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EXPERIMENTAL ASSESSMENT OF DIFFERENT CAR DRIVING STYLES AND THEIR ROLE IN ROAD TRAFFIC NOISE ANNOYANCE REDUCTION

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ABSTRACT

Noise is one of the major environmental health risks. To reduce harmful exposure to noise, behavioural approaches are increasingly considered in addition to technical measures to reduce sound emissions at the source. For road traffic, encouraging pro-environmental noise behaviour, such as anticipatory driving and early upshifts when switching gears, could be an important contribution to reduce noise conflicts. However, comparatively little research addresses the influence of noise-conscious driving behaviour on the resulting noise emission and annoyance. Thus, we performed a series of controlled pass-by measurements with two different cars (ICE, BE) and different driving styles using conventional and higher-order Ambisonic microphones for recording. Selected Ambisonic recordings served as stimuli for a listening experiment conducted in the Mixed-Reality-Lab of Berlin University of the Arts. At urban speeds, both the measurement and the listening experiment results showed significant differences between driving styles in terms of noise and psychoacoustic metrics, as well as in noise annoyance.

Keywords: *Road traffic noise, Noise behaviour, Psychoacoustics.*

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1. INTRODUCTION

Road traffic noise represents one of the leading environmental health risks [1]. Many people are exposed to harmful traffic noise and feel disturbed and annoyed by it. It is therefore important to plan and implement measures to reduce noise pollution at all intervention levels [2]. In addition to the measures at the source and propagation path as well as passive measures at the receiver site, further strategies are required for adequate health protection. To exploit the options for reducing road traffic noise, the focus is therefore increasingly shifting to noise caused by behaviour. People can make noise problems worse with noise-provoking behaviour.

Studies show that in road traffic different driving styles have a significant influence on noise generation. Driving experiments in [3] already demonstrated a direct correlation between personal driving behaviour and the resulting noise emissions, measured close to significant noise sources of selected passenger cars. A sporty-aggressive driving style, simulated by a professional driver, resulted in measured sound pressure levels (SPL) that were on average 8.3 dB(A) (near engine) and 4.4 dB(A) (near tyres) higher compared to moderate driving behaviour, regardless of the type of combustion engine. Within the scope of investigations for the noise reduction potential of a speed limit of 30 km/h [4], a comprehensive series of pass-by measurements with 22 different cars was carried out at 7.5 m distance from the driving lane. The results revealed on average 3 to 4 dB(A) higher maximum pass-by SPL during moderate acceleration manoeuvres compared to a constant pass-by speed of 30 km/h, and 7 to 9 dB(A) higher maximum pass-by

SPL during aggressive acceleration manoeuvres. If the vehicles were examined individually, the maximum pass-by levels during acceleration manoeuvres were between 0 dB(A) to 16.1 dB(A) higher than the maximum pass-by SPL at a constant pass-by speed of 30 km/h. Peak levels caused by such pass-bys or by other singular road traffic events were found to hardly influence long-term energy equivalent SPL in road traffic [5]. However, eventful noise was found to decrease the self-assessed quality of sleep, to increase the time to fall asleep as well as to increase the time between stages of sleep [6]. Surprisingly and in contrast to rail traffic and aircraft noise, investigated road traffic noise in the aforementioned study with high intermittency ratio was rated less annoying than continuous road traffic noise. These result also show the complexity of potential relationships between temporal variations in noise exposure and the resulting noise annoyance, which is usually related to long-term energy equivalent SPL like $L_{\mathrm{A,eq}}$ and L_{den} by deriving exposure-response relations [7].

While existing studies quantified the influence of different driving behaviours in terms of A-weighted time-averaged SPL or maximum SPL during a pass-by, little research has been conducted that takes perceptive aspects of the human hearing into account more comprehensively. In context of driving across road markings [8] and for simulated rail noise abatement measures [9], psychoacoustic metrics were employed to model the perceived noise annoyance in listening experiments more accurately as with conventional noise metrics. In addition, the increased availability of spatial recording and playback systems like Ambisonics [10] allow for acoustically more immersive investigations, as e.g., conducted in [11].

In this work, we aimed for an investigation of the noise emitted and the noise annoyance evoked by passenger car pass-bys with different driving styles while also employing immersive recording and playback technologies. To this end, we performed a series of controlled pass-by measurements using conventional and a higher-order Ambisonic (HOA) microphone, which are described in the subsequent section of this contribution. Besides the quantification of the acoustic difference of different driving styles with conventional noise metrics, the recorded pass-bys served as basis for acoustic stimuli of a listening experiment, which is described in detail in the third part of this paper. In the last part of this contribution we compare and discuss the results obtained from acoustic metrics, as well as from the experimental noise annoyance ratings for different driving styles with passenger cars. The investigations were primarily conducted within the VELMA (VErhaltensbezogene LärmminderungsMAßnahmen) project, which investigated the potential and promotion of pro-environmental noise behaviour in road traffic [12].

2. PASS-BY MEASUREMENTS

2.1 Concept and execution

In order to assess the noise mitigation potential of different car driving styles at an immission point near the road, we performed a series of controlled pass-by measurements. The associated measurement setup is based on aspects of the standards EN ISO 11819-1 [13] and ISO 362-1 [14] and is shown in Figure 1 left. In addition to a class-1 multichannel sound level meter (in accordance to IEC 61672-1 [15]) with microphones in 7.5 m distance from the center of the lane 1.2 m and 3 m above the road pavement, we employed a HOA microphone (Zylia ZM-1, 3rd-order Ambisonics) positioned in the same distance to the center of the test lane. Based on the recommended measurement height in ISO/TS 12913-2 [16] for binaural measurement systems, the center of the HOA microphone was placed 1.6 m above the road pavement, which shall represent the location of the ear channels of a typical adult person standing. The measurement setup was implemented near a rural street with an asphalt concrete road surface in the Federal State of Lower Austria. As visible in Figure 1 right, the ground below the acoustic sensors was a cultivated field. The pass-by measurements were carried in May 2024 when the road surface was dry and the following average environmental conditions were measured: a wind speed of ≤ 3 m/s, an air temperature of 17 degree Celsius and a static air pressure of 994 hPa. Depending on the day, background noise measurements before and after the pass-by measurements lead to $L_{\mathrm{A,eq}}$ values between 35 and 40 dB(A). To calibrate the HOA microphone in terms of overall SPL, an MLS sequence was played back as a reference signal via a loudspeaker, which was placed at the edge of the test lane where it had approximately the same distance to both the measurement microphone M1 and the HOA microphone.

For consistency reasons, we employed the same test cars that were already used in the driving experiment [17] of the VELMA project - a small sports utility vehicle (BMW X3, petrol engine, first registration 2006) with internal combustion engine (ICE) and manual gear shift as well as a small family battery electric (BE) car (Cupra Born, first registration 2023). Both vehicle classifications originate from Euro NCAP [18]. A driver familiar

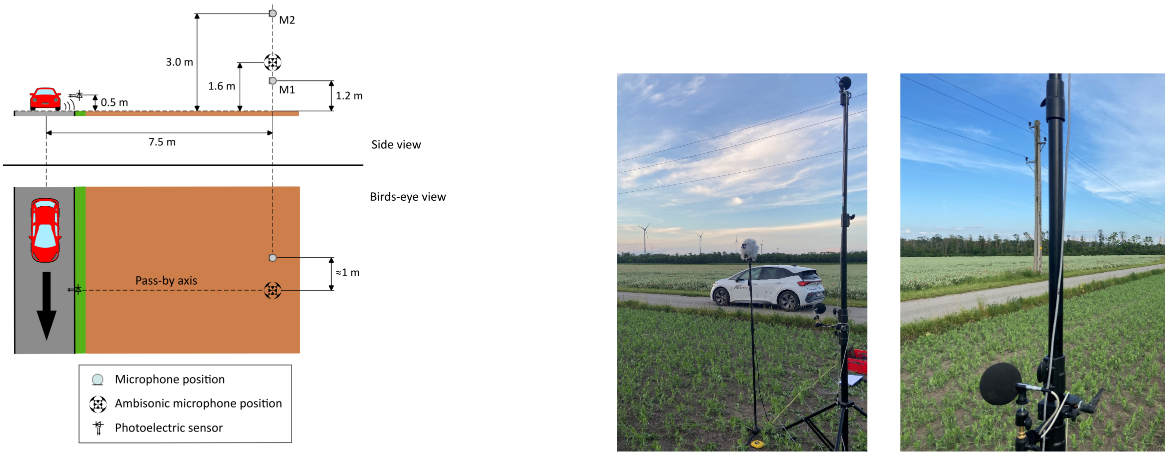

Figure 1. Side view and birds-eye view of measurement setup (left) and exemplary pass-by measurement (right).

with both cars carried out the pass-bys in two different ways: with constant speed and a specific gear (gear was selected only for ICE car) as well as with constant speed followed by a significant acceleration. These driving manoeuvres were intended to emulate a range of driving styles from prospective-ecological (low speed and high gear) to sporty-aggressive (acceleration to high speed with low gears) in a controlled and repeatable way. Depending on the desired speed at the pass-by axis (see Figure 1 left), the driver initiated the acceleration process approximately 10 m or 25 m before the pass-by axis. The performed driving manoeuvres covered target speeds from 10 km/h to 100 km/h at the pass-by axis. Geolocation, driving speed as well as the engine speed (in case of the ICE car) were recorded during the manoeuvres with a GNSS receiver and an OBD adapter, as used in [17].

2.2 Results and discussion

In total 60 valid pass-by formed the basis for the main analysis of the pass-by measurements. Based on EN ISO 11819-1 [13] and ISO 362-1 [14], the maximum A-weighted SPL with the time-weighting "fast" ($L_{\mathrm{AF,max}}$) was determined for every driving manoeuvre while considering the recorded speed closest to the pass-by axis (see Figure 1). Pass-bys where small stones in the tyre tread may have influenced the $L_{\mathrm{AF,max}}$ were discarded prior to the main analysis. Figure 2 contains the results for both vehicles (center) as well as determined logarithmic regression functions of the type $L_{\mathrm{AF,max}}$ = A + B $\log_{10}$(v / 1 kmh^{-1}) for comparable driving manoeuvres (left and right) for the microphone 1.2 m above the road surface (M1). For the ICE car with constant speeds between 10 km/h and 30 km/h, the $L_{\mathrm{AF,max}}$-values from the regression functions for the 1$^{\mathrm{st}}$ gear are between 3.3 dB(A) and 4.5 dB(A) higher than for the 2$^{\mathrm{nd}}$ gear (see also Table 1). Since the investigated ICE car is equipped with an engine that possesses a power of 110 kW, driving with up to 30 km/h in the 1$^{\mathrm{st}}$ gear may be considered as representative for a sporty-aggressive driving style for this car. For pass-bys at constant speeds above 30 km/h, the differences between the $L_{\mathrm{AF,max}}$-values for different gears and comparable speeds are $\leq$ 2 dB(A). However, manoeuvres with constant speed followed by a significant acceleration lead to higher $L_{\mathrm{AF,max}}$-values than pass-bys with constant speeds to up to approximately 60 km/h (between 1.5 dB(A) and 4.2 dB(A) based on the regression functions), as listed in Table 1 and shown in Figure 2. For the investigated BE car, manoeuvres with constant speed followed by a significant acceleration showed only significantly higher $L_{\mathrm{AF,max}}$-values to at around 30 km/h (1.4 dB(A) based on the regression functions) compared to pass-bys with constant speeds - for higher speeds, the measured difference becomes negligible due to the small sample size. For the ICE car to up to around 30 km/h, the measured higher $L_{\mathrm{AF,max}}$ of significant accelerations or driving at constant speed with low gears compared to driving at constant speed at higher gears are in line with the outcomes of the large-scale

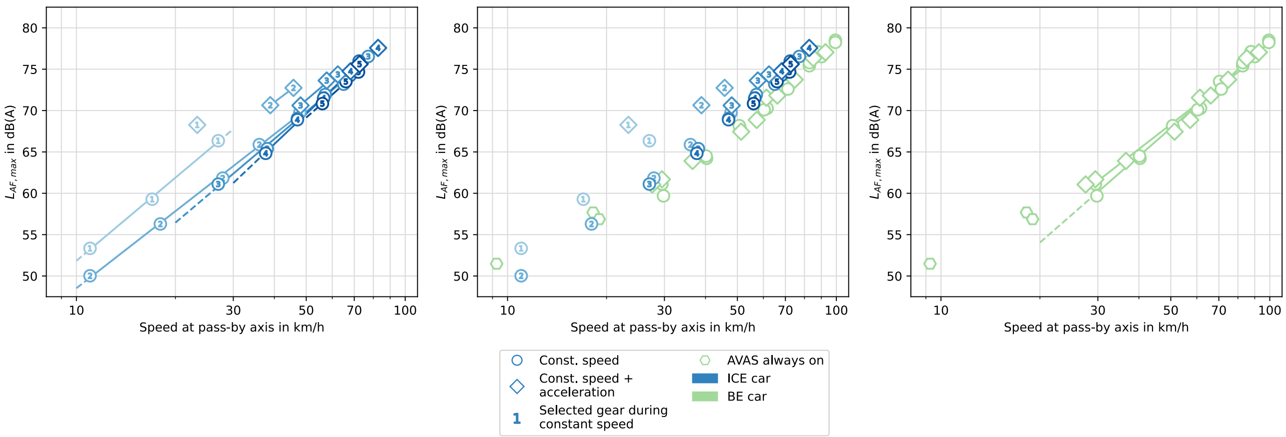

Figure 2. Maximum SPL for all (center), for investigated ICE car (left) and for investigated BE car (right). Straight lines represent logarithmic regression functions. Gears are indicated with the associated gear number and specific hues, different manoeuvres via different marker shapes. Pass-bys of BE car where the AVAS was always active were excluded from the regression analyses.

(22 different passenger cars) pass-by measurement series from [4] (see also Section 1). Due to the likely absence of Acoustic Vehicle Alerting Systems (AVAS) in 2015 for the measurements in [4] for the BE cars and the small combined sample size with this study, no clear conclusion can be drawn for BE cars. Depending on the ICE car, significant accelerations compared to driving with constant speed may lead to higher $L_{\mathrm{AF,max}}$ for speeds up to 50 km/h and even higher, as exemplary shown in Figure 2. The results for the microphone 3 m above the road surface lead to similar trends as shown in Figure 2 and listed in Table 1.

3. LISTENING EXPERIMENT

Besides assessing different driving styles with conventional noise metrics, we conducted an acoustically immersive listening experiment to investigate perceptive aspects as well as the noise annoyance caused by different car driving styles and road traffic noise scenarios. Furthermore, the experiment opens the possibility to explore whether different driving styles cause specific annoyance reactions that cannot be explained sufficiently well by SPL-based noise metrics alone.

3.1 Methodology

Within the listening experiment, participants had to rate acoustic stimuli of traffic noise scenarios according to a set of eight different perception attributes. The scenarios comprised 15 selected pass-by recordings from the measurements described in Subsection 2.1 and 15 different traffic noise recordings of urban environments. The rating attributes were selected to allow for a qualitative assessment of the multidimensional perception of road traffic noise, as proposed in [11, 19]. The selected attributes may be translated to English as *restful* (erholsam), *eventful* (ereignisreich), *threatening* (bedrohlich), *booming* (wummernd), *howling* (heulend), *close* (nah), *monotonous* (monoton) and *annoying* (lästig). All stimuli of traffic noise scenarios of urban environments are part of [20] and were recorded with the same type of microphone (Zylia ZM-1) as used for the car pass-by measurements in this study. The stimuli of urban environments already included behaviour-related individual sound events (e.g., honking, accelerating car, truck noise), or were augmented with some using VST plugins of the IEM suite [21]. From the acoustic recordings of the VELMA project, pass-bys with the following properties were selected from the ICE car: 6 with constant speed (from 11 km/h to 47 km/h and 996 rpm to 2607 rpm measured at the pass-by axis), 3 with constant speed followed by an acceleration (from 23 km/h to 58 km/h and 3174 rpm to 3782 rpm measured at the pass-by axis). The 6 selected recordings (3 at constant speed and 3 included an acceleration) for the BE car covered a speed range from

Table 1. SPL differences between two driving manoeuvres (first column) for ICE car (upper part) and BE car (lower part) at selected speeds based on regression functions as shown in Figure 2 for microphone M1.

ICE car			
Manoeuvre	$L_{AF,max}$-difference in dB(A)		
Const.	*10 km/h*	*20 km/h*	*30 km/h*
gear 1 / gear 2	3.3	4.0	4.5
Const.	*30 km/h*	*40 km/h*	*50 km/h*
gear 2 / gear 3	0.9	0.6	0.3
Const.	*40 km/h*	*50 km/h*	*60 km/h*
gear 3 / gear 4	0.6	0.2	-0.1
Const.	*60 km/h*	*70 km/h*	*80 km/h*
gear 4 / gear 5	0.7	0.8	1.0
Const.+acc. gear 1	*23 km/h*		
/ const. gear 1	4.2		
Const.+acc. gear 2	*40 km/h*		
/ const. gear 2	3.9		
Const.+acc. gear 3	*60 km/h*		
/ const. gear 3	1.5		
BE car			
Manoeuvre	$L_{AF,max}$-difference in dB(A)		
Acc. / const.	*30 km/h*	*50 km/h*	*70 km/h*
	1.4	0.5	0.0

9 km/h to 66 km/h measured at the pass-by axis. After the main part of the listening experiment, each participant had to rank the annoyance of selected different individual sound events (caused by honking, a truck or bus, emergency sirens, or high engine speeds) retrospectively, that were part of the stimuli.

The listening experiment was conducted in the Mixed-Reality-Lab of Berlin University of the Arts, which is equipped with a 21.2 loudspeaker system (see also Figure 3) that can be used for hermispheric HOA playback to create immersive sound fields in the central listening area (of approximately 3 x 3 m). On the software side, the digital audio workstation Reaper [22] in conjunction with the Panoramix Ambisonic decoder [23] was used for stimulus playback with an audio interface via the Dante (Low Latency Network Audio Protocol) network platform. For level-calibrated playback of the selected pass-by recordings we used the reference recording of the MLS signal mentioned in Subsection 2.1 to calibrate the playback system for these stimuli. After the experiment, a sound level meter with a class-1 [15] microphone was positioned at the listening position to create recordings of the stimuli, that include the same unavoidable influences caused by the acoustic properties of the loudspeakers and the playback room. For comparative analyses with the participant ratings, acoustic and psychoacoustic metrics were calculated from these recordings for this part of the work.

Figure 3. Ambisonic playback system in Mixed-Reality-Lab of Berlin University of the Arts used for the listening experiment. Source: *https://berlin-open-lab.org*

Each of the 33 participants had to rate the stimuli according to the aforementioned eight attributes on a 100-level rating scale. A tablet (Apple iPad, 10^{th} generation) with a graphical user interface with rating sliders served as input interface. The main part of the experiment was divided into two blocks - a part with urban road traffic noise scenarios (each with a duration of 40 s) and a second part with the recorded passenger car pass-bys (ICE car, BE car) with different driving styles (each with a duration of 10 s). While the distribution of the binary biological gender was almost equal (52 % male and 45% female), the majority of participants held a degree from a university or a university of applied sciences and was less than 40 years old (76 %).

3.2 Results and connections to measurement results

Within the listening experiment in total 990 observations were obtained, each containing a rating of a stimulus according to the 8 attributes introduced in Section 3.1. In order to investigate the noise annoyance evoked by different car driving styles, we normalised the results for the

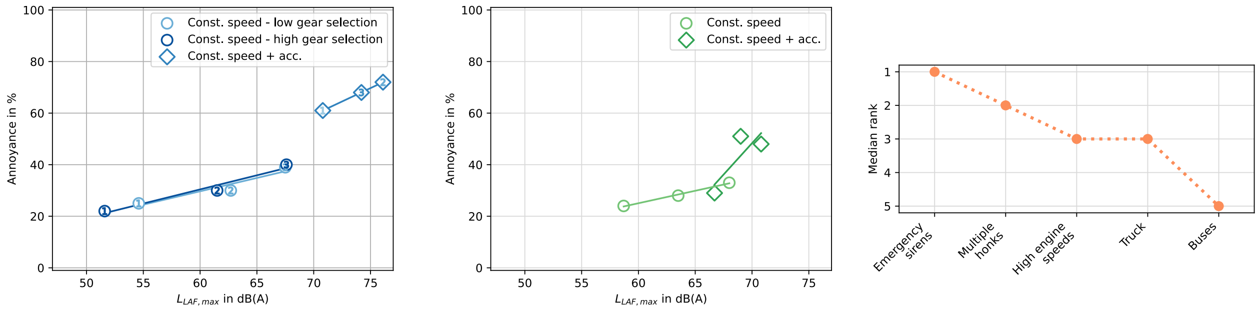

Figure 4. Noise annoyance and maximum SPL for ICE car stimuli (left), BE car stimuli (center), and median annoyance rankings for different individual sound events in urban road traffic noise scenarios (right). Straight lines represent logarithmic regression functions. Gears are indicated with the associated gear number, different manoeuvres via different marker shapes.

attribute *annoyance* and determined median values for the subsequent analyses. The obtained median values shown in Figure 4 left and center reveal that the average annoyance ratings for pass-bys with the ICE car and the BE car at constant speeds are within a similar value range (22 % to 40 % of the annoyance rating scale range). In contrast to the differences in terms of $L_{\mathrm{AF,max}}$ (see also Table 1), stimuli of the ICE car with pass-by speeds $\leq$ 30 km/h combined with comparatively low gears (and engine speeds on average 750 rpm higher) did not lead to noticeably higher average annoyance ratings than constant speeds with comparatively high gears. However, unsteady driving due to a sport-aggressive acceleration manoeuvre lead to predominately higher annoyance ratings. If linear regressions are applied between $L_{\mathrm{AF,max}}$ (shown in Figure 4 left and center) and median annoyance ratings, the regressions for acceleration manoeuvres posses higher slopes. The same trend was observed for regression analyses between $L_{\mathrm{A,eq}}$ and median annoyance ratings for both cars. The common trend to disproportionately higher ratings for sport-aggressive driving style with acceleration manoeuvres was also observed for the peak loudness N_5. Within the context of the listening experiment, comparatively high noise annoyance ratings (> 40 % of the annoyance rating scale range) caused by different car driving styles were predominantly accompanied by comparatively high measured $L_{\mathrm{AF,max}}$ and $L_{\mathrm{A,eq}}$. In contrast, comparatively higher measured $L_{\mathrm{AF,max}}$ caused by a change in driving style did not always lead to an increase of the median noise annoyance ratings. These observations may be connected to the potential significant influence of a sporty-aggressive driving style with unsteady speed in conjunction with significant accelerations on the evoked noise annoyance.

The influence of behavioural aspects connected to driving behaviour on the noise annoyance was also found in the results of the annoyance rankings, which were carried out in the listing experiment. As shown in Figure 4 right, only the present sounds of the emergency siren were ranked more annoying than honking (as part of driving behaviour) and driving with high engine speeds. Within the context of the listening experiment, the rating attribute *annoying* correlated significantly with several of the other seven investigated attributes. As shown in Figure 5, high and medium positive correlation coefficients (Pearson's r) were obtained for *annoying* with *threatening* (r = 0.69), *eventful* (r = 0.47) and *close* (r = 0.42). As somewhat expected, a negative correlation was found between the attributes *restful* and *annoying* (r = -0.43). All determined correlations in Figure 5 were highly significant ($p < 0.001$), except between *howling* and *booming* (p = 0.053), *monotonous* and *booming* (p = 0.667), as well as between *monotonous* and *close* (p = 0.038).

4. SUMMARY, DISCUSSION AND OUTLOOK

In this work we explored the potential influence of different car driving styles on noise emissions and the evoked noise annoyance. To this end, we conducted a series of controlled pass-by measurements with two different passenger cars as well as an associated listening experiment using higher-order Ambisonic recording and play-

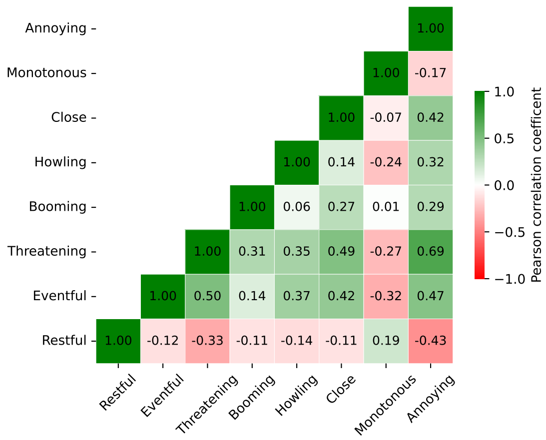

Figure 5. Correlation matrix for results from rating attributes of listening experiment.

back techniques. In total 60 different pass-bys within a speed range from approximately 10 km/h to 100 km/h were recorded with a petrol engine car and a battery electric car in 7.5 m distance from the center of the driving lane. 15 selected recordings with driving speeds to up to around 60 km/h were utilised together with a series of traffic noise environment recordings for the listing experiment. Within this study, a prospective-ecological driving style was represented by steady speed and comparatively low engine speeds. A sporty-aggressive driving style was emulated with steady speeds and comparatively high engine speeds or with a significant acceleration manoeuvre in conjunction with high engine speeds.

For the investigated petrol engine and battery electric car with speeds to up to around 30 km/h, a prospective-ecological driving style lead to 0.9 dB(A) to 4.5 dB(A) lower maximum pass-by SPL than a sporty-aggressive driving style. The trend of these results is generally in line with the findings of a large-scale study that employed a similar measurement setup with 22 cars equipped with different engine types. Although the influence of the tyre-road noise on the overall noise emission is known to increase towards higher speeds, a prospective-ecological driving style still lead to on average 1.5 dB(A) lower maximum pass-by SPL for speeds around 60 km/h. For the investigated battery electric car, the difference in terms of maximum pass-by SPL was negligible for speeds above 30 km/h. However, due to the limited number of different cars used for the measurements, no general conclusions can be drawn for speeds above 30 km/h, for different vehicle types like trucks or motorcycles, as well as for the influence of different AVAS implementations in conjunction with different driving styles.

Within the conducted listening experiment, an prospective-ecological driving style with speeds to up to around 60 km/h lead to significantly lower average noise annoyance ratings for both investigated cars, compared to a sporty-aggressive driving style, if it comprised significant accelerations. This trend was also reflected in psychoacoustic metrics like peak loudness, indicating the potential for noise annoyance reduction by ecological driving styles. However, compared to a driving style with comparatively high engine speeds but at steady driving speed, the positive influence of an prospective-ecological driving style on the perceived annoyance was negligible for the investigated petrol engine car. In contrast to this finding, pass-bys with constants speeds $\leq$ 30 km/h and comparatively low engine speeds lead to significantly lower maximum pass-by SPL than with comparatively high engine speeds. However, further investigations on the connection between SPL-based metrics and perception-based metrics for different driving styles seem to be worthwhile to determine the need for psychoacoustics related penalties, as the study results are far from being conclusive.

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