6-2015

Perception of Diesel Engine Gear Rattle Noise

Brandon Sobecki
Purdue University

Patricia Davies
Purdue University

J Stuart Bolton
Purdue University, bolton@purdue.edu

Frank Eberhardt
Cummins Inc.

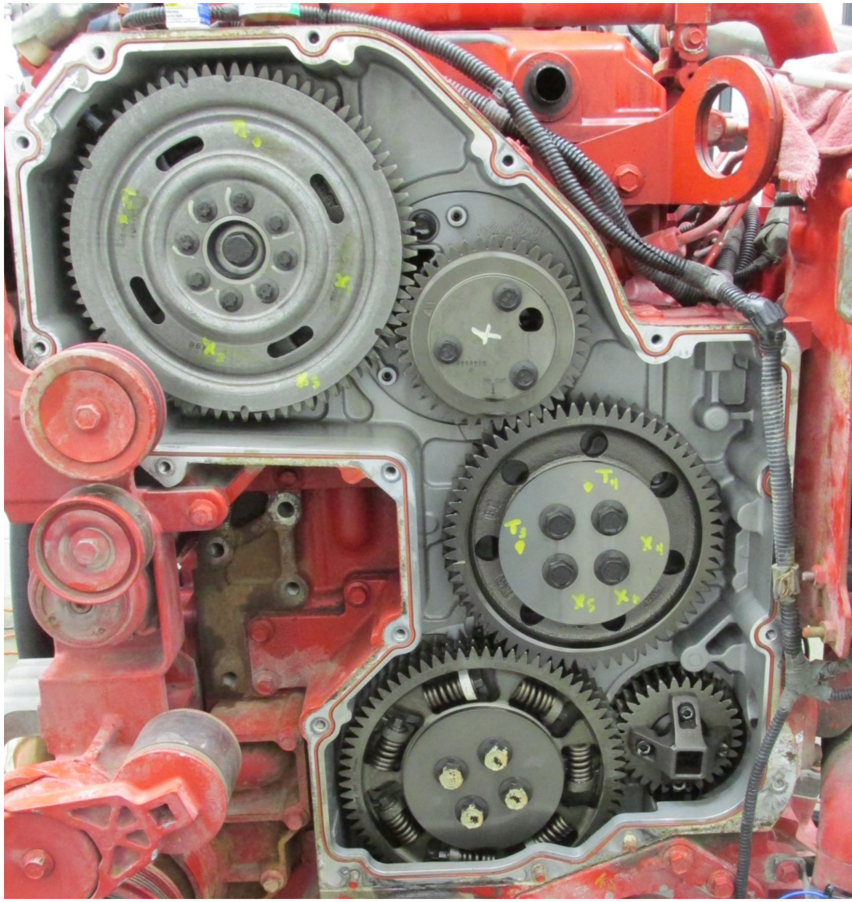
PERCEPTION OF DIESEL ENGINE GEAR RATTLE NOISE

Brandon Sobecki, Dr. Patricia Davies, Dr. J. Stuart Bolton,
Ray W. Herrick Laboratories, Purdue University,

Frank Eberhardt, *Cummins, Inc.*

Research Motivation

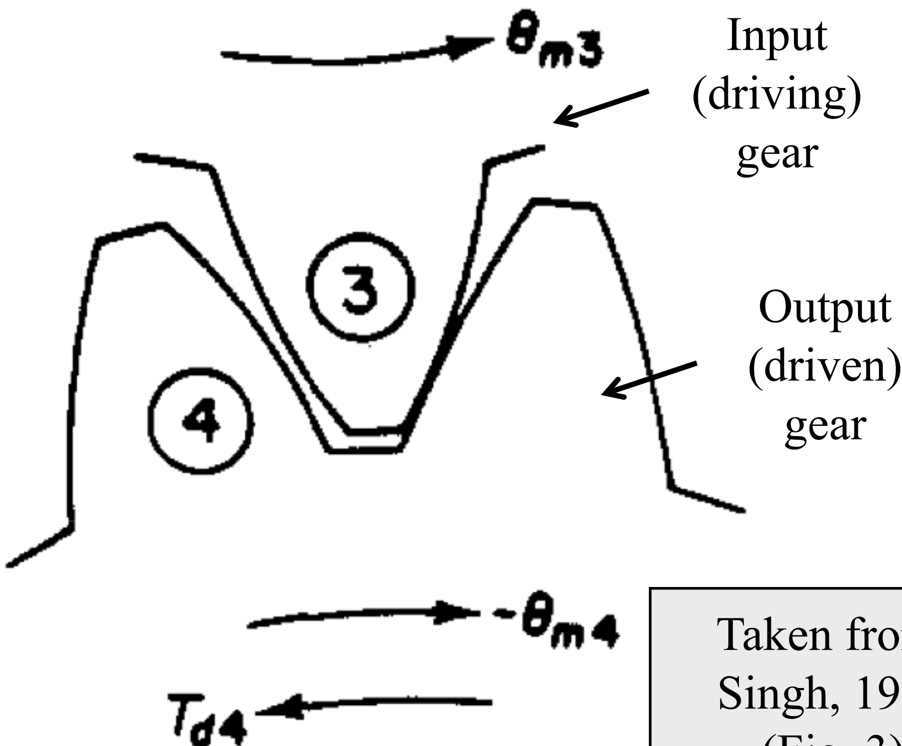
- Sound quality is an important factor in the design of competitive engines
- Gear rattle is a phenomenon that can greatly affect the quality of the overall diesel engine sound
- Currently used metrics (such as A-weighed Sound Pressure Level) might not adequately address the role of gear rattle noise on the overall sound quality of the engine
- An understanding of human's response to the gear rattle noise is needed



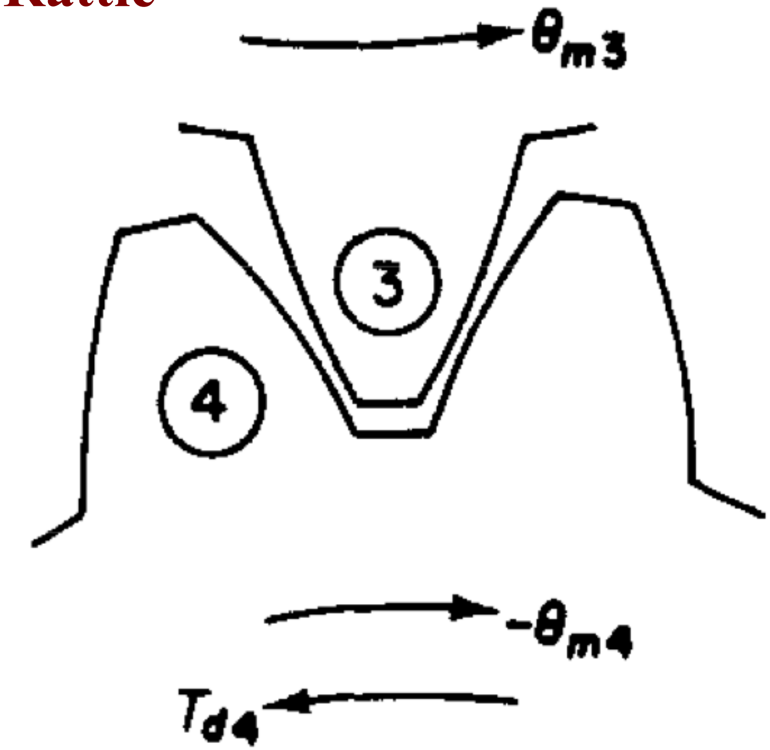
- With this understanding, metrics may be developed to quantify the influence of gear rattle on overall sound

Gear Rattle Mechanism Background

(a) No Rattle



(b) Rattle



Taken from Singh, 1989 (Fig. 3)

Stable (No Rattle) if:

$$T_{d4} > I_4 \ddot{\theta}_4(t)$$

Drag torque on output gear

Inertial torque on input gear

Unstable (Rattle) if:

$$T_{d4} \leq I_4 \ddot{\theta}_4(t)$$

* Cylinder firing events cause the inertial torque to exceed the drag torque (causing an impact)

Outline

Introduction
Motivations and objectives

Subjective Test Background

Detectability Test

Annoyance Test

Conclusions

Subjective Test

- A subjective test was designed to
  - determine detectable levels of gear rattle
  - investigate the perception of growth and attenuation of gear rattle
  - determine the increase of annoyance ratings for sounds with increasing levels of gear rattle
- Subjective Test Setup
  - Test was conducted in a double walled sound booth at Herrick Labs
  - Signals were presented to subjects using Etymotic Research ER-2 earphones
- Subject Population
  - 40 Subjects tested in total (20 women and 19 men; 1 did not answer)
  - Median age: 24 (Ranged from 19-36)
  - 13 Subjects identified as having experience with diesel engines

Test Procedure (IRB 1404014724)

- Signals were calibrated for consistent (and safe) playback
- Subjects were greeted, given a brief overview of the test, and signed inform consent document
- Subject's hearing was screened
- Part 1: Detectability
- Part 2: Annoyance
- Post-test comments were collected
- Subject's hearing was checked
- Subjects were compensated $10 for their participation

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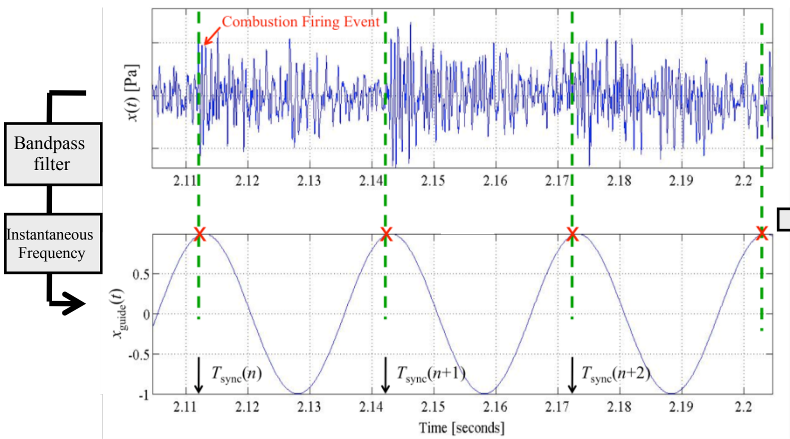
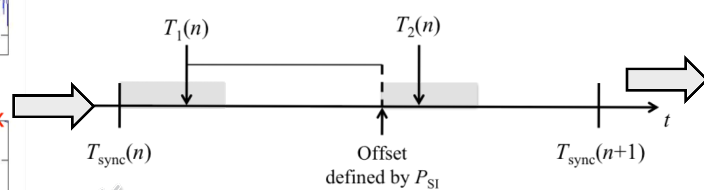
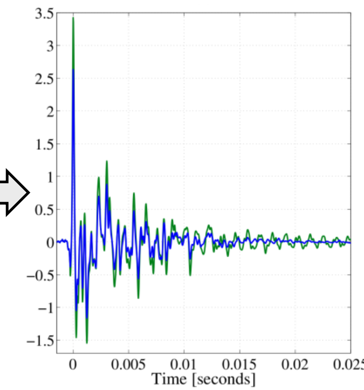
Detectability Test Background

- An experiment was designed to investigate detectable levels of gear rattle in diesel engines
- A simulation method was developed to generate realistic gear rattle noise (Sobecki, Davies, Bolton, 2014)







Baseline

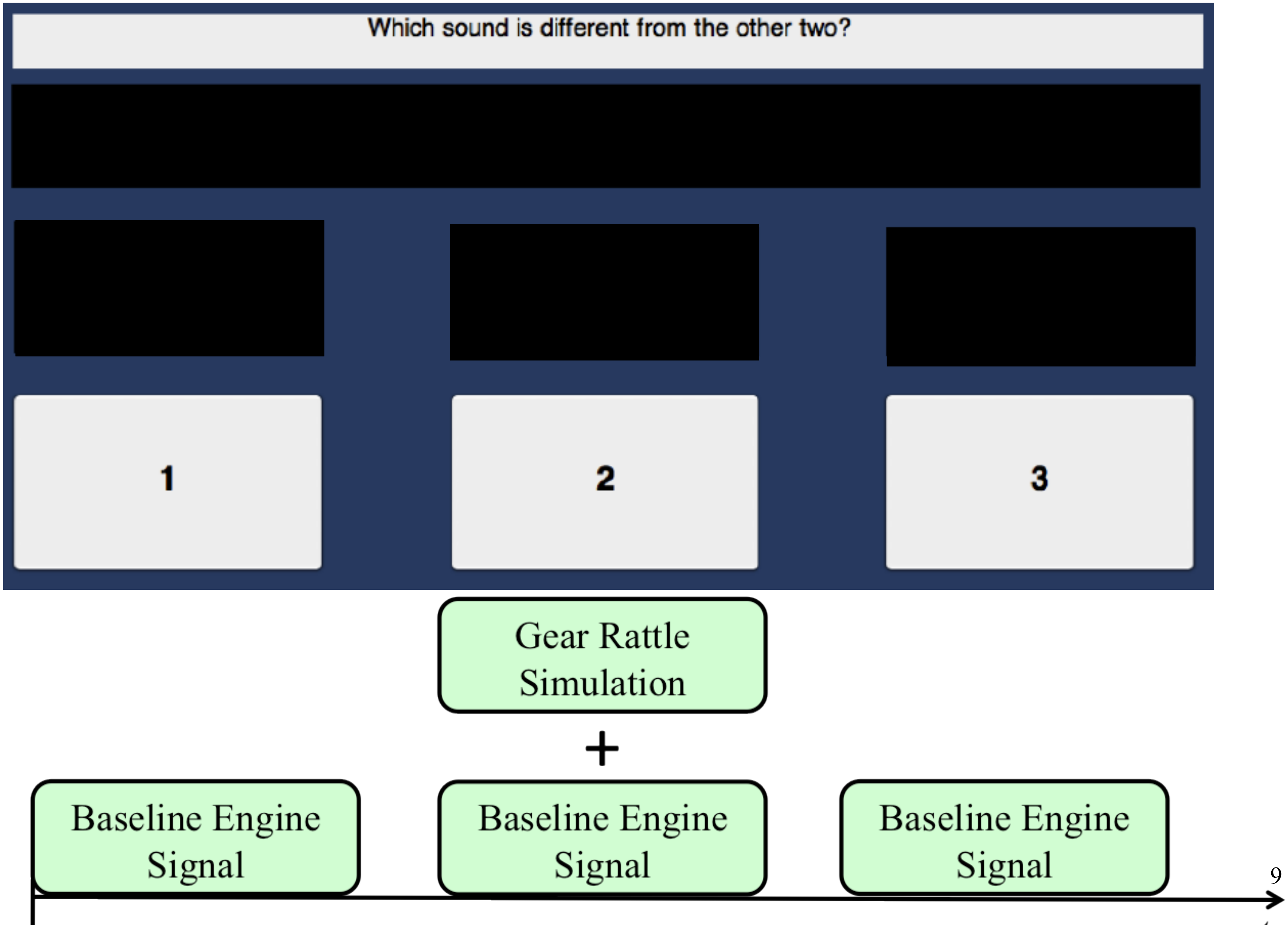
Gear Rattle Measurement

Gear Rattle Simulation ← **Allows for independent control of gear rattle noise level**

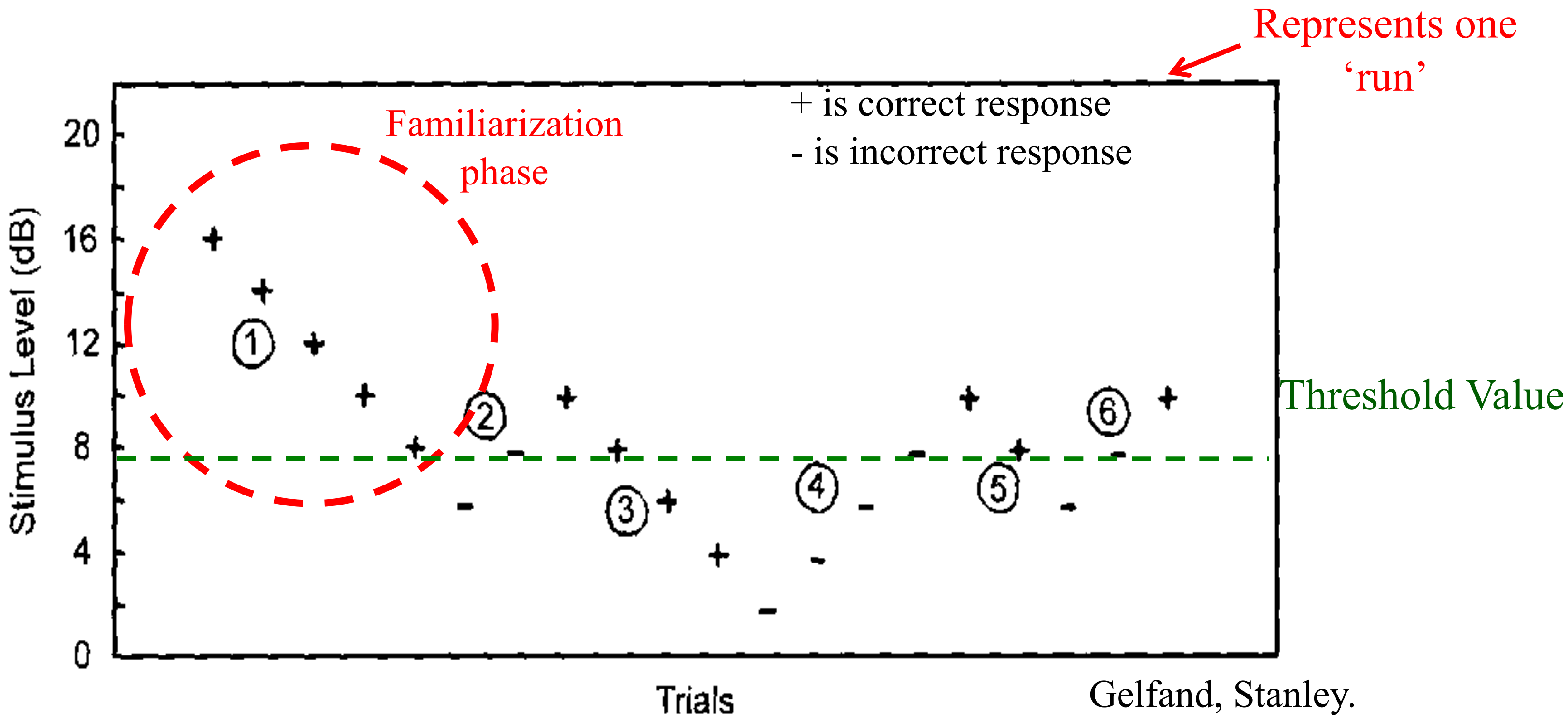
- 3-Alternative Forced Choice (3AFC) test was used to investigate:
  - Detectable levels of gear rattle
  - Noticeable differences in gear rattle levels

Introduction/ Motivation	Subjective Test Background	Detectability	Annoyance	Conclusions

Detectability Test – Trial Example



Signal Detection Theory

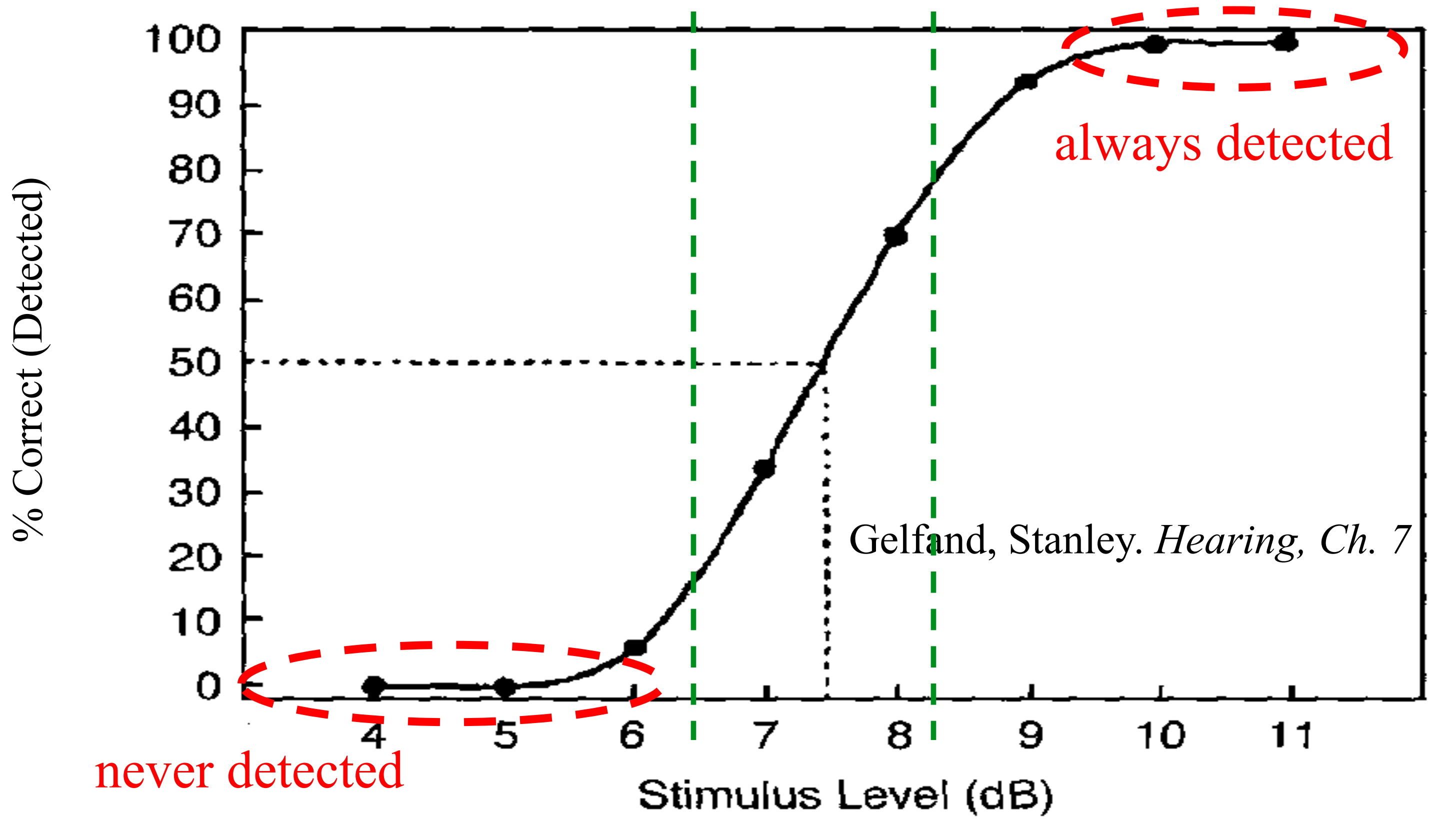


Gelfand, Stanley.
Hearing, Ch. 7

Introduction/ Motivation	Subjective Test Background	Detectability	Annoyance	Conclusions

Signal Detection Theory

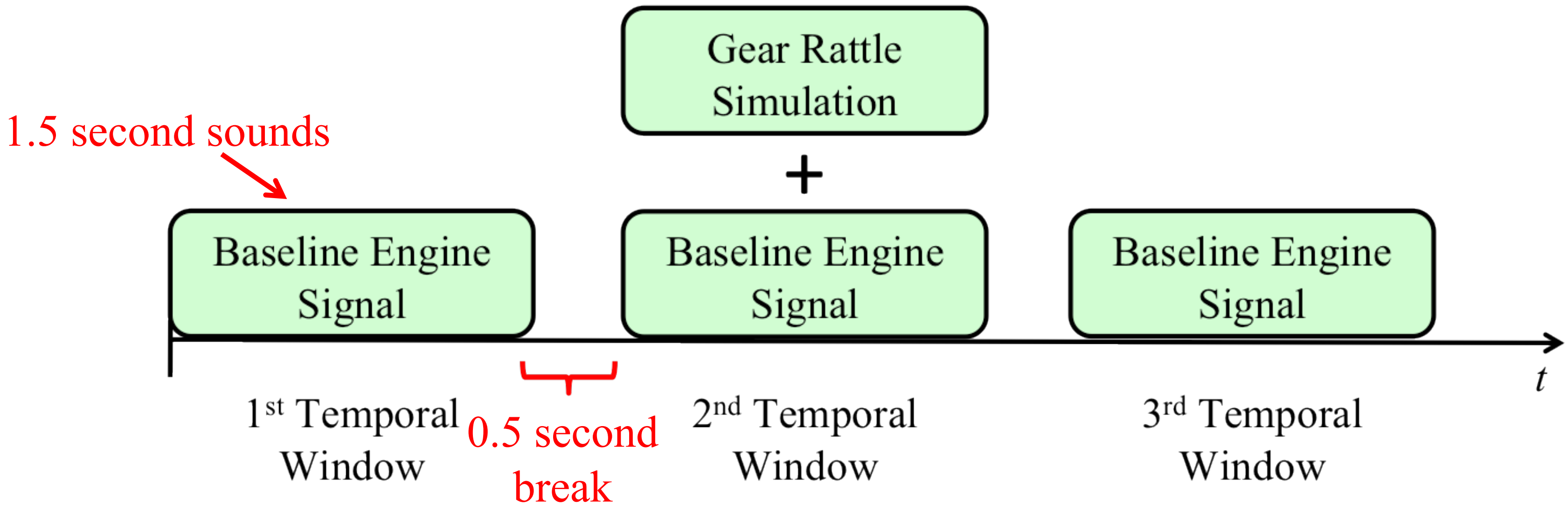
Underlying Psychometric Function



Can track various percent correct values on underlying psychometric function

Introduction/ Motivation	Subjective Test Background	Detectability	Annoyance	Conclusions

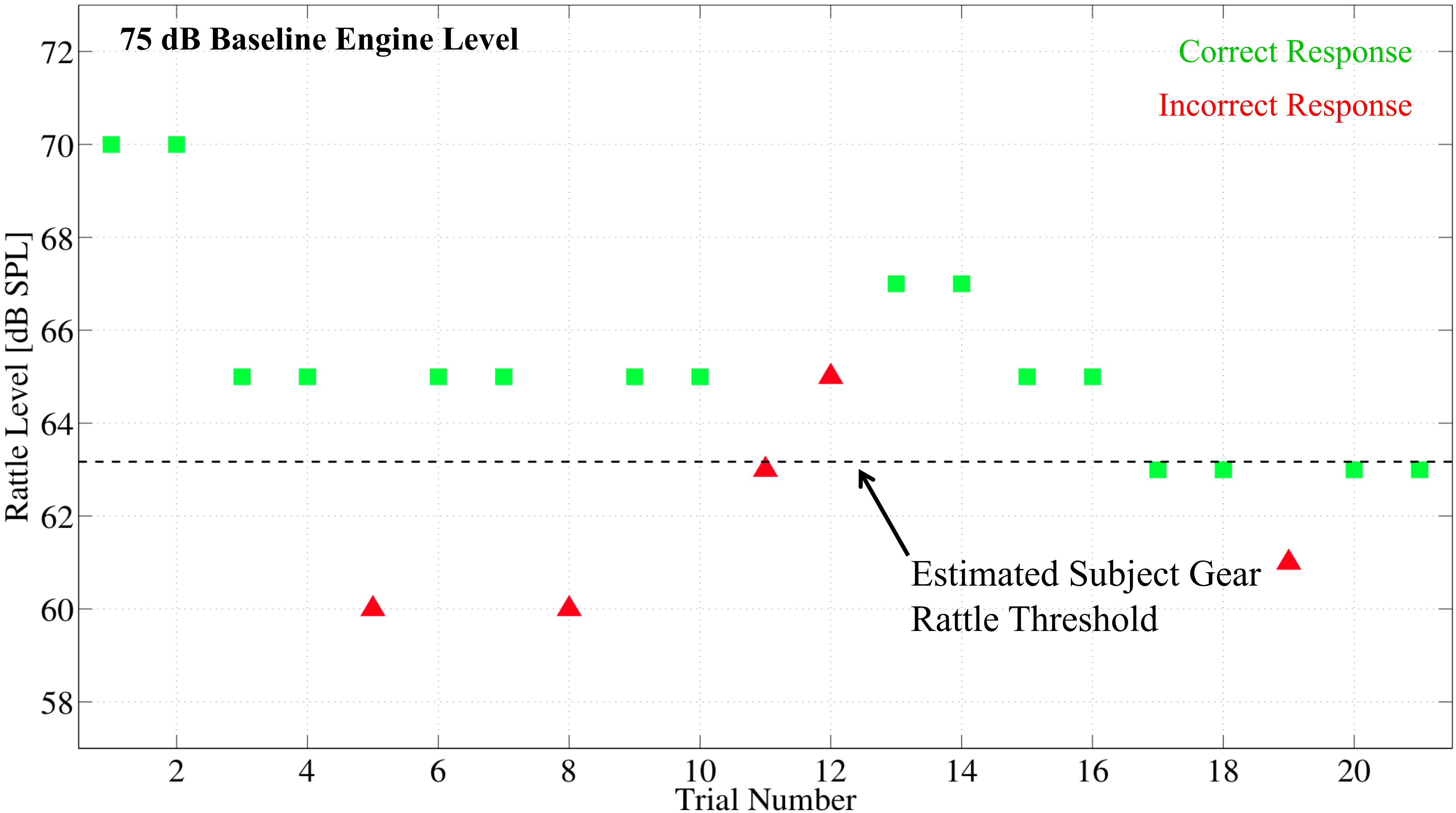
Detectability Test



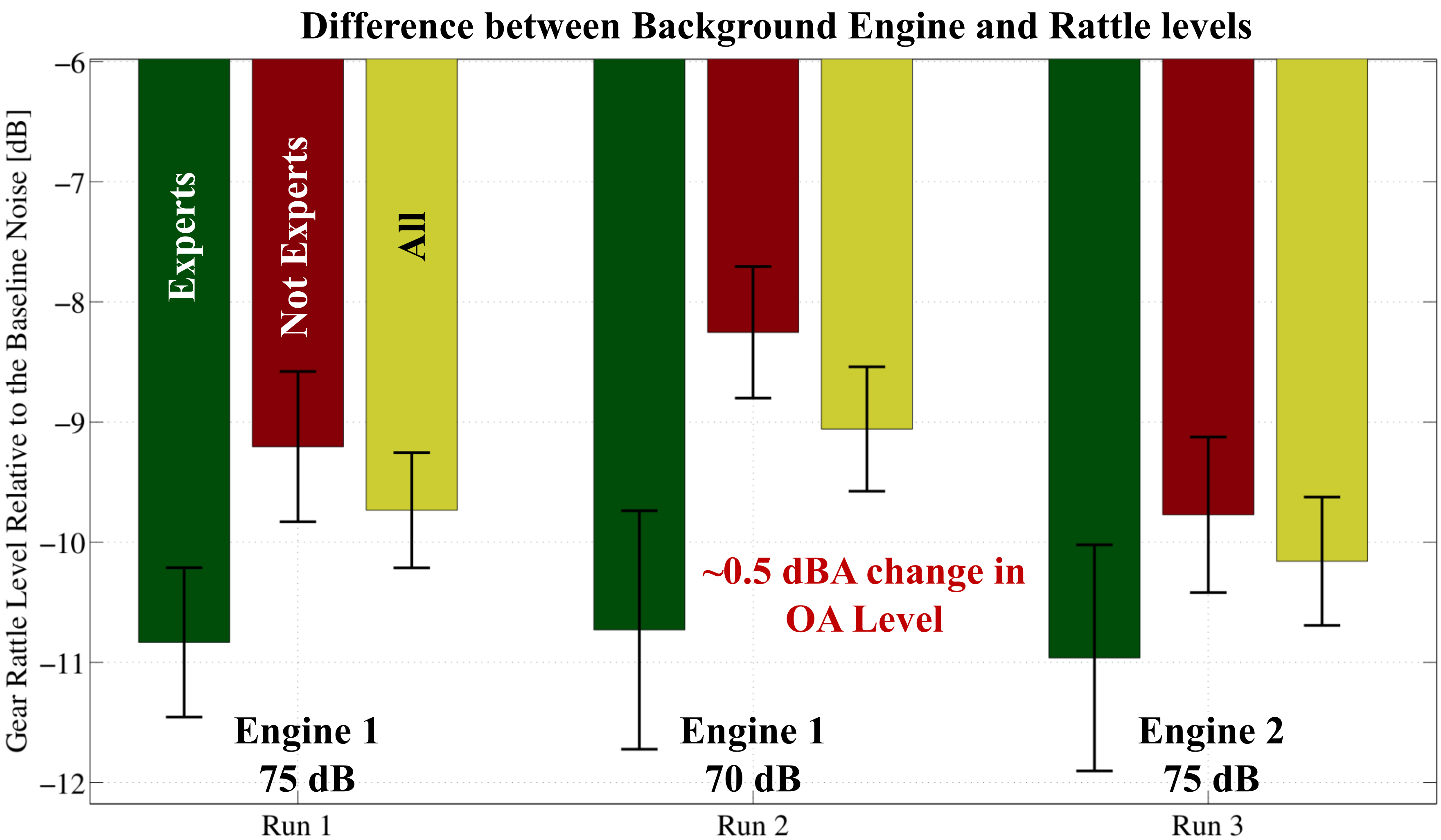
- Each subject participated in three runs to investigate thresholds (in random order)

Run	Background Engine Noise	Baseline Engine Level
1	Engine 1	75 dB
2	Engine 1	70 dB
3	Engine 2	75 dB

Detectability - Example Run 1

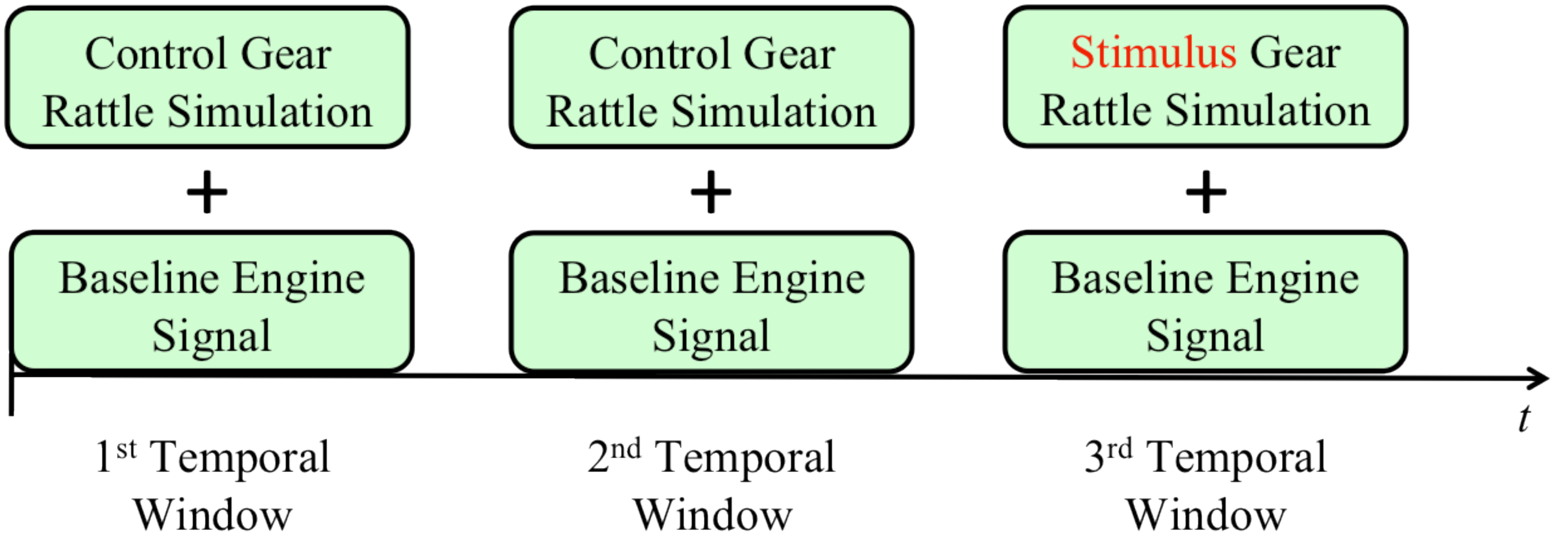


Detectability - Results



All Subjects (40) Diesel Engine Experts (13) Not Diesel Engine Experts (27)

Detecting Changes in Gear Rattle Level

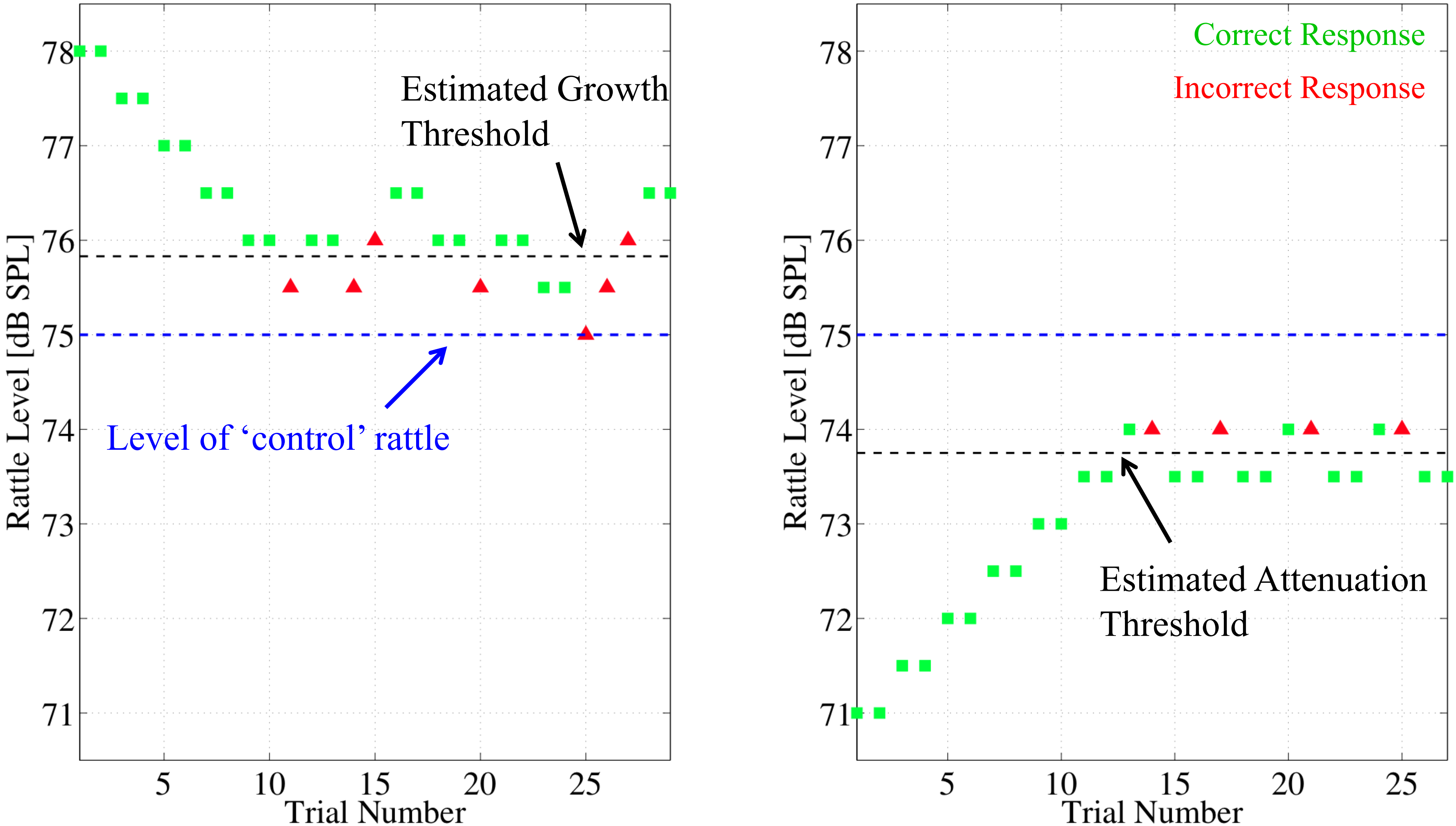


- Each subject participated in two runs to investigate discrimination thresholds

Run	Background Engine Noise	Background Level	Control Rattle Level	Initial Stimulus Rattle Level
4	Engine 1	75 dB	75 dB	79* dB
5	Engine 1	75 dB	75 dB	71 dB

* Set to 78 dB after 18 subjects (to allow subjects to start with ‘incorrect’ responses while maintaining safe listening levels)

Detecting Changes in Gear Rattle Level
Example Runs



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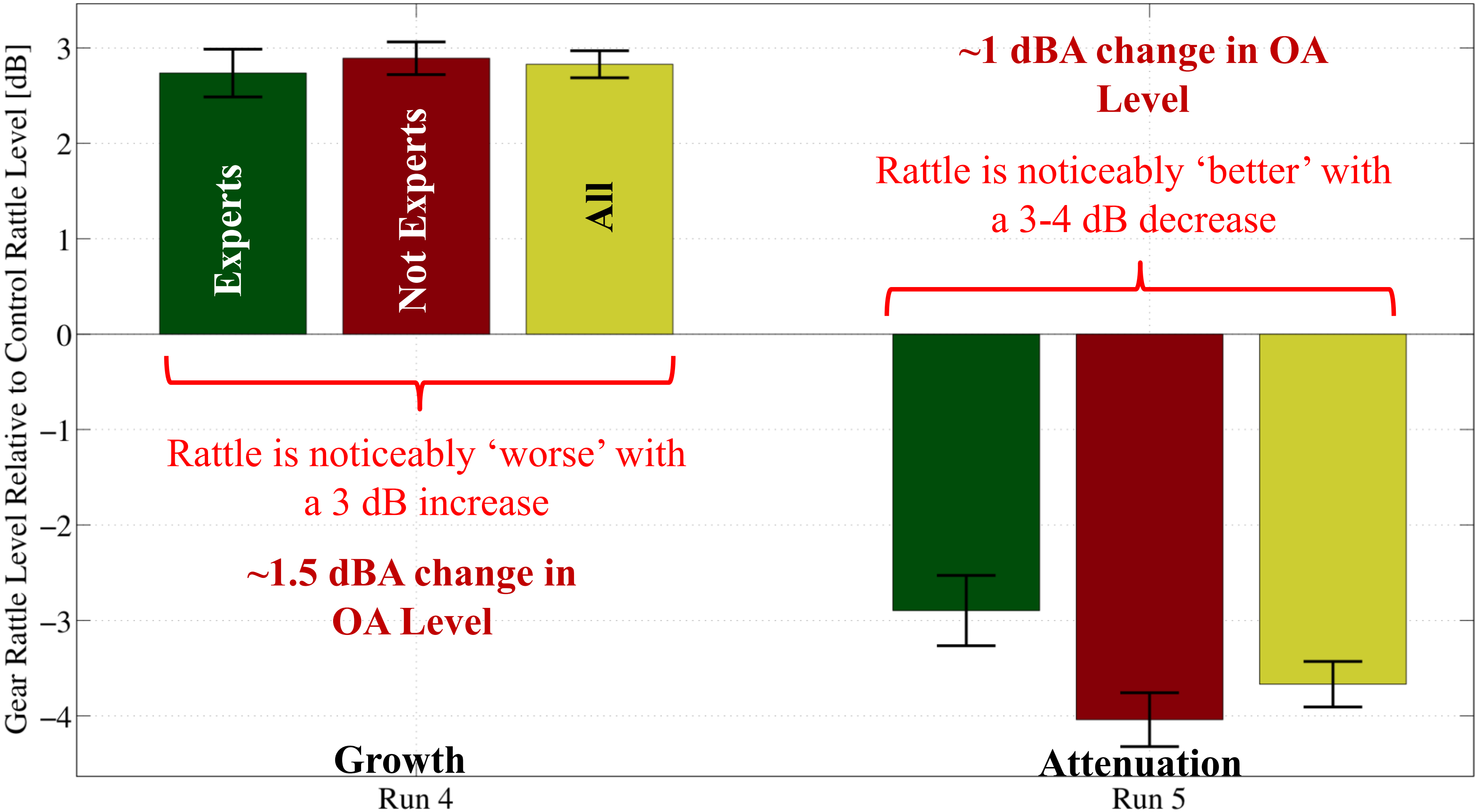
Detecting Changes in Gear Rattle Level Results



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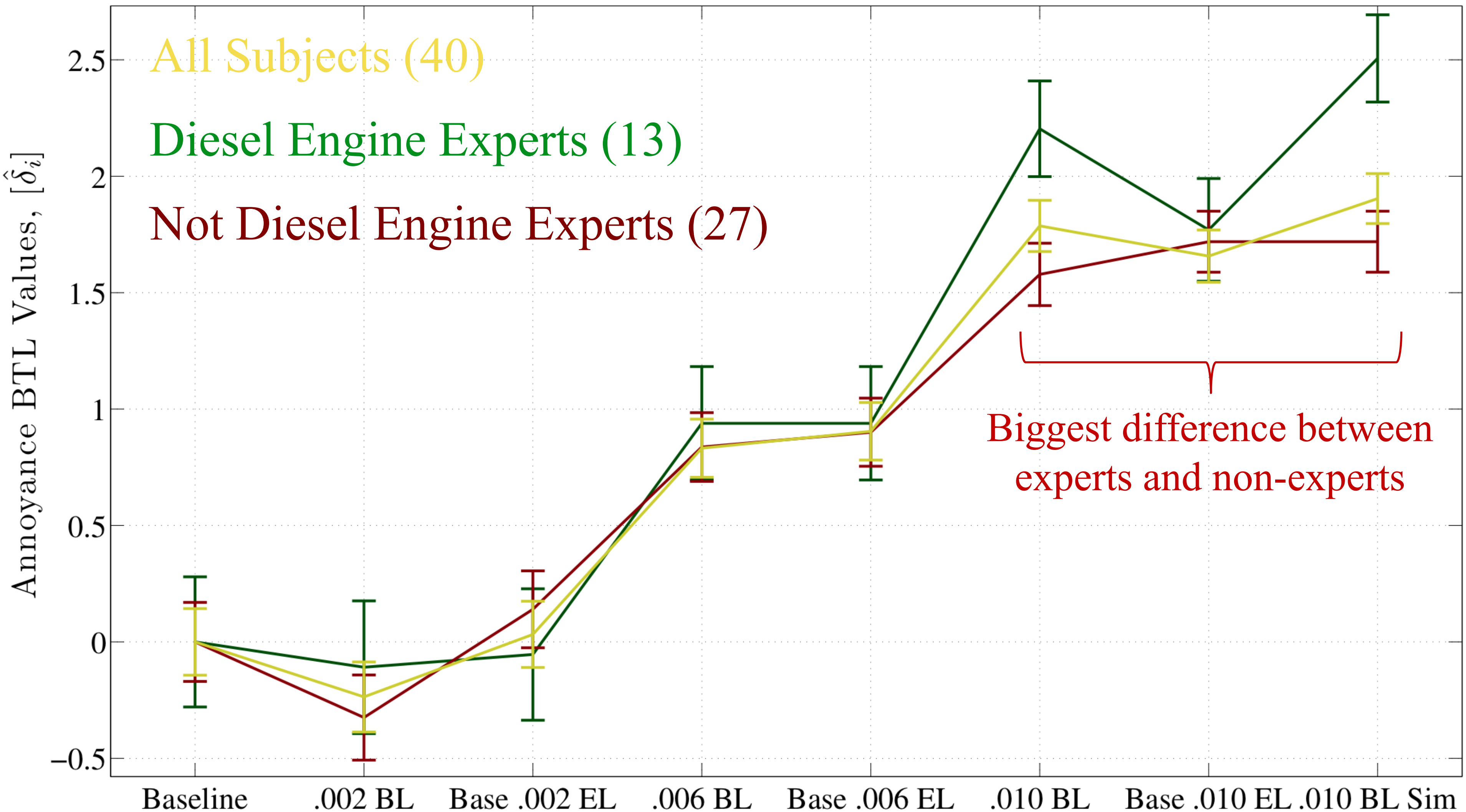
Part 2: Annoyance - Background

- A paired comparison test was used to investigate annoyance
  - Eight sounds (4-seconds each) were compared to every other sound in response to the question, “Which sound is more annoying?”
  - 56 total comparisons in random order
  - The BTL (Bradley-Terry-Luce) model was used to analyze the subject responses
- Signals used in paired comparison
  - 4 Gear rattle measurements
    (Baseline – Scissor Gear, 0.002, 0.006, and 0.010 inch backlashes)
    Increasing levels of gear rattle
  - 1 High gear rattle simulation
  - 3 Amplified Baseline measurements that were set to have equal loudness (EL) as the gear rattle measurements
    (Base .002 EL, Base .006 EL, Base .010 EL)

Part 2: Annoyance – BTL Analysis



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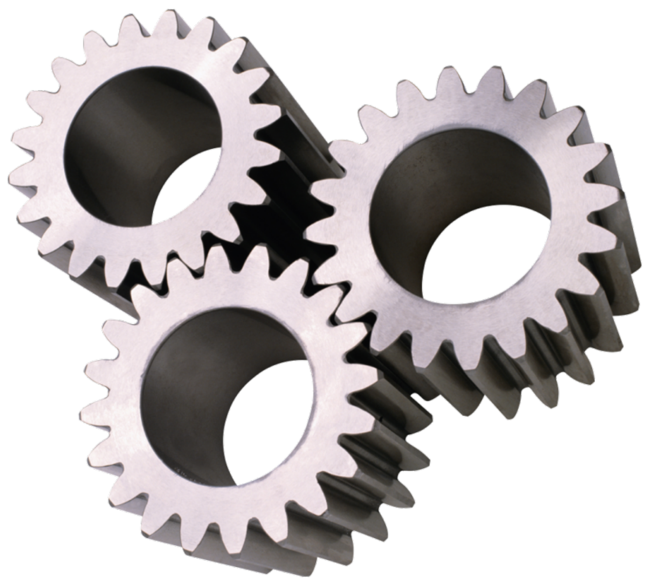
Conclusions

- In general, detectable rattle levels begin at 10 dB below the background (baseline) engine level
- A minimum change of 3 dB in rattle level (increase or decrease) is noticeable to subjects
- Diesel engine 'experts' responses differed from the general public
  - Better at detecting rattle by approximately 1-2 dB
  - Could detect attenuation of rattle with smaller changes (approximately 1 dB)
- Annoyance ratings increase with an increase in rattle
- Diesel 'experts' rated high rattle signals as more annoying than the general public

Acknowledgements

I would like to thank the members of the Walesboro Noise and Vibration Lab at Cummins for their help and advice throughout this research.



Thank you!

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