are intended to receive signal from the CANbus that will cause the pitch of their sound to vary in proportion to the vehicle speed up to the speed at which the sound is no longer needed. Some emit special sounds in reverse, or emit louder sounds in reverse, or increase in loudness briefly when the vehicle starts moving. The countermeasures systems were labeled “A” to “E”. A total of nine sounds were evaluated: A1, A2, A5, B, C, D, E1, E3, and E4. In addition to the countermeasures sounds, an ICE vehicle was included in the study as a baseline for comparison purposes. The ICE vehicle was labeled system ‘R’. Volpe Center staff prepared a qualitative description of the sound systems in Table 18. The acoustic characteristics of these countermeasure sounds were discussed in Section 5.2.

Table 18. Qualitative Description of Sound Countermeasures

System	Sound ID	Qualitative Description of Countermeasure Sounds (all sound are synthesized sounds)
A	1	Engine-or-pump-like sounds accompanied by turbine-like whine. The frequency of the most prominent peak in the spectral distribution varies from 150 to more than 300 Hz over the 0 to 20 mph range. The engine noise and the turbo sound include several harmonics. Both the engine noise and the turbo sound increase in pitch with vehicle speed, but there is no amplitude change under any condition.
A	2	Engine sound with enhanced valve noise. The fundamental varies from under 100 Hz to about 200 Hz over the 0 to 20 mph range. There are numerous harmonics too closely spaced to count with peak amplitude only a few dB below that of the fundamental. All components of the sound shift upwards in pitch with speed, but there are no amplitude modulations.
A	5	Whirring sound with Diesel engine sound. The fundamentals of the whirring noises are centered around 400 Hz at idle and rise to more than 600 Hz at 20 mph, while the repetition rate of the 'whirring' effect is about 1.6 Hz, varying slightly with speed. The Diesel valve noises are about 15 dB below the amplitude of the 'whirring'.
B	1	Sound emulates the exhaust note (the fundamental of the combustion noise) of an engine. The sound does not contain appreciable components above 250 Hz.
C	Activated	'Wavy, turbo-like' sound when driven forward. Most of the energy in the sound is broadband noise in the 200 Hz to 5 kHz band, but there is a distinct whistle sound that is few dB louder than the peak of the broadband noise. The pitch of the whistling noise varies from about 2.3 kHz at minimum speed to about 3.1 kHz at the maximum speed before the sound is deactivated. There is no sound emission at idle when the vehicle is in 'Drive' and stationary, but as soon as the vehicle begins to move there was a rapid ramp up in pitch and volume, with volume subsiding slightly after a second or two. The pitch of the turbo sound varied over a wide range as vehicle speed varies over the 1 to 20 mph range. When the vehicle is shifted into 'Reverse', it emits a sound that is several dB louder than sound emitted in 'Drive', whether or not the vehicle is moving.
D	Activated	Broad band designed to suggest that of an electric motor coupled to other rotating machinery, such as a blower. The initial amplitude of the sound when the vehicle is first shifted into gear (either forward or reverse) is 4 or 5 dBA higher than its normal running value. A real-time spectrum analyzer shows that individual peaks appear to move upward by several hundred Hertz as vehicle speed increases from 0 to the cutoff speed.
E	1	A pure engine-like sound with most energy below 300 Hz, but prominent second, third, and fourth harmonics. The peak energy lies below 60 Hz at idle, but increases to about 150 Hz at 10 mph, approximating the characteristics of an ICE.
E	3	A mostly engine-like sound, but with a 'whirring' character and a flatter spectral distribution than Sound E1. No prominent harmonics of the combustion note.
E	4	This sound contains short bursts of predominantly high-frequency sound with a repetition rate of 14 per second at 6 mph, combined with an engine-or pump-like sound. The sixth harmonic of the fundamental was particularly prominent, having amplitude almost equal to the fundamental. The peak amplitude of the fundamental varies in frequency from about 450 Hz to 700 Hz over the 0 to 10 mph range. On acceleration from stopped position, the initial amplitude of the sound is about 9 dB higher than its normal value. Ramp down to normal volume takes about 3 seconds.

7.4.1 Countermeasure Sound Pressure Levels and Calibration

The prototype sound systems tested were not designed to play their sounds at user specified levels. Although they included volume controls, these controls were not calibrated to sound pressure level values. Different sounds from the same system usually had different sound pressure level values, even if the volume control settings were the same for the different sounds. The outputs of Systems “A”, “B”, and “E” were recorded during 6 mph forward driving for all the sounds used in the experiment to facilitate presentation of different sounds to participants at the same sound pressure levels.

The sound pressure levels of the recorded ‘.wav files’ were normalized to 63.5 dB (A) (the higher level used in the human-subject study). Additional versions of each recording were normalized to 59.5 dB(A) (the lower level used in the human-subject study) and to 70 dB(A) (the level used for playback level calibration). Prior to each experimental session, the volume controls of the amplifiers that reproduced these sounds were adjusted so that the 70 dB(A) version produced 70 dB(A) as measured by the SAE J-2889 test procedure. The speaker systems for these countermeasure sounds were either installed inside the front grill or mounted on the hood, just above the front grill.

Two of the systems (“C” and “D”) were fully integrated into vehicles and had no accessible electrical connection from which a direct recording could be made. For system “C”, the provided volume control was manually adjusted to the target values of 59.5 and 63.5 dB(A) used in the experiments. For system “D”, the maximum level was used, which could only achieve the lower level desired for the human-subject testing.

7.5 Study Design

Human-subject testing includes data for three independent sessions. In the first session we tested as many conditions as possible and assessed participants’ responses while examining the feasibility of the experimental approach and study logistics with a large number of participants. Lessons learned from the first session were implemented in the following two sessions. The first session included four (4) operating modes: idle, acceleration from stop, start-up and 6 mph forward pass-by. The following two sessions included the 6 mph forward pass-by only.

7.5.1 Dependent Variables

Performance measures considered in the evaluation include:

- Proportion of Detection: The proportion of trials of a given condition in which the participant detected the sound anytime before the vehicle passed the participant.
- Detection distance: Physical lateral space, in feet, between the vehicle and the pedestrian at the moment the participant indicates detection.
- Time-to-vehicle-arrival: Time, in seconds, from detection of a target vehicle sound to the instant the vehicle passes the pedestrian location.

7.5.2 Independent Variables

The primary independent variables examined in the evaluation include:

- Countermeasure sounds;
- Sound level of the countermeasure (Low = 59.5 dB(A); High = 63.5 dB(A));
- Masking effect due to vehicle direction of travel (from left and from right); and
- Study session (to examine any effect due to the difference in the overall conditions at the test site from session to session).

Note: The ambient levels measured by the left microphone (binaural recording) were about 1.4 dB greater than the ambient levels measured by the right microphone, because most of the background noise was generated by air-conditioning fans on top of a building about 400 feet to the left of the subjects. The difference was greater for frequencies from 800 to 20,000 Hz, where the average difference between the two sides was about 3.1 dB. Thus, it is expected, because of the occlusion caused by the subject’s head, that the effective ambient will be greater for subjects when they attempt to detect vehicles approaching from the left.

Other variables that were considered (and controlled for) in the evaluation include:

- Countermeasure projection systems;
- Hearing ability of participants;
- Masking effect due to variable extraneous noise in the ambient (loud trucks, machinery, rustling tree leaves, etc.);
- Vision effect: performance blind versus sighted participants; and
- Participant location in the lineup.

7.5.3 Presentation of Trials

Each participant was presented with the same experimental conditions (within-subject design). Three independent sessions were conducted on July 31, August 7, and August 14. Trials were presented in four blocks. Each block contained 24 trials (except for session 1 which included 29trials per block). There were four (4) trials without a vehicle or countermeasure sound per block. Participants experienced a total of four (4) repetitions of each experimental condition. Half of the 6 mph forward pass-by trials were presented from the left side and half from the right side. Varying the direction in which the stimuli (i.e., vehicle approaching at constant speed) is presented reduces subjects predisposed to focus on one direction (e.g., left or right) more than the other thus providing a more realistic listening situation. The presentation order was randomized within a block.

Each session began with a practice session containing examples of the trials included in the evaluation. The practice session allowed participants to experience the range of sounds before the testing began, familiarize themselves with the task and use of the response button, and ask questions to the investigator. The investigator described the instructions and traveling situation before each experimental block. The experimenter described the task (in Sessions 2 and 3) as follows:

"Please imagine you are standing on the curb waiting to cross a street where there may be vehicles approaching from both your right and left. You will hear distant vehicles in the background in all trials. If and when you detect and recognize a vehicle that would affect your decision about when to start crossing the street, press and release your push button firmly."

The investigator provided general feedback during the practice trials about whether or not there was a target sound present that they may or may not associate with a vehicle. Feedback was not offered during the experimental trials.

7.6 Study Procedure

7.6.1 Research Staff Training

The investigators completed or renewed the National Institute of Health (NIH) Protecting Human Research Participants training. The research staff received training on how to give sighted guide to a person who is blind or visually impaired. The training was provided by a certified orientation and mobility instructor from the Carroll Center for the Blind. The training focused on four (4) techniques: positioning the guidee and the guide; guiding on level surfaces; guiding on stairs; and guiding through doorways (or other narrow spaces). We cannot assume that those individuals who are blind want sighted guide, however, by providing the training described above, the research staff was better prepared when such assistance was requested.

7.6.2 Recruitment of Study Participants

The target sample included sighted and blind adults who are independent travelers. Individuals must meet the criteria listed below in order to be eligible to participate in the study:

- 18 years or older at the time of the study;
- independent traveler (i.e., cross streets without assistance from another person);
- travel regularly (i.e., cross streets at least 10 times per week, on a regular week);
- blind participants: legally blind regardless of whether they are totally blind, blind with light perception or blind with partial vision;
- sighted participants must be able to guide a blind participant to their seats if needed;
- self report to have normal hearing on both ears without hearing aids;
- willing to be screened for hearing threshold shift;
- willing to wear blindfolds; and
- must have normal manual dexterity in both hands (for prompt button pressing).

Volpe Center personnel sent a recruiting email to representatives of various organizations that provide services to the blind community such as Carroll Center for the Blind, Perkins School for the Blind, Bay State Council of the Blind, and Massachusetts Commission for the Blind. These organizations then shared the information with their members. Sighted spouses, friends, etc. of blind individuals were also encouraged to serve as participants. Individuals were also recruited by word of mouth. Volpe Center employees, blind and sighted, were also recruited and contacted via email following procedure to send messages to the Volpe Center community.

Individuals interested in the study contacted the Volpe Center recruiting coordinator and completed an eligibility questionnaire. Potential participants were given a description of the experimental set up, the task to be performed, duration of the test, and the test protocol.

7.6.3 Informed Consent Form

All participants were briefed by a Volpe Center investigator following the New England IRB protocol for the protection of human subjects. Informed consent forms (ICF) were sent to eligible participants before the day of the study. On the day of the study, participants met with an investigator to review the ICF, discuss any questions, and obtain signatures. Volpe Center employees who participated in the study completed the consent process before the day of the study.

Training on how to give sighted guide to a person who is blind was available to sighted participants in two forms: A certified orientation and mobility specialist provided a live presentation and demonstration to Volpe Center employees who volunteered to participate in the study. A handout was provided to those volunteers that were unable to attend the presentation. The handout titled ‘How to Give Sighted Guide to a Person Who is Blind or Visually Impaired’ was prepared (and made available to the Volpe Center) by a certified orientation and mobility specialist from the Carroll Center for the Blind. The handout was provided to potential participants at the same time as the consent form.

7.6.4 Hearing Screening Procedure

A Tremetrics RA300 audiometer was used to screen participants’ hearings for later use if discrepancies arose. The screening procedure was used to estimate the number of participants with estimated hearing loss (HL) of 20 or more dB above the normal range (0-20 dB HL) in the frequency range of concern. This information was used to identify outliers in the data in an attempt to reduce sources of between-subjects variability.

7.7 Characteristics of Study Sample

Eighty-three participants completed the study. Four participants were excluded from the analysis either because of indication of moderate to severe hearing loss or irregular responses. Therefore a total sample of seventy nine participants was included in the analysis: 26 in session 1; 27 in session 2; and 26 in session 3. The number of males and females by vision category is shown in Table 19. Legally blind participants included individuals who are totally blind, blind with light perception, and blind with some usable vision. All participants were required to wear a blindfold during the study. The distribution of participants by age group for each of the three study session is shown in Table 20. Participant ages ranged from 18 to 72 years old (Mean age = 43).

Table 19. Distribution of Participants by Sex and Vision Category

Vision Category	Number of Males	Number of Females	Total of all Participants
Legally Blind	25	20	45
Sighted	17	17	34
TOTAL	42	37	79

Table 20. Summary Statistics for Age by Session

Age Category	Session 1	Session 2	Session 3	Total
< 30	6	8	12	26
30-39	1	3	2	6
40-49	4	3	4	11
50-59	10	9	6	25
>59	5	3	2	10
Not reported	0	1	0	1
TOTAL	26	27	26	79

The distribution of participants by estimated HL category is shown in Table 21. Three frequency categories were identified as: low = 500 Hz; medium = 2000 Hz; and high = 4000 Hz.

Table 21. Distribution of Participants by Hearing Loss Category

Hearing Loss Category	Session 1	Session 2	Session 3	Total Number of Participants
Normal range (0-20 dB HL)	3	10	12	25
Mild HL in Low Frequency	4	1	2	7
Mild HL in Medium Frequency	0	0	1	1
Mild HL in High Frequency	3	1	2	6
Mild HL in Low & High Frequency	0	1	0	1
Mild HL in Medium & High Frequency	2	1	1	4
Moderate HL in High Frequency	0	1	0	1
No audiogram	14	12	8	34
Total Number of Participants	26	27	26	79

7.8 Experimental Methods

7.8.1 Apparatus

7.8.1.1 Sound Sources

Three of the vendors of countermeasures were represented by HEVs fitted with a loudspeaker temporarily mounted on the hood (as shown in Figure 47). These vehicles were also equipped with notebook computers to play .wav files of various countermeasure sounds at predetermined levels and power amplifiers to drive the loudspeakers from the notebook computers. The other two vendors supplied vehicles with completely integrated countermeasure sound generators.

For the tests of detectability of idling, start-up and acceleration from stop sounds (performed only during the first experimental session), a line of six tripod-mounted loudspeakers was positioned 25 feet in front of the line of participants (illustrated in Figure 48). This arrangement allowed the sounds to be presented to all of the participants with less than 1 dB of variation among participants.

Figure 47. HEV Fitted With a Loudspeaker Temporarily Mounted on the Hood

Figure 48. A Line of six Tripod-Mounted Loudspeakers was Positioned 25 Feet in Front of the Line of Participants to Present the Idle, Start-Up and Acceleration-From-Stop Sounds

The order and timing of presentation of the various sounds was controlled by a counterbalanced schedule developed in advance by the experimenters. Appendix A-3 shows an example of the schedule for one session. The start of each trial was announced to participants over a public address system and simultaneously relayed to the drivers and computer operators in each of the test vehicles via walkie-talkies.

7.8.1.2 Recording of Subject Responses

A data acquisition system was constructed by Volpe Center staff to capture various aspects of the independent variables and record the occurrence of each subject response to each event. The input devices consisted of a pair of photo-electric sensors, positioned at measured locations at each end of the line of participants to determine the precise moment that each test vehicle passed, and push buttons for each subject, used to indicate when that subject detected a nearby vehicle.

The input devices were connected to a digital input card in a desktop computer running LabVIEW software (more information about LabVIEW available at http://www.ni.com/labview/whatis/). If a subject responded by pressing his/her button, the data acquisition system recorded the exact moment (plus/minus one millisecond) in relation to the time the trial started and the times that the vehicle passed through the beams of each photo-detector.

The LabVIEW software was programmed to generate a spreadsheet for each block of trials containing the following data items for each subject response:

- Trial number;

- Direction of vehicle passage;
- Time/date;
- Vehicle speed between the photo detectors;
- Number of milliseconds after the trial started until each subject responded;
- Calculated distance to the target vehicle (feet) at the moment each subject responded;
- Calculated time (milliseconds) between the moment each subject responded and the vehicle arrived at the subject's position; and
- For the sounds (idle, start-up, and accelerating from stop) played through the tripod-mounted loudspeakers, only the time that the sound began, and the times that each subject responded were recorded.

The calculated values are based on the assumption that the vehicle's speed is the same at all points as its average speed while traveling between detectors.

For the trials involving sounds for idle, start-up, and accelerating from stop, the LabVIEW data simply showed whether or not each subject responded and how many milliseconds after the trials started.

Subject responses by show of raised hands were also recorded in high-definition video during all practice trials and during Block 4 of Sessions 2 and 3. In Session 1, the data-acquisition system malfunctioned, and the video recordings provided the only data collected. Using the speed data from each trial, detection distances for each subject response could be estimated from the videos by noting the time the vehicle passed the "A" detector, the time that each subject responded, and the previously measured distance from the "A" detector to each subject. Although not as precise as the pushbutton system, this method yields estimates of detection distances that are closely correlated with those of the push-button method. However, it was not possible to judge the precise location of the test vehicle in many instances, and the camera's view of the more distant participants was often blocked by the test vehicle. The data that was extracted from the video recordings tended to indicate somewhat higher detection distances for the same sounds as the LabVIEW data collected in Sessions 2 and 3. In the left photo in Figure 49, many participants have detected a vehicle approaching from the left before it comes within the camera's view. A relatively ineffective sound emitted by the vehicle in the right photo was not detected by some participants even when it was immediately adjacent. However, there is too much uncertainty about this data to justify its presentation in this report.

Figure 49. Recording Participant Responses by Video

For the stationary-sound trials conducted during Session 1, the video recordings provided usable data, because there was no vehicle to block the camera's view, and the instant that the test sound was initiated could be determined from the audio track.

7.8.1.3 Monitoring of Experimental Conditions

The near real-world conditions of these experiments expose the participants to many more possible unintended stimuli than a normal laboratory experiment. Aircraft, distant noisy road vehicles, lawn mowers, and leaf blowers introduced sounds that could be confused with approaching ICE vehicles on numerous occasions. Other trials were disrupted by a malfunction in the steam-pressure- relief system on an adjacent building. Furthermore, because the presentation of stimuli was not controlled directly by computer, but rather depended on human actuation in response to a radioed instruction, there was a possibility for human error. To monitor all of these possibilities to determine which trials were invalid, four systems were used:

- High-definition video recordings of subject behavior and vehicle passage including a "shotgun" microphone recording of sounds from the area in the immediate vicinity of the participants;
- Recordings from a binaural head placed just behind the participants to approximate what the participants heard;
- Continuous recording of the noise level near the participants with the same acoustic measurement system used to characterize the vehicles; and
- A-weighted, fast-response, SPL values at 100 msec intervals during each trial.

Sessions 2 and 3 were planned to generate 96 trials each in total (4 blocks of 24 trials each). During the course of each block, it was immediately obvious that certain trials were spoiled by extraneous noises, such as, aircraft or malfunctioning steam valves. These trials were redone at the end of each block when time allowed. During data analysis, a few additional trials were discovered to have been invalidated by more subtle extraneous noises (e.g., intermittent, distant traffic on nearby street). The final data set contained 79 valid trials in Session 2 and 95 valid trials in Session 3. No response and detection after the vehicle passed the pedestrian location are considered missed detection.

7.9 Analysis of Countermeasure Evaluation

7.9.1 Detection Distance and Proportion of Detections

Trials with no detection or detection after a vehicle passed the participant are considered missed detections instead of missing data. This is done by assigning 0 feet to all cases where a sound was not detected. This procedure allows analyses of detection distance to include more participants for greater statistical power. In contrast, if no-detection trials were treated as missing data, the list-wise deletion of data required for repeated measures analysis would delete any participant who does not have valid detection distances for all two or four trials of a given sound-amplitude-direction condition. This initial analysis is described below.

First, we considered two potential dependent variables for the 6 mph pass-by scenario:

- Raw Detection Distance, being the number of feet the vehicle was from the participant when the participant indicated she or he heard the sound. A failure to detect the sound before the vehicle passes is treated as missing data.
- Proportion of Detection, being the proportion of trials of a given condition in which the participant detected the sound anytime before the vehicle passed the participant.

The analyses indicated relationships between raw detection distances and proportion of detection. Across all conditions, participants who detected relatively more sounds also tended to detect the sounds at greater distances than participant who detected relatively fewer sounds ($r = 0.326$, $n = 53$, $p = 0.0168$). Furthermore, high amplitude sounds were detected more often and at greater distances than low amplitude sounds (for raw detection distance, *M*s = 55 and 44 feet, $t(52) = 11.45$, $p < 0.0001$; for proportion of detections, *M*s = 0.95 and 0.92, $t(52) = 3.51$, $p = 0.0009$).These positive relations between raw detection distance and proportion of detection suggest they represent the same underlying construct. Thus, they are combined into a single "detectability" variable by assigning 0 feet to all cases where a sound was not detected.

Repeated trials for a given sound, amplitude and direction were averaged to create a single value per condition per participant for subsequent analyses.

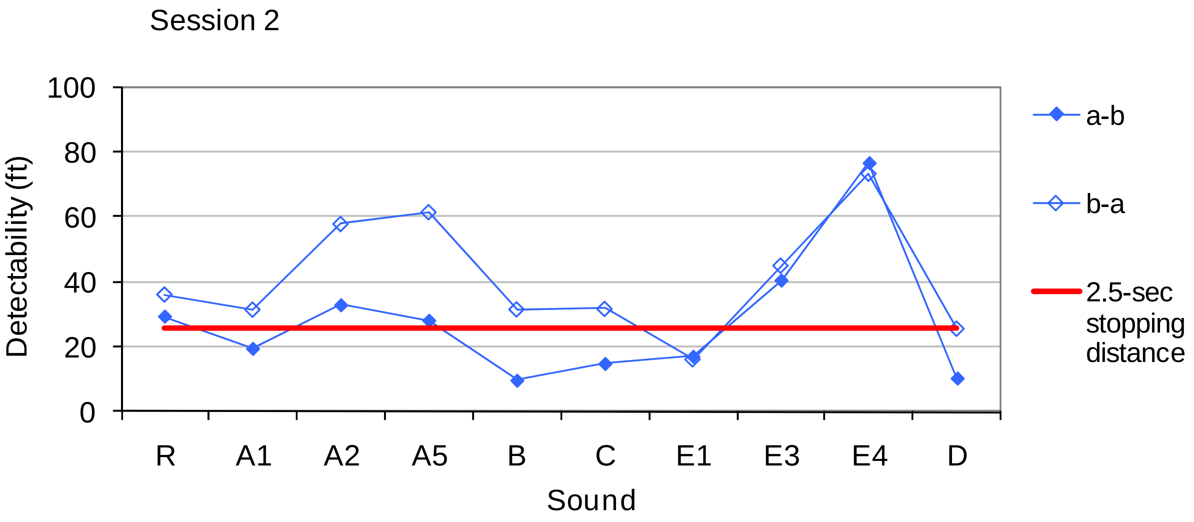
7.9.2 Detectability Relative to Reference Vehicle

To compare the countermeasure sounds to the detectability of the reference sound from an ICE-powered vehicle ('R'), a mixed design, analysis of variance (ANOVA) was performed on detectability with session and vision as between-subjects independent variables, and sound and direction as within-subject independent variables. Session refers to the date of the study; vision refers to whether the participant is blind or sighted; sound refers to countermeasure or ICE vehicle sound; and direction refers to vehicle direction of travel ('a' to 'b' = left to right; 'b' to 'a' = right to left).

The analysis only included low-amplitude sounds since their amplitude, 59.5 dB(A), correspond closely to the sound pressure level measured for the reference ICE vehicle , 60.0 dB(A). Using only low-amplitude sounds also allowed the inclusion of sound 'D', which produced only a low-amplitude sound (in addition to no artificial sound).

The analysis indicated significant main effects of sound ($F(4.3, 185.8) = 75.5$, $p < 0.001$, Greenhouse-Geisser corrected for sphericity), but, more importantly, a significant three-way interaction of session, sound, and direction ($F(5.6, 241.3) = 4.3$, $p = 0.001$, Greenhouse-Geisser corrected for sphericity). This interaction is depicted in Figure 50; a reference line is added to indicate the distance (25.5 ft) required to stop a vehicle traveling at 6 mph to stop, assuming drivers' reaction time of 2.5 seconds (see Section 2.2 for more information of stopping distance). This implies that the relative performance of each sound, including the reference sound, is jointly contingent on the direction it comes from and the session it was presented in. The directional effect results primarily from the fact that the roof-top fans on buildings to the west were the predominant source of ambient noise, which more effectively masks vehicles approaching from the west (the "a-to-b" direction), compared with the reverse. However the directional effect is more pronounced where spectral peaks in the ambient noise (shown in Figure 21) happen to coincide with the peaks of a particular countermeasure sound. Furthermore, there were slight differences in the spectrum of the ambient sound caused by rustling in the leaves of the nearby trees in different wind conditions. Thus, each direction-by-session condition may be regarded as constituting an independent test of the performance of each countermeasure sound relative to the reference sound. The frequency of Type I errors should thus follow a binomial distribution.

Based on this, the detectability of each countermeasure sound relative to the reference was evaluated by *t*-tests comparing each sound to the reference vehicle for the corresponding session and direction condition of each. With nine countermeasure sounds to compare to the reference, a Bonferroni post-hoc adjustment for family-wise error rate yielded a critical *p*-value of 0.0056 for deciding if a particular artificial sound is overall significantly different than the reference. Treating the four session-by-direction test conditions as independent samples of ambient sound, this critical *p*-value is achieved if at least two conditions show a significant difference at the 0.0311 level, according to binomial calculations. If this is observed then one can conclude that the sound has significantly different detectability than the reference sound. Table 22 shows the results of these *t*-tests (*Significant sums at Bonferroni adjusted 0.0056 rate per sound; ns = not significant).



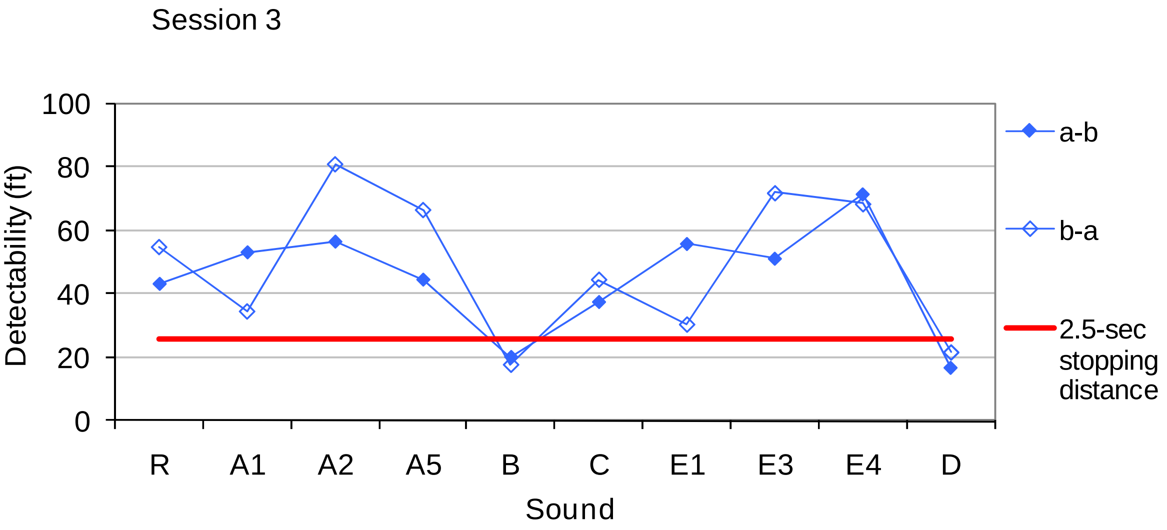


Figure 50. Mean Detectability at low Amplitude for all Sounds by Session and Direction. The Horizontal Line Indicates the Stopping Distance (25.5 Ft) for a Vehicle Traveling at 6 mph, Assuming a 2.5-sec Drivers Reaction Time

As can be seen in Table 22, sounds A2, A5, E3, and E4 have significantly better detectability than the reference sound in at least two of the four conditions. These sounds never have significantly worse detectability in any condition. Thus, these sounds overall have better detectability than the reference sound. In contrast, sounds A1, B, C, D, and E1 all have significantly worse detectability than the reference sound in at least two of the four conditions. These sounds never have significantly better detectability in any condition. Thus, these sounds overall have worse detectability than the reference sound.

Table 22. Comparison of Countermeasure Sounds to Reference Sound Across Conditions at *p* = 0.0311 Level.

Session	Direction	A1	A2	A5	B	C	E1	E3	E4	D
2	a-b	Worse	ns	ns	Worse	Worse	Worse	Better	Better	Worse
2	b-a	ns	Better	Better	ns	ns	Worse	ns	Better	Worse
3	a-b	ns	Better	ns	Worse	Worse	Better	ns	Better	Worse
3	b-a	Worse	Better	Better	Worse	ns	Worse	Better	Ns	Worse
Total Better		0	3*	2*	0	0	1	2*	3*	0
Total Worse		2*	0	0	3*	2*	3*	0	0	4*

(* indicates significant sums at Bonferroni adjusted 0.0056 rate per sound; ns indicates not significant).

7.9.3 Ranking of Countermeasure Sounds

To compare the detectability of the countermeasure sounds to each other, a mixed design ANOVA was performed on detectability with session and vision as between-subjects independent variables, and sound, direction, and amplitude as within-subject independent variables. The reference sound 'R' and sound 'D' were excluded from this analysis since they did not differ in amplitude. In any case, sound 'D' was significantly worse than the reference sound, so it is of minor interest for subsequent analyses.

The analysis indicated significant main effects of sound ($F(3.6, 132.0) = 78.3$, $p < 0.001$, Greenhouse-Geisser corrected for sphericity), but, more importantly, a significant four-way interaction of session, sound, direction, and amplitude ($F(5.2, 192.8) = 4.5$, $p = 0.001$, Greenhouse-Geisser corrected for sphericity). This interaction is depicted in Figure 51 and Figure 52, where 'Lo' refers to the low amplitude tested (59.5 dB(A)) and 'Hi' refers to the high amplitude tested (63.5 dB(A).

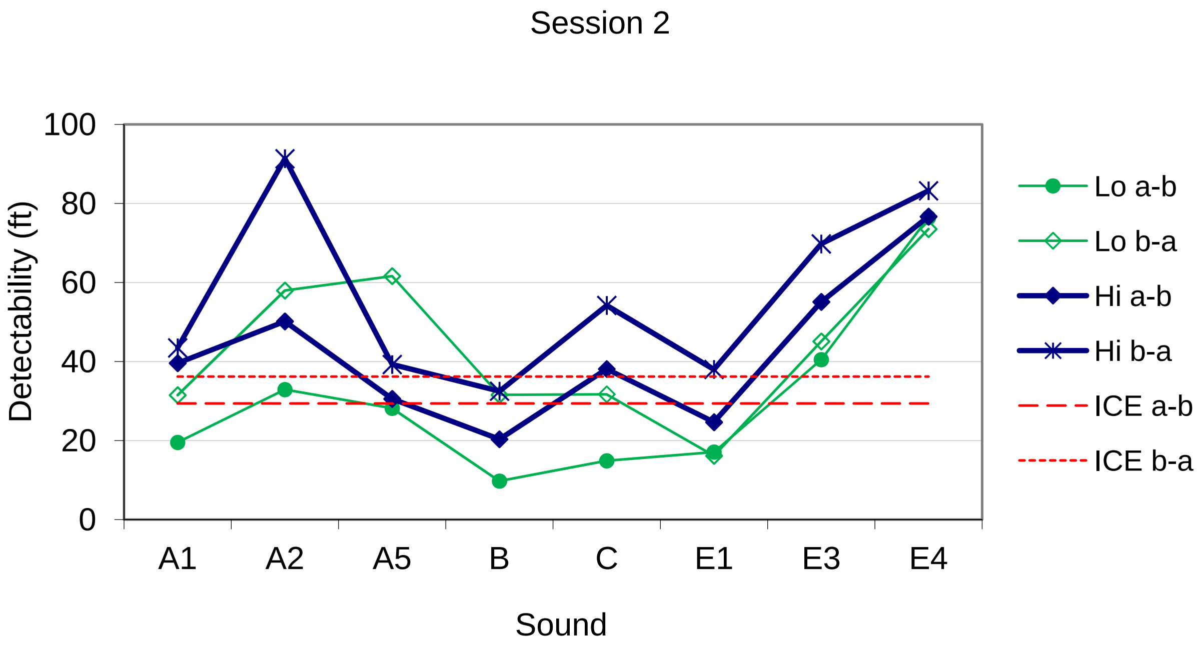


Figure 51. Mean Detectability of Artificial Sounds by Session, Direction, and Amplitude (Session 2)

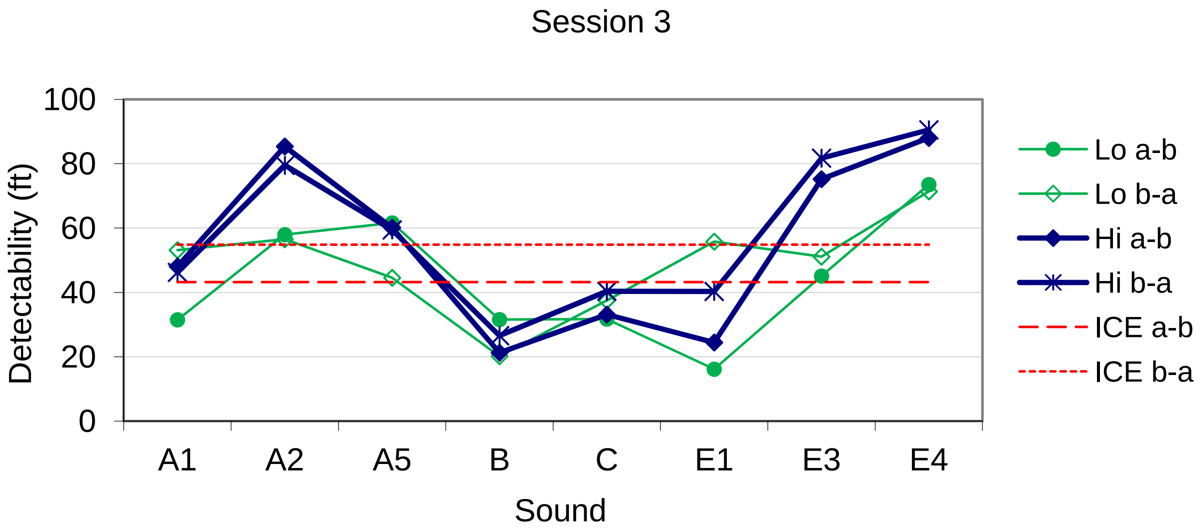


Figure 52. Mean Detectability of Artificial Sounds by Session, Direction, and Amplitude (Session 3)

This implies that the relative performance of each artificial sound is jointly contingent on the direction it comes from, the session it was presented in, and the amplitude that was used. Similar to when comparing only the low amplitude sounds, this is likely due to differences in the spectrum of the ambient sound among the directions and sessions interacting with the different amplitudes. Likewise, each condition may be regarded as an independent test of the performance of each artificial sound.

With this in mind, sounds are ranked by comparing each to the other with *t*-tests for each session-by-direction-by-amplitude condition. To assist in the control for family-wise error rate, the analyses only included the four sounds shown in the previous section to be superior to the reference sound. With four sounds to compare to each other, a Bonferroni post-hoc adjustment for family-wise error rate yielded a critical *p*-value of 0.00833 for deciding if a particular sound is overall significantly different than another sound. Treating the eight session-by-direction-by-amplitude test conditions as independent samples, this critical *p*-value is achieved if at least two conditions show a significant difference at the 0.0178 level, according to binomial calculations. If this is observed then one can conclude that the sound has significantly different detectability than the reference sound. Table 23 and Table 24 show the results of these *t*-tests; * significant sums at Bonferroni adjusted 0.0083 rate per comparison.

Table 23. Comparison of Artificial Sounds to Each Other Across Conditions at $p = 0.0178$ Level.

			A2 Versus			A5 Versus		
Amplitude	Session	Direction	A5	E3	E4	A2	E3	E4
Lo	2	a-b	ns	ns	*Worse*	ns	*Worse*	*Worse*
Lo	2	b-a	ns	ns	ns	ns	**Better**	ns
Lo	3	a-b	**Better**	ns	*Worse*	*Worse*	ns	*Worse*
Lo	3	b-a	ns	ns	**Better**	ns	ns	ns
Hi	2	a-b	**Better**	ns	*Worse*	*Worse*	*Worse*	*Worse*
Hi	2	b-a	**Better**	**Better**	ns	*Worse*	*Worse*	*Worse*
Hi	3	a-b	**Better**	ns	ns	*Worse*	*Worse*	*Worse*
Hi	3	b-a	**Better**	ns	ns	*Worse*	*Worse*	*Worse*
Total Better			5*	1	1	0	1	0
Total Worse			0	0	3*	5*	5*	6*

Table 24. Comparison of Artificial Sounds to Each Other Across Conditions at $p = 0.0178$ Level (Continuation).

Amplitude	Session	Direction	E3 Versus			E4 Versus		
			A2	A5	E4	A2	A5	E3
Lo	2	a-b	ns	**Better**	*Worse*	**Better**	**Better**	**Better**
Lo	2	b-a	ns	*Worse*	*Worse*	ns	ns	**Better**
Lo	3	a-b	ns	ns	*Worse*	**Better**	**Better**	**Better**
Lo	3	b-a	ns	ns	ns	*Worse*	ns	ns
Hi	2	a-b	ns	**Better**	*Worse*	**Better**	**Better**	**Better**
Hi	2	b-a	*Worse*	**Better**	ns	ns	**Better**	ns
Hi	3	a-b	ns	**Better**	*Worse*	ns	**Better**	**Better**
Hi	3	b-a	ns	**Better**	ns	ns	**Better**	ns
Total Better			0	5*	0	3*	6*	5*
Total Worse			1	1	5*	1	0	0

As can be seen in Table 23, sounds E4 has overall significantly better detectability than the other sounds, and within each condition it is never worse than any other sound, except for one condition when compared to A2. Sounds A2 and E3 are overall not significantly different than each other, showing only a difference in a single condition. Sound A5 has overall significantly worse detectability than the other sounds, and within each condition is it never better, except for one condition when compared to E3. The overall ranking of the sounds from most to least detectable is therefore:

- E4
- A2 and E3
- A5

7.10 Vision Effects

None of the analyses reported above found a significant effect of vision ability. Blind participants, on average, were no better or worse than sighted participants in detecting the approach sounds (smallest $p = 0.636$).

7.11 Idle, Acceleration, and Start-up Sounds

Discussions with blind individuals during Phase 1 of this research program led to the identification of three types of sounds emitted by motor vehicles that often prove useful for orientation and for warning of potentially threatening vehicle movements:

- Start-up sounds;
- Idling sounds; and
- Acceleration-from-stationary-position sounds.

Extensive, full-factorial, human-subject testing of such sounds from all of the vendors of countermeasure systems was contemplated for Phase 2 of this research program. However, none of the five vendors provided a system that generates a start-up sound. The two systems that were tested as pre-production prototypes fully integrated with a vehicle both mute the sound when a vehicle is idling in park, neutral, or drive, but one of them emits sound while idling in reverse. The demo hardware from the other vendors might or might not emit sound while the vehicle is stationary, depending on how it is programmed. All five systems emit sound during acceleration from 0 to 10 mph, with three of the five emitting at higher amplitude during the first few seconds of such acceleration.

During the first experimental session, it became clear that it would not be possible to conduct enough trials for both pass-by and stationary sounds within the two-hour fatigue limit for such testing. Furthermore, the generally louder startup and acceleration noises seemed to bias subject expectations in a way that detracted from prompt detection of vehicles in the pass-by trials. Hence, only a dozen trials of stationary sounds were conducted – all in the first experimental session.

In actual ICE vehicles, startup sounds and acceleration from a stationary position are relatively noisy, with mean $L_{Aeq\ .1/2\ sec}$ values of 70.7 and 66.7 dB (A) respectively (see Table 7 in Section

5.1.3) There is no doubt that such sounds would be immediately detected; rather, the experiment was designed to explore how much below the normal level of startup and acceleration sounds would synthetic sounds provide effective alerts to pedestrians at a distance of 25 feet. On the other hand, idle sounds in current ICEs are often difficult to perceive in urban ambients, since their mean $L_{Aeq\ .1/2\ sec}$ values are only 55.7 dB(A). Thus the experiment was designed to provide an indication as to how much above average ICE values idle sounds need to be to be detected at 25 feet. Note: The six speakers used to generate the sounds for idle, start-up and initial acceleration were positioned along a line parallel with the row of subjects, but separated from it by 25 feet in order to provide a safe clearance for the vehicles to pass through. The 25-foot separation also helped to make the SPL values at the subjects' ears relatively uniform, i.e., within 1 dB. The significant independent variable in these trials was the sound pressure level as measured at the subjects' location, not the distance to the source.

Although only a limited set of data from Session 1 (n=27) is available, the conclusion is that virtually everyone (more than 95%) can detect start-up sounds, even when they are presented at levels almost 10 dB lower than average actual ICEs, because even at those levels, they are approximately equal to or greater than the ambient noise. Conversely, broadband sounds that are presented about 3 dB below the ambient level may be missed by a large percentage of participants, and those 5 dB below ambient will be missed by almost everyone.

Table 25. Missed Detections for Various Start-up, Idle, and Acceleration Sounds

Maneuver	Sound	LAeq .5 Value	Missed Detections out of 27 participants Block A	Missed Detections out of 27 participants Block B
Start-up	actual ICE	58	0	N/A
Start-up	actual ICE	62	2	1
Idling	A1	59	1	1
Idling	A1	63	1	1
0 to 10 mph	A5	54	25	N/A
0 to 10 mph	E3	57	N/A	12, 8
0 to 10 mph	A5	58	1	N/A
0 to 10 mph	E3	60	N/A	5

7.12 Summary: Countermeasure Evaluation

- The ranking of the countermeasure sounds by peak Specific Loudness is not well correlated with the average detection distances measured in the human-subject testing.
- The relative performance of each sound, including the reference ICE sound, was jointly contingent on the direction it came from and the session it was presented in.
- Synthetic sounds that resemble those of an ICE produce similar detection distances as actual ICE vehicles.

- In some instances, synthetic sounds designed according to psychoacoustic principles can produce double the detection distances at slightly lower overall noise levels.
- Synthetic sounds that contain only the fundamental combustion noise are relatively ineffective.

8. DISCUSSION: POTENTIAL SPECIFICATIONS FOR VEHICLE SOUNDS

For the reasons given in the Phase 1 report on this research [DOT HS 811 304], the Phase 2 work focused initially on the following ideas: 1) the lack of *detectability* of quieter vehicles could be remediated if they are fitted with synthetic sound generators that emulate the sound of typical ICEs; and 2) the specifications for the vehicle sounds can be defined in terms of objective parameters – namely, overall sound output as measured by the SAE J2889-1 procedure and spectral distribution specifications for the minimum amount of sound level in one-third-octave bands. However, *recognizability* is more complex. Most sounds, and sounds as complex as those emitted by an ICE, have numerous properties in addition to loudness and spectral distribution that affect human perception. Among these properties are rise time, decay time, repetition rates, variations in pitch and loudness, and phase relations among various components of the sound. It can be demonstrated, for example, that changes in these properties can render a sound unrecognizable even though loudness and spectral distribution are unchanged by playing a recording of the sound backwards. There are no established quantitative metrics for many qualities of a sound that a person might use for recognition.

Some of the prototype sounds that were tested in this research were synthesized to resemble ICE sounds, while others were not. Some sounds were comprised of entirely synthetic, non-ICE sounds generated by a digital-signal-processor (DSP), and demonstrated that, in some instances, it is possible to achieve significantly better detection distances, at the same sound level (as measured by the SAE 2889-1 draft procedure), compared with ICE-like sounds. Sample sounds constructed according to established principles for auditory warnings were recognized on first hearing in the human-subject tests when they were played at a level approximately equal to or higher than the ambient noise level. These sounds lack the low-frequency, fundamental combustion noise of an ICE, which allows them to be played through small, well-sealed speakers similar to those used in back-up warning devices. However, an objective specification for non-ICE-like sounds is more difficult to develop than one for synthetic sound generators that emulate the sound of typical ICEs. This former approach could result in a wider variety of sounds, some of which might be not recognized as a vehicle or which might be perceived as annoying. Most of the sounds offered for testing by manufacturers were chosen through a jurying process.

In this section we discuss four potential options for defining specification for countermeasure sounds to alert pedestrians to the approach or proximity of vehicles operating in electric only mode while operating in the specified conditions. Note that these options have been derived with the intent of not increasing overall community noise by using the same or slightly lower level as that of current ICE vehicles.

The four options to define specifications for vehicle sounds are:

- Recording(s) of Actual ICE Sounds (Option A).
    1. Defined by overall A-weighted levels.
    2. Defined by one-third octave band average spectra.

    3. Defined by one-third octave band minima spectra.
    4. Combinations of the above.
- Synthesized ICE-Equivalent Sounds (Option B).
    1. Defined by overall A-weighted levels.
    2. Defined by one-third octave band average spectra.
    3. Defined by one-third octave band minima spectra.
    4. Combinations of the above.
- Alternative, non ICE-like Sounds Designed for Detectability (Option C).
- Hybrid of options listed above (Option D).

8.1 Scope

Previous research by NHTSA (Phase 1) shows that the overall sound levels for the HEVs tested are noticeably lower at low speeds than for the ICE vehicles tested. Considering the results of acoustic measurements and human subject data, countermeasures are only needed when vehicles are operated at speeds generally less than 10 to 20 mph where tire noise is not dominant. At the present time, synthetic vehicle sounds appear to be the only countermeasure that is useful in providing relevant sound cues needed by pedestrians. Relevant sound cues provide information about vehicle presence, speed, and rate of change in speed. Groups representing people who are blind have expressed a preference for sound(s) that will be recognized as that of an approaching vehicle so that it will be intuitive for all pedestrians.

Therefore, the elements of a specification for vehicle sounds should address the following issues:

- Sound output levels;
- Pitch changes that convey changes in vehicle speed; and
- Acoustic qualities that determine whether the sound is perceived as a vehicle.

The options discussed in this chapter (options A-D) assume that the vehicle acoustic countermeasure should:

- Alert pedestrians, including blind pedestrians, to vehicle presence and operation below 20 mph;
- Provide information at least equivalent to that provided by ICE vehicles, including speed change;
- Apply to vehicles operating in electric only mode while operating in the specified conditions; and
- Provide for detection of a vehicle in residential, commercial and other suburban and urban environments. Note: Human-subject tests cited in this chapter were conducted in an ambient level of approximately 58-61 dB(A).

Acoustic data acquired from a sample of ICE vehicles were used to determine the sound levels at which ICE-like synthetic vehicle sounds, developed as countermeasures, would be set. Measurements include overall sound levels and spectral content (i.e., one-third octave-band data).

Specifications discussed here also include input from psychoacoustic model(s) and human-subject testing. Psychoacoustic model(s) and human-subject testing were used to explore issues of detectability, masking, and recognition of alternative, non-ICE-like sound countermeasures.

Acoustic measurements were collected for the following vehicle operating modes:

- Low-speed pass-by forward at 6, 10, 15 and 20 mph;
- Low-speed pass-by reverse at 6 mph;
- Acceleration (from 0 to 10 mph);
- Idle; and
- Start-up.

One of the operating modes, deceleration from 20 to 10 mph (as if to turn right), tested in Phase 1 of the Quieter Cars and the Safety of Blind Pedestrian research program, could not be included in the Phase 2. Deceleration from 20 to 10 mph (as if to turn right) was not included in Phase 2 because a location of sufficient length to test vehicle deceleration was not readily available. In addition, to conduct a valid test of the detectability of decelerations with real vehicles, it would be necessary to limit the number of subjects being tested to only one or two in a single experimental session, so that they would hear the same thing. Conducting numerous additional sessions, or extending session durations to approximately six hours so that deceleration could be included was inadvisable for reasons of cost, timeliness of project completion, and the health and comfort of the subjects. Deceleration is a safety scenario identified in Phase 1 of our research and the noise-emission characteristics of a vehicle decelerating from 20 to 10 mph can be approximated by using the measured values for 20- and 10- mph pass-bys and programming the DSP to interpolate between these values as the vehicle decelerates.

Overall sound level by itself does not determine how well a sound is detected; spectral content has a significant impact on detectability. If sounds “X” and “Y” are similar, broad-band sounds (e.g., engine sounds) coming from the same direction, “X” may need to have a higher SPL than “Y” in order to be detected. If “X” and “Y” are different, comparisons are more complicated. For example, if “X” is a narrow-band sound, it may be detected even if its SPL is significantly *lower* than that of “Y,” provided that narrow-band sound *is not* in a frequency range where the ambient is especially strong. (“Narrow-band” sounds are those composed of a relatively small range of frequencies – a few octaves or less. “Wide-band” sounds are those containing frequencies from all or most of the ten-octave range of human hearing.) On the other hand, if “X” is a narrow-band sound that *is* in a frequency range where the ambient is especially strong, then “X” may not be detected even if its SPL is significantly *higher* than that of “Y”. In general, if sounds have similar spectral content and temporal variations, then their detectability will be similar. If the sounds vary in spectral content, then, detectability could be very different.

Sound characteristics such as rise time, decay time, repetition rate, and variation in pitch and loudness can affect recognizability without necessarily changing spectral balance. Duplicating the spectral balance of an ICE does not guarantee that the sound will be recognized as an ICE. This is a caveat to any specification.

Pitch-shifting is perhaps the easiest to specify and test for compliance. The discussion in the following section on pitch shifting applies to all of the alternatives described in subsequent sections relating to options for specifications related to sound levels, spectral content and recognizability.

8.2 Pitch-Shifting Specifications

Prototypes supplied by OEMs for this study shift the pitch of the sounds (generated or processed by a DSP) in proportion to vehicle speed. Testing to verify that a sound has pitch shifting is relatively insensitive to test conditions. One possible method to test for pitch shifting is to record the countermeasure sound at various speeds of interest and play them back in a spectrum analyzer. If the frequencies of spectral peaks identified as contributing to pitch increase about 40 percent over the speed range from 0 to 20 mph, which is typical of an actual ICE (e.g., tachometer goes from about 800 to 1100 RPM), then there is adequate pitch shifting. (Note: Not all peaks will positively contribute to pitch strength. In general, peaks that are harmonically related increase pitch strength while those that are not harmonically related decrease pitch strength.) A sample of pitch shifting analysis is shown in the graphs of Figure 53, which show the spectrum of sound A5 with engine RPM at idle and at about 20 mph. Figure 53 shows the frequency of the highest peak in the spectrum increases from 396 Hz at 0 mph to 653 Hz at 20 mph, an increase of 53 percent, which would satisfy the proposed criterion. The smaller peaks also shift in the same proportion.

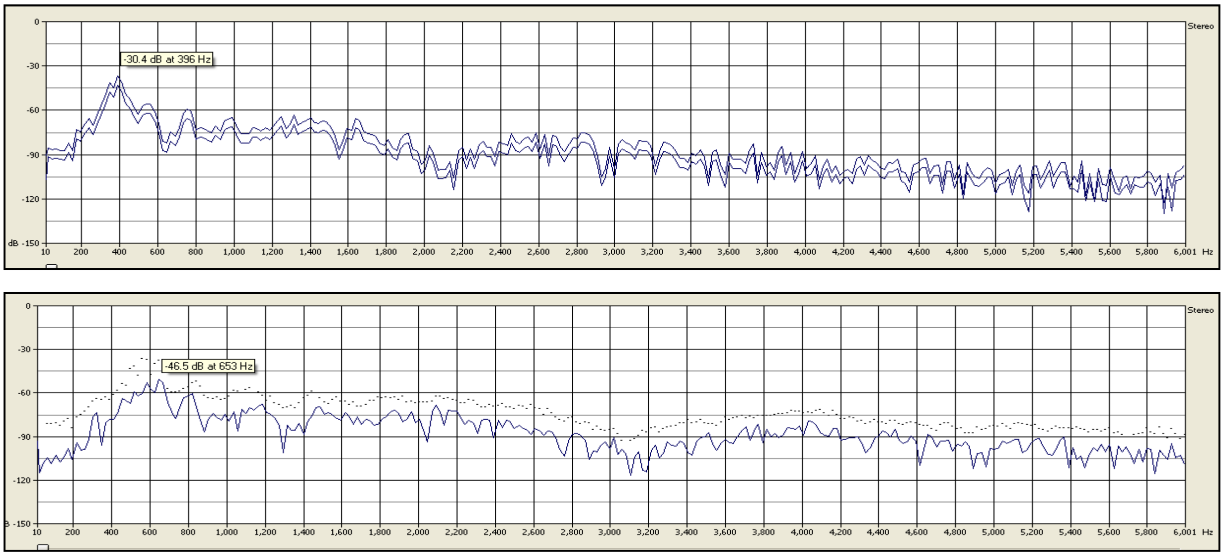


Figure 53. Spectra of Sound A5 at 0 and 20 mph

8.3 Minimum Sound Pressure Level and Spectral Content Specifications Based on ICE Vehicle Acoustic Characteristics

8.3.1 Performance Metrics

The following potential specifications for countermeasure sounds are based on the assumption that the ICE vehicles measured in this study are typical of the current fleet and emit an acceptable amount of noise during low-speed operations and that some (e.g., ICE-like) countermeasure sounds can be based on the statistical average of real-vehicle spectral characteristics. The actual ICE vehicle used in the human-subject experiments, which emitted the same noise level as the average of the 10 vehicles tested, was detected at a mean distance of 41 feet, or 4.66 seconds in a 6-mph pass-by. This amount of detection time is in close agreement with a 5-second value that has been suggested as safety guideline by some discussion groups. This means that the test vehicle traveling at 6mph was detected approximately 5 seconds before it arrived at the pedestrian's location.

These specifications represent the minimum overall A-weighted sound pressure level (Table 26), and the minimum level in each one-third octave-band (Table 27) for ICE-vehicle countermeasure sound. The derivations of these data are given in Section 5.

The A-weighted ½-second equivalent sound pressure level is defined as (IEC 61672-1, 2002):

$$L_{Aeq,\frac{1}{2}sec} = 20\, log_{10}\left\{\left[(1/T)\int_{t-T}^{t} p_A^2(\zeta)d\zeta\right]^{1/2}/p_0\right\} \qquad \textbf{dB(A)}$$

where $p_A^2(\zeta)$ is the squared, A-weighted instantaneous sound pressure.

Table 26 gives the specification for the broadband A-weighted sound pressure level for a vehicle generating a countermeasure sound.

Table 26. Minimum Overall A-weighted Level ($L_{Aeq,\ ½\ sec}$) by Vehicle Operation

Vehicle Operation	**$L_{Aeq,\ 1/2\ sec,}$ dB(A)**
6 mph	61.1
10 mph	63.6
15 mph	68.1
20 mph	70.2
Acceleration	66.7
Start-up	70.7
Idle	55.2

8.3.1.1 Sound Pressure Levels for A-weighted One-Third Octave Band Spectra

Table 27 shows the corresponding minimum A-weighted one-third-octave-band spectra for each operating mode that could apply to options A and B in the following sections. Each of these minima must be met in order to assure that the countermeasure sound emits sound at a level at least as great as the estimated typical ICE vehicle. The values in this table were derived by the procedures described in Section 5.

Table 27. A-weighted One-Third-Octave-Band Spectra at Microphone Line $L_{Aeq,1/2sec}$

1/3 Octave Band Center Frequency, Hz	6 mph	10 mph	15 mph	20 mph	Acceleration	Startup	Idle
100 to 20k	61.1	63.6	68.1	70.2	66.7	70.7	55.2
315	43.9	46.9	50.2	52.5	49.8	44.2	37.3
400	46.5	48.7	53.0	54.1	51.4	46.6	39.0
500	47.9	51.2	55.6	57.1	53.4	51.8	42.1
630	49.0	52.5	56.9	59.1	54.6	52.4	42.3
800	51.1	54.6	59.5	62.3	55.1	55.2	43.2
1k	51.4	55.2	60.2	63.2	55.6	57.8	44.9
1.25k	52.2	54.6	59.6	62.2	57.2	60.5	46.3
1.6k	52.0	54.3	58.8	61.3	57.0	61.1	45.4
2k	50.3	52.0	56.1	57.9	55.7	60.5	44.6
2.5k	49.1	50.3	53.9	54.9	55.1	61.1	43.8
3.15k	48.6	49.2	52.4	52.1	54.9	61.6	44.1
4k	46.9	47.5	50.5	49.5	53.2	60.9	42.4
5k	44.1	45.0	47.8	46.4	50.8	59.2	40.3

8.3.1.2 One-Third Octave Band Restrictions

ICE vehicles have energy components in all frequencies (e.g., 100 to 20k Hz), however, the psychoacoustic models show that energy components in the one-third octave bands ranging from 1600 Hz to 5000 Hz contributed the most to detection, and those ranging from 315 Hz to 1600 Hz contributed additional detection and pitch information. These spectral distribution limits are derived from the procedures described in Section 6, and depicted in Figure 38, in which all of the ICE sounds are masked by the ambient noise below 8 ERBs (which corresponds to 315 Hz). The implication of Figure 38 with the fact that many people have high frequency hearing loss is that frequencies from 300-5000 Hz are the ones most useful for detection. Very high frequency sounds – above 5 kHz – are not masked, but many older individuals cannot hear these frequencies well, and loudspeakers recessed behind the grill of an automobile may not radiate such sounds well. Therefore, a possible refinement to a countermeasure sound specification would be to limit the one-third octave band specification to cover the range of 315 Hz to 5000 Hz with the levels specified in other one-third octave bands (see Table 44) which could be limited to usage for guidance purposes only (based on psychoacoustic analyses/models).

8.4 Option A: Recordings of Actual ICE Sounds

The purpose of this option is to provide a method to generate countermeasure sounds that closely approximate the sound of typical motor vehicles.

8.4.1 Sound

In this approach, recordings of actual ICE sounds are used. Recordings are made when the vehicle is operating at constant speeds, forward from 0 to 20 mph and in reverse at 6 mph. Other components of the vehicles noise output (tire noise, aerodynamic noise, AC fan noise, etc.). will be emitted regardless of whether an ICE is in use and would not be included in these recordings.

8.4.2 System

Sound generation systems with signal processing capabilities would be used to continuously and monotonically vary the sounds from one operating condition to the next according to vehicle input (e.g. vehicle speed sensors, throttle sensors, etc.).

8.4.3 Test Methods

In this option, emitted sounds would be based on approved, standardized recordings (approval and standardization process to be determined) with processing limited to pitch shifting in proportion to vehicle speed and interpolation between sounds.

Option A1: Minimum overall A-weighted levels, similar to those listed in Table 26, would be met at the measurement location specified by SAE J2889-1 (or similar test method).

Option A2: Average one-third octave band levels, similar to those listed in Table 27, would be met at the measurement location specified by SAE J2889-1 (or similar test method) for one-third octave bands from 315 Hz to 5000 Hz.

Option A3: Minimum one-third octave band levels, similar to those listed in Table 27, but lower by 5 dB to allow for variation of individual vehicles, would be met at the measurement location specified by SAE J2889-1 (or similar test method) for one-third octave bands from 315 Hz to 5000 Hz.

Option A4: Combination of options A1 and A2 or options A1 and A3. Both of these level specifications (overall and one-third octave bands) are based on the total noise output of the test vehicle, i.e. sound generator plus tire and aerodynamic noises. In the higher portions of the speed range (10 to 20 mph), most of the noise emission is from tires, which would not be reproduced by the sound generator, because so doing would effectively double the noise output of the vehicle.

8.4.4 Assumptions

Option A assumes that vehicles used to create the standardized recordings have sound-emission characteristics that provide adequate recognizability for pedestrians.

Option A assumes that band-limited (315 Hz to 5000 Hz) ICE-like sounds will be recognizable as motor vehicles.

8.4.5 Observations

Observations for this approach include:

- It is driven by existing ICE-vehicle sound characteristics and levels, this approach helps with recognizability of the sound source (e.g., recognized as a vehicle).
- It reduces the possibility of having a wider variety of sounds, some of which might be not recognized as a vehicle or which might be perceived as annoying.
- More than one set of standardized recordings could be used.
- New recordings could be developed for future ICE vehicles.
- The countermeasure specification could be updated periodically, as needed, by providing a new set of standardized ICE recordings over time.
- This option precludes the use of sounds that may be more unique and effective than the basic ICE sound.
- It may provide fewer cues for blind pedestrians than other options. More cues may be advantageous since not all people respond to the same cues in the same way or use the same cues to navigate.
- It is difficult to make recordings of actual vehicles operating under actual road load without also introducing their tire noise, which should not be emitted by the sound generator, because the tires of the electric or hybrid vehicle will provide it.

8.4.6 Suggestions for Further Research

- Develop directivity specifications, and refine methods to test pitch-shifting, overall A-weighted levels, and one-third octave band levels of the engine sound alone.
- Produce and evaluate standardized recordings of actual ICE sounds operating at constant speeds, from 0 to 20 mph to validate the practicality of implementing countermeasure sounds in vehicles. Investigate the frequency response characteristics of the actual speakers that could be used for countermeasure sounds and the effect of their placement under the hood of vehicles.

8.5 Option B: Synthesized ICE-Equivalent Sounds

The purpose of this option is to provide a method to generate countermeasure sounds that closely approximate the sound of typical motor vehicles. Additional consideration has been given to make this option more flexible than Option A.

8.5.1 Sound

In this option, simulated ICE sounds would be synthesized directly by a digital-signal processor (DSP) programmed to create ICE-like sounds (based on actual target sounds) that would vary pitch and loudness depending on vehicle inputs. Target sounds are recordings of actual ICEs. This is in contrast to Option A in which the sounds come directly from recordings of actual vehicles, and the processor must store and interpolate among files representing every mode of operation and for every speed within the 0 to 20-mph range. Here, the resulting synthesized sounds would resemble those of Option A, but have fewer spectral components. A synthesizer could be simpler and cheaper than a sound generator based on real ICE sounds.

For this option,   target sounds, recorded from actual vehicles for the operations specified in Section 8.1 would be used. The synthesized sounds would then be developed to match the spectral shape of these target sounds within a tolerance of 3 dB per spectral line when comparing power spectra. (Note: by definition, power-spectra spectral lines have a resolution of 1 Hz). The tolerance here is for comparison between the synthesized sound and target sound. In Option A, no such additional tolerance is required since the sound file being played comes directly from a recorded ICE sound.

8.5.2 System

Sound generation systems with signal processing capabilities would be used to continuously and monotonically vary the sounds from one operating condition to the next according to vehicle input (e.g. vehicle speed sensors, throttle sensors, etc.) and the synthesis algorithms developed for their sounds.

8.5.3 Test Methods

Emitted synthesized sounds would be based entirely on ICE recordings with processing limited to pitch shifting in proportion to vehicle speed and interpolation between sounds.

Option B1: Minimum overall A-weighted levels, similar to those listed in Table 26, would be met at the measurement location specified by SAE J2889-1 (or similar test method).

Option B2: Average one-third octave band levels, similar to those listed in Table 27, would be met at the measurement location specified by SAE J2889-1 (or similar test method) for one-third octave bands from 315 Hz to 5000 Hz.

Option B3: Minimum one-third octave band levels, similar to those listed in Table 27, but lower by 5 dB to allow for variation of individual vehicles, would be met at the measurement location specified by SAE J2889-1 (or similar test method) for one-third octave bands from 315 Hz to 5000 Hz.

Option B4: Combination of options B1 and B2 or options B1 and B3. Both of these level specifications (overall and one-third octave bands) are based on the total noise output of the test vehicle, i.e. sound generator plus tire and aerodynamic noises. In the higher portions of the speed range (10 to 20 mph), most of the noise emission is from tires, which would not be reproduced by the sound generator, because so doing would effectively double the noise output of the vehicle.

8.5.4 Assumptions

Option B assumes that vehicles used to provide the templates for the synthesized sounds have sound-emission characteristics that provide adequate recognizability for pedestrians.

In addition, this option assumes that band-limited (315 Hz to 5000 Hz) ICE-like sounds will be recognizable as motor vehicles.

8.5.5 Observations

Observations for this approach include:

- It provides ICE-equivalent sounds which help with recognizability.
- Sounds could be developed to match a particular ICE vehicle make/model (e.g., sound signature) which would help with recognizability of the sound.
- It may be less expensive to build the sound emission systems electronics than Option A.
- Recordings are not needed a priori because the ICE recordings are not standardized in this option.
- If a poor recording was chosen, for example, one with too much engine exhaust, it might not have sufficient high-frequency components to ensure adequate detection.
- This option precludes the use of sounds that may be more unique and effective than the basic ICE sound.
- It may provide fewer cues for blind pedestrians than other options. The more cues the better since not all people respond to the same cues in the same way or uses the same cues to navigate.

8.5.6 Suggestions for Further Research

- Develop directivity specifications.
- Develop methods to test pitch-shifting, and refine test methods to record overall A-weighted sound levels and one-third octave band levels.

8.6 Option C: Alternative, non-ICE-like Sounds Designed for Detectability

Alternative countermeasure sounds with acoustic characteristics different from ICE vehicles were also examined. These alternative countermeasure sounds were shown to be effective for vehicle detection during human-subject experiments. At the same overall SPL values as ICE-like sounds, some non-ICE sounds were detected at almost double the distance of the ICE reference vehicle.

Alternatively, these sounds can be played at levels as much as several decibels below the noise output of typical ICEs while providing the same detectability, thus reducing community noise impact. Furthermore, these sounds may be cheaper to reproduce than ICE-like sounds, which have greater bandwidth specifications, necessitating more expensive loudspeakers. The design of a non-ICE sound involves a complex tradeoff among:

- Detectability (detection distance or detection time);
- Overall SPL value;
- Annoyance; and
- Cost.

While the required SPL values for non-ICE-like sounds will generally be lower than for ICE-like sounds for the same detection distance, there is no objective basis upon which to calculate the difference in SPL values for the class of non-ICE sounds as a whole. Rather, the equivalent-detectability-SPL value for a particular non-ICE sound must initially be determined experimentally by a jurying process that rates detectability. As psychoacoustic models improve, it may be possible to use them in place of jury testing to determine minimum SPL specifications for these sounds, but that approach is not yet sufficiently accurate.

8.6.1 Sound

The following characteristics can improve detectability of an alerting sound and are likely to be interpreted as hazard warnings on first hearing:

- Pitch shifting denoting vehicle speed change (approximately 40% pitch shift for 0 to 20 mph speed change and linear within that speed range).
- Pulsating quality with pulse widths of 100 to 200 msec; about 3 to 10 per second.
- Inter-pulse intervals of no more than 150 msec.
- Fundamental tonal component in the 150 to 1000 Hz range.
- At least three prominent harmonics in the 1 to 4 kHz range.
- 4 or more components (peaks in spectral distribution) exceeding 50 dB(A).

Sounds that conform to the guidelines above may not resemble the sound of an ICE, although recordings of ICE noise can be processed through a DSP to conform to the guidelines above while retaining a quality that immediately suggests an ICE. (Other kinds of sounds, such as, music or movie sound effects, could also be processed to give them the properties of effective auditory warnings.) Whether the original character of such sounds could still be recognized as a vehicle after processing could only be determined on a case-by-case basis through jury testing (see test methods below). In this option, any sounds constructed according to psychoacoustic principles for effective alerts, as listed above, would be permissible. Sounds could also include ICE-like sounds at reduced levels to enhance recognizability.

Additionally, sounds could be designed to include additional features to enhance detectability in certain situations, such as:

- Increased amplitude when driving in reverse.
- Briefly increased amplitude when accelerating from a stationary position.

8.6.2 System

Sound generation systems with signal processing capabilities would be used to continuously and monotonically vary the pitch and amplitude of sounds as appropriate to operating conditions according to vehicle inputs (e.g. vehicle speed sensors, throttle sensors, etc.). The appropriate relationship between sound amplitude and throttle position would need to be determined.

8.6.3 Test Methods

The detectability of a specific non-ICE sound can be best determined only through human-subjects testing, at the present state of the art. Because such testing is expensive, two alternative versions of this option are proposed. The first minimizes testing costs by constraining the number of permissible sounds. The second allows any sound that passes the jurying test, so long as the developers bear the cost of such testing.

Option C1: A single non-ICE sound, or a limited set of such sounds, might be tested by a jurying process to determine the SPL values at which they produce equivalent detection distances to ICE sounds.

Option C2: Applications of non-ICE sounds other than those developed in Option 1 would be required to conduct jury testing to establish the required playback levels for those sounds that would ensure equivalence to ICE-like sounds in terms of detection distance or time.

Jury testing is widely used in the automotive industry to make decisions about how vehicles should sound (Otto, Amman, Eaton, and Lake, 2001). For countermeasure sounds, juries could rate candidate sounds in terms of detection distance with speed (or detection time), recognizability, and annoyance to discover which sounds are optimal. An SAE-type test method would not be sufficient because SPL values for non-ICE sounds are only loosely correlated with detection distance/time and the SAE test is totally insensitive to annoyance. Although there are multiple experimental paradigms for the jury approach, the least problematic would be one in which the jury members register their ability to detect a test sound by pressing a button linked to an automatic data-collection system that records detection time for each member in each trial. By this means, it can be determined whether a given test sound has the same or greater detectability and recognizability as a reference ICE sound, when both sounds are played in identical and representative background noise conditions.

Further experimental work is required to determine:

- Ambient-noise specifications for the test.
- Repeatability of the jury.

In order to make jury-testing results more repeatable, synthetic ambient noise with a spectral characteristic that resembles typical urban conditions is likely to be used for jury testing.

8.6.4 Assumptions

Option C assumes that the jury process will screen out sounds that could be confused with non-vehicular threats to pedestrians and sounds that are annoying or offensive.

8.6.5 Observations

Some observations for this approach include:

- It could provide improved detectability over ICE-equivalent sounds.
- The limited frequency range works well for small speakers similar in size and construction to those currently used for backup warnings on commercial vehicles and some vehicle alerting systems.
- To survive the jury-screening process, sounds must be detectable while minimizing confusion and annoyance.
- This approach is very open-ended (e.g., can produce a wide variety of sounds, which could be confusing to pedestrians).
- In this approach, blind pedestrians must recognize a sound that has the properties of a warning sound (as described in 8.6.1) which are different from the properties of ICE-equivalent sounds. Nearly all subjects seemed to recognize a warning sound as such on first hearing, but during debriefing, some subjects expressed concern that there could be uncertainty if there are too many different warning sounds. Further research is needed on this issue.

8.6.6 Suggestions for Further Research

- Develop directivity specifications.
- Determine acceptability of jury testing.
- Develop methods to conduct jury tests including specifications for ambient noise conditions.
- Develop one or more standardized non-ICE sounds.
- Since these are novel sounds, further investigation into the negative impacts of these sounds should be conducted. These impacts include but are not limited to: annoyance to driver, pedestrians, and communities; confusion; and reduced recognizability.

8.7 Option D: Hybrid of Options Listed Above

8.7.1 Sound

This option is comprised of a combination of Options B and C in any of various proportions. For the portion of the sound derived by Option B, simulated ICE sounds would be generated directly by a digital-signal processor (DSP) programmed to create ICE-like sounds, which would vary pitch and loudness depending on vehicle inputs. The resulting sounds would resemble those of Option A, however the level of the ICE-engine sounds might be considerably lower than in Options A or

B. The portion derived from Option C would conform to the characteristics specified in Section 8.6.1.

8.7.2 System

Sound generation systems would be used with signal processing capabilities to continuously and monotonically vary the pitch and amplitude of sounds as appropriate to operating conditions according to vehicle inputs. This system would simultaneously generate both ICE-like sounds at a lower level than in Options A and B (levels to be determined by jury testing) and synthetic sounds designed for optimal combinations of alerting potential and minimal annoyance. The ICE-like sound components may not be heard in higher urban ambient-noise conditions, but their association with the alerting sound is learned during exposure in quieter environments.

8.7.3 Test Methods

The detectability of a specific non-ICE sound can be best determined only through human-subjects testing, at the present state of the art. Because such testing is expensive, two alternative tests methods are proposed.

Option D1: A single non-ICE sound, or a limited set of such sounds, might be tested by a jurying process to determine the SPL values at which they produce equivalent detection distances to ICE sounds.

Option D2: Applications of non-ICE sounds other than those developed in Option D1 would be based on jury testing to establish the required playback levels for those sounds that would ensure equivalence to ICE-like sounds in terms of detection distance or time.

Jury testing is widely used in the automotive industry to make decisions about how vehicles should sound (Otto, Amman, Eaton, and Lake, 2001). For countermeasure sounds, juries could rate candidate sounds in terms of detection distance with speed (or detection time), recognizability, and annoyance to discover which sounds are optimal. An SAE-type test method would not be sufficient because SPL values for non-ICE sounds are only loosely correlated with detection distance/time and the SAE test is totally insensitive to annoyance. Although there are multiple experimental paradigms for the jury approach, the least problematic would be one in which the jury members register their ability to detect a test sound by pressing a button linked to an automatic data-collection system that records detection time for each member in each trial. By this means, it can be determined whether a given test sound has the same or greater detectability and recognizability as a reference ICE sound, when both sounds are played in identical and representative background noise conditions.

Further experimental work is required to determine:

- Ambient-noise specifications for the test.
- Repeatability of the jury results.

In order to make jury-testing results more repeatable, synthetic ambient noise with a spectral characteristic that resembles typical urban conditions is likely to be used for jury testing.

8.7.4 Assumptions

Option D assumes that the jury process will also screen out sounds that could be confused with non-vehicular threats to pedestrians and sounds that are annoying or offensive.

8.7.5 Observations

Similar to Option C described in Section 8.6.5. However, the addition of ICE-like spectral content may facilitate recognition, thereby enhancing the appeal of these sounds to juries. This approach was used in some of the most effective sounds tested in this research (in terms of detection distance), for example, sounds A5 and E3. Since these sounds combine characteristics from both options B and C, the potential negative impacts (in terms of recognition) may be less than for Option C.

8.7.6 Suggestions for Further Research

- Develop directivity specifications.
- Develop methods to conduct jury tests, including specifications for ambient noise conditions.
- Develop one or more standardized non-ICE sounds.
- Since these are novel sounds, conduct further investigation into the negative impacts of these sounds. These impacts include but are not limited to: annoyance to driver, pedestrians, and communities; confusion; and reduced recognizability.

9. SUMMARY OF FINDINGS AND CONSIDERATIONS FOR FURTHER RESEARCH

9.1 Summary of Findings

Acoustic countermeasures should alert pedestrians, including blind pedestrians, of vehicle presence and operation. Information at least equivalent to the cues provided by ICE vehicles, including ideally, speed change, should be provided. In this research, acoustic data acquired from a sample of ICE vehicles was used to determine the sound levels at which synthetic vehicle sounds, developed as countermeasures, should be set. ICE-equivalent sounds were specified as overall A-weighted sound levels and spectral content, one-third octave band. Psychoacoustics models showed that frequency components between 1600 and 5000 Hz were more detectable due to strong signal strength and relatively low ambient levels in this range and frequency components below 315 Hz were often masked by urban ambient noise. Therefore, it is reasonable to specify minimum one-third octave band levels from 315 Hz to 5000 Hz. Minimum overall A-weighted levels and minimum one-third octave band levels (refer to Table 27 and Table 28) were developed and could form the basis for specifications to be met at the measurement location specified by SAE J2889-1. For recognizability as a vehicle under Options A and B, sounds should be either an ICE recording or modeled on a recording and include pitch shifting to denote vehicle speed. ICEs normally emit louder sounds during acceleration. This additional-loudness cue is most useful to blind pedestrians when a stationary vehicle first starts moving, but could be included over the whole 0 to 20 mph range by providing an input to the sound generator from the throttle-position sensor.

The disparity in noise emission levels between moving ICEs and vehicles in pure electric mode is greatest at about 6 mph (Garay-Vega, et. al, 2010), hence 6-mph pass-by scenarios were chosen for human-subject testing of the detectability of vehicles operating in EV mode with and without synthetic sound generators. At 6 mph, a typical ICE vehicle generated sufficient noise (60-61 dB (A)) to be detectable at an average distance of about 41feet in a typical urban noise environment with average noise level of 58 – 61 dB (A). This provides a detection time of slightly less than 5 seconds before the vehicle might collide with a pedestrian who ventured into its path.

Various synthetic sounds, along with a reference ICE vehicle and a no-vehicle condition were evaluated through the use of panels of human subjects to determine the distances at which the participants could detect and recognize an approaching vehicle. The synthetic sounds were played at two different levels with values for $L_{Aeq\,,1/2\ sec}$ of 59.5 (slightly below the typical ICE vehicle) and 63.5 (about 3 dB louder than a typical ICE. Each of the nine different synthetic sounds could be described as belonging to one of five categories:

- Sounds that emulate the sound of an ICE, including combustion noise, valve noise and fan noise.
- Sounds that emulate only the fundamental combustion noise (generally below 250 Hz for the low speeds of interest).

- Sounds based on ICE sounds but with exaggerated high-frequencies. Entirely artificial sounds designed to maximize detection range while minimizing overall loudness and annoyance.
- Hybrid sounds combining categories listed above to enhance both detection distance and recognizability.

The relative effectiveness (detection distance) of the tested sounds in these different categories of sounds may be summarized as follows (see also Table E2 and Figure 54):

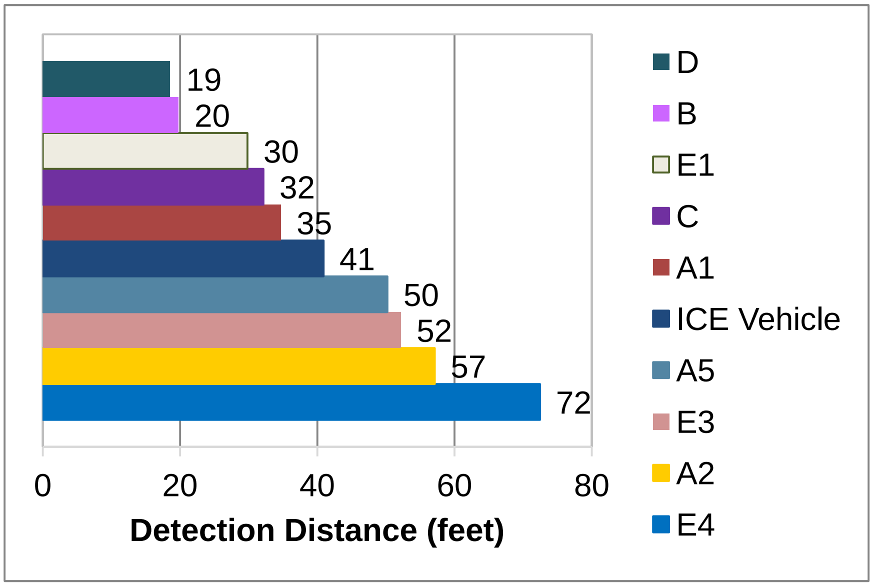


Figure 54. Average Detection Distance (for 6 mph Forward Pass-By & Sound Level = 59.5 dB(A)

- Figure 54 shows the mean detection distances for the sounds evaluated in the human-subject studies. Sounds at the top of the list can be described as ICE-like sounds with only the fundamental combustion noise or otherwise lacking in the qualities that support detectability. Sounds at the end of the list can be described as alternative sounds designed according to psychoacoustic principles.
- Sounds designed according to principles for auditory warnings (e.g. sound ‘E4’) with a substantial impulsive component worked best, sometimes providing detection at distances about double those of the ICE reference vehicle when played at the slightly lower (59.5 dB(A)) level.
- Next most effective were ICE-like sounds with exaggerated high-frequency components (e.g., sounds ‘A2’ and ‘E3’).
- Sounds that resembled normal ICEs in both timbre and loudness (e.g. ‘A1’ and ‘E1’) were detected at distances roughly similar to those of the ICE reference vehicle.
- Sounds bearing no resemblance to a piston engine or an auditory warning were detected at distances slightly, but not significantly, greater than those of the ICE reference vehicle, if played at the 63.5 dB(A) level (e.g., sound ‘C’). At the lower

playback level, 59.5 dB(A), sound ‘C’ was slightly inferior to the reference vehicle, while sound ‘D’ was detected at about half the distance of the reference vehicle.

- Sounds containing only combustion noise frequencies (e.g., sound ‘B’) were detected at about half the distance of the ICE reference vehicle.

Among the factors contributing to the superior detectability of sound ‘E4’ are the following:

- Most of the energy in the sound lies in the 500 Hz to 3 kHz region where human hearing is most sensitive.
- The impulsive quality of this sound means that the peak levels of the sound can be several dB louder than a continuous sound with the same $L_{Aeq,\ ½\ sec}$.
- Even if the peak level of a pulsating sound is equal to that of a continuous sound of similar spectral content, the pulsating sound will have a higher alerting potential.

The rapid bursts of high-frequency sound in ‘E4’ bear no resemblance to any ICE-like sound, yet many study participants indicated that they recognized it as an alert to an approaching vehicle immediately. Furthermore, in a practice trial, with all sounds played at the 63.5 dB (A) level, all but one of 24 participants detected the ‘E4’ sound on first hearing, and every subject detected it on second hearing. In contrast, 22 of the 24 subjects in the practice trial correctly made no response to a no-vehicle condition on the first exposure.

The ICE-like components of sound ‘E4’ are emitted at a level that is about 10 dB below the peak of the other component (i.e., the rapid bursts of high-frequency)and are not audible at the distances that participants detected this sound in the presence of the Volpe Center ambient noise. The ICE-like sounds became audible as the vehicle passed the participants, and may thus reinforce the association of the rapid bursts of high-frequency sound in ‘E4’with an approaching vehicle. However, there is insufficient evidence to conclude that they are necessary, since all but one subject recognized the ‘E4’ sound as an approaching threat on first hearing.

The implication of these experiments and the acoustic analysis of the sounds used is that countermeasures which emulate ICE sounds over the 300 to 5k Hz range can provide detection distances equivalent to typical ICE vehicles. However, synthetic sounds that are specifically designed for detectability have the potential to provide double the detection distance at the same average noise level.

The criteria for detectability can be met through various options to specifications, such as:

- Recording(s) of Actual ICE Sounds (Option A).
    1. Defined by overall A-weighted levels.
    2. Defined by one-third octave band average spectra.
    3. Defined by one-third octave band minima spectra.
    4. Combinations of the above.

- Synthesized ICE-Equivalent Sounds (Option B).
    1. Defined by overall A-weighted levels.
    2. Defined by one-third octave band average spectra.
    3. Defined by one-third octave band minima spectra.
    4. Combinations of the above.
- Alternative, non ICE-like Sounds Designed for Detectability (Option C).
- Hybrid of options listed above (Option D).

Other factors that must be considered, but that were not explored in this research include: effectiveness of the alerting sound when multiple vehicles are present; acceptance and annoyance of the countermeasure sounds; variability in the directivity of speakers systems; and alternative (lower) sound levels for hybrid sounds and for sounds that do not resemble ICE sounds.

9.2 Considerations for Further Research

Countermeasure sounds that emulate ICEs are expected to provide the same auditory cues to pedestrians and the same or lower community-noise impacts compared to current vehicles. In order to ensure that these sounds are emitted in a manner consistent with ICE vehicle emissions, it is necessary that the directivity of the ICE and countermeasure sources are similar. To this end, it is recommended that the directivity of ICE and vehicle sound countermeasure systems be determined. If these vary significantly, then steps will need to be taken to ensure that the countermeasure sounds are at least as loud as the ICE sounds at the location that the ICE sound was detected. Alerting sounds that work better to signal the approach of a single vehicle may, or may not, be more difficult for blind pedestrians to interpret in a multi-vehicle situation. Furthermore, even if their contribution to overall average noise levels is less than ICEs, their alerting characteristics may be more annoying than those of ICEs.

The issue of whether sounds designed for maximum detectability degrade pedestrian safety in multi-vehicle situations could possibly be addressed experimentally. The experiment could re-create the sounds heard by a pedestrian at a complex intersection with numerous vehicles moving at the same time. Conventional ICE sounds, synthetic sounds designed for maximum detectability, and various combinations could be presented to participants to determine if there is any difference in their ability to determine when it is safe to cross.

Annoyance is potentially a significant issue. The developers of countermeasure sounds use a jury process to determine which particular sounds combine good detectability with minimal annoyance.

10. BIBLIOGRAPHY

AASHTO. (2004). *A Policy on Geometric Design of Highways and Streets*. Washington, DC: American Association of State Highway and Transportation Officials, Retrieved from: https://bookstore.transportation.org/category_item.aspx?id=DS.

ANSI S3.4-2007. *American National Standard Procedure for the Computation of Loudness of Steady Sound.*

DIN 45 631, *Procedure for Calculating Loudness Level and Loudness*, Deutsches Institut für Normung.

Fletcher, H. and Munson, W. A. (1933). Loudness, Its Definition, Measurement, and Calculation. *Journal of the Acoustic Society of America.* Volume 5, Issue 1. pp. 82-108.

Fleming, Plotkin, Roof, Ikelheimer, and Senzig. (2005). *Assessment of Tools for Modeling Aircraft Noise in the National Park*s. Federal Interagency Committee on Aviation Noise (FICAN) Federal Aviation Administration.. Retrieved from: http://www.fican.org/pages/findings.html

Garay-Vega, L; Hastings, A.; Pollard, J.K.; Zuschlag, M. & Stearns, M. (2010, April). *Quieter Cars and the Safety of Blind. Pedestrians: Phase 1*. DOT HS 811 304 Washington, DC: National Highway Traffic Safety Administration.

Giguère, C.; Laroche, C.; Al Osman, R. and Zheng, Y. (2008). *Optimal Installation of Audible Warning Systems in the Noisy Workplace*, 9th International Congress on Noise as a Public Health Problem (ICBEN) 2008, Foxwoods, CT. Retrieved from: http://www.icben.org/proceedings2008/PDFs/Giguere_et_al.pdf.

Goodes, P.; Bai, Y.B. and Meyer, E. (2009). *Investigation into the Detection of a Quiet Vehicle by the Blind Community and the Application of an External Noise Emitting System*. SAE 2009-01-2189.

Hanna, R. (2009, September). *Incidence of Pedestrians and Bicyclists Crashes by Hybrid Passenger Vehicles:* National Center for Statistical Analysis Technical Report. DOT HS 811 204. Washington, DC: National Highway Traffic Safety Administration.

H.R. 5381--111th Congress: *Motor Vehicle Safety Act of 2010.* (2010). In GovTrack.us (database of federal legislation). Retrieved December 8, 2010, from http://www.govtrack.us/congress/bill.xpd?bill=h111-5381

IEC 61672-1 *Electroacoustics - Sound Level Meters* - Part 1: Specifications, International Electrotechnical Commission, 2002.

ISO 532-B. Acoustics - *Method for Calculating Loudness Level*, International Organization for Standardization.

Japanese Automobile Standards Internationalization Centre (JASIC). (2009). *A Study on Approach Warning Systems for Hybrid Vehicle in Motor Mode*. Presented at the 49th World Forum for Harmonization of Vehicle Regulation (WP.29) Working Group on Noise (GRB)-49. February 16-18, 2009. Document Number: GRB-49-10.

Kerber, S. & Fastl, H. (2008). *Prediction of Perceptibility of Vehicle Exterior Noise in Ambient Noise*. Proceedings DAGA, Dresden.

Maurer, M. (2008). *The Danger Posed by Silent Vehicles*. National Federation of the Blind. Remarks made for the United Nations Economic Commission for Europe, Working Party on Noise. 47th GRB session February 19, 2008 Geneva. Informal Document No. GRB-47-10. http://www.unece.org/trans/doc/2008/wp29grb/ECE-TRANS-WP29-GRB-47-inf10e.pdf

Moore B.C.J. (2003). *An Introduction to the Psychology of Hearing*, Fifth Edition, Academic Press".

Moore & Glasberg, (1997). A Model of Loudness Perception Applied to Cochlear Hearing Loss, *Auditory Neuroscience* Vol. 3 pp.289-311.

Moore, B. C. J., Glasberg, B. R., and Baer, T. (1997). A Model for the Prediction of Thresholds, Loudness and Partial Loudness, *J. Audio Eng*. Soc. 45, 224-240.

MLIT and JASIC (2010). *Guidelines for Measure Against Quietness Problem of HV*. GRB Informal group on Quiet Road Transport Vehicles (QRTV) Working papers of the 3rd informal meeting. Tokyo, 13-15 July 2010. Retrieved from: http://www.unece.org/trans/main/wp29/wp29wgs/wp29grb/QRTV_3.html.

Otto, N., Amman, S., Eaton, C. and Lake, S. Guidelines for Jury Evaluations of Automotive Sounds. *Sound and Vibration*. Volume 35(4).

Public Law 111-373: *Pedestrian Safety Enhancement Act of 2010.* (124 stat.4086; Date: 1/4/11; enacted S.841).

Rosenblum, L. (2008), *Hybrid Cars are Harder to Hear.* University of California Riverside Newsroom April 28, 2008.

Rosenblum, L. (2008). *Sound Measurement and Mobility.* Transcript of the Quiet Cars Public Meeting on June 23, 2008.Docket ID NHTSA-2008-0108-0023. pp. 53 -65. http://www.nhtsa.gov/DOT/NHTSA/NVS/Crash%20Avoidance/Technical%20Publications/2010/811304rev.pdf.

SAE. Measurement of Minimum Noise Emitted by Road Vehicles. SAE J2889-1 Draft 2009. Society of Automotive Engineers

Stanton, N. and Edworthy J. (Eds.). (1999). *Human Factors in Auditory Warnings*.

QRTV (2010). *Terms of Reference and Rules of Procedure for the GRB Informal Group on Quiet Road Transport Vehicles (QRTV)*. Retrieved from: http://www.unece.org/trans/main/wp29/wp29wgs/wp29grb/QRTV_1.html.

Wall Emerson, Naghshineh, Happen and Wiener (unpublished).*The Effect of Hybrid on Blind Pedestrian's Crossing*. Western Michigan University and Marquette University. Presented at SAE Vehicle Sound for Pedestrian Committee Meeting on April 23rd, 2009. Detroit, MI.

Zheng Y, Giguère C, Laroche C, Sabourin C, Gagné A, Elyea M., A Psychoacoustical Model for Specifying the Level and Spectrum of Acoustic Warning Signals in the Workplace, *J Occup Environ Hyg.* 2007 Feb;4(2):87-98.

Zwicker, E. and H. Fastl (1999). *Psychoacoustics: Facts and Models*. Berlin, Springer-Verlag.

APPENDIX A. SUPPLEMENTAL DATA AND INFORMATION

A.1 Intersections Used for Ambient Measurements for Countermeasure Testing

Table 28. Intersections Used for Ambient Measurements

ID	Location	Geometry and Traffic Control
1	Sergeant Street, Cabot Street, and Centre Street	“+” shaped, signalized
2	Richmond Road & Centre Street	T-shaped, stop sign
3	Colby Road & Centre Street	T-Shaped, stop sign
4	Boston College driveway & Centre Street	T-shaped, sidewalk set back 25ft from Centre Street
5	Mill Street & Centre Street	T-Shaped, stop sign
6	Ward Street & Centre Street	T-Shaped, stop sign
7	Nathan Road. & Centre Street	T-shaped, stop sign
8	Grafton Street & Centre Street	1-way street, enter from Centre Street
9	Commonwealth Avenue & Center Street	“+” shaped, signalized
10	Elmore Street & Ward Street	T-shaped
11	Langdon Street & Winchester Road	T-shaped
12	Cabot Street & Harvard Street	4-way stop
13	Atwood Avenue & Harvard Circle	Y-shaped
14	Gay Street & Frederick Street	T-shaped
15	Bonwood Street & Frederick Street	T-shaped
16	Harvard Street & Norwood Avenue	T-shaped
17	Walnut Street & Centre Street	T-shaped, signalized

A.2 Acoustic Measurement Results-Tabulated Data

Table 29. Overall A-weighted Uncorrected Sound Pressure Levels: 6 mph, Reverse

Vehicle	L_{Aeq}	$L_{AF, max}$	$L_{AF, min}$
1	56.3	56.7	55.3
1	58.4	58.9	57.6
1	60.4	60.8	60.2
1	61.2	61.5	60.9
2	56.6	57.0	55.7
2	57.3	58.4	57.0
2	57.5	57.9	57.1
2	57.9	58.3	57.3
2	58.3	58.5	58.2
2	59.0	59.4	58.7
3	59.3	59.4	59.0
3	59.5	60.0	58.8
3	59.9	60.1	59.4
3	60.0	60.5	59.5
3	60.4	60.9	59.8
3	61.4	61.7	60.5
4	54.9	55.2	54.6
4	55.3	55.6	55.1
4	55.9	56.4	55.5
4	56.3	56.5	56.1
4	56.8	57.1	56.3
4	57.2	57.4	56.7
5	56.0	56.2	55.5
5	57.0	57.4	56.1
5	57.3	57.5	57.2
5	57.8	58.1	57.6
5	59.0	59.4	58.9
5	59.4	59.5	59.2
6	61.0	61.4	60.4
6	61.9	62.3	61.3

Vehicle	**L_{Aeq}**	**$L_{AF, max}$**	**$L_{AF, min}$**
6	62.4	63.0	61.2
6	64.8	65.5	63.6
8	58.0	58.2	57.7
8	58.0	58.4	57.6
8	58.1	58.5	57.3
8	58.6	59.0	58.4
8	59.7	60.1	59.3
8	59.8	60.2	59.5
8	60.6	61.1	60.1
8	60.7	61.0	60.3
9	57.8	58.0	57.6
9	58.5	58.8	57.9
9	58.8	59.1	58.6
9	60.0	60.3	59.3
10	57.8	58.1	57.5
10	58.1	58.2	57.6
10	58.1	58.3	57.9
10	58.3	58.4	58.1

Table 30. Overall A-weighted Uncorrected Sound Pressure Levels: 6 mph, Forward

Vehicle	L_{Aeq}	$L_{AF, max}$	$L_{AF, min}$
1	62.0	62.5	61.2
1	62.3	62.7	61.7
1	62.9	63.2	62.3
1	63.1	63.6	62.9
2	59.8	60.2	59.0
2	60.1	60.5	59.5
2	60.6	60.7	60.4
2	60.8	61.3	60.5
3	58.3	59.1	58.0
3	58.6	59.1	57.9
3	60.3	60.6	59.7
3	61.1	61.2	60.5
3	62.2	63.0	61.9
3	62.7	62.9	62.4
4	59.0	59.9	58.6
4	59.5	59.7	59.3
4	60.3	60.7	59.4
4	61.2	61.6	61.2
4	61.7	62.6	61.3
4	63.2	63.7	62.8
5	57.3	58.2	57.1
5	58.7	59.1	58.3
5	60.4	61.5	60.3
5	61.4	61.9	60.1
6	59.7	60.2	58.4
6	60.5	60.8	60.3
6	61.3	61.5	61.1
6	63.9	63.9	63.8
8	62.6	63.3	61.1
8	62.8	63.2	61.7
8	62.8	63.2	62.7
8	63.3	64.1	62.8
9	60.0	60.1	59.9

Vehicle	**L_{Aeq}**	**$L_{AF, max}$**	**$L_{AF, min}$**
9	60.5	60.8	60.4
9	62.2	62.4	61.9
9	62.3	62.8	62.1
10	61.6	61.8	61.5
10	61.7	62.0	61.0
10	62.5	63.1	60.9
10	63.2	63.5	62.0

Table 31. Overall A-weighted Uncorrected Sound Pressure Levels: 10 mph, Forward

Vehicle	L_{Aeq}	$L_{AF, max}$	$L_{AF, min}$
1	62.9	63.4	62.2
1	63.1	63.4	62.6
1	63.6	64.2	62.4
1	63.6	64.3	62.5
2	60.0	60.9	59.7
2	61.6	61.8	61.5
2	61.8	62.9	61.3
2	62.7	63.2	61.3
3	63.1	63.7	62.8
3	63.8	64.2	63.5
3	64.3	64.7	64.1
3	64.5	64.7	64.3
3	64.9	65.2	64.6
3	65.5	65.8	65.2
4	62.4	62.8	62.3
4	62.7	63.1	62.3
4	63.5	64.0	63.2
4	63.7	64.0	62.9
5	63.3	63.7	62.7
5	64.0	64.6	63.6
5	64.1	64.5	63.8
5	64.8	65.1	64.6
6	62.9	64.2	62.4
6	64.4	64.6	64.0
6	65.5	66.2	63.9
6	66.4	66.7	66.1
8	63.0	63.7	61.5
8	63.7	64.0	63.6
8	64.2	64.9	63.9
8	64.4	64.8	63.9
9	62.2	62.4	61.9
9	62.3	62.6	61.9
9	62.8	63.2	61.9

Vehicle	**L_{Aeq}**	**$L_{AF, max}$**	**$L_{AF, min}$**
9	62.9	63.3	61.6
10	64.4	65.0	63.1
10	64.7	65.0	64.0
10	65.4	65.7	64.2
10	65.9	66.4	65.4

Table 32. Overall A-weighted Uncorrected Sound Pressure Levels: 15 mph, Forward

Vehicle	L_{Aeq}	$L_{AF,\ max}$	$L_{AF,\ min}$
1	68.6	69.0	67.6
1	68.6	70.1	67.7
1	69.1	69.5	67.9
1	70.3	70.6	69.4
2	65.9	66.2	65.1
2	66.5	67.2	65.1
3	65.3	66.7	64.6
3	67.1	67.8	65.6
3	68.4	69.5	67.8
3	69.3	69.8	67.9
3	69.5	70.1	67.9
3	69.9	70.6	69.5
4	69.3	69.6	68.5
4	69.9	70.1	68.6
5	65.4	66.3	63.4
5	66.7	67.9	64.3
5	67.1	67.6	66.8
5	67.4	68.1	67.0
6	66.0	67.1	64.2
6	68.8	69.0	67.8
6	69.3	70.3	67.4
6	70.2	70.4	69.0
8	68.7	69.1	67.3
8	70.2	70.4	69.9
9	65.8	67.0	63.1
9	67.7	68.1	66.7
9	68.0	68.4	66.1
9	68.5	68.8	68.1
10	62.7	65.2	62.2
10	67.9	68.2	67.6
10	68.0	68.5	65.9
10	69.4	69.5	69.2
10	69.8	70.7	69.1
10	71.2	71.6	69.8

Table 33. Overall A-weighted Uncorrected Sound Pressure Levels: 20 mph, Forward

Vehicle	L_{Aeq}	$L_{AF, max}$	$L_{AF, min}$
1	68.6	69.8	65.9
1	69.2	70.1	67.1
1	70.1	70.8	69.8
1	70.3	70.5	69.5
2	63.6	64.8	62.3
2	67.1	68.1	64.8
2	67.7	68.6	67.4
2	69.4	69.9	68.4
2	70.6	71.1	69.9
2	71.0	71.4	70.6
3	69.5	70.8	66.7
3	69.8	70.6	67.8
3	70.4	71.0	69.6
3	70.6	71.0	70.2
4	69.6	70.4	69.1
4	70.0	70.5	68.7
4	70.5	70.6	70.3
4	70.8	71.0	70.3
5	69.6	70.8	66.8
5	69.7	71.1	66.4
5	70.6	71.0	70.2
5	71.2	72.2	70.4
6	66.1	67.2	64.1
6	71.0	71.9	69.1
6	71.4	72.1	70.8
6	72.9	73.7	70.5
8	71.6	72.0	71.3
8	71.8	72.9	70.7
8	72.6	72.6	72.2
8	73.3	73.8	72.1
9	67.6	70.6	66.5
9	70.0	70.4	68.8
9	70.0	70.8	67.5
9	71.3	71.9	70.7

Vehicle	**L_{Aeq}**	**$L_{AF, max}$**	**$L_{AF, min}$**
10	69.8	71.1	67.0
10	72.3	73.4	71.5
10	73.6	74.1	73.2
10	73.9	74.3	72.7

Table 34. Overall A-weighted Uncorrected Sound Pressure Levels: Acceleration

Vehicle	**L_{Aeq}**	**$L_{AF, max}$**	**$L_{AF, min}$**
1	68.8	69.4	68.2
1	69.6	70.5	68.2
1	70.1	70.5	69.5
1	72.3	73.2	70.1
2	64.7	65.7	64.3
2	65.5	66.0	64.8
2	65.8	66.4	64.7
2	66.0	66.4	65.3
3	63.6	63.8	63.5
3	63.6	64.0	63.5
3	64.5	65.1	64.2
3	65.7	65.9	65.4
4	60.8	61.2	60.6
4	61.2	61.5	60.5
4	63.6	63.9	63.1
4	63.7	64.0	63.4
4	64.8	65.3	64.6
4	65.2	65.5	65.0
5	62.3	62.7	62.2
5	62.6	62.8	62.1
5	63.2	63.5	62.4
6	68.9	69.1	68.8
6	69.4	69.7	69.0
6	71.2	71.9	69.9
6	72.9	73.6	71.3
8	66.8	67.1	66.2
8	66.9	67.4	65.2
8	68.4	69.1	67.2
8	68.4	69.2	67.4
9	65.5	66.2	65.2
9	66.8	67.1	66.7
9	67.3	67.7	66.8
9	68.2	68.6	67.4

Vehicle	**L_{Aeq}**	**$L_{AF, max}$**	**$L_{AF, min}$**
10	67.0	67.2	66.9
10	68.6	69.1	67.7
10	68.7	69.1	68.3
10	69.1	70.0	67.3
10	69.4	69.7	68.5
10	71.1	71.5	70.2

Table 35. Overall A-weighted Uncorrected Sound Pressure Levels: Startup

Vehicle	L_{Aeq}	$L_{AF, max}$	$L_{AF, min}$
1	74.6	77.2	49.3
1	75.4	78.4	74.7
1	76.4	77.3	74.8
1	77.0	77.7	75.6
2	66.6	67.4	65.4
2	67.4	68.8	65.8
2	67.8	69.8	65.3
2	68.8	70.2	65.5
3	65.9	71.3	65.6
3	68.9	72.3	48.7
3	74.2	77.5	48.9
3	74.3	77.1	70.1
4	65.5	67.8	64.8
4	66.1	68.9	65.7
4	66.2	68.2	65.8
4	66.6	70.2	50.3
5	68.1	70.8	46.1
5	70.4	71.4	70.0
5	70.5	71.2	70.0
5	70.7	71.6	69.8
6	69.8	71.6	68.5
6	70.8	71.6	68.6
6	72.0	73.4	69.5
6	72.0	75.8	70.2
8	74.2	75.3	73.6
8	74.2	75.6	73.1
8	74.5	75.4	73.4
8	74.8	76.5	74.0
9	72.8	75.8	56.3
9	75.8	78.0	72.9
10	66.0	70.9	52.0
10	66.4	70.6	65.5
10	68.4	70.8	53.2
10	70.8	72.9	67.2

Table 36. Overall A-weighted Uncorrected Sound Pressure Levels: Idle

Vehicle	L_{Aeq}	$L_{AF, max}$	$L_{AF, min}$
1	59.2	59.6	59.0
1	59.4	59.9	59.2
2	53.1	53.5	52.9
2	53.9	54.4	53.7
3	54.8	55.2	54.5
3	54.8	55.2	54.6
4	52.5	53.2	52.2
4	53.7	54.4	53.4
5	52.9	53.4	52.7
5	53.1	53.5	52.9
6	57.4	57.7	57.2
6	60.1	60.4	59.9
8	55.9	56.3	55.8
8	56.4	56.8	56.3
9	55.2	55.5	55.0
9	55.5	55.8	55.3
10	56.7	57.1	56.5
10	57.4	57.8	57.3

Table 37. Overall A-weighted Uncorrected Sound Pressure Levels: Ambient

L_{Aeq}	$L_{AF, max}$	$L_{AF, min}$
49.1	50.2	48.2
47.8	48.9	47.0
48.6	49.9	47.7
47.5	48.5	46.8
47.2	47.7	46.9
46.8	47.4	46.5
46.9	47.5	46.6
46.5	47.1	46.1
50.1	51.0	49.4
50.1	51.2	49.3
46.2	47.5	45.4

L_{Aeq}	$L_{AF, max}$	$L_{AF, min}$
46.5	48.0	45.5
48.4	48.8	48.0
48.1	49.2	47.5
53.4	54.0	53.0
52.7	53.5	52.3
53.2	53.9	52.9
52.6	53.5	52.1
53.0	53.4	52.8
52.1	52.8	51.7
50.7	51.2	50.5
52.9	53.3	52.7
52.0	52.6	51.5
50.6	51.1	50.4
51.7	52.2	51.5
51.6	52.0	51.3
51.5	51.9	51.2
51.3	51.8	51.1
50.9	51.3	50.6
50.8	51.3	50.5

Table 38. Ambient Levels at Cottage Farm Measurement Site during ICE Measurements, A-Weighted Levels, dB(A)

1/3 Octave Band Center Frequency, Hz	Linear Average (1/3 Octave Band)	Minimum (Overall A-weighted) *	Maximum (Overall A-weighted)	Minimum (1/3 Octave Band) **	Maximum (1/3 Octave Band)
Broadband	49.8	46.3	53.5	45.4	54.8
Sum (100 to 20k)	49.6	46.1	53.4	45.3	54.7
12.5	-8.3	-8.4	-9.6	-10.9	-3.6
16	-2.6	-4.4	-2.8	-7.5	1.3
20	2.0	0.3	2.4	-4.7	4.3
25	8.4	5.8	9.1	2.0	10.2
31.5	14.7	12.6	14.4	11.5	17.2
40	19.0	17.5	19.1	16.1	21.4
50	24.0	21.2	23.8	19.6	30.0
63	29.2	25.5	28.7	25.5	34.4
80	32.2	27.7	32.3	27.7	36.3
100	34.6	30.7	34.1	30.7	38.4
125	35.5	32.4	36.8	32.4	42.1
160	36.1	32.1	37.9	32.0	41.5
200	36.9	32.7	37.9	32.7	41.2
250	36.5	33.9	38.1	33.1	40.7
315	36.5	32.5	37.6	32.1	41.5
400	36.0	31.9	38.1	31.8	39.7
500	36.7	33.6	39.8	33.1	41.1
630	38.2	34.4	41.7	34.0	42.2
800	40.2	36.0	46.1	35.8	46.1
1k	41.1	36.4	46.4	36.4	46.4
1.25k	40.0	35.3	45.1	35.3	45.1
1.6k	37.6	32.9	43.1	32.9	43.1
2k	34.7	30.3	37.8	30.3	37.8
2.5k	34.5	32.8	35.4	30.8	42.1
3.15k	35.5	36.9	37.1	30.0	39.6
4k	34.0	33.0	34.3	28.3	40.2
5k	29.0	25.0	29.8	24.3	32.8
6.3k	25.7	22.3	26.9	19.7	31.7
8k	20.2	16.6	22.4	14.1	24.2

1/3 Octave Band Center Frequency, Hz	Linear Average (1/3 Octave Band)	Minimum (Overall A-weighted) *	Maximum (Overall A-weighted)	Minimum (1/3 Octave Band) **	Maximum (1/3 Octave Band)
10k	14.4	10.3	17.3	7.6	18.3
12.5k	8.9	5.0	11.7	3.2	13.0
16k	3.1	0.7	5.6	-0.8	8.7
20k	-1.9	-3.1	-0.4	-3.5	2.0

Table 39. Idle A-Weighted Levels, dB(A) for ICE Vehicles Measured (Uncorrected) at Cottage Farm

	A-weighted Level, dB(A) for Vehicle Sample																		
Frequency, Hz	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Broadband	53.1	53.9	53.1	52.9	54.8	54.8	53.7	52.5	59.2	59.4	56.7	57.4	57.4	60.1	55.2	55.5	55.9	56.4	55.7
Sum (100 to 20k)	53.1	53.9	53.1	52.9	54.8	54.8	53.7	52.5	59.2	59.5	56.8	57.5	57.4	60.1	55.2	55.5	55.9	56.4	55.7
12.5	-5.3	-5.7	-8.0	-8.6	-6.2	-6.6	-7.6	-7.6	-6.2	-6.6	-6.9	-6.8	-9.3	-8.9	-5.9	-5.5	-9.3	-9.3	-7.2
16	-1.4	-0.7	-3.7	-3.0	-0.6	0.0	-3.2	-2.8	-0.8	-0.8	-0.5	-0.7	-2.2	-2.1	0.4	0.1	-2.8	-3.8	-1.6
20	16.7	14.9	1.7	1.3	2.6	1.9	15.7	14.2	2.8	2.5	4.3	4.7	4.2	3.7	2.4	3.5	3.1	3.0	5.7
25	23.5	21.7	7.6	7.9	7.5	8.0	17.8	16.4	8.7	8.2	11.0	10.0	25.9	23.6	23.5	25.1	9.7	9.3	14.7
31.5	15.4	15.0	22.2	24.0	16.0	14.1	13.2	12.6	14.8	15.4	15.8	16.8	29.1	26.9	16.2	16.2	15.8	15.8	17.5
40	18.6	18.6	31.1	33.0	22.7	19.8	19.3	18.6	18.9	20.1	21.8	22.2	19.7	19.8	20.2	20.6	20.1	19.6	21.4
50	25.1	25.0	22.5	21.7	22.8	22.4	22.9	22.6	24.0	23.8	25.6	25.2	28.4	27.0	31.1	28.9	27.7	27.5	25.2
63	27.8	29.5	28.2	28.0	28.5	27.9	26.2	26.0	26.8	27.3	29.5	29.3	30.1	29.9	29.0	28.9	29.0	28.5	28.4
80	31.9	31.1	31.5	31.9	31.9	30.6	30.7	30.8	36.4	35.1	34.4	34.0	33.8	33.1	34.8	34.2	35.4	35.5	33.2
100	35.7	34.3	32.1	32.1	32.4	31.4	32.2	32.0	42.5	42.4	38.9	37.7	38.6	39.0	36.2	35.7	34.4	33.9	35.6
125	33.3	33.3	33.3	33.2	33.4	33.4	33.6	33.9	42.2	42.1	35.8	35.4	35.4	35.2	35.0	34.7	34.8	34.8	35.2
160	33.9	33.9	35.0	34.0	34.8	35.1	34.8	34.9	40.8	41.5	39.5	38.1	38.5	37.9	38.3	37.0	38.2	36.6	36.8
200	35.2	34.9	35.6	35.1	36.4	36.9	35.5	37.2	38.6	38.4	38.9	38.0	39.9	38.8	38.2	36.7	39.8	38.3	37.4
250	36.1	35.6	36.2	36.9	40.5	39.4	38.2	37.2	38.6	38.7	38.7	38.3	38.9	39.7	37.1	36.7	38.8	39.7	38.1
315	35.8	35.5	36.6	38.9	36.9	37.2	37.8	36.2	42.3	43.1	38.9	39.0	40.5	40.7	38.2	37.9	39.5	38.6	38.5
400	36.5	35.7	37.3	38.0	37.4	37.8	42.2	38.5	44.2	45.5	40.4	41.4	41.8	41.0	39.5	39.4	40.9	40.9	39.9
500	41.0	48.3	41.9	41.7	39.6	40.5	39.0	38.8	44.8	45.0	43.2	44.0	43.7	44.0	42.5	42.6	43.2	44.7	42.7
630	40.1	39.5	44.1	44.2	41.8	38.5	40.7	40.5	46.4	47.0	43.8	44.3	44.5	44.5	42.7	43.5	44.3	44.0	43.0
800	42.7	42.0	40.1	40.5	41.8	41.4	42.0	41.4	45.9	46.4	45.3	46.2	46.2	48.0	45.1	45.2	46.8	46.9	44.1
1k	43.0	42.6	41.6	43.2	47.7	46.6	43.8	42.6	47.8	47.9	46.0	45.8	47.9	48.4	45.7	45.4	46.7	46.7	45.5
1.25k	43.2	43.8	42.1	42.5	47.9	49.3	46.5	44.0	50.6	50.0	48.1	48.1	48.3	50.4	44.5	45.2	48.7	48.2	46.7
1.6k	42.1	42.0	42.0	42.5	45.3	46.2	43.6	43.0	49.2	49.9	48.4	48.8	47.7	50.6	44.1	44.6	45.7	47.0	45.7

	A-weighted Level, dB(A) for Vehicle Sample																		
Frequency, Hz	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
2k	43.3	42.9	41.8	41.8	41.8	41.5	41.6	41.4	51.0	52.2	46.2	46.6	48.2	50.7	43.9	44.7	42.8	43.6	44.8
2.5k	42.1	41.7	42.6	40.4	42.1	42.0	41.8	39.9	47.8	49.2	45.7	47.6	45.1	47.7	46.1	45.2	42.4	43.8	44.1
3.15k	43.1	42.9	42.8	41.6	43.1	41.9	43.1	42.2	46.0	44.9	45.1	46.8	46.1	51.1	43.9	44.1	43.2	44.7	44.3
4k	40.5	40.3	40.4	39.2	39.3	38.4	39.5	38.7	45.8	45.0	45.2	47.0	45.1	50.6	43.3	45.1	40.8	42.9	42.6
5k	37.7	36.9	38.7	36.4	38.2	37.6	37.0	36.2	48.6	47.1	40.5	41.7	41.9	48.0	38.9	41.0	39.8	42.7	40.5
6.3k	35.5	35.0	36.5	34.4	37.6	36.1	33.4	31.8	41.5	41.6	38.9	39.9	39.1	45.7	37.8	39.5	36.6	37.9	37.7
8k	32.0	31.2	33.9	31.0	32.8	31.8	32.1	30.0	36.5	36.6	35.4	36.3	37.7	44.6	33.8	36.2	34.8	36.1	34.6
10k	28.0	26.9	30.2	27.9	30.0	29.0	29.5	27.9	33.6	33.7	33.4	32.2	31.4	38.8	29.5	31.4	32.0	32.6	31.0
12.5k	25.2	25.5	27.2	24.1	23.9	22.5	24.1	22.3	28.7	29.5	28.8	27.8	26.7	33.6	25.9	27.3	27.2	28.4	26.6
16k	21.8	21.9	22.1	19.4	18.8	18.0	21.1	19.6	25.1	26.2	23.8	23.5	20.8	28.1	19.7	21.1	19.3	20.8	21.7
20k	13.6	15.9	12.9	12.4	10.4	10.4	10.5	10.7	17.8	19.9	16.2	15.6	13.6	19.8	12.9	12.8	12.9	14.1	14.0

Table 40. 20 mph Pass-by Levels of ICE Vehicles Measured (Uncorrected) at Cottage Farm

	A-weighted Level, dB(A) for Vehicle Sample																		
Frequency, Hz	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Broadband	70.6	67.7	69.4	71.0	63.6	67.1	70.6	71.2	69.6	69.7	72.3	69.8	73.6	73.9	70.4	70.6	69.5	69.8	69.6
Sum (100 to 20k)	70.7	67.9	69.5	71.1	63.4	67.0	70.6	71.4	69.4	69.4	72.5	69.6	73.8	73.8	70.5	70.5	69.3	69.7	69.7
12.5	-13.0	-12.0	-3.4	-11.6	-7.6	-9.2	-4.8	-8.3	-10.6	-9.2	-11.6	-6.4	-12.3	-6.7	-12.3	-6.4	-10.6	-6.9	-17.0
16	-9.9	-1.5	-4.9	-7.3	-5.0	3.2	-6.6	-4.0	-1.9	-2.4	-4.1	-1.8	-1.1	-5.8	-3.5	-0.2	-1.4	-0.3	-5.0
20	0.1	10.1	-4.0	1.0	5.7	0.6	0.5	3.1	3.5	1.8	2.9	3.0	3.8	2.4	3.3	9.1	5.3	4.5	0.2
25	11.7	7.8	7.9	8.2	5.7	7.4	5.9	11.4	9.1	11.9	4.4	11.2	6.8	6.5	11.2	9.8	10.6	3.1	11.2
31.5	18.0	14.2	14.7	16.6	12.3	12.3	14.8	17.8	13.6	16.8	19.6	16.6	14.1	19.6	10.7	13.7	15.1	11.2	23.3
40	27.4	32.8	27.8	31.6	27.2	24.3	17.5	24.9	18.0	19.0	23.8	17.6	21.0	23.2	19.6	23.2	17.6	20.3	21.8
50	25.7	34.5	30.6	30.0	21.3	25.7	31.4	26.8	26.2	27.1	24.0	22.3	25.9	25.2	21.7	24.6	23.2	24.8	21.8
63	34.5	31.6	33.0	33.9	34.1	35.7	28.2	33.2	31.6	33.7	35.2	30.3	35.5	31.2	34.1	29.7	32.5	28.5	27.2
80	36.8	39.2	37.1	37.9	36.7	33.5	34.9	39.3	34.9	36.4	37.5	37.1	34.7	38.3	36.5	35.4	34.3	36.2	31.4
100	38.8	39.8	38.1	41.0	34.6	35.4	36.8	41.6	35.3	39.7	40.7	37.7	41.1	43.0	39.9	39.8	38.1	37.9	40.4
125	44.4	38.8	41.3	44.3	41.6	38.5	39.5	39.0	40.2	37.8	40.8	40.1	43.2	44.8	44.0	45.8	42.0	46.3	44.6
160	45.1	44.6	44.5	47.0	45.8	42.0	44.9	45.6	39.5	40.4	48.0	43.8	47.3	47.0	46.8	48.1	50.9	49.1	45.6
200	49.1	47.6	47.8	49.6	43.2	44.9	49.2	48.5	44.9	43.6	50.3	45.5	51.6	50.3	48.9	48.4	51.4	48.8	51.1
250	51.7	49.6	51.1	51.6	44.7	47.7	53.7	55.2	51.7	48.8	54.1	50.8	56.1	55.5	51.1	51.1	49.9	49.1	54.1
315	53.2	51.4	52.1	54.3	45.6	46.5	52.1	54.1	51.6	51.4	55.7	53.0	57.7	54.7	52.4	50.0	50.6	51.7	52.8
400	54.3	52.6	53.9	55.5	46.6	50.6	54.3	54.0	52.4	50.5	56.5	51.7	57.4	58.1	56.5	53.9	54.9	54.5	56.0
500	57.0	56.1	56.6	57.9	49.4	53.1	59.6	60.3	56.8	55.7	60.8	55.6	59.6	60.7	58.9	58.7	55.3	56.8	57.3
630	59.5	55.6	57.9	60.6	53.1	56.7	58.9	59.8	56.8	56.8	61.8	58.6	63.3	63.1	60.7	61.2	59.1	59.4	58.4
800	64.5	60.5	63.6	64.5	56.1	59.6	62.1	61.4	60.0	59.7	64.5	63.0	66.8	67.1	64.9	64.8	62.0	63.5	60.8
1k	63.5	60.4	62.1	64.3	55.7	59.8	63.8	64.0	62.3	62.6	66.4	62.9	67.4	67.5	61.9	62.6	61.9	62.2	63.7
1.25k	62.2	59.4	60.7	62.0	55.7	58.9	62.4	64.4	62.0	61.9	64.6	60.7	66.0	65.0	62.0	62.0	61.3	61.7	61.6
1.6k	61.3	58.2	59.5	61.6	54.3	58.2	62.4	63.2	62.2	62.6	63.2	61.0	64.2	64.5	61.0	60.7	60.3	60.1	60.6
2k	59.0	56.4	57.1	58.5	51.6	55.3	59.3	60.8	58.8	58.8	59.0	57.3	59.7	60.2	56.5	56.8	56.2	56.2	57.1

	A-weighted Level, dB(A) for Vehicle Sample																		
Frequency, Hz	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
2.5k	56.2	54.8	54.8	55.9	48.8	52.1	55.2	56.9	55.8	55.4	54.8	52.7	57.0	58.4	54.0	54.3	54.3	53.6	52.7
3.15k	53.2	51.9	52.4	53.5	46.0	49.8	51.9	53.1	51.4	52.7	53.8	52.8	55.4	57.2	50.9	50.2	50.8	50.5	49.4
4k	50.2	49.6	49.1	50.6	43.6	47.9	48.8	49.7	47.6	48.6	50.5	49.8	52.5	54.6	47.7	47.2	48.4	47.9	46.7
5k	46.6	46.0	45.6	47.2	40.5	44.3	45.3	46.2	44.2	46.2	47.8	45.9	48.8	50.6	45.4	44.8	45.7	44.9	43.8
6.3k	43.9	43.5	42.6	45.3	37.4	40.9	42.7	44.0	41.5	44.8	47.3	44.6	46.7	49.1	42.8	41.8	47.1	41.5	39.8
8k	40.9	40.7	40.8	41.9	34.3	38.3	40.2	41.0	38.0	40.9	43.6	41.6	43.1	45.2	39.7	38.4	39.8	38.2	37.1
10k	37.4	37.1	36.2	38.7	30.5	34.8	38.5	37.8	34.2	38.0	40.7	36.9	38.3	40.1	35.7	35.0	34.9	35.3	34.9
12.5k	33.0	32.6	31.9	34.4	25.9	31.1	34.5	32.7	29.4	33.2	37.0	33.2	34.3	36.7	30.4	29.8	29.0	29.6	31.5
16k	28.3	26.7	27.0	29.5	18.7	24.4	30.5	27.9	23.8	27.5	32.1	27.7	30.1	32.5	25.6	25.0	23.0	24.4	27.4
20k	21.5	19.7	20.1	21.5	9.2	16.4	24.6	21.4	15.5	19.7	24.4	19.8	22.3	24.5	18.7	17.8	14.5	16.8	20.1

Table 41. 20 mph Pass-by Levels of ICE Vehicles Measured (Uncorrected) at Cottage Farm

	A-weighted Level, dB(A) for Vehicle Sample																		
Frequency, Hz	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**
Broadband	70.0	70.5	70.8	71.4	71.0	72.9	66.1	67.6	70.0	71.3	70.0	71.6	71.8	72.6	73.3	70.1	68.6	70.3	69.2
Sum (100 to 20k)	69.9	70.4	70.8	71.5	71.0	72.8	66.0	67.9	69.9	71.4	70.0	71.7	71.9	72.6	73.3	70.2	68.4	70.1	69.0
12.5	-14.0	-13.3	-12.6	-6.6	-11.3	-4.1	-7.6	-8.0	-7.3	-5.1	-7.0	-8.3	-16.5	-9.2	-14.5	-11.1	-10.5	-15.2	-11.7
16	-2.5	-6.8	-6.1	-1.6	-1.5	0.7	2.1	-2.8	1.6	-8.0	0.9	0.7	-2.1	-0.1	-5.2	-2.2	-1.0	-9.2	-9.6
20	-1.0	-2.4	-0.1	5.3	2.8	4.0	6.0	3.1	4.0	2.3	-1.8	2.4	7.9	3.1	4.9	2.0	-1.0	-3.6	0.8
25	8.5	17.5	8.9	11.7	7.8	10.3	11.8	7.8	7.1	5.5	9.0	16.2	7.2	12.7	7.6	7.5	5.4	10.5	7.2
31.5	21.3	26.1	26.8	17.0	16.2	15.3	15.9	18.0	14.6	11.8	13.7	16.5	17.8	14.6	16.6	18.3	16.4	15.1	18.8
40	18.2	23.3	19.4	21.4	20.2	22.3	19.1	26.2	24.5	21.0	23.2	18.1	23.2	23.9	21.6	19.5	23.3	24.4	23.9
50	23.7	19.9	21.8	41.0	38.4	36.4	37.4	46.5	35.3	35.1	36.9	31.1	26.8	29.3	32.1	28.2	25.7	24.6	26.4
63	29.5	31.6	33.3	29.4	31.6	26.9	32.9	31.3	29.1	28.3	29.2	29.8	37.6	30.7	34.9	31.2	29.8	28.0	28.7
80	32.7	34.9	33.1	37.2	36.3	34.6	42.2	38.4	34.2	38.3	34.9	36.3	42.3	37.9	35.0	37.5	35.3	36.8	35.2
100	38.1	39.2	37.0	47.0	43.7	40.5	41.7	47.4	39.2	44.4	39.3	39.6	39.8	37.0	36.4	46.1	38.2	41.9	39.4
125	41.1	44.0	43.7	46.1	42.5	41.4	39.3	44.3	39.8	44.9	41.7	40.1	39.8	40.1	38.8	54.7	38.7	44.1	39.8
160	42.0	44.3	43.4	48.5	45.5	44.9	43.1	49.6	46.8	47.4	46.1	43.9	44.4	45.4	45.2	56.1	49.0	51.9	51.6
200	50.3	52.1	52.7	51.1	49.0	48.5	44.8	50.0	50.4	49.5	50.3	46.7	47.8	47.5	47.4	51.8	48.3	50.3	49.5
250	55.0	51.8	54.0	59.3	55.4	55.0	49.7	53.6	54.0	56.3	55.2	55.1	55.5	54.1	53.2	48.3	46.4	50.4	45.9
315	50.5	53.5	53.1	53.8	51.0	53.2	48.6	54.5	53.8	54.8	52.7	54.5	55.9	53.3	55.0	53.0	50.3	55.6	50.1
400	54.0	55.9	55.4	53.8	53.4	53.7	49.3	53.0	54.1	56.6	53.3	55.2	54.6	56.0	56.9	56.0	51.0	56.6	52.8
500	57.2	58.1	56.8	57.8	56.6	57.1	50.7	55.8	57.0	59.6	55.9	58.6	58.2	58.8	61.4	58.0	52.9	57.8	54.8
630	58.0	59.0	59.2	58.7	57.4	59.6	51.9	55.7	58.2	61.0	57.7	62.3	60.7	62.5	61.9	61.3	58.4	61.3	60.9
800	61.6	62.4	62.7	63.7	62.9	63.5	56.1	58.2	60.7	62.7	60.5	64.0	64.3	65.2	65.6	63.1	57.4	62.5	60.4
1k	63.5	64.4	65.0	65.0	63.1	65.5	59.2	60.6	63.8	64.5	63.7	64.8	65.2	66.4	66.2	61.0	61.2	61.0	61.4
1.25k	61.3	62.3	63.4	63.1	62.7	65.2	57.8	59.4	61.5	63.4	62.8	62.7	63.5	64.8	64.8	62.3	63.3	63.1	62.5
1.6k	62.6	61.6	61.9	61.7	61.7	63.2	57.0	59.5	61.3	62.3	60.8	63.4	63.4	63.9	65.5	59.9	59.7	60.3	59.8
2k	57.9	57.6	58.1	59.0	60.4	60.9	55.1	56.8	58.3	58.8	57.8	61.1	60.8	59.6	61.1	56.4	55.8	56.5	55.3

	A-weighted Level, dB(A) for Vehicle Sample																		
Frequency, Hz	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**
2.5k	53.0	53.6	52.9	57.2	57.8	60.1	53.7	53.3	55.2	56.2	55.1	55.6	56.4	56.0	58.0	54.2	52.2	54.5	52.7
3.15k	48.4	50.2	49.3	56.0	58.2	60.8	52.8	49.6	51.9	53.8	52.7	51.7	53.1	53.1	55.8	51.6	47.3	50.8	48.0
4k	45.6	48.4	47.0	53.5	56.2	59.4	51.2	46.3	50.9	52.9	52.4	48.4	51.2	50.1	53.6	48.5	43.9	47.7	44.8
5k	42.0	43.9	43.2	50.3	53.7	56.7	48.8	42.9	47.7	48.4	48.7	45.0	47.6	48.0	51.9	45.3	41.5	45.4	42.3
6.3k	38.3	40.9	39.3	49.0	52.4	56.5	46.7	41.6	45.3	47.4	46.7	41.2	44.1	43.2	47.5	42.8	39.8	42.2	40.4
8k	35.1	38.3	36.6	47.4	52.3	56.0	45.0	37.1	41.4	43.8	43.5	38.3	40.9	41.0	44.4	39.4	35.8	38.1	36.2
10k	32.6	36.3	34.1	40.5	44.7	47.6	36.6	33.8	37.5	39.2	38.8	36.2	37.6	37.9	40.8	35.3	32.0	33.8	31.8
12.5k	28.5	32.1	29.8	34.1	38.0	40.1	29.0	29.2	33.0	35.0	34.2	31.7	33.8	33.7	36.2	31.7	28.1	30.4	27.9
16k	24.2	28.3	25.4	27.7	30.9	33.8	21.2	23.1	27.0	28.4	27.8	24.1	28.2	26.6	29.2	27.2	22.7	25.8	23.2
20k	16.5	19.7	17.6	20.4	22.9	25.0	11.2	22.1	18.3	19.2	18.5	17.4	21.4	19.7	23.5	20.0	16.3	19.1	15.3

Table 42. Cottage Farm ICE Vehicles at Microphone Line - Event with *Minimum* $L_{Aeq1/2sec}$

1/3 Octave Band Center Frequency, Hz	**6 mph, Reverse**	**6 mph, Forward**	**10 mph, Forward**	**15 mph, Forward**	**20 mph, Forward**	**Acceleration**	**Startup**	**Idle**
100 to 20k	54.4	57.2	60.0	62.8	63.4	60.7	65.3	51.6
100	32.0	32.7	31.3	38.4	32.3	NA	36.2	NA
125	34.4	35.0	33.9	37.6	41.0	39.7	35.6	NA
160	34.1	36.9	37.9	39.7	45.6	41.1	40.2	NA
200	36.2	40.9	42.2	44.6	42.8	40.2	43.4	35.3
250	38.2	43.6	44.1	49.6	44.4	41.1	47.4	35.1
315	40.1	41.3	42.7	48.8	45.4	43.1	48.7	34.2
400	40.9	42.6	45.1	46.1	46.5	47.0	50.8	37.5
500	40.9	46.4	48.1	50.2	49.3	45.1	49.0	37.5
630	44.7	46.0	47.4	50.7	53.0	49.7	49.9	39.3
800	42.3	46.4	50.7	52.1	56.1	50.6	52.5	40.0
1k	44.5	49.3	51.8	56.7	55.6	50.4	51.2	41.4
1.25k	46.2	48.1	50.0	55.3	55.7	52.1	53.7	43.4
1.6k	45.8	48.0	49.6	54.0	54.3	53.4	55.6	42.5
2k	43.0	45.2	49.6	50.5	51.6	50.0	54.6	41.0
2.5k	42.1	43.5	49.8	46.4	48.7	48.8	54.2	39.3
3.15k	40.6	43.5	48.1	45.4	45.9	48.6	55.8	41.9
4k	39.4	41.9	44.9	42.5	43.5	46.1	56.4	38.2
5k	37.2	39.2	41.9	39.5	40.4	42.1	55.6	35.9
6.3k	35.2	36.9	39.9	38.1	37.3	40.2	52.6	31.6
8k	32.3	34.1	37.4	34.7	34.3	38.0	48.1	29.9
10k	30.2	31.8	33.7	30.5	30.5	36.4	43.3	27.9
12.5k	25.6	26.9	29.0	26.6	25.9	31.3	40.0	22.3
16k	21.4	22.3	24.5	20.9	18.7	27.5	35.7	19.5
20k	15.1	15.0	16.7	12.1	9.0	19.1	26.8	10.5

Table 43. Cottage Farm ICE Vehicles at Microphone Line – *Average** $L_{Aeq1/2sec}$

1/3 Octave Band Center Frequency, Hz	**6 mph, Reverse**	**6 mph, Forward**	**10 mph, Forward**	**15 mph, Forward**	**20 mph, Forward**	**Acceleration**	**Startup**	**Idle**
100 to 20k	58.4	61.1	63.6	68.1	70.2	66.7	70.7	55.2
100	35.8	35.5	36.3	38.9	39.2	39.7	35.7	36.1
125	36.6	38.4	40.1	41.3	41.5	44.3	36.0	36.3
160	38.3	40.2	42.6	44.9	46.0	45.1	37.3	37.0
200	40.4	41.3	44.3	48.1	48.6	46.7	40.3	36.6
250	41.4	42.8	45.9	50.4	52.2	47.7	40.9	36.5
315	42.1	43.9	46.9	50.2	52.5	49.8	44.2	37.3
400	44.2	46.5	48.7	53.0	54.1	51.4	46.6	39.0
500	45.4	47.9	51.2	55.6	57.1	53.4	51.8	42.1
630	47.0	49.0	52.5	56.9	59.1	54.6	52.4	42.3
800	48.3	51.1	54.6	59.5	62.3	55.1	55.2	43.2
1k	48.7	51.4	55.2	60.2	63.2	55.6	57.8	44.9
1.25k	49.3	52.2	54.6	59.6	62.2	57.2	60.5	46.3
1.6k	48.7	52.0	54.3	58.8	61.3	57.0	61.1	45.4
2k	46.9	50.3	52.0	56.1	57.9	55.7	60.5	44.6
2.5k	46.2	49.1	50.3	53.9	54.9	55.1	61.1	43.8
3.15k	45.6	48.6	49.2	52.4	52.1	54.9	61.6	44.1
4k	44.2	46.9	47.5	50.5	49.5	53.2	60.9	42.4
5k	41.9	44.1	45.0	47.8	46.4	50.8	59.2	40.3
6.3k	39.6	41.8	42.9	45.7	44.0	48.7	56.9	37.6
8k	36.5	39.0	40.0	42.8	40.9	45.9	53.8	34.6
10k	32.6	35.6	36.5	38.9	36.9	42.4	49.4	31.0
12.5k	28.3	31.1	31.9	34.2	32.3	38.0	44.6	26.6
16k	23.1	25.9	26.7	29.1	26.8	32.5	38.8	21.7
20k	15.6	18.2	19.1	21.1	19.2	24.9	30.9	13.9

* Note: Averages in some cases are biased high because some quiet measurements were close or below the ambient level. Rather than overestimate their level, they were excluded from the computation.

Table 44. Cottage Farm ICE Vehicles at Microphone Line - Event with *Maximum* $L_{Aeq1/2sec}$

1/3 Octave Band Center Frequency, Hz	**6 mph, Reverse**	**6 mph, Forward**	**10 mph, Forward**	**15 mph, Forward**	**20 mph, Forward**	**Acceleration**	**Startup**	**Idle**
Sum (100 to 20k)	64.8	63.8	66.3	71.1	73.8	72.9	77.0	59.9
100	41.9	40.2	33.3	37.4	42.7	37.5	35.6	38.3
125	39.9	35.9	40.7	42.2	44.5	41.0	36.3	-16.1
160	41.7	41.0	46.9	45.2	46.9	47.5	36.1	36.7
200	42.1	39.6	43.3	48.6	50.2	48.5	42.8	37.5
250	43.3	41.2	45.9	53.8	55.5	48.0	46.6	38.6
315	43.0	43.3	47.0	52.4	54.7	49.1	55.9	40.1
400	45.2	44.8	47.6	55.9	58.1	51.4	54.3	40.5
500	46.1	48.1	51.2	58.0	60.7	51.8	54.7	43.6
630	49.9	48.8	52.6	59.8	63.1	52.9	59.9	44.1
800	55.3	52.2	56.3	63.7	67.1	59.5	64.4	47.7
1k	53.8	53.7	56.6	64.4	67.5	61.3	63.5	48.1
1.25k	55.6	53.6	56.5	62.1	65.0	61.4	67.6	50.2
1.6k	54.9	54.2	56.2	62.4	64.5	61.7	71.2	50.5
2k	53.6	54.0	56.1	58.0	60.2	63.5	67.5	50.7
2.5k	54.6	52.7	54.8	56.7	58.4	62.8	68.7	47.6
3.15k	55.7	54.9	56.8	55.6	57.2	64.3	66.4	51.0
4k	53.8	53.7	55.1	53.3	54.6	63.4	65.3	50.5
5k	51.8	51.2	53.0	49.8	50.6	61.9	62.5	48.0
6.3k	50.9	49.5	52.3	48.1	49.1	62.0	58.6	45.7
8k	49.3	46.4	50.4	44.7	45.2	61.1	53.8	44.6
10k	42.0	41.4	43.6	39.4	40.1	53.3	50.0	38.8
12.5k	35.7	35.9	37.0	36.0	36.7	46.1	44.2	33.6
16k	29.8	30.7	31.5	32.5	32.5	39.9	39.6	28.1
20k	22.4	22.5	23.6	24.5	24.5	31.2	32.3	19.8

Table 45. Sample Ambient Level During Countermeasure Testing on August 14th, 2010, A-Weighted One-Third Octave Band Levels, dB(A)

1/3 Octave Band Center Frequency, Hz	Minimum	Mean	Maximum
12.5	-12.9	-6.2	-1.3
16	-4.2	0.6	6.2
20	-0.4	6.3	9.8
25	6.4	14.6	18.5
31.5	13.6	22.7	26.9
40	22.9	27.0	31.7
50	25.6	30.5	33.7
63	30.1	34.1	36.8
80	33.4	37.0	42.5
100	39.0	44.4	47.7
125	42.4	46.0	47.9
160	41.4	44.1	46.3
200	43.2	45.5	47.8
250	46.0	49.0	51.6
315	43.9	45.5	46.8
400	45.9	47.0	48.1
500	46.2	47.8	49.3
630	47.7	49.5	50.8
800	47.3	48.7	49.8
1k	46.4	47.8	49.4
1.25k	44.4	45.7	46.9
1.6k	43.1	44.2	46.2
2k	41.9	43.6	45.7
2.5k	36.1	37.1	39.1
3.15k	32.5	33.5	36.5
4k	28.4	29.4	32.4
5k	23.0	24.2	28.3
6.3k	19.7	20.3	23.6
8k	18.1	18.5	20.4
10k	16.6	16.9	18.8
12.5k	15.1	15.4	17.6
16k	14.0	14.4	16.6
20k	12.8	13.0	14.3

Table 46 Comparison of Ambient Level for Left and Right Sides of Binaural Head during Countermeasure Testing

1/3 Octave Band Center Frequency, Hz	SPL in Left Channel (dBA)	SPL in Right Channel (dBA)
12.5	-3.4	-3.7
16	4.3	3.4
20	10.2	10.1
25	17.6	17.2
31.5	21.1	21.4
40	27.8	27.2
50	32.3	32.4
63	36.8	36.6
80	37.7	38.0
100	45.3	45.5
125	47.7	47.4
160	46.4	46.2
200	47.4	46.6
250	49.3	48.2
315	48.2	48.0
400	50.2	49.7
500	49.8	49.1
630	52.4	51.2
800	54.4	51.9
1k	53.7	51.2
1.25k	50.7	48.6
1.6k	48.3	46.1
2k	44.9	43.1
2.5k	38.0	35.9
3.15k	33.9	31.3
4k	32.1	28.9
5k	31.1	25.5
6.3k	26.1	19.5
8k	22.7	16.4
10k	23.7	16.2
12.5k	19.2	16.0
16k	28.6	29.3
20k	28.0	28.9

A.3 Sample Experimental Script

Table 47. Sample Experimental Script: Block A for August 7th Session

Trial #	System	Maneuver	Sound ID	Level	File Name	Direction	Comments
1	A	Pass-by	5	High	P5High	B to A	
2	B	Pass-by	G	High	PGHigh	A to B	
3	E	Pass-by	1	Low	P1Low	A to B	
4	A	Pass-by	1	High	P1High	A to B	
5	No-signal	No-signal	No-signal	No-signal	No-signal	No-signal	40 sec
6	R	Pass-by	n/a	n/a	n/a	B to A	
7	A	Pass-by	1	Low	P1Low	A to B	
8	E	Pass-by	4	Low	P4Low	B to A	
9	D	Pass-by	Off	n/a	n/a	A to B	
10	No-signal	No-signal	No-signal	No-signal	No-signal	No-signal	35 sec
11	A	Pass-by	5	Low	P5Low	A to B	
12	E	Pass-by	3	Low	P3Low	A to B	
13	C	Pass-by	n/a	Low	n/a	B to A	
14	A	Pass-by	2	High	P2High	B to A	
15	No-signal	No-signal	No-signal	No-signal	No-signal	No-signal	30 sec
16	E	Pass-by	3	High	P3High	B to A	
17	C	Pass-by	n/a	High	n/a	A to B	
18	B	Pass-by	G	Low	PGLow	B to A	
19	D	Pass-by	Activated	Max	n/a	A to B	
20	E	Pass-by	4	High	P4High	A to B	
21	No-signal	No-signal	No-signal	No-signal	No-signal	No-signal	30 sec
22	A	Pass-by	2	Low	P2Low	B to A	
23	R	Pass-by	n/a	n/a	n/a	A to B	
24	E	Pass-by	1	High	P1High	B to A	

DOT HS 811 496
October 2011

U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**

NHTSA
www.nhtsa.gov