Descriptors of Sound from HVAC&R Equipment

Weonchan Sung
Purdue University, sung26@purdue.edu

Patricia Davies
Purdue University

J Stuart Bolton
Purdue University, bolton@purdue.edu

Follow this and additional works at: http://docs.lib.purdue.edu/herrick
Descriptors of Sound from HVAC&R Equipment

Weonchan Sung, Patricia Davies, J. Stuart Bolton
Ray W. Herrick Laboratories, Purdue University
Acknowledgement

• Many thanks to sponsors for funding this research

• Also thanks to:
  • Jelena Paripovic and Daniel Carr
Introduction

- HVAC&R equipment noise can be annoying

- Possible Noise induced sleep problems
  - e.g. ref. Passchier-Vermeer & Passchier, 2000

- HVAC&R noise can have a negative effect on work efficiency
  - e.g. ref. Holmberg, 1997

http://www.goodmanmfg.com/products/air-conditioners
Introduction

Vehicle HVAC systems
- Zwicker Loudness and annoyance highly correlated (Leita & Paul, 2009; Hohls et al., 2014)
- Articulation Index, Roughness, Sharpness are correlated with preference
  (Leita & Paul, 2009; Hohls et al., 2014)

Air-conditioning and refrigeration Equipment
- Sound Quality Indicator: tone penalized loudness metric (ANSI/AHRI 1140, 2012)

Fan
- Zwicker Loudness and annoyance highly correlated (Susina et al., 2004)
  (Susini et al., 2004; Schneider and Feldmann, 2015; Naji and Sanan, 2015)

Compressor
- Sharpness and beating affect sound quality (Wang, 1994)

Goal: To develop a sound quality model that predicts annoyance due to HVAC&R equipment noise
Overview of the Subjective Tests

**Signal Modification**
Loudness, sharpness, roughness, and tonality

**Test 1**
a. Description Test  
b. Rating Test

**Test 2**
Semantic Differential Test

**Test 3**
Rating Test

**Focus:**
- Classification of descriptors  
  → Semantic scale development  
- Preliminary annoyance model
Test Sounds: Original Recordings

- Refrigeration truck unit
  - Two measurement standards (ANSI, TNO)
  - 7 or 7.5m from unit (MIC 1-5)
  - 6 MICs

- Residential unit
  - 1.5m from unit
  - 1 MIC
Test Sounds: Modified Recordings, Why?

- If two metrics are always highly correlated in an application, we only need to use one of these metrics in our sound quality model.

If both metrics are important?
→ Modify signals to de-correlate metrics (fill in gaps)
Test Sounds: Modified Recordings

- Original Recording
- Filters
  - Increased Sharpness
  - Reduced Sharpness
  - Increased Roughness
  - Increased Tonality
  - Decreased Tonality
Test Sounds Selection

- Divide each correlation plot into 25 boxes
- Select sounds from loudness vs. roughness plot

- Total 36 sounds
  - 14 mobile truck (7 original), 22 residential (5 original)
Test Facility

- The test was performed in a Sound Quality Booth at Purdue University.

- Sounds were played back through a high quality LynxOne sound card, Tucker-Davis HB7 amplifier, and a set of Etymotic Research ER-2 tube earphones.

- Disposable foam eartips (ER-14A) were used with earphones.
Test Procedure

- Overview of the test
- Hearing Test
- Consent form & Questionnaire

- Listen to sounds for familiarization (5 sounds)
- Long list of sound descriptions (taken away)
- Practice describing

- MAIN DESCRIPTION TEST
- Test Scenario
- Practice rating

- MAIN RATING TEST

- Comments
- Repeat Hearing Test
- Payment

Approx. 1 hour
Test 1 MAIN PARTS

- Part A – Describe the Sounds
  - 24, 4 seconds HVAC&R sounds;
    played twice, 4 secs pause between each sound
  - Subjects describe each sound in their own words

- Part B – Rate the Sounds
  - 36, 4 seconds HVAC&R sounds
  - Test Scenario
    ‘While you are listening, it may be helpful to imagine yourself in your garden, at any time during the day or evening, hearing these sounds continuously’
  - Subjects rate the annoyance level of sounds

\[1 \quad 2 \quad 3.5 \quad 5 \quad 6.5 \quad 8 \quad 9\]

- Not at all
- Slightly
- Moderately
- Very
- Extremely
Subjects & Demographics

- Total Number of Subjects: 42
- Average Age: 27 (18 – 57)
- Median Age: 25

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caucasian</td>
<td>23</td>
<td>19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Caucasian</th>
<th>Asian</th>
<th>South American</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25 (4 mixed race: 2 White-Hispanic, 2 White-Black)</td>
<td>16 (2 grew up in U.S.)</td>
<td>1</td>
</tr>
</tbody>
</table>
# Examples of Results – Description Test

<table>
<thead>
<tr>
<th>Sound</th>
<th>Descriptor (Number of times used)</th>
<th>Average Annoyance Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>151</td>
<td>high frequency(2), irritating(2), racing car, helicopter(3), disturbing(2), drilling(6), shaking, heavy, loud(6), unbearable, annoying(4), old, pulsing, cutting(2), old tractor, motorcycle(3), choppy(3), rattle, intense, whirring, weed wacker, summer(3), rotation, bumpy, rough(2), deep, abrupt, consistent, harsh(2), near, propeller(3), grinding(2), chisel, very fast(2), crackling, distorted(2), isolated, distinct, broken muffler, wood chipper, electrical saw, vibration, banging, grrr</td>
<td>5.96</td>
</tr>
<tr>
<td>76</td>
<td>processing, vacuum(3), light vehicle move, distant(3), white noise, bearable, light(4), familiar, safe, typical, low noise(2), blender, digital, bees, acceptable, fan(3), medium(3), muffled, dull, hum(3), buzz, quiet, calm(5), cool(2), relaxed(3), home, lightly rough, soft(9), air blowing(4), itchy, uneven, spinning(3), long, washing(2), sucking, factory(2), systematic, problematic, inefficient, hurrr, powerful, generator, grinding, pleasant, dryer, whirring, distorted, faint, even</td>
<td>3.92</td>
</tr>
</tbody>
</table>

Level related expression
Annoyance related expression
Sound quality metric related expression
<table>
<thead>
<tr>
<th>Classifications</th>
<th>Descriptor (number of times used)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft / Loud</td>
<td>Soft (56), Quiet (29), Muffled (16), Mild (10), Faint (7), Gentle (3), Medium (19), Moderate (17)</td>
</tr>
<tr>
<td></td>
<td>Loud (210), Powerful (11), Intense (9), Strong (5), Vigorous (2), Not Soft (3)</td>
</tr>
<tr>
<td>Not Tonal / Tonal</td>
<td>Low (252), Low Frequency (12), Medium Frequency (10), High Pitch (54), Hum (43), High Frequency (17), High (17), Heavy (6), Prominent (3)</td>
</tr>
<tr>
<td>Dull / Sharp</td>
<td>Dull (3) / Metallic (21), Scratching (14), Sawing (12), Sharp (11), Squeal (6)</td>
</tr>
<tr>
<td>Smooth / Rough</td>
<td>Smooth (26), Even (5), Not Harsh (2), Whirling (25), Buzz (24), Harsh (23), Rough (15), Grinding (17), Rumble (16)</td>
</tr>
<tr>
<td>Fluctuating</td>
<td>Vibration (67), Pulsating (7), Uneven (6), Shaking (5), Beating (2), Oscillating (2), Constant (7), Even (5)</td>
</tr>
<tr>
<td>Impulsiveness</td>
<td>Drill (42), Choppy (25), Rattle (16), Repetitive (12), Drumming (6), Thudding (6), Thumping (4)</td>
</tr>
<tr>
<td>Pleasant / Annoying</td>
<td>Pleasant (4), Not Irritating (7), Not Annoying (3), Annoying (86), Irritating (26), Noisy (19), Disturbing (18)</td>
</tr>
<tr>
<td>Emotional Response</td>
<td>Calm (16), Relaxing (5), Hurt Ears (12), Scary (6), Headache (5), Painful (4)</td>
</tr>
<tr>
<td>Functionality</td>
<td>Safe (7), Efficient (4), High Performance (3), Properly Working, Old (15), Broken (4), Rusty (4), Ineffective (3), Dangerous (3), Unsafe (2)</td>
</tr>
<tr>
<td>Signal</td>
<td>(+) Soft/Loud (-)</td>
</tr>
<tr>
<td>--------</td>
<td>------------------</td>
</tr>
<tr>
<td>13</td>
<td>++</td>
</tr>
<tr>
<td>11</td>
<td>++</td>
</tr>
<tr>
<td>35</td>
<td>++</td>
</tr>
<tr>
<td>10</td>
<td>++</td>
</tr>
<tr>
<td>31</td>
<td>+</td>
</tr>
<tr>
<td>30</td>
<td>++</td>
</tr>
<tr>
<td>23</td>
<td>+</td>
</tr>
<tr>
<td>26</td>
<td>+</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>32</td>
<td>--</td>
</tr>
<tr>
<td>33</td>
<td>--</td>
</tr>
<tr>
<td>17</td>
<td>--</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>--</td>
</tr>
<tr>
<td>9</td>
<td>--</td>
</tr>
<tr>
<td>28</td>
<td>--</td>
</tr>
<tr>
<td>22</td>
<td>--</td>
</tr>
<tr>
<td>19</td>
<td>--</td>
</tr>
<tr>
<td>25</td>
<td>--</td>
</tr>
</tbody>
</table>
**Metric Analysis and Outliers**

\[ R^2 = 0.93 \]

- **N₅**: A = 38.60, B = 36.90
- **R₅**: A = 3.76, B = 2.72
- **F.S.**: A = 0.008, B = 0.014
- **SᵥBS**: A = 1.48, B = 1.08
- **Tonality**: A = 0.34, B = 0.18
- **Aures Tonality**: A = 0.31, B = 0.23

- **High pitch, loud, annoying, metallic, sharp, penetrate, cutting wood, sharp drill, whiny, painful, pounding**
- **Loud, humming, vibration, white noise, low, low pitch, whirring, buzz, large fan, smooth, irritating**

---

**Graph 1:**
- Average Annoyance vs. Zwicker Loudness [sone]
- \( R^2 = 0.93 \)

**Graph 2:**
- PSD: -dB ref \((20\mu Pa)^2/Hz\)
- Frequency - Hz
- \(20 \text{ dB} \)
Summary and Conclusions

- Descriptors from subjects were categorized into 9 groups
- Word scores were calculated by assigning numbers to descriptors
- Linear models of metrics to predict annoyance examined

- People noticed many different sound characteristics in addition to loudness
- Descriptions were consistent with annoyance ratings
- Zwicker loudness exceeded 5% of the time was the metric most highly correlated with annoyance
- Outliers in Test 1 (17 and 22) were described as: sharp, tonal, high pitched, loud, headache
- Categories were used to define end of scales in Test 2
Future Work

- **Test 2**
  - Semantic differential test was designed by using the descriptors from Test 1

- **More signal modification techniques**
  - Modify sharpness and tonality of the sound without changing loudness

- **Test 3**
  - Three sets of rating tests (organized by range of loudness)
References


References


Thank you!
Test 1 – List of Words

Afar, abrupt
bang, bark, bawl, bay, belling, bellow, blare, blatter, bleat, bong, boom, bowwow, brawl, bray, brushing, burning, buff, buzz, brief, burst, bouncing, beat

cackle, caterwaul, cau, chafing, chatter, cheep, cheer, chirp, chirrup, chuck, chuckle, clack, clang, clank, clap, clash, clatter, click, clink, cluck, clunk, coarse, coo, crack, crackle, creak, croak, crow, crunch, cry, cuckoo, can dropped, complicated, crinkle
drone, drumming, dropping, door opening (closing, shut), dull, distant, deep, dark
echo
fizz, fizzle, flutter, fritiniancy, falling object, flat, flexible, familiar, full
gaggle, giggle, gobble, grate, grating, grinding, groan, growl, gruff, grum, grumble, grunt, gruntle, guffaw, guggle, gurgle, glass, halloa, halloo, harsh, hiss, hoarse, hollow, hoop, hoot, horrysonous, horse, howl, howl, high-pitched, howl, low-pitched, hum, heavy
object, hitting the floor, high frequency, hard, high
insect cry, itch
jangle, jar, jingle
knock
latration, laugh, low, loud, long, light, low pitch, low frequency
meow, mew, mewl, moan, moo, metallic, musical, medium pitched, muffled
neigh, noisy, near
oil canning, ooh-tone
patter, peep, ping, pipe, pop, pounding, pule, purr, plastic container, paper on table, paper in it
quack, quick
rap, ratting, rattle, rebellow, reboation, ring, roar, rough, rumble, rustle, rapid, repetitive, resounding, rigid, rolling off, reverb, resonant
screeak, scream, screech, screech owl, scrub, sepulchral, shout, shriek, shrill, sizzle, slap, snap, snarl, sneeze, snigger, snore, snort, snuffle, squall, squash, squawk, squeak, squeal, stridulous, swish, swoosh, slow, short, slam, smooth, soft, simple, strange, sustained, sharp, stompting, scratched
tapping, thrumming, thud, thump, tick, ting, tinkle, tittler, troat, twang, twirling, twitter, thunder
ululation, unintelligible
vibratory
wheeze, whine, whirl, whirring, whistle, whiz, whoop, woodnote, whip, wiggle
yap, yarr, yaup, yawl, yell, yelp