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of Transportation

**National Highway
Traffic Safety
Administration**

Memorandum

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Subject: **ACTION**: Docket Submittal – Research on Minimum Sound Specification for Hybrid and Electric Vehicles

Date: JUL 3 2012

From: Christopher J. Bonanti
Associate Administrator for
Rulemaking

Reply to
Attn. Of:

To: U.S. DOT Docket No. NHTSA-2011-0148

Thru: O. Kevin Vincent
Chief Counsel

for KV

In support of activities related to the Pedestrian Safety Enhancement Act of 2010, the National Highway Traffic Safety Administration is sharing the attached report titled, "Research on Minimum Sound Specification for Hybrid and Electric Vehicles." The report aimed to identify parameters and criteria for sounds to be detectable and recognizable as the sound of a motor vehicle in operation. Two concepts to identify potential detectability specifications for alert sounds are discussed in the report.

Attachment

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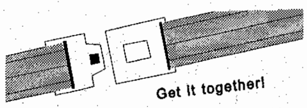

U.S. Department
of Transportation

**National Highway
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Administration**

June 2012

Research on Minimum Sound Specifications for Hybrid and Electric Vehicles

DISCLAIMER

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16. Abstract

This report documents research by the National Highway Traffic Safety Administration (NHTSA) to identify ways to develop sound specifications for electric and hybrid vehicles. The research was conducted to support activities related to the implementation of the Pedestrian Safety Enhancement Act of 2010. The Pedestrian Safety Enhancement Act (PSEA) requires NHTSA to conduct a rulemaking to establish a Federal Motor Vehicle Safety Standard (FMVSS) requiring an alert sound for pedestrians to be emitted by all types of motor vehicles that are electric or hybrid (EVs and HVs). The goal is to establish performance requirements for an alert sound that allows blind and other pedestrians to reasonably detect a nearby EV or HV. The alert sound must not require activation by the driver or the pedestrian, and must allow pedestrians to reasonably detect an EV or HV in critical operating scenarios such as, but not limited to, constant speed, accelerating, or decelerating. Sound specifications would include criteria for sounds to be detectable and recognizable as the sound of a motor vehicle in operation. Two concepts to identify potential detectability specifications for alert sounds are explored: (a) minimum sound levels based on psychoacoustic modeling and detection distances and (b) minimum sound levels based on the sound of internal combustion engine (ICE) vehicles. Potential detectability specifications are discussed in terms of frequency range and minimum sound level for selected one-third octave bands. Also considered is the relative proportion of acoustical energy emitted from a vehicle as a function of direction (directivity). Recognition includes two aspects: recognition that the sound is emanating from a vehicle and recognition of the type of operation that the vehicle is conducting. Potential specifications to aid in recognition are discussed in terms of broadband noise and tones (tone-to-noise ratio) and ways to denote changes in vehicle speed (pitch-shifting as a function of vehicle speed).

17. Key Words

Motor vehicle safety, Pedestrian Safety Enhancement Act of 2010, SAE J2889-1, Electric vehicle, Hybrid vehicle, Moore's Loudness model

18. Distribution Statement

This report is free of charge from the NHTSA Web site at www.nhtsa.dot.gov

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LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of variance
AASHTO	American Association of State Highway and Transportation Officials
dB	Decibel
dB(A)	A-weighted decibel level
ERB	Equivalent Rectangular Bandwidths
EVs	Electric vehicles
ft	Feet
HRTFs	Head-related transfer functions
HEVs	Hybrid-electric vehicles
HV	Hybrid vehicles
ICE	Internal combustion engine
JASIC	Japan Automobile Standards Internationalization Centre
km/h	Kilometers per hour
$\mathbf{L_{Aeq\ 1/2\ sec}}$	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
m	meters
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
s	Seconds
SAE	Society of Automotive Engineers
SLM	Sound level meter
SPL	Sound pressure level
TRC	Transportation Research Center
USDOT	United States Department of Transportation
Volpe Center	Volpe National Transportation Systems Center
VRTC	Vehicle Research Test Center, NHTSA

Acoustic Definitions

Ambient	Relating to the immediate environment or surroundings. Generally refers to unwanted sounds. In an acoustic measurement, after the main sound being studied is suppressed or removed, this is the remaining sum of sounds taken from the environment of the measurement.
Attenuation	A decrease in the intensity of a sound.
Auditory filter	A measure of the auditory systems frequency selectivity. An auditory filter is a band pass filter that closely approximates the shape of a rounded exponential filter or, to a lesser degree, a one-third octave band filter.
A-weighting	A filter that attenuates low and high frequencies and amplifies some mid-range frequencies. The A-weighting curve approximates the equal loudness contour at 40 dB.
Bandwidth	Range of frequencies. For example, a speaker may have an effective bandwidth from 150 to 5000 Hz. Alternatively, it is the minimum frequency subtracted from the maximum frequency. For the above example, this would be 5000 – 150 or 4850 Hz.
Basilar membrane	A membrane inside the cochlea that supports the organ of corti and vibrates as a response to sound.
Broadband	Signal with a spectrum that covers a broad range of frequencies.
Broadband levels	Levels regarding signal quantities that cover a wide range of frequencies.
Co-modulation masking release	The phenomena whereby masking effects are reduced to the cues provided by modulation that is correlated between both ears.
Directivity	The relative proportions of acoustical energy that are emitted from a source as a function of direction, typically expressed in polar coordinates.
Doppler effect	Change in the frequency of a sound wave due to the relative velocity between the source and the observer. As the sound source approaches the observer, the frequency is perceived to be higher and as it moves away it is perceived to be lower.
Equivalent Rectangular Bandwidth (ERB)	An idealized rectangular filter with a bandwidth defined such that it passes the same energy as an associated auditory filter. A set of contiguous ERB filters can be used to represent the frequency scale in a psychoacoustic sense. For example, an auditory filter centered at 1000 Hz has an equivalent rectangular bandwidth of 132 Hz and it takes 15.6 contiguous equivalent rectangular bandwidths to cover the auditory range below 1000 Hz. An auditory filter centered at 4000 Hz has an equivalent rectangular bandwidth of 456 Hz and it takes 27.1 contiguous equivalent rectangular bandwidths to cover the auditory range below 4000 Hz.

Free field	A sound field without boundaries such that sound is not reflected or scattered.
Frequency	Number of times a particle in a medium contracts and expands (cycles) per unit of time. Typically expressed in Hertz (Hz); one cycle per second is equal to 1 Hz. Humans can detect sound waves with a wide range of frequencies, nominally ranging between 20 to 20,000 Hz.
Fundamental frequency	The lowest frequency of a waveform.
Head-related transfer functions	Essentially a frequency response that is also a function of angle. It accounts for how a sound changes to an observer due to the relative position of the source and the head, pinna, and torso of the observer.
Loudness	Attribute of an auditory sensation that humans can use to judge sound intensity. Loudness is used to rank sounds on a scale from quiet to loud.
Loudness contours	Graphical representation of frequency (x-axis) versus levels (y-axis) such that tones of different frequency and different level are judged to be equally loud.
Octave	Also called octave band, Interval between two frequencies that have a ratio of 2:1. The range of human hearing covers approximately 10 octaves. For example, if the first octave is 20 to 40 Hz the next octave is 40 to 80 Hz, the next is 80 to 160 Hz, etc.
One-third Octave Band	Frequency band that is one-third of an octave band or whose lower and upper limits are 21/3 times the center frequency apart, as defined by their half-power points. For example a one-third octave band centered at 1000 Hz has upper and lower cutoff frequencies at about 890 and 1120 Hz and a bandwidth of 230 Hz. A one-third octave band centered at 4000 Hz has upper and lower cutoff frequencies at about 3560 and 4490 Hz and a bandwidth of 930 Hz.
Periodic modulation	A signal variation that is governed by a periodic function.
Power spectral density	A spectral estimation of a signal with, for sound signals, units of Pa^2 / Hz

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Executive Summary

This report documents research by the National Highway Traffic Safety Administration (NHTSA) to support activities related to the implementation of the Pedestrian Safety Enhancement Act of 2010.

The Pedestrian Safety Enhancement Act of 2010 requires NHTSA to conduct a rulemaking to establish a Federal Motor Vehicle Safety Standard (FMVSS) requiring an alert sound for pedestrians to be emitted by electric or hybrid vehicles (EVs and HVs). The FMVSS would establish performance requirements for an alert sound that allows pedestrians to reasonably detect an EV or HV in critical operating scenarios such as, but not limited to, constant speed, accelerating, or decelerating (Public Law 111-373, 124 Stat 4086, 2011).

The report also includes project history, an overview of international activities, and a summary of previous research by NHTSA.

PURPOSE

The purpose of this research is to identify parameters and criteria for sounds to be detectable and recognizable as the sound of a motor vehicle in operation. Two concepts to identify potential detectability specifications for alert sounds are explored: (a) minimum sound levels based on psychoacoustic modeling and detection distances and (b) minimum sound levels based on the sound of internal combustion engine (ICE) vehicles. The relative proportion of acoustical energy emitted from a vehicle as a function of direction (directivity) is also considered. Recognition includes two aspects: recognition that the sound is emanating from a vehicle and recognition of the type of operation that the vehicle is conducting.

METHODS

The John A. Volpe National Transportation Systems Center (Volpe Center), which is an element of the U.S. Department of Transportation, Research and Innovative Technology Administration, conducted this work under an inter-agency agreement with the National Highway Traffic Safety Administration (NHTSA). The researchers used psychoacoustic modeling, acoustic measurements and analyses, and sound simulations to meet the objectives of this study. The methods used are summarized below.

Minimum Sound Levels for Detection based on Psychoacoustic Model

Psychoacoustics is the study of how humans perceive sound and forms the basis for extracting objective data from the physical characteristics of acoustic pressure to quantify how humans perceive the loudness, pitch, and timbre of a sound. Humans interpret these psychological dimensions subjectively but some of them, such as loudness, can be quantified through psychoacoustic modeling. Loudness is an attribute of an auditory sensation that humans can use to judge sound intensity. Moore's Partial Loudness model (Moore and Glasberg, 1997) is used in this study to estimate the minimum sound level needed for a sound to be detectable in the presence of an ambient.

The inherent assumptions for this approach are that:

- sounds should be detectable in multiple one-third octave bands in the presence of an ambient;
- a psychoacoustic model can be used to determine minimum levels for detection of one-third octave bands in the presence of an ambient;
- minimum detection distances can be based on the stopping sight distance used in highway design, and
- a vehicle should be detectable based on a moderate suburban ambient (i.e., ambient at 55 dB(A)).

The use of psychoacoustic models in identifying acoustic parameters for an alert sound indicated which one-third octave bands contribute the most to a pedestrian's ability to detect vehicles and the minimum sound level needed for each of these bands. Minimum levels for detection, as computed using Moore's Loudness model and a simplified ambient at 55 dB(A), are first provided for a pedestrian at the vehicle location, that is, at a location 2 m from the center of the front plane (i.e., SAE J2889-1 microphone location). Of interest are the minimum sound levels at a distance at which a pedestrian would need to hear a vehicle in order to make a decision about whether or not it is safe to proceed. The distance at which a pedestrian would need to hear a vehicle is at least as long as the vehicle's stopping sight distance. The levels were then extrapolated to the critical distances required for each operating condition using an assumed attenuation of 6 dB per distance doubling.

Acoustic Parameters for Directivity

Detectability of a sound depends not only on the measured level and the change due to distance, but also depends on the relative change in level due to the orientation between the vehicle and the subject at the time of detection. Directivity refers to the relative proportions of acoustical energy that are emitted from a source, in this case a vehicle, as a function of direction (e.g., front, back, left, and right). The measurement procedure in this study consisted of measuring the overall sound pressure level of a 'stationary but activated' vehicle with microphone heights and orientations as described in SAE J2889-1, *Measurement of Minimum Noise Emitted by Road Vehicles*. The actual location of the microphones and the measurement procedure did not follow SAE J2889-1 because the purpose of the current test was to characterize sound levels around the vehicle, rather than to measure the level at a single point in space. Eight microphones were located around the perimeter of the vehicle. Two microphones were in the same locations as for the pass-by testing in SAE J2889-1.

Minimum Sound Levels for Detection based on Acoustic Characteristics of ICE Vehicles

The inherent assumption for this approach is that ICE vehicles produce adequate sound levels for detectability. Acoustic data for several ICE vehicles were analyzed and compared based on overall sound pressure levels by computing histograms of the data with a resolution of 1 dB. Mean values were computed as well as 95% and 99% prediction intervals by assuming normal distributions. A prediction interval is used to describe the interval within which a future sample is expected to fall with a given degree of certainty. Prediction intervals in this report were computed using the normal distribution. One-third octave band spectra were analyzed to compute minima, maxima, and mean values for each operating condition as well as 95% and

99% prediction intervals by assuming normal distributions. Means, minima, and maxima were computed for each band independently.

Acoustic Parameters for Recognition

The Volpe Center created a sound simulation program in MATLAB®[1] to facilitate the identification of acoustic parameters for alerting sounds that are associated with recognition of vehicle sounds. Sound simulations were developed for stationary but activated, constant speed pass-bys, and accelerating pass-bys. Pass-bys included Doppler shifts and accelerations also included a pitch shifting tied to vehicle speed. Levels changed as a function of speed and as a function of position relative to the receiver. Roughly two hundred sounds were generated and evaluated. Sounds produced by ICE vehicles were used as baseline so that alert sounds for HVs and EVs include similar cues to the sounds that pedestrians associate with current ICE vehicles.

RESULTS

The key findings of this study are summarized below.

Minimum Sound Levels for Detection based on Psychoacoustic Model

Results showed that opportunities for detection will be maximized if the alert signal contains detectable components over a wide frequency range; therefore minimum levels are prescribed for a set of one-third octave bands that includes mid-frequency one-third octave bands (315, 400, and 500 Hz) as well as high frequency one-third octave bands (2000, 2500, 3150, 4000, and 5000 Hz). Low frequency bands (below 315 Hz) are omitted due to the expected strong masking effects of the ambient at low frequencies and the likelihood that many practical alert devices may not be able to produce high level – low frequency sounds. Mid-frequency bands from 630 to 1600 Hz are omitted because analysis indicated that, for the ambient considered, these bands contributed more to the overall level than other bands for the same increase in detectability.

Table E1 shows the minimum sound levels for detection for this approach. These sound levels are based on minimum detection levels 2 m in front of the vehicle for stationary but activated, 5 m in front of the vehicle for 10 km/h, 11 m for 20 km/h and 19 m for 30 km/h. Levels for 'backing' or 'reverse' are based on the forward 10 km/h levels but adjusted down 3 dB to represent equivalent reductions in level of ICE vehicles at the back. For reference, overall levels are given at the bottom of the table for measurements according to SAE J2889-1. Because the one-third octave bands in the table were selected based on their contribution to detection, a sound meeting the minimum overall level will not necessarily be as detectable as a sound meeting the minimum level for each one-third octave band.

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[1] MATLAB, a product from MathWorks, is a programming tool that can be used for data analysis, algorithm development, and visualization.

Table E1: Minimum A-weighted Sound Levels for Detection based on Loudness model, dB(A)

One-Third Octave Band Center Frequency, Hz	0 km/h	Reverse	10 km/h	20 km/h	30 km/h
315	42	45	48	54	59
400	43	46	49	55	59
500	43	46	49	56	60
2000	42	45	48	54	58
2500	39	42	45	51	56
3150	37	40	43	49	53
4000	34	36	39	46	50
5000	31	34	37	43	48
Overall A-weighted SPL Measured at SAE J2889-1	49	52	55	62	66

Acoustic Parameters for Directivity

One of the scenarios of interest is vehicle backing. Acoustic measurements of ICE vehicles show that sound levels at the rear sides and rear center of the vehicle are generally 3 and 6 dB lower, respectively, than what is measured at the SAE 2889-1 microphones when the front of the vehicle is in line with the SAE microphones. If the directivity of conventional, ICE, vehicles is used to estimate directivity parameters for electric and hybrid vehicles, then, measurements made at the back of the vehicle should be no lower than 3 dB less than measurements made according to SAE J2889-1.

Minimum Sound Levels for Detection based on Acoustic Characteristics of ICE Vehicles

Two versions of potential minimum sound levels based on measured ICE levels are provided, one based on the mean levels (Table E2) and one based on the mean levels minus one standard deviation (Table E3). Levels for 'backing' or 'reverse' are based on the forward 10 km/h levels but adjusted down 3 dB to represent equivalent reductions in level of ICE vehicles at back. For reference, overall levels are given at the bottom of the table for measurements according to SAE J2889-1. Each one-third octave band in the table contributes to the character of the sound, therefore, under this approach the sound would have to meet the minimum level for each one-third octave band not just the overall level.

Table E2: Minimum A-weighted Sound Levels for Detection based on ICE Mean Levels, dB(A)

One-Third-Octave Band Center Frequency, Hz	0 km/h	Reverse	10km/h	20km/h	30km/h
315	40	42	45	52	55
400	41	44	47	53	57
500	43	45	48	54	59
2000	44	46	49	55	59
2500	44	46	49	53	56
3150	43	44	47	52	54
4000	41	42	45	49	51
5000	37	40	43	45	48
Overall A-weighted SPL Measured at SAE J2889-1	51	53	56	61	65

Table E3: Minimum A-weighted Sound Levels for EV and HV based on ICE Mean Levels minus 1 Standard Deviation, dB(A)

One-Third-Octave Band Center Frequency, Hz	0 km/h	Reverse	10km/h	20km/h	30km/h
315	34	37	40	48	52
400	35	40	43	49	53
500	37	42	45	51	56
2000	39	42	45	50	54
2500	39	41	44	49	51
3150	39	40	43	47	49
4000	36	37	40	42	44
5000	29	34	37	38	40
Overall A-weighted SPL Measured at SAE J2889-1	46	49	52	57	61

Acoustic Parameters for Recognition

Based on initial assessment and engineering judgment, at least one tone (and preferably more) should be included for the purpose of recognition. The lowest tone should have a frequency no greater than 400 Hz. Tones at frequencies above 2000 Hz could be included for purposes of detection rather than recognition. A component is considered to be a tone if the Tone-to-Noise ratio according to ANSI S1.13-1995 is greater than or equal to 6 dB. Broadband components, which may be modulated, should be in each one-third octave band from 160 Hz to 5000 Hz as the bands contribute to both detection and recognition.

A potential parameter for recognition of vehicle acceleration and deceleration is pitch-shifting of pedestrian-alert sounds. Simulations of pitch shifts of different rates as a function of speed change were evaluated. Based on these sounds and engineering judgment, it was determined that a suitable minimum pitch shift rate would be an increase of 1% of the tone frequency per 1 km/h increase of vehicle speed. That is, at a minimum, the frequency of pitch producing components (tones) must vary in proportion to vehicle speed and shift by at least 1% for each 1 km/h change in vehicle speed. Other considerations to aid in recognition are described in this report.

SUMMARY

The results of this study provide information to assist in the development of specifications for alert sounds to be emitted by electric and hybrid vehicles. Potential detectability specifications are discussed in terms of frequency range and minimum sound level for selected one-third octave bands. Two concepts to identify potential detectability specifications for alert sounds are explored: (a) minimum sound levels based on psychoacoustic modeling and detection distances and (b) minimum sound levels based on the sound of ICE vehicles. Minimum sound levels are provided for 0, 10, 20, and 30 km/h. Acoustic data for directivity is used to estimate minimum sound levels for 'reverse' or 'backing' maneuvers. Potential specifications to aid in recognition are discussed in terms of broadband noise and tones (tone-to-noise ratio) and ways to denote changes in vehicle speed (pitch-shifting as a function of vehicle speed). A possible method to identify tones and different ways for measuring pitch-shifting are discussed.

1. Introduction

This research was conducted to support activities related to the implementation of the Pedestrian Safety Enhancement Act of 2010. The Pedestrian Safety Enhancement Act (PSEA) requires NHTSA to conduct a rulemaking to establish a Federal Motor Vehicle Safety Standard (FMVSS) requiring an alert sound for pedestrians to be emitted by all types of motor vehicles that are electric or hybrid (EVs and HVs). The goal is to establish performance requirements for an alert sound that allows blind and other pedestrians to reasonably detect a nearby EV or HV. The alert sound must not require activation by the driver or the pedestrian, and must allow pedestrians to reasonably detect an EV or HV in critical operating scenarios such as, but not limited to, constant speed, accelerating, or decelerating (Public Law 111-373, 124 Stat 4086, 2011).

Acoustic measurements and analyses were completed to support the development of potential specifications for alert sounds and the development of a test procedure for compliance with agency requirements. This report documents work completed to assist in the development of specifications for alert sounds. The goal of this research is to identify parameters and criteria for sounds to be detectable and recognizable as the sound of a motor vehicle in operation. Two concepts to identify potential detectability specifications for alert sounds are explored: (a) minimum sound levels based on psychoacoustic modeling and detection distances and (b) minimum sound levels based on the sound of internal combustion engine (ICE) vehicles. Recognition includes two aspects: recognition that the sound is emanating from a vehicle and recognition of the type of operation that the vehicle is conducting.

This report identifies potential parameters and criteria for sounds to be detectable and recognizable as the sound of a motor vehicle in operation. Detectability specifications are discussed in terms of frequency range and minimum sound level for selected one-third octave bands. Also considered is the relative proportion of acoustical energy emitted from a vehicle as a function of direction (directivity). Potential specifications to aid in recognition are discussed in terms of broadband noise and tones (tone-to-noise ratio) and ways to denote changes in vehicle speed (pitch-shifting as a function of vehicle speed).

The report is organized in seven chapters. Chapter 2 includes project history, an overview of international activities, and a summary of previous research by NHTSA. The minimum sound levels for detectability of EV and HV sounds based on psychoacoustic modeling and detection distances are documented in Chapter 3. Chapter 4 presents the minimum sound level for detectability of EVs and HVs based on acoustic characteristics of ICE vehicles. Results for directivity analyses are presented in Chapter 5. Acoustic properties for recognition are discussed in Chapter 6. Results of this research and possible topics for future research are summarized in Chapter 7.

The John A. Volpe National Transportation Systems Center (Volpe Center), which is an element of the U.S. Department of Transportation (U.S. DOT), Research and Innovative Technology Administration (RITA), conducted this work under an Inter-Agency Agreement (IAA) with NHTSA.

2. Background

2.1 Project History

On May 30, 2008, NHTSA published a notice in the Federal Register announcing that the agency would hold a public meeting on June 23, 2008 for government policymakers, stakeholders from organizations representing people who are blind or visually impaired, industry representatives, and public interest groups to discuss the technical, environmental and safety issues associated with EVs, HVs, and quiet ICE vehicles, and the safety of pedestrians. NHTSA encouraged participants to add comments and ideas to the docket. NHTSA issued a research plan to investigate the topic of quieter vehicles and the safety of pedestrians on May 6, 2009 and has been hosting a series of roundtable meetings with industry, technical organizations and groups representing people who are blind since 2009.

The Society of Automotive Engineers (SAE) established the Vehicle Sound for Pedestrians (VSP) subcommittee in November 2007 with the purpose of developing a recommended practice to measure sounds emitted by vehicles and alert sounds for use on EVs and HVs. Their efforts resulted in standard SAE J2889-1, Measurement of Minimum Noise Emitted by Road Vehicles, published in September 2011. NHTSA has been participating as liaisons to the VSP since 2008.

In September 2009, NHTSA published a technical report documenting the incidence of crashes involving hybrid-electric passenger vehicles and pedestrians and pedalcyclists (Hanna, 2009). The results of the crash data analysis showed that HVs 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 at which the difference between the sounds emitted by ICE vehicles and HVs is substantial (Hanna, 2009). A recent analysis updated and verified these previous findings by adding additional years of state crash files and by increasing the number of states included in the analysis from 12 to 16, with a total of 24,297 HVs (approximately three times the HVs of the 2009 study) and 1,001,000 ICE vehicles by Honda and Toyota, with five different models, in 16 States during 2000-2008. The updated analysis indicates that a total of 186 HVs and 5,699 ICE vehicles were involved in pedestrian crashes. A total of 116 HVs and 3,052 ICE vehicles were involved in crashes with bicycles. A statistical analysis indicates that the odds of an HV being in either a pedestrian or bicycle crash is greater than the odds of an ICE vehicle being in a similar crash, 35 percent higher for pedestrian crash odds and 57 percent higher for bicycle crash odds (Wu, Austin, and Chen, 2011).

In April 2010, NHTSA issued a report presenting results of Phase 1 of the agency's research (Garay-Vega, Hastings, Pollard, Zuschlag, and Stearns, 2010). The report identifies critical safety scenarios for blind pedestrians and documents the overall sound levels and spectral content for a selection of ICE vehicles and HVs in different operating conditions. The auditory detectability of these vehicles was evaluated for two background noise levels in a controlled experiment. The report also discusses countermeasure concepts that are categorized as vehicle-based, infrastructure-based, and systems requiring vehicle-pedestrian communications. NHTSA initiated additional research (Phase 2) in March 2010 to identify concepts that could be used to specify vehicle sounds that would provide information at least equivalent to the cues provided by ICE vehicles in specific low speed conditions, including speed change (Hastings, Pollard, Garay-Vega, Stearns, and Guthy, 2011). Acoustic data from a sample of ICE vehicles was used to determine the sound levels at which synthetic vehicle sounds could be set. Psychoacoustic models and human-subject testing were used to explore issues of detectability, masking, and recognition of ICE-like and alternative sounds. The report discusses various concepts that could be used to specify sounds for detectability including: recording(s) of actual ICE sounds; synthesized ICE-equivalent sounds; alternative, non-ICE-like sounds designed for detectability; and a hybrid of these concepts.

In 2009, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan assembled a committee to study the issue of the quietness of HVs. 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 (Japan Automobile Standards Internationalization Centre, 2009). 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 Japan Automobile Standards Internationalization Centre, 2010).

The United Nations Economic Commission for Europe (UNECE) World Forum for Harmonization of Vehicle Regulation (WP.29) determined that road transportation vehicles propelled in whole or in part by electric means present a danger to pedestrians and directed the Working Party on Noise (GRB) to assess what necessary steps WP.29 should take to help mitigate the problem. In response, GRB established an informal group on Quiet Road Transport Vehicles (QRTV) to carry out the necessary activities to address the quieter vehicles issue and the potential need for global harmonization. NHTSA has been participating in the QRTV's meetings since its foundation in 2010 and has kept the group informed about ongoing agency research activities as well as the results from completed research studies.

Automotive manufacturers that produce EVs for the U.S. market have developed various pedestrian alert sounds. Manufacturers of HVs had not typically been equipping those vehicles with alert sounds for the U.S. market. As of the date of this writing, the authors have knowledge of only one system in the U.S. market; others are under development. Some manufacturers have made vehicles with sound alert systems available for lease by NHTSA for research purposes. Nissan has developed a system called Approaching Vehicle Sound for Pedestrians (VSP) for the 2011 Nissan Leaf (Konet et al, 2011). The system consists of a digital sound synthesizer connected to a speaker mounted under the hood of the vehicle and a sound control system. The VSP has an on/off switch for temporary deactivation by the driver. A forward sound activates at low speeds, fades off as the vehicle reaches 30 km/h, and fades back on as the vehicle speed reduces to 25 km/h. The pitch increases proportionally with vehicle speed. A unique sound is activated when the gear is in "reverse" and when the vehicle starts from a stopped position. No sound is emitted when the vehicle is in "drive" gear but stationary. A sound is emitted when the vehicle is stationary and in "reverse" gear. The VSP was set to have a similar sound pressure level as a Nissan Versa 1.8L at 10 km/h while having two peaks at 630 Hz and 2500 Hz, and a valley at 1000 Hz (Konet et al, 2011).

On January 4, 2011, the Pedestrian Safety Enhancement Act of 2010 (PSEA) was signed into law (Public Law 111-373). The PSEA requires NHTSA to conduct a rulemaking to establish a FMVSS requiring an alert sound for pedestrians to be emitted by EVs and HVs. The goal is to establish performance requirements for an alert sound that allows blind and other pedestrians to reasonable detect a nearby EV or HV. In early 2011, NHTSA initiated additional research to support rulemaking activities related to PSEA. Acoustic measurements and analyses were completed to support the development of potential specifications for alert sounds and the development of test procedure for compliance with agency requirements.

More information about previous research by NHTSA (Phase 1 and Phase 2) is presented below.

2.2 NHTSA Phase 1 Research

In April 2010, NHTSA issued a report presenting results of the agency's research (Phase 1). This research is summarized here and documented in NHTSA's Final Report No. DOT HS 811 304 (Garay-Vega, Hastings, Pollard, Zuschlag, and Stearns, 2010).

2.2.1 Scenarios

As part of Phase 1 research NHTSA sought to identify operating scenarios necessary for the safety of pedestrians who are blind. The researchers identified these scenarios based on literature reviews, crash data, and conversations with blind pedestrians and orientation and mobility specialists. The scenarios identified were:

- Vehicle approaching at a low constant speed (6 mph and 10 mph)
- Vehicle backing up at 5 mph (as if coming out of a driveway)
- Vehicle slowing from 20 to 10 mph (mimicking a vehicle preparing to turn right from the parallel street)
- Vehicle accelerating (from 0 to 10 mph)
- Vehicle stationary

2.2.2 Acoustic Measurements

The study aimed to investigate the acoustic characteristics (overall sound levels and spectral content) for HVs and ICE vehicles in the operating conditions listed above. The study also examined sound pressure levels as a function vehicle type (HVs and ICE vehicles) and speed (0, 10, 20, 30, and 40 mph). Test vehicles included three HEVs (Honda Civic, Toyota Prius, and Toyota Highlander) and their ICE twins (the Toyota Matrix serves as a twin for the Toyota Prius).

Phase 1 work follows recommendations of the SAE J2889-1 (a draft test procedure at the time of the study) with regard to instrument settings, calibration, meteorological monitoring, etc.; however, it deviates from the SAE method with respect to operating condition, data measured, as well as height, distance, and orientation of the microphones. For each measurement, one-half second contiguous average sound pressure levels were measured. The maximum of these for each event were analyzed for the development of Table 1. These levels are representative of the sound level when the vehicle is at or near the microphone line (line PP' in SAE J2889-1, Figure 1). Average A-weighted sound levels for each of the six vehicles tested are reported in Table 2.

Table 1: Maximum A-Weighted Sound Level, L_{Amax}, dB(A), at the Microphone Location (12 ft)

Scenario / Vehicle Operation	2010 Toyota Prius	2009 Toyota Matrix	Honda Civic Hybrid	Honda Civic ICE	2009 Toyota Highlander Hybrid	2008 Toyota Highlander
Approaching at 6 mph	45.1	54.2	49.5	52.6	54.9	55.9
Backing out (5 mph)	44.8	51.5	49	58.9	48.6	53.1
Slowing from 20 to 10 mph	53.4	54.6	57.2	55.3	53.7	55.8
Acceleration	63.1	63.6	65.8	63.8	65.0	65.6
Idling / Stationary but activated	background	48.1	45.1	46.4	background	48.5

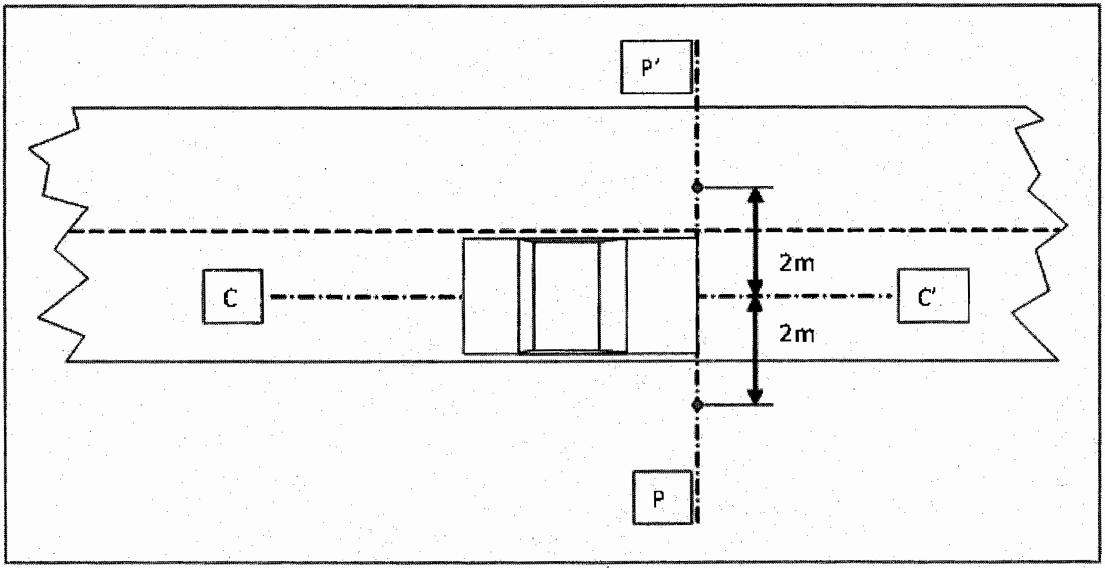

Figure 1: Microphone Line (PP') Relative to Vehicle Assuming Engine Mounted in Front of Vehicle. Vehicle Centerline is Labeled CC'

Table 2: Average A-Weighted Sound Level, $L_{Aeq0.5s}$, dB(A), at the Microphone Location (12 ft)

Scenario / Vehicle Operation	2010 Toyota Prius	2009 Toyota Matrix	Honda Civic Hybrid	Honda Civic ICE	2009 Toyota Highlander Hybrid	2008 Toyota Highlander
Approaching at 6 mph	44.7	53.5	49.3	52.0	53.2	55.5
Backing out (5 mph)	44.2	51.3	48.5	58.2	45.9	52.7
Slowing from 20 to 10 mph	53.0	54.2	56.6	55.0	53.0	55.4
Acceleration	62.9	63.1	65.4	63.5	64.8	64.9
Idling / Stationary but activated	background	47.8	44.8	46.0	background	48.1

The results of acoustic measurements in Phase 1 showed that:

- The sound levels for HEVs approaching at a constant speed of 6 mph were 2 to 8 dB lower than for ICE vehicles tested.
- Sound levels for the HEVs and ICE vehicles converge at higher speeds. The speed at which the vehicles converge varies among the three sets of vehicles tested. ICE vehicles converge with the HEVs tested after 10 mph, except for the Toyota Prius, which converges with the Matrix after 20 mph.
- The sound levels for HEVs traveling in reverse at 5 mph were 7 to 10 dB lower than the overall sound levels for ICE vehicles tested.
- The overall sound levels for HEVs and ICE vehicles did not differ considerable when slowing from 20 mph to 10 mph.
- There is a trend for HEVs to have less high frequency content relative to the overall sound level compared to ICE vehicles. There is an exception to this trend with a notable peak in the Toyota vehicles tested in the 5 kHz one-third octave band sound level when slowing or braking.
- The sound levels for the Toyota hybrids when stationary were too low to be measured under the ambient condition present.

2.2.3 Human Subjects Experiments

In Phase 1, NHTSA examined the auditory detectability of HVs and ICE vehicles by pedestrians who are legally blind. Forty-eight independent travelers, with self-reported normal hearing, listened to binaural audio recordings of two HVs and two ICE vehicles in three operating conditions, and two different ambient sound levels. Binaural recordings reproduce the acoustic characteristics of the sound similar to how a human perceives it. Binaural recordings reproduce a more realistic three dimensional sensation than conventional stereo and are intended for playback through headphones, rather than loudspeakers. The operating conditions included a vehicle: approaching at a constant speed (6 mph); moving in reverse at 5 mph (as if backing out of a driveway/parking spot); and slowing from 20 to 10 mph (as if to turn right). The ambient sound levels were a quiet rural (31.2 dB(A)) and a moderately noisy suburban ambient (49.8 dB(A)).

Data collection included missed detection frequency and response time (and corresponding time-to-vehicle arrival and detection distance). Missed detection frequency is defined as instances when the target vehicle is present and the participant fails to respond. Response time is computed as the time from the start of a trial to the instant the participant presses a space bar as an indication he/she detects the target vehicle. Time-to-vehicle-arrival is the time from first detection of a target vehicle to the instant the vehicle passes the microphone line/pedestrian location. Detection distance is the longitudinal space between the vehicle and the pedestrian (microphone) location at the instant the participant indicated detection of a target vehicle. A repeated measure of analysis of variance (ANOVA) was used to analyze the main and interaction effects of the independent variables; vehicle type, vehicle maneuver and ambient sound level. A separate analysis was completed for each scenario; a pair-wise t-test compared each vehicle with the other (ICE vehicle and HV twins) for each ambient sound level. Time-to-vehicle arrival for each vehicle-ambient condition is shown in Table 3, Table 4, and Table 5 for each of three scenarios.

Vehicle Approaching at 6 mph (9.6 km/h) Pass-by[2]*:* The first traveling situation examined was a pedestrian standing on the curb waiting to cross a one-way street when there may be vehicles approaching from the left. Some trials included a target vehicle and some trials only included background noise. The target vehicle in this scenario was traveling from the left at a constant speed of 6 mph. There were vehicles in the background in all trials. The pedestrian had to be able to detect a vehicle that would affect their decision about when to start crossing the street. This scenario tested the distance and time at which a pedestrian can detect a vehicle approaching at low speed. On average, participants took 1.1 s longer to detect vehicles in the high ambient sound condition than in the low ambient sound condition. The main effect of ambient was statistically significant. The mean time-to-vehicle-arrival was 5.5 and 4.3 s for the low and high ambient condition respectively. Participants detected both ICE vehicles sooner than the HV twins. The main effect of vehicle type was statistically significant. The interaction effect of vehicle type and ambient was also statistically significant. Table 3 presents the individual differences between ICE vehicles and their HV peers (i.e., Prius vs. Matrix and Highlander hybrid vs. Highlander ICE); pair-wise comparisons are statistically significant within a given ambient condition. Participants were more likely to miss the Toyota HVs than the Toyota ICE vehicles approaching at a constant low speed. The missed detection rates in the low ambient condition were: 0.02 for the Prius; 0.01 for the Matrix; 0.03 for the Highlander Hybrid; and 0.0 for the Highlander ICE vehicle. The corresponding values in the high ambient condition were: 0.21 for the Prius; 0.02 for the Matrix; 0.04 for the Highlander; and 0.01 for the Highlander ICE vehicle.

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[2] Scenarios were evaluated using binaural recordings and headphones.

Table 3: Time-to-Vehicle Arrival and Detection Distance for 6 mph Vehicle Pass-by by Vehicle Type and Ambient Condition

Vehicle	Ambient Sound Level	Time-to-Vehicle Arrival (s)	Detection Distance (ft)
2010 Toyota Prius	Low	4.3	37.9
	High	2.4	20.9
2009 Toyota Matrix	Low	5.5	48.4
	High	4.6	40.5
2009 Highlander Hybrid	Low	5.3	46.6
	High	4.1	36.6
2008 Highlander ICE	Low	6.8	59.4
	High	6.3	55.1

Vehicle Backing Out (5 mph (8 km/h) Reverse)[3]*:* The second traveling situation was a pedestrian walking along a sidewalk with driveways on the left side; the pedestrian heard distant vehicles in the background in all trials. This is similar to walking in an area that is a few blocks away from a main road. The target vehicle was a nearby vehicle backing towards the pedestrian at a constant speed of 5 mph. This task is complex for pedestrians since it is difficult to anticipate where there may be a driveway and when a vehicle will move out of a driveway. In addition, a driver's visibility may be limited and the pedestrian may have very limited time to respond to avoid a conflict. The main effect of ambient was statistically significant. The average time-to-vehicle-arrival was 4.4 and 2.7 s for the low and high ambient condition, respectively. Participants took longer to detect both HVs than their ICE twins. The main effect of vehicle type was statistically significant. Table 4 shows the individual differences between ICE vehicles and their HV twins; pair-wise comparisons were statistically significant within a given ambient condition. Participants were more likely to miss the Toyota HVs than the Toyota ICE vehicles in the backing out session. The missed detection rates in the low ambient condition were: 0.05 for the Prius; 0.02 for the Matrix; 0.10 for the Highlander Hybrid; and 0.02 for the Highlander ICE. The corresponding values in the high ambient condition were: 0.11 for the Prius; 0.0 for the Matrix; 0.26 for the Highlander; and 0.02 for the Highlander ICE. On average, participants took longer to detect vehicles in the high ambient sound condition than in the low ambient sound condition.

Table 4: Time-to-Vehicle Arrival for Vehicle Backing out by Vehicle and Ambient

Vehicle	Ambient Sound Level	Time-to-Vehicle Arrival (s)
2010 Toyota Prius	Low	4.0
	High	2.5
2009 Toyota Matrix	Low	5.2
	High	3.6
2009 Highlander Hybrid	Low	3.3
	High	1.4
2008 Highlander ICE	Low	5.2
	High	3.3

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[3] Scenarios were evaluated using binaural recordings and headphones.

Vehicle Traveling in Parallel Lane and Slowing ((Slowing from 20 to 10 mph (32 to 16 km/h)[4]*:* The third and last traveling situation examined in the study was a pedestrian trying to decide when to start crossing a street with the signal in his/her favor and a surge of parallel traffic on the immediate left. The sound of slowing vehicles in the parallel street helps blind pedestrians identify turning vehicles. In some trials (no-signal condition), a vehicle continued straight through the intersection at 20 mph, so pedestrians could cross whenever they choose. However, in other trials there was a vehicle slowing from 20 mph to 10 mph as if to turn right into the pedestrian path (target vehicle). The pedestrian had to be able to detect when the vehicle was slowing. This scenario tests whether the pedestrian perceived this information when the vehicle was in the parallel street. Participants were more likely to miss the ICE vehicles approaching in the parallel lane and slowing than the HVs in the same situation. Table 5 shows the time-to-vehicle arrival and detection distance for the 'vehicle slowing' scenario. Pair-wise comparisons (HV vs. ICE twin) were statistically significant within a given ambient condition. On average, participants detected HVs sooner than their ICE vehicle twins. The main effect of vehicle type was statistically significant. The trend observed in the vehicle-slowing scenario (i.e., HVs are detected sooner than their ICE vehicle twins) may be explained by a noticeable peak in the 5000 Hz one-third octave band for the HVs tested during this operation. The tone emitted was associated with the electronic components of the vehicles when braking (e.g., regenerative braking). The missed detection rates in the low ambient condition were: 0.05 for the Prius; 0.31 for the Matrix; 0.03 for the Highlander Hybrid; and 0.17 for the Highlander ICE vehicle. The missed detection rates in the high ambient condition were: 0.05 for the Prius; 0.35 for the Matrix; 0.03 for the Highlander Hybrid; and 0.17 for the Highlander ICE vehicle.

Table 5: Time-to-Vehicle Arrival and Detection Distance for Vehicle Decelerating from 20 to 10 mph by Vehicle Type and Ambient Condition

Vehicle	Ambient Sound Level	Time-to-Vehicle Arrival (s)	Detection Distance (ft)
2010 Toyota Prius	Low	2.0	35.9
	High	1.9	33.8
2009 Toyota Matrix	Low	1.1	18.0
	High	0.8	12.8
2009 Highlander Hybrid	Low	3.0	58.8
	High	2.7	51.6
2008 Highlander ICE	Low	1.5	25.7
	High	1.3	21.8

Table 6 shows the time-to-vehicle arrival by vehicle type, and ambient condition. Considering all three independent variables, there was a main effect of vehicle, vehicle maneuver, and ambient sound level. Similarly, there were interaction effects between vehicle type and ambient; vehicle type and maneuver, ambient and vehicle maneuver, and a three way interaction between ambient, vehicle type and vehicle maneuver.

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[4] Scenarios were evaluated using binaural recordings and headphones.

Table 6: Average Time-to-Vehicle Arrival by Scenario, Vehicle Type and Ambient Sound

	Low Ambient		High Ambient	
Scenario	**HVs**	**ICE Vehicles**	**HVs**	**ICE Vehicles**
Approaching at 6 mph	4.8 s	6.2 s	3.3 s	5.5 s
Backing out (5 mph)	3.7 s	5.2 s	2.0 s	3.5 s
Slowing from 20 to 10 mph	2.5 s	1.3 s	2.3 s	1.1 s

In summary, the human subjects experiment in Phase 1 showed that:

- Detection time varied by vehicle operating condition, ambient sound level, and, vehicle type (i.e., ICE versus HV in EV mode).
- Study participants were able to detect any vehicle sooner in the low ambient condition.
- ICE vehicles tested were detected sooner than their HV pairs in two of the three operating conditions tested. In the third operating condition (travelling parallel and slowing), study participants detected the HVs sooner than the ICEs because of the electronic components within the HVs regenerative braking system. (In regenerative braking, some of the kinetic energy is transformed into electrical potential during the braking process. This transformation, mechanically and electrically loads the hybrid system, creating a high pitched tone.)

2.3 NHTSA Phase 2 Research

In October 2010, NHTSA issued a report presenting results of the agency's research (Phase 2). This research is summarized here and documented in NHTSA's Final Report No. DOT HS 811 496 (Hastings, Pollard, Garay-Vega, Stearns, and Guthy, 2011).

2.3.1 Scenarios

The scenarios included in Phase 2 were:

- Vehicle approaching at a low constant speed (6, 10, 15, and 20 mph)
- Vehicle accelerating (from 0 to 10 mph)
- Vehicle start-up
- Vehicle stationary

2.3.2 Acoustic Measurements of ICE Vehicles

Phase 2 work focused initially on the following two ideas: (1) the lack of detectability of quieter vehicles can 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.

One concept, described in the Phase 2 final report, is based on the assumption that the ICE vehicles measured in this study are typical of the current fleet, emit an acceptable amount of noise during low-speed operations, and that some (e.g., ICE-like) alert sounds can be based on the statistical average of real-vehicle spectral characteristics. Researchers developed the potential specifications for alert sounds shown in Table 7 and Table 8 based on acoustic analysis of sounds produced by ICE vehicles to demonstrate what acoustic parameters for a vehicle alert sound might look like. The derivations of these data are given in Section 5 of the Phase 2 final report.

Table 7: Minimum Overall A-weighted Sound Level ($L_{\text{Aeq, ½ sec}}$) by Vehicle Operation, dB(A)

Vehicle Operation	$L_{\text{Aeq, 1/2 sec}}$, 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
Stationary but activated	55.2

ICE vehicles have energy components in all frequencies (e.g., 100 to 20k Hz), however, the psychoacoustic models implemented in the study 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. Table 8 shows the corresponding minimum A-weighted one-third-octave-band spectra for each operating mode. These spectral distribution limits are derived from the procedures described in Section 6 of the Phase 2 final report.

Table 8: A-weighted One-Third-Octave-Band Spectra at Microphone Line $L_{\text{Aeq, 1/2sec}}$, dB(A)

1/3 Octave Band Center Frequency, Hz	6 mph	10 mph	15 mph	20 mph	Acceleration	Startup	Stationary but activated
100 to 20000	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
1000	51.4	55.2	60.2	63.2	55.6	57.8	44.9
1250	52.2	54.6	59.6	62.2	57.2	60,5	46.3
1600	52.0	54.3	58.8	61.3	57.0	61.1	45.4
2000	50.3	52.0	56.1	57.9	55.7	60.5	44.6
2500	49.1	50.3	53.9	54.9	55.1	61.1	43.8
3150	48.6	49.2	52.4	52.1	54.9	61.6	44.1
4000	46.9	47.5	50.5	49.5	53.2	60.9	42.4
5000	44.1	45.0	47.8	46.4	50.8	59.2	40.3

2.3.3 Human Subjects Experiments

A human subject study was conducted to compare the auditory detectability of potential sounds for hybrid and electric vehicles operating at a low speed. The sounds evaluated included: (1) sounds produced by vehicles with integrated sound systems rented from manufacturers, and (2) sounds produced by prototype systems rented from manufacturers, and played back by loudspeakers temporarily mounted on the hood of HEVs rented separately. Five vendors, motor vehicle manufacturers or suppliers of automotive electronics, provided prototypes of synthetic sound generators for EVs or HEVs. The five systems were labeled "A" to "E". A total of nine sounds were evaluated: A1, A2, A5, B, C, D, E1, E3, and E4. Sounds were evaluated at two sound pressure levels typical of ICE vehicles at low speeds (i.e., A-weighted SPL of 59.5 dB and 63.5 dB, as measured by the SAE J2889 draft test procedure). An ICE vehicle that produced A-weighted SPL of 60 dB in the 6 mph pass-by test was used as a reference in this evaluation. The ICE vehicle was labeled 'R'.

Data was collected outdoors during three independent sessions conducted on three days in July and August 2010. The first session included four operating modes: stationary but activated, acceleration from stop, start-up and 6 mph forward pass-by. The following two sessions included the 6 mph forward pass-by. The sample included 79 pedestrians who are sighted and legally blind, independent travelers, with self-reported normal hearing. The study took place in a parking lot located on the USDOT/Volpe Center campus in Cambridge, Massachusetts. The road surface consisted of bituminous asphalt and was swept and washed down prior to each test session. The test site has the acoustic characteristic of an urban area with a typical ambient noise of approximately 58-61 dB(A).

The dependent variables included raw detection distance, proportion of detection, time-to-vehicle arrival, and detection distance. Raw detection distance is 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 passed was treated as missing data. Proportion of detection is the proportion of trials of a given condition in which the participant detected the sound any time before the vehicle passed the participant. Time-to-vehicle-arrival is the time, in seconds, from detection of a target vehicle sound to the instant the vehicle passes the pedestrian location. Detection distance is the calculated distance, ft, to the target vehicle at the moment each subject responded. Each subject had a push button device which they used to indicate when they detected a nearby vehicle. Participants were asked to press the response button when they detected and recognized a vehicle that would affect their decision about when to start crossing the street.

The results showed that 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. Furthermore, high amplitude sounds (63.5 dB(A)) were detected more often and at greater distances than low amplitude sounds (59.5 dB(A)). Table 9 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 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 qualities that support detectability.

Table 9: Mean Detection Distance (ft) for all Sounds at two Amplitudes and for the Reference ICE Vehicle

Sound Number	Average Detection Distance (ft) for amplitude equal 59.5 dB(A)	Average Detection Distance (ft) 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

The analysis also indicated significant main effects of sound and a significant three-way interaction of session, sound, and direction. 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 can mask vehicles approaching from the west (the “a-to-b” direction), compared with the reverse. Thus, each direction-by-session condition may be regarded as constituting an independent test of the performance of each sound relative to the reference sound.

Based on this, the detectability of each sound relative to the reference was evaluated by comparing each sound to the reference vehicle for the corresponding session and direction condition of each. Results show that 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.

To compare the detectability of the 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) The analysis indicated significant main effects of sound. There also was a significant four-way interaction of session, sound, direction, and amplitude. This implies that the relative performance of each sound is jointly contingent on the direction it comes from, the session it was presented in, and the amplitude that was used. With this in mind, sounds are ranked by comparing each to the other (t-tests) for each session by-direction-by-amplitude condition. The analyses only included the four sounds shown to be superior to the reference sound. Results show that 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, and A5. The acoustic characteristics of these sounds are discussed in Section 5.2 of NHTSA Report DOT HS 811 496.

In summary, the human subject testing in Phase 2 showed that:

- 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.
- Results suggest that 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 relative to the reference vehicle.
- The results also suggest that synthetic sounds that contain only the fundamental combustion noise are relatively ineffective. None of the analyses found a significant effect of vision ability.
- Participants who are legally blind, on average, were no better or worse than sighted participants in detecting the approach sounds.

2.3.4 Initial Concepts for Potential Sound Parameters

The Volpe Center described initial concepts for sound specifications. These four concepts are described below.

Recordings of Actual ICE Sounds

This concept explored using recordings of actual ICE vehicles as alert sounds. Recordings would be 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 (e.g., tire noise, aerodynamic noise, AC fan noise) would be emitted regardless of whether an ICE is in use and would not be included in these recordings. 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.). In this option, emitted sounds would be based on standardized recordings with processing limited to pitch shifting in proportion to vehicle speed and interpolation between sounds.

Synthesized ICE-Equivalent Sounds

This concept explored using simulated ICE sounds directly synthesized 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. This is in contrast to the first concept, described above, 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 the first concept, but have fewer spectral components. A synthesizer could be simpler and less expensive than a sound generator based on real ICE sounds. For this concept, target sounds, recorded from actual vehicles for the operations specified above would be used. The synthesized sounds would then be developed to match the spectral shape of these target sounds. (Note: by definition, power-spectra spectral lines have a resolution of 1 Hz).

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. The two options listed above assume that band-limited (315 Hz to 5000 Hz) ICE-like sounds will be recognizable as motor vehicles.

Alternative, Non-ICE-Like Sounds Designed for Detectability

Another concept, described in the Phase 2 final report, consists of alternative alert sounds with acoustic characteristics different from ICE vehicles. Some of the sounds evaluated in the human-subject studies have sound characteristics that could improve detectability when compared to ICE-equivalent sounds. The following sound characteristics can improve detectability of a sound source (Stanton & Edwothy, 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.

The design of a non-ICE sound involves a complex tradeoff among several factors including annoyance, cost, detectability, and overall sound pressure level values. The detectability sound pressure level value for a particular non-ICE sound could be determined experimentally by a jury process that rates detectability or by using psychoacoustic models to determine minimum sound pressure level specifications for these sounds. In this concept, 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.).

Hybrid of Concepts Discussed Above

Another concept to designing alert sounds, explored in the Phase 2 report, would be a combination of those discussed above, with the goal of gaining the benefits of each, while minimizing the disadvantages. A simulated ICE sound could be generated which would vary pitch and loudness depending on vehicle inputs. This system could simultaneously generate both ICE-like sounds at a lower sound pressure level than the first two options, and synthetic sounds designed for optimal alerting potential with minimal annoyance. The ICE-like sound components may not be heard in higher urban ambient-noise conditions, but their association with the alerting sound would be learned over time from when the pedestrian is exposed to the sound in lower ambients.

2.4 Current Research

The goal of the current research is to develop sound specifications for EVs and HVs. Sound specifications would include criteria for sounds to be detectable and recognizable as the sound of a motor vehicle in operation. Specifications should be practicable and objective, would consider directivity, and applicability to ICE-like and other sounds.

3. Minimum Sound Levels for Detectability of EV and HV Sounds Based on Psychoacoustic Model

3.1 Purpose

Two concepts were explored to identify potential detectability specifications for alert sounds: (a) minimum sound levels based on a psychoacoustic model and detection distances and (b) minimum sound levels based on the acoustic characteristics of ICE vehicles. This section describes the first concept. The outcome is an indication about which one-third octave bands contribute the most to a pedestrian's ability to detect vehicles and the minimum sound level needed for each of these bands.

The inherent assumptions for this approach are that:

- sounds should be detectable in multiple one-third octave bands in the presence of an ambient;
- a psychoacoustic model can be used to determine minimum levels for detection of one-third octave bands in the presence of an ambient;
- minimum detection distances can be based on AASHTO stopping sight distances, and
- a vehicle should be detectable based on a moderate suburban ambient (i.e., ambient at 55 dB(A)).

3.2 Psychoacoustic Models

Psychoacoustics is the study of how humans perceive sound and forms the basis for extracting objective data from the physical characteristics of acoustic pressure to quantify how humans perceive the loudness, pitch, and timbre of a sound. Amplitude and frequency of sound pressure are physical attributes of sound that can be related to perceptual dimensions such as loudness, pitch, and timbre. Humans interpret these psychological dimensions subjectively, but some of them can be quantified through psychoacoustic modeling.

Modeling the detectability of an alert sound based on overall sound pressure level, whether frequency weighted or not, does not provide a good estimate of true detectability when the alert sound and the ambient sound have different spectral shapes. For example, ambient sounds dominated by low frequencies will not mask an alert sound that is dominated by high frequencies as effectively as an ambient sound dominated by high frequencies. Psychoacoustic models take into account the physiological mechanisms for hearing to a greater degree than do simple sound pressure level based models.

Ideally a detection model for the current application will account for:

- Frequency sensitivity
- Frequency selectivity
- Temporal effects on loudness as they pertain to masking qualities of an ambient sound relative to an alert sound

Frequency sensitivity is the phenomenon by which, for example, tones at different frequencies require different sound pressure levels in order to be perceived as equally loud (See ISO 226: 2003 Equal Loudness Contours). *It is important to include frequency sensitivity in a detection model* because this accounts for the fact that sounds below 500 Hz need higher sound pressure levels to be detectable than do sounds between about 500 Hz and 10 kHz in a quiet environment. Frequency selectivity relates to the auditory system's ability to discriminate between two components at different frequencies. (Strictly speaking, the term "component" used here refers to a sound at a discrete frequency, that is, a pure tone. The term component is used instead of pure tone because this discussion can be roughly generalized to include sounds of a more complex nature.) Each component of a sound excites a region of the basilar membrane that is determined by the frequency and level of the component. The frequency of the component determines the central location along the basilar membrane of the excitation. The region of excitation increases as follows: 1) the region increases with increasing frequency of the component and 2) the region increases with increasing sound pressure level of the component. There can be overlap in the regions excited by two components. The closer the components are in frequency, the greater the overlap; the wider the regions of excitation the greater the overlap. *It is important to include frequency selectivity in a detection model* because this accounts for spectral masking of both frequency coincident and frequency non-coincident components between the alert sound and the ambient sound. Frequency coincidence is when the masking component and signal components are at the same frequency. Frequency non-coincidence is when the masking component is either at a lower or higher frequency than the signal component. The masking component can either be part of the sound of interest, e.g. the alert sound, or it can be part of a secondary sound, e.g. the ambient.

Temporal effects on loudness include 1) how loudness changes as a function of the rate of change of the sound pressure over time and 2) the masking effects of sounds that occur before or after the sound of interest occurs. Alert sounds can typically be described as either stationary or as varying periodically with time. Because time-varying characteristics, in this sense, may be more noticeable without changing loudness, alert sound performance due to periodic variations may not be well represented by loudness. Within the scope of this study, stationary sounds are considered to provide a baseline performance and it is expected that time varying sounds will perform better. That is, neglecting periodic variations is a conservative approach to modeling detection, *therefore periodic variations can be neglected when selecting a detection model.* Masking sounds that come immediately before or immediately after an alert sound can produce some masking. However, this effect is much weaker than the masking effect of sounds that occur at the same time as the alert sound. Further, for practical reasons[5], a stationary ambient is

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[5] The number of possible combinations of variation between the timing of a transient masking sound and an alert sound is essentially limitless. In order to produce meaningful predictions of detectability, a stationary ambient is needed for this study.

used to evaluate masking effectiveness in this study, *therefore temporal masking effects can be neglected when selecting a detection model.*

Eight psychoacoustic models were considered for this study. The selection criteria, derived from the above discussion, included: 1) coincident masking by an ambient, 2) non-coincident masking by an ambient, 3) model produces loudness of a sound partially masked by an ambient (this is termed partial loudness), and 4) a computer program to compute the model results must be publically available. A model was considered publically available if a version could be obtained by interested parties at no cost or for a nominal fee. Detection models considered included Audibility[6] and Detect Sound.[7] [8] These produce a pass / fail result, not loudness. Stationary Loudness models are those models that account for spectral masking within a single sound but not between sounds, that is, they do not account for masking by an ambient. These include Zwicker's Loudness[9] [10] [11] and Moore's Loudness.[12] [13] Time-varying models also account for the change in loudness due to transients (e.g. Moore's time-varying loudness algorithm[14]). Finally, there are models that can account for the masking effects of a secondary sound (ambient). These include Zwicker's Partial Loudness[15] and Moore's Partial Loudness. The models' capabilities are summarized in Table 10.

Each model was considered with respect to its ability to account for coincident and non-coincident masking. Models that could account for these were then considered with respect to the ability to compare two sound sources simultaneously (an ambient and a signal) in order to determine the masking effect of the ambient on the signal. Finally, consideration was given to the public availability of the model. The model that accounted for Loudness in the presence of an ambient according to Moore's model was chosen, because 1) it accounted for both types of spectral masking, 2) produced results for two simultaneous sounds, and 3) was publically documented and computer code was publically available for computing results according to the model.

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[6] Federal Interagency Committee on Aviation Noise (2005)

[7] Zheng, Y., Giguère, C., Laroche, C., Sabourin, C., Gagné, A., & Elyea, M. (2007)

[8] Giguère, C., Laroche, C., Osman,R.A., & Zheng, Y. (2008)

[9] Zwicker, E. and H. Fastl (1999)

[10] ISO 532-B

[11] DIN 45 631

[12] Moore B.C.J. (2003)

[13] ANSI S3.4-2007

[14] http://hearing.psychol.cam.ac.uk/Demos/demos.html

[15] Kerber, S. & Fastl (2008)

Table 10: Psychoacoustic Model Comparison

Model	Type	Accounts for Coincident Masking by Ambient	Accounts for Non-coincident Masking by Ambient	Result	Availability
Audibility	Detection	Yes (√)	No* (X)	Detection (X)	Not Publically Available (X) In-house Implementation (√)
Loudness (Zwicker)	Loudness	No** (X)	No** (X)	Loudness (X)	Publically Available (√) In-house Implementation (√)
Loudness (Moore)	Loudness	No** (X)	No** (X)	Loudness (X)	Publically Available (Free Download) (√)
Time Varying Loudness (Moore)	Loudness	No** (X)	No** (X)	Loudness (X)	Publically Available (Free Download) (√)
Detect Sound	Detection	Yes (√)	Yes (√)	Detection (X)	Not Publically Available (X) Purchased by Volpe (√)
Partial Loudness (Zwicker)	Masked Loudness	Yes (√)	Yes (√)	Partial Loudness (√)	Not Publically Available (X) Not Purchased by Volpe (X)
Time Varying Partial Loudness (Moore)	Masked Loudness	Yes (√)	Yes (√)	Partial Loudness (√)	Not Publically Available (X) Not Purchased by Volpe (X)
Partial Loudness (Moore)	*Masked Loudness*	*Yes* (√)	*Yes* (√)	*Partial Loudness* (√)	*Public Download* (√)

* Does not include masking outside coincident one-third octave band
** Only accounts for self-masking, does account for masking due to ambient

3.3 Analysis and Results

3.3.1 Detection of Sound in the Presence of an Ambient of 55 dB(A)

Moore's Partial Loudness model (Moore and Glasberg, 1997) is used in this study to estimate the minimum sound level needed for a sound to be detectable in the presence of an ambient. This model is useful for the prediction of thresholds in quiet ambient and for thresholds in the presence of a masker as well as for computing equal loudness contours. This model was developed for use with ISO 226, Normal Equal-Loudness Contours, (1987) and the absolute thresholds found in ISO 389-7, Acoustics -- Reference zero for the calibration of audiometric equipment -- Part 7: Reference threshold of hearing under free-field and diffuse-field listening conditions, (1996). Since its original development, both of these standards have been updated to ISO 226 (2003) and ISO 389-7 (2005). There are newer implementations of Moore's model that reflect these new data however, the authors are not aware of any implementations that include these updates as well as provide for computing thresholds in the presence of a masker. Since the computing of thresholds in the presence of a masker is of fundamental importance for the current application, and since the updates represent "fine tuning" of the model, the 1997 model was identified as the most suitable choice.

The general procedure for running Moore's loudness model is to provide un-weighted one-third octave band levels for both the signal (alert sound) and the masker (ambient) and to provide information on how the signal is presented. For the purpose of this study, free-field, frontal presentation was used, which is both accurately and conservatively compared to diffuse field or headphones. The model provides several levels of detail in the results, including the specific loudness as a function of the number of equivalent rectangular bandwidths (ERBs). It is the integral of this function, or simply Loudness in sones that was used. Loudness above 0.03 sones, according to Moore's loudness model, is detectable. It is important to note that this is a time-invariant model, it does not take into account differences in duration (sounds with very short durations are perceived differently than long duration sounds due to the temporal windows associated with the auditory system). Nor does it account for periodic modulations including the effect of co-modulation masking release.

A simplified background noise [with overall A-weighted SPL = 55 dB(A)] was used in the implementation of Moore's Loudness model to compute minimum sound levels for detection in a given one-third octave band and to identify frequency ranges relevant for alert sounds. The ambient selected for these analyses is representative of many common urban ambients. In particular, the simplified background noise consists of pink noise filtered to have the same spectrum as what a pedestrian would hear in real traffic but without the variations in amplitude over time. This standardized noise is an advantage for repeatability. Table 11 shows the attenuation values for the generation of the simplified background noise from pink noise according to Pedersen et al (2011). The values in Table 11 represent the frequency weighting that can be applied to a pink noise signal to obtain a simplified background noise. The values represent a simplified approximation to the average spectrum observed at different locations. Note that the spectra used here and observed by Pedersen et al (2011) are of similar shape as those observed by Volpe Center researchers (Garay-Vega et al, 2010, page 43). Figure 2 shows filtered white noise for comparison with the designed filter (Un-weighted and A-weighted one-third octave band spectra for the ambient used are shown in Appendix A).

Table 11: Attenuation Values for Generation of the Simplified Background Noise from Pink Noise (Reference: Pedersen et al, 2011 AV 1224/10)

Hz	dB	Hz	dB	Hz	dB
20	-7.5	200	-12.5	2k	-20
25	-5	250	-15	2.5k	-22.5
31.5	-2.5	315	-15	3.15k	-25
40	0	400	-15	4k	-27.5
50	0	500	-15	5k	-30
63	0	630	-15	6.3k	-32.5
80	-2.5	800	-15	8k	-35
100	-5	1k	-15	10k	-37.5
125	-7.5	1.25k	-15	12.5k	-40
160	-10	1.6k	-17.5	16k	-42.5

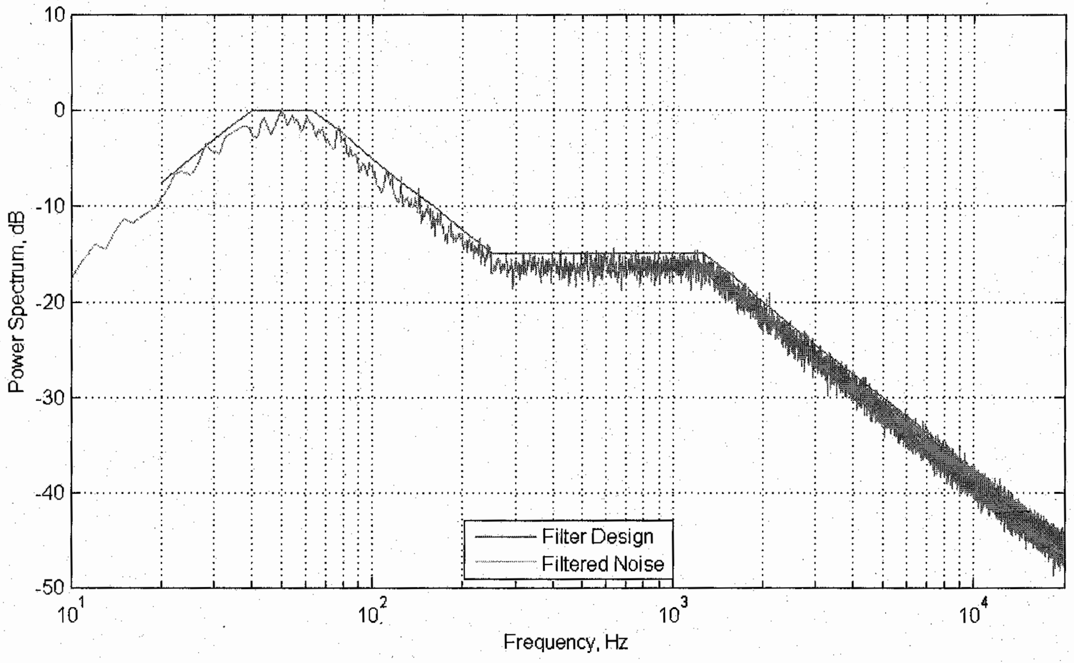

Figure 2: Un-weighted Spectra of the Masker Compared with the Filter Design

Minimum detection levels in the presence of the ambient described above were computed for each one-third octave band from 50 Hz to 10000 Hz as follows: Alert signals were generated with energy content in a single one-third octave band, starting at 20 dB(A). The partial loudness of the alert signal was computed. If the partial loudness in the presence of the masker exceeded 0.03 sones, then the threshold was achieved. If not, then the level of the alert signal was increased by 1 dB. The process was repeated until the threshold was achieved. The minimum detection level for the next one-third octave band was then computed.

Minimum levels for detection, as computed using Moore's Loudness model and a simplified ambient at 55 dB(A), are first provided for a pedestrian at the vehicle location, as shown in Table 13, that is, at a location 2 m from the center of the front plane (PP' line in Figure 3 which corresponds to the SAE J2889-1 microphone location).

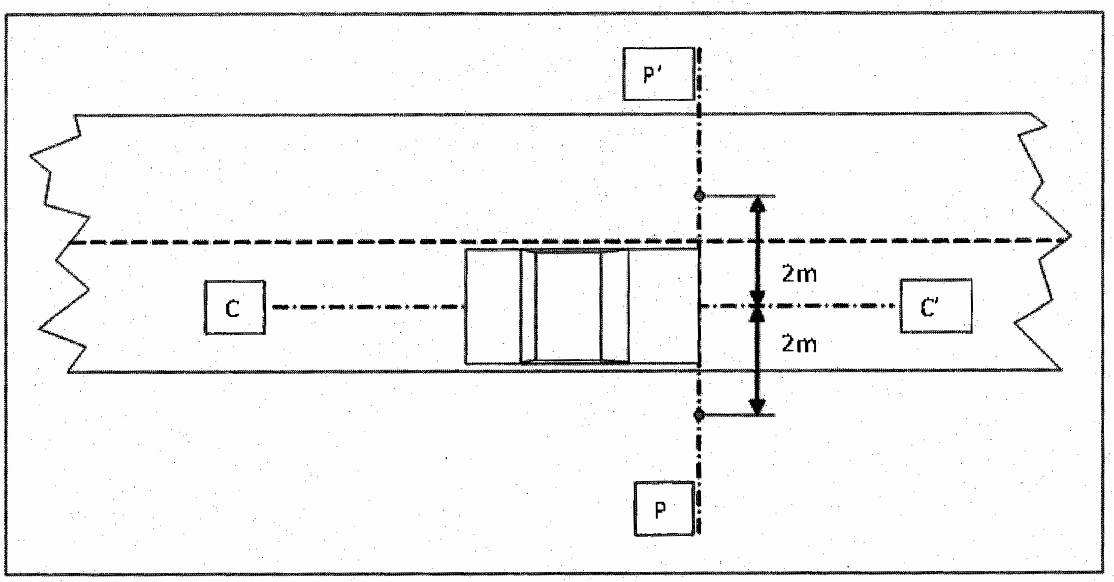

Figure 3: Microphone Line (PP') Relative to Vehicle Assuming Engine Mounted in Front of Vehicle. Vehicle Centerline is Labeled CC'

Human hearing is most sensitive in the range from about 1000 Hz to 5000 Hz. When modeling minimum detectable levels with the ambient described above, the 1250 Hz one-third octave band had the highest level at threshold, 45.6 dB(A). Human hearing is less effective at lower frequencies and the ambient used has significant energy at low frequency, therefore minimum thresholds at lower frequencies increase substantially. In order to restrict further analysis to a reasonable range, lower frequencies that had thresholds above the peak threshold in the 1000 Hz to 5000 Hz range were excluded from further analysis. Thus Table 12 begins with the 160 one-third octave band.

Table 12: Minimum Sound Level for Detections at 2 m (SAE microphone location)

One-Third Octave Band Center Frequency, Hz	Minimum Detection Level, dB(A)
160	43.6
200	42.1
250	40.4
315	41.4
400	42.2
500	42.8
630	44.1
800	44.2
1000	45.0
1250	45.6
1600	44.0

One-Third Octave Band Center Frequency, Hz	Minimum Detection Level, dB(A)
2000	41.2
2500	38.3
3150	36.2
4000	33.0
5000	30.5

3.3.2 Detection Distance

The minimum sound levels in Table 12 are for detection at the SAE microphone location (2 m). The sound pressure level decreases 6 dB with each doubling of distance from the source. Of interest are the minimum sound levels at a distance at which a pedestrian would need to hear a vehicle in order to make a decision about whether or not it is safe to proceed. The distance at which a pedestrian would need to hear a vehicle is at least as long as the vehicle's stopping distance. Otherwise a situation might develop in which the pedestrian steps off the curb and the driver of the vehicle would be unable to stop the vehicle in time to avoid a collision with the pedestrian.

Critical distances are computed as the stopping sight distance used in highway design (AASHTO, 2004). Stopping sight distance (d) is the distance that enables a vehicle traveling at or near the design speed to stop before reaching an object in its path. The stopping sight distance is the sum of the brake reaction distance and the braking distance. The brake reaction distance is the distance traveled by a vehicle from the instant the driver detects an object to the instant the driver applies the brakes. The braking distance is the distance needed to stop the vehicle once the driver applies the brakes. The sight distance for a vehicle traveling at the design speed and on a level road can be computed with the following formula:

$$d = 0.278Vt + 0.039\,\frac{V^2}{a}\ (m)$$

Where:

t = brake reaction time, s
V = design speed, km/h
a = deceleration rate, m/s^2

Drivers typically brake at an average emergency deceleration of about 5.4 m/s^2 on dry roads. A comfortable deceleration for most drivers braking on wet surfaces is 3.4 m/s^2. Drivers' expectation plays a role in driver reaction time. Mean reaction time to unexpected but common events (e.g. lead vehicle) is about 1.25 s. Mean reaction time for surprise events such as an object suddenly moving into the drivers' path is about 1.5 s (AASHTO, 2004; Green 2000). A longer brake reaction time, 2.5 s, would encompass the capabilities of most drivers, including older drivers. The values used in this analysis are 5.4 m/s^2 for deceleration and 1.5 s for brake reaction time. Table 13 shows the computed critical distances by vehicle operating condition. The results were rounded up to the nearest meter and provide input to the value 'X' described below.

Table 13: Critical Distances for Detection by Operating Condition

Operating Condition	Critical Distance, m
Stationary	0
Reverse[16]	5
10 km/h	5
20 km/h	11
30 km/h	19

3.3.3 Level Correction #1: Attenuation

The microphone layout in SAE J2889-1 measurement procedure specified the use of two microphones placed 2 m from the centerline of the test track and 1.2 m above the test surface. The minimum sound levels in Table 12 are for detection at the SAE microphone location. These levels were extrapolated to the critical distances required for each operating condition using an assumed attenuation of 6 dB per distance doubling (i.e., a divergence that follows $1/r^2$).[17] Figure 4 shows the relationship between the vehicle (sound source) and the SAE J2889-1 microphone position.

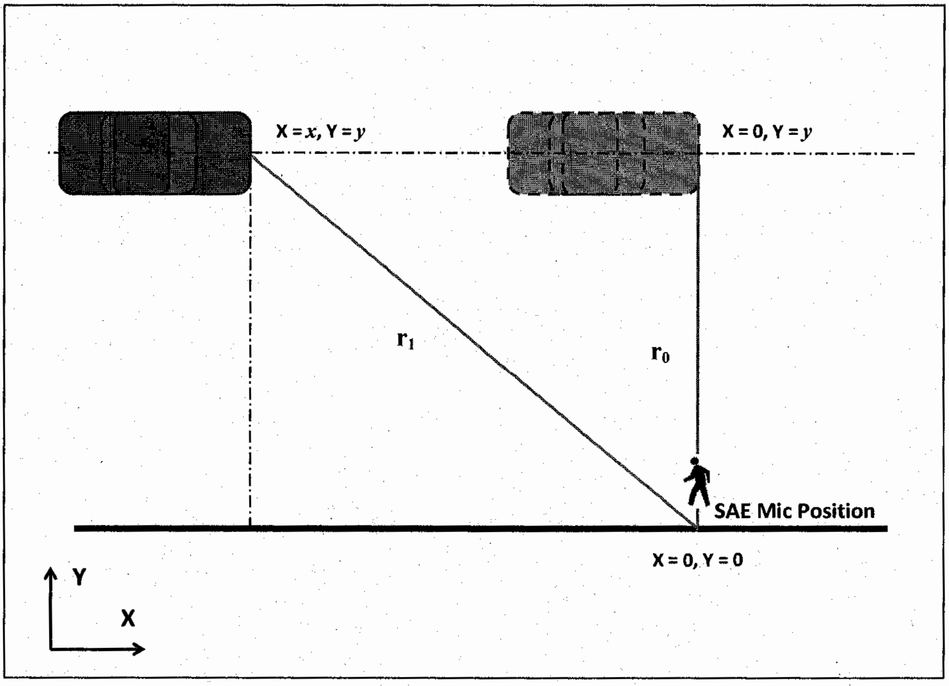

Figure 4: Path Lengths for a Source Relative to SAE J2889-1 Microphone Position

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[16] A speed of 10 km/h was assumed for the reverse condition.

[17] An attenuation of 6 dB per distance doubling is based on the assumption of a point source. Line sources attenuate at 3 dB per distance doubling. When the vehicle is close to the SAE location, this assumption is tenuous, therefore, for the first distance doubling an attenuation between a point and a line source was used, specifically 4.5 dB.

The variables ‘x’ and ‘y’ describe the distance between the vehicle and the microphone in the horizontal plane, ‘z’ describes the vertical distance between the source and receiver, r_0 is the total path length between the vehicle and microphone at the nearest point (i.e. at pass-by), and r_1 is the total path length at the point of interest. The number of doublings of r_0 is then given by $r_{doubling}$, which can then be used to compute attenuation for the first as well as for additional doublings. The derivation of distances and attenuations is given in the following equations:

$$r_0 = \sqrt{y^2 + z^2}$$
$$r_1 = \sqrt{x^2 + y^2 + z^2}$$
$$r_{doubling} = \log_{10}(r_1/r_0)/\log_{10}(2)$$
$$Attenuation = -6 \times r_{doubling}\ dB$$

For example, the values for Y and Z were held constant for this analysis at 2 and 1.2 m respectively, so when the source is closest to the microphone, X = 0 m, $r_1 = \sqrt{0^2 + y^2 + z^2} = r_0$ and $r_{doubling} = \log_{10}(r_0/r_0)/\log_{10}(2) = 0$. When the source is at X = 4.04 m, r_1 = 4.66 m = 2 r_0, or one distance doubling, thus when the source is at X = 4.04 m, the sound level at the microphone would be 4.5 dB less than when at X = 0 m (see note above). Similarly when the source is at 9.33 m, there are 2 distance doublings, producing a total attenuation of -4.5 - 6 = -10.5 dB. Thus the sound level at the microphone would be 10.5 dB less than when at X = 0 m.

Table 14 shows the adjustments from the source to the SAE microphone location. Table 15 shows the critical distances and level corrections by operating condition.

Table 14: Computation of Adjustment to Account for Distance between Source and SAE Microphone Location

	Variable	10 km/h	20 km/h	30 km/h
Inputs to the Equation	X source, m	5	11	19
	Y source*, m	2	2	2
	r0**, m	2.3	2.3	2.3
Outputs from the Equation	r1**, m	5.50	11.2	19.1
	r doubling	1.2	2.3	3
	Attenuation, dB	-6	-12.2	-16.8

* Assume effective source is at center of vehicle since propagation is forward

** Assume Z = 1.2 m

Table 15: Critical Distances and Level Corrections Relative to the Microphone Position by Operating Condition

Operating Condition	Detection Distance, m	Level Correction, dB
Stationary	0	0
Reverse[18]	5	6
10 km/h	5	6
20 km/h	11	12.2
30 km/h	19	16.8

Table 16 shows the resulting minimum sound levels needed at the SAE microphone location for detection of the vehicle at critical distances. Minimum sound levels are given for each one-third octave band from 160 Hz to 5000 Hz.

Table 16: Summary of Minimum A-weighted Levels, dB(A) Needed at SAE Microphone Locations for Detection of Vehicle at Critical Distances, Ambient 55 dB(A)

One-Third Octave Band Center Frequency, Hz	Stationary	10 km/h	20 km/h	30 km/h
160	44.1	50.1	56.3	60.9
200	42.6	48.6	54.8	59.4
250	40.9	46.9	53.1	57.7
315	41.9	47.9	54.1	58.7
400	42.7	48.7	54.9	59.5
500	43.3	49.3	55.5	60.1
630	44.6	50.6	56.8	61.4
800	44.7	50.7	56.9	61.5
1000	45.5	51.5	57.7	62.3
1250	46.1	52.1	58.3	62.9
1600	44.5	50.5	56.7	61.3
2000	41.7	47.7	53.9	58.5
2500	38.8	44.8	51.0	55.6
3150	36.7	42.7	48.9	53.5
4000	33.5	39.5	45.7	50.3
5000	31.0	37.0	43.2	47.8

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[18] A speed of 10 km/h was assumed for the reverse condition.

3.3.4 Level Correction #2: Minimum audible level relative to overall level

When all one third octave bands from 160 Hz to 5000 Hz are set to a minimum audible level, it can be seen that, relative to the overall level, some bands are less efficient at providing a detectable signal (as depicted by the arrows in Figure 5). Bands below 315 Hz and bands from 630 to 1600 Hz increase the overall level more for the same contribution to detection. The locations of these bands are indicated by the arrows in Figure 5. By removing the bands that are less effective at providing detection, the minimum specifications for the operating conditions measured according to SAE J2889-1, can be summarized by Table 17. Overall levels are given at the bottom of the table for reference.

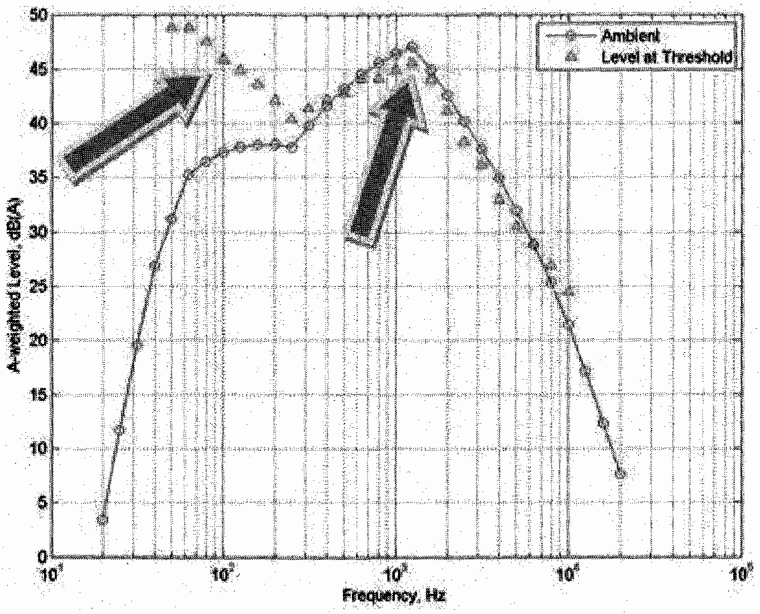

Figure 5: A-weighted Levels at Threshold, dB(A)

Table 17: Minimum A-weighted Sound Levels, dB(A) in Important Bands, Ambient 55 dB(A)

One-Third Octave Band Center Frequency, Hz	Stationary but activated	10 km/h	20 km/h	30 km/h
315	41.9	47.9	54.1	58.7
400	42.7	48.7	54.9	59.5
500	43.3	49.3	55.5	60.1
2000	41.7	47.7	53.9	58.5
2500	38.8	44.8	51.0	55.6
3150	36.7	42.7	48.9	53.5
4000	33.5	39.5	45.7	50.3
5000	31.0	37.0	43.2	47.8
Overall A-weighted Level Measured at SAE J2889-1 Microphone, dB(A)	49	55	62	66

3.3.5 Final Results

Due to masking effects of the ambient and potential hearing loss of the pedestrian, opportunities for detection will be maximized if the alert signal contains detectable components over a wide frequency range; therefore a minimum level is prescribed for a set of one-third octave bands that includes mid-frequency one-third octave bands (315, 400, and 500 Hz) as well as high frequency one-third octave bands (2000, 2500, 3150, 4000, and 5000 Hz). Low frequency bands (below 315 Hz) are omitted due to the expected strong masking effects of the ambient at low frequencies and the likelihood that many practical alert devices may not be able to produce high level – low frequency sounds. Mid-frequency bands from 630 to 1600 Hz are omitted because analysis indicated that, for the ambient considered, these bands contributed more to the overall level than other bands for the same increase in detectability.[19]

Table 18 shows the final results for minimum sound levels specified in the one-third octave bands based on psychoacoustic model and detection distances. These sound levels are based on minimum detection levels extrapolated 2 m in front of the vehicle for stationary but activated, 5 m in front of the vehicle for 10 km/h, 11 meters for 20 km/h and 19 m for 30 km/h. Backing was based on the forward 10 km/h levels, however, levels were adjusted down 3 dB to represent equivalent reductions in level of ICE vehicles at the back. For further information regarding this adjustment please see Chapter 5. Levels for all conditions include a 0.5 dB adjustment to provide a small factor of safety, essentially guaranteeing that the values are rounded up rather than down. Overall levels are given at the bottom of the table for measurements according to SAE J2889-1. Because the one-third octave bands in the table were selected based on their contribution to detection, a sound meeting the minimum overall level will not necessarily be as detectable as a sound meeting the minimum level for each one-third octave band.

Table 18: Minimum A-weighted Sound Levels for Detection, dB(A)

One-Third Octave Band Center Frequency, Hz	Stationary but activated	Reverse[20]	10 km/h	20 km/h	30 km/h
315	42	45	48	54	59
400	43	46	49	55	59
500	43	46	49	56	60
2000	42	45	48	54	58
2500	39	42	45	51	56
3150	37	40	43	49	53
4000	34	36	39	46	50
5000	31	34	37	43	48
Overall A-weighted Level Measured at SAE J2889-1 Microphone, dB(A)	49	52	55	62	66

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[19] The sounds could be made more detectable by increasing the sound above this minimum level; Appendix B provides data on this increase.

[20] Vehicle reference point is the rear end of vehicle

4. Minimum Sound Levels for Detectability of EV and HV Sounds Based on Acoustic Characteristics of ICE Vehicles

4.1 Purpose

This section describes the second concept where potential detectability specifications for alert sounds are based on the acoustic characteristics of ICE vehicles. This analysis is similar to the analysis of ICE vehicles described in NHTSA Phase 2 report. The dataset used in the current analyses includes additional acoustic data obtained from OICA (International Organization of Motor Vehicle Manufacturers). The inherent assumption for this approach is that ICE vehicles produce adequate sound levels for detectability.

4.2 Dataset

4.2.1 NHTSA Phase 2

In Phase 2, acoustic measurements were made of 10 conventional light duty vehicles for the following operating conditions: (1) low speed pass-by forward (6, 10, 15 and 20 mph); (2) low speed pass-by reverse (6 mph); (3) start-up; (4) stationary but activated; and (5) acceleration from stop pass-by. The procedure followed SAE-J2889-1 Rev 2009 with exceptions, e.g. different operating speeds described in the Phase 2 report. Vehicles included:

- Sedans, station wagons, and a pick-up truck
- Model years from 2000 to 2009
- Domestic, European, and Asian manufacturers
- Background levels during measurements were between 45 to 55 dB(A)

4.2.2 OICA

The inherent assumption for this approach is that ICE vehicles produce adequate sound levels for detectability. Key features of the dataset, as reported by OICA, are:

- Data from 12 manufacturers from USA, Europe and Japan
- Dataset includes data for 42 vehicles
- Data include: vehicle ID, engine size, engine power, engine type, transmission, background noise level, A-weighted sound pressure levels, and Un-weighted one-third octave band levels
- Data differ with respect to sample rate, filtering, etc. due to different data acquisition systems and software. However the data can be used for comparison
- Background levels during measurements were between 19.6 and 52.5 dB(A)
- The range of vehicles tested ranged from small sedans to a public bus

4.3 Analysis and Results

4.3.1 Data Processing

Data provided by OICA included measurements according to the SAE J2889-1 draft ($L_{Af,max}$ and $L_{Af,min}$). In some cases average levels and one-third octave band analysis were included. In most cases, the type of one-third octave band analysis was not indicated, for example, fast time weighting or equivalent average level. In addition to the SAE stationary and 10 km/h (6.2 mph) test, several manufacturers also measured vehicles under other operating conditions including reverse at 10 km/h, constant speed in the forward direction at 16, 24, and 32 km/h, as well as accelerating and decelerating pass-by events[21].

Given that 12 different manufacturers from three continents made measurements according to a draft test procedure and additional metrics, the resulting data required processing and reduction to consolidate it so that the largest set of common data could be compared. Additionally, efforts were made to compare the OICA data with the Volpe Center's Phase 2 data. The following steps were taken to create a comprehensive set of comparable data:

- Stationary data were compared based on the metric: $L_{Aeq,½ sec}$. For data that did not include $L_{Aeq, ½ sec}$ values, these were approximated using $L_{Af,max}$ and $L_{Af,min}$ data.
- Pass-by data were compared based on the metric: $L_{Af,max}$. For data that did not include $L_{Af,max}$ values, these were approximated using $L_{Aeq,½ sec}$, adjusting the level based on average differences between $L_{Af,max}$ and $L_{Aeq,½ sec}$ determined for each vehicle operation (see adjustment factors on Table 19).
- Overall sound levels were approximated by summing the full frequency range of the one-third octave band values if no overall levels were reported.
- Third octave bands were limited to the frequency range that was common to all one-third octave band data reported. That is from 100 Hz to 5000 Hz.

Table 19: Adjustment factor to go from L_{Aeq} to $L_{Af,max}$

Vehicle Operation	Adjustment, dB
Reverse, 10 km/h	1.1
10 km/h	0.8
16 km/h	1.2
24 km/h	1.4
32 km/h	2.0
Acceleration	2.9
Startup	1.6

Note that the difference between $L_{Af,max}$ and $L_{Aeq,½ sec}$ is dependent on speed, since faster pass-by events have steeper approach and departure slopes than do slow pass-by events. The error

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[21] The Volpe Center researchers provided a copy of the measurement procedure used at that time. The measurement procedure follows SAE-J2889-1 Rev 2009 with some exceptions which were clearly described. A copy of the test procedure sent to OICA is in Appendix C.

associated with converting from $L_{Aeq,½\,sec}$ to $L_{Af,max}$ is expected to be less than ½ dB for constant speed events, except for reverse and 32 km/h, where the error is expected to less than 0.9 dB. The error for acceleration is expected to be less than 2.9 dB. This higher error is likely due more to variation in operation (e.g, keeping a constant acceleration rate) rather than actual differences between $L_{Aeq,½\,sec}$ and $L_{Af,max}$.

Data for the bus were excluded from analysis as were vehicles that were noted as having extraneous sounds during the measurements, such as cooling fans, or if they were at least partially powered by electric motors, that is, hybrids or electric vehicles. The final data used in the analysis are given in Appendix D.

Because the OICA data are assumed to represent late model vehicles and the Volpe Center's Phase 2 represents earlier models, the data were analyzed both separately and combined. When the data were combined, all data samples were given the same weight, that is, no distinction was made between an OICA sample and a Phase 2 sample during the combined analysis. In order to maintain equal weighting, only two measurements were included from each vehicle for a given operation. This prevented a particular vehicle from having excessive influence on the analysis due to having more repetitions of a given operating condition than other vehicles.

4.3.2 Overall Sound Level

Data were analyzed and compared based on overall sound pressure levels by computing histograms of the data with a resolution of 1 dB. Mean values were computed as well as 95% and 99% prediction intervals by assuming normal distributions. A prediction interval is used to describe the interval within which a future sample is expected to fall with a given degree of certainty. Prediction intervals in this report were computed using the normal distribution. Given the sample size, prediction intervals determined using t-distributions would lead to wider intervals, that is lower minima and higher maxima.

Examples of the distributions are shown for 10 km/h pass-by events in Figure 6 to Figure 8. Ten kilometer per hour pass-by distributions are shown in Figure 6 for OICA data alone, in Figure 7 for Volpe Center Phase 2 data alone, and Figure 8 shows the combined data. These histograms have been formatted to represent estimated probabilities rather than total number of measurements to facilitate comparison with the estimated normal distribution. The 95% prediction interval is indicated by the red region of the estimated normal distribution associated with the data. The 99% prediction interval is indicated by the combined blue and red region of the estimated normal distribution associated with the data. The estimated mean value, standard deviation, and the prediction intervals are shown in the upper left hand corner of each graph.

Some operations have large standard deviations conveying that the distributions are wide. Although these standard deviations may decrease with more sampling, it may also indicate an operating mode with large variation. Although confidence intervals typically get smaller with more samples due to the $1/\sqrt{n}$ factor, prediction intervals typically do not get significantly smaller with increased sample size.

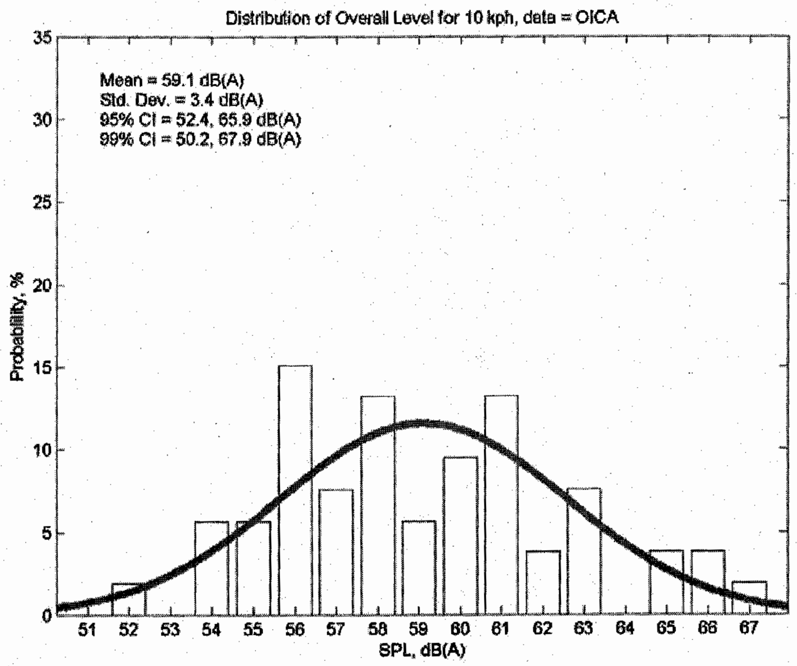

Figure 6: 10 km/h Pass-by Distribution for OICA Data

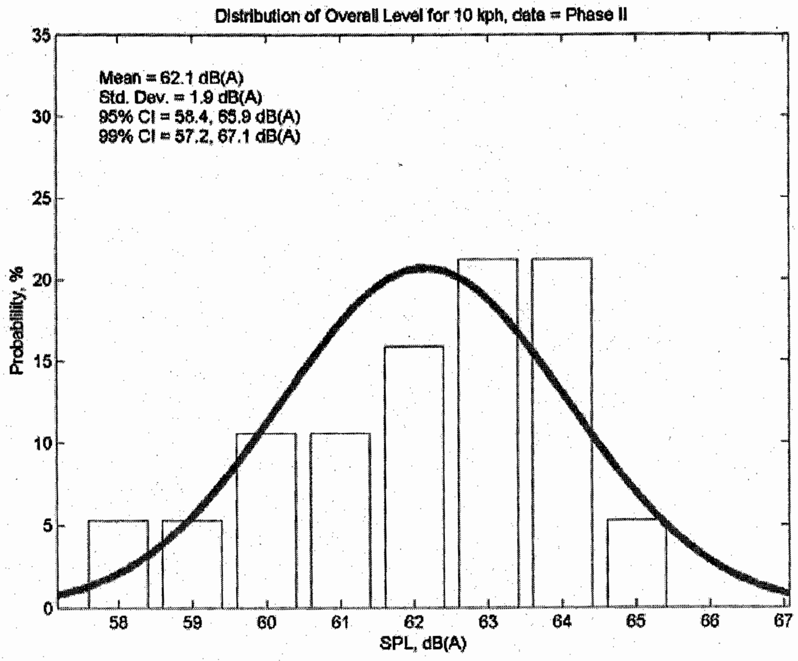

Figure 7: 10 km/h Pass-by Distribution for Volpe Center Phase 2 Data

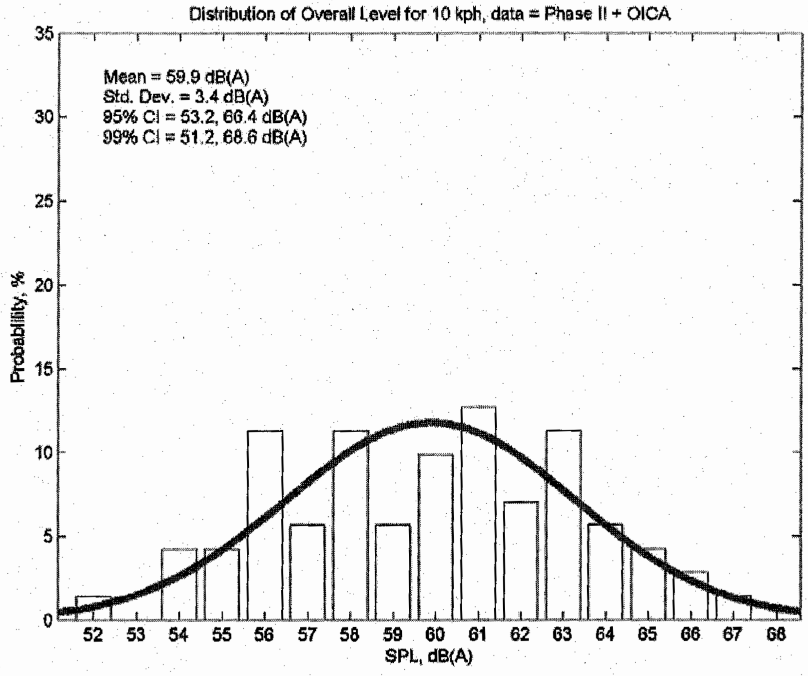

Figure 8: 10 km/h Pass-by Distribution for Combined Data

4.3.3 One-Third Octave Band Spectra

One-third octave band spectra were analyzed to compute minima, maxima, and mean values for each operating condition as well as 95% and 99% prediction intervals by assuming normal distributions. Means, minima, and maxima were computed for each band independently.[22] Examples of the various spectra are given for 10 km/h pass-by events in Figure 9 to Figure 11. Figure 9 shows spectra for the 10 km/h pass-by operation for the OICA data. Figure 10 shows the Volpe Center Phase 2 data. Figure 11 shows the combined data. For most cases, the 95% prediction closely matches the maximum – minimum interval. This indicates that the 95% prediction may be a generally applicable criterion for statistically estimating minimum levels of a population. Using a prediction interval to estimate extremes provides a method that is reasonably insensitive to outliers.

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[22] These values were not computed by determining, for example, the vehicle with the lowest overall level and then using the one-third octave band of this vehicle for the minimum. All data were aggregated and the minimum in each one-third octave band was identified from the aggregate.

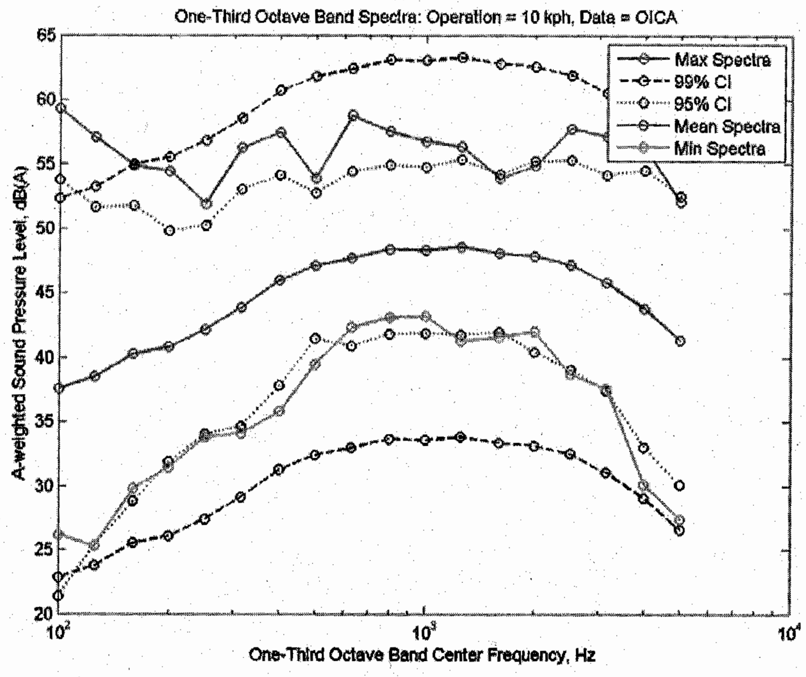

Figure 9: 10 km/h Pass-by One-Third Octave Band Spectra for OICA Data

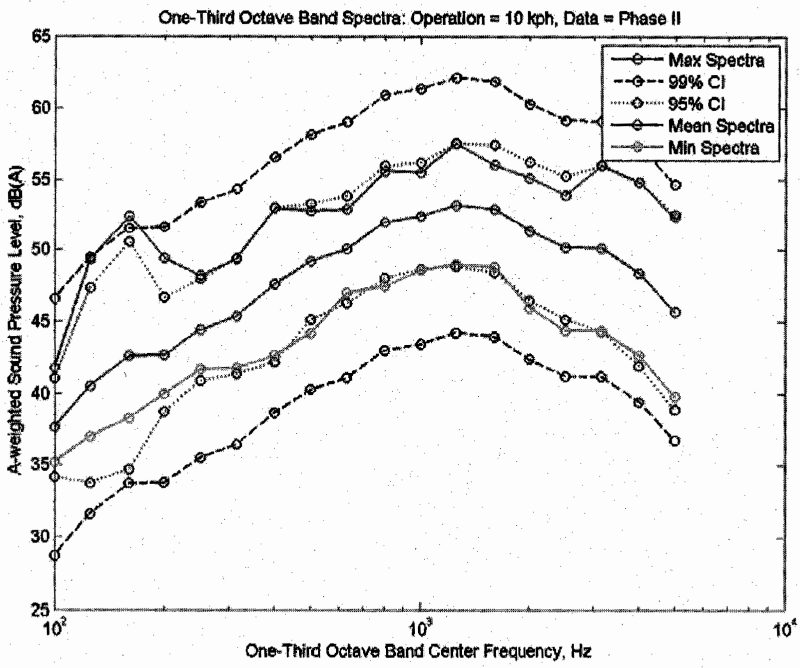

Figure 10: 10 km/h Pass-by One-Third Octave Band Spectra for Volpe Center Phase 2 Data

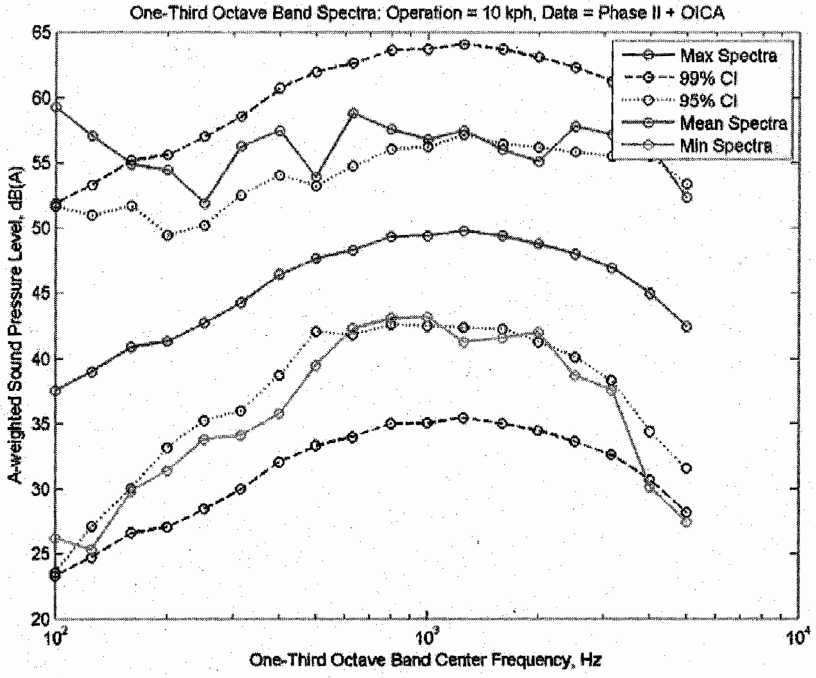

Figure 11: 10 km/h Pass-by One-third Octave Band Spectra for Combined Data

4.3.4 Final Results

Two versions of potential minimum sound levels based on measured ICE levels are provided here, one based on the mean levels (Table 20) and one based on the mean levels minus 1 standard deviation (Table 21).[23] The one-third octave bands included here are those identified in the previous chapter. Levels were not extrapolated to account for minimum stopping distance as this approach assumes that the conventional vehicles are sufficiently safe. Backing data were generally not available, therefore backing levels are based on the forward 10 km/h levels, however, levels were adjusted down 3 dB to represent equivalent reductions in level of ICE vehicles at the back. For further information regarding this adjustment please see Chapter 5. Overall levels are given at the bottom of the table for measurements according to SAE J2889-1. Each one-third octave band in the table contributes to the character of the sound, therefore, under this approach the sound would have to meet the minimum level for each one-third octave band not just the overall level.

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[23] Mean levels minus 2 standard deviations were also considered, however, these levels are not expected to be sufficiently detectable in many cases.

Table 20: Minimum A-weighted Sound Levels for EV and HV based on ICE Mean Levels, dB(A)

One-Third-Octave Band Center Frequency, Hz	Stationary but activated	Backing	10km/h	20km/h	30km/h
315	40	42	45	52	55
400	41	44	47	53	57
500	43	45	48	54	59
2000	44	46	49	55	59
2500	44	46	49	53	56
3150	43	44	47	52	54
4000	41	42	45	49	51
5000	37	40	43	45	48
Overall A-weighted Level Measured at SAE J2889-1, dB(A)	51	53	56	61	65

Table 21: Minimum A-weighted Sound Levels for EV and HV based on ICE Mean Levels minus 1 Standard Deviation, dB(A)

One-Third-Octave Band Center Frequency, Hz	Stationary but activated	Backing	10km/h	20km/h	30km/h
315	34	37	40	48	52
400	35	40	43	49	53
500	37	42	45	51	56
2000	39	42	45	50	54
2500	39	41	44	49	51
3150	39	40	43	47	49
4000	36	37	40	42	44
5000	29	34	37	38	40
Overall A-weighted Level Measured at SAE J2889-, dB(A)	46	49	52	57	61

5. Directivity

5.1 Purpose

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 refers to the relative proportions of acoustical energy that are emitted from a source, in this case a vehicle, as a function of direction (e.g., front, back, left, and right). One of the scenarios of interest, for example is vehicle backing. Directivity patterns describe the change in sound pressure level as a function of angular position relative to a reference line. The purpose of this task is to document the directivity of conventional, ICE, vehicle and use this information to estimate directivity parameters for electric and hybrid vehicles.

5.2 Dataset

The dataset for the directivity analysis includes 4 conventional light duty vehicles from 4 different manufacturers. All vehicles were measured at the same site, which had an ambient that ranged from 45 to 53 dB(A). The number of individual measurements (n) for each vehicle is included in the tables below. For this analysis 16 measurements were used for Vehicle 1 and Vehicle 2, 20 from Vehicle 3, and 17 from Vehicle 4.

5.3 Measurement Procedure

Acoustic measurements for directivity were conducted at NHTSA Vehicle Research Test Center (VRTC), East Liberty, Ohio. The measurement procedure consists of measuring the overall sound pressure level of a 'stationary but activated' vehicle with microphone heights and orientations as described in SAE J2889-1. The actual location of the microphones and the measurement procedure does not follow SAE J2889-1 because the purpose of this test is to characterize sound levels around the vehicle, rather than to measure the level at a single point in space. Figure 12 illustrates relative location of eight microphones located around the perimeter of the vehicle. Two microphones (#4 right and #5 left) are in the same location as for the pass-by testing in SAE J2889-1. Front center measurements added microphone #6 which was located 2 m north of the PP' line (see Figure 3) on the track centerline. Vehicle midpoint measurements added microphones #7 and #8 on the left and right side at the middle of the vehicle. Rear measurements at the bumper plane added microphones #9 and #10 on the left and right at the rear (2 m from the track centerline). To record the sound directly behind the vehicle microphone #11 was added 2 m on the track centerline behind the vehicle.

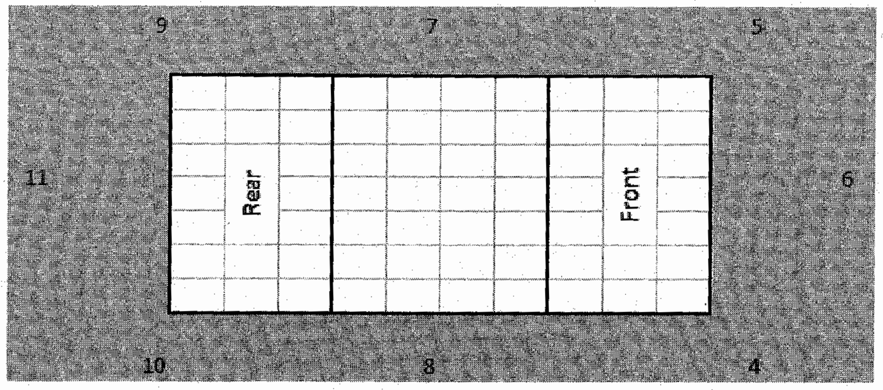

Figure 12: Eight Microphones (channels 4 to 11) were Located Around the Perimeter of the Vehicle for Directivity Measurements. Microphones 4 and 5 Correspond to the SAE J2989-1 Measurement Location

5.4 Analysis and Results

Data analysis for directivity include the mean sound pressure levels for each of the 8 microphones (Table 22), the standard deviation for the mean sound pressure level (Table 23), and the difference in sound pressure level relative to the minimum value of microphones #4 and #5 (SAE J2889-1 microphones) (Table 24).

All four vehicles tested have similar directivity patterns. Mean sound levels at the back and center of the vehicles (microphone #11) are 4.4 to 6.9 dB lower than the mean levels at the front and center (microphone #6). Standard deviation for the mean sound pressure level is relatively small (less than 1.5 dB(A)) except for Vehicle #1 (less than 2.7 dB(A)).

Table 22: Mean sound pressure level for each microphone by vehicle, dB(A)

Microphone ID	Vehicle 1 (n = 16)	Vehicle 2 (n = 16)	Vehicle 3 (n = 20)	Vehicle 4 (n = 17)
4	51.7	54.6	52.8	50.3
5	51.4	53.9	51.8	49.2
6	51.1	53.4	51.6	49.1
7	50.6	53.4	51.2	48.4
8	51.1	54.5	52.0	49.7
9	48.4	51.9	47.8	46.9
10	49.0	52.5	49.1	47.0
11	46.1	49.0	44.7	43.5

Table 23: Standard deviation for the mean sound pressure level, dB(A)

Microphone ID	Vehicle 1 (n = 16)	Vehicle 2 (n = 16)	Vehicle 3 (n = 20)	Vehicle 4 (n = 17)
4	2.7	1.1	0.8	1.1
5	2.7	0.8	0.8	1.2

Microphone ID	Vehicle 1 (n = 16)	Vehicle 2 (n = 16)	Vehicle 3 (n = 20)	Vehicle 4 (n = 17)
6	2.6	0.9	0.9	1.0
7	2.6	1.0	0.8	0.9
8	2.7	1.1	0.9	1.1
9	2.3	0.9	0.9	1.0
10	2.4	0.8	1.2	0.9
11	2.0	0.9	1.5	1.1

The average difference in sound pressure level relative to the minimum of microphones #4 and #5 ranges from 0 to approximately 5.8 dB as shown in Figure 13. The maximum difference in sound pressure level relative to the minimum of microphones #4 and #5 ranges from 0.0 to approximately 7.1 dB as shown in Figure 14.

Table 24: Difference in sound pressure level relative to the minimum of microphones #4 and #5

Microphone ID	Vehicle 1 (n = 16)	Vehicle 2 (n = 16)	Vehicle 3 (n = 20)	Vehicle 4 (n = 17)	Average
4	0.2	0.8	1.0	1.0	0.8
5	0.0	0.0	0.0	0.0	0.0
6	-0.3	-0.5	-0.1	-0.1	-0.2
7	-0.8	-0.4	-0.6	-0.8	-0.7
8	-0.3	0.6	0.3	0.5	0.3
9	-3.0	-2.0	-4.0	-2.3	-2.8
10	-2.5	-1.3	-2.7	-2.2	-2.2
11	-5.3	-4.9	-7.1	-5.8	-5.8

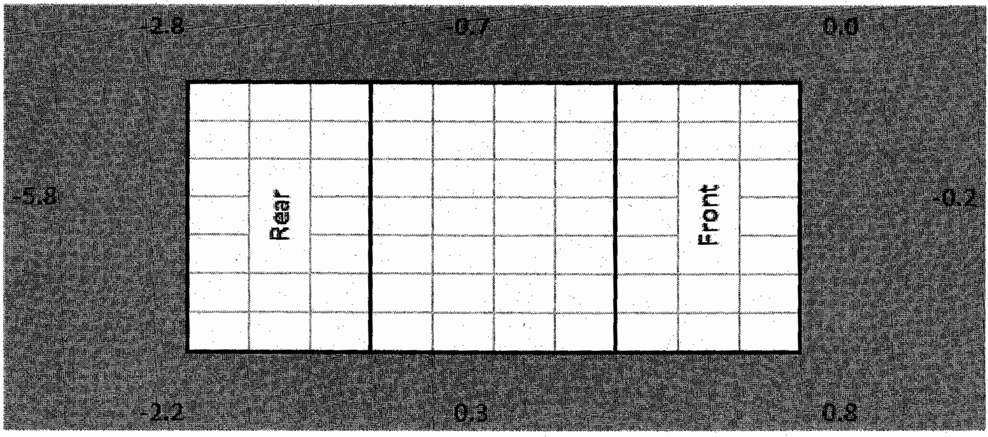

Figure 13: Diagram Shows the Average Difference in Sound Pressure Level Relative to the Minimum of Channels 4 and 5

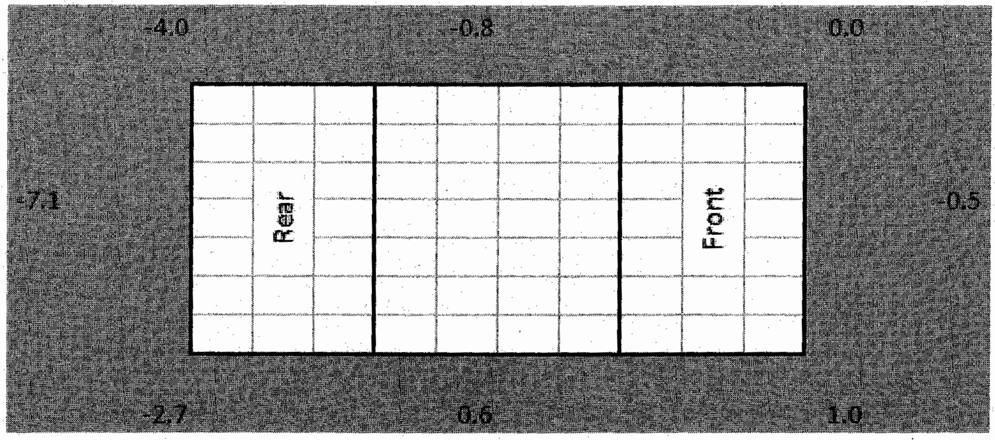

Figure 14: Diagram Shows the Maximum Difference in Sound Pressure Level Relative to the Minimum of Channels 4 and 5

5.5 Conclusion

Acoustic measurements of ICE vehicles show that sound levels at the rear sides and rear center of the vehicle are generally 3 and 6 dB lower, respectively, than what is measured at the SAE 2889-1 microphones when the front of the vehicle is in line with the SAE microphones. If the directivity of ICE vehicles is used to estimate directivity parameters for electric and hybrid vehicles, then, measurements made at the back of the vehicle should be no lower than 3 dB less than measurements made according to SAE J2889-1.

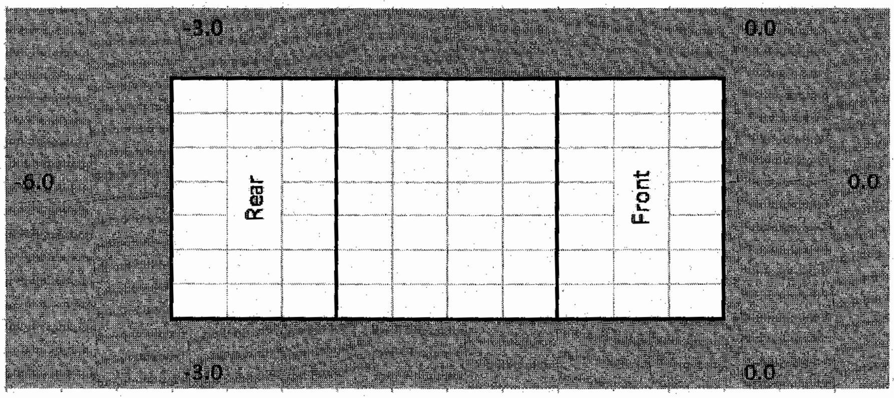

Figure 15: Representation of the Standardized Sound Pressure Levels Relative to the SAE J2889-1 Microphone with the Lowest Level

6. ACOUSTIC PROPERTIES FOR RECOGNITION

Recognition includes two aspects: 1) recognition that the sound is emanating from a vehicle, and 2) recognition of the type of operation that the vehicle is conducting.

6.1 Purpose

The purpose of this task is to identify acoustic characteristics that would aid in recognition of a sound as the sound of a motor vehicle. Acoustic characteristics were determined by simulating sounds. Sound simulations were developed for stationary but activated, constant speed pass-bys, and accelerating pass-bys. Pass-bys included Doppler shifts and accelerations also included a pitch shifting tied to vehicle speed. Levels changed as a function of speed and as a function of position relative to the receiver. Roughly two hundred sounds were generated and evaluated. Sounds produced by ICE vehicles were used as baseline so that alert sounds for HVs and EVs include similar cues to the sounds that pedestrians associate with current ICE vehicles.

6.2 Sound Simulation Program

The Volpe Center created a sound simulation program in MATLAB® to facilitate the identification of acoustic parameters for alerting sounds that are associated with detection and recognition of vehicle sounds. The following acoustic parameters can be examined in the sound simulation:

- Broadband noise (suggesting sound from fans, pumps, etc.)
- Number and relative level of tonal components
- Pitch and amplitude shifting in proportion to vehicle speed
- Amplitude and frequency modulation
- Fundamental frequency

The acoustic parameters listed above were selected for two reasons:

- They can be used to describe sounds attributes of internal combustion engines
- They also relate to the attributes of effective audible warnings.

The sound simulation program accounts for the position of the vehicle (sound source, S) and the pedestrian (receiver, R). Figure 16 shows the geometry used for the sound simulation program. Table 25 shows definitions for each of the parameter used in the sound simulation program.

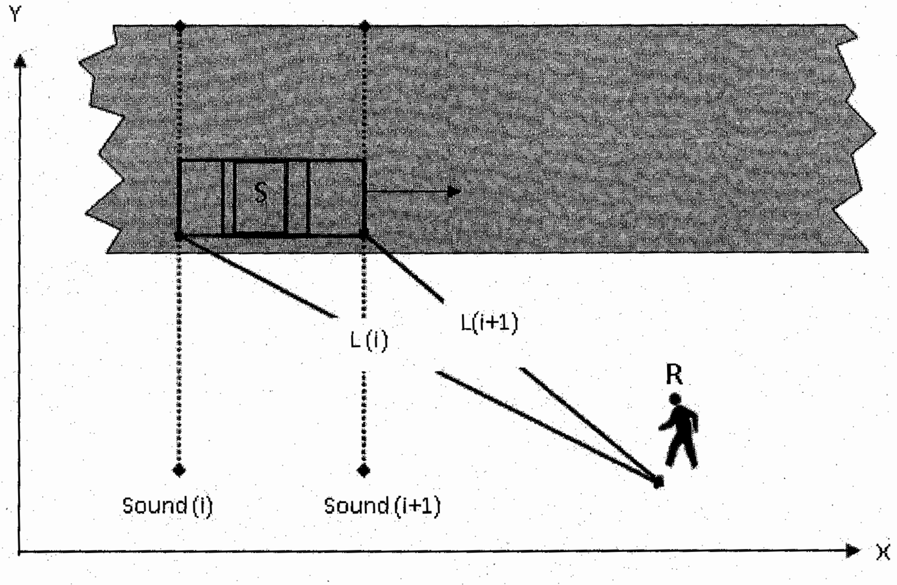

Figure 16: Sound Simulation Geometry, Position of the Vehicle (S) and the Pedestrian (R)

Table 25: Definition of Variables in the Sound Generation Program

Symbol	**Variable**
Xr	Position of receiver, x-axis, m
Xs_0	Initial position of the source , x-axis, m
Yr	Position of receiver, y-axis, m
Zr	Position of receiver, z-axis, m
Xs	Position of source, x-axis, m
Ys	Position of source, y-axis, m
Zs	Position of source, z-axis, m
Vx0	Initial velocity of source, m/s
As	Acceleration of source, m/s^2
Ax	Acceleration of source, m/s^2
L(i)	Length of propagation path, m
ts	Time vector for source, sec
tr	Time vector for receiver, sec
Δtr	Time increment for receiver, sec
Δts	Time increment for source, sec
Δtprop	Time for sound to travel from source to receiver
fs	Sampling frequency, Hz
c	Speed of sound in air, 343 m/s
Sound(i)	i^{th} emission of sound from source
TNR	Tone-to-Noise ratio, dB
A*shift*	Linear amplitude gain as a function of speed added to nominal level

6.2.1 Tone Design Parameters

The tone design parameters are used to design the portion of the alert sound signal that originates from tonal components. These are typically designed to relate to engine harmonics.

6.2.2 Noise Design Parameters

The noise design parameters are used to design the portion of the alert sound signal that originates from random noise. These are typically designed to the overall shape of the desired noise. Additionally, the noise will sound more natural if there is some variation that is correlated with variations associated with the tonal components (e.g. if tones are amplitude modulated at 4 Hz, then at least some portion of the noise should also be amplitude modulated at 4 Hz).

6.2.3 Assumptions

In theory, a simulation program can be developed that puts no constraints on the geometric and dynamic aspects of the sound source, however, this requires a level of complexity that would increase development time and is unnecessary in order to meet the goal to generate sounds that relate to how vehicles typically move along roads. The assumptions fall into one of two categories:

1) Assumptions related to vehicle operation relative to pedestrian
    - Position of receiver is constant (Xr, Yr, Zr), i.e. the pedestrian is listening at a crossing.
    - Source may only change horizontal position (Xs), other coordinates (Ys, Zs) are constant, i.e. the vehicle does not change lanes or veer off the road.
    - Acceleration of source is constant and constrained to the x-direction.
    - Acceleration may be zero, i.e. driver is either accelerating or not, transitions are not modeled.

2) Assumptions related to acoustic propagation
    - Time increment for receiver is constant ($\Delta ts = 1 / fs$; $tr(i+1) = tr(i) + \Delta ts$), i.e. the point of the simulation is to model the sound at the pedestrians location.
    - Time increment for source is not constant, but is selected such that sound emitted at time ts(i+1) reaches the receiver Δt after sound emitted from the source at time ts(i). Because the time it takes a sound to reach the pedestrian depends on distance between source and receiver, sampled time at the source cannot be constant unless the source is stationary.
    - Reflections can be ignored.
    - Atmospheric absorption can be ignored, because the distances are small.
    - Directivity and head-related transfer functions (HRTFs) were neglected, but can be accounted for by applying appropriate filters over small contiguous time segments.

- Sounds will be synthesized using random normally distributed noise and sine waves. These components will be modified by using deterministic functions.

6.3 Tonal Components and Broadband Content

Based on initial assessment and engineering judgment, at least one tone (and preferably more) should be included for the purpose of recognition. The lowest tone should have a frequency no greater than 400 Hz. Tones at frequencies above 2000 Hz could be included for purposes of detection rather than recognition.

A component is considered to be a tone if the Tone-to-Noise ratio according to ANSI S1.13-1995 is greater than or equal to 6 dB.[24]

6.4 Possible Method for Identification of Tones

The method described below is one possible way to identify tonal components that will be perceived as prominent. This method assumes that there is a single tone or multiple tonal components in a given one-third octave band; it assumes that the analysis is conducted by using a narrow band spectrum with a 1 Hz resolution; and assumes non-modulated broadband and tonal components. Modulated sounds will require an increased measurement period to account for variation.

The following steps, based on the ANSI S1.13-1995, can help identify tones:

1) Compute narrow band spectra (df = 1 Hz resolution, Hann window, at least 25 independent averages)
2) Identify candidate tone
3) Determine important frequencies, f_t, f_1, f_2 (all in Hertz) by using the following relationships

f_t = frequency of the tonal component

$$\Delta f_c = 25 + 75\left[1 + 1.4\left(\frac{f_t}{1000}\right)^2\right]^{0.69}$$

$$f_1 = -\frac{\Delta f_c}{2} + \frac{\sqrt{\Delta f_c^2 + 4f_t^2}}{2}$$

$$f_2 = f_1 + \Delta f_c$$

4) Compute the tonal power, W_t by computing a narrow band sum centered on the tonal component with a width of Δf_t. Δf_t is defined the number of spectral lines required to define the tonal component times the frequency resolution (1 Hz).
5) Compute the noise power by

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[24] The methodology in ANSI S1.13-1995 appears to be conservative for the current application. It may be better to: a) either reduce the bandwidth, or b) include all tones within the band for this calculation for the current application.

$$W_n = (W_{tot} - W_t)\frac{\Delta f_c}{\Delta f_{tot} - \Delta f_t}$$

where f_{tot} is the band over which W_{tot} is computed and W_{tot} is the total power.

6) Compute the Tone-to-Noise ratio by

$$\Delta L_T = 10\log_{10}(W_t/W_n)\ \mathrm{dB}$$

If $L_T \geq 6$ dB, then the component is considered to be a tone for the purposes of this work.[25]

Broadband components, which may be modulated, should be in each one-third octave band from 160 Hz to 5000 Hz as the bands contribute to both detection and recognition.

6.5 Pitch Shifting

Pitch is directly related to frequency. Humans interpret the fundamental frequency of a sound to be its pitch; the higher the frequency, the higher the pitch; the lower the frequency, the lower the pitch. A sound wave with a high frequency produces the sensation of a high pitch and a low frequency produces a low pitch. Pitch strength refers to the strength of the pitch's sensation and is dependent on the tone-to-noise ratio (TNR). The tonal components of a sound have periodic, sinusoidal waveforms, while the noise components are random (e.g., wind noise). However, if noise is constrained by some physical or electronic process to contain a relatively narrow band of frequencies, it can produce the sensation of pitch (e.g., some turbine sounds). The greater the noise levels relative to the tone level, the weaker the pitch strength.
There is a strong correlation between the pitch of a sound and the spectral location of its frequency components. When there are multiple frequency components present that are integer multiples of a single lowest frequency, the sound is said to be harmonic. The lowest frequency is commonly referred to as the fundamental. If there are harmonics present, the ability to detect pitch is improved. Even when the fundamental is not present (case of the missing fundamental), the human auditory system compensates for the loss of the lower harmonic. For example, a tone complex of 600, 800 and 1200 Hz is judged to have a pitch of 400 Hz because this corresponds to the shortest common wave period.

A potential parameter for recognition is pitch-shifting of pedestrian-alert sounds. Simulations of pitch shifts of different rates as a function of speed change were evaluated. Based on these sounds and engineering judgment, it was determined that a suitable minimum pitch shift rate would be an increase of 1% of the tone frequency per 1 km/h increase of vehicle speed. That is, at a minimum, the frequency of pitch producing components (tones) must vary in proportion to vehicle speed and shift by at least 1% for each 1 km/h change in vehicle speed. The pitch shift (positive or negative) must correspond to the speed change (positive or negative). That is, the coefficient of proportionality must be positive.

As an example of pitch shifting, a 40-second recording of a prototype sound generator from the Phase 2 experiments was recorded (Sound 1). In this recording, the vehicle was driven over a

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[25] Refer to ANSI S1.13-1995 A.4.6 for additional details and for dealing with multiple tonal components within a critical band.

distance of a few blocks at varying speeds between 0 and 30 km/h. It is a monophonic recording set to loop:

Driving with Sound 1.WAV

Sound 1: Sample Sound with Pitch Shifting

6.5.1 Measuring for Pitch Shifting (Possible Approaches)

There are several possible approaches that could be pursued for measuring pitch shifting. Each approach combines methods of addressing three factors: 1) method of alert sound production, 2) instrumentation and setup, and 3) operating conditions for measurements. The method of alert sound production refers to whether the alert sound is generated, for example, by a vehicle under the specified operating condition (*in situ*), by a vehicle on a dynamometer emulating the specified operating condition, or by a component programed to generate the sound for the specified operating condition. Operating conditions refer to the associated vehicle operating condition, e.g. stationary but active, constant speed pass-by, or accelerating. Instrumentation and setup relate to the type of sensor, e.g. microphones, accelerometers, or voltage sensors. The method of alert sound production is the most critical choice since the technical challenges are very different for each and the method of addressing the other two factors depend on the method of alert sound production.

In situ measurements most closely emulate the conditions that a pedestrian may experience. Further, these measurements do not make any assumptions on how the alert sound is generated. The base *in situ* measurement method would be to measure the narrowband spectrum of a vehicle for stationary but active and for constant speed pass-by operating conditions while the vehicle is at the microphone line P-P' (see Figure 3). The presence of ambient noise, vehicle motion, and Doppler effects could make it difficult to measure the alert sound for a long enough period with a sufficiently high signal-to-noise ratio to be able to clearly track the frequency of a specific tonal component from one operating condition to the next. There are several options for mitigating this issue. Instead of using a stationary microphone a microphone could be installed on the vehicle. This would allow the microphone to measure a strong alert signal over the entire operation, rather than just a short period during the pass-by. However, the ambient noise would increase for higher operating speeds due to increased wind noise. At the highest speeds, 20 and 30 km/h, it may not be possible to sufficiently shield the microphone from wind noise. Another variant that could increase the ability to track the tone would be to conduct an acceleration test from 0 to 30 km/h. In this case the tone could be visually tracked throughout the measurement. One issue with this variant is that it may be difficult to obtain a good signal-to-noise ratio throughout the entire operation. To mitigate this, the vehicle should either begin the operation at 0 km/h at the closest point to the microphones or, as described previously, a microphone could be installed on the vehicle. A final variant of this approach is to utilize *a priori* information about the tone frequency and rate of frequency shifting. That is, it would be reasonable to expect that manufacturers will be able to provide the expected frequency of a target tone as a function of speed.

Because obtaining good signal-to-noise ratios can be difficult for *in situ* measurements, another method for generating alert sounds for pitch shifting measurements is to use a vehicle on a dynamometer. In this method all microphones are essentially "installed" in the sense that they do not move relative to the vehicle. This method removes the problem of Doppler shifts and short time periods for measurements. It does remove some tire and aerodynamic noise, which may affect the final sound, however, the main issue with this approach is the expense and challenge of finding a suitable anechoic or hemi-anechoic chamber with a dynamometer. Because of the possible complexity of alert sounds, tracking a single tone may still be an issue, which can be mitigated by using acceleration tests or *a priori* information as described in the previous paragraph. The use of a dynamometer is a compromise between *in situ* and the next approach, a component or bench test.

Component or bench tests assume that the alert sound generation system exists as a component that can be separated and programmed to operate independently of a vehicle. In such a case, the component can be tested in an anechoic or hemi-anechoic chamber in a stationary condition, in a manner similar to the dynamometer approach. Because there is no need for the space and machinery to support a car with moving wheels, the chamber can be smaller and quieter. An additional variant of this approach is to measure the voltage input to the speaker rather than to measure the sound produced by the speaker. This would further simplify the testing, however; the advantages gained by this approach are outweighed by the inability to account for the speaker performance in this case. Drawbacks to this approach are that it is not technology agnostic with respect to the alert system, requires further details not yet developed for microphone location, and does not account for tire and aerodynamic noise as well as vehicle shielding of the alert device sound when installed.

Based on the desire to have a measurement that is technology agnostic and most closely represents a pedestrian's exposure to an alert sound, the *in situ* approach seems to be the most feasible concept. This approach has the greatest challenges with respect to tracking a tone. One way to address this issue is to have *a priori* knowledge of the frequency of a target tone at 0 km/h and a rate of frequency shifting as a function of speed over the range from 0 to 30 km/h.

6.5.2 Post-processing for Pitch Shifting

Power spectral density could be computed for each operating condition measured for the last second prior to pass-by. The exception to this is for 0 km/h, for which the entire signal may be used. The frequency resolution should initially be set to 1 Hz, using a Hann window with seventy-five percent overlap.[26] If the signal proves to be too noisy, then a lower frequency resolution may be analyzed with the minimum resolution being 10 Hz.[27]

The target tone could be identified and tracked by relying on a priori knowledge of the frequency of a target tone at 0 km/h and a rate of frequency shifting as a function of speed over the range

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[26] Overlap will only occur for resolutions less than 1 Hz.

[27] Resolution below 10 Hz run the risk of including the initial and shifted frequency components within the same spectral line.

from 0 to 30 km/h. If, for example, a manufacturer cannot provide this information, then agreement with the potential specification could be determined by tracking the component with the highest un-weighted level in the 315 Hz one-third octave band at 0 km/h and by assuming a frequency shifting rate of 1 % per km/h.

For each operating condition the prominence of the tone could be determined according to ANSI S1.13 Appendix A.4 Tone-to-Noise Ratio method, with the exception that the measurement period is one-second. A tone is considered sufficiently prominent for pitch shifting if the TNR is at least 6 dB. This 6dB level could be refined as it may be a conservative level for recognition purposes. If the identified tone is sufficiently prominent for each operating condition, then the rate of pitch shifting is computed as follows:

Pitch Shifting Rate = min (Rate (0 to 10 km/h), Rate (10 to 20 km/h), Rate (20 to 30 km/h))

where:
Rate (0 to 10 km/h) = [f(10 km/h) – f(0 km/h)] / 10 km/h
Rate (10 to 20 km/h) = [f(20 km/h) – f(10 km/h)] / 10 km/h
Rate (20 to 30 km/h) = [f(30 km/h) – f(20 km/h)] / 10 km/h

where f(Hz) is the target tone frequency in Hz. An alert system then would agree with the potential specification if the 'Pitch Shifting Rate' is greater than or equal to 1 Hz / km/h.

6.6 Other Possibilities to Increase Recognition

The following are other considerations to increase recognition:

- No greater than 50% amplitude modulation at stationary but activated, at a frequency equal to the modeled combustion frequency.
- Ratios of the total tonal power to the total broadband power should not exceed 15 dB. (Note, this is not the same as the Tone-to-Noise Ratio)
- Multiple harmonics of a fundamental equal to a hypothetical combustion frequency. Note, the fundamental itself (as well as some low harmonics), will likely be too low to produce by most alert systems.
- The lowest harmonic included should be as low in frequency as the alert system can reliably produce.
- Tone complexes and broadband spectra can be based on measurements of actual ICE vehicles. (However, matching an ICE vehicle's spectrum should not be done at the expense of meeting the detection parameters)
- The first or second harmonic present should have the highest amplitude with higher harmonics generally decreasing in amplitude.
- Amplitude should increase as a function of speed beyond the required change for minimum detection (but not beyond the maximum level).

6.7 Conclusion

For the purpose of recognition, at least one tone (and preferably more) should be included in an alert sound. The lowest tone should have a frequency not greater than 400 Hz. Tones at frequencies above 2000 Hz can be included for purposes of detection rather than recognition. A component is considered to be a tone if the Tone-to-Noise ratio according to ANSI S1.13-1995 is greater than or equal to 6 dB. Broadband components, which may be modulated, should be in each one-third octave band from 160 Hz to 5000 Hz.

The pitch (as measured by one of the included tones) should increase by at least 1% per 1 km/h increase to provide additional cues for recognition of vehicle acceleration and deceleration. A pitch shifting specification would keep out melodies or sounds that change over time. The low-frequency parameters would convey the sound of rotating machinery. The consideration to limit amplitude modulation would reduce annoyance and help with recognition.

An *in situ* approach to measure pitch shifting is technology agnostic and most closely represents a pedestrian's exposure to an alert sound. This approach has the greatest challenges with respect to tracking a tone. One way to address this issue is to have *a priori* knowledge of the frequency of a target tone at 0 km/h and a rate of frequency shifting as a function of speed over the range from 0 to 30 km/h.

7. Summary

This report documented possible parameters and criteria for sounds to be detectable and recognizable as the sound of a motor vehicle in operation. The results of this study provide information to assist in the development of specifications for alert sounds to be emitted by electric and hybrid vehicles.

Two concepts were discussed that focused on different ways to determine the minimum sound levels needed for detectability. The first concept in determining the minimum levels for detectability centered on the use of a psychoacoustic model. Moore's Partial Loudness was used to estimate the minimum sound levels needed for a sound to be detectable in the presence of an ambient. A simplified background noise, with an overall A-weighted sound level of 55 dB(A), was used in the implementation of Moore's Loudness model to compute minimum sound levels for detection in a given one-third octave band and to identify frequency ranges relevant for alert sounds. Sound levels, that would be measured from the minimum of the two SAE J2889-1 microphones, were then adjusted to account for the detection distances for each vehicle operation (0, 10, 20, and 30 km/h). Detection distances or critical distances were computed as the stopping sight distance used in highway design (AASHTO, 2004). Stopping sight distance is the distance that enables a vehicle traveling at or near the design speed to stop before reaching an object in its path. The stopping sight distance includes the distance traveled by a vehicle from the instant the driver detects an object to the instant the driver applies the brakes and the distance needed to stop the vehicle once the driver applies the brakes. Levels for 'backing' or 'reverse' are based on the forward 10 km/h levels but adjusted down 3 dB to represent equivalent reductions in level of ICE vehicles at the back. The second approach in determining minimum levels for detectability was based on acoustic properties of ICE vehicles. Analyses included data from OICA and Phase 2 research. Two versions of potential minimum sound levels based on measured ICE levels are provided, one based on the mean levels and one based on the mean levels minus 1 standard deviation.

Potential specifications for detectability based on these two concepts are presented in this report in terms of frequency range and minimum sound level for selected one-third octave bands. Based on analysis it was determined that, due to masking effects of the ambient, opportunities for detection could be maximized if the alert signal contains detectable components over a wide frequency range. A minimum level is prescribed for a set of one-third octave bands that includes mid-frequency one-third octave bands (315, 400, and 500 Hz) as well as high frequency one-third octave bands (2000, 2500, 3150, 4000, and 5000 Hz). Low frequency bands (below 315 Hz) are omitted due to the expected strong masking effects of the ambient at low frequencies and the likelihood that many practical alerting devices may not be able to produce high level, low frequency sounds. Mid-frequency bands from 630 to 1600 Hz are omitted because analysis indicated that, for the ambient considered, these bands contributed more to the overall level than other bands for the same increase in detectability.

For the purpose of recognition, it was determined that at least one tone (and preferably more) should be included in an alert sound. That lowest tone present in the alert should have a frequency no greater than 400 Hz. Broadband components should also be present in each one-third octave band from 160 Hz to 5000 Hz. To further aid in the recognizability of vehicle acceleration and deceleration, the pitch (as measured by a prominent tone) should increase by at least 1% per 1 km/h increase. An *in situ* approach to measure pitch shifting is technology agnostic and most closely represents a pedestrian's exposure to an alert sound. A priori knowledge of the frequency of a target tone at 0 km/h and a rate of frequency shifting as a function of speed over the range from 0 to 30 km/h would facilitate the implementation of this method.

A pitch shifting specification would keep out melodies or sounds that change over time. The low-frequency parameters would convey the sound of rotating machinery. The recommendation to limit amplitude modulation would reduce annoyance and help with recognition. Additional cues for recognition will be obtained by the movement of the vehicle relative to the pedestrian.

Areas of future research may include the refinement of the psychoacoustic model approach for determining the minimum levels needed for detectability using input from human subject experiments. Further analysis could also include refinements of the procedures to identify and track primary tones through different operating condition to verify pitch shifting.

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APPENDICES

A. Ambient Noise Spectrum

Figure 17 shows the Un-weighted and A-Weighted one-third octave band spectra for the ambient used in the acoustic analyses described in this report.

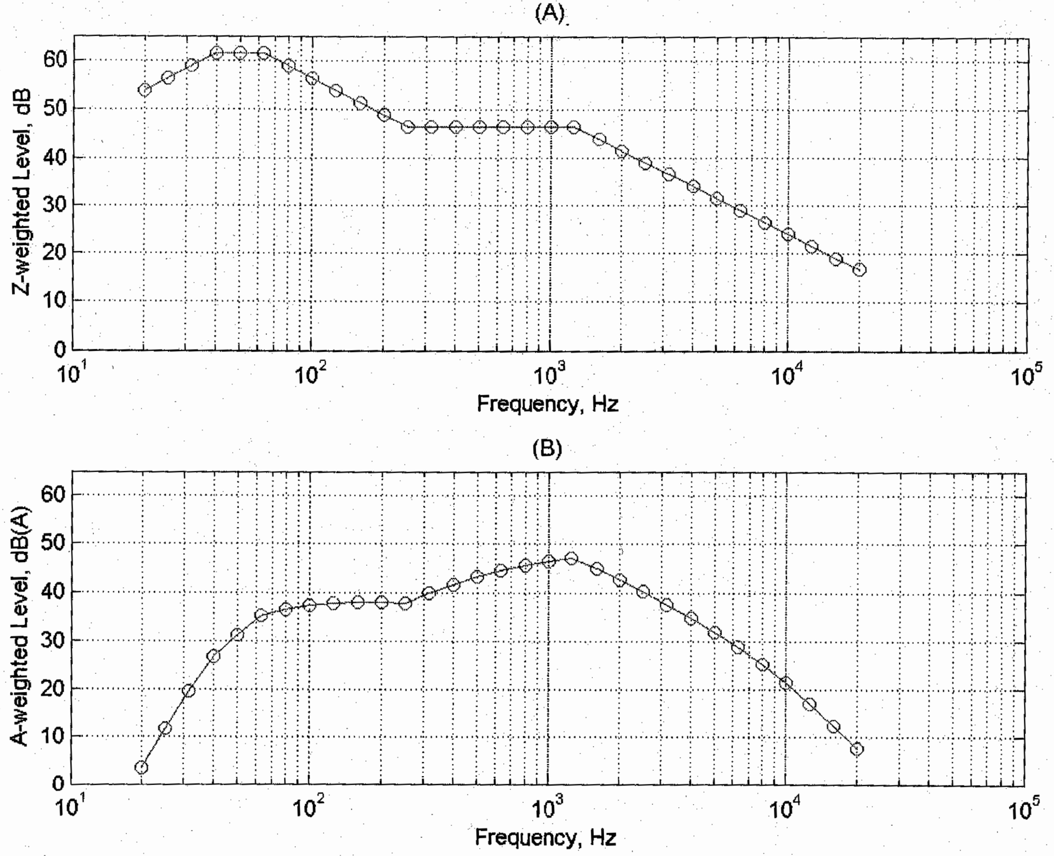

Figure 17: Ambient at 55 dB(A): (A) Un-weighted One-Third Octave Band, (B) A-weighted One-third Octave Band Spectra

B. Possible Increase in Sound Level above Minimum

The removal of these bands (from 630 to 1600 HZ) provides an overall reduction of about 5 to 6 dB. One may consider if some of this level reduction could be used to increase detection. It can be seen in Table 26**Error! Reference source not found.** that an increase of 3 dB will increase the loudness of each component by about 4 times. An increase of only 1.5 dB will increase the loudness of each component by about 2.5 times. Adding 1.5 dB to each band in the reduced set provides a significant increase in the loudness (and detection) while only slightly impacting the overall level. Adding 1.5 dB provides a good compromise between maximizing detectability while at the same time minimizing the overall level.

Table 26: Increase in Loudness due to Increase in Level above Masked Threshold

1/3 OB Center Frequency, Hz	dB(Z)	N, Threshold	N, Threshold+3 dB	Loudness Increase	N, Threshold+1 .5dB	Loudness Increase
50	79	0.0475	0.2193	4.6	0.1202	2.5
63	75	0.0504	0.2318	4.6	0.1262	2.5
80	70	0.0383	0.1805	4.7	0.0981	2.6
100	65	0.0353	0.156	4.4	0.0865	2.5
125	61	0.0497	0.1693	3.4	0.102	2.1
160	57	0.056	0.1713	3.1	0.1074	1.9
200	53	0.0544	0.161	3.0	0.1022	1.9
250	49	0.035	0.1268	3.6	0.0758	2.2
315	48	0.0488	0.1595	3.3	0.0988	2.0
400	47	0.0488	0.1694	3.5	0.1033	2.1
500	46	0.0408	0.1648	4.0	0.0966	2.4
630	46	0.0623	0.2093	3.4	0.1295	2.1
800	45	0.0364	0.1761	4.8	0.0987	2.7
1000	45	0.042	0.1864	4.4	0.1073	2.6
1250	45	0.0535	0.2163	4.0	0.1279	2.4
1600	43	0.0683	0.2262	3.3	0.141	2.1
2000	40	0.0471	0.1913	4.1	0.1127	2.4
2500	37	0.032	0.1706	5.3	0.0945	3.0
3150	35	0.0538	0.2058	3.8	0.1237	2.3
4000	32	0.031	0.1558	5.0	0.0871	2.8
5000	30	0.0355	0.1276	3.6	0.0773	2.2
6300	29	0.0433	0.1002	2.3	0.0697	1.6
8000	28	0.0333	0.0651	2.0	0.048	1.4
10000	27	0.0315	0.0574	1.8	0.0434	1.4
		Average (315 - 5000Hz):		4.0		2.4

The results of adding 1.5 dB to the parameter and rounding up to the next integer (for simplicity) are shown in Table 27.

Table 27: Possible A-weighted Minimum Levels for Detection

	Ambient = 55 dB(A)				
	Operating Condition	**Stationary/Activated**	**10 km/h**	**20 km/h**	**30 km/h**
One-Third Octave Band Center Frequency, Hz	315	44	50	56	61
	400	45	51	57	61
	500	45	51	57	62
	2000	44	50	56	60
	2500	41	47	53	58
	3150	39	45	51	55
	4000	35	41	48	52
	5000	33	39	45	50
	Measured at SAE J2889-1Microphone	51	57	63	68

C. Test Procedure Sent to OICA

Scope

This is the acoustic measurement procedure used by NHTSA/Volpe Center to document the sound levels (minimum, average, and maximum) of typical ICE vehicles for identified critical operating modes. This measurement procedure follows SAE-J2889-1 (Rev 2009) with some exceptions as noted below.

Measuring ICE Vehicles under Critical Operating Modes

It is necessary to develop a quantitative description of the sound level on a one-third octave band basis of typical ICE vehicles under identified low speed operating conditions. To this end, a sample of ICE vehicle sound level measurements will be collected for the following operating conditions: (1) low speed pass-by forward at 6, 10, 15 and 20 mph; (2) low speed pass-by reverse at 6 mph; (3) start-up; (4) stationary but activated; (5) acceleration from stop pass-by; and 6) deceleration. These measurements will include both overall sound levels and spectral character (one-third octave band data).

The measurement procedure follows SAE-J2889-1 Rev 2009 with the following exceptions.

1) Additional operating modes will be measured. See below for details.
2) Overall sound levels for each event will be reported for L_{AFmax}, L_{AFmin}, and $L_{Aeq,\ ½\ sec}$.
3) For transient events (pass-by and start up), one-third octave band sound levels for each event will be reported for $L_{Zeq,½\ sec}$ (no spectral weighting function) for the ½ second measurement interval which includes the actual pass-by / start up event. One-third octave bands should include at a minimum bands from 50 Hz to 10 kHz.
4) For stationary but activated and ambient measurements one-third octave band sound levels will be reported for $L_{Zeq,½\ sec}$ for the measurement interval with the maximum overall level, the minimum overall level, as well as the average of $L_{Zeqs,½\ sec}$ for the entire measurement event.
5) In 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 startup, in which case, the vehicle will be positioned at PP' (see Figure 18) with the engine off prior to measurement.
6) For deceleration, measurement will also be made at the DD' location to capture the beginning of the deceleration.
7) For the purposes of this measurement procedure, two measurements are sufficient rather than four[28].

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[28] 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.

8) With the exception of stationary but activated and ambient $L_{Aeq,\ ½\ sec}$, measurements shall not be averaged but rather reported per event.

Operating Modes:

Low Speed Pass-by Forward Measurement Procedure

- Vehicle will accelerate to a constant specified speed
    - Target speeds include 6, 10, 15, and 20 mph.
    - Target speed will be attained at least 1.5 s prior to passing PP', the microphone line[29].
    - Target speed will be maintained within a tolerance of +/- 1 mph
- A minimum of 2 repetitions for this operating condition will be measured for each vehicle. Any data that is clearly not representative of a typical vehicle (dogs barking, backfires, etc.) will be rejected.

Low Speed Pass-by Reverse Measurement Procedure

- Vehicle will accelerate to a constant specified speed
    - Target speed is 6 mph in reverse.
    - Target speed will be attained at least 1.5 s prior to passing PP', the microphone line.
    - Target speed will be maintained within a tolerance of +/- 1 mph
- A minimum of 2 repetitions for this operating condition will be measured for each vehicle. Any data that is clearly not representative of a typical vehicle (dogs barking, backfires, etc.) will be rejected.

Start-up Measurement Procedure

- Starting with the vehicle off, the vehicle will be turned on with the drive train in Park.
- A minimum of 2 repetitions for this operating condition will be measured for each vehicle. Any data that is clearly not representative of a typical vehicle (dogs barking backfires, etc.) will be rejected.

Stationary but Activated Measurement Procedure

- Vehicle will start and remain at rest adjacent to the microphones.
- The measurement will begin after the vehicle has come to steady state stationary but activated.
- The engine will be running at stationary but activated, but all unnecessary accessory devices will be off.
- A 1- minute measurement will be conducted for each vehicle.

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[29] 1.5 s insures that the measurement at pass-by will not be affected by changes in vehicle speed.

Acceleration from Stop Pass-by Measurement Procedure

- Vehicle will start at rest at a distance of 3 m from the microphone (as measured along the road) and then accelerate at a constant rate of 1 m/s^2 to a speed of 10 mph.
    - The driver(s) will attempt to accelerate at the same rate for each repetition using the provided accelerometer as a guide.
    - In some cases, attaining the specified acceleration may be difficult. In such cases, characterize either quantitatively or qualitatively as best as possible.
- A minimum of 2 repetitions for this operating condition will be measured for each vehicle. Any data that is clearly not representative of a typical vehicle (dogs barking backfires, etc.,) will be rejected.

Deceleration Measurement Procedure

- Vehicle will accelerate to a constant speed of 20 mph
    - Target speed will be attained at least 1.5 s prior approaching DD'
    - Target speed will be maintained within a tolerance of +/- 1 mph
- Upon reaching DD', vehicle will begin to decelerate at a rate of 1 m/s^2 reaching a target speed of 10 mph at the microphone line, PP'
    - Target speed will be maintained within a tolerance of +/- 1 mph
- A minimum of 2 repetitions for this operating condition will be measured for each vehicle. Any data that is clearly not representative of a typical vehicle (dogs barking, backfires, etc.,) will be rejected.

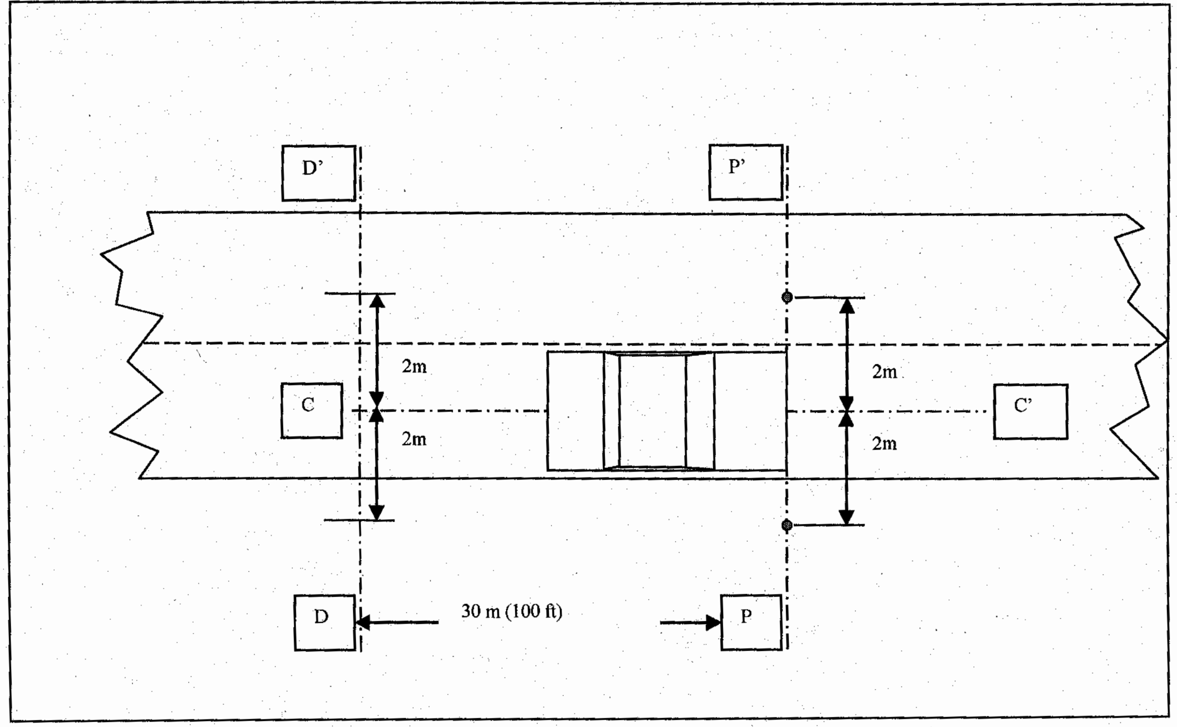

Figure 18: Microphone Line Relative to Vehicle Assuming Engine Mounted in Front of Vehicle

Reported Results:

Reported results will include A-weighted one-third octave band levels for each measurement event at the point where the vehicle is adjacent to the microphone for both passenger and driver side microphones. Any measurements which may be contaminated, or for any other reason unsuitable for analysis will be discarded. Data will not be aggregated as is done in SAE-J2889-1 for the reasons given by footnote 28.

Sample results are shown in Table 28.

Table 28: Sample Results with Inner One-Third Octave Bands Omitted for Space

		$L_{Aeq\text{-}1/2\ sec}$	L_{AFmax}	L_{AFmin}	Unweighted One-Third Octave Band Levels, $L_{eq\text{-}1/2\ sec}$, dB							
		dB(A)	dB(A)	dB(A)	50 Hz	63 Hz	80 Hz	100 Hz	...	6300 Hz	8000 Hz	10000 Hz
Ambient	Average	39.5	41.0	38.5	44.4	44.7	44.1	43.2	...	14.9	10.4	6.1
	Min	37.2	37.7	36.9	38.9	38.3	38.9	39.2	...	9.1	6.1	2.2
	Max	44.9	46.7	43.0	49.4	53.4	48.7	49.8	...	28.5	18.8	10.8
Stationary but Activated	Average	52.5	53.2	52.2	52.8	52.1	53.3	51.0	...	31.9	31.1	30.4
	Min	51.7	51.9	51.4	45.2	45.7	49.0	46.3	...	30.6	30.4	29.5
	Max	55.8	58.2	53.5	60.4	56.9	56.9	55.7	...	35.1	33.7	31.5
Startup		66.1	68.9	65.7	61.3	49.5	52.1	49.5	...	54.0	49.4	45.5
Startup		67.2	70.6	50.0	52.5	50.5	49.9	51.2	...	52.2	48.9	45.6
Acceleration		63.7	64.0	63.4	50.4	52.3	53.0	61.0	...	43.9	42.5	42.0
Acceleration		64.8	65.3	64.6	52.7	54.1	51.9	66.3	...	44.3	42.9	42.5
Deceleration (DD')		69.6	70.4	69.1	52.0	53.4	53.9	59.5	...	39.9	38.2	37.4
Deceleration (DD')		70.0	70.5	68.7	53.9	55.7	55.2	57.2	...	38.4	36.2	35.1
Deceleration (PP')		61.0	62.4	59.8	53.5	56.5	58.8	58.0	...	36.6	34.6	33.5
Deceleration (PP')		62.7	63.1	62.3	52.4	57.7	58.5	55.6	...	40.3	38.0	37.9
Forward (6 mph)		60.3	60.7	59.4	52.8	57.1	54.9	52.7	...	38.2	37.1	36.3
Forward (6 mph)		62.0	62.5	61.6	52.4	54.5	57.5	55.7	...	41.5	40.5	40.1
Forward (10 mph)		61.0	62.4	59.8	53.5	56.5	58.8	58.0	...	36.6	34.6	33.5
Forward (10 mph)		62.7	63.1	62.3	52.4	57.7	58.5	55.6	...	40.3	38.0	37.9
Forward (15 mph)		65.9	67.2	63.3	52.8	51.8	53.5	53.0	...	42.7	40.8	40.6
Forward (15 mph)		65.9	67.0	63.8	48.4	55.0	56.2	53.9	...	34.7	32.0	30.8
Forward (20 mph)		69.6	70.4	69.1	52.0	53.4	53.9	59.5	...	39.9	38.2	37.4
Forward (20 mph)		70.0	70.5	68.7	53.9	55.7	55.2	57.2	...	38.4	36.2	35.1
Reverse (6 mph)		55.6	55.8	54.9	53.9	54.3	53.7	56.5	...	36.5	34.8	33.4
Reverse (6 mph)		54.3	54.7	53.9	52.1	56.8	55.2	51.6	...	34.9	33.6	32.4

D. Overall Sound Level Final Dataset

D.1 OICA Data

Table 29: A-weighted One Third Octave Band Level, dB(A) for Stationary but Activated (OICA data)

Operating Condition	Overall, LAeq,1/2 sec, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
Stationary/Activated	59.5	38.2	41.6	43.3	43.2	44.0	47.1	48.0	46.6	48.4	47.2	47.3	47.8	47.7	50.8	50.3	47.0	47.3	43.0
Stationary/Activated	53.0	25.8	25.8	39.8	35.8	34.2	34.9	38.7	38.3	42.4	40.2	40.6	42.1	44.8	45.4	43.0	41.9	38.2	35.1
Stationary/Activated	52.3	27.6	27.6	29.5	35.2	32.3	34.7	38.4	42.9	37.4	37.6	38.9	39.4	42.2	46.4	41.7	40.4	42.7	29.5
Stationary/Activated	60.6	38.0	37.2	38.1	35.6	39.2	46.1	49.6	46.5	48.3	51.0	53.2	52.7	48.4	48.8	48.2	46.9	48.7	42.4
Stationary/Activated	60.1	38.1	40.3	41.4	39.1	40.5	46.2	47.6	48.9	48.5	50.8	50.5	51.9	49.8	50.3	48.0	45.7	43.9	40.3
Stationary/Activated	51.8	32.4	31.5	26.2	33.1	43.9	38.5	41.6	40.7	40.4	39.8	40.1	40.6	40.9	39.3	39.2	39.2	37.0	35.5
Stationary/Activated	50.7	29.2	31.3	26.5	32.2	41.2	36.7	38.9	39.5	38.1	39.8	40.6	40.1	39.5	38.5	39.7	38.7	37.5	34.5
Stationary/Activated	55.9	35.3	41.5	33.7	38.2	42.2	42.6	45.1	46.2	42.5	47.8	45.9	47.3	42.9	42.2	43.1	42.3	37.4	35.4
Stationary/Activated	58.4	49.8	43.5	38.9	36.6	36.8	40.6	46.7	46.5	46.2	48.9	48.1	48.4	48.0	45.2	45.7	45.5	43.5	39.6
Stationary/Activated	52.4	24.1	25.8	24.7	25.3	26.2	32.3	35.7	37.8	39.2	39.9	38.9	40.5	43.1	44.0	42.4	44.3	43.3	40.9
Stationary/Activated	52.4	24.1	22.2	24.5	22.2	30.5	27.0	33.0	35.9	38.1	37.6	38.7	40.5	44.1	44.3	42.9	44.0	43.4	42.0
Stationary/Activated	52.9	28.3	30.4	30.2	31.4	33.5	35.0	35.6	39.5	41.1	42.3	45.1	42.8	42.3	43.4	41.1	39.6	41.4	42.2
Stationary/Activated	60.5	37.8	42.8	44.8	44.3	46.2	50.0	45.4	48.4	49.5	50.4	46.9	48.1	48.7	49.0	49.4	49.3	48.0	49.0
Stationary/Activated	61.4	54.5	51.1	52.1	47.6	45.0	47.4	48.4	49.6	48.1	47.5	46.6	46.3	47.2	48.5	47.5	46.8	46.1	45.5
Stationary/Activated	57.5	30.1	36.5	42.1	45.5	41.7	48.5	50.7	48.3	46.6	45.2	43.7	42.8	44.5	44.4	42.5	41.5	41.0	39.5
Stationary/Activated	51.3	31.8	28.1	31.7	30.4	32.9	35.3	36.9	37.8	37.3	40.8	40.1	38.5	39.9	41.5	40.9	40.3	44.0	38.8
Stationary/Activated	63.1	38.6	44.7	39.5	46.6	49.6	54.4	49.5	50.3	53.0	54.2	52.9	51.9	50.5	50.6	50.9	50.9	49.3	46.0
Stationary/Activated	69.8	40.1	51.3	51.7	55.2	57.9	54.6	57.3	59.4	61.2	62.5	60.9	60.4	58.7	55.3	50.5	48.0	44.4	40.9
Stationary/Activated	56.4	31.6	33.1	36.7	35.9	40.7	44.1	43.6	42.4	42.2	45.4	48.2	50.2	45.3	43.1	43.9	43.4	42.8	37.7
Stationary/Activated	52.8	28.0	31.8	29.9	31.0	34.4	34.3	37.4	39.4	38.9	41.1	43.3	43.4	43.6	45.6	43.3	43.2	32.8	26.4
Stationary/Activated	53.0	29.6	30.8	32.2	34.9	39.3	39.8	38.2	39.6	40.9	44.5	44.4	45.1	41.1	40.8	40.7	42.9	32.0	29.2
Stationary/Activated	58.6	31.2	34.4	40.4	40.2	46.6	44.1	47.9	47.1	49.3	50.7	50.1	48.4	45.7	45.8	44.3	44.6	34.6	30.5

Operating Condition	Overall, LAeq,1/2 sec, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
Stationary/Activated	58.6	31.2	34.4	40.4	40.2	46.6	44.1	47.9	47.1	49.3	50.7	50.1	48.4	45.7	45.8	44.3	44.6	34.6	30.5
Stationary/Activated	55.7	29.9	31.6	30.4	34.8	37.4	40.5	40.8	39.6	45.6	44.0	46.0	47.5	44.7	44.1	45.3	45.3	45.5	40.7
Stationary/Activated	52.2	32.2	32.3	34.2	36.3	32.1	35.2	36.1	37.9	37.7	41.2	40.7	42.0	40.7	41.2	42.4	42.1	44.0	40.1
Stationary/Activated	71.3	37.9	44.0	52.0	52.8	54.1	56.8	56.9	59.4	60.5	65.2	64.3	61.8	59.3	57.3	54.6	54.3	53.4	49.1
Stationary/Activated	52.3	31.3	30.1	32.0	36.1	36.3	37.6	37.7	40.9	41.7	44.0	43.1	43.9	41.5	40.3	40.8	39.9	32.6	30.9
Stationary/Activated	51.9	33.9	34.4	36.9	35.4	36.7	38.3	38.4	39.4	41.5	43.6	43.3	43.0	41.5	39.0	38.1	37.8	31.5	26.2
Stationary/Activated	49.8	22.9	23.6	28.7	29.2	37.7	30.4	32.7	36.5	35.3	36.5	37.1	39.6	41.0	39.7	41.4	40.1	37.7	36.9
Stationary/Activated	49.3	22.2	23.2	28.4	28.4	36.8	30.1	33.3	36.8	35.4	36.2	36.8	39.0	40.4	39.8	40.6	39.4	37.1	36.8
Stationary/Activated	47.6	20.9	23.3	25.1	24.8	28.4	32.6	33.5	36.1	37.4	40.2	35.2	38.0	37.8	35.2	36.1	36.7	33.3	32.9
Stationary/Activated	48.2	25.9	26.4	30.1	29.8	29.3	31.0	32.2	35.1	34.9	35.6	36.3	39.4	39.3	38.6	38.2	37.4	36.6	36.5
Stationary/Activated	48.7	22.7	22.5	24.7	27.8	25.5	33.3	35.8	34.1	36.9	35.1	35.7	39.6	39.8	37.8	38.2	41.0	37.3	34.5
Stationary/Activated	48.5	21.3	31.7	28.6	28.2	24.7	33.4	36.7	34.8	36.4	36.8	35.5	39.0	39.5	39.9	39.2	36.1	36.1	32.5
Stationary/Activated	49.1	22.9	25.5	27.3	28.8	29.3	35.5	35.8	34.3	35.5	35.6	38.4	39.0	39.7	39.4	41.3	39.2	36.7	34.0
Stationary/Activated	50.5	29.3	27.7	26.3	27.4	29.8	34.5	33.1	34.6	37.6	40.9	41.0	42.8	41.3	40.3	41.4	38.2	36.3	34.5
Stationary/Activated	51.7	28.0	32.2	30.9	29.8	33.4	38.1	41.6	40.2	40.6	40.1	41.1	42.0	43.7	41.4	40.1	36.8	36.5	34.5
Stationary/Activated	50.3	35.8	28.1	29.4	35.3	35.3	34.6	37.8	39.4	35.3	39.8	39.0	40.5	41.2	40.6	39.6	37.4	34.9	34.2
Stationary/Activated	52.6	27.8	27.1	30.3	34.3	36.7	34.6	37.8	37.2	36.6	39.2	44.2	42.9	45.0	42.7	43.6	41.3	39.2	36.7
Stationary/Activated	48.9	19.5	21.1	27.0	27.4	31.9	33.9	34.2	34.7	36.7	36.2	39.4	42.5	40.7	38.2	37.5	35.4	34.3	30.5
Stationary/Activated	52.9	31.1	32.9	33.8	31.7	35.5	36.8	39.0	40.9	42.0	43.8	45.1	44.3	42.0	41.2	39.6	39.0	37.2	39.2
Stationary/Activated	46.4	23.7	25.7	24.8	24.5	31.8	33.1	34.1	34.7	33.0	37.1	35.5	36.3	35.9	36.0	35.9	35.8	32.1	32.1
Stationary/Activated	53.2	28.4	31.3	31.9	35.5	37.4	41.9	43.9	41.9	40.3	41.5	43.5	44.2	44.2	41.9	41.2	37.3	35.4	36.8
Stationary/Activated	53.3	35.8	33.3	31.2	39.4	42.5	39.0	41.9	46.1	43.8	42.6	42.0	40.8	40.3	40.3	40.3	38.1	35.3	35.4
Stationary/Activated	51.2	33.6	31.1	39.2	39.6	38.8	38.3	38.2	39.1	36.6	41.6	39.5	41.1	40.2	40.0	40.4	36.5	34.5	32.8
Stationary/Activated	52.8	29.9	31.1	32.1	34.7	35.3	33.2	38.6	42.9	40.6	41.3	40	40.9	42.8	44.4	42.8	42.9	40.6	38.8
Stationary/Activated	61.0	32.1	37.5	42.0	45.2	51.9	46.2	46.6	47.0	44.7	46.6	53.3	52.8	50.5	48.8	49.5	48.5	47.2	43.2
Stationary/Activated	55.2	38.9	43.2	39.6	37.4	41.9	44.0	44.0	42.8	46.6	48.6	43.7	41.9	43.1	39.3	36.9	38.1	34.4	-0.9
Stationary/Activated	74.0	47.7	57.6	56.5	53.9	58.4	56.5	61.7	61.4	62.7	67.6	63.9	62.4	63.9	64.2	60.9	60.0	56.1	-1.4

Table 30: A-weighted One Third Octave Band Level, dB(A) for Reverse 10 km/h (OICA data)

Operating Condition	Overall, LAfmax, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
Reverse 10 km/h	57.7	40.7	35.4	36.3	37.2	40.6	43.6	43.9	44.9	44.7	47.3	47.7	46.7	46.8	47.8	48.3	47.1	46.6	41.2
Reverse 10 km/h	58.6	41.1	35.0	34.1	36.3	38.5	44.8	46.1	46.3	46.4	48.3	47.8	48.6	48.6	49.5	48.9	46.3	46.0	41.5
Reverse 10 km/h	56.2	29.7	32.9	33.5	37.9	43.1	40.3	44.5	44.4	47.0	46.3	47.5	46.4	44.9	43.7	42.1	45.1	41.3	39.4
Reverse 10 km/h	56.9	30.7	31.9	34.7	39.7	43.8	42.6	44.3	46.9	48.1	47.3	47.8	47.4	45.8	44.5	42.1	43.7	40.8	38.2
Reverse 10 km/h	55.6	38.6	34.0	35.8	39.9	40.9	42.0	42.6	44.4	45.6	45.6	45.2	44.7	45.9	44.8	43.2	41.0	43.9	36.0
Reverse 10 km/h	57.1	46.0	46.1	38.6	40.0	40.8	42.2	42.1	45.2	45.7	46.2	46.2	46.3	46.6	47.0	44.9	42.6	44.2	36.2
Reverse 10 km/h	59.7	41.2	37.6	39.9	42.5	41.5	46.4	45.0	42.1	48.7	52.9	52.1	50.1	48.7	47.2	45.8	43.9	45.5	43.8
Reverse 10 km/h	61.3	40.6	39.5	43.4	42.2	44.0	48.6	50.8	47.2	51.9	53.3	52.6	51.0	49.6	48.8	47.1	45.6	47.4	45.2
Reverse 10 km/h	57.7	38.1	44.6	37.9	40.4	40.8	42.5	45.3	46.8	46.0	47.6	46.7	48.9	48.4	47.4	44.9	44.0	41.6	38.7
Reverse 10 km/h	58.4	39.5	41.7	40.0	42.4	41.7	44.9	46.1	46.7	47.1	47.8	47.3	49.7	48.8	47.8	45.7	46.1	43.5	40.8

Table 31: A-weighted One Third Octave Band Level, dB(A) for 10 km/h (OICA data)

Operating Condition	Overall, LAfmax, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
10 km/h	61.8	44.5	42.9	41.5	43.1	43.5	50.1	48.1	49.6	48.2	48.2	49.1	50.3	51.1	53.9	53.5	50.0	49.2	46.5
10 km/h	62.2	44.0	44.0	43.1	43.8	44.4	49.1	48.6	50.2	48.7	49.4	49.4	50.6	50.8	54.4	54.3	50.9	49.1	46.5
10 km/h	60.1	34.2	37.9	48.3	43.9	42.6	44.2	47.4	46.9	51.0	49.7	48.2	52.3	49.7	48.4	47.0	46.9	45.3	43.6
10 km/h	60.6	33.9	34.9	51.6	47.8	41.3	42.9	48.7	48.1	50.4	48.4	49.1	52.5	49.5	48.4	47.4	47.5	45.6	42.9
10 km/h	56.2	30.4	35.0	32.5	38.4	41.8	41.1	42.0	44.2	44.1	46.0	45.6	46.2	46.7	47.6	45.0	43.4	44.6	36.0
10 km/h	58.1	37.9	42.9	43.9	41.5	44.5	46.9	46.7	45.9	45.9	46.9	46.0	46.5	47.1	48.9	46.3	44.2	46.3	37.9
10 km/h	63.2	38.8	42.0	46.0	39.5	44.5	53.4	55.0	50.6	50.7	52.6	54.8	54.2	51.0	49.7	48.2	48.2	49.4	45.7
10 km/h	64.9	41.3	40.8	47.2	39.2	45.7	56.3	56.3	52.1	51.8	55.2	56.4	55.7	52.3	52.1	49.3	49.6	50.2	46.5
10 km/h	60.3	39.6	40.0	44.6	40.1	42.6	46.4	46.3	48.8	48.5	50.3	49.9	51.0	51.1	51.7	48.5	46.5	44.4	41.2
10 km/h	60.6	40.9	40.4	44.5	41.3	42.3	44.6	45.3	48.6	49.0	51.3	50.2	50.9	51.2	52.9	48.4	46.9	45.2	41.1
10 km/h	55.8	28.6	39.9	32.5	34.7	44.9	40.2	46.4	45.4	42.8	44.0	45.5	44.3	45.7	44.0	44.9	43.3	41.6	39.7
10 km/h	56.8	33.4	46.3	32.0	34.9	43.8	40.3	45.8	45.9	43.2	45.3	48.4	45.5	46.2	44.8	45.1	44.4	41.9	40.1
10 km/h	56.5	47.9	41.6	37.0	34.7	34.9	38.7	44.8	44.6	44.3	47.0	46.2	46.5	46.1	43.3	43.8	43.6	41.6	37.7
10 km/h	58.9	48.7	45.3	41.5	40.5	44.6	44.8	47.1	47.0	47.5	48.0	48.5	49.2	47.6	45.6	46.7	45.9	43.2	39.9
10 km/h	58.9	27.5	25.3	29.8	36.3	33.8	37.8	42.7	48.2	46.1	46.5	44.3	46.9	50.5	50.7	49.4	49.4	48.4	46.0
10 km/h	60.9	29.8	28.6	36.9	31.4	36.5	36.4	40.8	49.7	45.4	46.7	46.4	47.3	52.5	52.6	52.9	52.1	51.6	48.2
10 km/h	52.5	26.2	28.5	30.5	32.0	33.8	34.1	35.8	39.5	46.6	43.6	43.2	41.3	41.6	42.2	38.7	37.6	37.5	36.0
10 km/h	63.5	36.7	37.8	39.4	41.1	43.3	43.6	45.5	50.0	58.0	53.0	54.6	53.4	52.9	52.7	50.2	49.3	48.3	46.9
10 km/h	61.3	40.3	37.0	40.6	40.5	43.1	45.4	44.6	49.1	48.5	53.3	49.7	50.3	49.6	48.3	51.7	51.0	50.8	50.2
10 km/h	62.9	35.6	40.3	41.3	47.4	46.3	44.7	48.9	49.6	47.2	54.0	49.6	49.2	49.9	53.8	53.2	53.4	53.4	52.1
10 km/h	66.4	59.3	54.9	53.4	49.8	51.9	51.5	57.5	52.6	51.1	50.3	48.4	54.3	53.4	52.7	57.0	51.2	51.0	50.5
10 km/h	66.4	58.8	55.2	54.9	45.1	49.3	50.4	51.3	50.6	49.2	48.9	50.5	48.8	51.2	54.9	57.8	57.2	56.2	52.0
10 km/h	67.1	58.5	57.1	50.0	54.5	47.7	44.9	50.0	53.9	58.8	57.6	56.8	55.8	52.3	53.5	52.9	51.5	50.1	48.7
10 km/h	60.5	57.4	41.8	38.7	35.4	34.5	39.4	47.0	48.4	43.4	49.3	49.8	48.6	49.1	43.8	42.2	39.5	38.5	36.7
10 km/h	61.0	50.4	52.0	50.6	48.4	43.9	42.6	50.2	52.6	51.0	51.2	47.3	45.4	43.4	47.7	41.7	40.4	42.1	39.3
10 km/h	54.2	29.6	35.0	37.1	36.8	38.0	39.3	41.4	45.4	44.8	44.4	43.6	43.2	42.5	42.0	41.1	39.0	43.2	38.0
10 km/h	59.0	34.5	38.2	38.6	41.1	41.8	50.5	44.1	45.6	48.7	49.0	47.8	48.1	47.7	47.2	47.4	47.9	47.1	43.3

Operating Condition	**Overall, LAfmax, dB(A)**	**100 Hz**	**125 Hz**	**160 Hz**	**200 Hz**	**250 Hz**	**315 Hz**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**	**1250 Hz**	**1600 Hz**	**2000 Hz**	**2500 Hz**	**3150 Hz**	**4000 Hz**	**5000 Hz**
10 km/h	60.1	35.6	39.9	42.3	42.7	44.7	46.4	48.6	46.9	51.6	52.0	49.9	52.1	48.1	46.1	46.4	43.9	45.6	42.0
10 km/h	60.0	37.8	36.7	37.5	39.8	43.1	49.9	48.5	46.9	48.0	48.9	51.6	51.0	49.0	48.7	47.9	46.9	46.0	41.2
10 km/h	54.4	31.8	33.5	35.0	40.9	40.6	39.8	41.8	44.3	46.1	45.5	43.2	43.7	43.8	43.1	41.8	39.8	30.1	28.8
10 km/h	56.6	34.5	36.7	39.6	42.3	41.4	42.0	43.6	45.7	46.5	47.6	48.5	47.1	46.0	44.0	43.8	43.0	32.7	28.6
10 km/h	54.5	33.5	37.7	34.8	40.5	41.4	38.0	41.3	43.2	43.8	44.7	45.0	43.8	42.5	42.3	44.4	41.9	41.9	37.4
10 km/h	56.6	33.1	35.8	36.1	38.9	44.2	42.6	44.4	45.2	47.1	46.7	46.2	46.9	45.8	46.2	45.6	43.7	32.2	27.7
10 km/h	55.1	33.7	37.9	36.7	38.5	40.1	42.8	41.7	44.8	45.5	46.1	46.5	45.0	44.0	43.1	41.8	41.5	32.8	27.4
10 km/h	57.7	31.3	28.9	39.4	38.5	35.5	40.1	41.6	46.6	46.1	45.7	45.6	49.6	48.7	49.2	47.7	46.6	42.0	41.2
10 km/h	56.4	31.5	29.7	33.7	37.8	46.2	42.5	46.1	47.2	47.9	46.0	45.1	45.6	43.2	43.3	43.6	43.5	39.7	37.9
10 km/h	57.9	36.6	35.1	40.3	41.9	42.4	43.3	43.0	43.8	45.1	43.8	45.1	49.4	50.3	48.4	47.3	46.4	44.4	43.8
10 km/h	57.6	35.6	36.4	35.3	39.0	37.8	39.8	43.0	45.8	49.3	49.5	48.8	47.4	46.4	45.1	45.3	45.5	42.6	41.5
10 km/h	55.5	39.8	36.6	38.2	42.8	40.4	44.8	45.2	45.5	45.6	44.9	45.3	45.2	44.0	42.6	40.9	38.8	36.2	35.7
10 km/h	56.5	36.3	32.4	41.9	42.0	41.9	39.5	42.2	42.4	43.7	45.7	45.4	46.0	46.8	47.0	46.8	44.9	43.0	41.6
10 km/h	58.3	38.6	40.9	46.1	44.5	41.6	42.0	44.1	46.4	47.7	47.9	49.2	48.6	47.2	46.2	46.3	45.8	42.3	41.6
10 km/h	57.6	33.1	36.3	38.6	38.5	37.5	40.3	46.9	46.6	47.2	47.5	47.6	46.8	48.4	46.5	47.4	44.4	43.2	41.0
10 km/h	56.8	30.4	35.0	38.1	40.5	38.2	41.3	43.1	43.4	45.3	47.6	47.9	46.1	48.4	47.1	45.8	43.2	40.8	39.5
10 km/h	55.8	26.6	30.1	34.4	36.7	38.2	39.6	43.1	45.3	45.6	45.8	48.0	46.1	44.6	45.2	44.5	41.9	40.5	37.9
10 km/h	56.3	30.5	32.8	37.5	37.0	38.4	43.1	42.4	44.3	42.3	43.4	46.6	46.8	48.1	47.9	46.6	42.9	39.7	38.2
10 km/h	58.5	35.4	36.4	40.7	43.6	44.7	43.9	44.5	45.7	46.6	48.9	49.8	49.3	48.6	46.6	45.9	44.0	43.6	45.8
10 km/h	56.3	32.3	29.9	34.7	35.5	38.0	40.2	46.0	45.4	46.3	45.9	45.4	47.5	45.6	45.0	45.4	44.9	40.3	40.1
10 km/h	54.8	31.0	32.0	37.4	40.0	40.0	43.4	43.1	43.8	42.9	43.1	44.2	45.1	45.1	43.9	42.6	41.0	39.4	39.7
10 km/h	60.7	41.8	41.4	45.1	44.7	47.8	52.5	49.8	49.4	51.8	52.0	48.6	47.4	47.6	46.8	47.3	45.3	40.7	41.4
10 km/h	61.1	47.6	45.6	47.7	44.6	50.1	47.7	46.7	49.2	48.5	51.4	50.8	51.5	51.1	49.3	48.9	44.8	41.9	41.2
10 km/h	63.1	30.5	36.6	36.4	38.5	43.8	45	46.3	48.3	53.3	54.2	53.4	52.7	51.8	54.3	52.7	53.6	48.1	47.9
10 km/h	64.6	37.2	41.2	39.0	50.5	47.9	51.4	55.7	50.3	51.3	51.6	55.6	56.4	53.9	52.5	52.8	52.8	50.8	46.7
10 km/h	58.1	42.3	42.8	41.2	42.9	42.7	44.5	44.9	48.1	48.9	49.3	48.8	49.0	46.0	45.2	42.9	41.9	38.8	33.8
10 km/h	76.8	56.7	62.2	55.1	56.3	57.9	59.7	63.6	64.4	66.8	68.9	65.8	64.7	67.8	67.0	64.4	65.3	61.5	57.5

Table 32: A-weighted One Third Octave Band Level, dB(A) for 16 km/h (OICA data)

Operating Condition	**Overall, LAfmax, dB(A)**	**100 Hz**	**125 Hz**	**160 Hz**	**200 Hz**	**250 Hz**	**315 Hz**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**	**1250 Hz**	**1600 Hz**	**2000 Hz**	**2500 Hz**	**3150 Hz**	**4000 Hz**	**5000 Hz**
16 km/h	65.0	37.8	37.0	45.5	45.1	46.4	47.4	47.9	50.1	53.4	56.5	53.9	53.7	55.4	56.4	55.3	53.7	53.0	51.0
16 km/h	67.5	44.7	39.3	50.6	47.0	48.2	49.9	53.4	54.5	54.6	58.0	56.4	56.4	57.3	59.1	58.5	56.3	54.6	52.9
16 km/h	65.0	32.0	36.8	42.0	47.1	48.0	49.1	51.0	52.9	55.7	55.6	54.6	55.4	55.0	55.1	53.9	52.7	50.7	48.3
16 km/h	65.1	31.8	38.5	42.8	44.9	45.8	47.6	48.9	53.7	56.8	55.2	54.3	55.7	55.0	55.4	54.3	52.4	50.9	49.0
16 km/h	62.8	36.2	41.5	43.1	42.8	46.7	47.9	48.4	50.1	51.8	53.2	53.6	53.5	53.3	54.1	50.7	48.6	49.1	42.7
16 km/h	62.9	38.7	42.9	43.2	40.5	45.7	45.6	47.7	49.4	51.7	53.7	53.3	53.8	53.2	54.6	51.6	48.7	50.0	42.6
16 km/h	68.5	35.5	46.8	47.4	44.9	48.9	54.9	60.5	56.9	58.9	60.0	58.6	58.8	56.5	56.0	54.2	53.3	54.1	50.6
16 km/h	69.2	36.9	46.5	48.5	47.9	48.5	56.8	60.4	57.8	60.1	60.4	60.1	59.3	57.3	56.2	54.3	54.2	54.3	51.2
16 km/h	65.5	37.4	42.1	47.2	47.2	47.6	48.3	48.7	51.9	53.7	56.0	55.6	56.9	55.4	58.5	55.0	50.7	47.4	45.0
16 km/h	65.6	39.3	46.5	45.7	45.4	47.8	49.7	49.2	51.7	54.0	56.3	54.8	57.2	56.2	57.9	54.7	51.5	49.6	46.5
16 km/h	64.1	41.9	38.6	37.1	45.0	44.1	54.3	51.6	50.3	50.3	55.5	52.3	50.5	53.1	54.7	50.7	54.0	52.2	52.7
16 km/h	66.0	37.1	42.9	46.2	48.3	51.2	55.1	51.0	54.9	53.4	47.7	55.3	58.0	55.6	53.6	55.8	55.9	51.5	52.8
16 km/h	68.4	41.2	54.1	55.0	58.1	55.4	55.3	47.2	53.5	53.1	53.8	55.6	56.2	58.2	57.6	57.6	57.4	57.1	58.1
16 km/h	70.4	62.4	56.1	63.9	52.6	50.3	59.4	57.8	54.7	54.6	56.6	57.7	54.2	56.2	57.3	59.2	55.5	52.8	55.5
16 km/h	61.9	37.2	37.6	36.4	41.3	45.3	43.4	50.4	46.0	52.4	53.7	54.4	51.3	51.0	52.3	48.6	47.5	45.7	45.0
16 km/h	63.6	32.9	42.0	35.5	36.3	44.5	50.6	51.2	52.4	56.8	55.9	53.1	51.9	52.0	49.5	50.8	48.5	50.3	46.3
16 km/h	59.2	36.6	37.8	39.3	44.0	41.9	43.0	47.6	49.9	51.0	48.4	48.0	48.9	48.4	48.2	47.9	45.0	43.4	39.5
16 km/h	63.0	39.1	40.5	39.3	47.5	46.9	54.6	51.1	50.3	52.8	53.8	52.5	51.3	50.9	50.3	50.7	50.9	49.2	46.7
16 km/h	62.5	46.5	45.0	42.7	47.2	45.6	49.5	50.6	51.0	52.4	54.7	53.3	53.9	51.5	47.8	47.6	44.8	44.3	44.1
16 km/h	59.9	32.0	39.2	38.4	41.2	45.5	49.3	48.1	48.4	50.4	49.9	50.3	50.6	48.7	46.8	46.4	46.6	45.7	40.8
16 km/h	59.0	34.9	38.3	39.0	40.5	44.1	43.3	47.2	48.8	50.4	49.5	47.9	48.4	48.9	49.0	47.7	46.4	36.0	30.6
16 km/h	60.0	34.7	35.8	38.4	46.6	45.9	43.9	46.8	48.5	51.3	50.4	51.3	51.0	50.0	47.3	47.2	46.8	35.8	31.0
16 km/h	63.6	41.5	44.2	45.7	46.5	49.9	54.5	51.2	53.1	55.1	55.7	54.1	53.7	49.9	49.2	47.5	46.5	35.1	31.5
16 km/h	63.6	41.5	44.2	45.7	46.5	49.9	54.5	51.2	53.1	55.1	55.7	54.1	53.7	49.9	49.2	47.5	46.5	35.1	31.5
16 km/h	60.7	35.0	36.0	35.3	38.9	42.8	45.9	47.4	48.6	49.5	49.1	51.0	52.7	50.6	49.5	49.6	50.3	47.6	43.8
16 km/h	59.9	34.7	37.6	41.6	46.9	43.5	50.7	50.4	49.1	50.8	50.3	49.3	48.5	47.5	46.2	44.3	44.0	44.6	39.5
16 km/h	66.3	39.8	40.6	43.3	45.9	54.4	52.0	53.0	55.4	54.9	57.6	59.0	57.7	55.5	53.3	51.3	51.6	49.5	46.7

Operating Condition	Overall, LAfmax, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
16 km/h	60.9	34.0	39.7	41.8	45.1	49.2	49.4	49.3	50.7	51.1	51.1	49.8	50.6	50.6	48.8	48.9	46.8	35.3	32.6
16 km/h	58.8	38.3	36.9	39.7	44.3	44.2	44.9	47.5	48.1	49.8	48.5	48.7	49.3	48.9	46.4	46.9	46.2	34.0	30.8
16 km/h	63.4	41.8	38.7	37.1	40.4	44	45.8	47.1	47.4	50.9	53.4	51.6	52	52.6	55.4	55.2	54.3	51.6	46.4
16 km/h	64.4	42.7	41.8	46.2	45.0	50.9	52.0	52.2	55.1	52.2	52.5	55.7	56.7	53.8	51.5	49.9	50.1	48.9	44.1
16 km/h	60.7	44.5	43.8	41.1	41.8	47.0	48.7	50.2	52.5	51.8	52.5	49.9	50.3	47.7	46.2	43.6	42.9	40.4	35.4
16 km/h	79.1	54.6	63.9	57.1	56.3	59.2	60.8	71.3	67.6	67.3	70.1	67.7	68.2	69.6	69.1	66.8	65.2	63.4	58.4

Table 33: A-weighted One Third Octave Band Level, dB(A) for 24 km/h (OICA data)

Operating Condition	Overall, LAfmax, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
24 km/h	70.9	38.8	44.3	52.7	52.2	55.4	58.1	57.6	56.9	58.3	64.3	59.6	59.0	60.0	60.6	60.8	57.9	56.9	54.8
24 km/h	71.1	38.0	42.0	53.9	52.0	58.4	59.0	57.3	57.9	58.0	64.5	59.0	59.3	59.7	60.5	61.0	57.7	56.7	55.2
24 km/h	70.9	46.2	40.8	45.1	59.0	56.6	56.4	58.3	58.3	59.5	61.6	61.1	60.7	61.3	60.4	58.4	58.4	55.8	52.7
24 km/h	71.3	45.6	40.6	44.2	60.0	55.0	57.3	58.7	59.1	60.0	62.3	62.0	61.0	61.2	60.8	58.5	58.3	55.9	52.9
24 km/h	69.7	45.9	41.1	46.4	51.8	53.4	56.0	55.4	54.6	57.7	60.3	60.5	60.0	60.4	62.0	58.6	56.1	51.9	48.6
24 km/h	69.8	45.7	40.6	42.3	49.7	53.4	55.1	57.0	55.4	56.4	60.6	59.8	61.2	61.1	62.2	58.0	55.6	52.2	48.0
24 km/h	75.3	60.4	41.5	57.0	53.4	56.9	62.4	63.8	60.0	63.4	67.0	67.2	65.6	64.9	64.1	63.7	59.9	59.9	56.3
24 km/h	75.3	62.3	43.0	57.1	55.0	57.7	60.9	63.0	60.8	64.3	66.5	67.5	65.2	64.9	64.9	62.5	59.3	59.5	55.9
24 km/h	67.5	40.6	43.1	46.4	53.7	55.9	51.3	50.2	54.7	57.3	59.2	56.7	58.0	56.9	59.6	54.9	50.8	48.3	45.3
24 km/h	68.0	36.7	41.4	44.4	53.5	54.8	52.0	51.1	55.2	58.0	59.8	57.8	58.8	58.2	59.5	54.7	51.9	50.0	46.2
24 km/h	68.3	40.3	38.1	37.1	51.5	51.6	53.5	54.4	59.1	55.6	60.3	60.3	57.1	57.7	56.3	55.8	53.9	54.7	52.8
24 km/h	69.8	35.5	44.6	44.9	48.1	52.1	50.1	56.7	58.6	56.9	61.0	61.1	61.4	62.0	58.8	56.0	55.8	54.0	52.8
24 km/h	73.0	47.5	56.6	60.8	64.1	58.9	52.6	57.6	57.8	58.9	59.1	61.9	62.4	63.7	60.0	63.0	60.5	60.3	60.6
24 km/h	74.5	48.9	56.0	64.0	67.5	56.8	56.1	62.1	58.4	65.6	59.4	63.5	62.0	61.1	60.5	63.6	63.1	57.4	58.3
24 km/h	68.0	31.6	30.0	45.5	53.8	50.6	51.3	58.8	59.3	59.8	57.8	58.6	54.7	58.5	54.1	53.8	52.0	49.8	51.2
24 km/h	68.1	32.9	39.6	49.4	50.9	50.2	54.4	47.1	52.6	59.3	61.6	61.4	56.7	57.7	55.2	53.0	50.8	50.2	51.7
24 km/h	65.8	37.8	40.1	47.5	53.1	52.3	51.9	51.2	57.2	57.7	58.3	55.5	55.5	53.5	50.6	51.0	47.6	45.6	40.0
24 km/h	64.7	35.9	40.0	42.3	44.7	45.8	49.1	53.8	57.9	57.2	55.9	54.4	54.6	53.5	50.7	47.8	44.7	44.5	40.0
24 km/h	65.9	38.0	46.6	46.9	47.1	47.5	49.7	52.3	53.9	57.8	59.3	57.9	56.2	54.0	52.3	50.0	49.8	46.6	43.4
24 km/h	66.2	37.9	44.9	45.3	53.7	51.2	52.0	54.5	57.3	59.5	58.1	55.9	56.3	53.0	49.6	46.9	43.8	44.7	40.1
24 km/h	64.5	35.5	38.8	44.5	48.4	49.9	54.6	52.9	56.1	56.4	55.4	54.4	53.7	51.9	49.7	48.2	48.2	46.5	42.9
24 km/h	64.4	36.1	39.1	42.0	48.9	48.2	50.1	54.3	55.5	56.8	55.4	54.3	54.4	53.3	51.6	48.3	47.1	36.0	31.0
24 km/h	64.6	35.4	41.0	45.3	46.6	50.7	52.4	54.7	56.1	56.2	54.2	55.7	55.2	51.7	50.5	49.0	47.9	36.0	35.1
24 km/h	68.0	40.0	42.1	45.8	53.6	50.2	51.8	54.8	55.6	61.7	60.5	57.8	59.0	56.8	55.1	52.6	50.2	37.1	35.1
24 km/h	68.0	40.0	42.1	45.8	53.6	50.2	51.8	54.8	55.6	61.7	60.5	57.8	59.0	56.8	55.1	52.6	50.2	37.1	35.1
24 km/h	63.2	33.5	39.4	42.5	44.6	45.3	48.8	49.0	53.2	54.1	53.8	54.9	54.6	52.7	51.0	48.2	49.5	47.8	43.9
24 km/h	63.0	35.1	36.5	42.2	47.9	46.4	50.1	50.7	54.4	55.8	54.9	52.4	53.0	51.8	48.1	45.1	44.0	45.3	40.6

Operating Condition	Overall, LAfmax, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
24 km/h	71.1	37.6	44.3	51.1	53.7	54.4	54.3	56.4	60.5	61.1	63.7	64.7	62.4	58.7	56.7	54.1	53.8	52.8	48.2
24 km/h	65.6	35.4	38.9	44.2	49.2	52.6	55.5	53.6	56.2	58.2	55.8	56.0	55.9	53.8	50.9	49.1	47.5	35.0	32.8
24 km/h	63.0	36.4	36.8	43.5	44.5	45.8	48.2	52.2	53.7	56.3	54.5	54.6	52.8	50.5	47.3	45.3	44.8	33.8	29.7
24 km/h	69.9	40.2	43.4	46.4	49.3	52.1	53.3	56.5	58.4	61	63.4	60.7	59.3	60.2	57.3	54.7	56.7	53.1	51.2
24 km/h	67.9	38.6	40.5	50.8	51.6	51.0	54.8	57.0	59.7	59.2	58.4	59.2	58.5	56.1	53.5	50.5	51.8	49.8	43.7
24 km/h	67.1	42.6	50.5	45.9	50.1	55.0	51.6	54.3	60.8	60.8	58.1	55.7	54.6	51.5	50.7	48.1	47.0	44.7	39.6
24 km/h	80.4	63.9	71.6	60.1	61.5	62.9	67.6	65.0	66.8	70.7	71.6	68.1	68.4	69.9	69.2	68.6	67.2	65.0	61.9

Table 34: A-weighted One Third Octave Band Level, dB(A) for 32 km/h (OICA data)

Operating Condition	Overall, LAfmax, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
32 km/h	75.7	54.8	46.7	57.1	60.5	62.3	63.1	61.9	61.4	63.5	65.1	65.1	65.8	65.3	66.2	66.2	63.1	61.0	59.6
32 km/h	75.8	55.4	46.4	55.5	60.0	61.5	63.2	62.5	61.2	63.9	65.3	65.4	66.2	65.5	66.0	66.5	62.8	61.1	59.6
32 km/h	77.2	36.3	59.4	57.2	54.4	59.6	60.8	60.3	64.3	65.5	67.6	68.4	68.9	68.3	66.7	66.7	63.6	62.5	58.3
32 km/h	77.3	35.8	58.5	59.6	57.5	61.8	63.4	63.3	65.1	66.7	67.7	70.0	68.4	67.2	65.0	65.0	62.1	61.1	57.4
32 km/h	75.0	41.0	53.5	47.1	56.2	61.5	57.1	63.2	61.2	61.5	63.8	65.0	66.8	66.8	66.9	64.1	60.4	56.9	52.8
32 km/h	75.2	38.4	51.5	46.9	55.0	61.1	58.5	61.1	59.8	61.3	64.8	65.4	67.1	68.2	66.7	63.7	60.4	57.5	52.9
32 km/h	78.1	53.2	66.6	51.5	51.7	60.4	64.9	65.3	63.4	65.0	67.4	68.9	70.4	68.0	69.0	65.4	63.5	62.1	57.5
32 km/h	78.4	54.9	66.6	49.4	52.1	60.6	65.2	66.0	63.9	66.1	67.5	69.1	70.6	68.2	68.9	66.7	64.1	62.2	58.1
32 km/h	71.1	37.9	42.0	47.7	46.2	55.3	57.9	54.5	57.0	60.8	64.4	60.9	61.3	61.4	63.0	58.2	53.8	50.6	46.8
32 km/h	71.7	40.6	43.5	49.6	47.7	55.8	58.1	55.2	57.5	61.6	64.2	62.4	62.8	61.5	63.7	58.6	54.9	51.5	47.8
32 km/h	71.4	41.1	41.0	40.1	51.0	52.0	54.2	53.7	54.3	63.8	60.2	62.0	66.4	60.2	59.2	58.6	54.5	54.2	53.8
32 km/h	72.2	41.0	38.2	41.9	49.7	57.7	58.1	53.9	59.3	59.7	65.4	65.1	64.6	60.2	60.9	57.0	56.0	55.0	52.1
32 km/h	72.5	38.5	51.3	45.5	49.8	56.5	54.1	52.6	52.1	55.3	63.7	64.9	65.7	66.3	57.8	58.7	57.7	56.5	55.3
32 km/h	77.5	62.7	55.1	63.9	62.0	63.1	60.4	60.8	60.8	62.8	67.2	67.5	65.4	66.8	70.0	66.8	64.9	64.9	63.9
32 km/h	78.1	64.9	64.5	64.2	64.6	62.0	58.3	60.6	63.0	62.8	68.1	67.6	69.6	66.6	66.3	68.1	66.2	64.7	63.4
32 km/h	70.7	40.8	36.0	38.3	46.0	48.6	57.4	57.8	53.9	61.8	63.9	64.6	58.7	57.3	59.3	55.9	56.4	53.6	52.7
32 km/h	72.2	38.9	37.5	32.8	48.5	49.5	50.9	55.8	60.1	60.4	63.3	68.0	61.7	61.3	57.7	59.1	57.1	55.9	53.3
32 km/h	70.2	44.4	40.0	45.0	53.9	57.0	54.4	57.0	59.9	63.5	63.2	60.9	59.9	59.5	55.6	50.4	47.8	46.4	41.2
32 km/h	68.5	33.3	39.7	40.6	50.4	48.3	49.5	57.1	58.9	62.8	61.0	58.1	58.9	56.8	53.5	49.9	47.4	44.8	41.0
32 km/h	69.7	39.9	45.4	45.3	54.2	56.9	51.8	55.0	57.2	61.8	62.3	62.5	61.0	58.0	54.5	52.7	51.1	47.3	44.5
32 km/h	70.5	38.4	51.3	50.4	54.8	58.6	54.9	57.8	61.3	61.9	62.9	61.9	60.8	58.9	55.6	51.0	48.3	46.5	42.6
32 km/h	70.5	39.4	40.7	42.6	51.4	56.0	57.0	60.1	60.5	63.6	62.7	61.3	60.3	57.1	54.8	52.7	51.9	50.6	47.3
32 km/h	68.6	35.8	38.8	42.3	48.4	53.7	51.3	56.7	60.9	61.5	60.9	58.6	58.8	56.7	55.0	51.4	49.2	40.2	32.8
32 km/h	68.5	38.2	36.6	44.6	51.9	52.0	54.0	54.7	59.8	60.9	59.7	59.9	59.4	56.9	54.7	53.8	51.0	39.0	35.3
32 km/h	72.5	40.0	45.3	46.5	52.1	59.6	56.3	59.4	61.7	66.0	65.4	62.9	62.5	60.5	59.1	56.3	52.3	38.4	35.6
32 km/h	72.5	40.0	45.3	46.5	52.1	59.6	56.3	59.4	61.7	66.0	65.4	62.9	62.5	60.5	59.1	56.3	52.3	38.4	35.6
32 km/h	68.6	36.4	38.4	41.7	46.8	49.7	53.4	54.2	58.9	58.9	60.4	60.3	61.4	58.3	55.4	52.7	52.6	50.4	47.4
32 km/h	68.4	37.5	40.5	42.2	52.1	54.0	52.5	54.5	59.1	60.1	60.7	60.8	59.7	56.9	52.8	50.3	47.9	45.1	41.3
32 km/h	71.8	40.2	49.6	50.8	52.6	55.5	54.7	60.1	64.3	62.7	63.0	64.8	62.5	59.5	55.6	52.9	52.3	49.9	45.4
32 km/h	70.2	37.9	41.6	42.8	50.9	56.7	55.9	57.1	61.8	63.2	62.8	61.4	59.4	58.0	54.2	50.6	48.2	36.2	32.9
32 km/h	66.2	33.7	39.5	41.8	46.1	49.2	51.0	53.8	57.0	60.4	58.3	57.0	56.5	53.5	49.3	46.9	45.7	33.8	29.0
32 km/h	72.0	39.1	47.1	49.0	50.7	53.6	53.5	58.0	61.2	63.6	64.8	66.4	63.0	59.1	56.3	52.1	49.0	46.3	44.1

Operating Condition	Overall, LAfmax, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
32 km/h	69.0	41.9	47.3	48.8	51.9	55.8	52.1	55.5	56.0	58.8	61.6	62.0	61.3	58.3	54.2	51.0	48.8	45.9	41.8
32 km/h	70.2	44.8	50.9	52.0	52.1	53.7	55.7	56.8	59.9	64.6	63.6	61.1	57.7	56.3	53.2	51.1	48.3	46.8	43.8
32 km/h	70.7	48.2	46.9	56.1	56.6	55.4	59.2	57.6	61.5	63.6	63.6	61.7	58.2	55.8	53.4	51.5	47.8	45.4	42.7
32 km/h	71.3	38.1	42.0	49.3	52.1	53.2	55.5	60.8	64.4	63.3	64.2	62.6	59.9	56.6	54.6	52.7	50.5	49.2	45.3
32 km/h	71.8	38.2	37.8	42.4	50.1	55.7	54.4	56.4	59.3	62.9	66.1	61.7	61.1	61.8	59.7	56.9	59.5	53.6	49.5
32 km/h	72.4	37.1	43.5	50.9	55.5	58.3	58.9	62.7	64.7	63.2	63.4	63.3	63.3	60.5	57.0	52.8	50.7	50.4	44.0
32 km/h	69.0	44.9	48.8	45.8	48.7	51.4	53.6	56.9	63.8	62.8	61.0	57.5	55.1	51.6	50.2	46.7	47.5	45.6	41.0
32 km/h	84.8	53.7	60.9	57.2	60.2	63.2	64.4	68.8	71.5	74.5	79.0	75.0	72.7	74.9	75.0	71.9	73.3	70.1	67.2

Table 35: A-weighted One Third Octave Band Level, dB(A) for Acceleration (OICA data)

Operating Condition	Overall, LAfmax, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
Acceleration	66.6	37.2	38.9	44.4	53.3	53.7	51.1	50.9	51.9	53.8	54.4	54.6	56.4	57.5	58.7	56.4	55.0	53.8	51.1
Acceleration	68.4	39.0	40.7	46.6	54.0	57.3	54.5	53.6	54.1	56.0	55.8	56.3	58.1	58.1	59.9	59.1	55.7	55.9	53.9
Acceleration	66.7	44.4	42.1	46.7	49.7	53.4	54.3	52.9	55.6	56.5	53.6	54.1	54.8	57.1	58.1	56.0	55.1	53.3	50.7
Acceleration	67.2	44.8	44.3	46.3	51.4	51.2	54.3	53.9	57.2	58.6	54.5	54.8	56.1	57.2	58.0	55.9	54.2	53.1	50.7
Acceleration	66.9	50.3	45.1	46.4	49.6	52.3	52.0	52.5	53.1	53.0	54.3	54.0	57.3	59.6	59.8	56.1	52.8	51.4	46.1
Acceleration	67.7	41.6	47.6	48.5	49.3	52.7	52.1	54.5	56.3	54.5	52.6	54.7	60.3	59.7	60.2	55.9	53.1	52.7	45.6
Acceleration	69.1	44.5	43.6	46.2	47.2	52.1	55.4	57.0	57.2	61.2	59.9	57.0	59.1	58.9	58.9	58.1	54.7	53.2	50.9
Acceleration	71.9	47.8	45.4	51.4	53.8	56.3	57.1	59.9	61.3	61.5	60.2	61.9	61.1	61.2	63.7	60.1	59.1	57.8	55.3
Acceleration	72.5	50.8	54.4	53.2	60.3	53.8	56.4	58.5	59.0	62.5	61.8	62.4	63.0	63.6	63.8	60.3	58.4	54.9	52.0
Acceleration	75.2	57.4	60.0	57.9	57.5	54.8	57.7	59.7	65.5	65.2	63.1	64.7	64.8	64.9	67.1	64.3	62.5	58.4	55.4
Acceleration	69.8	58.6	47.9	52.1	53.1	54.6	53.1	63.8	55.9	55	57.4	56.1	57.4	56.5	56.3	61	58.4	55.2	52.9

Table 36: A-weighted One Third Octave Band Level, dB(A) for <u>Deceleration</u> (OICA data)

Operating Condition	Overall, LAfmax, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
Deceleration (DD')	62.7	36.3	43.8	46.7	46.5	43.7	45.6	48.0	48.9	49.8	53.3	50.9	50.4	51.0	54.7	53.9	51.9	50.5	47.9
Deceleration (PP')	76.6	55.9	46.3	54.5	63.6	60.6	64.2	63.6	64.3	62.3	66.0	66.7	66.3	66.1	67.6	66.9	63.2	61.1	60.1
Deceleration (DD')	59.7	35.3	31.5	40.7	42.6	44.9	45.9	46.5	47.4	51.2	50.0	50.2	50.7	49.2	48.6	47.1	45.9	43.3	39.9
Deceleration (PP')	70.1	30.5	50.2	52.3	50.3	54.8	57.6	55.7	58.6	60.4	59.6	63.1	61.1	60.1	57.2	57.5	53.3	51.9	48.1
Deceleration (DD')	61.4	37.5	44.1	43.5	43.0	44.3	45.8	47.0	47.7	50.8	52.6	52.2	52.5	52.5	52.0	49.1	45.8	42.8	40.3
Deceleration (PP')	75.0	40.9	53.1	47.2	55.2	60.8	59.2	59.8	59.6	60.5	64.5	65.1	67.1	67.8	66.7	63.4	60.8	57.7	53.0
Deceleration (DD')	65.9	40.2	40.8	53.1	47.2	48.9	51.0	54.6	53.8	58.3	56.8	56.3	55.5	53.5	53.3	52.0	50.9	52.0	48.9
Deceleration (PP')	77.4	51.4	66.1	49.6	51.6	56.9	57.7	59.2	64.2	62.6	65.1	68.0	69.9	68.0	68.8	66.8	64.1	63.4	61.5
Deceleration (DD')	63.7	35.4	45.2	47.8	47.7	49.5	48.0	48.5	51.6	52.8	55.1	53.0	54.3	53.8	55.6	51.3	47.0	44.7	42.3
Deceleration (PP')	71.4	37.7	42.9	47.9	46.8	57.0	58.6	56.1	56.7	61.2	64.8	61.4	61.4	61.5	63.1	58.0	54.1	51.0	47.2

Table 37: A-weighted One Third Octave Band Level, dB(A) for <u>Start-up</u> (OICA data)

Operating Condition	**Overall, LAfmax, dB(A)**	**100 Hz**	**125 Hz**	**160 Hz**	**200 Hz**	**250 Hz**	**315 Hz**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**	**1250 Hz**	**1600 Hz**	**2000 Hz**	**2500 Hz**	**3150 Hz**	**4000 Hz**	**5000 Hz**
Startup	70.5	38.3	44.4	48.5	53.0	56.4	55.0	57.8	58.9	59.0	62.2	60.1	61.0	58.0	58.7	61.2	57.9	56.7	54.4
Startup	71.4	36.3	42.1	46.6	53.4	54.8	56.6	57.2	57.8	59.7	63.0	62.8	61.2	60.5	59.9	61.6	59.6	57.8	56.4
Startup	65.6	35.4	37.4	41.7	42.2	42.8	49.8	56.5	55.3	54.0	52.6	56.9	55.4	57.5	53.9	54.2	52.3	50.1	48.9
Startup	66.0	28.3	34.6	39.1	40.8	42.7	46.9	60.0	53.1	52.3	55.0	57.8	54.6	57.0	53.9	53.9	52.6	49.5	47.5
Startup	65.9	42.3	40.8	44.5	46.4	48.9	59.3	58.3	53.6	55.7	54.1	54.9	54.2	54.8	52.4	50.1	49.3	47.5	44.8
Startup	67.7	32.1	36.1	40.9	43.8	48.9	58.8	62.0	59.1	56.9	53.7	58.4	55.7	54.3	53.1	52.1	50.9	47.6	45.4
Startup	65.0	46.2	41.0	42.2	43.5	42.1	44.8	48.9	50.2	48.7	51.6	56.1	55.7	52.8	56.7	56.6	55.6	53.7	50.8
Startup	66.0	47.3	41.5	45.1	46.1	45.5	49.9	51.6	51.9	50.9	51.7	56.3	55.9	54.1	57.5	57.6	56.4	55.5	51.5
Startup	67.7	51.0	53.2	48.7	46.0	48.8	54.2	51.8	51.4	52.4	56.4	57.3	57.1	58.0	59.6	57.0	56.5	56.0	54.1
Startup	71.7	36.2	41.4	42.8	46.8	49.1	49.6	53.2	54.7	53.4	55.3	63.0	63.3	60.9	61.3	63.1	61.7	61.7	62.2

D.2 NHTSA Phase 2 Data

Table 38: A-weighted One Third Octave Band Level, dB(A) for Stationary/Activated (NHTSA Phase 2 data)

Operating Condition	Overall, LAeq,1/2 sec, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
Stationary/Activated	53.1	35.8	33.5	34.0	35.3	36.2	36.0	36.7	41.1	40.3	42.8	43.1	43.4	42.2	43.5	42.2	43.3	40.6	37.8
Stationary/Activated	53.9	34.4	33.4	34.0	35.0	35.7	35.6	35.8	48.4	39.6	42.1	42.7	43.9	42.1	43.0	41.8	43.0	40.4	37.0
Stationary/Activated	55.7	36.0	35.6	37.2	37.8	38.5	38.9	40.3	43.1	43.4	44.5	45.9	47.1	46.1	45.2	44.5	44.7	43.0	40.9
Stationary/Activated	52.9	32.2	33.3	34.2	35.3	37.0	39.1	38.1	41.9	44.4	40.7	43.4	42.6	42.7	42.0	40.5	41.7	39.3	36.5
Stationary/Activated	53.1	32.4	33.6	35.2	35.9	36.4	36.8	37.5	42.2	44.3	40.3	41.8	42.3	42.3	42.1	42.8	43.0	40.7	39.0
Stationary/Activated	56.7	39.0	35.9	39.6	39.0	38.8	39.0	40.5	43.2	43.9	45.4	46.1	48.2	48.5	46.3	45.8	45.2	45.3	40.6
Stationary/Activated	57.4	37.8	35.5	38.2	38.1	38.4	39.1	41.5	44.1	44.4	46.3	45.9	48.2	48.9	46.7	47.7	46.9	47.1	41.8
Stationary/Activated	54.8	31.5	33.4	35.1	36.9	39.5	37.2	37.9	40.6	38.6	41.5	46.7	49.4	46.3	41.5	42.1	42.0	38.4	37.6
Stationary/Activated	54.8	32.5	33.5	34.9	36.5	40.6	37.0	37.5	39.8	41.9	41.9	47.8	48.0	45.4	41.9	42.2	43.2	39.4	38.3
Stationary/Activated	52.5	32.0	34.0	35.0	37.3	37.3	36.3	38.6	38.9	40.5	41.5	42.7	44.1	43.0	41.4	40.0	42.3	38.7	36.2
Stationary/Activated	53.7	32.3	33.7	34.8	35.6	38.3	37.9	42.2	39.1	40.8	42.1	43.9	46.6	43.7	41.7	41.9	43.2	39.6	37.1
Stationary/Activated	57.4	38.7	35.5	38.6	40.0	39.0	40.6	41.9	43.8	44.6	46.3	48.0	48.4	47.8	48.3	45.3	46.2	45.3	42.0
Stationary/Activated	60.1	39.4	35.5	38.3	39.1	40.0	41.0	41.3	44.3	44.9	48.3	48.7	50.7	50.9	51.0	48.0	51.4	50.9	48.3
Stationary/Activated	55.2	36.3	35.1	38.5	38.4	37.2	38.3	39.6	42.6	42.8	45.2	45.8	44.6	44.2	44.0	46.2	44.0	43.4	39.0
Stationary/Activated	55.5	35.9	34.8	37.2	36.9	36.9	38.1	39.5	42.8	43.7	45.4	45.6	45.3	44.7	44.9	45.4	44.3	45.3	41.1
Stationary/Activated	55.9	34.5	34.9	38.3	39.9	38.9	39.6	41.0	43.3	44.4	46.9	46.8	48.8	45.8	42.9	42.5	43.3	40.9	39.9
Stationary/Activated	56.4	34.0	34.9	36.7	38.4	39.8	38.8	41.0	44.8	44.1	47.0	46.8	48.3	47.2	43.7	43.9	44.9	43.1	42.9
Stationary/Activated	59.2	42.6	42.3	40.9	38.7	38.7	42.3	44.3	44.9	46.5	46.0	47.9	50.6	49.3	51.1	47.9	46.1	45.9	48.7
Stationary/Activated	59.4	42.4	42.1	41.6	38.4	38.7	43.1	45.6	45.1	47.1	46.5	48.0	50.0	49.9	52.3	49.2	45.0	45.1	47.1

Table 39: A-weighted One Third Octave Band Level, dB(A) for <u>Reverse 10 km/h</u> (NHTSA Phase 2 data)

Operating Condition	Overall, LAfmax, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
Reverse 10 km/h	57.7	35.5	37.5	39.8	40.3	41.3	41.8	42.1	46.4	46.6	47.7	48.3	47.9	47.4	47.4	46.4	46.9	44.7	40.0
Reverse 10 km/h	60.1	39.6	41.4	42.4	43.8	42.9	42.7	43.8	46.8	47.9	49.9	50.1	50.7	50.6	51.3	49.2	48.3	45.8	43.7
Reverse 10 km/h	57.1	37.4	35.9	40.4	41.5	43.1	42.1	47.3	44.8	44.9	47.3	48.5	47.7	47.1	44.9	43.6	43.2	41.4	38.6
Reverse 10 km/h	60.5	35.6	35.2	42.4	42.9	44.7	47.4	47.7	50.0	49.2	50.8	50.9	51.3	50.9	49.6	48.0	46.1	44.0	42.5
Reverse 10 km/h	58.9	41.3	38.4	39.1	42.3	41.8	43.3	42.0	44.5	45.4	48.5	50.5	50.6	50.5	46.7	46.8	47.1	45.8	42.2
Reverse 10 km/h	59.4	38.0	39.0	38.0	40.1	41.4	43.6	43.5	44.3	46.7	49.3	50.2	50.5	50.6	48.0	48.4	48.3	47.9	43.6
Reverse 10 km/h	60.4	37.4	42.2	42.8	49.6	44.6	44.3	52.0	47.3	47.8	49.9	50.0	51.3	49.7	48.3	48.1	46.6	44.2	42.1
Reverse 10 km/h	62.5	35.5	39.9	43.2	47.5	44.9	45.6	52.2	49.0	51.7	52.9	53.8	54.7	52.0	50.4	49.3	48.0	46.0	43.5
Reverse 10 km/h	56.0	35.6	37.7	37.4	39.0	40.6	41.9	42.6	42.8	46.3	44.4	46.3	47.7	47.2	44.4	43.6	42.2	40.9	38.6
Reverse 10 km/h	58.3	37.0	38.8	39.2	41.7	44.7	42.5	45.3	46.3	46.9	48.0	48.8	50.2	50.0	45.7	45.1	44.0	42.6	39.9
Reverse 10 km/h	62.1	40.8	38.7	42.0	41.6	42.9	44.3	43.8	46.3	52.5	52.1	53.1	53.1	52.4	52.5	50.8	50.5	49.2	46.1
Reverse 10 km/h	65.9	43.6	42.0	43.5	44.0	45.1	44.7	46.8	47.7	51.4	56.7	55.3	57.0	56.3	55.0	56.0	57.1	55.2	53.2
Reverse 10 km/h	58.9	37.7	38.0	39.7	42.8	42.7	45.3	49.0	48.4	49.3	48.3	49.4	49.3	47.2	45.9	46.0	44.4	45.3	40.8
Reverse 10 km/h	61.1	39.4	38.3	39.0	40.7	43.2	44.8	44.9	47.3	53.2	49.6	50.0	51.9	50.8	49.3	49.4	49.9	51.5	46.2
Reverse 10 km/h	59.1	38.3	36.7	37.4	41.2	42.3	43.2	44.9	46.7	49.3	51.3	50.0	49.7	49.0	47.4	46.0	45.9	45.2	41.7
Reverse 10 km/h	61.8	36.6	38.2	41.4	42.4	45.2	45.6	47.4	50.8	51.5	52.1	53.0	53.6	53.5	49.2	47.6	47.3	46.3	45.6

Operating Condition	**Overall, LAfmax, dB(A)**	**100 Hz**	**125 Hz**	**160 Hz**	**200 Hz**	**250 Hz**	**315 Hz**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**	**1250 Hz**	**1600 Hz**	**2000 Hz**	**2500 Hz**	**3150 Hz**	**4000 Hz**	**5000 Hz**
Reverse 10 km/h	57.4	45.3	43.6	44.5	40.8	41.9	40.1	43.7	43.4	47.0	47.8	48.1	47.9	46.9	46.2	45.2	41.0	37.9	37.2
Reverse 10 km/h	62.3	44.6	46.4	44.3	42.3	44.9	46.9	48.7	48.3	50.8	52.1	52.0	53.7	53.9	50.6	50.3	49.9	47.5	46.9

Table 40: A-weighted One Third Octave Band Level, dB(A) for 10 km/h (NHTSA Phase 2 data))

Operating Condition	Overall, LAfmax, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
10 km/h	60.6	36.9	43.5	42.7	41.6	42.5	41.8	45.1	49.4	48.0	50.5	48.6	51.2	51.3	51.6	49.8	50.6	46.7	44.1
10 km/h	61.6	35.2	40.1	38.9	41.5	42.4	42.6	45.8	48.9	48.9	51.9	50.3	52.2	52.6	53.0	51.2	51.0	48.3	45.8
10 km/h	58.1	35.5	37.6	38.8	42.2	44.7	42.5	43.6	47.3	47.0	47.5	50.2	49.0	48.8	46.0	44.4	44.4	42.8	40.0
10 km/h	62.2	38.1	37.8	43.7	41.6	46.5	48.4	49.3	50.9	50.6	52.3	54.3	52.7	53.0	51.5	49.2	47.9	45.9	43.2
10 km/h	62.4	36.5	37.3	40.7	41.7	44.7	46.3	47.7	48.6	51.2	52.8	52.2	52.6	54.6	51.8	51.2	51.3	49.4	45.5
10 km/h	64.0	37.8	39.5	42.5	44.2	48.2	47.1	48.8	50.4	52.3	52.9	54.0	54.9	56.0	53.4	53.9	52.7	51.6	47.6
10 km/h	59.1	35.8	37.0	38.7	42.2	43.0	45.1	45.6	44.2	47.8	49.3	50.6	52.2	49.2	46.4	46.3	45.5	43.6	39.9
10 km/h	63.5	35.6	44.8	49.6	49.4	43.4	49.4	52.0	49.5	51.9	54.6	52.6	55.3	53.9	51.6	51.6	49.7	47.7	44.3
10 km/h	59.8	37.7	42.4	38.7	41.4	44.5	45.4	45.6	48.6	49.9	51.3	50.7	50.7	50.5	47.3	45.7	44.9	42.7	39.8
10 km/h	64.0	37.0	42.0	41.7	43.9	46.5	46.2	53.0	50.1	52.3	52.5	55.5	57.5	54.2	52.1	51.5	50.8	48.2	45.0
10 km/h	60.5	39.2	38.2	38.3	40.0	41.7	43.2	42.7	45.7	47.0	48.7	50.4	51.2	50.5	52.8	49.1	50.4	50.1	47.0
10 km/h	64.7	41.8	38.6	42.6	41.5	42.9	44.7	46.1	49.3	50.0	53.4	54.9	54.8	55.3	55.1	53.8	56.0	54.8	52.3
10 km/h	60.8	37.8	37.0	41.9	41.9	43.7	44.5	46.8	48.6	48.4	51.9	52.2	50.7	50.3	49.6	50.3	48.6	48.1	45.3
10 km/h	63.1	40.7	39.5	42.3	43.4	44.2	44.5	48.2	50.5	49.9	52.3	52.9	53.0	53.4	53.2	52.6	52.7	53.3	49.2
10 km/h	63.4	38.8	40.3	41.5	44.6	45.9	47.1	48.3	52.8	52.8	53.9	53.1	54.0	54.5	51.3	50.9	51.7	50.6	48.9
10 km/h	64.1	36.9	38.8	42.7	42.9	47.0	46.8	47.6	52.3	52.9	55.6	54.0	56.1	55.5	52.1	50.3	51.8	50.0	49.2
10 km/h	62.8	38.6	49.3	49.6	41.8	43.2	45.9	50.0	48.6	49.7	51.7	53.2	54.4	53.6	52.4	50.3	50.9	48.0	47.5
10 km/h	63.9	37.2	46.0	52.4	42.6	45.1	45.4	50.7	50.4	50.5	52.8	54.1	55.1	55.6	53.2	51.6	51.9	49.2	48.1

Table 41: A-weighted One Third Octave Band Level, dB(A) for16 km/h (NHTSA Phase 2 data)

Operating Condition	Overall, LAfmax, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
16 km/h	61.2	35.1	37.3	40.0	43.8	45.5	44.2	46.4	49.3	48.7	51.9	53.0	51.2	50.8	50.8	51.0	49.3	46.1	43.1
16 km/h	63.9	30.9	38.0	39.1	44.2	45.7	45.3	48.7	51.2	53.2	55.4	54.5	55.0	54.4	54.7	52.1	51.6	48.7	45.6
16 km/h	64.5	36.5	39.2	41.5	43.9	49.0	49.7	49.2	53.7	53.8	56.3	56.6	55.5	55.8	53.0	49.7	48.2	46.1	44.5
16 km/h	66.0	39.6	39.0	44.4	47.5	49.9	49.1	50.5	54.3	55.5	55.0	58.9	58.2	57.3	55.1	51.5	49.1	47.9	46.2
16 km/h	65.6	35.1	40.3	42.0	46.0	48.2	48.6	51.6	52.5	54.3	57.3	57.2	56.2	57.1	54.0	52.5	53.4	51.7	48.4
16 km/h	67.1	38.7	41.9	42.8	47.7	51.1	49.9	51.3	52.8	54.5	57.3	59.3	58.2	58.7	56.7	55.3	55.0	53.1	49.2
16 km/h	64.3	35.6	41.4	44.8	43.5	46.2	50.0	49.9	53.3	54.1	56.6	55.2	55.3	54.7	52.9	50.8	48.5	47.1	44.9
16 km/h	66.7	37.9	48.9	43.5	51.5	49.0	51.7	53.2	53.6	56.1	58.0	57.3	58.8	56.8	55.2	53.4	53.1	51.0	48.2
16 km/h	63.6	40.9	44.7	44.7	46.0	46.6	47.7	50.0	51.3	53.0	54.4	56.4	55.0	54.8	51.2	49.0	47.3	44.8	42.5
16 km/h	64.9	38.6	43.4	44.1	46.1	49.6	48.3	50.9	53.6	53.9	55.4	57.8	56.8	55.9	51.9	49.8	48.7	46.7	43.1
16 km/h	64.1	39.1	46.3	47.6	43.8	46.8	49.0	48.3	51.5	52.3	54.9	56.3	55.7	54.4	52.6	51.5	50.5	48.6	45.7
16 km/h	67.6	36.8	42.9	48.6	45.3	47.7	48.7	49.3	52.9	54.3	57.9	58.2	58.1	57.8	57.7	56.4	58.4	56.7	54.6
16 km/h	63.4	36.3	41.2	44.7	46.6	47.9	47.9	49.5	52.1	52.7	54.1	55.2	53.8	53.1	51.4	51.2	49.7	48.7	46.2
16 km/h	64.1	38.6	40.2	43.2	46.7	47.1	48.1	50.7	52.2	52.3	54.4	56.2	54.1	54.3	53.2	52.8	51.1	51.3	47.6
16 km/h	64.2	48.9	40.7	44.4	44.8	47.2	47.7	50.1	52.6	54.8	55.9	55.7	55.0	55.5	51.7	49.6	48.7	46.2	44.5
16 km/h	65.6	36.8	40.9	45.6	44.6	48.1	48.6	50.6	54.2	54.6	57.9	57.8	56.9	55.9	53.2	50.9	51.1	49.0	48.9
16 km/h	64.1	42.6	43.9	44.4	46.3	44.6	48.2	49.8	51.7	54.2	55.7	56.0	56.0	54.4	51.7	51.0	48.3	46.1	44.5
16 km/h	64.8	39.9	49.6	50.1	47.9	46.1	45.0	50.0	50.8	55.1	55.9	56.0	57.4	56.0	52.0	49.7	48.7	46.9	44.7

Table 42: A-weighted One Third Octave Band Level, dB(A) for Reverse 32 km/h (NHTSA Phase 2 data)

Operating Condition	Overall, LAfmax, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
32 km/h	65.6	36.8	43.8	48.0	45.4	46.9	47.8	48.8	51.6	55.3	58.3	57.9	57.9	56.5	53.8	51.0	48.2	45.8	42.7
32 km/h	73.0	42.9	46.2	48.9	51.5	53.5	56.2	57.4	59.8	62.5	66.4	66.2	63.9	63.5	60.4	57.8	55.4	52.5	49.1
32 km/h	71.6	37.5	42.4	41.7	47.1	53.9	53.8	54.6	59.0	59.0	62.2	64.5	64.2	64.4	61.0	58.0	53.6	49.8	46.4
32 km/h	73.2	43.4	40.8	47.4	50.3	57.0	55.9	55.8	62.1	61.6	63.2	65.8	66.2	65.0	62.6	58.7	54.9	51.5	48.0
32 km/h	71.8	39.9	42.3	46.0	47.7	53.0	55.2	53.9	57.8	60.8	65.2	65.1	62.9	63.2	59.5	54.9	55.0	52.0	48.1
32 km/h	75.9	45.1	46.9	49.1	52.4	57.6	56.8	60.2	62.8	65.2	69.2	69.6	67.1	66.6	62.3	60.5	59.3	56.7	52.7
32 km/h	71.5	40.3	44.2	53.1	53.6	52.1	52.8	57.1	57.5	61.3	64.2	64.1	63.5	62.5	58.4	56.5	53.0	50.6	47.9
32 km/h	72.6	41.9	47.9	50.2	50.5	53.2	52.1	56.0	60.8	63.3	66.9	64.7	64.1	62.8	58.9	56.4	52.3	49.3	46.9
32 km/h	71.6	42.3	46.5	47.5	53.0	56.0	54.7	57.9	59.2	60.3	62.7	65.6	63.5	62.5	59.0	54.6	51.3	48.6	45.7
32 km/h	72.8	39.0	45.7	45.4	54.7	56.0	55.1	57.4	58.8	61.2	64.7	67.0	65.4	63.9	60.1	54.9	51.3	49.0	45.2
32 km/h	68.1	43.9	41.5	45.3	47.0	51.9	50.8	51.5	52.9	54.1	58.3	61.4	60.0	59.2	57.3	55.9	55.0	53.4	51.0
32 km/h	74.9	42.8	43.7	47.2	50.8	57.3	55.5	56.0	59.4	61.9	65.8	67.8	67.5	65.5	63.2	62.4	63.1	61.7	59.0
32 km/h	69.6	49.1	46.0	51.3	51.7	55.3	56.2	54.7	57.5	57.4	59.9	62.3	61.1	61.2	58.5	55.0	51.3	48.0	44.6
32 km/h	73.3	46.3	46.8	49.3	51.4	58.2	56.7	58.5	61.5	62.9	64.6	66.4	65.3	64.2	60.7	58.1	55.7	54.8	50.3
32 km/h	73.6	41.5	42.0	45.8	48.6	57.0	56.4	57.1	60.5	64.2	65.9	66.7	64.6	65.3	63.0	57.5	53.6	50.3	46.9
32 km/h	75.3	38.5	40.9	47.3	49.5	55.3	57.1	59.0	63.5	64.0	67.7	68.3	66.9	67.6	63.2	60.1	57.9	55.7	54.0
32 km/h	70.6	40.4	40.9	51.2	50.5	48.6	52.5	53.2	55.1	60.6	59.6	63.4	65.5	61.9	58.0	54.4	49.5	46.1	43.7
32 km/h	72.3	44.1	46.3	54.1	52.5	52.6	57.8	58.8	60.0	63.5	64.7	63.2	65.3	62.5	58.7	56.7	53.0	49.9	47.6

Table 43: A-weighted One Third Octave Band Level, dB(A) for Acceleration (NHTSA Phase 2 data)

Operating Condition	Overall, LAfmax, dB(A)	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
Acceleration	67.6	38.6	47.6	45.6	47.8	52.1	52.5	53.3	55.5	53.7	57.7	56.1	59.3	58.6	56.6	56.8	57.6	54.3	51.7
Acceleration	68.9	39.9	48.4	44.2	48.0	54.6	51.4	51.0	57.1	55.6	57.7	56.5	61.2	59.5	59.6	58.5	58.4	55.4	53.4
Acceleration	65.2	46.9	40.8	43.4	52.7	50.7	52.2	50.9	53.8	53.5	53.5	55.3	55.7	56.1	54.1	53.2	52.6	50.9	49.1
Acceleration	66.1	44.8	40.4	45.0	51.0	48.0	51.2	54.6	54.2	54.8	53.9	55.3	56.6	56.2	56.5	55.5	54.4	52.0	51.9
Acceleration	69.9	44.8	45.1	46.0	49.1	52.3	53.9	53.7	58.5	57.6	58.6	59.0	60.4	62.1	58.9	59.3	60.0	57.5	54.8
Acceleration	74.0	54.3	45.9	46.8	54.2	54.6	61.2	55.6	59.6	61.7	63.0	62.1	64.3	64.8	64.5	63.5	65.0	62.1	58.6
Acceleration	66.5	34.9	47.3	48.7	46.5	48.8	50.3	58.1	50.7	53.8	54.6	57.7	57.1	56.8	55.6	55.8	54.1	52.3	49.5
Acceleration	68.6	39.8	48.9	49.5	59.0	49.2	53.4	55.7	55.1	57.2	57.3	59.8	59.2	58.0	57.4	56.7	56.2	54.6	51.9
Acceleration	63.7	34.1	43.4	44.6	43.9	44.7	46.4	50.1	48.4	52.8	53.7	53.6	55.2	56.4	53.0	51.9	51.7	49.2	45.2
Acceleration	68.1	49.9	41.3	50.3	47.3	50.7	52.5	53.7	56.2	56.5	57.9	58.4	59.9	59.2	57.0	56.6	55.9	54.5	50.3
Acceleration	71.8	44.5	52.7	47.5	50.5	50.8	54.9	54.2	54.1	57.0	60.4	62.5	61.7	60.6	64.8	60.8	62.2	60.7	58.3
Acceleration	75.8	41.9	45.2	51.2	52.2	51.7	52.8	55.0	55.5	56.6	63.1	64.9	65.0	65.3	67.1	66.4	67.9	67.0	65.5
Acceleration	68.4	49.1	54.8	49.4	50.7	51.8	51.0	52.0	55.1	58.7	58.5	60.0	58.4	58.4	56.5	56.7	55.6	54.6	52.4
Acceleration	71.1	43.2	53.9	49.2	49.7	49.1	51.7	51.7	57.2	57.5	59.8	60.8	61.8	63.6	61.3	60.8	60.1	59.8	56.7
Acceleration	69.7	38.6	41.3	46.3	47.0	51.6	54.4	58.1	59.1	60.3	62.1	59.8	59.3	59.6	56.6	57.5	55.4	55.5	52.9
Acceleration	71.3	39.8	43.1	46.2	48.2	52.2	54.1	55.6	63.6	63.3	61.9	59.8	61.3	60.3	58.9	58.1	58.6	57.1	56.3
Acceleration	71.7	45.0	67.1	59.0	54.1	51.7	54.3	56.1	60.7	62.3	57.9	59.5	60.1	58.7	56.4	56.2	54.8	53.3	51.1
Acceleration	75.2	47.7	67.6	62.1	54.3	57.2	57.3	59.5	66.9	68.0	61.8	64.4	63.7	62.4	61.4	59.8	59.5	58.0	55.7

Table 44:A-weighted One Third Octave Band Level, dB(A) for <u>Startup</u> ((NHTSA Phase 2 data)

Operating Condition	**Overall, LAfmax, dB(A)**	**100 Hz**	**125 Hz**	**160 Hz**	**200 Hz**	**250 Hz**	**315 Hz**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**	**1250 Hz**	**1600 Hz**	**2000 Hz**	**2500 Hz**	**3150 Hz**	**4000 Hz**	**5000 Hz**
Startup	68.2	36.5	37.9	32.6	36.9	38.3	39.7	42.7	52.9	49.9	56.0	55.7	61.1	58.6	57.7	60.0	60.0	56.9	56.2
Startup	70.4	34.5	36.3	38.1	39.7	42.1	42.1	43.2	49.2	50.8	60.8	57.0	58.6	59.8	59.7	62.1	65.3	59.4	57.6
Startup	69.7	34.1	34.2	34.1	35.9	39.6	39.3	43.3	50.6	51.1	50.3	55.3	62.8	61.2	60.6	60.8	62.4	59.5	56.3
Startup	72.3	34.4	33.8	37.0	37.4	43.8	45.4	46.4	52.7	55.4	54.0	60.8	64.2	63.0	65.3	63.8	63.4	61.2	59.4
Startup	67.6	37.5	38.9	38.4	38.8	38.9	40.4	42.7	50.6	49.3	53.3	53.6	58.7	58.5	55.5	61.1	59.9	57.6	56.3
Startup	72.4	41.2	38.6	44.0	46.0	48.0	51.6	52.7	53.4	53.5	56.6	56.0	59.1	62.6	61.6	62.9	64.7	65.7	64.4
Startup	67.5	36.5	37.4	40.7	42.7	44.1	50.7	51.7	53.9	51.4	53.3	54.9	56.5	56.7	55.1	57.1	60.2	58.2	59.4
Startup	75.9	32.0	38.5	39.0	39.1	39.8	49.9	55.5	59.4	57.0	60.2	68.8	67.7	67.1	67.1	68.7	63.8	61.9	60.1
Startup	67.1	39.4	39.4	42.9	45.9	49.7	50.9	53.0	51.2	52.1	54.7	53.4	55.9	57.7	56.7	56.3	57.9	58.5	57.7
Startup	68.2	35.3	35.4	35.0	36.7	37.4	41.6	46.2	42.4	48.1	51.0	56.0	56.8	59.4	58.5	60.6	61.4	59.0	57.7
Startup	71.4	38.0	39.9	45.1	54.0	51.6	52.1	54.1	57.9	57.2	56.5	58.9	60.5	59.2	62.4	60.2	61.8	64.4	62.3
Startup	73.6	40.0	42.1	49.2	51.1	48.7	52.5	56.1	56.5	57.5	60.3	60.0	63.9	63.3	63.6	62.5	65.4	66.0	64.5
Startup	74.4	38.3	37.5	38.7	44.7	40.6	44.2	47.5	57.5	53.3	58.1	60.8	62.3	62.6	65.3	64.4	66.9	67.5	66.9
Startup	77.4	39.3	36.2	40.9	45.2	43.2	47.8	48.4	58.0	54.0	58.6	60.1	61.6	66.9	65.6	69.8	68.6	69.9	71.9
Startup	75.8	40.7	42.2	43.4	45.8	49.7	51.7	51.9	57.5	56.7	57.6	63.1	64.3	67.0	66.2	66.9	66.2	68.7	67.3
Startup	76.4	39.8	40.0	40.9	42.7	42.7	49.6	48.2	56.4	58.6	57.5	68.1	68.3	66.7	65.6	66.7	66.3	68.7	65.4
Startup	76.2	37.2	39.7	41.0	43.7	44.3	45.8	49.6	58.3	53.7	64.6	64.6	67.3	66.2	66.7	67.2	69.2	66.3	64.5
Startup	78.6	38.5	39.5	39.2	44.9	48.5	57.6	56.0	56.4	61.6	66.1	65.2	69.3	72.9	69.2	70.4	68.1	67.0	64.2

D.3 Sound Levels Analysis: ICE Vehicles at 20km/h & 30km/h

Minimum levels are desired for vehicles operating at speeds of 20 and 30 km/h, however, most data that has been collected to date for this project has been collected at 0, 10, 16, 24, and 32 km/h. Therefore, interpolation is required to determine the appropriate levels at 20 and 30 km/h. The standard model used by the FHWA (Fleming, Gregg G., Rapoza, Amanda S., and Lee, Cynthia S. Y., 1995) for the growth of sound pressure level as a function of speed for road based vehicles is given by the following equation and is shown in Figure 19.

$$L_{A,passby}(S) = 10\log_{10}\left[10^{C/10} + \left(S^{A/10}\right)\left(10^{B/10}\right)\right] \tag{1}$$

Depending on the location along the abscissa, the change in level due to a change in speed varies depending on the speed itself. This is due to the fact that there are two regimes that define the upper and lower speed ranges and these regimes are joined by a transition region. If changes are to be computed at very low or very high speeds, then the model is reasonably linear. However, if changes are to be computed in the transition region, then a linear model is not appropriate. Because the PSEA focuses on speeds that may be in the transition region, it is not appropriate to assume a linear model without first examining the data.

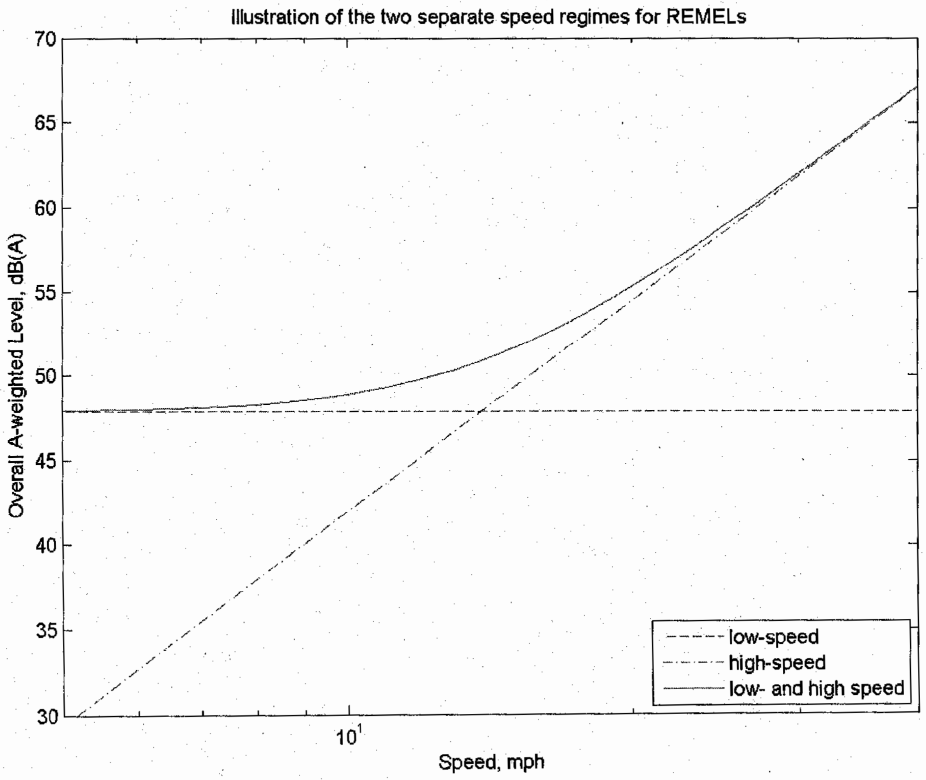

Figure 19: Illustration of two Speed Regimes for Vehicle Sound Pressure Level

The OICA, Phase 2, and VRTC data were fit to the model given in Equation (1) for one-third octave band frequencies centered at 315, 400, 500, 2000, 2500, 3150, 4000, and 5000 Hz. Figure 20 to Figure 27 give the results. The low frequency one-third octave bands (315 to 500 Hz) have reasonably linear changes in sound pressure level as a function of the log of speed above 10 km/h. The high frequency one-third octave bands become less linear with increasing center frequency such that, above 2500 Hz, a linear relationship would only be appropriate for small changes in speed.

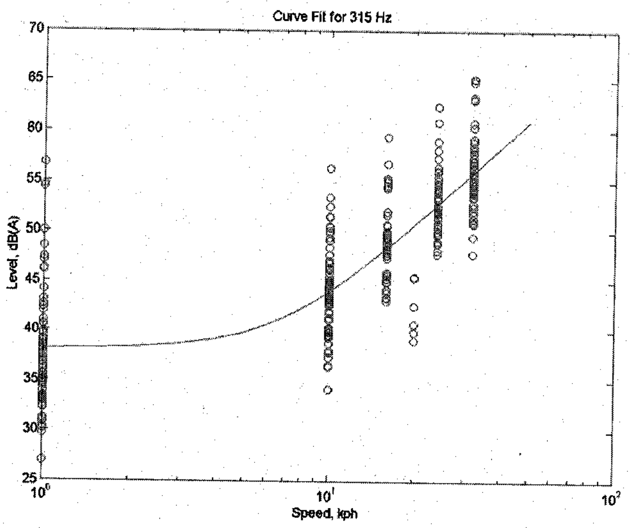

Figure 20: Curve Fit for 315 Hz

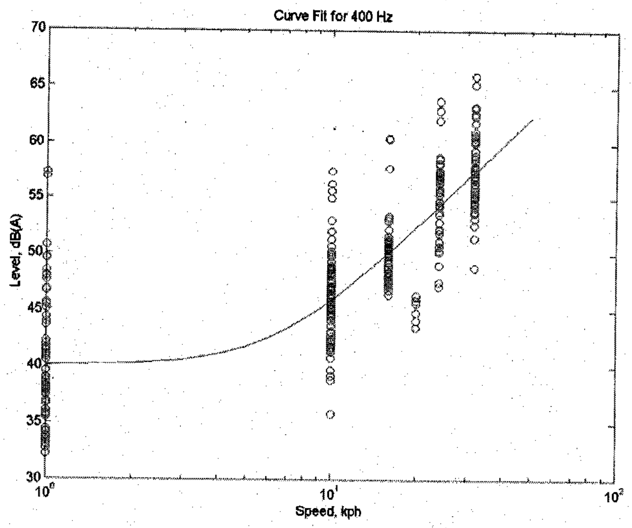

Figure 21: Curve Fit for 400 Hz

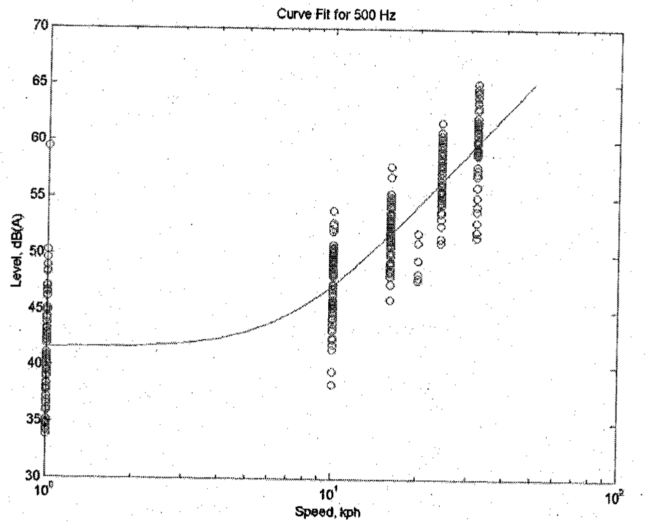

Figure 22: Curve Fit for 500 Hz

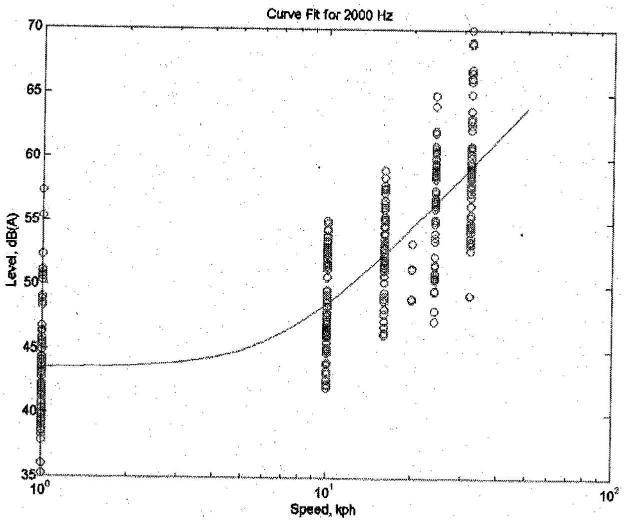

Figure 23: Curve Fit for 2000 Hz

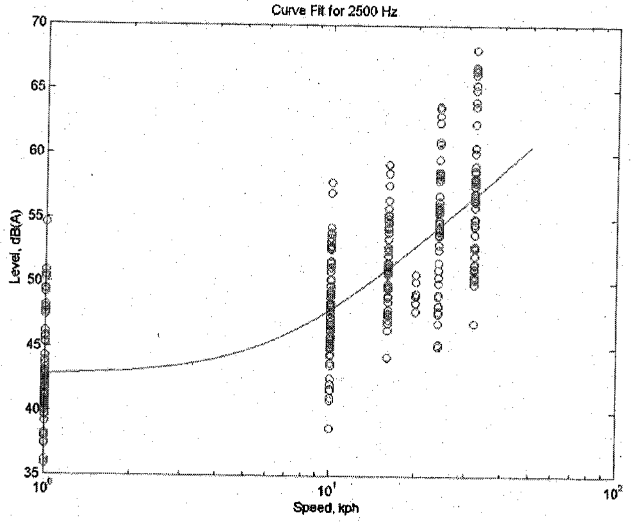

Figure 24: Curve Fit for 2500 Hz

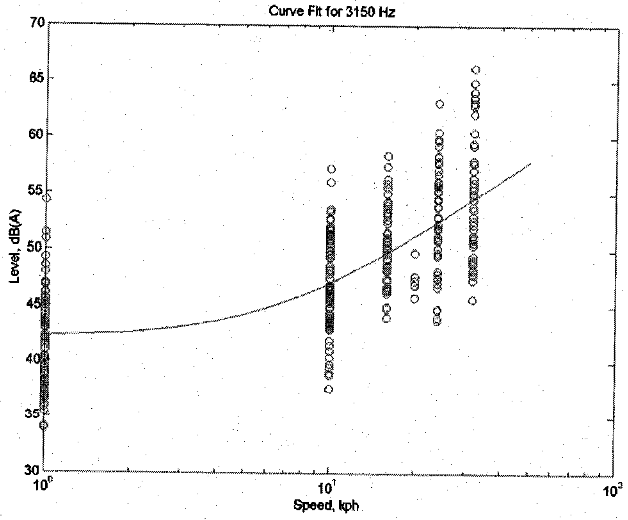

Figure 25: Curve Fit for 3150 Hz

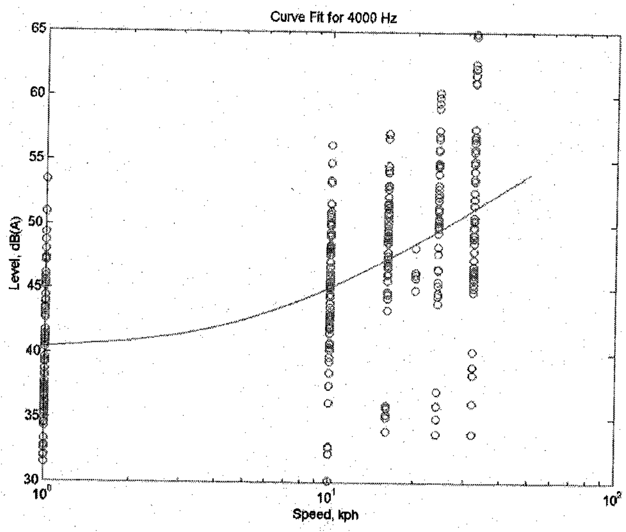

Figure 26: Curve Fit for 4000 Hz

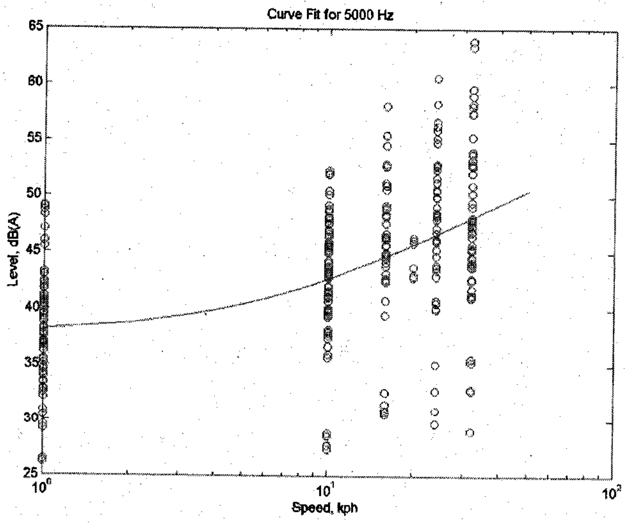

Figure 27: Curve Fit for 5000 Hz

Based on these results, the following methodology was chosen for determining minimum specifications for speed of 20 and 30 km/h:

D. Model the change in level due to speed per equation 1.
  - For 20 km/h, reference 16 km/h data and compute the delta between 16 and 20 km/h using the model.
  - For 30 km/h, reference 32 km/h data and compute the delta between 32 and 30 km/h using the model.

E. Apply the deltas computed in step one to the data for 16 and 32 km/h. This gives the minimum levels for the specification based on the mean (less any safety factor, we used 0.5 dB).

F. For the specification based on the mean minus one standard deviation, use a standard deviation based on a linear interpolation between 16 and 24 (for 20 km/h) and 24 and 32 (for 30 km/h).

Note: A linear interpolation is used because there was no evidence that the standard deviation increased logarithmically with speed. Note also that the modeling process also produces intervals that can be used to estimate standard deviations; however, these confound sensitivities of the model with actual variation of the data and were not deemed to be appropriate estimates of the standard deviation of expected samples. Final results are shown in Table 45 and Table 46 with no safety factor and in Table 47 and Table 48 are with a 0.5 dB safety factor.

Table 45: Minimum A-weighted Sound Levels based on Mean Values with no Safety Factor, dB(A)

	315 Hz	400 Hz	500 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz	Sum
Stationary/Activated	39	41	42	44	43	43	40	37	51
Reverse	41	43	45	46	45	44	42	39	53
10 km/h	44	46	48	49	48	47	45	42	56
20 km/h	52	53	54	55	53	52	49	45	61
30 km/h	55	57	59	59	56	54	51	48	65

Table 46: Minimum A-weighted Sound Levels based on Mean Values minus One Standard Deviation with no Safety Factor, dB(A)

	315 Hz	400 Hz	500 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz	Sum
Stationary/Activated	33	35	36	39	39	38	35	28	45
Reverse	37	39	41	42	41	39	37	34	48
10 km/h	40	42	44	45	44	42	40	37	51
20 km/h	48	49	51	50	49	47	42	38	57
30 km/h	52	53	56	54	51	49	44	40	61

Table 47: Minimum A-weighted Sound Levels based on Mean Values with 0.5 dB Safety Factor, dB(A)

	315 Hz	400 Hz	500 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz	Sum
Stationary/Activated	40	41	43	44	44	43	41	37	51
Reverse	42	44	45	46	46	44	42	40	53
10 km/h	45	47	48	49	49	47	45	43	56
20 km/h	52	53	54	55	53	52	49	45	61
30 km/h	55	57	59	59	56	54	51	48	65

Table 48: Minimum A-weighted Sound Levels based on Mean Values minus One Standard Deviation with 0.5 dB Safety Factor, dB(A)

	315 Hz	**400 Hz**	**500 Hz**	**2000 Hz**	**2500 Hz**	**3150 Hz**	**4000 Hz**	**5000 Hz**	**Sum**
Stationary/Activated	34	35	37	39	39	39	36	29	46
Reverse	37	40	42	42	41	40	37	34	49
10 km/h	40	43	45	45	44	43	40	37	52
20 km/h	48	49	51	50	49	47	42	38	57
30 km/h	52	53	56	54	51	49	44	40	61