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PSYCHOACOUSTIC ASSESSMENT OF LOUD VEHICLES RECORDED BY A NOISE RADAR

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ABSTRACT

Road traffic is one of the most critical noise sources, leading to considerable noise pollution. Besides several aspects, vehicle manipulations and individual driving behavior also contribute to the extent of road traffic noise. Thus, the city of Berlin has installed a prototype noise radar to detect excessively loud vehicles and to investigate the need for measures to tackle this problem. During an 8-week test phase, around 2500 vehicles were recorded that exceeded a L_{Fmax} of 82 $dB(A)$. Based on the recorded data, psychoacoustic analyses were performed to determine the apparent reasons for level exceedances and to investigate the noise annoyance potential of loud vehicles as functions of vehicle characteristics and psychoacoustic parameters. It was found that certain vehicle classes systematically exhibited higher psychoacoustic annoyance values than others. When comparing motorbikes and cars, for example, a systematic shift in the loudness level was observed when the L_{Amax} is the same. Motorbikes sound louder than the conventional sound pressure level indicator suggests. In addition, machine learning was used to predict noise-provoking driving behavior and technically induced vehicle noise.

Keywords: *psychoacoustics, noise monitoring, noise annoyance*

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1. INTRODUCTION

Large parts of the population in Europe are affected by harmful traffic noise posing a considerable risk to human health [1]. Comparing the traffic related noise sources, road traffic noise is the most serious source in terms of disability adjusted life-years and the number of people feeling highly annoyed respectively in Germany [2]. In order to reduce road traffic noise and its noise effects, a range of measures and interventions are discussed [3], [4].

Measures to avoid or reduce noise directly at source level are particularly recommended. Regarding interventions at source level, the use of noise radar technologies are discussed to penalize the drivers of noisy vehicles as particularly loud vehicles might affect noise annoyance significantly. It is assumed that loud single events attract attention and thus increase disproportionately noise annoyance, an effect that has been frequently observed in the context of aircraft noise (see [5]). In the context of health effects caused by transportation noise, the metric 'intermittency ratio' (IR) is proposed to characterize traffic noise. The IR metric considers the proportion of the contribution that is created by individual noise events above a certain threshold related to total energetic dose. The magnitude of IR might be relevant for health risks putting special emphasis on single loud events [6]. Although the IR metric leads to inconsistent findings so far regarding road traffic noise compared to railway and aircraft noise [7], the relevance of particular loud events in the context of noise annoyance appears undisputed.

In order to face this problem we tested a noise radar system in Berlin to determine how frequent excessively loud vehicles occur, their pass-by noise levels and finally their contribution to road traffic noise annoyance. The city of Berlin addresses in its current noise action plan the reduction of noise provoking behavior by appropriate measures and thus initiated the test of an available noise radar system [8].

2. NOISE RADAR TECHNOLOGIES

Noise radar systems are more and more utilized in practice. Although in several countries the legal framework for penalizing loud vehicles including setting maximum allowed levels has not been clarified completely, noise cameras are already being used successfully in countries like Belgium, France, Canada or UAE (see for a detailed overview [9]).

State of the art systems for the automatic detection of the exceedance of a threshold due to a single loud vehicle are combined with video recording to identify the respective license plate. However, although there is a strong interest in those automatic noise detection systems, many of these systems are still at a prototype stage, and legal thresholds have yet to be defined (cf. [9]). In order to determine the contribution of a single vehicle in multi-source scenarios, some kind of source localization techniques are frequently applied and combined with video systems to exclude other noise sources and to estimate the emitted noise of the loud vehicle only.

3. PILOT STUDY IN BERLIN

To investigate the occurrence of particular loud vehicles, the noise radar system *Hydre* from Bruitparif (France) was installed at Kurfürstendamm, Berlin Charlottenburg (see Fig. 1) as this location is popular in Berlin for illegal motor vehicle racing according to a police's traffic safety report. The system was in use in 2023 June 4 and July 26. The noise radar system *Hydre* operates with two units consisting of 4 microphones each to localize loud events, it separates the contribution of that vehicle from the background noise and determine the L_{Amax} for the identified vehicle related to a fixed distance (such as 7.5 m) and height (1.2 m). For more information about the used noise radar system see [10].
The available data (videos, audio signals, vehicle data) was provided by the system for the purpose of analyses. The data was processed internally by the system and thus the accuracy of measurements cannot be fully verified.

Figure 1. Installed noise radar system *Hydre* (Bruitparif) at Kurfürstendamm in Berlin, Germany. Photos were taken from two angles by the authors.

4. RESULTS PART I: DETERMINED LOUD VEHICLES IN THE PILOT STUDY

In the 8 weeks test phase more than 2500 vehicles were identified and recorded [8]. After a quality and plausibility check of all recorded events, 56 measurements were classified as invalid for example due to noises potentially originating from behind the camera or mixed inseparable sound sources. In few cases, the license plate could not be determined and thus needed to be disregarded for later analyses as no vehicle data could be related to the recorded event. Finally, more than 2300 events (audio signals) remained for subsequent psychoacoustic analyses.

The average sound pressure level L_{Amax} of all recorded vehicles was about 85 dB(A) with values higher than 105 dB(A). All detected loud vehicles can be clustered into global vehicle classes (e.g. light and heavy motor vehicles and powered two-wheelers (motorbikes)) and their psychoacoustic properties were compared. It turned out that the majority of recorded loud vehicles belong to the class of motorbikes, followed by light motor vehicles (passenger cars including oldtimer cars) (see Table 1).

Moreover, in average the highest number of loud vehicles were detected during the evening (5 to 9 pm). Although the number of loud vehicles were almost equally distributed over the week, there was the trend that at the weekend slightly more loud events occurred [8]. The share of loud vehicles exceeding the used threshold value of L_{Amax} of 82 dB(A) compared to the daily traffic volume amounts about 0.5 %. The average of speed of the detected loud vehicles was 42 km/h, which indicates that most loud events are not due to high vehicle speed. This observation is confirmed by the fact that a correlation analysis between speed and determined L_{Amax} values of the loud vehicles does not exhibit any meaningful statistical relationship.

Table 1. Share in % of detected loud vehicles according to global vehicle classes: Light (LV) and heavy motor vehicles (HV) and motorbikes (MB)

	Light Motor Vehicles	Heavy Motor Vehicles	Motor-bikes
in %	19	28	53

Figure 2 shows that many loud heavy motor vehicles are recorded with a L_{Amax} slightly exceeding the specified threshold, while in the range of 85 to 95 dB(A) the majority of detected vehicles are motorbikes and the proportion of loud heavy motor vehicles decreases considerably. For even louder events that exceed a L_{Amax} value of 95 dB(A) almost no heavy motor vehicles were detected. However, light motor vehicles and motorbikes still exceeded this high level threshold regularly.

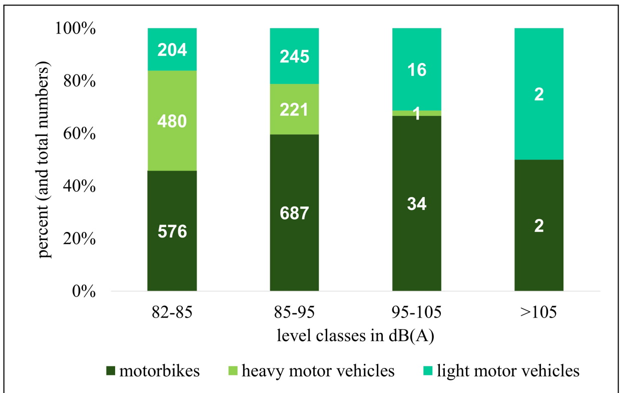

Figure 2. Distribution detected loud vehicles clustered in global vehicle classes related to sound pressure level classes. The total numbers of detected cars are displayed in the stacked bars.

5. RESULTS PART II: PSYCHOACOUSTIC ANALYSIS OF RECORDED LOUD VEHICLES

5.1 Data processing

The acoustic analyses are based on the audio signals provided by the noise radar technology as stereo files in flac format and a sampling frequency of 52 kHz. The available recorded time signals do not correct the different distances of the detected loud vehicles as the system determines the L_{Fmax} value in relation to a distance of 7.5m independent from the exact distance of the source to the measurement device. Thus, the considered audio signals have to be interpreted as the resulting noise of excessively loud vehicles at a given receiver position. However, distance related influences should be less relevant due to the high amount of events and the fact that several psychoacoustic parameters are only partially dependent on the overall sound pressure level.

5.2 Analysis of the parameter loudness

Figure 3 displays the determined loudness values (ISO 532-1) over the vehicle classes of all detected loud events. It becomes clear that *emergency vehicles* are expected to be very loud due to their usually very conspicuous siren noises in order to increase the attention of all other road users. In contrast to it, other vehicle classes do not vary strongly in their loudness values in average. However, it is obvious from the boxplot shown in Fig. 3 that certain vehicle classes stick out regarding outliers. For the classes *passenger cars* and *motorbikes* very high loudness values were observed during the pilot study reaching loudness values higher than 50 *sone* as Fig. 2 already suggests.

To investigate whether the indicators for sound pressure level and loudness provide the same results, the relationship between sound pressure level (L_{AFmax}) and loudness level (N_{max}) was determined. Figure 4 displays the observed linear regression lines for the relationship between level and loudness for the global vehicle classes types *passenger cars* and *motorbikes*. As expected, it can be seen that there is plausible link: With an increase of the level in $dB(A)$ the loudness in *phon* increases as well. The determined correlation coefficients are highly statistical significant. Interestingly, there is a small shift between the vehicles types: Motorbikes are for a given A-weighted sound pressure level sightly louder in terms of the psychoacoustic loudness than light motor vehicles. The small shift lies in the range of about 2 *phon*. This means that the loudness of motorbikes are slightly but systematically underestimated if only standard sound pressure level indicators are considered.

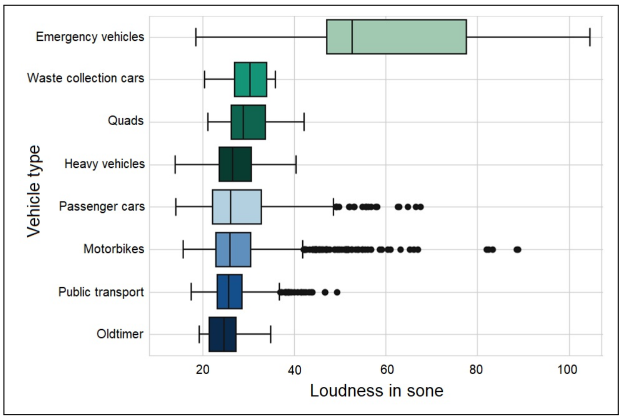

Figure 3. Boxplots of loudness values N_5 (according to ISO 532-1) by vehicle type sorted from top to bottom by median values in descending order

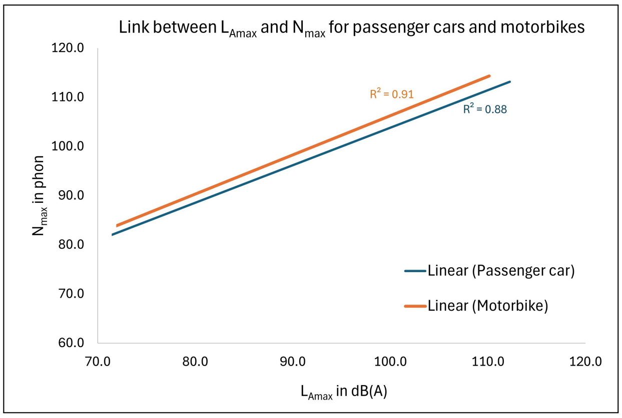

Figure 4. Linear regression lines indicating the link between indicators quantifying volume for the vehicle classes *passenger cars* and *motorbikes*. Loudness according to ISO 532-1 (N_{max} in $phon$) over A-weighted sound pressure level (L_{AFmax} in $dB(A)$)

5.3 Analysis of further psychoacoustics parameters

Apart from the psychoacoustic loudness, the recorded events were analyzed with respect to other psychoacoustic parameters, i.e. sharpness, roughness, fluctuation strength and tonality. Moreover, additional indicators were considered, such as booming [11] or the TETC index (total energy of tonal components) [12].

As expected it was observed that the detected emergency vehicles exhibit high loudness (3) as well as sharpness, fluctuation strength and tonality values (see for details [13]). This is a plausible result as their warning noises are primarily designed to attract attention of other road users. Moreover, it could be observed that in average light motor vehicles tend to show lower sharpness values and higher tonality values compared to motorbikes and heavy motor vehicles ([13]). Motorbikes pass-by events showed higher roughness values than light and heavy motor vehicles. Moreover, motorbikes exhibit the highest low frequency content investigated by the booming or TETC index. More information about the results with respect to various psychoacoustic parameters see [13].

5.4 Analysis of the psychoacoustic annoyance metric

Fastl and Zwicker (2007) proposed a metric to analyze the general psychoacoustic annoyance level (PA) of sounds due to their prominent psychoacoustic characteristics and patterns [14]. The PA metric- which is based on *loudness*, *roughness*, *sharpness*, and *fluctuation strength* - is a measure to estimate the psychoacoustic elements of sound quality [14]. Di et al. (2016) extended the PA metric by adding tonality to the set of considered psychoacoustic parameters [15].

Figure 6 shows that there is a systematic relationship between the indicator L_{AFmax} and the psychoacoustic annoyance value of recorded loud motor vehicles. As expected, higher sound pressure levels are strongly associated with higher psychoacoustic annoyance. The correlation coefficient between these variables amounts to 0.81 indicating that the sound pressure level (and loudness respectively) is the most important factor for the psychoacoustic annoyance of loud vehicle noises. Besides the missing explained variance by a level or loudness indicator of more than 30 %, it can also be seen that the relationship between sound pressure level and PA has a non-linear component; the PA increases faster at very high sound pressure levels than at lower sound pressure levels. Especially exceeding 95 dB(A) leads to a significant increase in psychoacoustic annoyance calling for severe penalties. Further analyses showed that the combined metric PA did not show any strong correlation to engine power or engine displacement, which indicates that the exceedance of the given threshold value frequently occurs due to noise-insensitive and provoking driving behavior as it is not strongly dependent on the engine characteristics.

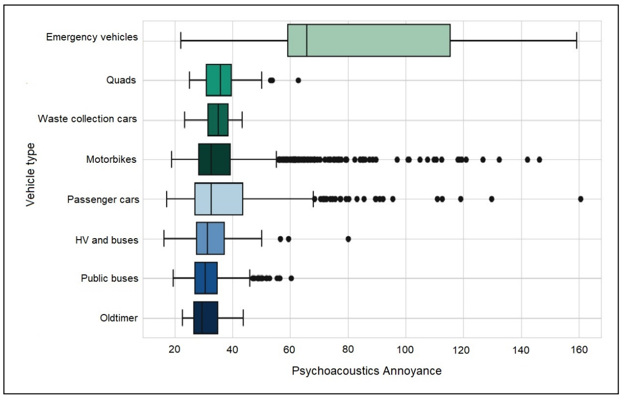

Figure 5. Boxplot of psychoacoustic annoyance values according to Di et al. (2016) sorted by vehicle class by median values from top to bottom in descending order

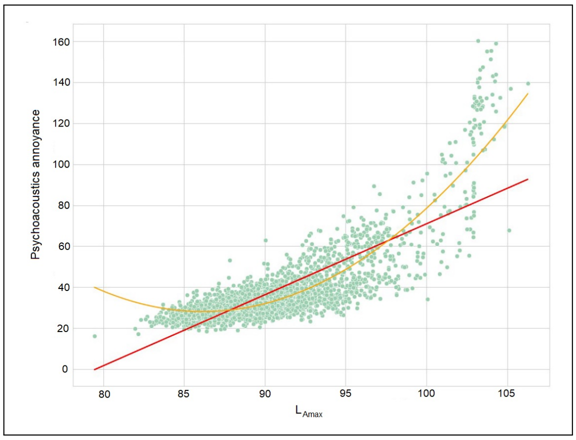

Figure 6. Relationship between the L_{Amax} and the PA according to Di et al. (2016) for all detected loud vehicles. Red (linear) and orange (quadratic) regression functions model the mathematical relationship between L_{AFmax} and PA.

6. IDENTIFICATION OF NOISE-PROVOKING DRIVING BEHAVIOR

There was the goal to determine the number of excessively loud events that can be attributed to noise-provoking driving behavior, which could be prevented by a change in driving style. Before applying a support vector machine classifier, which is a supervised machine learning algorithm, it was first necessary to decide which of the recorded sounds were likely caused by noise-provoking driving behavior.

Table 2. Distribution of responses regarding identified cause for excessive noise. The cause 'noise provoking behavior' was further clustered in 'accelerating', 'braking' and 'high rpm' and 'exhaust burst'.

Cause	Number
inconspicuous	166
noise provoking behavior - accelerating	75
noise provoking behavior - braking	3
noise provoking behavior - high rpm	49
noise provoking behavior - exhaust burst	15
honking	56

The annotation was based on a headphone listening test with a total of 7 participants. The assignment of an event to a category was decided on the basis of the majority in the listening test (based on the question: Which of the following aspects contributes to the significant noise generated by the vehicle?). 384 pass-by noises from loud cars were analyzed and classified. Participants could choose between two main categories (inconspicuous driving style vs. noise-provoking driving style). There were 5 sub-categories for the main category 'noise-provoking driving style' (sporty acceleration, aggressive braking, high-speed or low-speed driving, accelerating at idle, honking). For more information see [16]. Table 2 displays the result of the analyses of the causes for loud vehicle events. It can be seen that in several cases noise provoking driving behavior played a role in the detected events, at least in the class of passenger cars.

For classification different feature combinations and pre-processing methods were tested with a Support Vector Machine. The optimal hyperparameters were determined using a grid search. Based on the criteria accuracy, precision, recall, F1 score and confusion matrix different approaches were evaluated. The best classification result was achieved with a MFCC-mix method performing with an accuracy rate of 79.1 %, followed by a psychoacoustics feature based approach with an accuracy of about 76 %. After a 10-fold mean cross-validation the MFCC based method achieved over 78 % directly followed by the psy-

Table 3. Median values of the psychoacoustic parameters loudness (N), sharpness (S), roughness (R) of loud passenger vehicle events clustered by driving style.

Cluster	N in sone	S in acum	R in asper
Inconspicuous driving	22.4	1.69	0.15
Noise provoking behavior	32.5	1.72	0.31
Honking	38.9	1.93	0.14

Table 4. Median values of the psychoacoustic parameters fluctuation strength (FS), tonality (T) and psychoacoustic annoyance (PA) of loud passenger vehicle events clustered by driving style.

Cluster	FS in vacil	T in tu	PA
Inconspicuous driving	0.19	0.13	27.4
Noise provoking behavior	0.63	0.14	43.5
Honking	1.19	0.21	54.4

choacoustics approach with a mean cross-validation performance of 76 %. Considering the confusion matrix result, it turned out that the psychoacoustic model had the best true positive rate and the lowest false positive rate. This indicates that the psychoacoustic approach might be able to identify reliably the positive cases of noise provoking driving behavior. This also illustrates that psychoacoustic patterns are generated through noise insensitive driving behavior (shown in Table 3 and 4)), which would explain the general identifiability of those events (as observed in the listening experiment) and suggests stronger human responses to pass-by noises caused by noise provoking driving styles [17].

7. LIMITATIONS

The noise radar system processes internally the data. It provides audio signals and determined L_{AFmax} values related to the defined distance, which cannot be verified in detail. Moreover, the psychoacoustic analyses depend on recalibrated signals with a limited accuracy. Although plausibility checks proved to be successful and psychoacoustic analyses are less susceptible to the total sound pressure level, this approach causes an uncertainty. However, despite this uncertainty, most comparisons and results of analyses proved to be statistically significant (e.g. correlations, vehicle class differences regarding psychoacoustic quantities), see [16].

In addition, for a more reliable psychoacoustic assessment of vehicle classes, it must be mentioned that for some classes only very few events were registered (e.g. quads, buses, oldtimer) limiting the generalization of the results.

Finally, the classification of loud vehicle events into the categories 'noise provoking behavior' and 'inconspicuous driving behavior' is based on annotations provided by a small group of listeners. In some cases the listeners do not agree upon the apparent reason of a level exceedance and for the sake of simplicity only the majority judgment was used. Although the automatic classification based on machine learning worked well in this context, it must be mentioned that only passenger cars were considered limiting again the generalization of the results.

8. CONCLUSION

Based on a noise radar technology over 2500 excessively loud vehicles were identified over a period of two months right in the middle of Berlin. Vehicles with a pass-by noise level exceeding considerably 90 dB(A) were frequently observed indicating high noise exposure for the residents along those city roads. A psychoacoustic analysis of the loud events showed that the psychoacoustic loudness does not fully follow the results of common level indicators. Motorbikes seem to be slightly louder in average compared to light motor vehicles in case of the same sound pressure level.

Moreover, the psychoacoustic analyses have shown that it is not only the loudness that might be relevant for noise annoyance. The metric of psychoacoustic annoyance, which

concept is based on Zwicker and Fastl [14] trying to determine the general degree of psychoacoustic saliency of signals, showed that loudness has the greatest influence on whether a motor vehicle's noise is particularly annoying or not. However, based on the PA model other psychoacoustic parameters besides loudness also have an influence on the psychoacoustic annoyance level. This metric could be used to predict the perceived annoyance related to specific vehicle types and classes more in detail.
In case of noise-provoking driving behavior, significant differences in psychoacoustic characteristics such as roughness and fluctuation strength were observed. Based on a listening test, the recorded events of passenger cars were classified as caused by non-noise provoking behavior or noise-provoking behavior. The analysis of these classes showed clear psychoacoustic differences likely resulting in different noise annoyance levels. Based on machine learning, it was observed that the subjectively made distinctions between the evens related to the cause for the loud noises, can be imitated by a trained model based on psychoacoustic features. This could be later useful when imposing fines for particularly noisy driving behavior.
It appears important that authorities recognize the importance to monitor the achievements of interventions, for example by means of a noise radar. Consequently, the WHO demands to investigate further the effectiveness of interventions to reduce noise and its impact on health. Still according to the WHO, the quality of evidence on the effectiveness of interventions to reduce exposure to and health outcomes from environmental noise is somewhat variable and further studies directly linking noise interventions to health outcomes are required [3]. Also in the context of noise radar systems, it would be beneficial to understand how the use of noise radar could reduce road traffic noise in the long term.

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