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Psychoacoustic evaluation of different rumble strip designs

Kasess, Christian H.[1]
Acoustics Research Institute, Austrian Academy of Sciences
Wohllebengasse 12-14, 1040 Vienna, Austria

Maly, Thomas[2]
Institute of Transportation, Vienna University of Technology
Karlsplatz 13/230-2, 1040 Vienna

Kluger-Eigl, Wolfgang[3]
Institute of Transportation, Vienna University of Technology
Gusshausstraße 28/230-3, 1040 Vienna

Waubke, Holger[4]
Acoustics Research Institute, Austrian Academy of Sciences
Wohllebengasse 12-14, 1040 Vienna, Austria

ABSTRACT

The purpose of rumble strips is to alert the driver through noise and vibration before running off the road. As a side effect, rumble strips cause noise and thus annoyance in the surrounding areas. The noise emission depends on parameters such as the shape and the depth of the groove as well as the spacing. The aim of the work presented was to evaluate different design parameters of rumble strips in terms of exterior and interior noise as well as the degree of vibration on the seat and the steering wheel. For this, indoor and outdoor recordings using a head-and-torso-simulator were performed for a car and a commercial vehicle running on various test strips. Furthermore, using recordings and the boundary element method synthetic stimuli were produced for strips that could not be manufactured on the test track. In a lab experiment annoyance of outdoor noise as well as perceived urgency and reaction time were evaluated based on 16 listeners. The investigation lead to no clear optimal solution, in particular due to the large difference of the effect inside the car compared to the inside the commercial vehicle, where vibration as well as sound level increase were much lower.

[1]christian.kasess@oeaw.ac.at

[2]thomas.maly@tuwien.ac.at

[3]wolfgang.kluger-eigl@bmvit.gv.at

[4]holger.waubke@oeaw.ac.at

1. INTRODUCTION

Rumble strips (RS) are typically milled patterns often located on the side of a road with the purpose of alerting drivers through noise and vibration of the imminent danger of running of the road. Investigations showed that rumble strips have a positive effect on traffic safety [1].

The basic mechanism of the noise generation is the excitation of the tire when hitting a groove resulting in an increased noise emission. This excitation also leads to vibration that is transmitted into the interior of a vehicle (e.g. [2–4]).

Unfortunately, the noise generated by the tire is also transmitted into the surroundings. In addition to this increase in noise emissions the sound of rumble strips is also very salient, i.e. it is quite different from typical tire noise. The use of rumble strips in the close vicinity of populated areas is thus problematic due to the increased noise burden. Previously, sinusoidal depth profiles have been suggested to decrease the noise burden by causing less tire excitation [5, 6].

The aim of the work presented was to find rumble strip designs that cause less noise in the environment without significantly affecting the alerting effect inside the vehicle. For this purpose, a number of conventional designs as well as three alternative concepts were investigated: conical grooves to guide the noise under the car, pseudo-random groove spacing to reduce tonality and thus annoyance, as well as sinusoidal depth profiles which should produce mostly vibration and only little noise and which are already used in practice [5, 6].

To achieve this aim, a test track was established covering a range of different milling patterns in order to measure the effects of rumble strips for a car and a commercial vehicle running over them. These two vehicle types were chosen as previous results suggest that there is a significant decrease in effectiveness inside commercial vehicles [2, 4]. Patterns also varied in spacings and groove depth as it is known that narrower spacings and deeper grooves in general lead to higher sound levels [1, 7]. Acoustic measurements using microphones and a head-and-torso-simulator were done inside the vehicle as well as in the surroundings of the track. Furthermore, the vibration of the steering wheel and the driver seat were measured. In addition to the A-weighted sound pressure level, spectra and different psychoacoustical parameters were determined. Perception tests with 16 listeners were performed where the annoyance of the immissions as well as the urgency and reaction times for the sounds generated in the interior were determined also using synthetic stimuli to cover a larger range of rumble strip designs. For validation purposes a further test track was established, measured, and the results were analyzed.

2. METHODS

2.2.1. Test track

16 different rumble strip patterns (Fig. 1) were milled on two separate tracks located on a highway near Vienna. The first test track comprised 9 designs (RS0a to RS7) and was located on the hard shoulder of the outbound lanes, the second track (7 patterns, RS8 to RS14) was located on the shoulder of the inbound lanes. Three conventional patterns

with a spacing of roughly 300 mm (RS0a and RS0b with RS0a having a slightly smoother profile and less depth) and 600 mm (RS1) were milled. Furthermore, two sinusoidal rumble strips with a curved milling drum (300 mm for RS7 and 600 mm for RS5) were produced. The curved milling drum resulted in grooves that are deep in the middle and shallow towards the lateral outer bounds of the strip. RS6 was a 600 mm sinusoidal pattern with the regular flat drum. RS2 and RS3 were similar to RS0a, just with the groove tilted inwards (RS2) and outwards (RS3). RS4 was a pseudorandom pattern with an average spacing of 300 mm (200 to 470 mm). For this each groove was produced separately and the depth profile of the grooves of RS4 was most similar to RS0b. All patterns on the first track were 300 mm wide. The second track was produced in a later stage of the project and consisted of 7 patterns, each 350 mm wide using a flat milling drum. RS8 to RS10 where sinusoidal (600 mm) of depths 2, 5, and 7 mm. RS11 was similar to RS7, just wider and with a flat lateral profile. RS12 was like RS1, just slightly shallower (7 mm) and RS13 had a 400 mm spacing. RS14 used the doubled pseudo-random spacing of RS4 and a lower depth (7 mm). The depth profiles were measured with a custom-made measurement device using a linear potentiometer. Due to the coarse surface of the road and the inherent variability of the milling process the precision was deemed sufficient for this particular task.
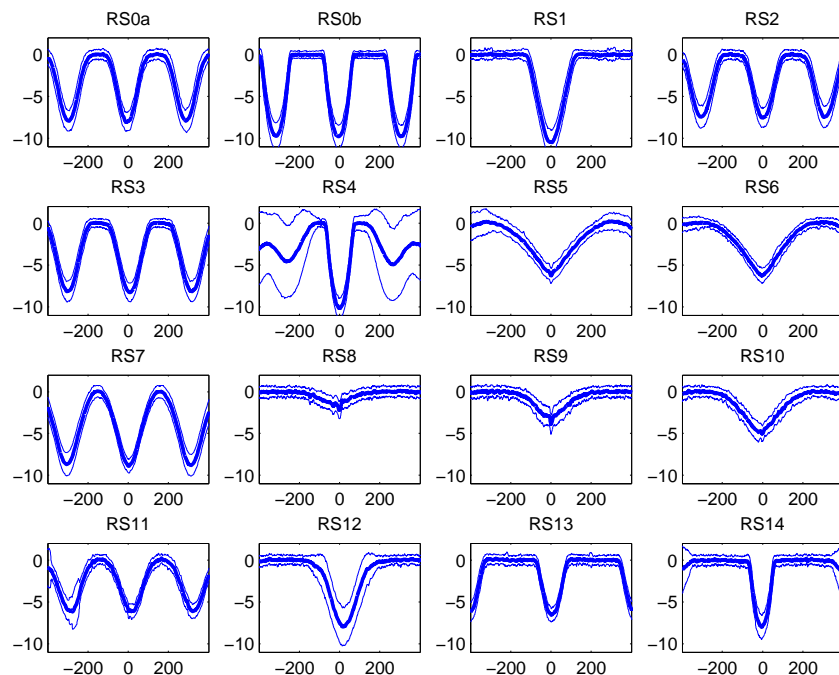

Figure 1: Test track profiles. Shown are the average groove profiles in mm (thick line) and the standard deviation (thin lines). The spacings for RS4 and RS14 are pseudorandom, hence the increased standard deviation for the neighboring grooves when averaging over ±400 mm around the groove.

2.2.2. Measurements

All measurements were done with two test vehicles (car BMW 320d and commercial vehicle MAN 84S), each equipped with a GoPro action camera to evaluate the coverage of the right front tire of the rumble strip for each test run. To determine the point in time when vehicles crossed the measurement cross-section and to verify predefined passing speeds (car 100 km/h, and commercial vehicle 80 km/h), reflecting strips for stationary light barriers were mounted on the vehicles for acoustic measurements beside the track. Furthermore, GPS data were logged during all test runs to estimate (onboard measurements) respectively verify (stationary measurements) the vehicles pass-by speeds.

The measurements comprised three different measurement setups: stationary pass-by measurements for single grooves, stationary pass-by measurements for 50 m long rumple strip segments, and onboard measurements with the same setup for pass-overs of single grooves and rumble strip segments. For the first setup two conventional microphones (40AE, G.R.A.S.) were placed 1.0 m and 7.5 m from the midpoint of the groove and 1.2 m above the road surface.

For stationary rumble strip measurements the microphones were positioned 7.5 m and 25.0 m from test segment midpoints and 1.2 m above the road surface to consider noise emissions as well as sound immissions. In addition, a head-and-torso simulator (HATS, HMS IV, HEAD acoustics) was placed 25.0 m from the rumble strips (1.0 m beside the corresponding microphone and at the same height) for binaural recording. For some rumble strips of the second test track (RS9, RS10, RS11 and RS14) only a simplified setup with one microphone at 7.5 m was applied to verify the sound emissions. Due to the extremely low depth, RS8 was only measured in the interior. Stationary video recording enabled subsequent visual verification of the pass-bys and the identification of measurements with overtaking vehicles. All stationary measurements were done at good climate conditions (low wind, no rain and dry road surface). In the end, for each rumple strip pattern and for each of the test vehicles typically 10 to 20 pass-bys, as well as several pass-bys without covering the rumple strips, were available for further analysis.

The interior noise during pass-overs was recorded by a microphone and the head-and-torso simulator. In the car the HATS was placed at the front passenger seat and the microphone was placed in the middle between driver and front passenger seat. In the commercial vehicle both measurement devices were placed between driver and front passenger. Additionally vibrations were measured by a triaxial miniature accelerometer (66A11, Meggitt) mounted at the top of the steering wheel and a triaxial whole-body seat accelerometer (SV 38, Svantek) following the ISO 8041 [8] placed at the driver's seat. The measurement runs were done on a dry road surface and with deactivated ventilation and air condition in the vehicles. The measurements provided typically 15 to 20 recording sets for each rumble strip of the test. Furthermore, the interior noise and the vibrations of the first track RS0a to RS7 were re-recorded in the course of measuring the second test track.

2.2.3. Synthetic Stimuli

Investigations were planned such that the data of the first test track was to be included in the perception tests. To extend the range of possible rumble strip designs, synthetic rumble strip signals were generated.

For the exterior, from averaged single groove recordings at a distance of 1 m and noise propagation simulations using the 2.5D boundary element method (BEM, [9]), synthetic

signals using e.g. a spacing of 400 mm were generated. A binaural reproduction was simulated assuming plane-wave scattering on a sound hard sphere based on the direct source-receiver direction. These signals were overlayed with a regular pass-by noise of the respective vehicle. A high-frequency noise component (above 2 kHz) emitted during pass-bys of the car which was not present in the RS-signal synthesized from averaged single-groove measurement was modified depending on the RS-parameters and also overlayed.

For the interior, a deconvolution approach based on the pseudorandom RS was chosen to derive a single groove signal as in particular in the commercial vehicle the single groove run was barely audible and thus had a very poor signal-to-noise ratio (SNR). The groove shape was partly taken into account using filters derived from the rumble strip measurements. Again, in the case of the car a high-frequency component only present in measured pass-bys was modified and overlayed. The regular vehicle interior noise was overlayed to generate a realistically sounding rumble strip noise.

2.2.4. Perception tests

For the perceptual evaluation, 16 normal-hearing listeners (9 female, 7 male, age 26±6 years) participated in the study. Three different experiments were performed: an annoyance judgement of the exterior noise; a rating of the perceived urgency of the interior noise; a reaction test. For each condition one pass-by/pass-over was selected to be used in the test based on the rumble strip coverage. Binaural recordings and synthetic signals were played back via headphones (HD 650, Sennheiser).

The annoyance rating comprised a free magnitude estimation (see e.g. [10]). While the listeners were free to choose their range of ratings, the ratings had to be proportional to the perceived annoyance and only positive-valued ratings were allowed. Listeners had to rate the annoyance of roughly 2.5 (car) and 3 seconds (commercial vehicle) long segments consisting of either the car or the commercial vehicle running over a rumble strip. In addition to 8 RS-profiles of track 1 measured at 25 m, 12 synthetic RS-signals were presented, two of which were synthetic versions of RS0a and RS7. To cover a wider range of sound pressure levels the RS-noise of four of the synthetic stimuli (300, 400, and 600 mm regular as well as 300 mm pseudo-random) were also presented at -6 dB for the car and +4 dB for the commercial vehicle. Pass-bys of the same two vehicles without a rumble strip noise were also included at different levels (up to +15 dB for the car and +9 dB for the commercial vehicle) as reference trials. Each signal was presented eight times in the course of 4 sessions.

The perceived urgency [11, 12] was evaluated on a pre-defined scale ranging from "not at all" to "extremely" using a slider. 5 anchor points were given and 4 intermediate steps were possible resulting in a 9 point rating scale. The stimuli consisted of a normal driving sound lasting 0.7 s followed by a rumble strip noise of 1.8 s duration. Listeners were asked to rate how alarming they would find the particular change in noise. All 9 RS from track 1 as well as 13 artificially generated samples where presented (including synthetic versions of RS0a, RS0b, RS1, RS4, and RS7). Again, 4 of the synthetic RS were also presented at -6 dB (car) and +4 dB (commercial vehicle). Regular vehicle sounds were also included as a catch trial, i.e. no change in noise was present. This resulted in a total of 27 conditions per vehicle.

The reaction time was measured in an experiment where listeners were exposed to a continuous normal interior sound with overlayed/faded-in RS-sounds. Subjects were asked to hit the space bar as quickly as possible whenever they perceived a change of

the interior noise. While listening to the sounds, participants had to perform a simple motor task which consisted of following a randomly moving target with the mouse [12]. Participants had to use their non-dominant hand, or, in the case of left handed participants, the hand which is typically not used to handle the computer mouse. A single run for one vehicle consisted of 54 events (each RS twice including catch trials with no RS noise) in random order and at random temporal spacings to rule out adaptation. 6 runs for the car as well as for the commercial vehicle were presented resulting in 12 repetitions of each RS per vehicle.

2.2.5. Analysis

From experiment 1, the perceived annoyance was represented by the ratings which were log-transformed (base 2 logarithm). Invalid ratings (4 out of 7424) were removed and then the median of the ratings across repetitions per subject and condition was calculated. These data were then averaged across subjects.

The perceived urgency was analyzed in a similar manner without the log-transform of the data, except that the mean of the urgency ratings was used.

For the reaction time responses within the first 100 ms were excluded (17 out of 10368). Reactions past the 1.2 s stimulus interval and complete non-responses amounted to 973 cases. 768 out of these cases occurred in 4 conditions (no rumble strip for both vehicles and RS5, RS6 for the commercial vehicle). 16 outliers were detected lying outside the 3-fold standard deviation. In the case of more than 50 % missing reactions in a single condition per subject, no reaction time was calculated.

Vibration was analyzed using whole-body vibration weighting curves from ÖNORM ISO 2631-1 [13] whereas the steering wheel vibration was determined using the DIN EN ISO 5349-1 [14] weighting curves. A highpass filter was applied to omit frequencies below 25 Hz which were present during regular operation and thus unrelated to the rumble strips, in particular on the commercial vehicle seat.

3. RESULTS

The analysis of the annoyance ratings yielded the peak loudness level L_{N5} (i.e. 5% of the loudness level values exceed this threshold) as the single best predictor explaining 88 % percent of the variance (when excluding the level-scaled regular pass-bys). Fig. 2 (upper panel) shows the relation between annoyance and peak loudness. It can be clearly seen that regular pass-by noise (triangles) is perceived differently from rumble strip noise (circles) except for 600 mm spaced sinusoidal strips which are located on the same line as regular pass-bys. Synthetic stimuli seem to agree with the general trends of the measured signals. Using a forward-backward model selection scheme (stepAIC in the R-package MASS [15, 16]) resulted in an optimal model including median loudness level L_{N50}, vehicle type, and L_{Aeq} which explained about 95 % of the data (again excluding the level-scaled regular pass-bys).

Similarly, the perceived urgency increased with the size of the jump in the median loudness level (Fig. 2, lower panel) which explained 96 % of the total variance. Urgency ratings are shown as numbers ranging from 1 (not at all) to 9 (extremely). An optimal model was also derived: ΔL_{N50}, ΔL_{N5}, peak Aures sharpness ΔS_{A5}, and ΔL_{Ceq} which explained about 97 % of the data.

Fig. 3 shows the predictions based on the optimal models for all RS where the exterior noise was measured in 25 m (thus only RS12 and RS13 from the second test track are
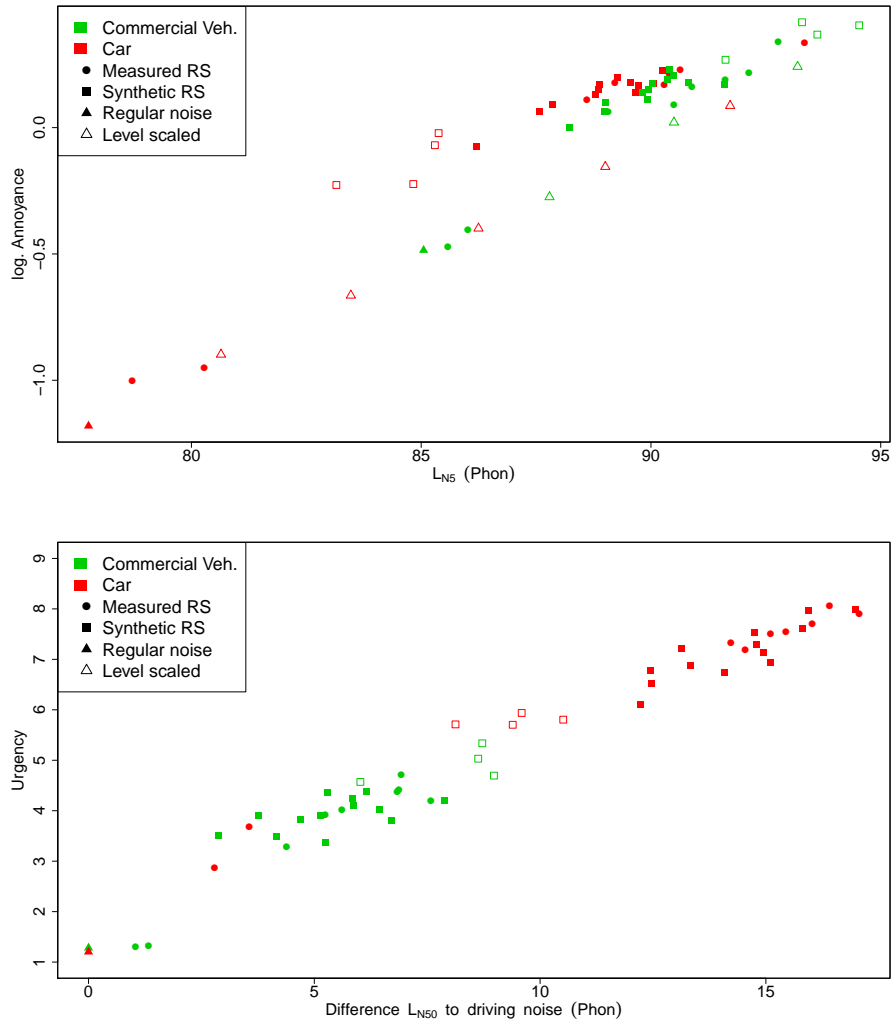
Figure 2: Annoyance and urgency. Relation between the single best correlating (psycho)acoustic parameter and annoyance of the exterior RS-noise (upper panel) as well as perceived urgency of the interior noise change (lower panel).

shown). Only pass-bys/pass-overs with a good coverage of the RS were used. The confidence intervals were calculated separately for the annoyance and urgency as the recordings were performed on different days. What can be seen in the graph is a strong correlation between interior and exterior rating and that the difference in the loudness (and the change in the noise in general) is much smaller inside the commercial vehicle than inside the car. This led to much smaller ratings for the urgency in the commercial vehicle.

For the reaction time two interesting results were extracted. First, the long sinusoidal rumble strips (RS5 and RS6) were not distinct enough to produce a reliable reaction (less than 10% reactions) in the case of the commercial vehicle. The boundary seemed to lie roughly at 2 to 3 dB for the difference in the A-weighted level. For jumps above of 5 dB, the reaction time decreased on average 3.6 ms per dB increase.

Fig. 4 illustrates the comparison of the change of the interior loudness level L_{N50} to the change of the RMS acceleration W_H at the steering wheel. Data points in the upper left corner exhibit high noise levels and little vibration, points in the lower right corner have
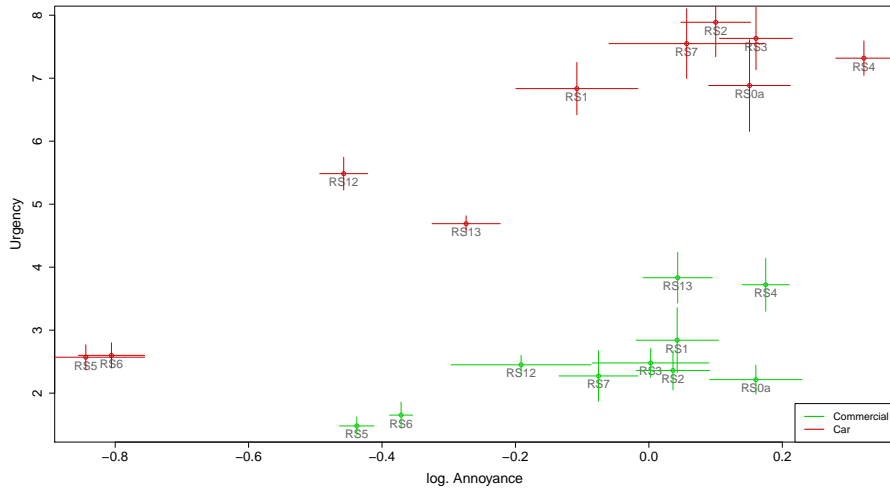
Figure 3: Annoyance vs urgency. Relation between predicted annoyance and predicted urgency for all rumble strips where the exterior noise was measured. Error bars show the univariate confidence interval.
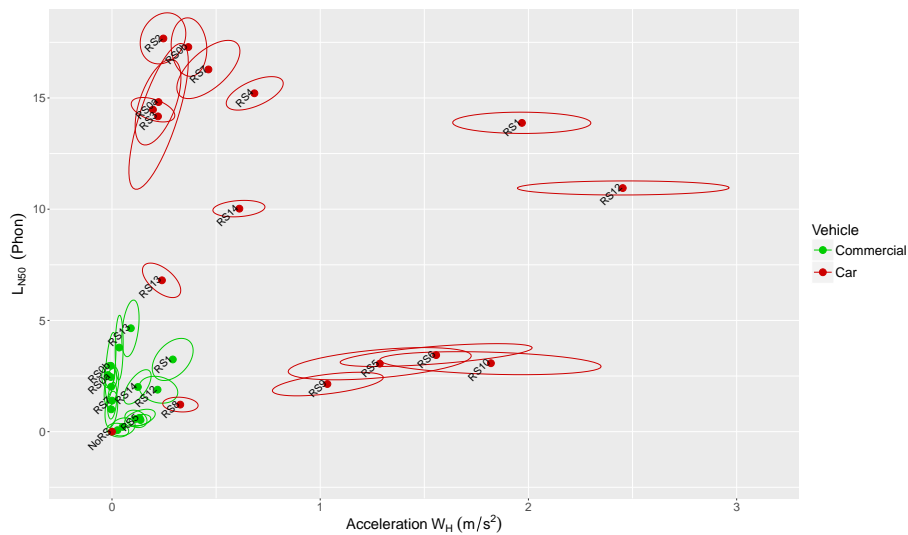

Figure 4: Interior noise and vibration. Shown is the relation between increase in median loudness level and increase in steering wheel vibration including bivariate confidence ellipses.

the opposite properties. As these were data from the same recording session, bi-variate confidence ellipses were calculated. Here it becomes immediately clear that rumble strip induced changes in vibration in the commercial vehicle are very small compared to the car. It can also be seen that in the car the sinusoidal RS with 600 mm spacing (except the extremely shallow RS8) produce relatively high vibrations but little change of the noise level. 300 mm spacing produces, in general, less vibration than 600 mm. Note that these results are according to the applied frequency weighting which favors the lower fundamental frequency of the 600 mm patterns. The seat vibration is not shown here as RS-induced vibrations were extremely low.

4. CONCLUSIONS

The results show that the effect of the rumble strips inside as well as outside of the vehicle heavily depends on the properties of the vehicle, making general statements about the effect of the designs difficult. While in the surroundings (for loud rumble strips) the commercial vehicle and the car produce similar emissions, in the interior the increase of noise and vibration is considerably lower inside the commercial vehicle. In particular the acoustic effects are sometimes not even perceptible. In addition, the noise levels inside and outside of the vehicle depend on each other to a large degree, thus typically resulting in a diminished effect in the interior when the emission is reduced. Conical grooves seem to behave similar to rumble strips with conventional design. Although, randomized milling patterns did reduce the tonality of the noise, higher noise pressure levels probably caused by the wide band excitation counteracted potentially positive effects. Sinusoidal rumble strips with longer wave lengths essentially had the expected effects: reduction in the noise while for the most part keeping up the vibration levels. However, the use of such patterns requires careful consideration whether the alerting effect is still given when the acoustic warning signal disappears or is strongly diminished.

5. ACKNOWLEDGEMENTS

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