

## Single and combined effects of air, road and rail traffic noise on sleep

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### ABSTRACT

**INTRODUCTION:** It is a well known fact that noise annoyance depends on the traffic mode. Much less is known about differences in physiological effects, especially on combined effects. Therefore, we investigated the effects of air (AI), road (RO) and rail (RA) traffic noise on sleep in the AIRORA study.

**METHODS:** 72 subjects ( $40 \pm 13$  years, 32 male) were polysomnographically investigated during 11 consecutive nights in the laboratory. Electrophysiological signals included EEG, EOG, EMG, EKG, respiratory movements and finger pulse amplitude. Cortisol and noradrenalin were measured in nocturnal urine samples. Each traffic mode consisted of five noise categories (maximum SPL 45, 50, 55, 60 and 65 dBA) with 8 different noise events, i.e. 40 noise events in total. Therefore, between 40 and 120 noise events were realistically played back during single (AI, RO, RA, RORO), double (AIRO, AIRA, RORA) and triple (AIRORA) exposure nights. The design was complemented with a noise-free control night and carefully balanced.

**RESULTS:** Annoyance due to aircraft noise was stronger compared to both rail and road traffic noise. However, according to multivariable random subject effect logistic regression models, awakening probability increased in the order AI, RO, RA (AI<RO, AI<RA, both  $p < 0.0001$ ; RO<RA,  $p = 0.513$ ). Cumulative effects in double and triple exposure nights were both lower (S1, SWS) and higher (Wake, REM) compared to expectations based on single exposure nights. Nocturnal traffic noise exposure had no influence on stress hormone excretion rates.

**CONCLUSIONS:** Traffic modes differ in their noise effects on sleep. Field studies are needed to validate our results.

### INTRODUCTION

It is a well known fact that noise annoyance depends on the traffic mode. Much less is known about differences in physiological effects, especially on combined effects. Therefore, the German Aerospace Center (DLR) investigated the effects of air (AI), road (RO) and rail (RA) traffic noise on sleep in the AIRORA study.

### STUDY DESIGN AND PROTOCOL

Subjects were investigated for eleven consecutive nights. Night one served as adaptation. Nine different noise scenarios were played back during exposure nights two to ten. Night eleven served as a backup night, i.e. if signals of relevant electrodes were lost and sleep stage classification was impossible for one subject in nights two to ten, the respective noise scenario was presented in night eleven again.

**Table 1:** Composition of exposure nights

Scenario	Number of Noise Events			Total	$L_{AS,eq}$
	Air	Road	Rail		
AI	40	0	0	40	39.7
RO	0	40	0	40	36.9
RA	0	0	40	40	39.7
RORO	0	80	0	80	39.7
AIRO	40	40	0	80	41.2
AIRA	40	0	40	80	42.5
RORA	0	40	40	80	41.2
AIRORA	40	40	40	120	43.3
NO	0	0	0	0	30.0

There were nine different noise scenarios (see Table 1) with single, double and triple exposure nights. The three single exposure nights each consisted of 40 noise events from one traffic mode only, i.e. aircraft (AI), road (RO) or rail (RA). Noise events belonged to one of five maximum sound pressure level categories: 45, 50, 55, 60 or 65 dB. Sound pressure levels were A-weighted with the time constant set to slow. Therefore, single exposure nights consisted of eight noise events from each of the SPL categories. For rail noise, each SPL category was divided into four noise events from freight trains and four noise events from passenger trains. For road noise, each category was divided into five noise events from passenger cars with dry roads, one noise event from passenger cars with wet roads, one noise event from motorcycles and one noise event from trucks. Aircraft noise was not divided further.

There were three double exposure nights: Aircraft plus road noise (AIRO), aircraft plus rail noise (AIRA) and road plus rail noise (RORA). Each of the double exposure nights consisted of both 40 noise events from the respective single exposure nights, i.e. 80 noise events in total. There was one triple exposure night (AIRORA) consisting of all 120 noise events from the single exposure nights.

With this study design, exposures with different traffic modes were comparable according to number and maximum SPL of noise events. Additionally, the equivalent continuous sound levels  $L_{AS,eq}$  of the single exposure nights of aircraft and rail traffic noise were identical. This was accomplished by cutting out middle pieces of two 65 dB freight trains. Because of the shorter duration of road traffic noise events, the  $L_{AS,eq}$  of the road traffic single exposure night was lower than 39.7 dB. In order to get an  $L_{AS,eq}$  of 39.6 dB, the number of road noise events was doubled in exposure night RORO. In that way, it was possible to compare single exposure nights according to the  $L_{AS,eq}$  as well. Additionally, there was one night free of any traffic noise. Here, the  $L_{AS,eq}$  of 30 dB(A) was caused by the constant sound of the air-condition system.

### Design of study periods

In order to be able to balance the study design, i.e. that each exposure was applied in each study night position once, there were nine study periods with eight subjects each. Therefore, 72 subjects ( $40 \pm 13$  years, 32 male) were investigated polysomnographically in total. Electrophysiological signals included EEG, EOG, EMG, EKG, respiratory movements and finger pulse amplitude. Cortisol and noradrenalin were measured in nocturnal urine samples. Because sound insulation of sleep cabins was

not absolute, in each study period, all eight subjects received the same noise pattern in the same night. There were no noise-free nights interposed between two exposure nights, i.e. there were no wash-out periods.

On the one hand, the noise strain of study participants should be high enough to be able to observe noise effects during the night and in the next morning, but, on the other hand, it should not be too high in order to prevent subjects from discontinuing the study early. Therefore, nights were divided into high exposure nights (AIRO, AIRA, RORA, RORO, AIRORA) and low exposure nights (AI, RO, RA, NO), and the study was designed in a way that

- (1) each exposure pattern was applied in every position (N2 to N10) once, and
- (2) there were no more than two high exposure nights in a row.

Archdeacon et al. (1980) described a sequentially counterbalanced square for nine exposures, where each exposure is applied in every position once and is preceded by every other exposure once as well. There are  $9! = 362,880$  possibilities of attributing the nine different noise scenarios to this square. All possible combinations were tested, but in every combination there was at least one study period with three high exposure nights in a row.

Therefore, all designs meeting both criteria (1) and (2) were calculated with a computer program, and one design was chosen. Of the possible study designs the one was chosen with the best balance according to prior exposure (see final design in Table 2). Low exposure nights were preceded by high exposure nights in six and by low exposure nights in two cases, allowing a direct comparability between single exposure nights and with the noise-free night according to prior exposure.

**Table 2:** Composition of study periods (abbreviations explained in the text)

Period	Study Night								
	2	3	4	5	6	7	8	9	10
1	AI	AIRA	AIRORA	RO	RORO	RA	AIRO	RORA	NO
2	AIRA	NO	RORA	AIRO	RO	AIRORA	RA	RORO	AI
3	AIRO	RORO	AI	NO	AIRA	RO	RORA	RA	AIRORA
4	AIRORA	AIRO	NO	AI	RA	RORA	AIRA	RO	RORO
5	RORA	AI	RO	AIRA	AIRORA	NO	RORO	AIRO	RA
6	RA	RO	AIRO	RORO	AI	AIRA	AIRORA	NO	RORA
7	RORO	RARO	RA	AIRORA	AIRO	AI	NO	AIRA	RO
8	RO	RA	RORO	RORA	NO	AIRO	AI	AIRORA	AIRA
9	NO	AIRORA	AIRA	RA	RORA	RORO	RO	AI	AIRO

### Composition of single noise nights

The length of the time interval between the start of two noise events differed depending on the number of noise events per night and was otherwise randomly chosen using block randomization techniques. The length of the interval differed in nights with

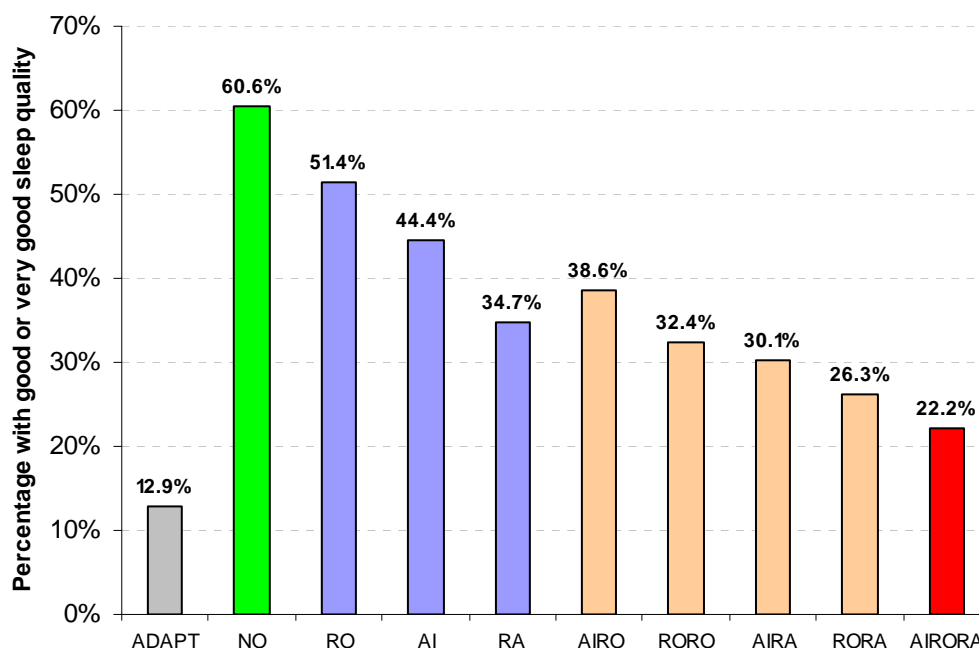
- 40 noise events between 3 and 21 min,
- 80 noise events between 3 and 9 min and
- 120 noise events between 3 and 5 min.

In single, double and triple exposure nights playback of noise events started after twelve, six and four minutes, respectively. Playback always started at the beginning of a full minute, which coincided with the beginning of a 30-second sleep epoch.

## RESULTS

### Sleep quality

Questionnaires were filled out by study participants about 10 minutes after wake up time. Subjects were asked about their sleep quality on a five-point scale. The percentage of subjects choosing the upper two categories depending on traffic pattern are shown in Figure 1.

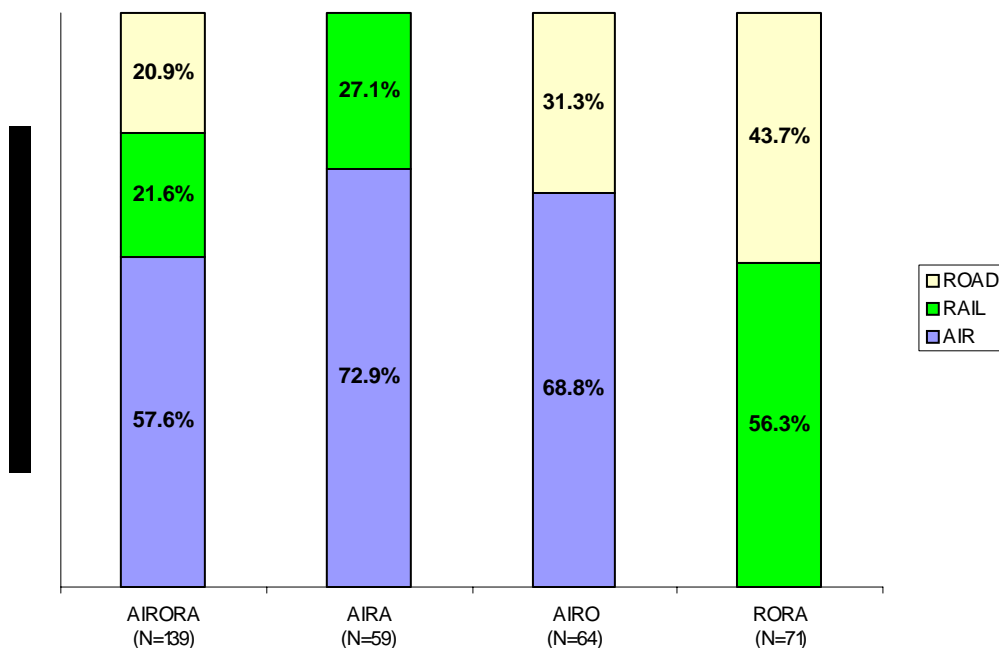


**Figure 1:** Sleep quality depending on traffic noise pattern (ADAPT = adaptation night #1, NO = noise free night, AI = air traffic, RO = road traffic, RA = rail traffic)

Only 12.9 % of the subjects rated the sleep quality of the adaptation night as good or very good, whereas 60.6 % of the subjects evaluated the noise-free night as good or very good. Sleep quality decreased in single exposure nights in the order road (51.4 %), air (44.4 %) and rail (34.7 %) traffic noise. Sleep quality in double exposure nights was generally perceived worse than in single exposure nights, except for nights with rail traffic noise only, which was perceived worse than nights with road and air traffic noise. Sleep quality in the triple exposure night AIRORA was perceived worst and only a little better compared to the adaptation night.

### Annoyance

Subjects were asked whether they perceived air, road or rail traffic noise during the night. If they perceived noise of two sources, they were asked by which they felt more annoyed. If they perceived all three traffic modes, they were first asked which annoyed them most, and then which of the remaining two annoyed them more. Results are shown in Figure 2.



**Figure 2:** Noise annoyance comparison between the three modes air (AI), road (RO) and rail (RA) traffic. Number of nights given in parentheses

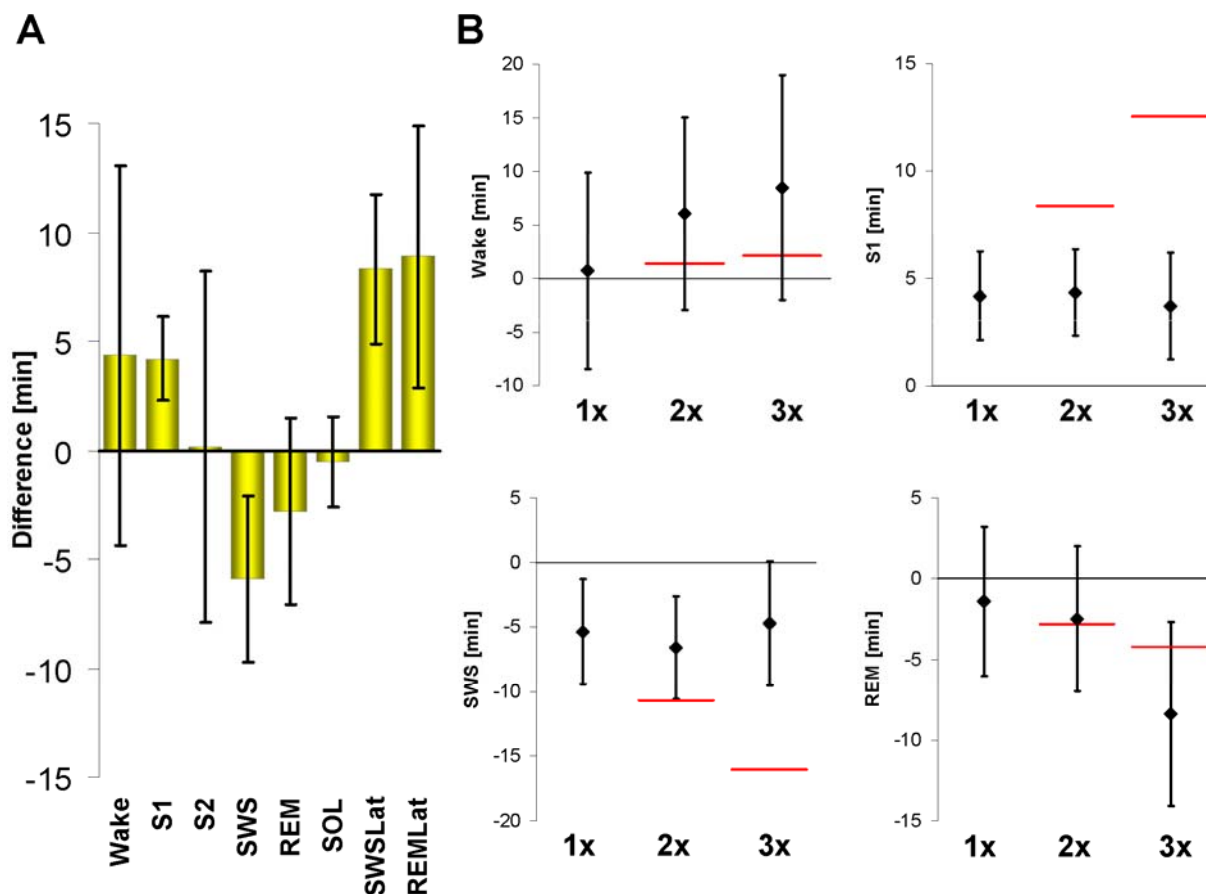
If subjects had exactly perceived what had been played back, N=72 would be expected in each category. N=139 in the AIRORA category indicates that in many nights with two or even one traffic mode all three categories have been perceived. Here, subjects felt most strongly annoyed by aircraft noise (57.6 %), followed by equal percentages of road (20.9 %) and rail (21.6 %) traffic noise. If two traffic modes were perceived including aircraft noise, subjects felt stronger annoyed by aircraft noise then by road or rail traffic noise in 68.8 % and 72.9 %, respectively. At the same time, annoyance ratings between road and rail traffic noise did not differ if both traffic modes were perceived. In conclusion, subjects felt most strongly annoyed by aircraft noise, followed by equal annoyance ratings of road and rail traffic noise.

### Stress hormones

There was no statistically significant influence of traffic noise exposure on excretion rates of cortisol and noradrenalin. All values were within normal limits.

### Polysomnography

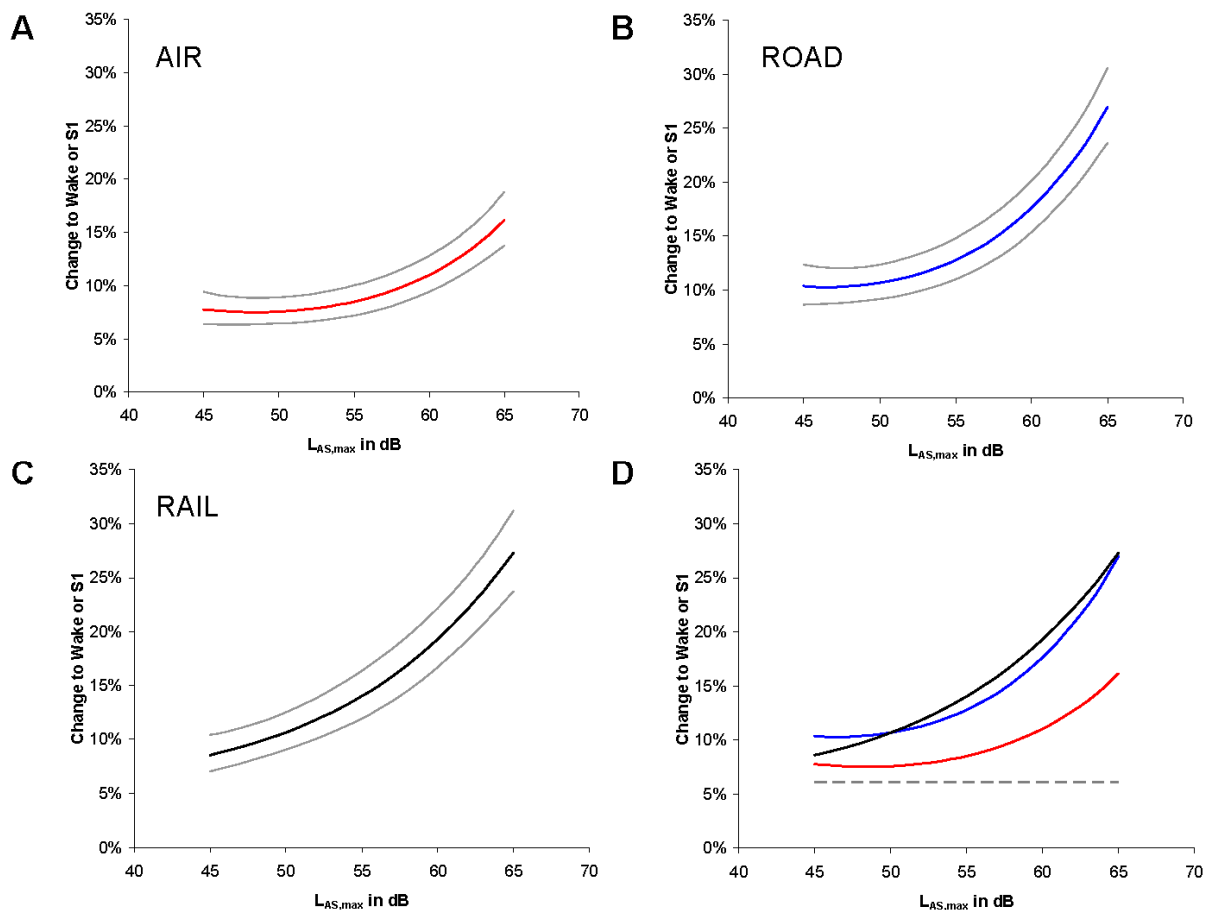
Figure 3 A summarizes the effects of traffic noise on sleep structure irrespective of traffic mode and number of noise events per night (i.e., pooled data of all exposure nights are compared to noise-free baseline nights). Typical for studies on the effects of noise on sleep (Basner & Samel 2005; Griefahn et al. 2006, 2008), amounts of wake and S1 were increased while amounts of SWS and REM were decreased. Also, both latencies to SWS and REM were significantly increased.



**Figure 3:** **A** Effects of traffic noise (pooled data of all nights with noise exposure vs. noise-free nights) on sleep structure  $\pm$  95 % confidence intervals (SOL=sleep onset latency, SWSLat=latency to slow wave sleep, REMLat=latency to REM sleep). **B** Cumulative effects of traffic noise in single (1x), double (2x) and triple (3x) exposure nights. The y-axis shows the difference in the amount of the respective sleep stage relative to the noise-free control night. The horizontal red bars represent the value one would expect if the values observed in single exposure nights were doubled or tripled.

In Figure 3 B, amounts of wake, S1, REM and SWS are compared for single, double, and triple exposure nights. The effects were more than additive for REM and wake, while they were less than additive for S1 and SWS.

Event correlated analysis of changes to sleep stage S1 or Wake under the influence of traffic noise was performed as described in Basner et al. (2004). Random subject effects logistic regression (SAS Systems Inc., Version 9.1) were adjusted for  $L_{AS,max}$ , age, gender, current sleep stage, elapsed sleep time and study night. Reaction probability increased with  $L_{AS,max}$  ( $p < 0.0001$ ), age ( $p = 0.263$ ), male gender ( $p = 0.0488$ ) and elapsed sleep time ( $p < 0.0001$ ). It decreased towards the end of the study ( $p = 0.0739$ ). Reaction probability was lower in SWS and REM sleep compared to sleep stage S2 (both  $p < 0.0001$ ). In a combined model for all three traffic modes, reaction probabilities were significantly higher for road and rail traffic noise compared to aircraft noise (both  $p < 0.0001$ ), while road and rail traffic noise did not differ significantly ( $p = 0.5130$ ). Exposure-response relationships are shown in Figure 4.



**Figure 4:** A-C Exposure-response relationships for aircraft (A, red), road (B, blue), and rail (C, black) traffic noise depending on maximum sound pressure level  $L_{AS,max}$ . Point estimates and 95 % confidence limits are given. Three separate multivariable models were calculated for each of the traffic modes. Exposure-response relationships were calculated for the reference categories female, 40 years, sleep stage S2, middle of the 6th study night. The dashed gray line in D represents spontaneous reaction probability in noise-free nights.

## DISCUSSION AND CONCLUSIONS

Differences in the effects of air, road and rail traffic noise on sleep were investigated in a polysomnographical study with a carefully balanced cross-over design. Additionally, the effect of combined exposures to two or three traffic modes was examined.

Sleep quality (questionnaire data) decreased in the order road, air and rail traffic noise, with lower sleep quality in double and the lowest sleep quality in triple exposure nights. In a comparative analysis, subjects felt most annoyed by air traffic noise, and equally annoyed by road and rail traffic noise.

Stress hormone excretion rates were not significantly altered by noise exposure, corroborating earlier findings (Maaß & Basner 2006). The method does not seem sensitive enough.

Exposure to traffic noise led to typical changes in sleep structure. Obviously, exposure to more than one traffic mode led to more severe changes in objective and subjective sleep structure variables than exposure to a single traffic mode. Depending on the outcome variable, these effects were found to be both more and less than additive. Regardless, all traffic modes should be simultaneously taken into account by legislative and political bodies. More data from field studies are needed to corroborate these findings.

Event-related analyses based on multivariable regression models indicate decreasing awakening probabilities in the order rail, road and air traffic noise. This finding is corroborated by a recent study of Marks et al. (2008), where the same ranking was found. Therefore, the order observed for annoyance reactions during the day is reversed for sleep fragmentation effects during the night, most probably caused by the special acoustical properties of the three traffic modes (e.g. high rise times, see Marks et al. 2008).

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