Combined annoyance response from railroad and road traffic noise in an alpine valley

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Abstract

Context: The aim of this study was to verify the contributing effect in the cases of combined road traffic noise and railroad traffic noise on total noise annoyance. Materials and Methods: After opening the four-track railway of the Lower Inn Valley Route in Austria, an evaluation study was conducted by an interview survey (n=1003). The data of this survey included answers on annoyance caused by railroad, road traffic noise and total annoyance as well as self-evaluated noise sensitivity. Results: When annoyance is only related to one of these sources, a 10% share of highly annoyed persons was observed at 59 dB for road noise and 60 dB for railroad noise. The annoyance model including both noise sources with a coefficient of 0.145 for road noise, 0.034 for railroad noise and 0.431 for noise sensitivity (all p-values < 0.01) showed a regression coefficient R² of 0.299. The presence of road background noise did not influence the annoyance on railway noise. Conclusion: The combined influence of road and railway noise showed an increase of total annoyance.

Keywords: combined effects, background noise, equivalents model, field study, total annoyance

INTRODUCTION

Environmental noise annoyance is usually rated via exposure-response relations based on standardised noise indices. It is state of the art to define legal limits for each of aircraft, railroad and road traffic noise. Such legal limits can be based on guidelines such as those from EEA or WHO to keep the number of (highly) annoyed persons below acceptable thresholds or to avoid adverse health effects [1–4]. Usually when building new infrastructure, or planning noise interventions for existing highways, roads or railway lines, decisions are based on noise indices for each source separately. A combined evaluation is not currently generally accepted as state of the art, although it has been described in literature. Miedema et al. 2004 presented an equivalence method to correlate annoyance to the exposure to multiple noise sources [5]. The approach was also included in guidelines on noise exposure of the European Environment Agency [2]. However, there is no clear recommendation to use a combined approach at the European Policy level or national levels. Practical experience with the Miedema method is limited and literature reports only limited correlation to measured total noise annoyance from field studies [6]. In Germany the technical regulation VDI 3722 –2 was introduced in 2013 and is also based on this combination methods [7]. In its introduction section it describes the limited evidence for using the method and recommends it mainly for estimates of annoyance and as an auxiliary means for the acoustic evaluation of planning alternatives.

Major criticism on the equivalents model is related to the presence of masking effects and missing empirical verifications of the assumptions made by Miedema et al [5]. The method was not based on global assessment

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itself, but on studies evaluating each noise source independently and as a theoretical concept.

This paper performs a global assessment for a dedicated region in a valley with major roads and railways in Austria. The main research questions are:

(1) Is there a relevant influence of road traffic noise exposure on the annoyance reaction due to railroad noise?
(2) Does the influence of road traffic noise in combination with rail traffic noise lead to an increase of the overall noise annoyance effect?

**Methods and Materials**

**Field study — description of area:**

In order to build a major railway track in the Tyrolean Lower Inn Valley, the environmental impact analysis recommended a detailed noise assessment 3 to 5 years after opening. The new project, which is part of a Trans-European railway corridor, consists of 4 tracks in a 40 km section within the valley. The new tracks are mainly located in tunnels and incisions, which led to a reduction of the noise levels resulting from the train traffic because 2 tracks mainly above ground were actively used before. The survey of this analysis took place from November 2015 to January 2016, while full activation of the new railway line took place in 2014.

At the same time the Lower Inn Valley is exposed to road traffic noise from a highway, regional and local roads. The road noise model included the major highway in the Lower Inn Valley and any other public roads. Traffic data was available from a detailed analysis which was previously used for air pollution assessment in 2010. This detailed traffic model was necessary in order to include small roads which are often close to the buildings in the densely populated valley.

**Noise index calculations**

Noise indices \( L_{\text{den}} \) and \( L_{\text{nigh}} \) have been calculated according to the European Directive 2002/49 EC at the facade of the exposed buildings, at a height of 4 m.

For railway noise, the Austrian prediction method ONR 305011 calculates sound power values in octave bands for the different train types, train length and speed [8]. The railway traffic numbers were available in detail for the year of the survey. Sound propagation is calculated based on ISO 9613-2 taking into account the digital terrain model including noise barriers and the dimensions of buildings in detail [9]. Up to three reflections were considered. Buildings were modelled with a reflection coefficient of \( \alpha = 0.2 \). Ground absorption was modelled explicitly also considering reflecting surfaces such as the River Inn. For settlement areas, the regions without roads and buildings were defined to have 20% reflective areas which was characterised by a ground absorption factor \( G = 0.8 \). The calculations were limited to favourable sound propagation conditions of ISO 9613-2. Air absorption was considered for an air temperature of 10°C and 70% relative humidity.

Road traffic noise was calculated using the Austrian prediction Method RVS 04.02.11 with the update of the emission values in 2009 [10]. This method considers the specific road surface, traffic flow (light, medium and heavy vehicles), speed and the road gradient. The ratio between light and medium/heavy vehicles was available in detail. The detailed ratios between medium and heavy vehicles according to the RVS 04.02.11 recommendations were 25:75 for highways and 90:10 for all other roads. The ground model and propagation condition parameters were identical to the railway parameters.

The calculations were performed with the commercial system CadnaA (Version 4.6.155, DataKustik GmbH, Gilching, Germany). The software provided \( L_{\text{den}} \) and \( L_{\text{nigh}} \) values. In addition, the cumulated parameter \( L_{\text{nigh}, r, kum} \) was calculated. The noise index of railroad noise was converted to an equally annoying road traffic level, which could then be summed to the road traffic level according to the method described by Miedema in 2004 [5]. The method performs a conversion from the railroad noise index to the road noise equivalent level, which enables energetic summation to calculate the cumulative index.

**Survey**

The observed area includes in total around 83,500 persons living in 34,000 households in 26 communities. The population is distributed as 51% female and 49% male. The age distribution in the population is 16% below 15 years, 68% from 15 to 65 years and 16% above 65 years. Within the age group from 15 to 65 years, 76% are economically active and the rate of unemployment is 3%. Distribution according to education level shows that 28% of the population over 15 years old has a primary level, 63% a secondary level and 9% a tertiary level.

The survey was planned with a sample size of at least 1000 persons using random-address-cluster sampling. This selection process ensures the establishment of a uniform distribution of the respondents according to the criteria of exposure to railway noise (3 corridors), age (3 age groups), gender and population distribution in the 26 communities where interviews were performed. The three railway noise exposure corridors were defined based on highly exposed persons (\( L_{\text{nigh}} > 55 \text{ dB} \)), intermediate exposed persons (\( L_{\text{nigh}} > 45 - \leq 55 \text{ dB} \)) and no substantial exposure (\( L_{\text{nigh}} \leq 45 \text{ dB} \)).

The survey was performed with a standardised questionnaire and expert interviewers. Exposure and annoyance was assessed according to ISO/TS 15666 [11,12]. Questionnaires included socio-demographic data, the housing situation, noise perception, living conditions, subjective assessments of quality of life, sensitivity to noise, state of health, annoyance by noise in general and during sleep, noise coping, mobility and railway use as well as questions about changes in noise levels and attitudes to the new railway track.
**Statistics**

**Exposure-effect relationships:**

Exposure-effect relationships were calculated using the noise index value of the most exposed facade of the building for each of railroad and road noise. These values were sorted in 1 dB bins and linked with the frequency of the answers from the questionnaire. Bins were created by rounding. Curves were established via logistic regression with descriptive parameters following Miedema und Oudshoorn 2001 (little annoyed 3-10, annoyed 5-10, highly annoyed 8-10) [13].

**Linear regression & Multiple linear regression**

The multiple linear regression was based on Formula (1)

\[ A = \beta_0 + \beta_{\text{road}} \cdot L_{\text{den,road}} + \beta_{\text{rail}} \cdot L_{\text{den,rail}} + \epsilon \]  

with

- \( A \) annoyance (scale 0 to 10)
- \( L_{\text{den,road}} \) Noise index for road traffic
- \( L_{\text{den,rail}} \) Noise index for railroad traffic
- \( \beta_0 \) constant intercept
- \( \beta_{\text{road}} \) regression/slope coefficient for road traffic noise
- \( \beta_{\text{rail}} \) regression/slope coefficient for railroad traffic noise
- \( \epsilon \) random component

The significance of the established regressions was tested with the F-Test. The multiple regression was extended by the additional factor noise sensitivity \( E_{\text{sens}} \) and the regression coefficient \( \beta_{\text{sens}} \) in Formula (2)

\[ A = \beta_0 + \beta_{\text{road}} \cdot L_{\text{den,road}} + \beta_{\text{rail}} \cdot L_{\text{den,rail}} + \beta_{\text{sens}} \cdot E_{\text{sens}} + \epsilon \]  

The noise sensitivity is available from the questionnaires as a subjective estimate on a scale from 0 to 10. Because the assessment of the self-reported state of health correlates with the sensitivity to noise, this factor was not included in the model. The dependence of sensitivity on age was tested with a Kruskal-Wallis test and not explicitly included into the regression model. All analyses were calculated by the statistical analysis software SPSS 23 (IBM, Armonk, NY, USA).

Descriptive statistics were performed using the F-test, Kruskal-Wallis-test and Mann-Whitney-U-test.

**RESULTS**

**General results**

The survey sample resulted in 1003 interviews, which was 54% of persons asked to participate, 504 of them women (50.2%) and 499 men (49.8%). The interviewed persons ranged in age from 18 to 94 (mean age 49). Three age groups were established (<35, 36-55, > 55 years) and tested for differences in subjective noise sensitivity. The noise sensitivity as estimated by the subjects themselves showed statistically significant differences between those age groups (Kruskal-Wallis test \( p=0.039 \)). The mean noise sensitivity was 3.72 for respondents aged 35 and below, while it was 4.24 for the 36-55-year-olds and 4.20 for the over 55-year-olds.

Men and women did not differ significantly in the subjective assessment of noise sensitivity (Mann-Whitney-U-Test \( p=0.341 \)). Furthermore, the subjective assessment of the state of health was queried and this parameter correlated with the subjective sensitivity to noise. Persons with a subjective assessment of their state of health in the group "good to very good" differ significantly (Mann-Whitney-U-Test \( p = 0.001 \)) in their subjective sensitivity to persons with a subjective assessment of their state of health in the group "not particularly good". It clearly shows that for people with "less good" health, the sensitivity to noise is significantly higher. Men and women did not differ statistically significantly (Mann-Whitney-U-Test \( p=0.680 \)) in their subjective assessment of their state of health.

Respondents' annoyance reactions to road traffic noise, rail noise and total noise were presented in three groups as a first step. The first group describes the reaction "highly annoyed" with a response of 8 to 10 on the 11-part survey scale. The second group describes the middle range from 5 to 7 and is called "annoyed". The third group covers the range of 0 to 4 and is referred to as "not / slightly annoyed". The groups are disjoint and represent all possible answers. In this context, there were no missing values, so that the total number of interviews of 1003 resulted in valid values.

The table below shows the frequency of replies in percent in the three groups of annoyance to road noise, rail traffic noise, and total noise:

The mean value of railway exposure was 43 dB \( L_{\text{den}} \) while the mean answer in the annoyance scale was 2.23. The mean value of motorways exposure was 52 dB, of main roads 48 dB and of small local roads 46 dB \( L_{\text{den}} \). This shows the non-negligible relevant contribution from smaller roads with less traffic. The mean value of the answers in the annoyance scale from road traffic noise was 3.56. The highest noise reaction was found for the total annoyance with a mean of 3.78.

It was investigated whether there is a difference in the self-reported noise annoyance reaction depending on the subjective assessment of noise sensitivity. This was done for road traffic noise, rail noise and total noise. In all cases, there is a statistically significant correlation (Mann-Whitney-U-test \( p < 0.001 \)) between the annoyance reaction and subjective noise sensitivity. The subjective noise sensitivity
was therefore included in the regression model. In order to understand the annoyance rate in the observed region in comparison to other studies the exposure-effect curves are first presented for each traffic noise source separately. Figure 1 shows the exposure-response relationships and their 95% confidence intervals for road and rail traffic noise in the study area.

Comparisons of the curves show 10% highly annoyed from road noise at $\sim 59\, \text{dB}$ and from railroad noise at $\sim 60\, \text{dB}$. At a rate of 20% highly annoyed, the road curve shows 64 dB versus 67 dB for railroad.

A recent published study on combined effects on annoyance in Innsbruck [14] also showed exposure-response-curves for different noise sources. The curves were derived with nearly the same methodology as in this research. Figure 2 shows the comparison of the dose response curves from the Lower Inn Valley compared with the results from the Innsbruck study.

While in Innsbruck the annoyance response on road and rail traffic noise is nearly the same, there is a notable difference below 55 dB $L_{\text{den,road}}$ in the Lower Inn Valley. All four curves get closer to each other at around 60 dB $L_{\text{den,road}}$ with a percentage of highly annoyed close to 15%.

The work from Miedema and Oudshoorn 2001 [13] and the recent published WHO Guidelines [4] are included for this comparison in Figure 3 for road traffic noise and in Figure 4 for rail traffic noise.

There is moderate agreement between the Miedema 2001 curves for urban roads and the present study. The different annoyance reaction between road and railroad is much smaller compared to Miedema 2001. These results are valid for the definition of %HA above 72% annoyance rate.

With a focus on road traffic noise the present research was compared with other recent studies, namely the Danish road study [15] and the Swiss SiREN study [16]. These comparisons are illustrated in Figure 5.

The curves for urban roads of the Danish road study is aligned with the Miedema-Oudshoorn curve, whereas the curve for motorways shows a much higher annoyance rate. A pooled data curve is located in-between. The Exposure Effect Curve of the present study is in good agreement with the Danish study for pooled data. This is remarkable as pooled local road and motorway exposure data were also used in the present study.

**Linear regression results**

Table 2 shows the results of the multiple linear regression. Lines 1 und 2 show the relation between the annoyance from road noise $A_{\text{road}}$ and railroad noise $A_{\text{rail}}$ to the noise index for Road $L_{\text{den,road}}$ and the noise index for railroad $L_{\text{den,rail}}$ separately. Both relations are highly significant and show a clear correlation between annoyance and noise level. Line 3 shows the annoyance from railroad noise, but depending on both noise indices from railroad and road. The regression analysis shows a significant dependence from rail noise but not from road noise. If the analysis is performed for the annoyance from road noise, the result is similar, as now the dependence from the road noise index only is significant. As a next step, the total annoyance is linked to both noise indices (Line 5). Now both noise indices show a significant effect on annoyance. The global annoyance score is significantly dependent on the road noise and the railway noise indices.
Line 6 shows the regression with the cumulative equivalent level $L_{den,r,kum}$ which is the summation of road and railroad noise according to the Miedema equivalents model. It shows a slightly lower correlation compared to the previous analysis. The slope of the regression is higher compared to the slopes from Line 5.

The multiple regression analysis was extended by the noise sensitivity as reported by the subjects. By means of this, the correlation coefficient $R^2$ can be increased from 0.128 as in Line 5 of Tables 1 and 2 to 0.299 in Table 3. This is a remarkable impact for the explanation of annoyance reactions. Considering the annoyance scale from 0 to 10...
and the found $\beta_{\text{sens}}$ of 0.432, the sensitivity to noise by $\beta_{\text{sens}}$ can result in a 4.3 dB variance.

**DISCUSSION**

The relation between %HA and noise, defined via the noise index $L_{\text{den}}$, has been shown by many studies. A systematic review recently collected the current evidence [3]. The %HA for road from the full dataset for road traffic noise at 60 dB $L_{\text{den}}$ was $\sim$15 %, this study showed nearly the same amount of $\sim$16 %. The difference of the exposure response curves shows in the steepness. While up to 60 dB in the Lower Inn Valley the percentage of highly annoyed
road noise caused substantially more %HA at 60 dB L_{den} as cut-off on the annoyance scale for defining a %HA_{60}, compared to railroad noise. This study could only find 14 % at this level. Again, a study from the same Alpine valley was one cause of the higher annoyance levels in the systematic review. Comparing the results with a recent study analysing the combined effect of aircraft, road and railroad traffic noise shows good agreement [18]. At 60 dB L_{den} and using 60% as cut-off on the annoyance scale for defining a %HA_{60}, road noise caused substantially more %HA at 60 dB L_{den} compared to railroad noise. When using the usual %HA definition with a cut-off value of 72% annoyance rate, the difference between road to railroad becomes less than 3 dB.

However, this study focused on the combined exposure from road and railroad noise. The annoyance reaction due to railroad noise is not significantly influenced by the presence of road traffic noise. It could not be shown that road traffic noise has a protective effect. However, the total annoyance reaction depends on the sound level of both noise sources and leads to an amplified effect. These results are based on the specific situation where there is no clearly dominating source, but the presence of road noise and railroad noise at comparable levels due to their close vicinity in the Alpine valley. One of the strengths of the present study is the modelling of all road traffic sources from motorways down to local roads. This detailed analysis also considers contributions from small roads with low traffic which are often not considered in noise mapping. This can result in underestimation of the road noise exposure and therefore higher %HA compared to railroad studies which usually always contain the entire railroad noise exposure. Another strength of this study is the use of 1 dB bins in contrast to the often used 5 dB bins.

The results of this study are in line with previous observations, where the total annoyance was found to be significantly higher in the case of combined exposure compared to areas with one dominant noise source with the same total sound exposure [19]. Based on a recent French Socio-Acoustic Survey, the relevant direct and indirect relationships of different parameters with annoyance were studied using structural equation modelling [20]. The study also contains sites with combined exposure from road and railroad traffic noise. Noise sensitivity was identified as the parameter with the strongest effect on partial road noise annoyance as well as partial railroad noise annoyance. The total noise annoyance was analysed assuming a psychophysical model and a perceptual model. In all models, the visibilities of the noise sources were additional contributing factors. In the psychophysical model the highest contribution to the total annoyance in the situations with combined noise exposure was again noise sensitivity. The road traffic noise exposure caused a higher effect on the total annoyance compared to the railroad noise exposure. In contrast, in the perceptual model the difference between the effects from road to railroad noise exposure becomes smaller, but still shows a higher effect for road noise. This is in agreement with the findings of this study where, for the total annoyance A_{total}, the B_{road} is 0.148 compared to 0.048 for B_{rail}. In contrast to the French study, the exposure from road traffic was caused by urban and highway traffic, and not only urban roads, but still shows a higher contribution from road noise exposure.

Lam et al. found different contributions depending on which noise source dominates [21]. Although the exposure-effect curves for road and railroad noise were comparable, factors contributed at different magnitudes to the overall annoyance.

**Table 1: frequency of replies in percent of annoyance to road noise, rail traffic noise, and total noise**

|                | Total | Road | Rail |
|----------------|-------|------|------|
| not / slightly annoyed | 52.9  | 57.7 | 75.6 |
| annoyed        | 28.5  | 22.7 | 13.7 |
| highly annoyed | 18.5  | 19.5 | 10.8 |

**Table 2: Linear regression results**

|   | Depending variable | Independent variable | R2  | β0   | p   | βroad | p   | βrail | p   | P   |
|---|-------------------|----------------------|-----|------|-----|-------|-----|-------|-----|-----|
| 1 | A_{road}          | L_{den,road}         | 0.167| −8.691| 0.000| 0.212 | 0.000| −     | −   | −   |
| 2 | A_{road}          | L_{den,rail}         | 0.191| −4.011| 0.000| −     | −   | 0.142 | 0.000| −   |
| 3 | A_{rail}          | L_{den,road}         | 0.192| −4.840| 0.000| 0.018 | 0.207| 0.137 | 0.000| −   |
| 4 | A_{road}          | L_{den,road} & L_{den,road} | 0.170| −8.996| 0.000| 0.200 | 0.000| 0.023 | 0.042| −   |
| 5 | A_{total}         | L_{den,road}         | 0.128| −6.466| 0.000| 0.148 | 0.000| 0.048 | 0.000| −   |
| 6 | A_{total}         | L_{den,road} & L_{den,road} | 0.115| −6.073| 0.000| 0.168 | 0.000| −     | −   | −   |

**Table 3: regression coefficients, standard error and p-value of the included variables**

| R2    | 0.299 | standard error | p   |
|-------|-------|----------------|-----|
| β0    | −8.121| 0.803          | 0.000|
| βroad | 0.145 | 0.014          | 0.000|
| βrail | 0.034 | 0.010          | 0.001|
| βage  | 0.431 | 0.028          | 0.000|
in their study. Dominating road noise causes noise disturbance from the peaks of train pass-by which causes indirect noise annoyance. When railroad exposure dominates, the railroad noise induces annoyance directly.

In the results of the recent Norah Study aircraft noise, as the main evaluated noise source, dominated the total annoyance reaction compared to railroad and road noise \cite{18}. This isn’t in contrast to the current results and the conclusions of Gille et al. \cite{20}. In case of aircraft noise, which can be neglected in the current study, the aircraft noise exposure dominates over road noise exposure.

Gille et al. used the Miedema equivalents model to calculate total equivalent noise exposure \cite{6} as performed in this study. The predicted total noise annoyance was not suitable. This can be explained by using the equivalent model in our study with the lower regression coefficient. As further explanation, it seems possible that the equivalent model can only be used if the underlying road-rail exposure-response curves are available in the investigated area as was the case in this study. The same explanation seems possible, i.e. that the equivalent model can only be used if the underlying exposure-effect curves for road and railroad are useful in the studied area. Another explanation for confirming the equivalents model in this study may be that the equivalent model is based on normalised L_{den} values, resulting in an equivalent percentage of highly annoyed. The regression analysis was not carried out for \% HA, but for the annoyance score (0-10) itself. This approach also proved to be suitable in the study in Innsbruck \cite{14}.

Limitations
In contrast to other sound prediction methods, the Austrian model considers only favourable sound propagation as it occurs during down-wind or medium temperature inversion. The assumption of such favourable sound propagation conditions for all periods of time results in a slight systematic overestimation of the calculated noise indices. However, especially at night, which dominates the L_{den} calculation for both railroads and roads, there is only a small variation introduced, as inversion often causes favourable sound propagation conditions.

Another potential bias could have been introduced by disclosing the Austrian Railway Infrastructure company as a supporter of this study. It may be that this could introduce a link to the annoying railroad noise in the analysed valley and hence the considerable high annoyance rates at already low noise levels could be explained as a result of a negative view of the neighbours towards that company.

Conclusions
The evaluation of a controlled annoyance survey with road and railroad noise showed independent exposure-effect curves for both noise sources. Above an L_{den} of 59 dB the percent highly annoyed persons are higher for road compared to railway noise. For the overall model road traffic leads to higher annoyance than rail noise. However, annoyance is dominated by the noise sensitivity of the individual persons. The annoyance from railroad noise correlated with the rail noise L_{den} without an influence of the ambient noise caused by road traffic. This study results could not support a protective effect of ambient noise through road traffic on annoyance from the specific railway noise source. However, total annoyance was caused significantly by both exposures. The influence of road traffic noise in combination with rail traffic noise leads to an increase of the overall noise annoyance effect.

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Conflicts of interest
There are no conflicts of interest.

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