Modeling the perception of electric vehicle sound

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eVADER Workshop, 21.11.2013
We know:

Sounds of electric vehicles differ from the sounds of conventional vehicles

- Interior car sounds
- Exterior car sounds

Because of the increasing number of electric vehicles => investigations
General question

We know:

Sounds of electric vehicles differ from the sounds of conventional vehicles

- Interior car sounds
- Exterior car sounds

Because of the increasing number of electric vehicles => investigations

Comparison and description of the sound quality of an electric vehicle and a conventional vehicle

Our questions:
- Relevant aspects to characterise the sounds?
- Adjectives most appropriate:
  - to describe these aspects?
  - to distinguish between different cars / driving conditions?
We know:

Sounds of electric vehicles differ from the sounds of conventional vehicles

Because of the increasing number of electric vehicles => investigations

Audibility of exterior sound of cars

Our questions:
- In what driving conditions is there a difference?
- Can the audibility be predicted with a perceptual model?
Overview

Comparison and description of the interior sound quality of an electric vehicle and a conventional vehicle

I. Open questioning after test rides.

II. Compilation and application of an extensive adjective list. Reduction of this list in an assessment task.

III. Assessment task with the reduced adjective list.
Vehicles

Conventional car

- Mitsubishi Colt
- internal combustion engine (ICE)

Electric vehicle (eCar)

- Mitsubishi i-MiEV
- pure electric vehicle (eCar)

Participants

- 24 persons aged 23-40 years
- 8 persons ICE, 23 persons eCar (7 persons both cars)
  - ICE: male 6; female: 2
  - eCar: male 17, female: 6
- no experience with electric vehicles
- test rides as a passenger
## Test ride sections

(30 min. per ride)

<table>
<thead>
<tr>
<th>Section</th>
<th>Type of road*</th>
<th>Mean velocity</th>
<th>Main operational state</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>motorway</td>
<td>100-130 km/h</td>
<td>constant velocity - high</td>
</tr>
<tr>
<td></td>
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<td>cvh</td>
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<tr>
<td>2</td>
<td>country road</td>
<td>70-80 km/h</td>
<td>constant velocity - high</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>cvh</td>
</tr>
<tr>
<td>3</td>
<td>country road</td>
<td>0-50-0 km/h</td>
<td>acceleration / deceleration</td>
</tr>
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<td></td>
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<td>acc/dc</td>
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<tr>
<td>4</td>
<td>country road</td>
<td>0-70-0 km/h</td>
<td>acceleration / deceleration</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>acc/dc</td>
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<tr>
<td>5</td>
<td>city traffic</td>
<td>50 km/h</td>
<td>constant velocity - low</td>
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<td></td>
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<td></td>
<td>cvl</td>
</tr>
<tr>
<td>6</td>
<td>city traffic</td>
<td>30 km/h</td>
<td>constant velocity - low</td>
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<tr>
<td></td>
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<td>cvl</td>
</tr>
</tbody>
</table>

*All trips for the test ride were carried out on public roads.
Results: Some statements translated

- **Increasingly noticeable road noise**
- **High-pitched whine**
- **Different road surfaces audible**
- **Neither good or bad (high pitched whine)**
- **Wind and engine noise of other road users**
- **Hardly noticeable engine vibration**
- **Traffic noise is very noticeable**
- **Rumble**
- **Shaking**
- **Traffic noise is very noticeable**
- **Cars outside clearly audible**
- **Unusually strong awareness of other road users**
- **Strong wind noise**
- **High-frequency cheeping at high speed**
- **Engine does not sound smooth**
- **Cheap**
- **Luxurious soundscape**
- **Roaring**
- **Unusually strong awareness of other road users**

- **Idle sound very pleasantly quiet**
- **Actually quite pleasant**
- **Similar to the start of a jet engine**
- **Noise of the tires**
- **You can hear electric motor**
- **Buzzing is annoying**
- **Low grumbling while driving**
- **Low vibration**
Results: Some statements translated

- high-frequency cheeping at high speed
- low grumbling while driving
- almost noticeable road noise
- similar to the start of a jet engine
- idle sound very pleasantly quiet
- engine does not sound smooth
- different road surfaces audible
- neither good or bad (high pitched whine)
- actually quite pleasant
- hardly noticeable engine vibration
- Traffic noise is very noticeable
- strong wind noise
- high-frequency cheeping at high speed
- cheap
- low vibration
- rumble
- noise of the tires
- shaking
- cars outside clearly audible
- low grumbling while driving
- cars outside clearly audible
- Tram similar sounds
- unusually strong awareness of other road users
- buzzing is annoying

Altogether (for both cars and all test ride sections):

826 statements
Psychoacoustic sound description

- high pitch howling
- similar to the start of a jet engine
- roaring
- ...

Sound evaluation

- buzzing is annoying
- cheap
- actually quite pleasant
- ...

Naming of sound source

- noise of the tyres
- different road surfaces audible
- engine does not sound smooth
- ...

What do I hear?

Surrounding

- strong wind noise
- cars outside clearly audible
- ...

Others

- low vibration
- rumble
- shaking
- ...

Results - sorted by categorisation
Results - sorted by categorisation

Psychoacoustic sound description

Most statements
- buzzing is annoying
- cheap
- actually quite pleasant
- …

Others
- low vibration
- rumble
- shaking
- …

Sound evaluation
- strong wind noise
- cars outside clearly audible
- …

Surrounding
- noise of the tyres
- different road surfaces audible
- engine does not sound smooth
- …

Naming of sound source
Part II

The adjective list

<table>
<thead>
<tr>
<th>aufmunternd</th>
<th>ermüdend</th>
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<tbody>
<tr>
<td>schnell</td>
<td>langsam</td>
</tr>
<tr>
<td>trübsinnig</td>
<td>heiter</td>
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<tr>
<td>leise</td>
<td>laut</td>
</tr>
<tr>
<td>offensiv</td>
<td>defensiv</td>
</tr>
<tr>
<td>schlecht</td>
<td>gut</td>
</tr>
<tr>
<td>unregelmäßig</td>
<td>kontinuierlich</td>
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<tr>
<td>sportlich</td>
<td>unsportlich</td>
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<tr>
<td>unangenehm</td>
<td>angenehm</td>
</tr>
<tr>
<td>abstoßend</td>
<td>anziehend</td>
</tr>
<tr>
<td>aufgemotzt</td>
<td>dezent</td>
</tr>
</tbody>
</table>
Method

Sound assessment task in the lab:
- 5 sounds (3 x eCar, 2x ICE-car), artificial head recording of part I
- 76 pairs of adjectives (taken from the literature and part I)
- 7 step scale
- 12 participants (7 male, 5 female; 26 to 31 years; 8 experienced)
- sound presentation via open headphones and an additional subwoofer in a sound proofed booth

Data analysis:
- factor analysis of the adjectives used
- additional t-tests identifying efficiently distinguishing adjectives
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<thead>
<tr>
<th>No.</th>
<th>Reduced list of adjectives</th>
<th>Dimensions</th>
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<td></td>
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<td>Movement</td>
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<td>Comfort</td>
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<td>Annoyance</td>
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<td>1</td>
<td>aufmunternd (encouraging)</td>
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<tr>
<td></td>
<td>- ermüdend (fatiguing)</td>
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<td>2</td>
<td>schnell (fast)</td>
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<tr>
<td></td>
<td>- langsam (slow)</td>
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<tr>
<td>3</td>
<td>sportlich (sporting)</td>
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</tr>
<tr>
<td></td>
<td>- unsportlich (unsporting)</td>
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<tr>
<td>4</td>
<td>offensiv (offensive)</td>
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<tr>
<td></td>
<td>- defensiv (defensive)</td>
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<tr>
<td>5</td>
<td>heiter (cheerful)</td>
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</tr>
<tr>
<td></td>
<td>- trübsinnig (sad)</td>
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<tr>
<td>6</td>
<td>leise (soft)</td>
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<tr>
<td></td>
<td>- laut (loud)</td>
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<td>7</td>
<td>röhrend (belling)</td>
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<tr>
<td></td>
<td>- nicht röhrend (not belling)</td>
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<td>- aufdringlich (obtrusive)</td>
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<td>dezent (discreet)</td>
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<td>- aufgemotzt (exaggerated)</td>
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<td>angenehm (pleasent)</td>
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<tr>
<td></td>
<td>- unangenehm (unpleasent)</td>
<td></td>
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<tr>
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<td>gut (good)</td>
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<tr>
<td></td>
<td>- schlecht (bad)</td>
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<td>15</td>
<td>anziehend (attractive)</td>
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<td>- abstoßend (repulsive)</td>
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<td></td>
<td>- unsympathisch (not sympathetic)</td>
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<td></td>
<td>- hässlich (ugly)</td>
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<td>- unsicher (unsafe)</td>
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<td>26</td>
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<td>- dunkel (dark)</td>
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<td></td>
<td>- dumpf (hollow)</td>
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<td>28</td>
<td>tieffrequent (low frequency)</td>
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<td></td>
<td>- hochfrequent (high frequency)</td>
<td></td>
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<td>29</td>
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<td>- nicht brummend (not humming)</td>
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<td>30</td>
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</tr>
<tr>
<td></td>
<td>- nicht grummelnd (not grumbling)</td>
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</tr>
</tbody>
</table>
Final test with 30 adjectives

Participants
• 27 persons (18 male, 9 female; 22 to 41 years)
• part of them participated also in the studies in part I and / or II

Adjective list
• reduced adjective list (30 adjectives, seven-step scale)
• computer based procedure

Sounds and sound presentation
• in total: 14 different interior car sounds
• here: - results for eight sounds at constant velocity
  (4 of each car, velocity 30, 50, 100 and 130 km/h)
  - one repeated measurement
• presentation like in part II (headphones, subwoofer, sound proof booth)
• all participants assessed all sounds (sequence was randomised)
Adjectives with real antonyms

- cv 30 km/h
- cv 50 km/h
- cv 100 km/h
- cv 130 km/h

- fatiguing
- slow
- unsporting
- defensive
- sad
- loud
- obtrusive
- exaggerated
- unsteady
- irregular
- not cosy
- unpleasant
- bad
- repulsive
- uncomfortable
- not sympathetic
- ugly
- unsafe
- dark
- hollow
- high frequency

- encouraging
- fast
- sporting
- offensive
- cheerful
- soft
- unobtrusive
- discreet
- steady
- continuous
- cosy
- pleasant
- good
- attractive
- comfortable
- sympathetic
- nice
- safe
- bright
- clear
- low frequency
Activity, Dynamics, ...

- CV 30 km/h
- CV 50 km/h
- CV 100 km/h
- CV 130 km/h

Graphs showing the perception of different acoustic characteristics at various speeds.
Activity, Dynamics, ...

cv 30 km/h

cv 50 km/h

cv 100 km/h

cv 130 km/h

Evaluation, Comfort, ...

unpleasant

pleasant

fatiguing
slow
unsporting
defensive
sad
loud
obtrusive
exaggerated
unsteady
irregular

encouraging
fast
sporting
offensive
cheerful
soft
unobtrusive
discreet
steady
continuous

good
attractive
comfortable
sympathetic
nice
safe
bright
clear
low frequency
Summary

Part I  
- Sound character descriptions varied depending on
  - type of the car (for example: tonal components)
  - velocity
  - operational states (most frequent trigger: acceleration)

Part II  
- Development of a list with 30 adjectives:
  - representing six relevant dimensions for sound characterization
  - including efficiently distinguishing adjectives

Part III  
- Assessments changed with increasing velocity in a different way
  - For the sound aspects (adjectives) representing the dimension “evaluation” the assessments in the eCar are more affected by changes of the driving velocity than in the conventional car
Study of exterior sound: 
Motivation

● Introduction of electrical Cars:
  ● Reduced SPL emitted at low speeds
  ● A new acoustical traffic situation
● Auditory detection of an approaching vehicle is reduced
  ● May be dangerous if audibility does not match expectation
Motivation

- In a quiet rural environment
- Even without engine sound, tire noise may be audible
Motivation

- In a more noisy environment
  - Traffic noise can mask a specific approaching car
  - No longer a single source to attend to
  - Detection thresholds can be increased
- Initiatives to equip e-Cars with extra warning sounds (car industry & legislation)
Motivation

- Criteria warning sounds for electrical Cars:
  - Level high enough for audibility
  - Low level for avoiding noise pollution
- Can an auditory model be used to predict the audibility of cars in complex acoustical environments?
Aim

- Can an auditory model be used to predict the detection threshold in a noisy environment?
  - Psycho-acoustical measurements of detection thresholds
  - Model predictions of detection thresholds
Recordings

Binaural recordings of traffic noise (50 m away from street)

Binaural recordings of approaching cars to be detected:

- Mitsubishi Colt (Combustion engine)
- Mitsubishi i-MiEV (Electric engine)
Recordings

Binaural recordings of traffic noise (50 m away from street)

Binaural recordings of approaching cars to be detected:
  - Mitsubishi Colt (Combustion engine)
  - Mitsubishi i-MiEV (Electric engine)
Thresholds measurement - method

- 1-Interval 2-AFC (10 sec. intervals)
- Adaptive staircase method
- Presentation of binaural recordings via open headphones & subwoofer in listening booth
- Maskers:
  - Pink noise & traffic noise
  - L = 67 dB(A)
- 7 participants, = 27.7 years
- Task: Was the approaching car present in the current interval?
Thresholds measurement – results – Colt

Colt (pink noise)

Colt (traffic noise)
Thresholds measurement – results – I-MiEV

I-MiEV (pink noise)

- $L_{\text{masker}}$
- $L_{\text{max}}$

I-MiEV (traffic noise)

- $L_{\text{masker}}$
- $L_{\text{max}}$
Model simulations

- Simulation with an auditory signal processing model
  - Dau et al. 1996
- Adaptive 2-IFC procedure
- Model functions as an artificial observer
Dau et al. (1996) model

Optimal detector:
- Build templates of masker alone and Masker + Signal internal representations
- Correlate templates with internal representation

\[
D = \sum_F \sum_T \left[ IR(X) - IR(N) \right] \cdot \left[ IR(N+C) - IR(N) \right]
\]
Auditory model predictions – results – Colt

Colt (pink noise)

Colt (traffic noise)
Auditory model predictions – results – I-MiEV

I-MiEV (pink noise)

\[ L_{\text{masker}} \]
\[ L_{\text{max}} \]
\[ L_{\text{mod}} \]

I-MiEV (traffic noise)

\[ L_{\text{masker}} \]
\[ L_{\text{max}} \]
\[ L_{\text{mod}} \]
Evaluation of the model predictions:

- Good agreement with the subjective thresholds
- Model tends to be lower
  - Optimal detector
  - Informational masking for eCar?
- Potentially be used to test a warning sound
- Loud vs. Quiet
  - Acceptable/desirable engine sound level
Comparison of the conventional car and electrical car:

- At low velocities the electrical car is less audible
- Presence vs. absence of engine sound
- Reaction times of an approaching car was measured
Thank you for your attention