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A-WEIGHTED EQUIVALENT SOUND LEVEL AS A PREDICTOR OF THE ANNOYANCE CAUSED BY ROAD TRAFFIC CONSISTING OF VARIOUS PROPORTIONS OF LIGHT AND HEAVY VEHICLES

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A laboratory study was conducted to examine the relationship between noise annoyance and the proportion of heavy vehicles in a mixture of trucks and passenger cars. Twenty normal-hearing subjects were asked to judge the annoyance caused by the sounds from a continuous stream of vehicles, assuming they were exposed to it at home on a regular basis. The number of passby events as well as the *A*-weighted equivalent sound level were kept constant. Results showed that in such conditions, the annoyance is virtually independent of the proportion of heavy vehicles.

1. INTRODUCTION

As a method of rating road-traffic sounds with respect to the expected community response, both ISO/R 1996 [1] and ANSI S12.9 [2] recommend the measurement of the equivalent continuous *A*-weighted sound pressure level (L_{Aeq}) as the basic quantity. However, results from various laboratory and field studies [3–10] suggest that this method should be refined: the annoyance caused by the sounds from light vehicles is different from that caused by the sounds from heavy vehicles, provided that the *A*-weighted levels are the same.

If this were true, then the overall rating sound level for road traffic should depend on the proportion of light and heavy vehicles. At provincial or arterial roads, the portion of medium–heavy and heavy vehicles may be as low as 10% of the total number of vehicles for various periods of the day, whereas for motor- or highways, this portion may be 15% for the day and evening time, and increase to over 30% for the nighttime. In the early morning hours, the proportion of heavy vehicles driving on highways may be as large as 50% [11].

In the present laboratory study, the adequacy of L_{Aeq} as a predictor of annoyance caused by road-traffic sounds is tested for conditions in which the proportion of heavy vehicles in a flow of light and heavy vehicles (passenger cars and trucks, respectively) is systematically varied.

The present study was not explicitly designed to test the validity of an alternative maximum single-event-level model (e.g., see references [12–14]). Additional analyses pertinent to this latter model are presented in section 5.3.

Before we give a detailed description of the experimental method, a summary of previous results that are related to our study is given.

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2. PREVIOUS RESULTS

2.1. LABORATORY STUDIES

Cermak and Cornillon [4] and Cermak [3] presented their subjects with fragments of traffic noise consisting of passenger cars, trucks, buses, and various mixtures. No significant contribution of measures that could differentiate between the passenger cars and the heavy trucks was found. This indicates that there probably was little difference between the annoyance of passenger cars and heavier vehicles at the same sound exposure level, despite the finding that fragments containing heavy traffic were clearly discernible from those containing only light vehicles.

Similar results were reported by Yaniv *et al.* [8], who conducted an experiment in which subjects had to judge the annoyance of 3-min samples containing either passenger cars, trucks, or both. Their conclusion was that simple noise-rating indices such as L_{Aeq} could describe the data at least as well as more complex indices.

In one of the previous laboratory studies reported by Versfeld and Vos [7], however, it was found that the annoyance caused by the sounds from light vehicles was higher than that caused by the sounds from heavy vehicles, provided that the A-weighted sound exposure levels (L_{AE}) were the same.

Figure 1 shows the annoyance ratings as a function of indoor L_{AE} for light vehicles (two different passenger cars and a delivery van) and for heavier vehicles (a bus and a truck with trailer); these data are adopted from Part B of Table I in reference [7]. For each vehicle category, the function $y = 1 + 9\,\boldsymbol{\Phi}[(L_{AE} - \mu)/\sigma]$ was fitted (least squares) to the mean annoyance ratings; $\boldsymbol{\Phi}(z)$ denotes the standardized cumulative normal distribution. The value of μ denotes the L_{AE}-value at which an annoyance rating (y) of 5·5 is obtained. With σ fixed at 10·5 dB, the optimal μ-values for the light and heavy vehicles were about 55 and 61 dB respectively. This result implies that for equal L_{AE}-values, the degree to which the light vehicles were judged to be more annoying than the heavy vehicles corresponded to the change in annoyance produced by a 6-dB shift in the A-weighted sound exposure level.

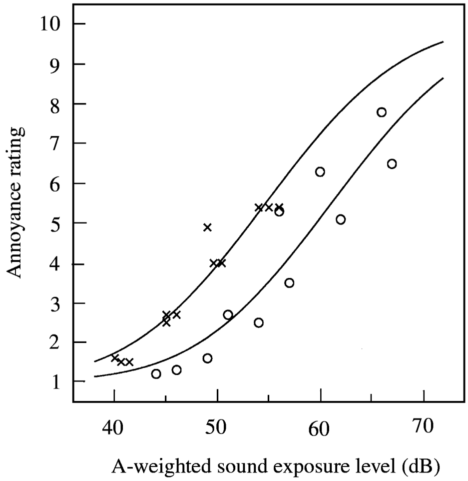

Figure 1. Annoyance ratings obtained in a previous study from Versfeld and Vos [7], as a function of the indoor A-weighted sound exposure level for light and heavy vehicles. The solid lines represent least-squares fits to the data sets. Vehicles: ×, light; ○, heavy.

Lastly, both Rylander *et al.* [6] and Labiale [5] varied the number of truck passages per unit of time in the presence of freely flowing road traffic composed of lighter vehicles. The level of the truck passages was fixed in all conditions, and to keep the overall L_{Aeq} constant, the level of the lighter vehicle passages was slightly dependent on the number of heavy vehicles included.

The results of Rylander *et al.* [6] showed that at the same L_{Aeq} of 60 dB, the annoyance decreased with increasing number of heavy passages. Labiale [5] ran the experiments for overall L_{Aeq}-values of 50, 55, and 60 dB. At $L_{Aeq} = 60$ dB, the annoyance was unaffected by the number of truck passages. In these conditions, the level of the truck passages was about 10–12 dB higher than that of the lighter vehicle passages. At L_{Aeq}-values of 50 and 55 dB, the annoyance increased with the number of truck passages. In these conditions, the level of the truck passages was about 16 to more than 20 dB higher than the level of the lighter vehicle passages. Since such large differences are no longer representative for normal road-traffic situations, these latter results should be interpreted with caution.

2.2. FIELD SURVEYS

In a field survey on the annoyance caused by road-traffic noise, Langdon [9] found that for the 24 sites where generally free-flow conditions prevailed, 71% of the variance in the median annoyance scores was explained by L_{Aeq}. For the 29 sites where free-flow conditions were not maintained, however, this percentage was as small as 10, and insignificant. For the 29 sites with "non-free flow" traffic, 50–55% of the variance in the median annoyance scores could be explained by measures of traffic composition, such as the logarithm of the percentage of heavy vehicles. For the total sample of all traffic conditions, the variance explained in the annoyance scores changed from 26 to 49% if in addition to L_{Aeq}, the logarithm of the percentage of heavy vehicles was used as a second predictor.

The results of these analyses suggest that the adequacy of L_{Aeq} as a predictor of annoyance caused by mixed road traffic diminishes as the traffic flow changes from free to non-free: for non-freely flowing traffic, which is characterized by slow running, stopping, starting, and acceleration in low gears, the difference in annoyance between heavy and light vehicles is greater than predicted from one single relation between annoyance and the *A*-weighted sound level. Results from Versfeld and Vos [7] on the annoyance caused by various passby sounds of a military tracked vehicle suggest that especially the alternation between acceleration and deceleration yields aversive responses.

Miedema [10] re-analyzed the data from seven field surveys on the community response to road-traffic sounds. He concluded that for the same *A*-weighted day–night level, road-traffic sounds from highways yielded higher percentages of "highly annoyed" respondents than the traffic sounds from other roads. For example, at a day–night level of 70 dB, the percentage of "highly annoyed" respondents for highways was about 15% points higher than that for other roads. Although Miedema [10] did not specify the proportion of heavy vehicles in the various studies, this factor might explain at least part of the differences between the two road categories.

As an alternative to L_{Aeq}, Rylander and colleagues (e.g., see references [12–14]) suggested that the community response to road-traffic noise is mainly determined by the level of the noisiest events, and therefore in most cases by the sounds from the heavy vehicles. This topic is further discussed in section 5.3.

2.3. CONCLUSIONS

The laboratory study results are inconsistent about the difference in annoyance between light and heavy vehicles: at equal sound exposure levels, heavy vehicles could be either less annoying [6, 7], in at least some conditions reported in reference [5] more annoying, or as annoying as light vehicles [3, 4, 8].

Although the difference in annoyance between the sounds from highways and other roads, as reported in reference [10] may be attributed to several factors, the proportion of more annoying heavy vehicles is at least one likely candidate. The analyses of the field survey data described in reference [9] suggest that, again at equal sound levels, heavy vehicles are more annoying than light vehicles only in the case of non-freely flowing traffic.

3. EXPERIMENT

In the present study, the adequacy of L_{Aeq} as a predictor of annoyance caused by road traffic noise is tested for conditions where the proportion of heavy vehicles in a flow of light and heavy vehicles is systematically varied. Moreover, both the number of vehicle passages and the level difference between the heavy and light vehicle passby sounds in each condition are fixed. In these respects, this study is different from previous experiments [5, 6] in which these latter two variables were confounded with the proportion of heavy vehicles.

3.1. STIMULI AND DESIGN

Stimuli with a fixed number of passby events per unit of time, but comprising a different number of heavy vehicles were created by concatenation of single-vehicle passby recordings. Sound recordings were made of four different passenger cars and four different trucks (two of them with trailer), driving by on a two-lane road at a constant speed of approximately 80 km/h. Recording distances were 12·5 and 100 m from the road axis, in order to create realistic-sounding stimuli with L_{Aeq}-values of 50 and 38 dB respectively. Sounds were sampled at 16 kHz with a 16-bit amplitude resolution, and were stored on a computer hard disk. Single vehicle passages lasted about 20 s, and were added overlappingly to form stimuli of 200 s in duration. Each stimulus comprised 20 vehicle passages, evenly distributed in time, i.e., one passby event in every 9·5 s. By concatenation of the passby events of the appropriate vehicles, the proportion of heavy vehicles could be set to either 0·0, 0·1, 0·25, 0·5, 0·75, 0·9, or 1·0. At the same recording distance, the sound level of the heavy vehicles was on average about 10 dB higher than that of the light vehicles. This 10-dB difference was maintained in all stimuli. To ensure identical L_{Aeq}-values for stimuli that differed with respect to the proportion of heavy vehicles, the overall level of stimuli containing small proportions of heavy vehicles had to be increased by at most 5 dB, whereas the overall level of stimuli containing high proportions of heavy vehicles had to be decreased by at most 5 dB.

Signals were played back via a finite impulse response (FIR) filter that was designed to compensate for the non-flat frequency response due to room resonances and audio-chain imperfections. Furthermore, this filter was utilized to realize a frequency-dependent outdoor-to-indoor reduction in sound level. In line with the experiments reported by Versfeld and Vos [7], it was intended to simulate an indoor listening condition in which the windows were slightly opened. To obtain the intended reduction, the signals were attenuated by 10 dB, and low-pass filtered at 125 Hz with a -2 dB/octave slope. A soft background noise comprising remote traffic sounds ($L_{Aeq} = 30$ dB) was present throughout the entire experiment, and was added to increase the realism of the presentation. Stimuli

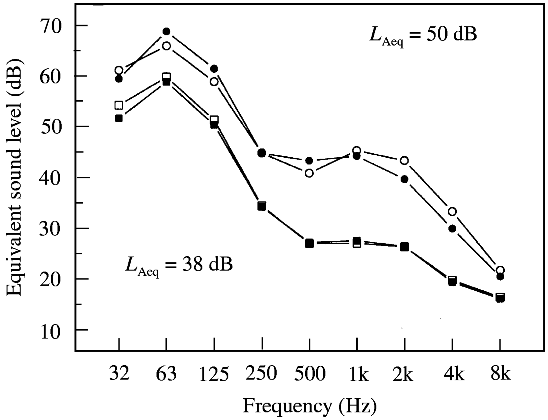

Figure 2. Equivalent sound level (in octave bands) for four stimulus conditions. Spectra are measured at the position of the subject. Open and closed symbols indicate light and heavy vehicles respectively. Squares and circles indicate the overall A-weighted equivalent sound levels of 38 and 50 dB respectively. ○, light vehicles; ●, heavy vehicles; □, light vehicles; ■, heavy vehicles.

were presented via a JBL4425 loudspeaker. The octave-band equivalent sound levels of the light and heavy vehicles at the L_{Aeq}-values of 38 and 50 dB, as measured at the position of the subject, are displayed in Figure 2.

Especially for $L_{Aeq} = 38$ dB, the spectral differences between the light and the heavy vehicles were very small. For frequencies between 250 and 4000 Hz, the differences between the two overall L_{Aeq}-values were greater than for the frequencies lower than 250 Hz.

3.2. SUBJECTS

Twenty young normal-hearing adults participated in this experiment. They were paid for their services.

3.3. PROCEDURE

The experiment was conducted in two sound-insulated rooms simultaneously. Each subject was seated in the middle of his own room of approximately 35 m^3. The loudspeaker was positioned approximately 2 m in front of the subject, and was hidden behind a curtain. After each stimulus presentation, the subject was requested to respond to the following question: *How annoying would you find the sounds in the preceding period if you were exposed to it at home on a regular basis*? Subjects responded on a rating scale, ranging from "1" to "10". "1" was labelled "not annoying at all"; "10" was labelled "extremely annoying". Numbers "2"–"9" were not verbally labelled. They responded by pressing the appropriate button on a terminal keyboard.

The experiment was partitioned into two blocks with a short break in between. Subjects started each block with four practice trials. One-half of the subjects first received all (experimental) stimuli with $L_{Aeq} = 50$ dB (i.e., the passages recorded at a distance of 12·5 m), followed by all stimuli with the $L_{Aeq} = 38$ dB (i.e., the passages recorded at a distance of 100 m). The other half of the subjects received the stimuli in reversed order with respect to

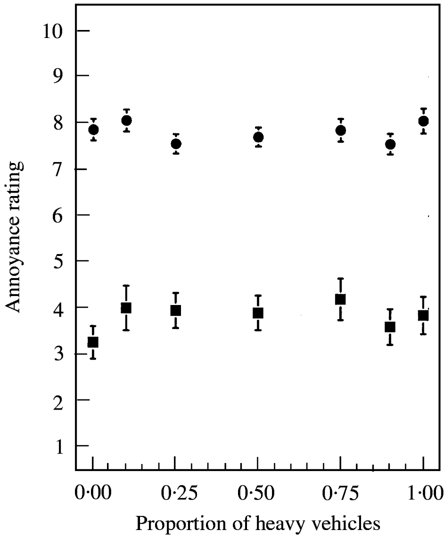

Figure 3. Annoyance scores as a function of the proportion of heavy vehicles. Squares and circles indicate A-weighted equivalent sound levels of 38 and 50 dB respectively. Error bars indicate the standard deviation of the mean. ■, $L_{Aeq} = 38$ dB; ●, $L_{Aeq} = 50$ dB.

the overall sound level. Within each block, stimuli were presented in a randomized order. The sequence of the different passby events within a stimulus was also randomized, and was different for each and every stimulus.

4. RESULTS

Figure 3 shows the mean annoyance ratings as a function of the proportion of heavy vehicles. Squares and circles indicate annoyance ratings for stimuli with indoor L_{Aeq}-values of 38 and 50 dB respectively. Error bars indicate the standard deviation of the mean. A three-way [2 (overall L_{Aeq}) by 7 (proportion of heavy vehicles) by 20 (subjects)] analysis of variance was performed on the entire dataset. Annoyance ratings were affected significantly by the overall L_{Aeq} [$F(1, 19) = 122$, $p < 0{\cdot}00001$], and by the proportion of heavy vehicles [$F(6, 114) = 3{\cdot}19$, $p < 0{\cdot}01$]. No significant interaction was observed between L_{Aeq} and proportion [$F(6, 114) = 1{\cdot}64$, $p > 0{\cdot}1$]. A post hoc Tukey test showed that the main effect of proportion is caused by significant differences between 0% heavy vehicles and 10 and 75% heavy vehicles. The post hoc test also revealed that the differences obtained between 0 and 25, 50, 90 and 100% heavy vehicles were not statistically significant.

5. DISCUSSION

In the present experiment, no significant differences in annoyance rating were observed between stimuli with 10% heavy vehicles or more. Thus, it seems justified to conclude that the present data indicate that L_{Aeq} is a good predictor of the annoyance caused by a mixture of light and heavy vehicles, irrespective of the proportion of heavy vehicles.

This finding is in agreement with the results of Cermak [3], Cermak and Cornillon [4], and Yaniv *et al.* [8], but contradicts the results of Rylander *et al.* [6] and Labiale [5]. Moreover, this finding had not been expected from the results reported by Versfeld and Vos [7].

The occurrence of a significant effect of the proportion of heavy vehicles could, up to a point, also have been related to the difference in community response to the sounds from highways and other roads, as noted by Miedema [10]. From a recent reanalysis based on much more field data than utilized earlier, however, Miedema and Vos [15] concluded that the type of road was no longer an important factor for predicting noise annoyance. This is consistent with the findings reported by Langdon [9] for free-flow conditions.

In the present experiment, there was little difference between the average spectra of the light and heavy vehicles (see Figure 2). In section 5.1, it will be shown that the spectral contents of our passby sounds are similar to those reported earlier by Olson [16] and Lewis [17]. This observation supports that the present conclusion about the adequacy of L_{Aeq} as a predictor of the annoyance from mixed road-traffic sounds may be applied more widely.

In section 5.2, the annoyance caused by the vehicle passby sounds is, in line with noise zoning procedures, related to outdoor rather than to indoor L_{Aeq}. Although the results of this analysis did not affect the conclusions mentioned above, it is of interest to note that a relevant part of the discrepancy between present and previous results could be reduced.

Additional analyses of the present data pertinent to a maximum single-event-level model for the prediction of the annoyance caused by road-traffic sounds are given in section 5.3.

5.1. SPECTRAL CONTENT FOR LIGHT AND HEAVY VEHICLES

The absence of an important effect of the proportion of heavy vehicles on the annoyance might be understood from the fact that in our experiment the average spectra of the light and heavy vehicle passby sounds were almost equal. The applicability of these results depends on the degree to which the selected passby sounds are representative for the two vehicle categories in real life.

It was considered relevant to compare the spectra of our four light and four heavy vehicle passbys with spectral information given by Olson [16] and Lewis [17]. For the eight passbys in the present study, the spectral analysis was based on the unprocessed microphone signal at a recording distance of 12·5 m. The linear octave-band levels relative to the overall A-weighted level are given for the four light and the four heavy vehicles in Figure 4(a) and 4(b) respectively. Similar spectral information was derived from the data reported by Olson for the passenger cars and tractor trailers (see Figure 9 in reference [16], for a comparable driving speed of 50–59 mph), and from data reported by Lewis for the light and heavy vehicles (see Table 6 in reference [17]). The average spectra obtained on the basis of the data from Olson and Lewis were very close. The mean results are represented by the solid lines in Figure 4(a) and 4(b).

From Figure 4(a) it may be concluded that the relative levels of our passenger cars are close to those reported by Olson and by Lewis. Only for one car, the relative levels at the 125 and 250 Hz frequency bands differ from the average levels by more than 6 dB. For the heavy vehicles (Figure 4(b)), the overall match is great as well.

Standard deviations of the sound levels within the various octave bands were adopted from Olson's Table 6. The dotted lines in Figure 4(a) and 4(b) represent two standard deviations above and below the mean. On the assumption that the raw data are normally distributed, the range between the two dotted lines includes 96% of the individual spectra. It must be concluded that the spectra of the passby sounds utilized in the present experiment are not significantly different from the spectra that were based on the much larger samples analyzed by Olson [16] and Lewis [17].

In spite of the similarity of the spectral contents of the passby sounds, both our subjects and those participating in other studies (e.g., see reference [4]) were able to

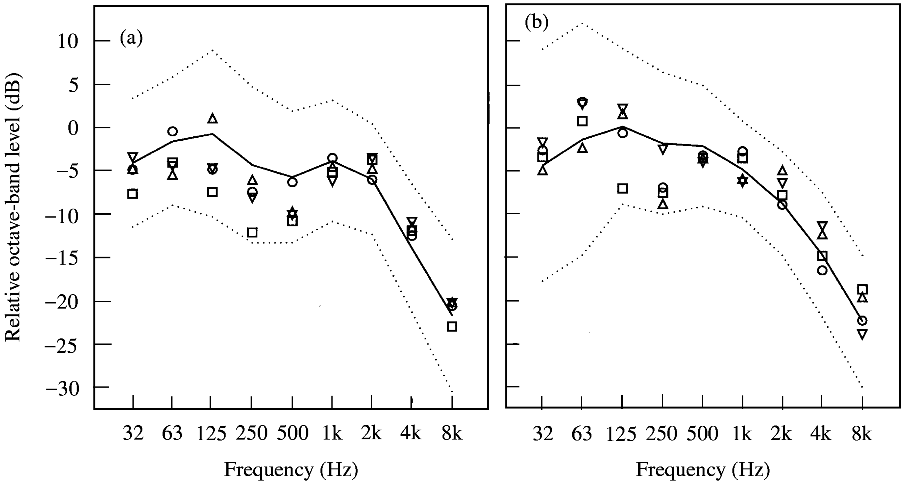

Figure 4. Linear octave-band levels relative to the overall A-weighted level for vehicle passby sounds included in the present experiment. As references (solid lines), similar spectral information is given for passby sounds included in surveys of Olson [16] and Lewis [17]. The range between the dotted lines covers 96% of the individual spectra: (a) ○○△▽, passenger cars; (b) ○○△▽, trucks.

discriminate between the light and heavy vehicles. One cue is the relative difference in the overall sound level. Another cue might be based on differences in the spectro-temporal fine structure.

Modulation spectra (modulation depth as a function of modulation frequency) were determined for the four light and the four heavy vehicle passby sounds at the two recording distances. Especially for modulation frequencies between 10 and about 100 Hz, the spectra for the heavy vehicles were characterized by higher peaks and lower valleys than those for the light vehicles. The differences in modulation spectra might therefore be a second cue for the discrimination between light and heavy vehicle passby sounds.

5.2. ANNOYANCE AS A FUNCTION OF OUTDOOR SOUND LEVEL

The results from a previous laboratory study [7] implied that for obtaining indoor L_{AE} of equally annoying light vehicle passbys, L_{AE} of the heavy vehicle passbys had to be reduced by 6 dB (see Figure 1). A common practice in noise-zoning procedures, however, is to measure (or calculate) the sound level outside, near the façade of the dwelling.

In Figure 5, the levels are expressed as outdoor L_{AE}-values. Again, cumulative normal distribution functions were fit to the data. With σ fixed at about 12 dB, the optimal values for the light and heavy vehicles were 72 and 74 dB respectively. Consequently, with the noise dose expressed as outdoor levels, the 6 dB bonus to the heavy vehicle sound levels is reduced to 2 dB.

In Figure 3, the mean annoyance ratings obtained in the present study were related to the proportion of heavy vehicles for conditions in which the indoor L_{Aeq} was fixed. Since the overall spectra for the light and heavy vehicles, as measured at the ears of the subjects, were almost equal (see Figure 2), the outdoor levels in the various conditions must have been equal as well. This means that the interpretation of the results obtained in the present study is not affected by the position (indoors or outdoors) at which the sound level is determined. Presence versus absence of overall spectral differences between light and heavy vehicles, as

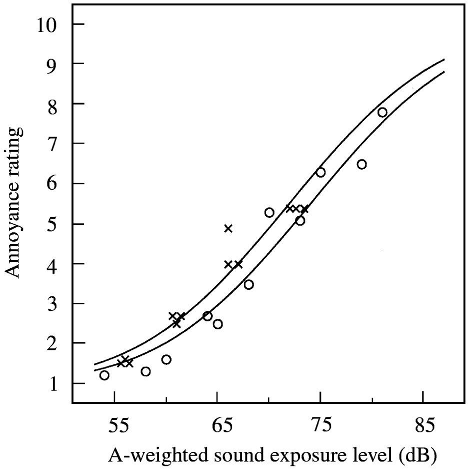

Figure 5. Annoyance ratings from Figure 1, replotted as a function of the outdoor A-weighted sound exposure level for light and heavy vehicles. The solid lines represent least-squares fits to the data sets. Vehicles: ×, light; ○, heavy.

found in the previous and the present study, respectively, might be explained by differences in sample size.

One might wonder to what extent the results obtained in the related studies discussed in section 2.1 are dependent on the position at which the sound level is measured.

In the laboratory experiments conducted by Cermak and colleagues [3, 4], the traffic sounds were presented to the subjects as they had been recorded in the field. Frequency-dependent outdoor-to-indoor sound level reductions had not been applied. The subjects, in fact, rated the sounds as if they were outdoors. In such conditions it is unlikely to find differences in annoyance between the light and heavy vehicles (also see reference [18]).

In the laboratory study reported by Yaniv *et al.* [8], a frequency-dependent façade attenuation was applied to 12 of the 24 conditions. By combining the information given in Tables I–III in reference [8], we could determine the outdoor L_{Aeq} for the 12 conditions. As expected, the predictability of the annoyance from the outdoor L_{Aeq} ($r^2 = 0{\cdot}97$) was even higher than that from indoor L_{Aeq} ($r^2 = 0{\cdot}90$).

5.3. ANNOYANCE PREDICTED BY A MAXIMUM SINGLE-EVENT-LEVEL MODEL

It has been suggested that the annoyance caused by road-traffic sounds is determined mainly by the level of the noisiest events (e.g., see references [12, 13]). The number of these events is less important: the community response increases with the number of events up to a saturation point above which a further increase in number does not affect the response. Since in most cases heavy vehicles produce higher sound levels than light vehicles do, this would imply that the annoyance is determined by the levels of the heavy vehicles.

It should be emphasized, however, that for several field surveys reported by Rylander and colleagues, the results support the adequacy of L_{Aeq} as a predictor as well. Firstly, with the percentage of respondents describing themselves as "very annoyed" as a function of the number of (heavy) vehicles on a *logarithmic* scale, it is either impossible to detect any saturation point [12], or the indication for such a point is found for over 2000 (heavy) vehicles per day [13]. Secondly, both Rylander *et al.* [12] and Björkman [13], found highly

TABLE 1

Mean A-weighted sound exposure levels (in dB) of single light and heavy vehicle passages for various proportions of heavy vehicles and two overall A-weighted equivalent sound levels. Mean annoyance ratings obtained for the various mixtures of the vehicle passages are also included

Proportion of heavy vehicles	$L_{Aeq} = 38$ dB			$L_{Aeq} = 50$ dB		
	Light vehicle	Heavy vehicle	Mean annoyance rating	Light vehicle	Heavy vehicle	Mean annoyance rating
0·0	48·0	—	3·3	60·0	—	7·9
0·10	45·2	55·2	4·0	57·2	67·2	8·1
0·25	42·9	52·9	4·0	54·9	64·9	7·6
0·50	40·6	50·6	3·9	52·6	62·6	7·7
0·75	39·1	49·1	4·2	51·1	61·1	7·9
0·90	38·4	48·4	3·6	50·4	60·4	7·6
1·0	—	48·0	3·9	—	60·0	8·1

significant relationships between the percentages "very annoyed" and L_{Aeq}, with correlation coefficients equal to 0·78 and 0·70, respectively.

Quite recently, Sato *et al.* [14] showed that with stratified personal noise exposures, highly significant relationships were found both between average annoyance and L_{Aeq} and between average annoyance and the maximum sound level of single vehicle passages. In sum, it is therefore tempting to determine the relationship between the annoyance rating and the maximum single-event-level for our experimental results as well.

Table 1 shows the average A-weighted sound exposure levels of the vehicle passages for all conditions investigated. Both in the conditions in which total $L_{Aeq} = 38$ dB and in the conditions in which total $L_{Aeq} = 50$ dB, the maximum single-event-level was for six of the seven proportions investigated determined by the level of the heavy vehicles. Only for the conditions in which the proportion of heavy vehicles was equal to zero was the maximum level determined by the level of the light vehicles. The mean annoyance ratings obtained in the various conditions with $L_{Aeq} = 38$ or 50 dB are given in columns 4 and 7 of Table 1 respectively.

For $L_{Aeq} = 38$ dB, there was a weak tendency for the annoyance ratings to increase with the maximum single-event-level; the (Pearson) correlation coefficient was equal to 0·47. This relationship, however, was not statistically significant ($t = 1{\cdot}2$, $p > 0{\cdot}25$).

For $L_{Aeq} = 50$ dB, the correlation coefficient was as low as 0·08. Consequently, the relationship between the maximum level and the annoyance in these latter conditions was not significant as well.

6. CONCLUSIONS

A laboratory experiment was conducted in which the effect of the proportion of heavy vehicles in road-traffic noise on annoyance was determined. Results indicate that for the particular stimuli tested, the A-weighted equivalent sound level is a good predictor of the annoyance caused by a mixture of light and heavy vehicles, irrespective of the proportion of heavy vehicles.

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