SLEEPNOISE - A SIMULATOR BASED STUDY OF THE EFFECTS OF NOISE ON DRIVER SLEEPINESS

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Abstract – In the current study, a detailed model of in-vehicle road noise was developed in order to test effects of road noise on driver sleepiness. The model synthesizes realistic road noise based on real world measurements of road texture and of corresponding interior noise. Two different scenarios were used, representing a mid-sized hatchback car on a coarse road texture versus a large wagon on a smooth road. The synthesized noise was validated against in-vehicle recordings, and was ultimately used to investigate influence on driver sleepiness. Results show that the model is well suited for such studies, and that there was indeed an effect on driver sleepiness. In addition, a carry-over effect was found for the onset of the noise test cases. It suggests that the effect on e.g. self-reported sleepiness was determined by the first stimulus presented, masking the effect of later stimuli, thus emphasizing the need for methodological design considerations.

Key words: drowsiness, low frequency, noise, vibration, harshness

1 Introduction

The use cases for a technically complex system such as a driving simulator are typically continuously changing, as the problems they help solve are changing. This calls for systems that allow for development on an as-needed basis. In the current use case, the initial research question arose from informal self-reported feelings of fatigue and tiredness when driving a car on particularly worn roads and a notion that certain cars make the driver sleepier than others. These effects were attributed to the variations in interior road noise, and investigating if increased levels of road noise would reduce wakefulness in drivers made for a novel simulator use case.

The fact that sleepiness in drivers is a contributing factor in accidents is well known today, however what role external factors such as type of road, sound/noise, vibrations, etc. have on the ability to stay awake is rather unknown. Previous studies on noise related driver fatigue have mainly concerned heavy vehicles where infrasound and low frequency noise has been shown to be related to increased fatigue but also increased stress and impaired performance in drivers, both in real traffic situations [Löf1] as well as in simulator settings [Söd1][Mor1] and in laboratories [Lan1]. While the sound level and frequency distribution inside a car cabin is different from those inside a lorry cabin, the interior sound is still dominated by its low frequency content since the efficiency of the various abatement measures employed declines with decreasing frequency. It was thus hypothesised that increased low frequency road noise in the car cabin would increase drowsiness also car drivers.

The simulator development needed to test the hypothesis was identified as the need for a very realistic road noise model that would allow for variations in frequency content and level due to variations in road conditions as well as due to the sound attenuating properties of different vehicles.

2 Method

2.1 Measurements

To couple a noise model to real conditions, road surface texture measurements were performed on one relatively smooth road texture and on one coarse road texture, the latter chosen for the high levels of low frequency noise experienced in the car when driving over the surface. The measurements were performed using the VTI Road Surface Tester measurement vehicle (Figure 1). It uses a 19-channel laser interferometer array to measure the road texture profile from micro to macro levels in combination with accelerometers, inclinometers and differential GPS receivers. The resulting data is in the form of surface texture height values for each of the 19 tracks recorded each millimeter along the stretch of road under study.

Figure 1. The VTI Road Surface Tester measurment van with its front mounted laser interferometer array.

In addition to the road surface texture measurements, the resulting interior road noise from driving on the same road textures at different speeds were recorded in two different vehicles. Microphones were placed adjacent to the driver's ears in accordance with ISO 5128:1980, Measurement of noise inside motor vehicles, in order for the recording to be as representative as possible for the sound experienced by the driver.

2.2 Model

VTI has developed SIREN, a simulator sound renderer allowing for versatile sound environment adoption to specific use cases. In the core of SIREN is a sound manager software that connects sound streams for engine and road noise with event-based sounds such as passing traffic and warning sounds and places the sounds in the sound field surrounding the driver. The sound streams for road and engine noise are synthesized by sound models implemented in Csound, a scripting language for real-time sound synthesis and manipulation. The texture and noise measurements were used as basis for an updated road noise model that would allow synthesizing very realistic road noise inside the driving simulator in real-time. The noise model consisted of two parts – one representing the road surface textures and the other representing the transfer functions from tyre/road interaction to the vehicle cabin noise. Analysing the texture measurements it was found that the smooth road surface texture could be reasonably well modeled by white noise filtered with a first order Butterworth low pass filter determined by the distribution of road surface texture wavelengths. The coarse road surface texture was modeled using two cascaded low pass filters allowing for the increased long-wavelength content found in the analysis (Figure 2). When driving along the road, the wheels vibrate vertically at frequencies determined by the texture wavelengths and the speed of the vehicle. Also, the intensity of the vibrations varies with speed since the vertical acceleration is greater at greater horizontal speed. Therefore, the texture model was created as a varying filter with a cutoff frequency and overall level determined by the speed of the vehicle and the cutoff wavelength of the road texture. When driving the simulator, the sound would thus vary in frequency content and level as a function of the simulated speed.

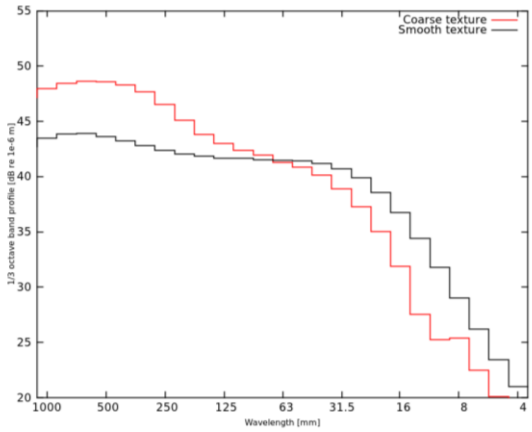

Figure 2. Road surface texture spectra in 1/3 octave bands for the coarse texture (red) and the smooth texture (black).

Recorded interior vehicle sound is comprised of the road surface texture causing direct air borne sound radiation from the tyres into the car cabin as well as causing vibrations to propagate through the suspension and chassis making panels inside the car radiate sound as well. In order to create a basis for the vehicle cabin transfer function model, the influence of the texture on the recorded sound needed to be compensated for. This was in fact one reason for keeping the texture model for the smooth road as simple as possible, as it allowed for the inverse of the smooth road first order low pass filter to be applied to the recorded sound. As the sound is dependent on vehicle speed, the inverse filter for a speed of 110kph was applied to the 110kph smooth road sound recordings for both vehicles. The vehicle cabin transfer functions were then created by fitting an Auto-Regressive (AR) model to the resulting sound using Burg's method [Bur1] with 32768 coefficients. Finally, the impulse response for each of the AR models was generated and the sound in the simulator was created by applying either of the texture related low pass filters with speed dependent cut-off frequency to a white noise generator and convolving the result with either of the cabin related impulse responses.

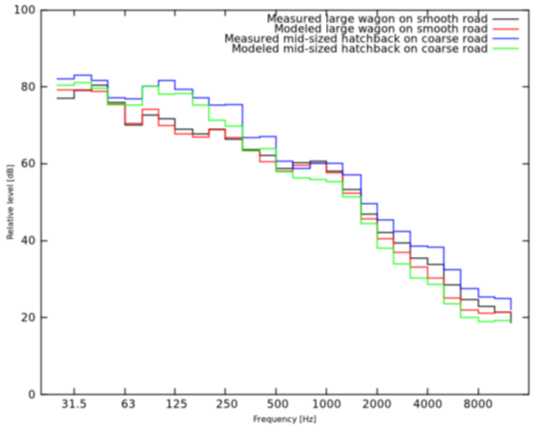

Figure 3. Spectra of recorded and modelled road noise for the two conditions used in the sleepiness experiment

The resulting sound inside the simulator was found to correspond well to the in-vehicle recordings (Figure 3). The two driving conditions used in the sleepiness experiment were represented by either a vehicle of large wagon type driven on the relatively smooth asphalt road surface (quiet case), or a vehicle of mid-size hatchback type driven on the relatively coarse road surface (loud case). The differences between the two sound settings were mostly within the one-third octave bands between 63Hz and 250Hz corresponding to the differences in suspension, chassis and car body between the two vehicle models as well as to the differences in road texture between the two road surface types. For both infrasonic frequencies and higher frequency content (e.g. wind noise), as well as for vibrations and harshness both sound settings were more or less identical, thus focussing on the effects of road texture induced low frequency noise.

2.3 Experiment

The sleepiness experiment was performed in the VTI Moving Base Simulator IV (Figure 4). The simulator has a Volvo XC60 vehicle cabin with three LCD-displays for side and rear view mirrors mounted on a platform with a visualization system consisting of a curved screen and nine projectors creating a 210-degree forward field of vision. The platform is mounted on a motion system permitting significant linear movement along both x and y axes as well as pitch and roll rotations.

Figure 4. VTI Moving Base Simulator IV (Sim IV).

The scenario for the experiment was a straight highway with a speed limit of 110kph, in daylight conditions with a small amount of fog. There was no traffic in the same lane as the own vehicle but some oncoming vehicles to make the scenario more realistic. A random sample of 20 drivers (30-50 years old) were recruited, 10 male and 10 female, with self-reported normal hearing. Before arrival, they were asked to avoid a number of confounding issues such as undue naps or excessive intake of coffee etc. Each participant drove one session during day time/evening (alert) and one session during nighttime (sleepy). All participants were subjected to each driving condition in altering orders of occurrence for the different sessions. The participants drove two passes of 35 minutes each in each session, divided by a short intermission where they answered a questionnaire while still seated in the car. The simulator data acquisition system was used to sample speed and lateral position as measures of driving performance, and self-reported sleepiness (Karolinska Sleepiness Scale, KSS) and blink duration recorded by an eye camera system were used as sleepiness measures. In total seven performance indicators (PI) were used in order to analyse driving performance and sleepiness level: KSS (self-reported verbally every 5 minutes), blink duration (s), fraction of blinks longer than 0.15 s, mean speed (km/h), average and variability of lateral position (m) and average number of line crossings to the left or to the right per km driven. The data was analysed using traditional mixed model ANOVAs.

3 Results

When analysing the results, no main effect of the different sound settings could be found at first, but the time of day (day or night) had an effect for all variables, as expected since drivers are likely to be more sleepy during nighttime conditions. Upon further analysis, and considering there was also a main effect found when comparing first and second 35-minute parts across all drive cases, an unexpected carry-over effect was identified. This may be interpreted as if one starts to drive with high levels of low frequency road noise in the car the influence will be present even if there is a change in low frequency noise. This effect was present both for sleepiness measures such as KSS-ratings as well as for performance measures such as mean vehicle speed. For both day and night conditions, the loud test case rated higher on the KSS scale than the quiet case in the first part of the drive, but in the second part the situation was the opposite. Considering that the participants were presented with one test case in the first part and the other test case in the second part, this would mean that participants were responding as if the first case was continued after the short intermission. Those who were first presented with the loud case responded as if the second part was the loud case as well, and vice versa. In an attempt to account for this carry-over effect, an additional analysis was performed where only the first 35-minute part of each drive was included. While this would exclude the data that in effect was masking any main effects of varying the sound setting, it also meant that the statistical basis was reduced, in some cases causing a weaker statistical significance level. Including only the first 35 minutes for day and night time driving a tendency was found for KSS meaning that the self-reported sleepiness was higher for the loud test case during nighttime driving. For measured mean vehicle speed, the effect was even greater showing statistically significant reduction in speed for the loud test case when just including the first part of each drive. Several additional measures of both sleepiness and of driving performance showed similar.

4 Conclusions

The resulting sound model proved to work very well for the intended use, facilitating detailed investigations of the influence of sound on driver behavior in addition to providing realism and presence in the simulated environment. It allows for changing vehicle cabin sound model independently from the influence of road texture, so more combinations of vehicle cabins and road textures can easily be investigated if needed. The realism of the road noise model was validated by NVH experts from Volvo Car Corporation well acquainted with the modelled vehicles. The simulator experiment was found to support the hypothesis that high levels of low frequency road noise in the car contribute to increased driver sleepiness and impaired performance during nighttime. The unexpected carry-over effect suggests that the onset of conditions such as those found in realistic road noise has a lasting effect, which cannot be neutralized by a short break while still seated in the vehicle. The carry-over effect might have been neutralized by allowing participants to exit the simulator e.g. to stretch their legs and have a drink of water or so, which might also imply that countermeasures against driver fatigue need to have a proper impact to counter such lasting effects. These are issues that require further research.

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