Research on Sound Specifications for Hybrid and Electric Vehicles

Presented at UNECE Global Technical Regulation
Informal Working Group on
Quiet Road Transport Vehicles

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Prior to the Legislation

- 2007 ~ SAE established working group to develop a recommended practice.
- 2008 ~ NHTSA holds first public meeting and announces intent to publish comprehensive research plan.
- 2009 ~ NHTSA publishes research plan, first study evaluating crash risk, and Report to Congress.
- 2010 ~ NHTSA publishes first research report and continues additional research including acoustic measurements and human subject studies.
- January 4, 2011 ~ President signs Pedestrian Safety Act of 2010 requiring a finalized rule in 3 years.

Previous Research

- NHTSA’s Phase 1

Compared acoustic parameters of HE and ICE vehicles, examined auditory detectability, and reviewed possible countermeasures.

- NHTSA’s Phase 2

Discussed options to specify vehicle sounds for pedestrians.

Current Work

- Conduct research to support activities related to the implementation of the Pedestrian Safety Enhancement Act of 2010.

- Identify parameters and criteria for sounds to be detectable and recognizable as the sound of a motor vehicle in operation.

Research Facilities

- NHTSA's Vehicle Research & Testing Center (East Liberty, Ohio)

- USDOT, Volpe National Transportation Systems Center (Cambridge, Massachusetts)

Technical Approach

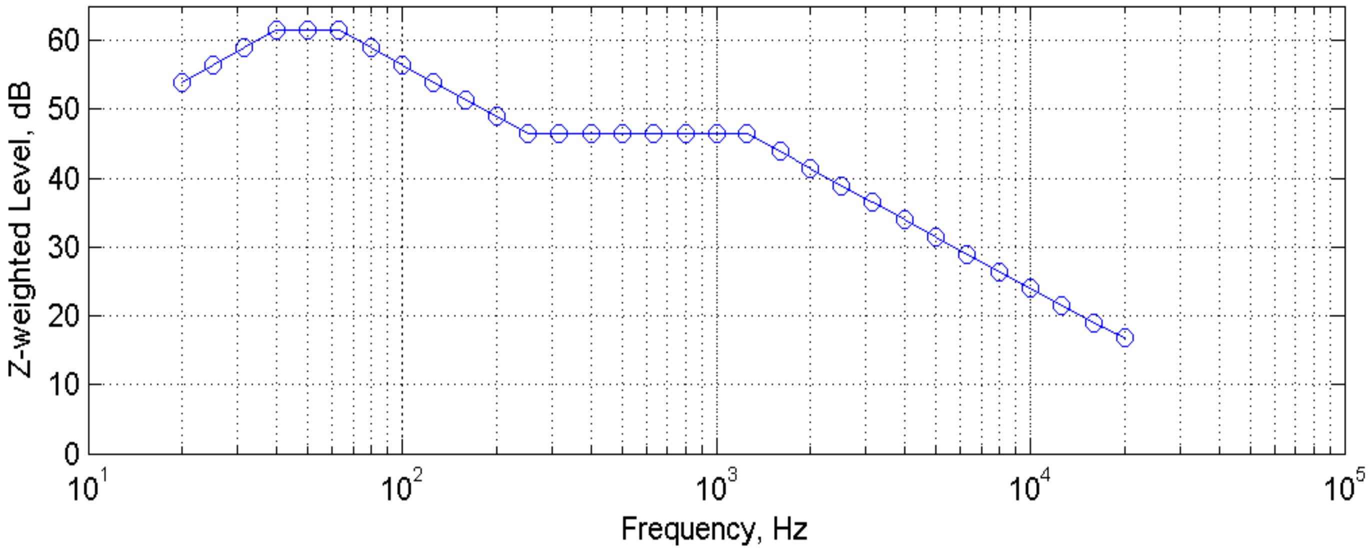
- Research designed to develop several potential specifications for EVs and HVs
  - Sound Levels for Detection based on:
    - ✓ Psychoacoustic Model and Detection Distances
    - ✓ Acoustic Characteristics of ICE Vehicles
  - Acoustic Parameters for Directivity
  - Acoustic Parameters for Recognition

A-weighted Sound Levels
(based on Psychoacoustic Model and Detection Distance)

Assumptions:

- A vehicle should be detectable on a moderate suburban ambient (55 dB(A))
- Sounds should be detectable in multiple one-third octave bands
- A psychoacoustic model can be used to determine minimum levels for detection of one-third octave bands
- Minimum detection distances can be based on the stopping sight distance used in highway design

Ambient Noise Spectrum (One-Third Octave Bands)



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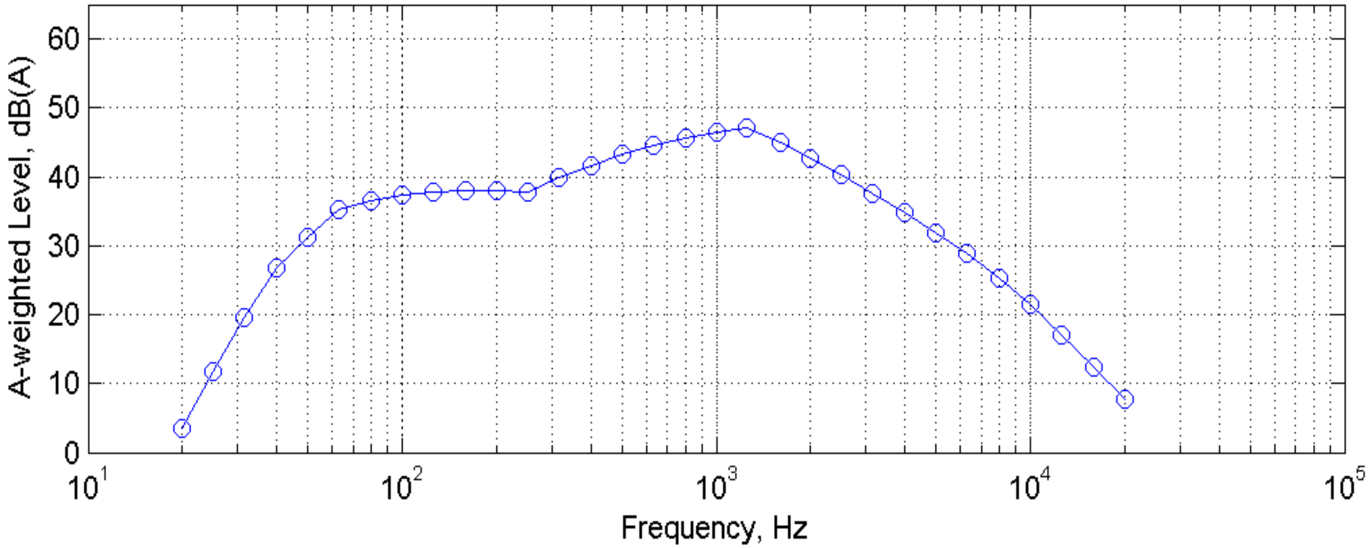


Psychoacoustic Model: Moore's Partial Loudness

- Selection factors:
  - Coincident masking and non-coincident masking by an ambient
  - Model produces loudness of a sound partially masked by an ambient
  - Computer program documented and publically available
- Application:
  - Un-weighted one-third octave band levels for the signal and the masker
  - Information on how the signal is presented (free-field)
  - Loudness above 0.03 sones, is detectable, according to model

Detection Distance and Level Adjustments

1. Computed levels for pedestrian at vehicle location (2 m from center of vehicle front plane)
2. Computed detection distance for each operation
3. Adjusted levels to detection distances (attenuation based on distance doubling)
4. Levels corrections applied to selected important bands

Operation	Distance (meters)	Level Correction, (dB)
Stationary	0	0
Reverse	5	6
10 km/h	5	6
20 km/h	11	12.2
30 km/h	19	16.8

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

where:

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

A-weighted Sound Levels
(based Psychoacoustic Model and Detection Distance)

1/3 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	49	52	55	62	66

*Measured at SAE 2889-1 microphone. A sound meeting the overall level will not necessarily be as detectable as a sound meeting the level for each 1/3 octave band.

Summary: Sound Levels Based on Psychoacoustic Model

- Multiple bands can provide greater opportunity for detection
- Other bands omitted due to contribution to overall level
- Approach considers masking effect of the ambient and detection distance

A-weighted Sound Levels
(based Acoustic Characteristics of ICE Vehicles)

- Approach assumes that ICE vehicles emit adequate sound levels for detectability
- Dataset includes ICEs measured by OICA and NHTSA's Phase 2

Dataset: International Organization of Motor Vehicle Manufacturers (OICA)

- Vehicles
  - 42 vehicles
  - Types of vehicles ranged from small sedans to a public bus*
  - 12 manufacturers from USA, Europe, and Japan
- Data included
  - Vehicle ID
  - Engine size , power, and type
  - Transmission
  - Background noise level
  - A-weighted sound pressure levels
  - Un-weighted one-third octave band levels
- Background levels during measurements were between 19.6 and 52.5 dB(A)
- Followed SAE J2889-1 draft ($L_{Af,max}$ and $L_{Af,min}$).

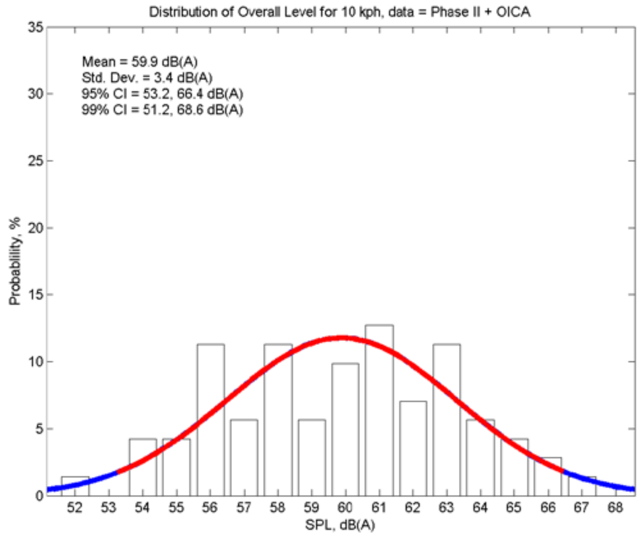
* Not included in current analysis

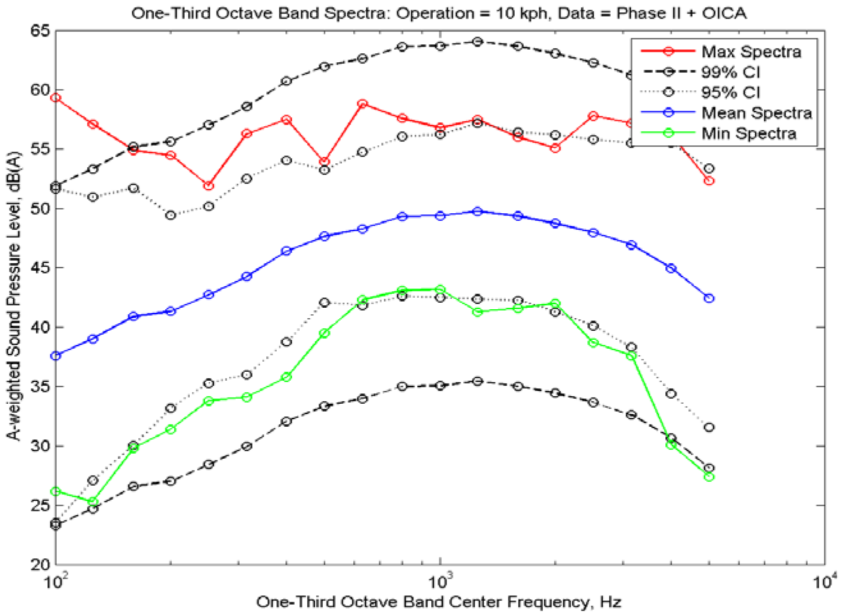
Dataset: NHTSA Phase 2

- Vehicles
  - 10 conventional vehicles
  - Sedans, station wagons, and a pick-up truck
  - Model years from 2000 to 2009
  - Domestic, European, and Asian manufacturers
- Operating conditions
  - low speed pass-by forward (6, 10, 15 and 20 mph)
  - low speed pass-by reverse (6 mph)
  - stationary but activated
- Background levels during measurements were between 45 to 55 dB(A)
- Followed SAE-J2889-1 Rev 2009

Data Analyses

- Data analyzed separately and combined
- When combined, used two measurements per vehicle for a given operation
- Overall levels
  - Computed mean and prediction intervals
- One-third octave bands
  - Computed mean, minimum, maximum, and prediction intervals





A-weighted Sound Levels
(based on ICE Mean Levels)

	Leq dB(A)	Lmax dB(A)			
One-Third Octave Band Center Frequency, Hz	**0 km/h**	**Reverse**	**10 km/h**	**20 km/h**	**30 km/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	51	53	56	61	65

*Each one-third octave band in the table contributes to the character of the sound, under this approach the sound would have to meet the level for each 1/3 octave band not just the overall level

A-weighted Sound Levels
(based on ICE Mean minus 1 Standard Deviation)

	Leq dB(A)	Lmax dB(A)			
One-Third Octave Band Center Frequency, Hz	**0 km/h**	**Reverse**	**10 km/h**	**20 km/h**	**30 km/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	46	49	52	57	61

*Each one-third octave band in the table contributes to the character of the sound, under this approach the sound would have to meet the level for each 1/3 octave band not just the overall level

Summary: Sound Levels Based on ICE Vehicles

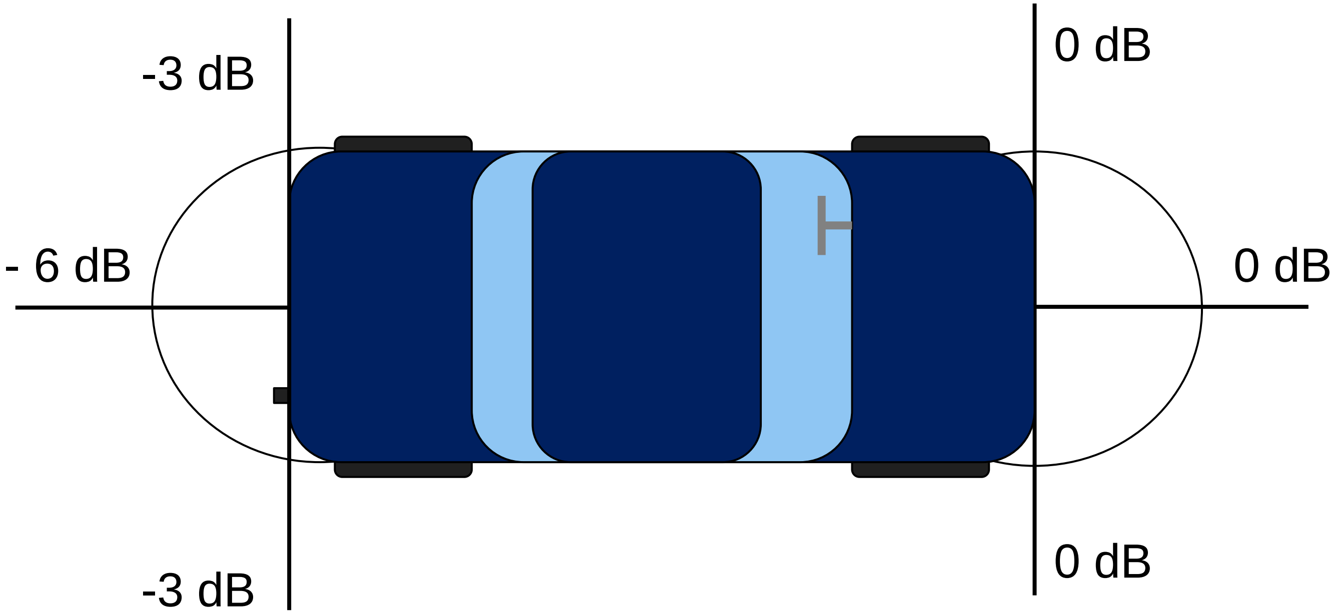
- Levels are based on statistical analysis of a set of ICE vehicles
  - Mean levels
  - Mean minus 1 standard deviation
- Approach does not consider masking effect of the ambient

360-Degree Static Sound Measurement (Directivity)

- Static measurement (0 km/h)
- Eight microphones around the perimeter of the vehicle

Directivity

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



Acoustic Parameters for Recognition

- Recognition
  - That sound is emanating from a motor vehicle in operation
  - The type of operation
  - Sound emitted by ICE vehicle used as baseline
- Sound simulations
  - Stationary but activated, constant speed, and accelerating pass-bys
  - Doppler shifts; pitch shifting tied to vehicle speed; number and relative level of tonal components; amplitude and frequency modulation; fundamental frequency

Acoustic Parameters for Recognition

- Broadband components, which may be modulated, should be in each one-third octave band from 160 Hz to 5000 Hz.
- 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.
- A component is considered to be a tone if the Tone-to-Noise ratio is greater than or equal to 6 dB*.
- Frequency of pitch producing components (tones) should vary in proportion to vehicle speed and shift by at least 1% for each 1 km/h change in vehicle speed.

* ANSI S1.13-1995

Summary

- Sound Levels for Detection based on:
  - ✓ Psychoacoustic Model and Detection Distances
  - ✓ Acoustic Characteristics of ICE Vehicles
- Acoustic Parameters for Directivity
- Acoustic Parameters for Recognition

References

- AASHTO (2004). *A Policy on Geometric Design of Highways and Streets*. Washington, DC: American Association of State Highway and Transportation Officials
- Hastings et al (2012). *Research on Minimum Sound Specifications for Hybrid and Electric Vehicles.* National Highway Traffic Safety Administration. Docket No. NHTSA-2011-0148
- Moore, Glasberg & Baer (1997). *A Model for the Prediction of Thresholds, Loudness and Partial Loudness*, J.Audio.Eng.Soc. 45 224-240
- Pedersen, Torben et al (2011) *White Paper on External Warning Sounds for Electric Cars: Recommendations and Guidelines.* DELTA SenseLab
- Public Law 111-373: *Pedestrian Safety Enhancement Act of 2010*. (124 stat.4086; Date: 1/4/11; enacted S.841)
- SAE J2889-1 *Measurement of Minimum Noise Emitted by Road Vehicles*. Society of Automotive Engineers

Dockets

www.regulations.gov

NHTSA-2011-0148

Notice of Proposed Rulemaking and Support Material for Quiet Vehicle Alert Sound Rulemaking

NHTSA-2011-0100

Notice of Intent to Prepare Environmental Assessment for Pedestrian Safety Enhancement

NHTSA-2008-0108

Quiet Cars - Notice and Request for Comments

Backup Slides

Attenuation Values for Generation of Simplified Background Noise from Pink Noise

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

Reference: Pedersen et. al, (2011)

Optimization Relative to Overall Level