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Sound Quality Evaluation of Refrigerated Truck Noise

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Outline

- Goal and Motivation
- Research Overview and Findings
- Test 3 Overview
- Test 3 Results and Models
- Preliminary Model Validation
- Conclusions

Goal and Motivation

Goal

To develop models to evaluate sounds from HVAC&R equipment that can be used in product design optimization

Motivation

Current methods of evaluation need improvement

Background Literature
(Metrics for HVAC&R/Engine Noise)

- HVAC&R systems
  - A-weighted SPL is related to an annoyance of the sound (Seybert *et al.,* 1973*;* Bradley, 1993)
  - Loudness of the sound affects the preference/annoyance (Susini *et al.,* 2004; Sato *et al.*, 2006)
  - Glasberg and Moore Loudness model (Glasberg and Moore, 2002)
  - Sound Quality Indicator - tone corrected loudness (ANSI/AHRI 1140, 2014)
- Fans
  - Zwicker Loudness and annoyance highly correlated
  - Tonalness of fan noise (Yamaguchi *et al.,* 2014)
- Compressors
  - Loudness and Sharpness affect annoyance (Wang, 1994; Cho *et al.,* 2000; Park *et al.,* 2012)
  - Time varying sound pressure level affects annoyance (Wang, 1994)
- Diesel Engine
  - Loudness, roughness, and sharpness (Ingham *et al.,* 1999)
  - Narrow band modulation analysis (Bodden and Heinrichs, 2005)
  - Integrated Satisfaction Index (ISI) (Liu *et al.,* 2015)

- Generally, metrics related to the level were found, mostly A- weighted SPL and loudness used, sometimes with tone corrections
- A few impulsiveness related models, adapted to specific applications

Research Overview

1) Discover how people describe HVAC&R sounds

   (Test 1 and 1A) – Ref. W. Sung, P. Davies, J.S. Bolton, Proceedings of Noise-Con 2017

2) How many independent attributes are present and how do they affect annoyance

   (Test 2) – Ref. W. Sung, P. Davies, J.S. Bolton, Proceedings of INTER-NOISE 2017

3) Develop/validate residential unit models to predict annoyance

   (Test 3) – Ref. W. Sung, P. Davies, J.S. Bolton, Proceedings of INTER-NOISE 2018

4) Develop refrigerated truck unit models to predict annoyance

   (Test 3)

5) Validate refrigerated truck unit model performance

Research Overview

- Examined refrigerated truck and residential unit noise

Refrigerated Truck

Compressors, fans, diesel engine, motors,…

‘High Amplitude’ – Level
‘Metallic’ – Spectral balance
‘Drilling’ – Impulsiveness

Residential

Compressors, fans, motors,…

‘Loud’ – Level
‘scratching’ – Spectral balance
‘Hum’ – Tonalness
‘Harsh’ - Roughness

Test 3

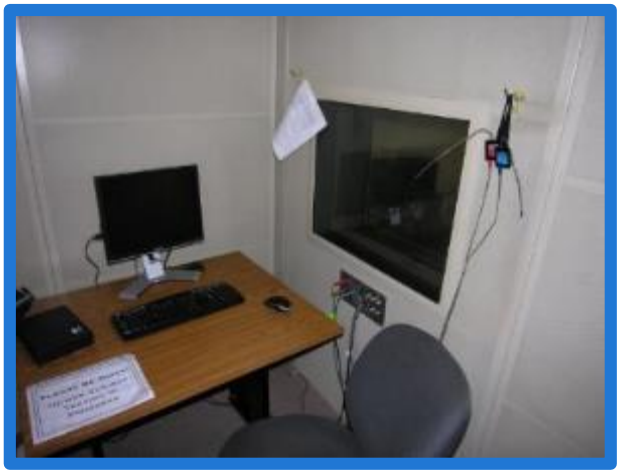
Procedure, Sounds, Subjects

Test 3 Procedure

- Overview of the test
- Consent form (Purdue IRB # 1507016324) & Questionnaire

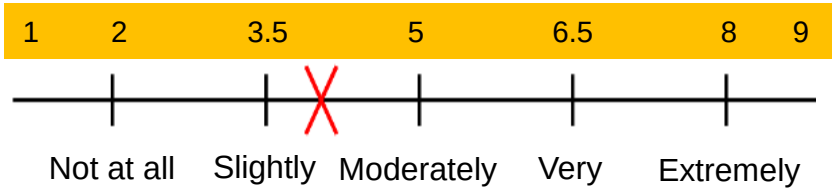
- Hearing Test
- Listen to sounds for familiarization
- Read Test Scenario
- Practice Test
- **MAIN TEST**
- Comments
- Repeat Hearing Test

QUIET ROOM



- Payment

Approx. 1 hour



'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'

Test 3 Sounds

Part A (Quieter Test, 50 sounds)

- Mostly residential + quieter refrigerated truck, recordings + modified sounds
- Familiarization (10 sounds) and Practice (2 sounds)

Part B (Louder Test, 50 sounds)

- Mostly refrigerated truck + louder residential, recordings + modified sounds
- Familiarization (10 sounds) and Practice (2 sounds)

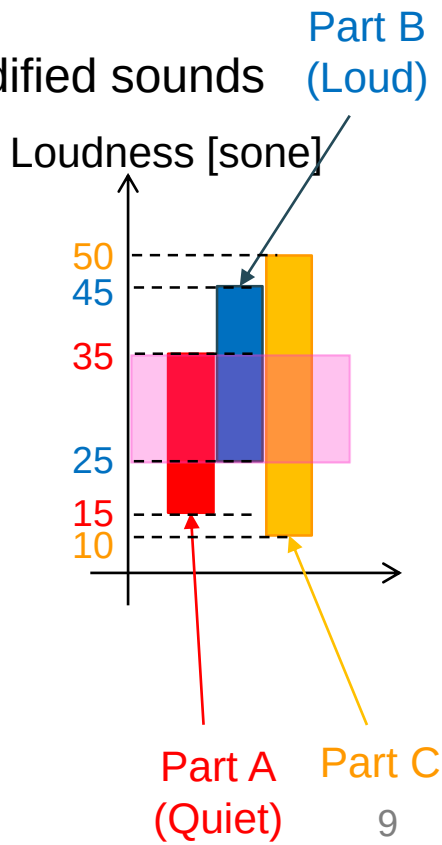
Part C (Wider Loudness Range Test, 50 sounds)

- Refrigerated truck + residential, recordings + modified sounds
- Familiarization (10 sounds) and Practice (2 sounds)

½ of subjects take Part A first and ½ of subjects take Part B first

Group of 15 signals common to Part A, B, and C

Total 120 sounds



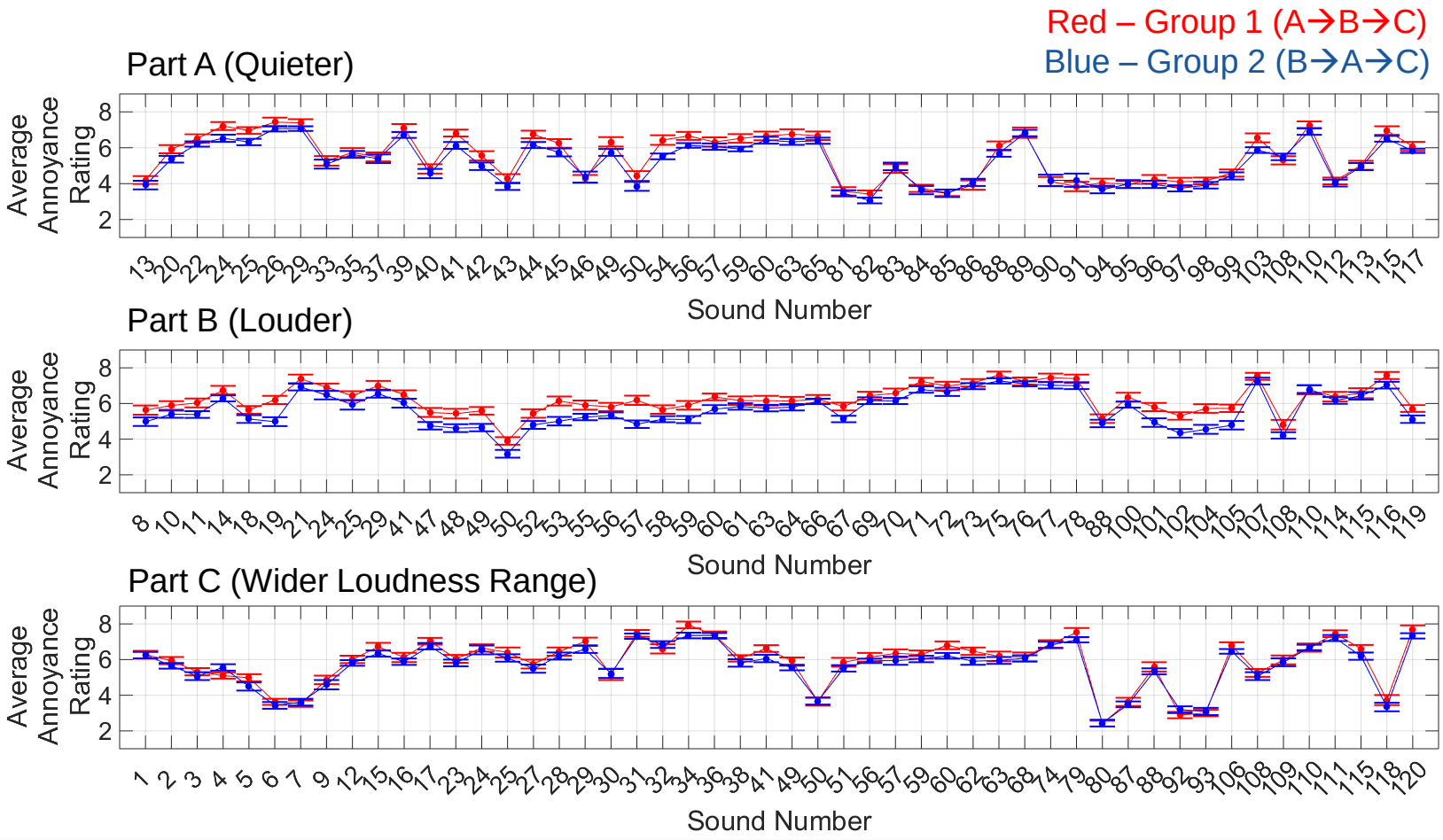
Test 3 Sounds and Subjects

Test	Part	Sounds	Subjects
Test 3	Part A (Quieter)	50 Sounds - 28 original, 22 modified - 36 residential, 14 refrigerated truck	60 Subjects (18 – 62) - Ave. age: 28.4 - Median age: 26.1 - 30 males, 30 females - 32 U.S., 25 Asia, 1 South America, 2 Africa
	Part B (Louder)	50 Sounds - 30 original, 20 modified - 11 residential, 39 refrigerated truck	
	Part C (Wider Range)	50 Sounds - 19 original, 31 modified - 24 residential, 26 refrigerated truck	
120 unique sounds, 15 sounds common to 3 parts			

Group 1: A(Quieter) → B(Louder) → C(Wider Range)
Group 2: B(Louder) → A(Quieter) → C(Wider Range)

Test 3 Results and Models

Test 3 Results : Average Annoyance Ratings



- Responses were affected by the order of the parts in the experiment
- Group 1 subjects tended to rate the louder sounds (Part B) slightly higher
- Group 2 subjects tended to rate the quieter sounds (Part A) slightly lower
- Both groups rated sounds in Part C similarly

Test 3 : Modeling the Average Annoyance Response

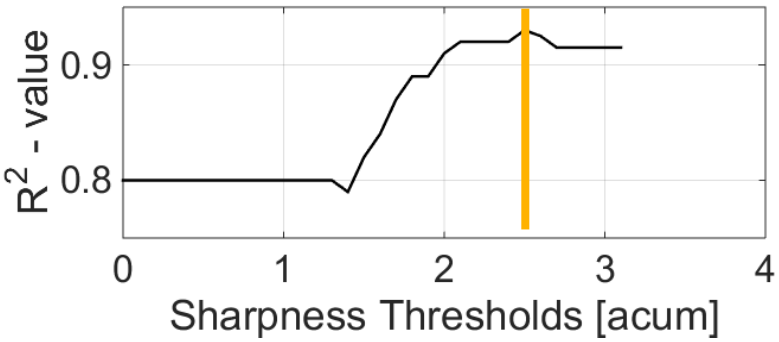
- Linear regression models
  → Examined 1, 2, and 3 metric models

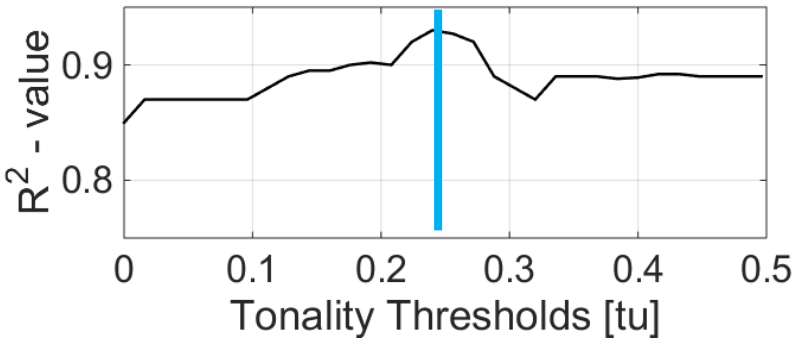
- In Test 1, subject described sounds using words like ‘hum’, ‘high frequency’ and ‘heavy tone’, but sharpness and tonality metric models did not perform well
  → looked at thresholding metrics

- Test 3 models estimated using 79 refrigerated truck sounds from Parts A, B and C of test

Test 3 : Metric Modification / Thresholding

- Assume that sound quality metric value above certain level is significant in annoyance prediction





→ Sharpness Threshold = 2.5 acum, Tonality Threshold = 0.25 tu

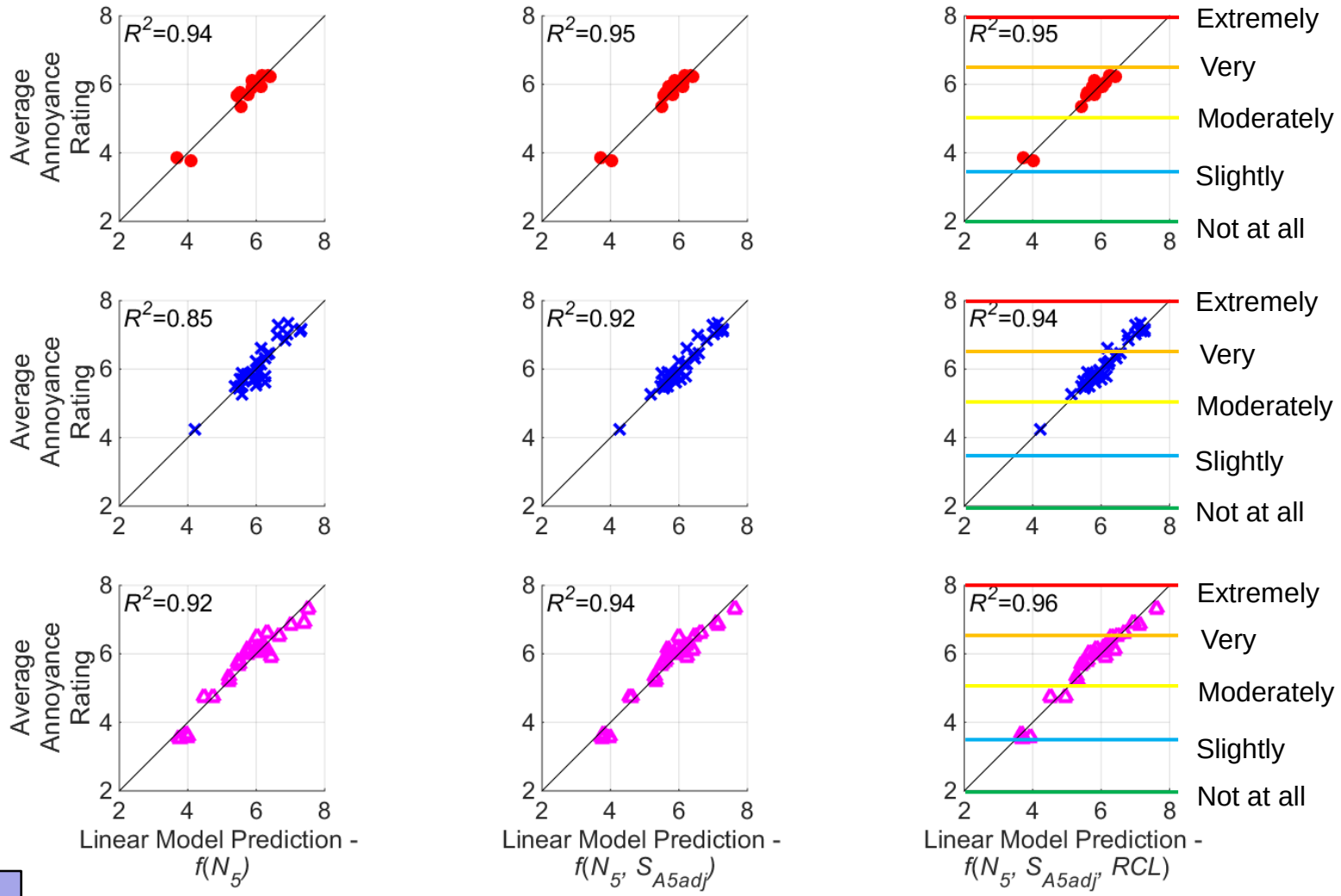
Example Metric Adjustment

S_{A5}	$S_{A5} - 2.5$	S_{A5adj}
3.20	0.70	0.70
2.20	-0.30	0.00

Examined Metrics

Metric	Abbrevia-tion	Sound Characteristics
Zwicker Loudness exceeded 5% of the time	N_5	Level
A/C weighted Sound Pressure Level	dBA, dBC	
Sound Quality Indicator	SQI*	Level, Tonalness
DIN Tonality exceeded 5% of the time	T_5, T_{5adj}	Tonalness
Tone-to-Noise Ratio	TNR	
Prominence Ratio	PR	
Aures' Tonality	AT	
von Bismark Sharpness exceeded 5% of the time	S_{VB5}	Spectral Balance
Aures' Sharpness exceeded 5% of the time	S_{A5}, S_{A5adj}	
Heaviness (dBC – dBA)	H	
Fluctuation Strength exceeded 5% of the time	FS_5	Fluctuations
Roughness exceeded 5% of the time	R_5	
Kurtosis	K	Sharpness of the Peak
Rate of change of the Loudness exceeded 2% of the time	RCL	Impulsiveness

Test 3 : Annoyance Models' Predictions (Refrigerated Truck)

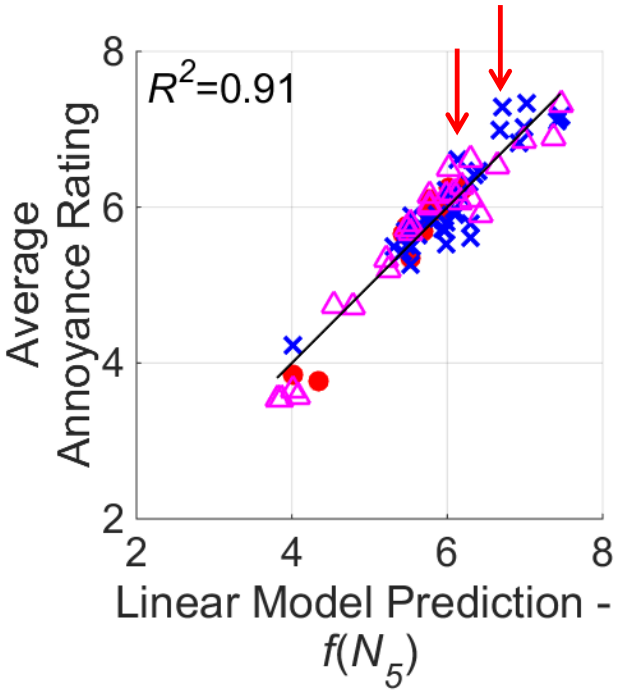


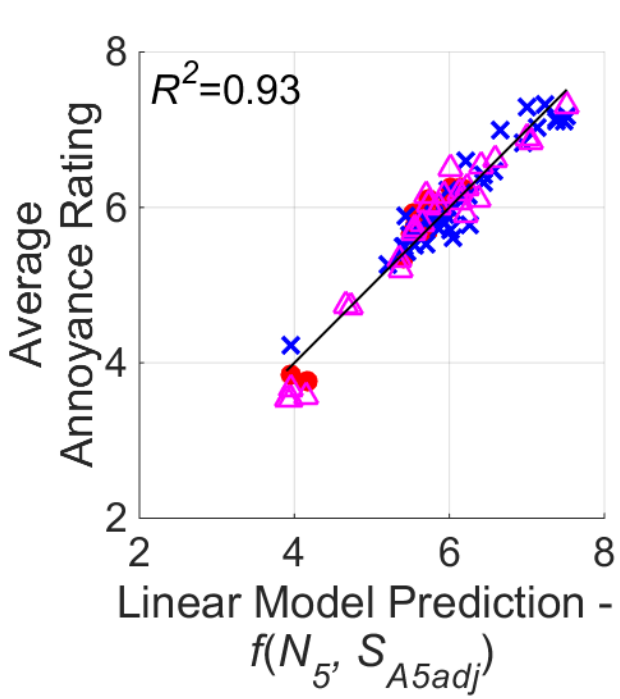
Predictions for:
- ● Part A
- x Part B
- △ Part C

- Most significant metric was N_5
  → R^2-value of Part B (Louder sounds) is lower
- *RCL* added → Part B,C effective, Part A not effective

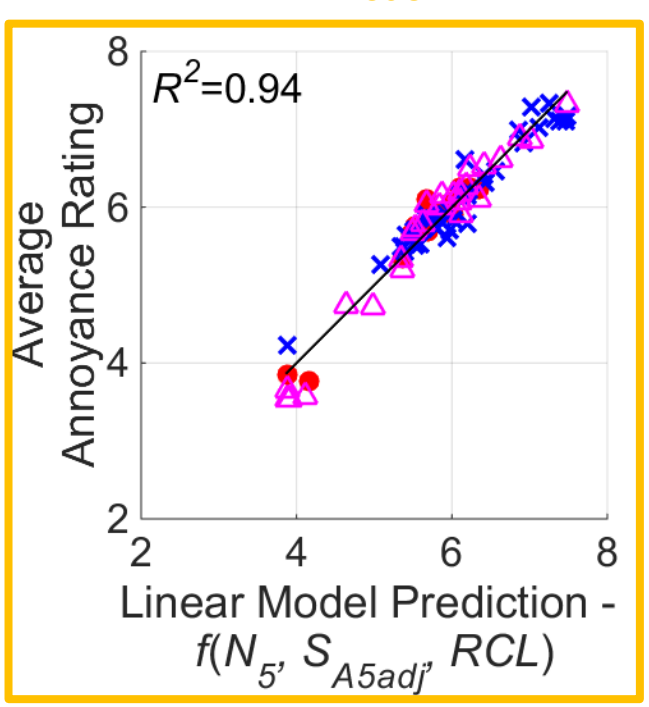
Test 3 : Annoyance Models' Predictions (Refrigerated Truck)

Models generated using responses in Parts A,B and C





Best Model

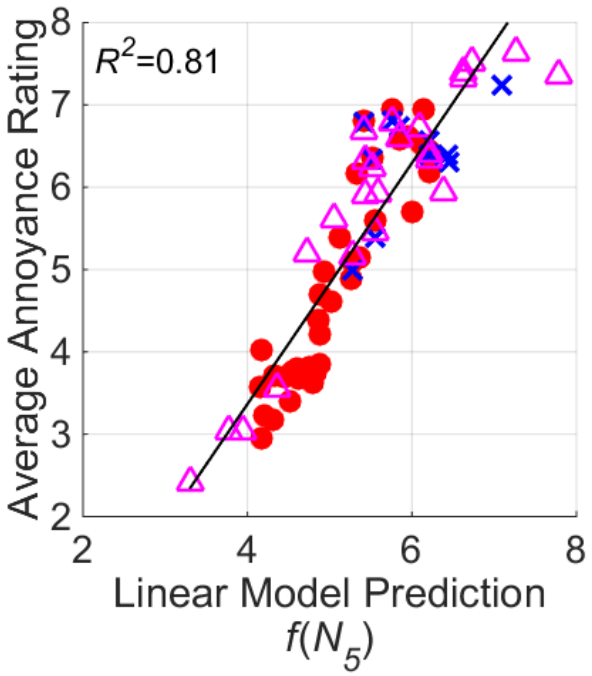


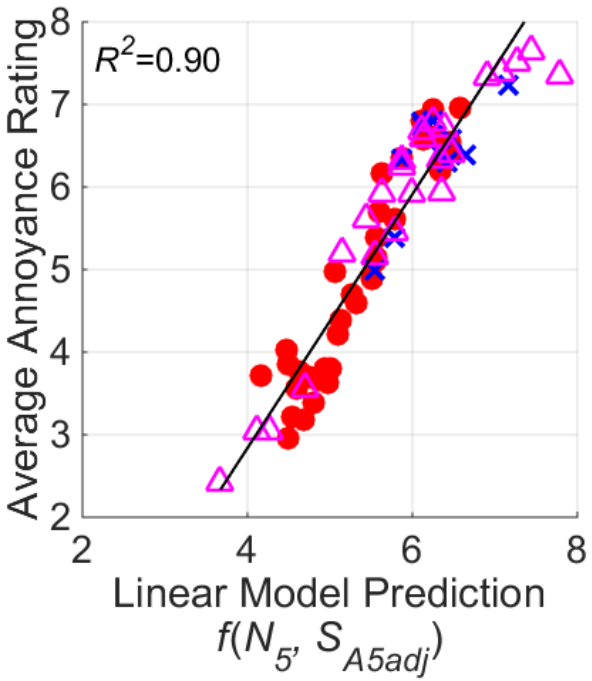
Predictions for:
- ● Part A
- x Part B
- △ Part C

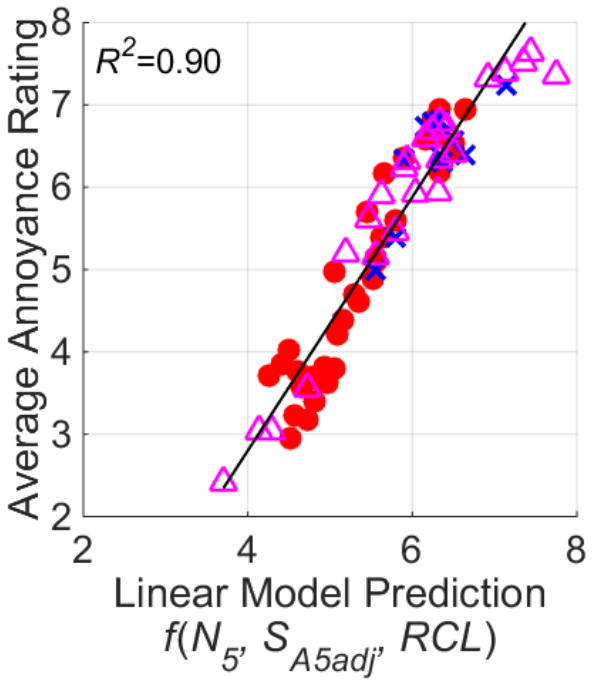
- Adjusted sharpness increased the prediction
- Including *RCL* metric was also helpful

Preliminary Validation of Model

Validation : Test 3 Refrigerated Truck Models Predicting Average Ratings of Residential Unit Sounds





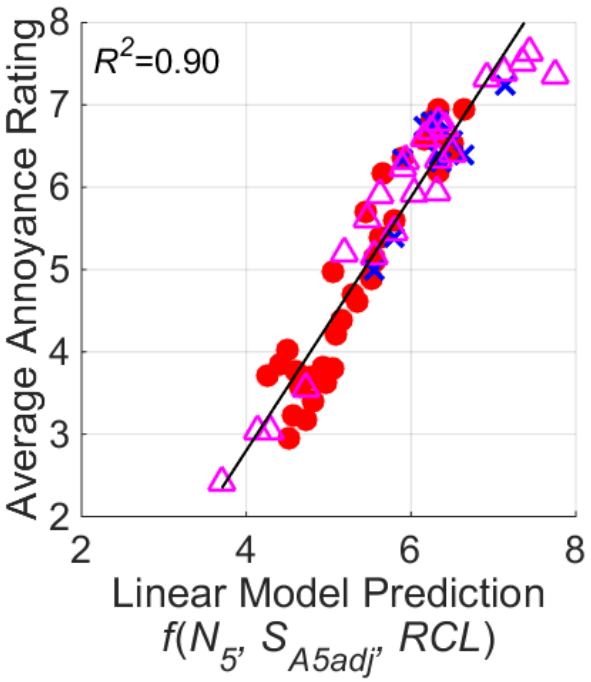


Predictions for:
- ● Part A
- x Part B
- △ Part C

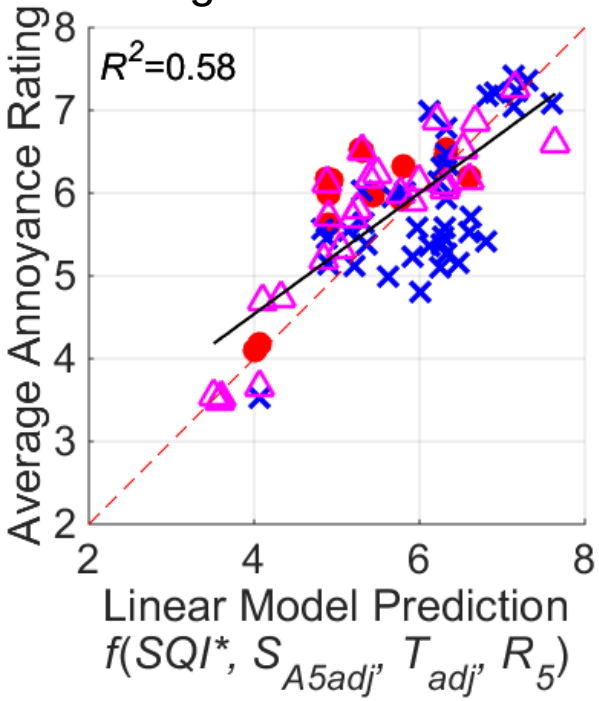
- *RCL (rate of change of the loudness)* is not significant in residential unit sound prediction

Validation : Test 3 Refrigerated Truck/Residential Models Predicting Average Ratings of Residential/Refrigerated Truck Sounds

Refrigerated Truck Model Predicting RES. Unit



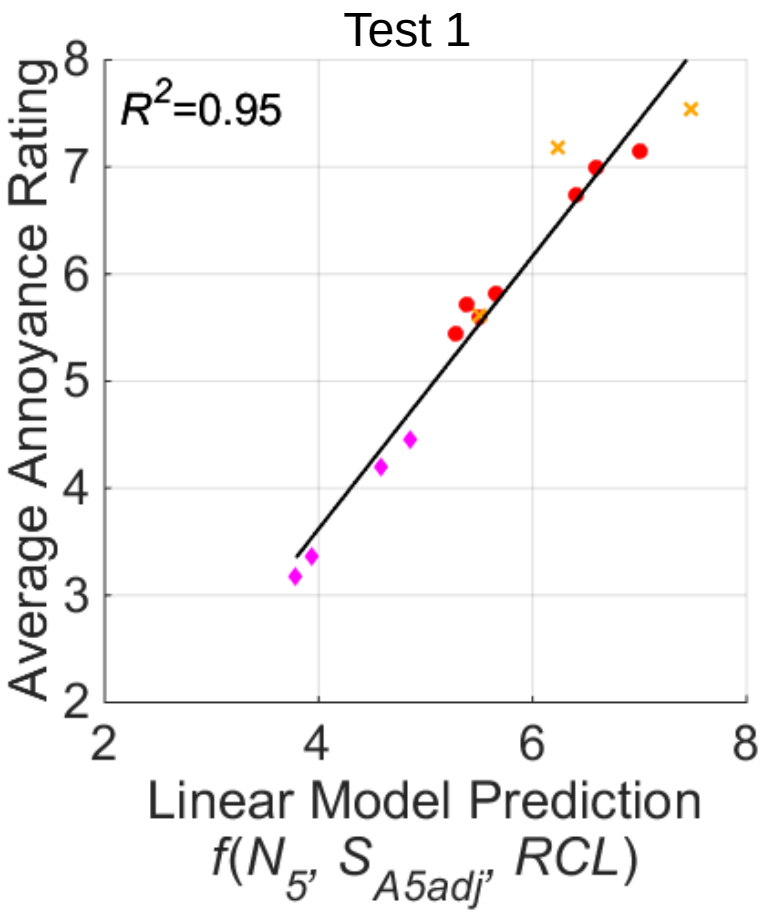
RES. Model Predicting Refrigerated Truck Unit

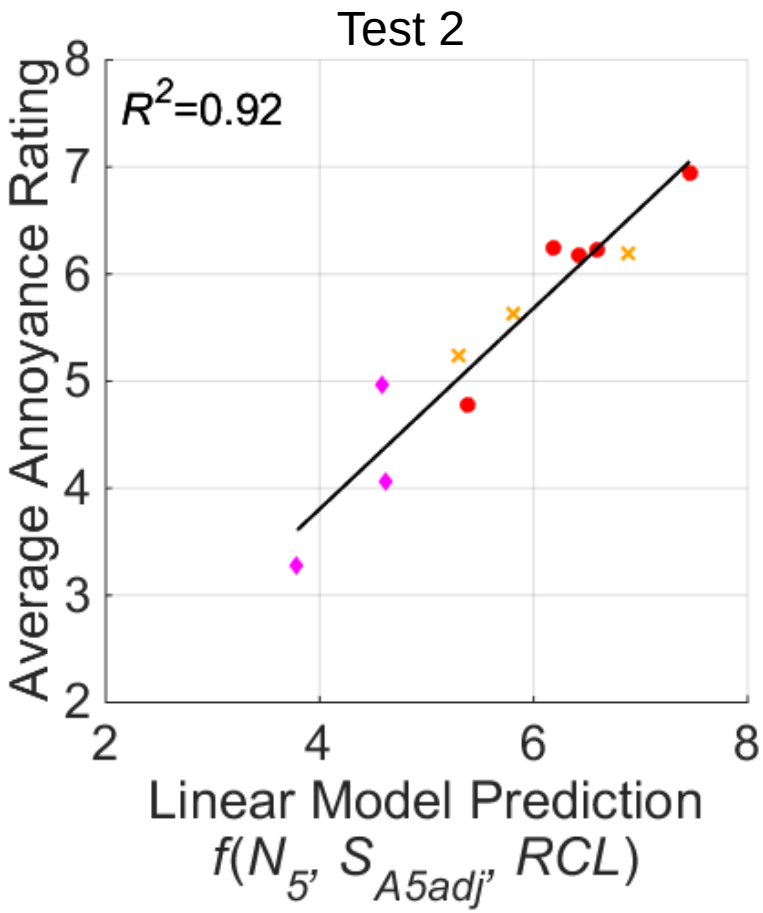


Predictions for:
- Part A
- Part B
- Part C

- Need separate models for refrigerated truck and residential units

Validation : Test 3 Refrigerated Truck Best Model Predicting Average Ratings of Test 1 and Test 2 Refrigerated Truck Sounds





- Annoyance ratings from Test 1 and Test 2 were predicted quite well

Conclusions

- Zwicker Loudness exceeded 5% of the time (N_5) performs very well in the models
- Adding a Sharpness metric with a threshold (S_{A5adj}) improved the accuracy
- Small but significant improvements were made by including a rate change of the loudness (*RCL*) metric
- Analysis shows that there is a need for separate models for residential and refrigerated truck units
  - RES. Model: loudness, sharpness, tonality, and roughness
  - REF. Model: loudness, sharpness, rate of change of the loudness
- Thresholding of sharpness and tonality metrics led to significant improvements
- Annoyance predictions of two previous tests' sounds using the three-metrics refrigerated truck model were reasonably accurate

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Thank you!!