Research on Sound Specifications for Hybrid and Electric Vehicles

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

July 19, 2012
Washington, D.C.
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.
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
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)
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

<table>
<thead>
<tr>
<th>Operation</th>
<th>Distance (meters)</th>
<th>Level Correction, (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stationary</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Reverse</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>10 km/h</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>20 km/h</td>
<td>11</td>
<td>12.2</td>
</tr>
<tr>
<td>30 km/h</td>
<td>19</td>
<td>16.8</td>
</tr>
</tbody>
</table>

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

where:
- $t$ = brake reaction time, s
- $V$ = design speed, km/h
- $a$ = deceleration rate, m/s²
## A-weighted Sound Levels
*(based Psychoacoustic Model and Detection Distance)*

<table>
<thead>
<tr>
<th>1/3 Octave Band Center Frequency (Hz)</th>
<th>0 km/h</th>
<th>Reverse</th>
<th>10 km/h</th>
<th>20 km/h</th>
<th>30 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>315</td>
<td>42</td>
<td>45</td>
<td>48</td>
<td>54</td>
<td>59</td>
</tr>
<tr>
<td>400</td>
<td>43</td>
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<td>500</td>
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<td>2000</td>
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<td>2500</td>
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<td>42</td>
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<td>56</td>
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<tr>
<td>3150</td>
<td>37</td>
<td>40</td>
<td>43</td>
<td>49</td>
<td>53</td>
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<tr>
<td>4000</td>
<td>34</td>
<td>36</td>
<td>39</td>
<td>46</td>
<td>50</td>
</tr>
<tr>
<td>5000</td>
<td>31</td>
<td>34</td>
<td>37</td>
<td>43</td>
<td>48</td>
</tr>
<tr>
<td><em>Overall A-weighted SPL</em></td>
<td>49</td>
<td>52</td>
<td>55</td>
<td>62</td>
<td>66</td>
</tr>
</tbody>
</table>

*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
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 ($L_{A_f,\text{max}}$ and $L_{A_f,\text{min}}$).

* 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)

<table>
<thead>
<tr>
<th>One-Third Octave Band Center Frequency, Hz</th>
<th>Leq dB(A) 0 km/h</th>
<th>Reverse</th>
<th>Leq dB(A) 10 km/h</th>
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*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)

<table>
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<th>0 km/h</th>
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<td>38</td>
<td>40</td>
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</tbody>
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*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.*
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


- 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
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
<table>
<thead>
<tr>
<th>Hz</th>
<th>dB</th>
<th>Hz</th>
<th>dB</th>
<th>Hz</th>
<th>dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>-7.5</td>
<td>200</td>
<td>-12.5</td>
<td>2k</td>
<td>-20</td>
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<td>25</td>
<td>-5</td>
<td>250</td>
<td>-15</td>
<td>2.5k</td>
<td>-22.5</td>
</tr>
<tr>
<td>31.5</td>
<td>-2.5</td>
<td>315</td>
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<td>3.15k</td>
<td>-25</td>
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<td>-27.5</td>
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<td>5k</td>
<td>-30</td>
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<td>-32.5</td>
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<td>800</td>
<td>-15</td>
<td>8k</td>
<td>-35</td>
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<tr>
<td>100</td>
<td>-5</td>
<td>1k</td>
<td>-15</td>
<td>10k</td>
<td>-37.5</td>
</tr>
<tr>
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<td>-7.5</td>
<td>1.25k</td>
<td>-15</td>
<td>12.5k</td>
<td>-40</td>
</tr>
<tr>
<td>160</td>
<td>-10</td>
<td>1.6k</td>
<td>-17.5</td>
<td>16k</td>
<td>-42.5</td>
</tr>
</tbody>
</table>

Reference: Pedersen et. al, (2011)
Optimization Relative to Overall Level