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MANCHESTER

UNIT9

ŠKODA

Development & evaluation of noise cancellation resistant micro-mobility alert sounds

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Table of contents

1. Executive Summary

Salford Acoustics was engaged by Unit9 to investigate the production of an acoustic warning device (AWD) for cycles, which would be designed to mitigate the effects of active noise cancellation (ANC) on detectability for normal hearing listeners.

Salford Acoustics designed a series of test signals to investigate the effects of impulsivity, activation rate, tonality and frequency on the response of ANC devices supplied by Unit9. It was found that attenuation from ANC was less effective for tonal signals, particularly those at frequencies below 1000 Hz.

Salford Acoustics tested a range of AWDs designed for cyclists that are currently available on the market to determine the SPL of these kinds of devices and the attenuation applied to the sounds by ANC. It was found that bell type sounds were attenuated less than horn-type sounds.

Virtual reality detection tests were performed at the University of Salford using:-

- reference sounds selected from the commercially available AWDs
- sounds supplied by Unit9
- digitally altered sounds designed to fit the spectrum that the earlier testing suggested might optimally reduce ANC attenuation

It was found that in situations where ANC is the predominant factor in attenuating external sound, lower tuned bells (~750 Hz) resulted in greater detection distances and lower detection SPLs. In situations where background noise dominates, this effect is reversed; bells with standard frequency spectra perform better despite ANC.

As such it is advised that a bell designed to take ANC users into account should incorporate both lower frequency and high frequency components. The bell should also ensure that the low and high frequency components are comparable in sound power.

2. Background and Literature Review

2.1 Noise cancellation

Active Noise cancellation (ANC) is a popular feature of headphones. (Rane, Coleman, Mason, & Bech, 2022) reports that 39% of headphone users cite ANC as an important feature when choosing a set of headphones with 46% of users reporting typical usage times in excess of 3 hours per day. A 2022 market share survey estimated that 19% of the global market share for headphones is held by Apple, who offer ANC as a feature in all of their headphone products. Although the ANC systems used in the headphones that were included in this study are proprietary, they are likely based on prior art which is described in (Haykin, 1996). Figure 1 shows the schematic of the dataflow of a typical ANC system.

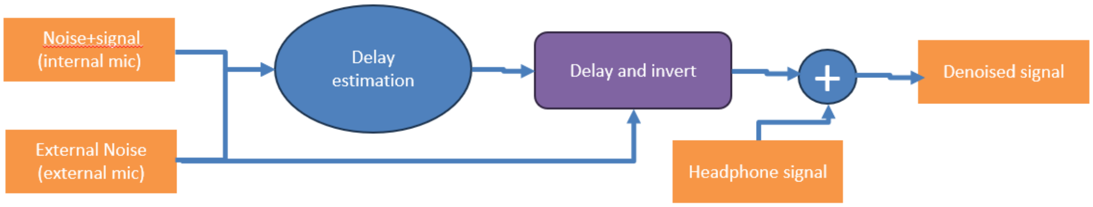


Figure 1: Signal flow of a textbook ANC system

An external microphone is used to capture the ambient soundfield of the environment. An internal microphone is then used to capture the sound pressure on the inside of the earcup or ear canal of the listener. This signal contains a mixture of any noise that has been transmitted through the headphone and the signal that the user wants to hear. These signals are compared to calculate a delay function which describes how long it takes for the noise to transmit to the interior microphone. By mixing in a delayed, inverted, and scaled copy of the exterior noise signal, the ANC system attempts to cancel out this noise.

In addition to delaying the signal, there may also be adaptive filtering implemented in these systems. Digital filters are commonly used mathematical functions which are used to selectively attenuate or boost frequencies or frequency bands in a signal. Adaptive filtering covers a range of algorithms which are used to estimate a filter to suppress or isolate a signal automatically. Such adaptive systems include Weiner optimisation and Kalman optimisation to estimate filter coefficients (Haykin, 1996). Due to the proprietary nature of the devices being measured, we cannot know exactly which algorithms are implemented. However, we can expect some adaptive filtering to be implemented on some devices. This would be observed as a change in attenuation characteristics under changing acoustic conditions.

2.2 Road safety and cycling

It is generally accepted that walking and cycling carry inherent risk. Highway Code H1 and H2 states that the position of cyclists in the hierarchy of road users means that they are responsible for minimising risk to pedestrians and should give way to pedestrians on turnings and crossings (The highway code - guidance - GOV.UK, n.d.). Despite these guidelines and improvements in road safety for cyclists in recent years, government statistics show that cycling is still associated with the potential for collisions. Between 2019 and 2023 there were 3,348 recorded collisions involving pedal cycles and no other vehicle, resulting in 84 fatalities, 1,560 serious injuries and 1,704 slight injuries (Reported road casualties in great britain: Pedal cycle factsheet, 2023 - GOV.UK, n.d.). However, it has been estimated that near-miss events between pedestrians and cyclists may be in the order of 50x more frequent than actual collisions (Mesimäki & Luoma, 2021) and pedestrians are more likely to suffer from more serious outcomes (Pucher & Dijkstra, 2011). Any measures that mitigate the risks to riders and pedestrians would contribute to safer and more inclusive urban spaces.

2.3 Impact of detectability on road safety

In order to reflect the changes in soundscapes as internal combustion engines are phased out, UN regulation 138 (United Nations, 2021) has been homogenised into UK law governing the specification of electric car alert sounds. Although no such regulation exists for pedal cycles mandating the sound character of alert sounds for cycles, Highway code Rule 63 and 66 recommend the use of a bell to alert pedestrians and that cyclists bear in mind that other road users may be hearing impaired (The highway code - guidance - GOV.UK, n.d.). ISO 14878 outlines recommendations for cycle bell design, specifying sound pressure level criteria for acoustic warning devices (AWDs) for cycles. Class I AWDs are defined as emitting sound pressure levels of between 85 dBA and 95 dBA @ 2m. Sound pressure levels are reduced for Class II AWDs to between 75 dBA and 85 dBA @ 2m. The standard recommends a sound profile consisting of an impact sound followed by a tonal signal with frequency content between 1.9 kHz and 4.6 kHz with a decay between 1-2 seconds (International Standards Organisation, 2015).

Standardisation of alert and warning sounds notwithstanding, research has identified signal features which are associated with increased detection distances when used in vehicle alert sounds. Amplitude modulated tones in the range 800 Hz-1 kHz (Walton, Torija, & Elliott, 2022) are associated with improved detection of e-scooters. It has been shown that environmental sound has a significant effect on the detectability of vehicle alert sounds. However, the detectability of sounds with high frequency components is less strongly affected by environmental noise levels (Hsieh, Chen, Tong, & Yan, 2021). This is explained by frequency masking effects where tones which are within the spectrum of competing noise are masked due to the frequency response of the inner ear (Hugo & Zwicker, 2007). Where alert sounds are outside the spectrum of interfering noise, detectability will be improved. In addition to environmental noise affecting detectability, it has been shown that distraction has a significant effect on detectability. Smart phone use has been shown to be detrimental to situational awareness and detection of alert sounds (Lin & Huang, 2017). By mitigating the effects of ANC on the detectability of cyclists to pedestrians and other road users using headphones, we can contribute to the safety of road users in an environment with a complex risk profile.

3. Active Noise Cancellation Objective Measurements

3.1 Introduction

Salford Acoustics were commissioned to perform measurements of headphones with active noise cancellation (ANC) features to inform the design of a bicycle bell / alert sound which is more detectable by users of ANC-enabled headphones. Measurements were performed at the University of Salford Acoustic Laboratories between 3/12 and 10/12/25.

3.2 Material and methods

Measurements were performed in a hemi-anechoic chamber at the University of Salford Acoustic Laboratories. The hemi-anechoic chamber features sound absorption on five surfaces and a floor which reflects sound. This facility simulates outdoor environments in a controlled manner. The experimental setup consisted of:

- 1x GRAS Kemar head and torso simulator (HATS)
- 2x Genelec 8050B active loudspeakers
- 1x Dewesoft data acquisition (DAQ)
- 1x MOTU 8M audio interface

The HATS system features soft removable pinnae with human-like ear canals which lead to precision microphones to capture sound as if it were heard by a human listener. Microphones were calibrated before each measurement session using a GRAS 42AA pistonphone calibrator.

Loudspeakers were positioned 1 m from the HATS at 90° to the right and left of the apparatus. The acoustic centre of the loudspeakers was positioned at ear height of the HATS. Signal levels were set so that the A-weighted slow time weighted sound pressure level (L_{AS}) of a pink noise signal set to -12dBFS was 97 dBA for each loudspeaker, and 100 dBA when both signals were active (measured inside the ear canal of the HATS).

3.2.1 Test signals

Test signals were selected to measure particular behaviours and characteristics of the headphones under test. The following signals were included in the suite of measurements:

- Logarithmic sine sweep
- Pink noise bursts

- Tone sequence rising from 63 Hz – 1 kHz in 16 evenly spaced intervals
- Tone sequence falling from 1 kHz – 63 kHz in 16 evenly spaced intervals
- Combinations of tone sequences and noise modulated to produce mixtures of impulsive signals and constant level signals
- Existing bike bell/alert devices (Section 4)

Sine sweep

Sine sweeps are a signal used to measure the time, frequency response and harmonic distortion of a system (Farina, 2000). This measurement assumes that the system is time-invariant and the response does not change with respect to the input signal or over time. These measurements will be used to assess the performance of the passthrough functions of the headphones.

Noise bursts

Pink noise bursts are used to estimate the frequency response of the system with respect to time. This method is less accurate than the sine sweep method, but does not rely on the device under test to be time-invariant.

Tone and noise combinations

In order to test the response of the ANC to external noise that is tonal or broadband in nature, and to test if sudden changes in the external noise are suppressed to the same degree as steady state noise, a series of test signals were designed. The test signals consist of a mixture of rising or descending tones, and/or noise bursts. One component of this mixture is shaped with an exponential decay function to produce an impulsive sound which decays over a given period of time, the decay rate. This decay rate is varied between signals. The component with the constant level is set to a level which is varied between signals. The combinations of tests signals used are shown in Table 1.

Table 1: Combination of test signal factors and levels

Factor	**Values**	**Levels**
Signal type	Tone / Noise	4
Decay time	100 ms to 2 s	8
Constant tone level	+6 dB to -30 dB	8
Total:		256

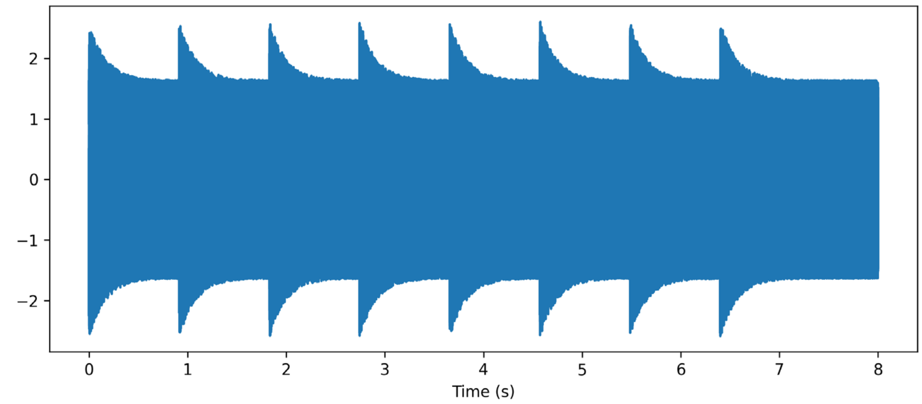


Figure 2: Test signal (impulsive tones+noise), decay time : 910ms, baseline level: -4.3dB

Figure 2 shows an example of one of these test signals. The decay time (τ) controls the rate that the impulsive component decays according to the function $w(n) = e^{-n\tau}$. The baseline level sets the level to which the overall level decays.

3.2.2 Analysis methods

Sine sweeps will be processed according to (Farina, 2000). Noise bursts and test signals described in Section 3.2.1.3 are analysed in the following way:-

- Broadband instantaneous A-weighted fast time weighted SPL (L_{AF}) were calculated for signals without headphones
- Broadband instantaneous A-weighted fast time weighted SPL (L_{AF}) were calculated for signals with each headphone in passthrough mode
- Broadband instantaneous A-weighted fast time weighted SPL (L_{AF}) were calculated for signals with each headphone with ANC enabled
- Frequency dependent instantaneous A-weighted fast time weighted SPL (L_{AF}) were calculated for signals without headphones
- Frequency dependent instantaneous A-weighted fast time weighted SPL (L_{AF}) were calculated for signals with each headphone in passthrough mode
- Frequency dependent instantaneous A-weighted fast time weighted SPL (L_{AF}) were calculated for signals with each headphone with ANC enabled

Time aligned differences between no-headphone/ANC and passthrough/ANC combinations were calculated. The statistical distributions of differences under these conditions were analysed to determine the appropriate statistical tests. Hypothesis tests were performed to determine if tone/noise combination, impulse decay time and baseline level are associated with statistically significant differences in attenuation due to ANC being enabled.

3.3 Results and discussion

Table 2 shows the mean A-weighted attenuation for the headphones tested. It can be seen that not all headphones performed equally in attenuating the test signals. The Airpod Max headphones performed the best, producing the highest mean attenuation and the lowest variance across all signals. The other headphones displayed higher variance, showing differences in attenuation in response to different signal types.

Table 2: Mean ANC Attenuation for all signals

Headphone	Form factor	Mean Attenuation
Apple Airpod Max	Over-ear	26 dBA
Bose Quietcomfort	Over-ear	18 dBA
Sony WX1000	Over-ear	20 dBA
Apple Airpod Pro	In-ear	14 dBA
JBL live pro	In-ear	17 dBA
Samsung Galaxy Bud	In-ear	8 dBA

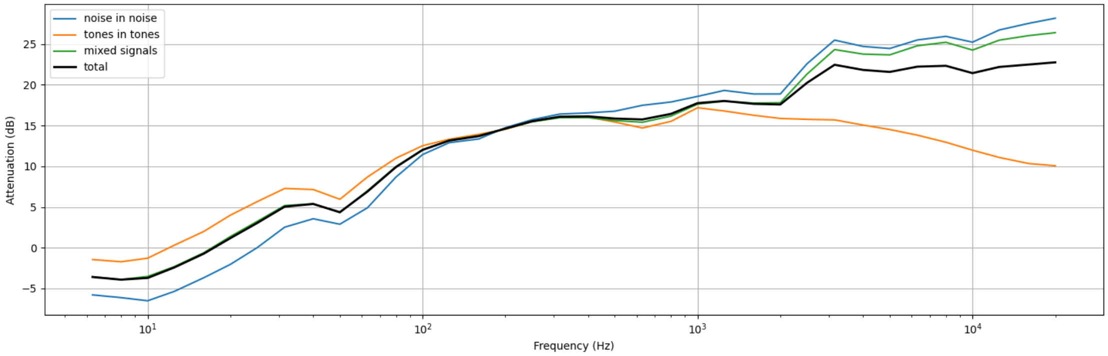


Figure 3: Attenuation by frequency for different types of test signal

Figure 3 shows the average third-octave band attenuation spectrum across all headphones for the test signals. It can be seen that for signals which contained broadband noise, there is an increase in attenuation above 2 kHz, corresponding to approximately 6 dB. However, for tones-in-tones signals, this increase is not observed. There is a local dip of approximately 3 dB in the attenuation curve for tone-in-tone and mixed signals in the 800 Hz band. When controlling for differences between headphones it was found that tone-in-tone signals were attenuated by 4.9 dB less than mixed signals and 8.9 dB less than noise-in-noise signals ($p< 0.05$). There was no statistically significant association between impulsivity of the sounds or the decay time of the sounds.

3.4 Conclusions

From the tests described above it is advised to design the bell around a tonal sound. Given the observed attenuation profile across all headphones tested it is advised to tune the bell to below 1000 Hz in order to target the range of frequencies which are less well attenuated by ANC. Including high frequency components is also advised as attenuation at high frequencies is shown to be poorer in low noise conditions which will aid in detectability in these situations.

4. Bell Objective Tests

4.1 Introduction

Acoustic warning devices (AWD) that were supplied by Unit9 were measured in controlled conditions to determine the SPL that would be experienced by a pedestrian with and without ANC headphones. This was done to evaluate the SPLs of devices currently on the market and to provide a baseline for the bell that would be designed as part of this project. The AWDs that were supplied are described in Table 3 and comprise of bells, air-horns and electric sounders.

Table 3: Description of AWDs tested

Device name	**Type**
Hornit dB140	Electric sounder
Greallthy Classic Vintage Bell	Mechanical bell
Trixes retro horn	Air horn
Greallthy bike bell	Percussive bell
MyBestBike Bicycle bell	Percussive bell
YHT Bike Bell	Percussive bell
Hand held airhorn	Air horn

4.2 Materials and methods

Measurement apparatus was as described in Section 3.2 with the array of bells placed 2 m behind the HATS. Bells were activated with and without ANC headphones fitted to the hats and left to right. Fast time weighted A-weighted SPL was recorded and tabulated.

4.3 Results

Table 4 presents the acoustic warning devices, their peak time-weighted SPL, the corresponding level with ANC applied and the reduction due to ANC. The overall mean SPL for all bells was 94.0 dB. The mean change in SPL due to ANC ($\mu(\delta L)$) was -10.3 dB.

Although some AWDs remained louder after ANC, it was observed that some devices were attenuated less than others. Notably, the ‘classic’ mechanical bell and MyBestBike brand percussive bell were attenuated less than the mean attenuation for all bells. As such, these devices were selected as the baselines for comparison with the newly designed bell.

Table 4: Description of AWDs tested

Device name	No HP SPL	ANC SPL	Reduction	$\delta L - \mu(\delta L)$
Hornit dB140 sound 1	115.7 dBA	97.3 dBA	-18.3 dB	-3.7 dB
Hornit dB140 sound 2	111.5 dBA	94.7 dBA	-16.8 dB	-2.3 dB
Greallthy Classic Vintage Bell	82.9 dBA	72.9 dBA	-10.0 dB	+4.6 dB
Trixes retro horn	95.8 dBA	81.7 dBA	-14.1 dB	+0.4 dB
Greallthy bike bell	95.5 dBA	77.0 dBA	-18.5 dBA	-4.0 dB
MyBestBike Bicycle bell	78.0 dBA	67.5 dBA	-10.5 dB	+4.0 dB
YHT Bike Bell	68.5 dBA	55.4 dBA	-13.1 dB	+1.4 dB
Hand held airhorn	104.4 dBA	89.5 dBA	-14.9 dB	+0.4 dB

5. Bell Subjective Tests

5.1 Introduction

Bells designed by Unit9 were tested for detectability in an immersive environment designed to maximise the ecological validity of the test scenario. Subjects were asked to carry out a distraction task while immersed in a 360 video and audio scene. Bicycle bell sounds under test were rendered at reducing distances and participants were asked to respond by pressing a trigger on a controller when a bell was heard. Mixed effects modelling showed that the main effect on detection threshold was the scenario (quiet park vs busy street). However, there were statistically significant differences in detection threshold associated with ANC use and between bells.

5.2 Materials and methods

5.2.1 VR Scenario

In order to produce an ecologically valid controlled environment for the tests, an immersive virtual environment was constructed in the Unity game engine (Unity Technologies, n.d.). Visual scenes were captured using an Insta360 X4 360 camera and first order ambisonic (FOA) audio was captured using a Zoom H3-VR audio recorder. Bell sounds and simulated bicycle noise was spatially rendered using first order ambisonics and attenuated for distance using the equation

$$\Delta P = 10log_{10}\frac{r_{ref}}{r}$$

Where r is the bicycle distance and r_{ref} is the reference distance, in this case 2 m.

Figure 4 shows the basic schematic for the experiment procedure. Virtual bicycles were generated at 100 m behind the listener and proceeded to move towards the listener at a speed of 6.5 m/s after a random delay of up to 10 seconds. As the bicycle was moving, the bell was repeatedly sounded at an interval of 1 second. When the listener detected the bell, they were asked to pull a trigger on their controller. On detection the bell sound was stopped and the bicycle position was reset. The procedure was repeated for the duration of the scene. All scenes were 1 minute in length. Scenes were presented in random order, with two scenes for each virtual location. Each location featured a scene aligned with both directions of the road/path i.e. North/south for the park scenes and east/west for the street scenes.

Tests were performed in the spatial audio booth at the University of Salford. This room has a reverberation time of < 175ms and a background noise level of < 25 dBA. Visuals were presented using the HTC Vive Pro head mounted display (HMD) and audio was presented using a 16-channel spherical periphonic loudspeaker array. Figure 5 shows the equipment setup for the VR tests.

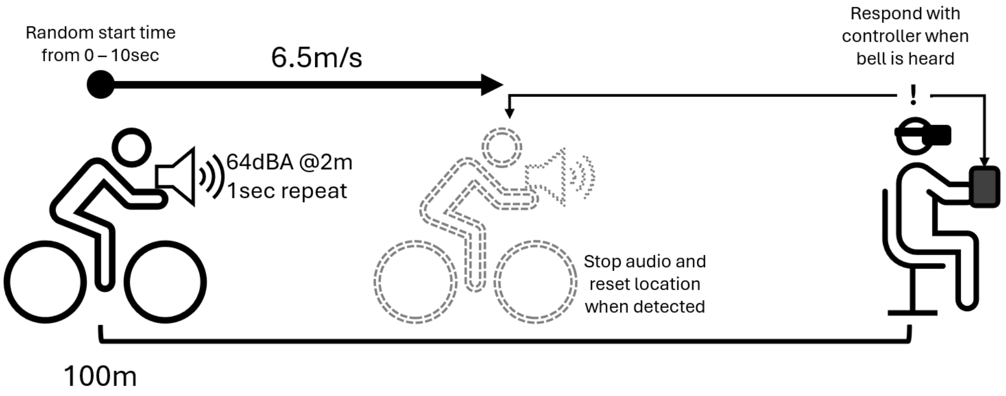
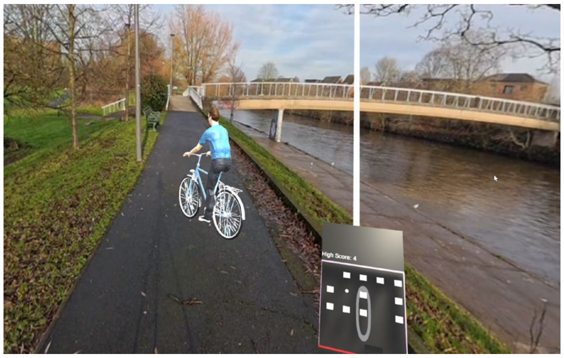
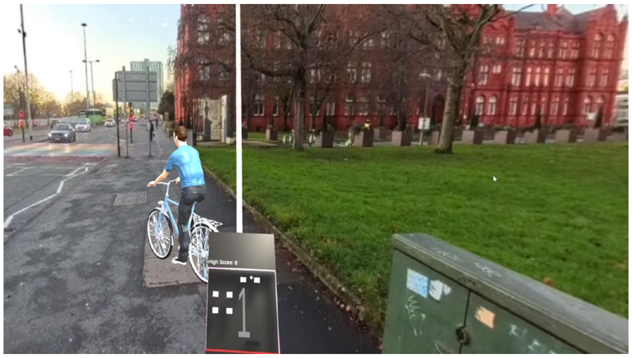


Figure 4: Experiment procedure

Figure 5: The equipment setup for the VR tests in the Audio Booth at the University of Salford



(a) VR view of park scene



(b) VR view of street scene

Figure 6: Examples of stimuli including distractor game interface and virtual bicycle passbys

5.2.2 Sounds

Signals were generated by digitally pitch-shifting recordings of the test bells using the pitch-shift function from the Librosa library (B. McFee et al, 2015). Bells were shifted from their original frequency to have the following fundamental frequencies:

- 100 Hz
- 250 Hz
- 500 Hz
- 750 Hz
- 1.5 kHz
- 3 kHz

Original fundamental frequencies were determined using instantaneous frequency estimation by the Hilbert transform method (Boashash, 1992). The measurement setup was as described in Section 4.2, with the Gras HATS system used to measure sound reproduced from a Genelec 8040 loudspeaker positioned 1 m on axis from the left ear of the HATS.

5.2.3 Analysis

Response data were cleaned before analysis to mitigate any ceiling effect that was present and to ensure a statistical distribution that was valid for analysis. The cumulative distribution function was calculated and the upper inflection point was identified. Responses above this inflection point were rejected, as they represented responses to bells that were immediately detected. Removal of these values resulted in an approximately uniform distribution of detection distances.

Kruskal-Wallis tests were used to analyse simple one-way effects between predictor variables and response distance. To test the interaction between multiple variables, mixed effects linear modelling was employed. This is a hierarchical model which assumes that treatments are nested within groups which have their own mean. The structure of this model was as follows:

- Random effect: Headphones/no headphones
- Fixed effect: Scenario/bell sound interaction

Statistical significance was taken for terms where $p<0.05$.

5.3 Results and discussion

5.3.1 Simple effects

Table 5 shows the results of Kruskal-Wallis hypothesis tests on the simple effects of headphones, scenario and whether the response was the first response in a scene.

Table 5: Simple effects analysis

Factor	Median G1	Median G2	Difference	p-value
Headphones on/off	34m	54m	10m	5×10^{-34}
First bell/All responses	37m	45m	8m	0.0002
Scenario street/park	32m	57m	15m	2.5×10^{-54}

The analyses show that these factors significantly affect the detection distance for all bell sounds. Headphone use was associated with a 10 m increase in detection difference, and the increase of background noise level from 45 dB to 69 dB resulted in a median detection distance increase of 15 m. Comparing the first detection in each scene to all detections within each scene shows that the 'element of surprise' accounted for an 8 m reduction in detection distance across all other conditions.

5.3.2 Mixed effects

Table 6 shows the results of a mixed effects model which separates out the individual contributions of different conditions on detection distance.

Table 6: Mixed effects model - Detection threshold (A-weighted dBSPL) by scenario and bell with headphones as random effect

	Level (dB)	**Distance (m)**
Global average detection	44.2	25.0
Noisy Street - double_750hz	+2	-6.4
Noisy Street - double_original	-1.2	+5.4
Noisy Street - myBESTbell 2.725 cm	-2.2	+8.9
Noisy Street - triple 750hz 2.725 cm	+1.1	-3.1
Noisy Street - triple original	-1.8	+7.8
Quiet park	-5.1	+21.8
Quiet park - double_750hz_1s	-2.3	+9.2
Quiet park - double_original_1s	+1.9	-7.8
Quiet park - myBESTbell	+3.2	-14.3
Quiet park - triple_750hz	-1.2	+4.1
Quiet park - triple_original	+2.8	-11.6
ANC on/off (Random effect)	+/- 1.7	+/-7.3

The use of headphones was defined as the random effect group, which is treated as the top of the hierarchy of the breakdown of the effects of each condition within the analysis. The estimate of the effect was +/-7.3 m (+/-1.7 dB) on the average detection distance/SPL. This means that headphone use was associated with a reduction in detection distance of 14.6 m or an increase of 3.3 dB SPL to detect a bell sound, accounting for other factors.

The next level of analysis is scenario. It was found that in the Quiet Park scenario, detection distance was 21.8 m further and detection level was 5.1 dB lower than in the Noisy Street condition, accounting for the effect between bell sounds.

Between bells, there was a dependence on the scenario condition. Between bell comparisons were made against the Greallthy classic model, which performed close to the within-scenario mean for all bell conditions. In the Quiet Park scenario, bells tuned to the lower fundamental frequency of 750 Hz performed better than the reference bell, with the ‘double stack’ bell tuned to 750 Hz increasing detection distance by 9.2 m and decreasing detection SPL by 2.3 dB. Bells tuned to their original fundamental frequency performed worse than the reference in this condition. However, in the Noisy Street condition, lower tuned bells performed worse, with their average detection distance decreasing and detection level increasing. This can be interpreted as lower tuned bells performing better when ANC is the predominant factor in reducing the sound level of the bell experienced by the listener. However, when competing noise is the main factor, other psychoacoustic effects such as time and frequency masking are stronger than the benefit provided by attempting to circumvent the ANC. In this case, existing guidelines for acoustic warning devices remain valid; ensuring AWDs or bells are sufficiently loud and have a spectrum which is unlikely to be masked by street noise.

5.4 Conclusions

Virtual reality detection tests were performed with simulated approaches and passbys of cycles in both a quiet park and noisy street scenario. Participants performed the task both with and without ANC headphones, and were asked to play a game on a virtual phone as a distraction task during the task. Detection distances and SPL were analysed and it was found that ANC headphones and the first response to a bell significantly decreased detection distances. Multilevel mixed-effects modelling was performed to test for effects between bells within scenarios and it was found that when background noise was high, standard tuned bells perform well. However when ANC is the main factor in reducing external sound to the listener, bells tuned to 750 Hz were detected further away, corresponding to a 9.2 m improvement in detection distance and 2.3 dB improvement in detection threshold.

6. Technical Specifications & Design Recommendations

To successfully alert pedestrians, particularly those acoustically isolated by Active Noise Cancellation (ANC) headphones, the proposed device will aim to operate at the parameters outlined in the previous section. The objective is to maximize acoustic penetration and psychoacoustic recognition while maintaining practical viability for bicycle mounting and hearing safety.

6.1 Targeted Acoustic Parameters

Based on psychoacoustic and empirical testing, the device must consistently output the following auditory signal profile:

- **Frequency Response Target:** The primary acoustic energy must be concentrated in two distinct bands:
    - 700-800 Hz (Suggested range for penetrating ANC passive isolation)
    - 2000+ Hz + Bell Harmonics (Distinctive “bike bell” psychoacoustic range)
- **Sound Pressure Level (SPL):** The device must achieve a minimum output of 83 dBA at a distance of 2 meters. This ensures the signal retains enough energy to overcome both the attenuation of ANC headphones and that of ambient environmental noise (e.g., heavy traffic).
- **Transient Attack:** The device must produce a sharp transient attack, meaning acoustic energy is front-loaded at the start of the signal. This sudden onset is critical for defeating the processing latency of Active Noise Cancelling algorithms.

6.2 Signal Generation Approaches & Evaluation

The fundamental engineering challenge is the efficient transfer of energy into the specified acoustic signal. Current approaches can be broadly categorized into electronic and mechanical actuation.

Note: The following evaluation is not an exhaustive inventory of all acoustic devices, but highlights primary areas of active research and development.

Evaluation Criteria

To objectively assess each technology's suitability for a bicycle-mounted application, we derive the following five criteria, scored from 1 (Poor) to 5 (Excellent):

1. **Acoustic Profile Match:** Ability to reliably hit the 83 dBA @ 2m target with the dual-band frequency requirements.
2. **Power Autonomy:** Independence from external power or complex infrastructure.
3. **Form Factor & Weight:** Volumetric efficiency and suitability for handlebar mounting.
4. **Environmental Durability:** Resilience against water ingress, temperature fluctuations, and mechanical vibration.
5. **Ergonomics & Latency:** Ease of rider actuation and speed of acoustic onset (attack/ trigger time).

6.2.1 Electronic Generation

Electronic systems offer high precision regarding frequency output but introduce system complexity.

- **Standard Electromagnetically Driven Speaker Cones**
    - Pros: Higher degree of control over the emitted waveform.
    - Cons: Highly susceptible to water/dust damage; requires significant power to reach 83 dBA; bulky enclosures required for low-frequency resonance.
- **Ultrasonic Transducer / Parametric Speaker**
    - Pros: Highly directional beam; can create sound that appears to originate near the listener's head.
    - Cons: Extremely high power consumption; narrow dispersion angle makes targeting moving pedestrians potentially difficult.
- **Solenoid-Driven Striker and Bell / Resonant Structure**
    - Pros: Combines electronic actuation with the acoustic efficiency of a physical bell; sharp transient attack.
    - Cons: Added weight of the solenoid; moving parts prone to jamming if exposed to grit/ water ingress.

- **Electromechanical Motor-Driven Siren**
    - Pros: Exceptionally high SPL capabilities.
    - Cons: Slow attack time (needs to spool up), which fails to provide the sudden transient needed to shock ANC algorithms; heavy power draw; would require some significant design to get into a compact form factor.
- **Electromechanical Solenoid Valve (Pressurized Gas)**
    - Pros: Instantaneous attack time; massive SPL output.
    - Cons: Requires a compressed gas reservoir (danger of depletion); potentially dangerous to maintain; requires necessary safety pressure release systems.

Summary of Electronic Generation: While electronic actuation offers superior tuning of the frequency response, potentially even dynamically, especially considering the cone/ ultrasonic speaker systems, its primary drawback is the reliance on battery power. This mandates additional infrastructure, increases overall system volume and weight, and introduces failure points (e.g., a dead battery renders the device useless). Perhaps a mechanical charging system that can take energy from the bike, or through solar would be a viable route of exploration. Ideally, the system should not rely on batteries to ensure absolute reliability.

6.2.2 Mechanical Generation

Mechanical systems excel in reliability and energy density (utilizing human kinetic energy), though they offer less precise/ harder to refine control over the acoustic signal generated.

- **Bell and Sprung Striker Mechanism**
    - Pros: Infinite power autonomy; excellent durability; compact; produces naturally high-frequency transients.
    - Cons: Generating sufficient energy in the lower 750-800Hz band would require a physically larger bell dome, or thinning walls, conflicting with form factor constraints and mechanical durability.
- **Bell and Geared Lever Rotary Striker Mechanism**
    - Pros: Multiple rapid strikes increase perceived loudness and sustain; highly reliable.
    - Cons: Mechanical wear over time; SPL is entirely dependent on user thumb-force.
- **Squeeze Horn / Bicycle Horn (Clown Horn)**
    - Pros: Simple pneumatic operation; distinct, recognizable timbre.

  - Cons: Rubber bulb could degrade in UV light/weather; difficult to tune to specific high-frequency harmonics; low SPL; potentially too comical.

- **Whistle (Mouth or Bellows Driven)**
  - Pros: Extremely high frequency and SPL; highly compact.
  - Cons: Mouth operation is unsafe/impractical while riding; bellows integration is mechanically clunky.

- **Hand-Powered Siren**
  - Pros: High SPL without batteries.
  - Cons: Takes time to "Spin-up" to tone generating frequency; potentially difficult to design a system that is hand driven; more complex if energy is harvested from the bike momentum.

6.3 Technology Suitability Matrix

Table 7 below summarizes the evaluation, scoring each approach against our derived criteria to determine the most viable path forward for prototype development.

Table 7: Evaluation of each approach against derived criteria

Technology Type	Acoustic Match	Power Autonomy	Form Factor	Durability	Ergonomics	Total Score
Electronic: Speaker Cone	5	1	2	2	5	15
Electronic: Ultrasonic	4	1	2	3	5	15
Electronic: Solenoid + Bell	4	1	3	3	5	16
Electronic: Motor Siren	2	1	2	4	4	13
Electronic: Solenoid + Gas	5	1	1	3	5	15
Mechanical: Sprung Striker	3	5	5	5	4	22
Mechanical: Rotary Striker	4	5	4	4	4	21
Mechanical: Squeeze Horn	2	5	3	2	4	16
Mechanical: Whistle (Bellows)	3	5	3	3	2	16
Mechanical: Hand Siren	3	5	2	4	1	15

- **Preliminary Conclusion:** Mechanical bell systems (both sprung and rotary strikers) currently present the most viable architecture for bicycle integration due to their independence from battery infrastructure and superior durability. However, future design phases must focus on acoustic chamber engineering to ensure a mechanical bell can reliably project the necessary 750-800 Hz frequencies alongside its natural high-frequency transients.

6.4 Regulatory Standards & Compliance

To ensure market viability in the UK and broader international adoption, the proposed acoustic “bike bell” device must adhere to established transportation, product safety, and environmental standards. While the primary objective is penetrating ANC headphones, the device must remain legally compliant and safe for public use.

6.4.1 UK & International Bicycle Regulations

To the best of our knowledge there are no strict, quantifiable acoustic or mechanical standards set specifically by UK law for bicycle warning devices. Because overarching international standards have recently been withdrawn, the engineering parameters for the proposed device must be guided by a combination of basic national safety requirements and established European engineering benchmarks.

- UK Market (PBSR): Under the Pedal Bicycles (Safety) Regulations 2010, all new bicycles sold in the UK must be fitted with a bell at the point of sale. However, UK law does not define a strict minimum or maximum acoustic profile, nor does it rigidly dictate the internal mechanism or frequency output of the device. This lack of specific acoustic regulation places the onus on general product safety directives and manufacturer discretion to ensure the device is fit for purpose (The Pedal Bicycles (Safety) Regulations 2010, n.d.).

- The European Benchmark (DIN 33946): In the absence of defined UK acoustic standards, and following the 2019 withdrawal of the international standard ISO 7636, the industry defaults to the strictest national frameworks. The current de facto engineering standard is Germany’s DIN 33946:2010 (Deutsches Institut für Normung). While we acknowledge that DIN 33946 establishes a minimum acoustic threshold of 85 dBA, our primary engineering target is set at 83 dBA at 2 meters to balance our specific frequency goals with physical form-factor constraints. However, we believe we should adhere to the rigorous environmental and mechanical durability tests outlined within DIN 33946 where possible, ensuring the device remains robust enough to satisfy European safety expectations even with the modified acoustic output.

6.4.2 Acoustic Public Safety & Nuisance Limits

While the device must be loud enough to penetrate acoustic isolation, it must not pose a health hazard to pedestrians in close proximity.

- **Hearing Protection:** The targeted output of 83 dBA at a distance of 2 meters is acoustically robust but falls safely below the upper exposure action values are 85 dBA for daily exposure and 137 dBA for peak noise. Because a bicycle bell produces a transient impulse rather than sustained continuous noise, an 83 dBA output poses no risk of hearing damage, aligning with UK Health and Safety Executive (HSE) guidelines for acoustic exposure (Health and Safety Executive, n.d.).
- **Psychoacoustic Nuisance:** By targeting the 2000+ Hz range to maintain a traditional "bike bell" harmonic profile alongside the lower 700-800 Hz ANC-penetrating band, the device remains universally recognizable. This prevents the public nuisance complaints and pedestrian confusion often associated with aggressive air horns or high-decibel electronic sirens.

6.4.3 Environmental & Ingress Protection (IP)

Although purely mechanical systems are immune to electrical shorts, they are highly susceptible to mechanical jamming and acoustic dampening caused by environmental ingress.

- **Acoustic Chamber Sealing:** The introduction of advanced acoustic principles (such as internal tines or dual-resonators) creates cavities where water, mud, or road grit can accumulate. The accumulation of mass on a vibrating element (like a cantilever tine) will drastically alter its fundamental frequency and dampen its amplitude.
- **Target IP Equivalent:** While IP ratings (e.g., IP54, IP65) are traditionally applied to electrical enclosures, the device's mechanical housing must be engineered to an equivalent standard of IP54 (protected against dust ingress and splashing water from any direction).
- **Material Selection:** To comply with general consumer product longevity standards, all exposed acoustic radiating surfaces and internal resonant structures should be fabricated from corrosion-resistant alloys (e.g., specific grades of brass, stainless steel), or treated to prevent rust-induced frequency shifting over the product's lifecycle.

6.5. Chapter Conclusion & Strategic Engineering Directive

Based on the comparative analysis of signal generation approaches, mechanical actuation - specifically sprung and rotary striker bell mechanisms - emerges as the most viable architectural foundation for the proposed device.

While electronic systems offer superior theoretical control over the required dual-band frequency profile (700-800 Hz and 2000+ Hz), their reliance on external power infrastructure, increased mass, and susceptibility to environmental degradation introduce unacceptable points of failure for a critical safety mechanism. Mechanical systems inherently solve for power autonomy, immediate latency, and environmental resilience, ensuring the device is always available during an alerting event.

However, adopting a mechanical architecture dictates the primary engineering challenge for the subsequent design phase. Traditional bicycle bells naturally excel at producing the high-frequency transients (>2000 Hz) necessary for psychoacoustic "bike bell" recognition. Yet, generating sufficient acoustic energy in the lower 700-800 Hz band, the frequency range identified for penetrating Active Noise Cancellation (ANC), typically requires a prohibitive increase in the bell dome's physical volume, or significant reduction in thickness of the walls potentially compromising structural integrity.

The limitation of the traditional bell dome is rooted in the physics of spherical shell vibration. To significantly lower the fundamental frequency of a bell, the physical diameter must be drastically increased, or the walls severely thinned, both of which can violate the form-factor and durability constraints of a bicycle-mounted device. Therefore, future prototype development will focus on innovating the traditional mechanical bell paradigm. The core engineering directive is to design an acoustic structure capable of mechanically generating this lower frequency band while strictly adhering to volumetric constraints. This will likely require exploring acoustic principles, such as:

- **Transverse Beam Resonators (Cantilevers/Tines):** Investigating the integration of fixed-beam structures alongside traditional shell vibration. Because the fundamental pitch of a vibrating cantilever is dictated primarily by its length to thickness ratio rather than volumetric displacement, a tuned metallic tine can reach the 700-800 Hz target within a highly compact space.
    - *Trade-offs:* While packaging is efficient, a vibrating beam inherently displaces less air than a bell dome, potentially resulting in a lower Sound Pressure Level (SPL) and weaker acoustic projection. To overcome this, the tine must be efficiently coupled/ impedance matched to a resonant chamber/ soundboard. Additionally, this introduces mechanical complexity, requiring an actuation mechanism capable of simultaneously striking both the high-frequency dome and the low-frequency tine with sufficient force.

- **Dual-Resonator Geometries:** Designing structures that vibrate at distinct, isolated frequencies without phase cancellation.
- **Integrated Acoustic Chambers:** Utilizing principles like Helmholtz resonance to selectively amplify the lower-frequency waves generated by the mechanical strike to compensate for the tine's lower air displacement. Although this may be difficult given the size constraints.
- **Variable Wall Thicknesses:** Manipulating the geometry and alloy selection of the primary acoustic radiating surface to artificially lower its fundamental resonance.

Crucially, these acoustic modifications must be achieved while preserving a compact, lightweight form factor that allows for secure, ergonomic, and standardized mechanical fixation to a bicycle handlebar. By solving this specific frequency-to-volume challenge, the resulting device will successfully combine the acoustic penetration required to alert isolated pedestrians, with and without ANC headphones, with a mechanically sound and reliable system.

7. Bibliography

B. McFee et al. (2015). Librosa: Audio and music signal analysis in python. *14th python in science conference*.

Boashash, B. (1992). Estimating and interpreting the instantaneous frequency of a signal. I. fundamentals. *Proceedings of the IEEE*, *80*, pp. 520-538. doi:10.1109/5.135376

Deutsches Institut für Normung. (n.d.). DIN 33946:2010-09, Bells for bicycles and mopeds - Requirements and testing. DIN 33946:2010-09.

Farina, A. (2000, February). Simultaneous measurement of impulse response and distortion with a swept-sine technique. *Audio Engineering Society*.

Haykin, S. (1996). *Adaptive filter theory* (3rd ed.). Prentice-Hall.

Health and Safety Executive. (n.d.). *Noise*. Retrieved from https://www.hse.gov.uk/agriculture/topics/noise.htm#:~:text=The%20action%20levels%20are%20defined,animal%20housing%20at%20feeding%20times;

Hsieh, M. C., Chen, H. J., Tong, M. L., & Yan, C. W. (2021). Effect of environmental noise, distance and warning sound on pedestrians' auditory detectability of electric vehicles. *International Journal of Environmental Research and Public Health, 18*. doi:10.3390/ijerph18179290

Hugo, & Zwicker, E. F. (2007). *Psychoacoustics: Facts and models* (Third ed.). Springer.

International Standards Organisation. (2015). *ISO 14878: Cycles - audible warning devices-technical specification and test methods*. Retrieved from www.iso.org

Lin, M. I., & Huang, Y. P. (2017, April). The impact of walking while using a smartphone on pedestrians' awareness of roadside events. *Accident Analysis & Prevention, 101*, 87-96. doi:10.1016/j.aap.2017.02.005

Mesimäki, J., & Luoma, J. (2021). Near accidents and collisions between pedestrians and cyclists. *European Transport Research Review, 13*. doi:10.1186/s12544-021-00497-z

Pucher, J., & Dijkstra, L. (2011, October). Promoting safe walking and cycling to improve public health: Lessons from the netherlands and germany. *93*, 1509-1516. doi:10.2105/AJPH.93.9.1509

Rane, M., Coleman, P., Mason, R., & Bech, S. (2022). Survey of user perspectives on headphone technology. *AES Show Spring 2022.* Audio Engineering Society.

Reported road casualties in great britain: Pedal cycle factsheet, 2023 - GOV.UK. (n.d.). Retrieved from https://www.gov.uk/government/statistics/reported-road-casualties-great-britain-pedal-cyclist-factsheet-2023/reported-road-casualties-in-great-britain-pedal-cycle-factsheet-2023

The highway code - guidance - GOV.UK. (n.d.). Retrieved from https://www.gov.uk/guidance/the-highway-code

The Pedal Bicycles (Safety) Regulations 2010. (n.d.). Retrieved from https://www.legislation.gov.uk/uksi/2010/198/regulation/4/made

United Nations. (2021). UN reg 138.

Unity Technologies. (n.d.). *Unity Real-Time Development Platform | 3D, 2D, VR & AR Engine*. (Unity) Retrieved from https://unity.com/

Walton, T., Torija, A. J., & Elliott, A. S. (2022, December). Development of electric scooter alerting sounds using psychoacoustical metrics. *Applied Acoustics, 201*. doi:10.1016/j.apacoust.2022.109136