Improving Motorcycle Safety: Designing and Assessing Auditory Alert Systems for Motorcyclists

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Introduction

In the current state of the art, the sensors which are mounted on the motorcycle are almost all “inward looking”, meaning that they are concerned with the running of the vehicle engine and ancillary systems such as brakes and suspension. In the event that such systems encounter a problem this is almost always communicated back to the rider using an indication on the dashboard. This indication may take the form of a warning light or a pop-up message, but in all cases the communication can only be deemed successful when the rider next looks at the dashboard and takes note of the message. Typically, the delay between the fault condition being identified and the rider being informed can vary from a few seconds to a few minutes, however this lag is not normally an issue because very few fault conditions linked to “inward looking” sensors require such a rapid reaction from the rider.

In the future though this dynamic will change. Most cars are now fitted with “outward looking” sensors, such as cameras, radars, or radio connections with other vehicles. This provides the opportunity to make the driver more ‘aware’ of their surroundings should an undesirable situation occur – for example if there will be a collision with the vehicle in front, or if a correction is required to stay in the driving lane. Bit by bit such innovations are starting to transfer across to motorcycles; however, the issues detected by outward looking sensors are quite different from the inward-looking sensors. The circumstances of the outside environment can change quite rapidly from ‘safe’ to ‘risky’ and often for the rider to get the benefit of such warnings they need to be able to react to them as soon as they are announced – there is no longer the luxury to wait several minutes for a reaction.

In the automotive world OEMs have been resorting to audio warnings to supplement the ‘urgency’ of situations which require an input due to outward looking sensors, and this approach could also make sense for motorcyclists, however it is not as straightforward as for cars. Motorcycles do not have by default an auditory means to alert the rider, and the wind noise created at speed forms a significant obstacle on the reliable delivery of such a warning. Based on this, this paper aims to analyze such obstacles, assess the limitations of acoustic feedback, and demonstrate the feasibility of implementing auditory warnings for motorcyclists.

There are many sounds in life that we are familiar with and have a distinctive reaction to (for example a bicycle bell or a train horn) it would be desirable if there could be such a standardized tone for motorcyclists which would also trigger an appropriate reaction without them having to think about what the signal means. While various auditory warnings in cars can alert drivers to hazards—such as open doors, unfastened seatbelts, nearby vehicles during parking, lane departures, and potential collisions—motorcyclists have not yet benefited from similar acoustic signals due to several challenges. This project aimed to analyze these obstacles, assess the limitations of possible acoustic feedback, and demonstrate the viability of implementing auditory warnings for motorcyclists through a perceptual study.

Understanding the Design Constraints

The primary requirement for any warning sound is that it must be noticeable in the intended usage scenarios. Consequently, the initial step involved examining the properties of the acoustic communication channel in motorcycle riding environments.

Real Driving Recordings & Wind Tunnel Measurements

Motorcyclists are exposed to significantly higher levels of ambient noise because helmets provide only limited attenuation, unlike cars, which effectively reduce external ambient sounds such as wind noise within the cabin. To evaluate the ambient noise levels at a motorcyclist's ear, both real-world driving tests and wind tunnel experiments were conducted, using a miniature microphone positioned inside the helmet. Simultaneously, velocity data was captured through the CAN bus during the driving scenarios. In the wind tunnel, participants were seated in front of the airflow while varying their speed, posture, helmet type, and head orientation. To ensure that warning sounds would be perceptible, the study assumed a worst-case scenario involving high-speed riding at the maximum legal limit of 130 km/h, which is common in many countries. Figure 1 illustrates the peak hold levels from various measurements. The driving tests reached speeds between 120 and 130 km/h, prompting wind tunnel measurements to be conducted at a corresponding airflow speed of 120 km/h. For reference, one measurement at 90 km/h is shown in blue. This data helps establish the frequency-dependent minimum sound levels required for the warning signals to remain audible above the ambient noise.

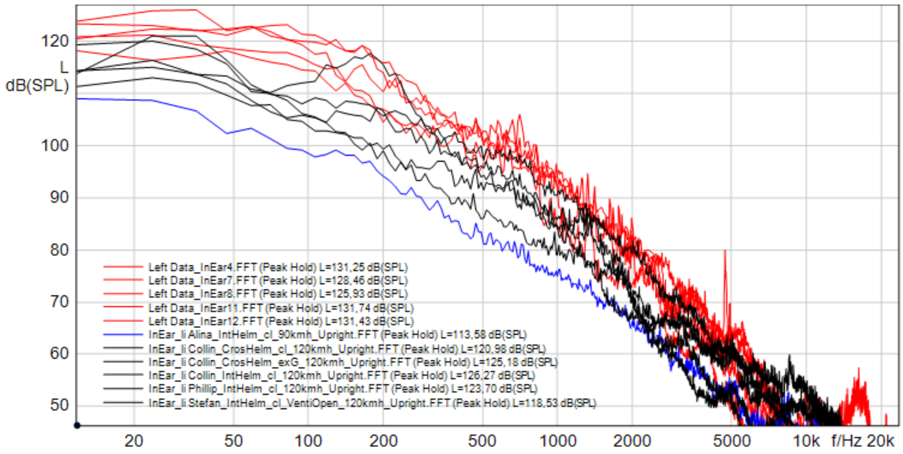


Fig.1. Ambient noise (peak hold FFT) for wind tunnel measurements (red) and real riding measurements (black) for different riders at 120 km/h and 90 km/h (blue)

Audio Reproduction System Characterization

The previously identified high ambient noise levels suggest that any audio system used to produce warning sounds must deliver a sufficiently high sound pressure level. Unlike cars, which have space for larger voice coil drivers, motorcyclists rely on smaller headphones, which may produce lower output levels. Additionally, Bluetooth helmet communication systems for motorcycles are typically optional accessories, meaning their sound output can vary significantly even with the same input signal from the motorcycle. To explore this variability, eight different headsets, varying in brand and speaker size, were chosen as representative of commonly used models. The maximum output at the ear was measured for each headset, showing how their performance differs across frequencies (see Fig. 2). This data provides insight into the highest output levels these systems can achieve for sinusoidal signals (refer to the dashed line in Fig. 2).

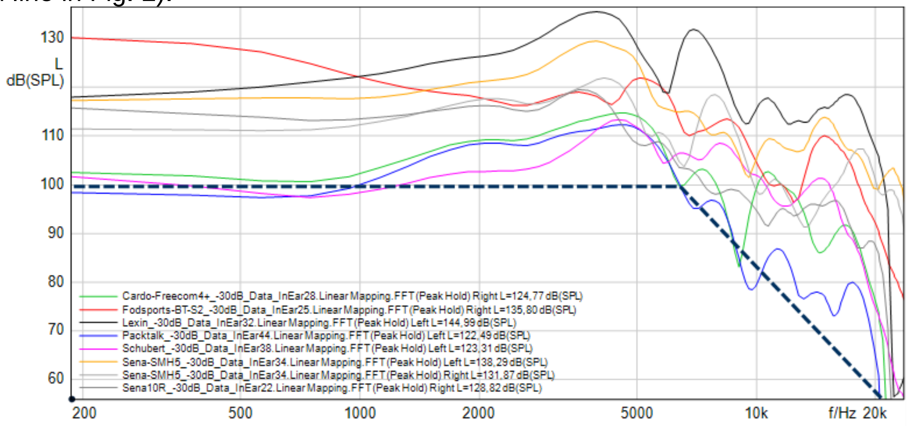


Fig.2. Maximum output of various in helmet blue tooth headsets.

Human Factors and Psychoacoustics

Psychoacoustic considerations also played a crucial role in the design process [1]. The hearing threshold establishes the minimum level for warning sounds, though ambient noise typically surpasses this threshold for healthy individuals. However, older adults, (starting from the age 50), often experience increased hearing thresholds at higher frequencies. To account for this, warning sounds must be designed to exceed the hearing threshold of a 70-year-old male who have a higher threshold compared to a similar aged female (as shown in Fig. 3). On the other hand, there is also a need to avoid sound pressure levels above 90 dB, which pose a risk of ear damage (see Fig. 3). This upper limit of course also depends on exposure time, but regardless, excessively loud sounds would likely lead to poor user acceptance

Resulting Design Space

By summarizing all the different requirements, a design framework for warning sounds in motorcycle applications can be established (see Fig. 3). It becomes clear that only a limited frequency range, approximately between 1000 Hz and 8000 Hz, and a sound level between 50 dB and 90 dB can be effectively used to deliver acoustic warnings to motorcyclists.

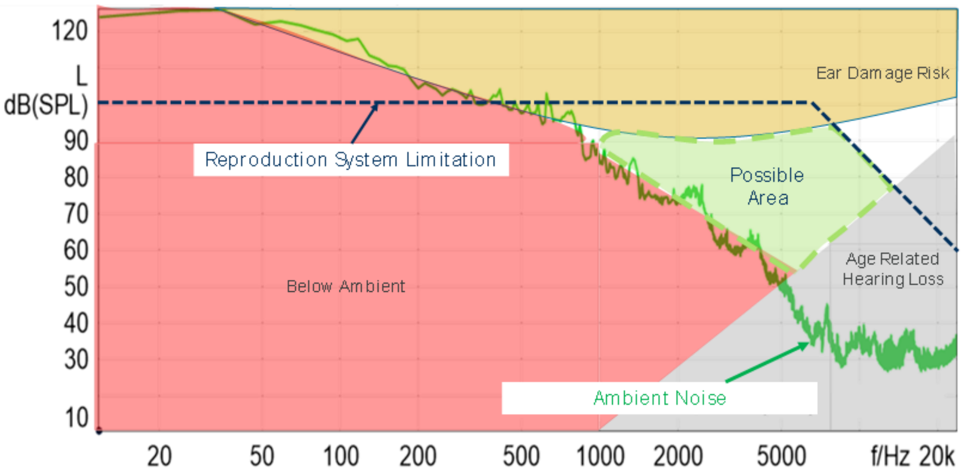


Fig.3. Design space for warning sounds for motorcycle riders

Designing the set of Warning Sounds

Following the definition of the design space, warning sounds must be specified to meet these constraints. The objective of these sounds is to intuitively communicate feedback about potential threats (e.g., an obstacle in the path) without requiring extensive training to understand their meanings. Ideally, the message should be conveyed quickly to allow motorcyclists sufficient time to respond to the danger. Generally, fewer, shorter feedback messages promote intuitive understanding and rapid recognition, while a higher number of more complex messages can provide more expressive feedback. To prioritize the acoustic warning system, potential threats were categorized into five directions (front high, front dashboard, left, right, back) and two levels of criticality (low and high), resulting in a total of ten feedback messages (Table 1).

Table 1.1. Definition of design states

Design	Direction	Urgency
1	Front	Low
2	Dashboard	Low
3	Back	Low
4	Left	Low
5	Right	Low
6	Front	High
7	Dashboard	High
8	Back	High
9	Left	High
10	Right	High

Building on psychoacoustic research regarding warning sounds, pulsating tonal sounds are preferred [2,3,4,3,4]. The duration of individual pulses should exceed the temporal integration interval of 200ms, as the masking threshold for pulses of 20ms duration can be raised by up to 10 dB [1]. However, the overall length of the warning sound affects the time needed for the motorcyclist to process the feedback and should be kept as short as possible. Given that these warning sounds are designed to alert riders to unexpected events, the sound duration should be significantly less than the reported reaction time of 1.5 seconds for surprise events [5]. According to the design constraints, a base frequency of 1500 Hz was established, with two additional frequency components added to enhance robustness against masking by ambient noise. To avoid creating a harmonic impression unsuitable for warning sounds, the frequency ratios were set to 1:1.625 and 2.25. From a musical theory perspective, these three frequency components approximate a D# diminished triad, which conveys a sense of being “unfinished,” thereby serving as an alert signal. This close spacing between components also results in a relatively narrow bandwidth, allowing for adjustments in the base frequency to encode information while staying within the defined design space.

Due to individual variations in the average head-related transfer function, binaural rendering of directional cues is not reliably achievable. Instead, for the front and dashboard directions, successive shifts in the base frequency were defined, as their intuitive associations suggest looking up or down. For the resulting ascending or descending arpeggio, the base note frequencies were selected to sound dissonant. Musically, the sequence of base frequencies forms an F# minor seven and flat five chord, a half-diminished chord that conveys tension, making it suitable for warning sounds.

Since the headsets operate in stereo, both channels can be utilized to code left and right directional cues through level differences between the channels. Discriminating the back direction from the front is challenging without broadband reproduction that can render differences in directional frequency bands. Therefore, a sound alternating between the left and right channels was chosen, easily distinguishable from the left cue with constant left channel reproduction, the right cue with constant right channel reproduction, and the frontal cues with simultaneous signals in both channels. Criticality information was encoded in the pulse rate: a faster pulse rate indicated a more urgent danger, while a slower pulse rate signaled less urgency. Additionally, reverb was applied to create the impression of a greater distance from the threat. Figure 4 illustrates the warning sounds for the ten feedback messages, all of which fall within the frequency range of 1500 Hz to 6500 Hz.

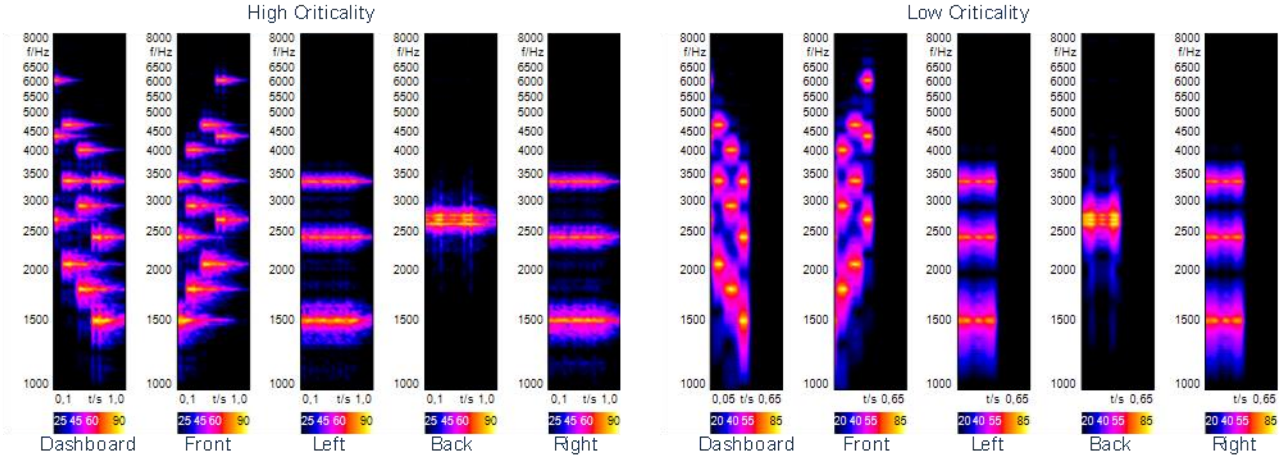


Fig.4. Designed feedback sounds for the high criticality level (left) and the low criticality (right) for each of the five directions

Perceptual Sound Experiments

Following the development of the ten warning signals, their effectiveness was evaluated through two listening experiments. The first experiment employed a Likert scale to assess the perceptibility, urgency, and annoyance of the signals. This initial experiment also served to familiarize participants with the sounds but did not clarify the specific meanings of each warning. In the second experiment, participants' recognition times were measured alongside their accuracy in identifying warning sounds played over ambient sounds recorded from real motorcycles, simulating decision-making under time pressure in a realistic context. Participants were instructed to respond as soon as they “heard and understood the information conveyed by the warning sound.” Their immediate reactions stopped the playback, recorded their reaction time, and required them to choose one of the ten feedback sounds. The reaction times are illustrated in Fig. 5, indicating that the times for high-threat scenarios were close to the 0.7 seconds reported for fully attentive drivers in existing literature. Additionally, reaction times tended to decrease with each successive trial, as shown in Fig. 6.

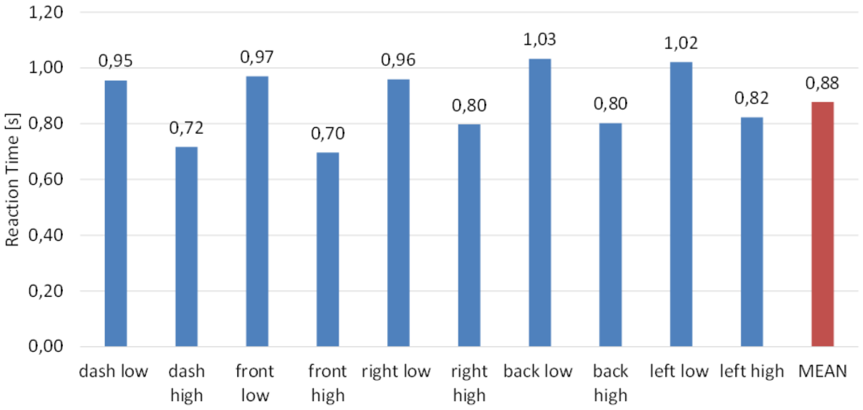


Fig.5. Reaction times measured for the recognition of the feedback sounds averaged over six trials

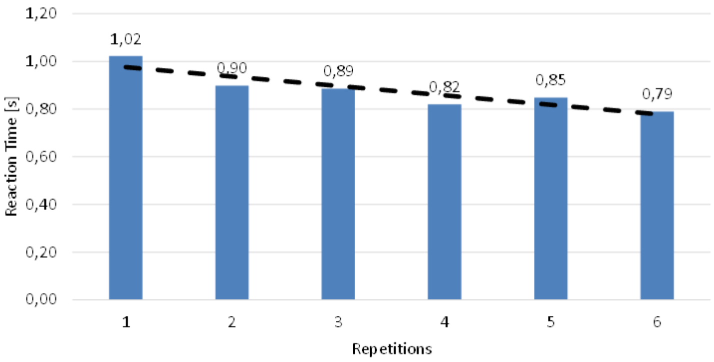
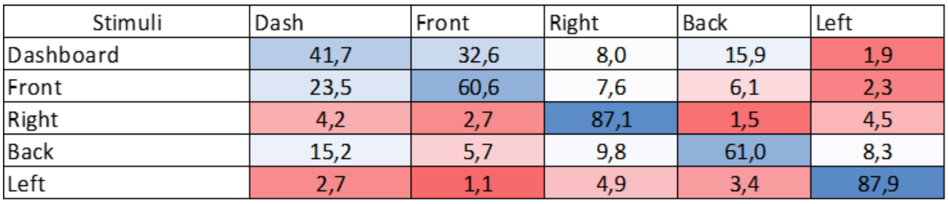


Fig.6. Change in reaction times measured for the recognition of the feedback sounds over six trials

The confusion matrix displaying the rates of correct identifications for the five directional cues is presented in Fig. 7. The accuracy for right and left warning sounds was predictably high due to their clarity. In contrast, participants could still accurately determine the correct direction for front, back, and dashboard cues up to 60% of the time. Considering that the guessing rate is 20% for purely random selection, this accuracy is relatively strong. However, the results were less favorable regarding urgency. Regardless of whether the sound indicated low or high urgency, participants tended to classify the sounds as low urgency 60% of the time, suggesting that without visual context, they could not perceive significant differences in urgency. Nevertheless, the binary choice format of the second experiment limited the ability to detect nuances in urgency perception. A comparison with the 100-point rating scale from the first experiment shows significant but small differences in urgency levels. Given the constrained design space, communicating high differences in urgency through absolute sound levels may be inherently challenging. However, participants might learn to discern differences in urgency through extended exposure to the warning sounds in real situational contexts.



Stimuli	Dash	Front	Right	Back	Left
Dashboard	41,7	32,6	8,0	15,9	1,9
Front	23,5	60,6	7,6	6,1	2,3
Right	4,2	2,7	87,1	1,5	4,5
Back	15,2	5,7	9,8	61,0	8,3
Left	2,7	1,1	4,9	3,4	87,9

Fig.7. Percentages of recognitions for the directional cues communicated by each directional feedback sound group

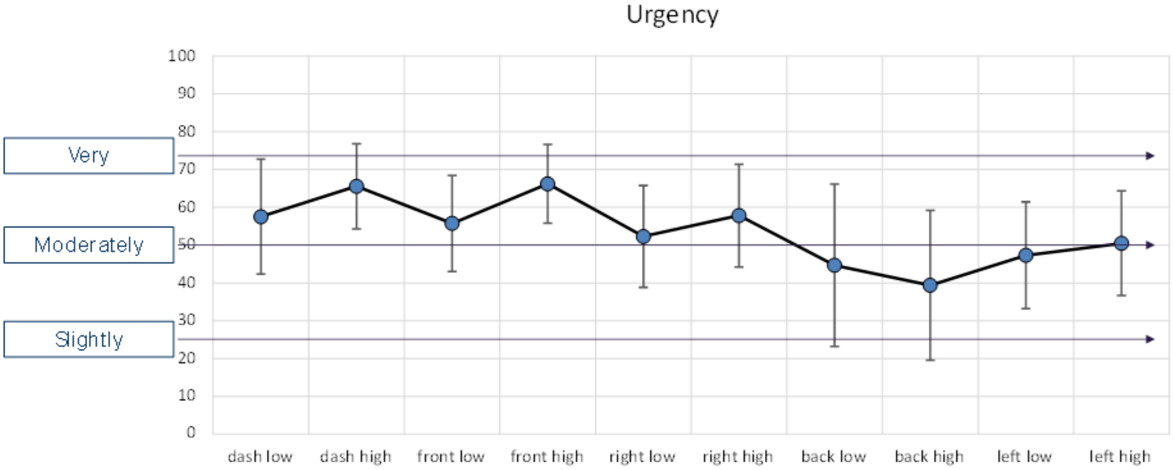


Fig.8. Perceived urgency ratings for the feedback sounds

Conclusion

The study examined the key design constraints for warning sounds intended for motorcycles. Factors such as wind noise, the audio reproduction characteristics of common headsets, elevated hearing thresholds in older motorcyclists, and the risk of ear damage together established a limited design space for these warning signals. Within this context, a set of ten feedback messages was developed to convey both the direction and severity of potential threats. Findings from a perceptual study revealed that participants were able to intuitively grasp the directional cues, achieving high accuracy without any prior training or explicit instructions regarding the meanings of the messages. However, it was challenging to communicate an absolute level of urgency effectively within the defined constraints. Therefore, understanding urgency might require initial learning in a visual context before participants can differentiate it in relative terms. Alternatively, the warning tones could be designed to indicate just a single level of urgency. In all cases, and regardless of how many tones there may be, stakeholders should consider carefully any potential opportunities to harmonize such warnings in order to hasten the correct and desired reaction from the motorcyclist.

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