Design and Evaluation of Auditory Warning Sounds for Motorcyclists

Serkan Atamer[1], Robert Rosenkranz[2], Colin Ballantyne[3], Alina Kuttler[3], M. Ercan Altinsoy[2],
[1,2]*Professur Akustik und Haptik, Technische Universität Dresden, 01062 Dresden,* [2] *E-Mail:robert.rosenkranz@tu-dresden.de*
[2]*Centre for Tactile Internet with Human-in-the-Loop (CeTI)*
[3]*KTM AG)*

Introduction

Like all drivers, motorcyclists are often exposed to dangerous situations in traffic. However, compared to car drivers they sustain greater injuries in an accident. In the car, advanced driver-assistance systems are available which can provide warnings to the driver, for example. auditory warnings are utilized to alert the driver to open doors, unfastened seatbelts, vehicles in close proximity while parking, accidental departure from the lane as in lane assist systems and even collision warnings e.g. for emergency breaking. Due to a number of challenges, motorcyclists could so far not benefit from such acoustic warning signals. Therefore, this project attempted to analyze some of these challenges, quantify the boundaries of potential acoustic feedback and demonstrate the feasibility of an optimal acoustic warning for motorcyclists in a perceptual study.

Definition of Design Constraints

The most fundamental requirement of any warning sounds is that they need to be perceptible in the planned contexts of utilization. Therefore, the first step was the investigation of the characteristics of the acoustic communication channel in motorcycle riding situations.

Real Driving Recordings & Wind Tunnel Measurements

In contrast to cars that provide a high attenuation of exterior ambient noise such as wind noise to the driver in the cabin, motorcyclists are exposed to a much higher ambient noise due to the helmet only providing comparatively lower attenuation. To assess the ambient noise level at the ear of the motorcyclist, real driving measurements and wind tunnel measurements were conducted using a omnidirectional miniature microphone (DPA SC4060) positioned inside the helmet at the position of the ears. Velocity information was recorded simultaneously via the CAN. In the wind tunnel, subjects were sitting in front of the air stream with varying velocities, postures, helmets and head orientations. To ensure perceptibility of the warning sounds, a worst case of ambient noise exposure was assumed, i.e. high-speed driving scenarios at the maximum speed limit of 130 km/h ubiquitous in the majority of countries. Fig. 1 shows the peak hold levels of different measurements. In the driving scenarios, the maximum velocity was around 120 to 130 km/h and thus wind tunnel measurements were conducted with an equivalent airflow velocity of 120 km/h. As a comparison, one 90 km/h measurement is also provided in blue. The obtained data informs the frequency dependent minimum level required for the warning sounds to not be masked by the ambient noise.

Audio Reproduction System Characterization

The high ambient noise levels identified previously imply that any audio reproduction system utilized for the warning sound generation needs to output a sufficiently high sound pressure level. In contrast to cars that provide room for larger voice coil drivers, helmet dimensions and protection requirements limit motorcyclists to slim headphones that generate potentially lower output levels. Furthermore, motorcycle Bluetooth helmet communication systems are an optional accessory to the helmet and the effective sound output level can thus vary significantly for the same input signal provided by the motorcycle. Therefore, a

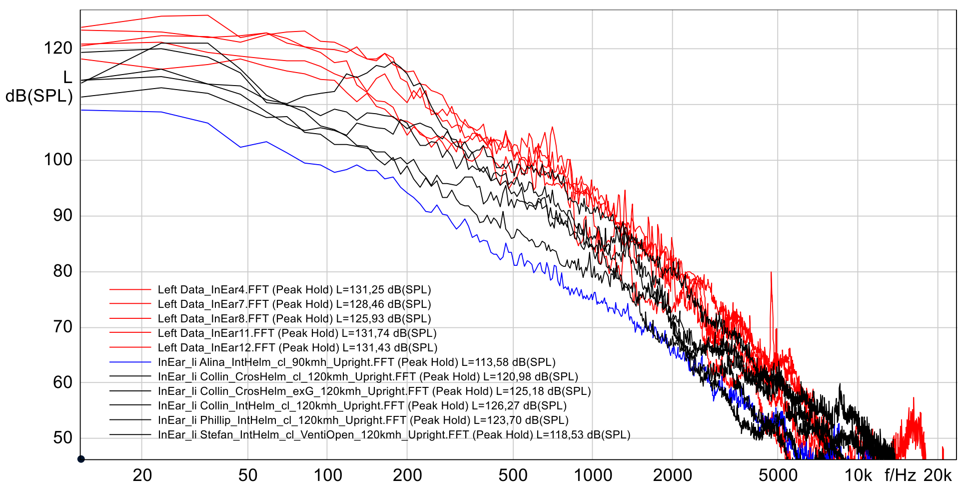

Fig. 1: Ambient noise (peak hold FFT) for wind tunnel measurements (red) and real riding measurements (black) for different riders at 120 km/h and 90 km/h (blue)

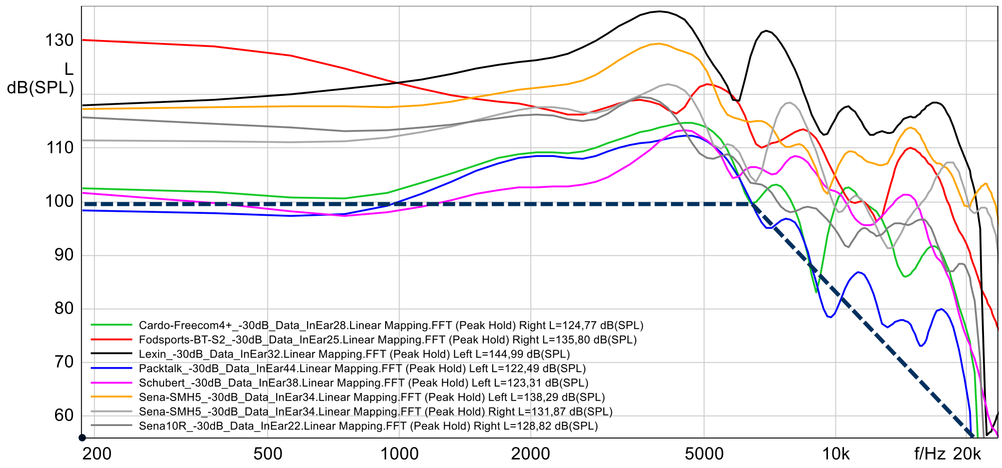

Fig. 2: Maximum output of various in helmet blue tooth headsets.

representative set of eight headsets that with all typically encountered speaker sizes of various brands. For each headset the frequency dependent maximum volume i.e. sound pressure output at the ear was measured (see Fig. 2). Again, the obtained data informs the frequency dependent maximum level, which these reproduction systems can be expected to at least be capable of reproducing for sinusoidal excitation (see dashed line in Fig. 3).

Human Factors and Psychoacoustics

Lastly, psychoacoustic factors needed to be taken into account for design [1]. The hearing threshold defines an obvious minimum warning sound level. Even though the ambient noise level should usually exceed the hearing threshold in healthy subjects, older subjects usually exhibit a raised hearing threshold at higher frequencies [1]. Again, assuming a worst-case scenario, warning sounds need to exceed the hearing threshold of a 70-year-old male (see Fig. 3). Another factor that needs to be considered is the ear damage risk associated with high sound pressure levels above 90 dB (see Fig. 3) defining an upper level limit. Although this limit depends on the exposure time, the user acceptance would prevent utilizing excessive levels anyway.

Resulting Design Space

Summarizing all the various requirements, a design space for warning sounds in motorcycle applications can be derived (see Fig. 3). It is obvious that only a relatively narrow frequency range from about 1000 Hz to 8000 Hz and a level from about 50 dB to 90 dB can be utilized for communicating acoustic warnings to the motorcyclist.

Designing the Set of Warning Sounds

After the definition of the design space, warning sounds need to be specified that fulfill these constraints. The goal of the warning sounds is to convey the intended feedback message for a threat (e.g. obstacle in motion path) intuitively instead of requiring long training for learning their meanings. Preferably, the message should be conveyed as quickly as possible to provide the motorcyclists with ample time to react to the danger. Generally, a lower number of short feedback messages facilities intuitive understanding and fast recognition, while higher number of more complex structures messages allows for a more expressive feedback. Given the priorities for an acoustic warning system, potential threats were grouped to five categories (front, dashboard, left, right, back) and two criticality levels (low and high) resulting in a total of 10 feedback messages.

Building onto psychoacoustic investigations on warning sounds, pulsating, tonal sounds are preferable [2]. The duration of the single pulses should be above the interval for

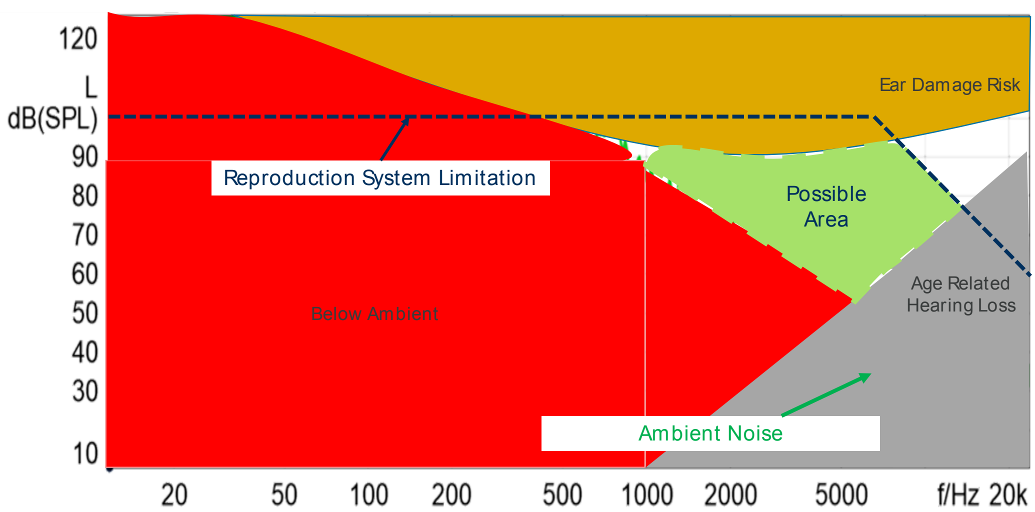

Fig. 3: Design space for warning sounds for motorcycle riders

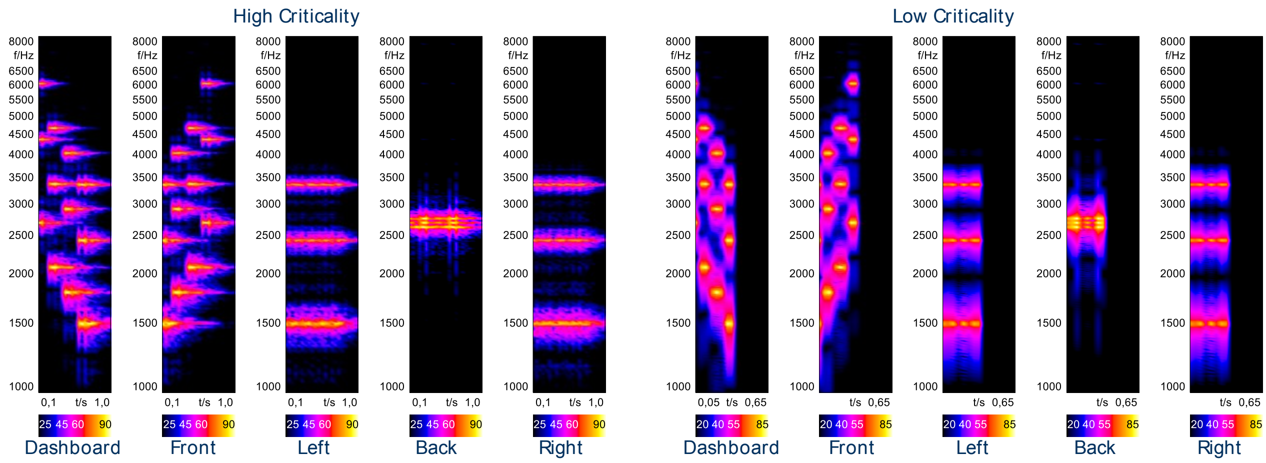

Fig. 4: Designed feedback sounds for the high criticality level (left) and the low criticality (right) for each of the five directions

temporal integration of 200 ms [1] since the masking threshold for the pulses is raised up to 10 dB for pulses of 20 ms duration. However, the total duration of the warning sound will determine the duration necessary for the motorcyclist to process the feedback and thus should be as short as possible. Considering that the warning sounds are supposed to alert the driver to surprise events, sound duration warning should be well below the reaction time of 1.5 s reported for surprise events [3]. According to the design constraints, the base frequency was set to 1500 Hz. Two additional frequency components were added to provide more robustness against masking by ambient sounds. Since the addition of frequencies with full or half multiples of the base frequency convey a harmonic impression unsuitable for warning sounds, the frequency ratios were set to 1:1.625 and 2.25. Considering these three frequency components from a music theory perspective, it approximates a D# diminished triad, conveying the impression of being “unfinished” i.e. alerting. This compact spacing between the components also has the advantage of resulting in comparatively narrow bandwidth that allows for shifts in base frequency for encoding information, while remaining in the limited design space.

Due to the individual deviations from an average head related transfer function, binaural rendering of directional cues is not reliably possible. Instead, for front and dashboard direction successive base frequency shifts upwards and downwards were defined due to their intuitive connotation of moving up and down and thus communicating to the driver to look up or down. For the resulting arpeggio upwards or downwards the base note frequencies were chosen to sound disharmonious. From a music theory perspective, the succession in bas frequency constitutes an F sharp minor seven and flat five chord, which is a half-diminished chord that conveys tension suitable for warning sounds. Since the headsets are always stereo, both channels can be utilized to communicate the left and right direction by level differences between both channels. Discriminating the back direction from the front direction is difficult without broadband reproduction to render differences in directional frequency bands. Therefore, it was decided to instead fall back on a sound alternating between left and right channels that can easily be discriminated from the left cue with a constant left channel reproduction, the right cue with a constant right channel reproduction and the frontal cues with constant and simultaneous signals reproduced in both channels. The criticality information was encoded in the pulse rate. If the danger is more urgent, the pulse rate is faster, and if the danger is less urgent, the signal has a lower pulse rate. An additional reverb was added to convey the impression of a higher distance of the threat. Fig. 4 shows the warning sounds for the ten feedback messages. The sounds all fall within a frequency range from 1500 Hz to 6500 Hz.

Auditory Validation Experiments (User Study)

After designing the set of ten warning signals, their efficiency was investigated in two listening experiments. The first experiment was a Likert scaling experiment, which investigated the perceptibility, urgency and annoyance of the signals. This also provided a familiarization for the second experiment but did not explain the intended meanings of each warning sound. In the second experiment, recognition

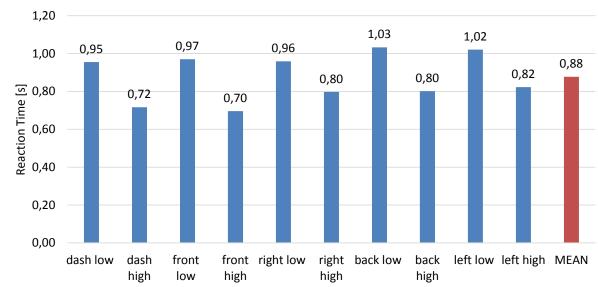

Fig. 5: Reaction times measured for the recognition of the feedback sounds averaged over six trials

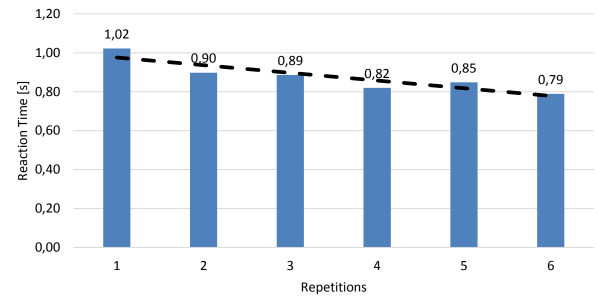

Fig. 6: Change in reaction times measured for the recognition of the feedback sounds over 6 trials

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 correct recognitions for the directional cues communicated by the each directional feedback sound group

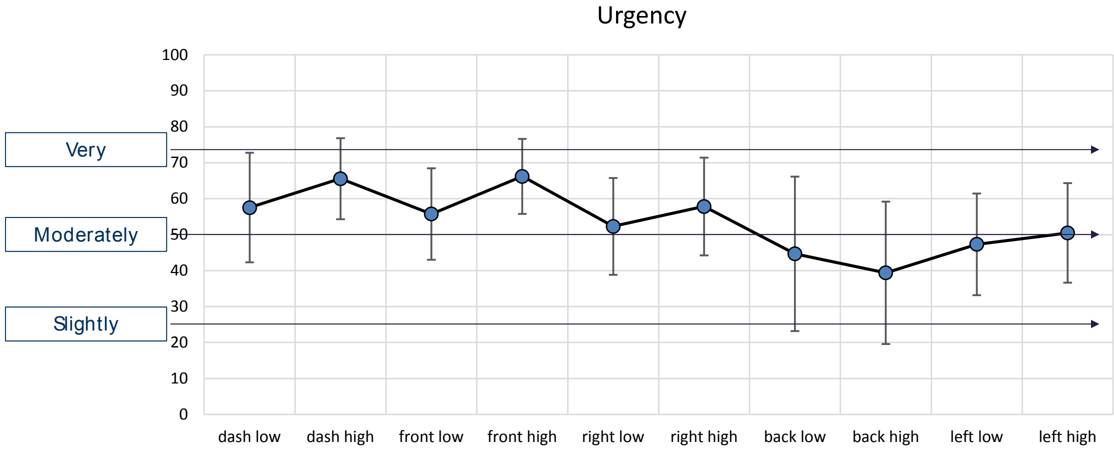

Fig. 8: Perceived urgency ratings for the feedback sounds

times of the participants were measured simultaneously to the correctness rate of the recognitions of the warning sounds superimposed to the ambient sounds recorded on real motorcycles to reflect decision under time pressure in the real application scenario. 28 Participants (9 motorcyclists, 19 non-motorcyclists) with an average age of 31 years were instructed to react to the randomly presented scenarios as soon as they "hear and understand the information conveyed by the warning sound". Their reaction immediately interrupted the playback of the sound, saved the reaction time and they were forced to select one of the ten feedback sounds. The reaction times (Fig. 5) of the high threat scenarios approximate the 0.7 seconds of fully attentive drivers [3]. Furthermore, the reaction times were trending lower for each successive trial as evident in Fig. 6

The confusion matrix containing the rates of correct detections for the five directional cues is shown in Fig. 7. For right and left warning sounds, it was expectedly high, since the cues were obvious. However, for front, back and dash, participants were still able to decide the correct direction with an accuracy up to 60%. Given the guessing level of 20% of correctly deciding purely by chance, it is a relatively high accuracy. However, the results were not so effective for the urgency. Independently of low or high urgency sound, participants decided for low urgency with a rate of 60%, seemingly implying no difference in perceived urgency without any visual context. However, due to the binary choice between high and low urgency in experiment two, no nuance in perceived urgency can be detected. A comparison to the ratings on the 100-point rating scale of experiment one, demonstrates significant although small differences in urgency. Given the very constrained design space, high differences in urgency (e.g. by drastic level differences) are likely difficult to communicate intuitively for absolute urgency level. However, subjects might learn differences in urgency level by prolonged exposure to the warning sounds in the real situational contexts.

Conclusion

The fundamental design constraints for warning sounds in motorcycles were analyzed. The wind noise, the reproduction characteristics of typical headsets, raised hearing thresholds for older motorcyclists, and ear damage risk thresholds in sum defined a very constrained design space for such warning sounds. Within this design space, warning sounds for ten feedback messages were defined to communicate the direction of the threat and the level of the threat. A perceptual study demonstrated, that the direction can be intuitively conveyed to subjects resulting in a high accuracy even without prior training or explicit instruction of the meaning of the message. However, conveying an absolute urgency level intuitively is not easily possible within the constraint design space and thus the urgency meaning would need to be learned initially in the situational visual context and subsequently discriminated in a relative fashion. Alternatively, the warning tones would be utilized to communicate only one level of urgency.

References

[1] H. Fastl and E. Zwicker, *Psycho Acoustics - Facts and Models*, 3rd ed. Springer Verlag, Berlin, 2010.

[2] E. C. Haas and J. Edworthy, "Designing urgency into auditory warnings using pitch, speed and loudness," *Computing & Control Engineering Journal*, vol. 7, no. 4, pp. 193–198, 1996.

[3] M. Green, " How long does it take to stop?" Methodological analysis of driver perception-brake times," *Transportation human factors*, vol. 2, no. 3, pp. 195–216, 2000.