Effects of railway noise and vibration in combination: field and laboratory studies

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ABSTRACT
Most socio-acoustic surveys show that railway noise causes less general annoyance than road traffic and aircraft noise. While speech interference is recognized as a dominating effect of railway noise, few studies have investigated how railway noise affects sleep. Vibrations induced by trains may be a severe problem in areas where the ground consists of clay, especially near railway lines with heavy freight traffic. There is, however, little knowledge of the combined effects of noise and vibrations from railway traffic, especially on sleep. Railway transport is steadily increasing both in number, speed and more heavily loaded freight trains. New knowledge is therefore needed on the combined effects (e.g. annoyance and sleep disturbances) of noise and vibration, effects of a very large number of trains and if and under what conditions a railway bonus is justified. The large Swedish research project TVANE (Train Vibration and Noise Effects) addresses these research questions. This paper presents preliminary results from ongoing socio-acoustic surveys involving residents (n=980) living at different distances from the railway line in areas without train vibrations and in areas with different levels of vibrations (0.10 - 1.43 mm/s) induced by trains. Furthermore, results from experimental studies on the combined effects of noise and vibrations on sleep quality and sleep disturbances are presented. It is concluded that railway vibration levels used in the experiment (1.4 mm/s) disturb sleep to a greater extent than the railway noise levels (Lnight 31 dB). Results from field studies confirm the strong effect of railway vibrations on sleep. An interaction effect exists between noise and vibration and general annoyance to railway noise increases when combined with railway vibration.

1. INTRODUCTION
It is estimated that 500 000 residents in Sweden are exposed to railway noise outside their dwellings that exceeds the long term goal set by the Swedish Parliament (L_{Aeq,24h} =55 dB). Railway traffic may also cause problems with vibrations especially in areas where the ground consists of clay. About 5 000 residents are estimated to be exposed to vibrations from trains that exceed 1 mm/s inside their dwellings. The policy by The Swedish Rail administration and the Swedish Environmental Protection Agency is a level of at most 0.4 mm/s as a long term goal for vibrations in dwellings. Vibrations levels of 0.5 mm/s (RMS-
value) are "clearly noticeable" and levels above 1.2-1.5 mm/s are by most people characterized as "strongly noticeable". Vibrations have been reported to cause a number of different effects such as fear of damage to the house, make things move or furniture/household items rattle as well as sleep disturbances. A recent literature review shows that there is little knowledge on the health effects of railway vibrations alone or vibrations in combination with railway noise. The results from field studies point, however, in the same direction as our previous study in 15 different areas with and without vibrations, i.e. that railway noise annoyance is considerably higher in areas simultaneously exposed to strong railway vibrations. Railway transport, both passenger and freight transport, is increasing and new railway lines are planned for environmental reasons. The combination of more frequent railway traffic and faster and heavier trains will, most probably, lead to more disturbances from railway traffic in the near future. To be able to plan for effective mitigations against noise and vibration from railway traffic new studies are needed to obtain a better basis of knowledge on adverse health effects of combined effects of railway noise and vibration. New knowledge is especially needed on general annoyance and sleep disturbance.

The results on annoyance and sleep disturbances from studies within the TVANE-project that are presented in this paper are based on empirical studies in the field in areas with similar railway noise exposure and different levels of railway vibration and on experimental studies on sleep performed in a sleep laboratory.

The main objectives of the field studies were to obtain knowledge on the effects of railway noise on (i) general annoyance, (ii) activity disturbances (listening activities, relaxation) and (iii) sleep disturbances in residential areas exposed to no/weak vibrations and in areas exposed to strong vibrations from railway traffic. The main objectives of the laboratory experiments were to study effects of different levels of railway noise in combination with weak or strong vibrations from railway traffic on sleep quality aspects (without referring to noise or vibration) (i) falling asleep, awakenings, sleep quality and tiredness next day and (ii) to study how disturbed the test subjects were by noise and vibration respectively.

2. METHOD AND MATERIALS

A. Field studies: Exposures and study sample

Two study sites (Töreboda and Falköping) were selected in areas with no or very weak vibrations from railway traffic and another two study sites (Alingsås and Kungsbacka) were selected in areas where the trains caused strong vibrations in the ground and the dwellings. The first three study sites are situated at the railway line "Västra Stambanan" between Gothenburg and Stockholm and the fourth site is situated at the railway line "Västkustbanan" south of Gothenburg.

Preliminary calculations of noise and measurements for control of noise and vibration levels were performed before the final selection of study areas. A GIS-based method was used to determine the noise levels. Calculations of noise levels at the most exposed side were provided for each residential building using the validated model Nordic Prediction Method and the calculation program Cadna. All calculation points were determined at 2 and at 4 meters above the ground as free field values. Sound levels were calculated as $L_{Aeq,24h}$, $L_{Aeq}$ day, evening, and night, and as $L_{Amax}$ and $L_{den}$.

Vibration levels were measured outside in the ground and inside in 5 houses in each of the two study sites in areas with strong vibrations. Vibration levels measured in the ground varied between 0.10 and 1.43 mm/s and was on average 0.341 mm/s (SD=0.266) in study site Alingsås and on average 0.203 (SD=0.099) in study site Kungsbacka.
Table 1 shows the number of participants in the two types of study areas. The highest sound exposure category includes two 5-dB categories since rather few participants were exposed to high sound levels. The study comprised 980 participants and the overall response rate was 53%.

Table 1. Study sample: number of respondents in different sound exposure categories.

<table>
<thead>
<tr>
<th>Number of respondents per sound exposure category</th>
<th>&lt;45 dB</th>
<th>45-50 dB</th>
<th>51-55 dB</th>
<th>56-65 dB</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Areas with weak vibrations (Töreboda and Falköping)</td>
<td>15</td>
<td>127</td>
<td>266</td>
<td>113</td>
<td>521</td>
</tr>
<tr>
<td>Areas with strong vibrations (Alingsäs and Kungsbacka)</td>
<td>66</td>
<td>218</td>
<td>112</td>
<td>63</td>
<td>459</td>
</tr>
</tbody>
</table>

B. Field studies: Evaluation of effects

A postal questionnaire on effects of noise and vibration of railway traffic was distributed to the selected residents (aged 18 to 75 years) together with an introductory letter in April 2007 or in November 2007. The design of the questionnaire was based on previous research on the adverse health effects of noise7-9 and included 50 questions in total. Annoyance caused by noise was evaluated with a five-point verbal category scale and an 11-point numerical scale according to the ISO standardization of annoyance scales10. The questions were phrased as follows: “Thinking about the last 12 months or so, when you are here at home, how much does noise from (source) bother, disturb or annoy you?” (Alternatives: “not at all”, “slightly”, “moderately”, “very”, and “extremely”). In the presentation of the results, the “annoyed” category consists of those who were moderately, very, or extremely annoyed. Various activity disturbances and sleep disturbances were evaluated both in terms of “How often” (0=“never”, 1=sometimes, 2=“often” and “How much” (2=“slightly”, 3=“moderately”, 4=“much”) railway noise affected the activity. Thus, the scale value for each question ranges from 0 to 6.

C. Laboratory experiment: Settings and test subjects

The experimental studies on sleep were conducted in the new Sound Environment Laboratory at the University of Gothenburg during 2007 and 2008. The sound laboratory rooms were furnished as a homelike apartment with three bedrooms, a combined kitchen and living room (see photos Figure 1).

The background sound levels (ventilation etc.) in the laboratory were very low, $L_{\text{Aeq}}=13$ dB. The sound exposures used in the sleep study were played from the control room via two loudspeakers mounted on the wall in the bedrooms at the same side as the bed. The temperature in the bedrooms could be adjusted according to the subjects’ requests. They had their own keys to the dwelling and could come and go as they pleased during the day. During the experimental period, sleep during daytime hours or consumption of alcohol was not permitted.

Twenty-one healthy subjects, 14 women and 7 men aged 18 – 30 years (average age 23 years, SD $\pm$ 3.6) took part in the sleep experiment.

All subjects had normal hearing and passed the audiometric test without any remarks.
D. Laboratory experiment: Design and exposures

The experiment lasted 5 nights and started with two nights for habituation followed by three nights with railway noise at two sound levels combined with low or high vibration levels (see Table 2).

Figure 1: The laboratory environment, bedroom (upper left) and combined kitchen and living room.

The three exposure nights (night 3-5) were presented in a randomized order during the eight experimental sessions. The railway noise was synthesized using recordings of freight, local and long distance trains with the same composition during night as on the railway line Västra Stambanan between Gothenburg and Alingsås, i.e. 46 trains between 11 pm and 7 am. The frequency spectra of the sound exposures were filtered to correspond to a realistic situation in the home with the bedroom window slightly open. Two sound levels were used, (1) $L_{Aeq,8h}$ 31 dB/$L_{Amax}$ 54 dB and (2) $L_{Aeq,8h}$ 28 dB/$L_{Amax}$ 48 dB. The railway noise consisted of 25 freight trains with $L_{Amax}$-levels (exposure 1) of 48.6-53.9 dB, 9 fast passenger trains ($L_{Amax}$ 42.8-48.6 dB) and 10 local passenger trains ($L_{Amax}$ 40.3-42.7 dB).

Two vibration levels were chosen for the experiments, (1) strong vibrations with a weighted vibration level of 1.4 mm/s and (2) weak vibrations with a weighted vibration level of 0.4 mm/s. The vibrations were presented together with the freight train passages, but not together with other types of trains. A detailed description of sound exposures and vibration levels used in the experiment is given in the paper by Ögren et al. “Effects of railway noise and vibrations on sleep – experimental studies within the Swedish research program TVANE” presented at this conference.

Table 2: Sound levels and number of train passages 11 pm-7 am during different nights.

<table>
<thead>
<tr>
<th>Night No. and exposure</th>
<th>$L_{Aeq,8h}$ dB</th>
<th>$L_{Amax}$ dB</th>
<th>Vibrations mm/s</th>
<th>No. of trains</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Habituation</td>
<td>31</td>
<td>54</td>
<td>0.4</td>
<td>46 (25 with vibr.)</td>
</tr>
<tr>
<td>2: Habituation</td>
<td>13</td>
<td>13</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3-5: Low noise/strong vibr.</td>
<td>28</td>
<td>48</td>
<td>1.4</td>
<td>46 (25 with vibr.)</td>
</tr>
<tr>
<td>3-5: High noise/strong vibr.</td>
<td>31</td>
<td>54</td>
<td>1.4</td>
<td>46 (25 with vibr.)</td>
</tr>
<tr>
<td>3-5: High noise/weak vibr.</td>
<td>31</td>
<td>54</td>
<td>0.4</td>
<td>46 (25 with vibr.)</td>
</tr>
</tbody>
</table>

$^1$ Highest sound level for one or more noise events during 8 hours.
E. Laboratory experiments: Evaluation of effects on sleep
The test subjects answered a questionnaire each morning, within 15 minutes after the final awakening. The questionnaire contained questions on sleep quality parameters (falling asleep, awakenings, sleep quality, movements and tiredness in the morning) evaluated by category scales and 11-point numerical scales.

Furthermore, two questions were posed on annoyance due to sound/noise and due to vibrations during night: “Were you annoyed by sound/noise (vibrations) during night?” and “Do you think that sound/noise (vibrations) during the night affected your sleep in such a way that you: had difficulties to fall asleep (a), woke up (b) got worse sleep quality? (c). Answer alternatives were; “not at all”, “slightly”, “moderately”, “very” and “extremely”. In the presentation of the results, the “sleep disturbed” category consists of those who were moderately, very, or extremely disturbed by noise or vibrations. The test subjects also answered a questionnaire each evening within 15 minutes before going to bed with questions on tiredness during the day and evening.

3. RESULTS
A. Field studies: Annoyance due to railway noise and vibrations
Figure 2 shows annoyance due to railway noise (% annoyed) in areas with weak and strong vibrations. Percentage annoyed is low in both areas at levels below $L_{Aeq,24h} 50 \text{ dB}$ but there is a steep increase in noise annoyance at higher sound levels especially in the areas with strong vibrations (left panel). The difference in annoyance between the two type of areas increases at higher noise levels and is significant ($p<0.001$) at the two highest noise categories $L_{Aeq,24h} 51-55$ and 56-65 dB (right panel).

Annoyance due to railway noise and vibrations (mean value, scale 0-10) at different distances from the railway line is shown in Figure 3 for areas with weak and strong vibrations. Annoyance due to vibrations is similar, or even higher, than noise annoyance in areas with strong vibrations (right panel). Annoyance due to vibrations is reported also in areas with weak or no vibrations (left panel) up to about 150 m from the railway line. Noise annoyance is however significantly higher than vibration annoyance ($p<0.001$).
B. Field studies: Interaction effects of combined exposure to noise and vibration

To study possible interaction effects of combined exposure to noise and vibrations from railway traffic the study material was divided into different groups based on vibration level in the ground (no vibrations, 0.10 - 0.39 mm/s and 0.40 - 1.50 mm/s) and based on noise exposure (L_{Aeq,24h} 45-50 dB, 51-55 dB and 56-65 dB). Due to the small variation in vibration levels there are very few respondents in some of the groups (see Figure 4).

Figure 3: Annoyance (scale 0-10, mean value) due to railway noise and railway vibrations in relation to distance from the railway line in areas with weak (left panel) and strong vibrations (right panel).

Figure 4: Annoyance (% annoyed) by railway noise in relation to sound levels in L_{Aeq,24h} for three groups of respondents with different vibration exposure (left panel) and annoyance (% annoyed) by vibrations in relation to ground vibration level in mm/s for three groups of respondents with different noise exposure (right panel).
The percentage annoyed by railway noise (left panel) varies with vibration level and is lowest for the group not exposed to vibrations. The group exposed to the strongest vibrations (0.40 – 1.50 mm/s) is the most noise annoyed except for at 56-65 dB. Due to few individuals in some of the groups statistical analyses could only be performed in some cases. Thus, at 51-55 dB there was a significant increase in noise annoyance with increased vibration level \((p<0.001)\) from 9 % (no vibrations) to 22 % (0.10-0.39 mm/s) and 32 % for the group with strongest vibrations (0.40-1.50 mm/s).

The percentage annoyed by railway vibrations (right panel) is lowest for the group with the lowest noise levels (45-50 dB) and highest for the group with the highest noise levels (56-65 dB). Differences in vibration annoyance between groups with different noise levels could be statistically tested for the group with weakest vibrations (0.10-0.39 mm/s). Vibration annoyance increased with higher noise levels from 16 % annoyed at the lowest noise levels (45-50 dB) to 28 % in the group with 51-55 dB and 50 % in the group with highest noise levels \((p=0.001)\).

C. Field studies: Sleep disturbance due to railway noise and vibration

Figure 5 shows the relation between sleep disturbance due to railway traffic as measured by an index for sleep disturbance and \(L_{\text{night}}\) with windows closed (left panel) and windows open (right panel) in areas with weak and strong vibrations. The index for sleep disturbance is based on the mean value of the sum of the values on “How often” and “How much” for the three questions on difficulties falling asleep, woke up, and worse sleep quality.

![Figure 5](image)

**Figure 5:** Index (mean value) for sleep disturbances due to railway noise (difficulties falling asleep, woke up, worse sleep quality) in relation to sound level in \(L_{\text{night}}\) in areas with weak and strong vibrations. With bedroom window closed (left panel) and with bedroom window open (right panel).

There was very little sleep disturbances at sound levels below \(L_{\text{night}}\) 55 dB in areas with weak vibrations in situations with windows closed and open. Sleep disturbances (closed windows) due to railway traffic is significantly higher in areas with strong vibrations, e.g. four times higher at \(L_{\text{night}}\) 55-59 dB and twice as high at 60-65 dB (left panel). Sleep disturbances increase with higher sound levels for both type of areas and the mean value for sleep disturbance is about twice as high with bedroom windows open (right panel) as with bedroom windows closed (left panel).
D. Laboratory experiment: Sleep quality
The overall results of the laboratory experiments showed that railway vibrations have a large negative impact on sleep. When the vibration level increased from 0.3 to 1.4 mm/s, at the same sound level (L_{night} 31/L_{A,max 54dB}) sleep quality decreased significantly, the sleep became more restless and the test subjects felt more tired the following morning, day and evening (see Table 3, column c1 and c2). There was, however, no significant differences in sleep quality parameters between nights with high and low noise exposure and the same vibration exposure (column c2 and c3) except for a higher value on alertness the evening after the night with lower noise levels ($p=0.048$).

Table 3: Sleep quality after different exposure nights.

<table>
<thead>
<tr>
<th>Sleep quality parameters (mean value, scale 0-10):</th>
<th>31 dB/0.4 mm/s (c1)</th>
<th>31 dB/1.4 mm/s (c2)</th>
<th>28 dB/1.4 mm/s (c3)</th>
<th>p-value c1/c2</th>
<th>p-value c3/c2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difficulties to fall asleep$^1$</td>
<td>3.14</td>
<td>4.05</td>
<td>3.86</td>
<td>0.08</td>
<td>-</td>
</tr>
<tr>
<td>Sleep quality $^1$</td>
<td>7.05</td>
<td>6.05</td>
<td>5.81</td>
<td>0.02</td>
<td>-</td>
</tr>
<tr>
<td>Movements$^1$</td>
<td>3.67</td>
<td>4.76</td>
<td>4.10</td>
<td>0.04</td>
<td>-</td>
</tr>
<tr>
<td>Tired – alert morning after $^2$</td>
<td>5.10</td>
<td>4.43</td>
<td>4.38</td>
<td>0.04</td>
<td>-</td>
</tr>
<tr>
<td>Tired – alert day after $^2$</td>
<td>5.90</td>
<td>4.43</td>
<td>4.71</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>Tired – alert evening after $^2$</td>
<td>4.10</td>
<td>2.95</td>
<td>3.67</td>
<td>0.03 0.048</td>
<td>-</td>
</tr>
</tbody>
</table>

$^1$Higher value = worse, $^2$ higher value = better.

E. Laboratory experiment: Sleep disturbance due to noise and vibrations
Perceived sleep disturbance due to noise was significantly higher (difficulties falling asleep 10 vs. 38 % and awakenings 14 vs. 48 %) when noise was presented together with high vibration levels (1.4 mm/s) as compared with low vibration levels (0.4 mm/s), see Table 4 column c1 and c2. There was no such interaction effect for perceived sleep disturbance due to vibrations, i.e. sleep disturbance due to vibrations was the same irrespective of noise level (see Table 4, column c2 and c3).

Table 4: Annoyed or sleep disturbed by sound/noise and vibrations during different nights.

<table>
<thead>
<tr>
<th>Sleep disturbances (% moderately, very and extremely sleep disturbed):</th>
<th>31 dB/0.4 mm/s (c1)</th>
<th>31 dB/1.4 mm/s (c2)</th>
<th>28 dB/1.4 mm/s (c3)</th>
<th>p-value c1/c2</th>
<th>p-value c3/c2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise annoyed during night</td>
<td>14</td>
<td>33</td>
<td>33</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Vibr. annoyed during night</td>
<td>0</td>
<td>43</td>
<td>52</td>
<td>0.002</td>
<td>-</td>
</tr>
<tr>
<td>Noise causes difficulties falling asleep</td>
<td>10</td>
<td>38</td>
<td>24</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>Vibr. causes difficulties falling asleep</td>
<td>5</td>
<td>38</td>
<td>43</td>
<td>0.008</td>
<td>-</td>
</tr>
<tr>
<td>Noise causes awakenings</td>
<td>14</td>
<td>48</td>
<td>24</td>
<td>0.02 0.06</td>
<td>-</td>
</tr>
<tr>
<td>Vibr. causes awakenings</td>
<td>5</td>
<td>48</td>
<td>52</td>
<td>0.006</td>
<td>-</td>
</tr>
<tr>
<td>Noise causes worse sleep quality</td>
<td>14</td>
<td>38</td>
<td>24</td>
<td>0.06</td>
<td>-</td>
</tr>
<tr>
<td>Vibr. causes worse sleep quality</td>
<td>0</td>
<td>33</td>
<td>43</td>
<td>0.008</td>
<td>-</td>
</tr>
</tbody>
</table>
4. COMMENTS AND CONCLUSIONS

The results from the field studies confirm earlier findings from studies in the field\textsuperscript{4,5,11-13} that general annoyance due to railway noise increases in the presence of simultaneously occurring vibrations from the trains. Possible reasons for the increased noise annoyance are that vibrations may facilitate the perception of noise and thereby make it more difficult to habituate to the railway noise. Railway vibrations caused annoyance to the same extent as railway noise in the areas with strong vibrations. Furthermore, there were strong interactive impacts of annoyances due to noise and vibrations. Noise annoyance was higher in groups exposed to strong vibrations and vibration annoyance was higher in groups with high sound levels.

The findings from the experimental studies on sleep are in fairly good agreement with the results obtained on sleep disturbances in the field study. Few subjects/residents were sleep disturbed at low vibration levels and a large proportion was sleep disturbed at strong vibration levels (see Table 4, column 1 and Figure 5, left panel).

Thus, the results from both the field studies and the laboratory experiment suggest that it will not be sufficient to reduce the noise levels to protect from sleep disturbances and annoyance from railway traffic, e.g. by sound insulating windows och noise barriers, if vibration levels are strong (1.4 mm/s or higher). Also vibration levels must be reduced.

ACKNOWLEDGEMENTS

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