



An overview of concepts and past findings on noise events and human response to surface transport noise

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ABSTRACT

Noise events are well established in the measurement and management of aircraft noise. While there have been attempts to apply similar noise-event concepts to road and rail traffic noise signals for many decades, the idea has remained largely peripheral to the current paradigm of surface traffic noise measurement, assessment and management. The latter is based, almost exclusively, on metrics that utilize integrated energy of the traffic noise signal, or exceedance levels. This paper, as an introduction to a session that focuses on noise events from transportation noise, provides an overview of concepts and past findings on human responses of annoyance and interference with human activities, including sleep disturbance, that have been related to noise events and other pattern measures of the noise from surface traffic flows.

Keywords: Noise events, Human response, Transport
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1. HUMAN RESPONSE TO NOISE EVENTS FROM TRANSPORT SOURCES

Noise events have been postulated as playing some role in the way humans respond to transport noise. The effects of events in a traffic noise stream may include:

- sleep disturbance
- community response such as annoyance
- human activity interference (albeit with this interference often hypothesized to mediate the relationship between noise exposure and annoyance)

Evidence regarding the relationship of these responses to noise events is briefly summarized below. There is also some limited evidence that noise events evoke cardiac responses (1,2). No new data or analyses are presented in this paper—its intent is to assemble the scattered evidence and concepts that have accumulated over several decades regarding the role of noise events in surface transport noise streams as predictors of human response to transport noise exposure.

By way of illustration of the presence of noise events from road traffic in an urban area, we quote results from Mietlicki (3) who describe monitoring from eight stations near the Paris ring road: “*The study has allowed us to....quantify the events that significantly exceed (by over 10 dB(A) the background traffic noise, which is already quite high)...between 100 and 1,600 noise emerging events (sudden noise events that significantly exceed the background noise levels) were recorded daily. Such noise emerging events can be related to the passage of particularly noisy vehicles on the ring-road, and also to the passage of isolated vehicles on the service lanes between the ring-road and the first line of residential buildings. Significant noise emerging events (reaching up to 25 dB(A)) have been observed in the middle of the night. These are mainly related to the passage of two-wheeled motor vehicles, which are either particularly noisy or driving at an excessive speed. The intensity of such events and their occurrence at night make them an important source of nuisance and sleep disorders for residents. As for sirens, they were mainly identified during the day or in the evening when traffic is dense or saturated*”. We note that, despite widespread noise mapping, specific and quantified descriptions such as this of the noise events experienced by a population are rarely available.

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2. NOISE EVENTS AND SLEEP DISTURBANCE

Brown (3) has previously summarized the findings of the sleep literature. Based on both field and laboratory studies, sleep disturbance is directly related to noise events in transport noise streams. Sufficient evidence exists for the sleep effects listed in Table 1. However, the Night Noise Guidelines for Europe (5) note: *The health relevance of these (instantaneous) effects cannot be easily established. It can be safely assumed, however, that an increase in the number of such events over the baseline may constitute a subclinical adverse health effect by itself leading to significant clinical health outcomes.* When the noise is not of a continuous nature as occurs when individual vehicles can be heard in the traffic stream, the overall conclusion is that noise metrics that reflect the maximum noise level of single noise events, and the number of noise events, are better predictors of noise induced sleep disturbances than energy-averaged metrics.

Table 1 - Instantaneous sleep effects and threshold (dB) at the ear of the sleeper (extracted from 5).

Effect		Indicator	Threshold
Biological effects	Change in cardiovascular activity	*	*
	EEG awakening	$L_{Amax,inside}$	35
	Motility, onset of motility	$L_{Amax,inside}$	32
	Changes in duration of stages of sleep/sleep structure	$L_{Amax,inside}$	35
Sleep quality	Waking up in the night and/or too early in the morning	$L_{Amax,inside}$	42
	Prolongation sleep inception/difficulty getting to sleep	*	*
	Sleep fragmentation, reduced sleeping time	*	*
	Increased average motility when sleeping	$L_{night,outside}$	42

The Night Noise Guidelines (5) suggest that events should be measured, not just by average L_{Amax} or average SEL (Sound Exposure Level – in use for aircraft noise) but by combination of a number of events and their level. However the Guidelines (5) point out that “...there is no generally accepted way to count the number of (relevant) noise events. Proposals range from the number of measured L_{Amax} , the number of units (vehicles, aeroplanes, trains) passing by, to the number exceeding a certain L_{Amax} level (commonly indicated by N_{Axx} ; N_{A70} is the number of events higher than 70 dB”. The European Commission (6) notes that L_{night} summarizes the complex nocturnal time pattern of exposure into a single value but its use necessarily leads to information loss. Noise scenarios which differ in number, acoustical properties and placement of noise events, may calculate to the same L_{night} but differ substantially in their effects on sleep. The Environmental Noise Directive (7) allows use of noise events as supplementary noise indicators to the standardized energy-based measures of noise exposure, L_{den} and L_{night} .

In summary, research on noise and sleep disturbance shows that events in the noise signal need to be assessed, and that both level and number of these events are important to human reaction. There is thus a need for agreed, unambiguous, and replicable, measurement of both level, and count, of noise events arising from transportation sources. Brown (4) however, has pointed out that while there is little ambiguity in the concept of a single noise event, there are differences and difficulties in applying this concept across different transport modes for the range of traffic flows likely to be encountered in practice. In particular, application to road traffic noise is problematic for measuring the number of events.

3. NOISE EVENTS AND COMMUNITY RESPONSE

3.1 Events and annoyance

The research on the effects of noise events on annoyance has been less extensive than on sleep disturbance, with much of it conducted several decades ago.

Studies, predominantly from Sweden, examined maximum levels generated by individual vehicles and/or number of events, as determinants of annoyance (8, 9, 10, 11). Several studies, mostly of road

traffic but also of aircraft and railways, reported that level and number described the relationship with annoyance better than did noise indices based on equal energy. For example, Björkman (12) found that increase in the number of road traffic events lead to increasing annoyance (but with a ceiling on this relationship), as did increases in the maximum noise levels from individual vehicles. He also reported annoyance was predicted by number of heavy vehicle on the roadway (as had Langdon in the UK (13, 14)) with number of heavy vehicles in the traffic stream being a good predictor of number of noise events. In general, these studies measured the outside maximum A-weighted noise level arising from the passage of a vehicle, using F time response, or the average across a number of vehicles. In Björkman's (12) study, for example, outdoor maximum event levels from road traffic ranged from 80 to 94 dB(A), in traffic streams of 500 to 63,000 vehicles per day, with 10% of these heavy vehicles. By contrast, Sato et al. (15) found no relationship between annoyance and number of vehicles exceeding 75 dB(A), but a strong relationship between annoyance and maximum noise level. The descriptors used by Sato et al. (15) for the dynamics of the traffic noise signal included the maximum noise level (defined as the level that was exceeded at least three times per 24 hours—thus excluding single very high level events), the number of vehicle noise events in excess of 75 dB(A), and the number of heavy vehicles as a proxy measure of number of noise events.

Response to maximum levels from TGV passages were also measured by Lambert et al. (16). They suggested that the number of noise events exceeding 70 dB(A) (or their total duration) was a more relevant noise index for assessing human response than was L_{Aeq} at certain periods of the day, and specifically with respect to activity interference.

Öhrström et al. (17) conducted a laboratory experiment on annoyance with noise events from different types of vehicles (lorries, trains, mopeds and aircraft). Subjects were exposed to five passages of the one type of vehicle in 25 minutes. The L_{Aeq} and L_{01} were better correlates with annoyance than were than the maximum levels. The individual vehicle stimuli used in these experiments had an indoor peak level (presumably L_{AFmax}) of either 70 or 80 dB(A) and was heard against a background of 36 dB(A). The relative shapes of the events of each vehicle type for the same maximum were very different, with the truck having a much shorter duration and rise time (11 s and 6 s respectively), compared to the aircraft (59 s and 14 s) or the train (28 s and 10 s). The consequence of the duration of the aircraft and rail events being much longer than the road vehicles was that, when controlled to give the same number of events at the same maxima, the L_{Aeq} and L_{A01} in the experiments for aircraft and rail were considerably greater than they were for road vehicles.

Versfeld and Vos (18), in a laboratory study, provided counter evidence to this emphasis on the presence of heavy vehicles as determinants of annoyance. They demonstrated that, where the number of pass by events and the A-weighted equivalent sound levels were kept fixed, annoyance was independent of the proportion of heavy vehicles in the traffic stream – varied in their experiments from 0% to 100% heavy vehicles.

However, Jakovljevic et al. (19), in a study of road traffic noise and community annoyance in Belgrade, found that number of vehicles during nighttime and daytime correlated with annoyance, with the highest correlation was the number of heavy vehicles at nighttime. The results (extracted from 19), are shown in Table 2.

Table 2 Odds ratios of sound-related variables^a for a high level of noise annoyance)

Sound-related variables	Odds Ratio	Confidence Interval	95% p value
Nighttime Leq	1.018 ^b	1.009–1.028	0.000
Number of heavy vehicles at night	1.005 ^c	1.002–1.008	0.004
Constant	0.107		0.000

^a Independent variables included in model: Daytime Leq, Daytime Lmax (maximum noise level), Evening Leq, Nighttime Leq, Nighttime Lmax (maximum noise level), Number of light vehicles at day, Number of heavy vehicles at day, Number of light vehicles at night, Number of heavy vehicles at night.

^b Increase of risk per 1 dBA.

^c Increase of risk per 1 vehicle per hour

In summary, there is evidence from some studies, and for different noise sources, that level and number of events may describe the relationship with annoyance at least as well as do integrated

measures of noise level, and that the number of heavy vehicles in the traffic stream may be considered a surrogate measure for number of noise events. However, several other studies reported counter evidence to these findings.

3.2 Children' annoyance at school

Dockrell and Shield (20) examined children's perceptions of their acoustic environment at school, reporting that external L_{Amax} of a sound was related to reporting of annoyance in the classroom, whereas L_{A90} and L_{A99} were related to whether or not a child reported hearing that source

3.3 Two-parameter noise descriptors—level and variability

A traffic noise signal in which separate events can be readily identified will generally also be one in which there is considerable range and variability of the signal. For this reason, a large dynamic range, or high variability in level, in a traffic noise signal will often be associated with the occurrence of noise events. Descriptors have been proposed which combine level of the noise signal with variability of the traffic noise signal (either the standard deviation σ of the levels over the measurement period, or a measure of the interdecile range of the distribution, $L_{A10}-L_{A90}$). These indicators are the Traffic Noise Index (TNI) (21)

$$TNI = L_{10} + 4.(L_{10}-L_{90}) \quad (1)$$

and the Noise Pollution Level (22)

$$L_{np} = L_{Aeq} + 2.56 \sigma \quad (2)$$

Robinson (22) provides an eloquent description of the Noise Pollution Level (formulated from his reanalysis of data sets of response to road traffic noise, to aircraft noise, and to duration/intensity trade-offs): *"...reveal(s) its essential simplicity of conception...annoyance is compounded of two terms...one related in the simplest possible manner to the total amount of (frequency-weighted) sound reaching the auditor, and the other related to the fluctuations in the noise. The second term...is governed by the time dependence of the intruding noise rather than on the mean energy content and is thus greatly influenced by the prevailing background noise. (It) embodies the following simple principles: (1) other things being equal, the higher the noise levels the more the disturbance caused; (2) other things being equal, the less steady the level of a noise the greater its distracting and hence annoying quality."* A traffic noise signal containing noise events will likely have large "fluctuations in the noise", and a higher L_{np} than one of the same L_{Aeq} but without noise events.

If noise events (or more correctly, the dynamics of the traffic noise signal) do play a role in human response to traffic noise, then one would have anticipated these two-parameter descriptors would have performed well in (community) exposure-response studies. This has not been the case with their correlation with annoyance generally being lower than the single-parameter measures L_{Aeq} or L_{A10} (e.g. 13). However, it is possible that this result is an artefact of the nature of the design of most annoyance exposure-response studies. For TNI, Langdon (13) illustrated why: the terms L_{10} and L_{90} were highly intercorrelated in the sample of noise exposures included within his field data set (these data sets consisted of sites at similar distances to roadways of different traffic flows, and as levels increased, so did backgrounds) with the variability term, within a multiple regression analysis, not being able to explain additional variance in human response.

In Langdon's (13) work, L_{np} did predict human response (as did the logarithm of the percentage of heavy vehicles in the traffic stream) better than any other acoustic measure, for the subset of his sites where traffic was not free-flowing. However, in further analysis of L_{np} , the energy term contributed to the correlation with annoyance but the "fluctuation" term played no significant role. He concluded that this was also due to the correlation between σ and L_{Aeq} in his data set (the variability σ of the traffic noise decreasing as its overall level L_{Aeq} increased for the sites in his study) and the limited range of σ in this data set.

The two-parameter noise descriptors for road traffic noise are conceptually appealing but correlation of these scales with community annoyance have been no better than descriptors based on level alone. However it may be that this is attributable to multicollinearity in the level and variability terms—an artifact of the nature of the data sets gathered in most exposure-annoyance studies—and further investigation of such scales in data sets that do not exhibit multicollinearity is warranted.

The HARMONICA project (23), directed at developing a new transport noise index that reflects community perception of that noise, yet more easily understood by the general populations than are conventional transport noise indicators, has revived interest in noise indicators that include a combination of signal variability with level measures. The formulation and testing for this Common

Noise Index (CNI) are described by Ribeiro et al. (24), and all are based on levels that can be derived from $L_{Aeq,1s}$ monitoring—none on spectral composition of the signal. Examination of multiple indices in exposure data (some 60 initial variables were utilized from a wide range of sites) identified discrete factors that could explain much of the variance in the physical exposure data:

L_{Aeq} and L_{A90}	33% of variance
Noise dynamics $L_{A10} - L_{A90}$	20% of variance
Number of noise events $> L_a$ of 55 (NNEL55)	15% of variance

While still to be tested further, the recommended formulation for the CNI (24) was a linear combination of the background L_{A90} , the signal variability (or climate or dynamic) $L_{A10} - L_{A90}$, and a measure of the count of noise events, $\log(1 + \text{NNEL55}/50)$. The final coefficients for these terms will be determined at a later stage.

3.4 A “ceiling effect” on annoyance from noise events?

Various authors have reported a breakpoint, or ceiling/plateau, beyond which increasing numbers of events (or increasing numbers of heavy vehicles) have no further effect on annoyance. Björkman (12) suggested a breakpoint at about 1500 to 1800 road traffic events in 24 hours. He commented this was similar to ceiling effects observed in an aircraft study by Rylander et al. (25) and a railway study by Sörensen and Hammar (10)—though the breakpoint in those studies was of the order of 50 events in 24 hours. However, Fields (26), in his metaanalysis of aircraft (and one railway) study, found that, while some studies exhibit a ceiling to response, others do not. He concluded that there was no consistent finding about the form of the number effect on community response.

Brown (4) has demonstrated, by modelling the time history of noise levels adjacent to roadways of different traffic flows, that as traffic volumes increase there is a transition in the acoustical macrostructures of the event signals for roadways, with a filling in of the background and a reduction in the emergence of individual events above this background, resulting in identification and counting of events becoming increasingly complex at moderate to high traffic flows. Mathematically, Maurin (27) has shown that as the number of events increase, the identification of individual events is not possible. He describes this as “events kill events” or, more exactly, “events absorb events” into a growing population of emerging high noise levels, and what is killed is rather the identification of isolated events. One can speculate that a ceiling effect on annoyance as the number of events increase could potentially be related to a transition in the event macrostructure of the noise signal as traffic flow rates increase.

4. NOISE EVENTS AND ACTIVITY INTERFERENCE

4.1 Activity interference

Hall et al. (28) and Taylor et al. (29) departed from earlier approaches to noise exposure-response studies by postulating a model in which activity interference was a central component mediating the relationship between noise exposure and annoyance. They argued as follows: “*If one assumes that the primary determinant of annoyance at noise is acoustical, it seems sensible to consider closely the way in which noise gives rise to annoyance, and then to try to model that process. In our model it is proposed that noise leads to annoyance through its interference with activities, particularly those involving speech communication and sleep. Two implications follow from this: first, the noise to be measured is that produced by specific noisy events, because it is these events and not the average noise conditions which cause activity interference*”. They reported from their field investigations that an event-based model based on single event noise levels and number of events was able to estimate activity interferences better than did $L_{Aeq,24h}$.

Of interest in these studies (28,29) was their method of measurement of road traffic noise events as road volumes increased. They operationalize this by adjusting the level of the threshold above which individual events would be identified, depending on the background level, adopting a low background in quiet residential streets (eg 55 dB) but a higher one along arterial roadways (e.g. 65 dB or even 75 dB). This “variable threshold” approach to noise event counting was also used by Fidell et al. (30) in their identification of events from aircraft noise (using a dual threshold of 50 or 60 dB(A) indoors).

There has been more recent experimental work on the effects on cognitive tasks while people are subject to different noise signals involving streams of events. Lavandier and Terroir (31) examined interference of railway noise events heard as emergences above a steady background of road traffic noise on a reading task. The number of rail noise events, distance to the train passby, and level of

steady road traffic noise background against which rail events were heard, were experimentally manipulated. The effect of the events on a reading task was measured by how much respondents reported they were annoyed by the sound environment while they were undertaking the reading task. Lavandier and Terroir (31) describe this short-term effect in a laboratory test as *functional annoyance*. They note that some authors also refer to this measure as *acute annoyance* or even *activity disturbance*, but clearly it differs from both annoyance and activity disturbance measures obtained in field surveys of effects of environmental noise—in terms of both the nature of the effect being measured and the period over which respondents integrated information in reporting the effect. The significant finding (31) was that *functional annoyance* decreased with number of events. This appears contrary to earlier findings regarding the influence of events on human response to a traffic noise signal, but the authors suggest the result was due to the equal energy requirement they imposed (fixed LAeq of 53dB from every sequence required on all event sequences) included in the experimental exposures—resulting in sequences in which there were higher numbers of events also being those where the maxima of each individual event had to be lower (to maintain the equivalent energy levels of the sequence). Because of this, and the fact that the effect measure was *acute annoyance*, it is difficult to draw conclusions regarding the relationship between noise events and activity disturbance from this work.

Terroir et al. (32) also reported, from this same experiment, the number of train event passbys that respondents recalled as having occurred during each noise event sequence. Despite the title of this paper referring to “activity interference” from traffic noise, the results presented were restricted to a *comparison* of the number of train event passbys that respondents recalled noticing during the experiment with the number of *salient sound events (notice events)* that were estimated by a computational procedure of auditory attention – effectively an evaluation of the latter model (see 4.2 below). The computational model was applied to the acoustic conditions, and cognitive task undertaken, in the Terroir et al. (32) experiment. In this case, the activity task was the simple reading exercise described in Lavandier and Terroir (31). The computation model was reasonably good in predicting the number of train events that respondents would notice.

4.2 Notice Events

The previous section referred to *notice events* and a *model of auditory attention*. Based on the hypothesis that the perception of environmental sound is primarily determined by consciously noticed sounds, De Coensel et al. (33), De Coensel and Botteldooren (34), and previously de Meur et al. (35), defined a *notice-event* as “*an instant of attention focus on the sound*” (also as “*an instance of consciously observing a sound*”). They reported in these papers (and elsewhere) a computation procedure based on a complex simulation of how listeners switch their attention over time between the different sounds present in an auditory scene.

As well as being used to compute the number of train events that would be noticed under the acoustic conditions and mental task in the experiment (32) above, the model has also been applied, *inter alia*, to characterizing the quiet rural soundscape (36) and thus potentially useful to assist in soundscape design, and to explain certain observations with respect to annoyance measured in exposure-effect studies (33).

This model of auditory attention simulates how listeners switch their attention over time between different auditory streams, based on bottom-up and top-down cues. The bottom-up cues are determined by the time-dependent saliency of each stream including the intensity and spectral/ temporal irregularities of the sound, and masking for the different streams. The top-down cues are determined by the amount of volitional focusing on particular auditory streams by the observer (and hence dependent on the cognitive task being undertaken). A competitive mechanism determines which stream is selected for entry into the working memory and the time periods during which particular streams are attended to (34). In this model, the occurrence of a notice-event depends on, in the first instance, the emergence of the event (level of the sound above the background, or signal-to-noise ratio) but then on a range of other acoustical factors and on listener-related factors such as alertness, current activity, sensitivity and adaptation etc.:

A notice-event may occur when any of these factors change, not just when triggered by a noise event (e.g. a notice event generated by the start of a continuous sound may stop because of adaptation). They specify a range of conditions and relationships for these factors (attention, gating, habituation and focussing – all time dependent, and all with exponential decay/rise time constants specified) in a computer-based time-domain simulation model of auditory perception. Once an event is noticed, new events will not trigger a new notice-event unless they are sufficiently more noticeable (termed

“gating”—with the gating effect having an exponential decay). Thus multiple events in say a road traffic signal that may occur close together may be lumped into a single notice event.

While further evaluation and calibration in different acoustic environments and where different activities are being performed is required, a model such as this may increase understanding of the relationship between events in transport noise signals and human response to these temporal patterns. Certainly, in their meta-analytic synthesis of noise effects on human perception, Szalma and Hancock (37) indicate that such a model of sound perception based on notice events produces results that are largely consistent with the argument that variations in noise can impair performance, possibly by diverting attention.

5. SUMMARY

Research on noise and sleep disturbance shows that events in the noise signal need to be assessed, and that both level and number of these events appear to be important in human reaction. There is evidence from some studies that level and number of events in road traffic and rail noise correlate with annoyance at least as well, if not better, than integrated-energy noise measures. In some studies, the number or percentage of heavy vehicles was considered a surrogate for number of noise events. Other studies reported contrary evidence.

Concepts relevant to noise events from surface transport that need further investigation include two-parameter noise measures of both level and variability, a ceiling effect on the number of events that contribute to annoyance, and a transition in the acoustical macrostructures of traffic noise signals from roadways—as traffic volumes increase from low flows where individual events are readily recognized to higher flows where identification and counting of events becoming increasingly complex. A variable-threshold approach to noise event counting has been utilised where background levels are high as a result of high traffic volumes, but the effectiveness of this approach needs further investigation. The *notice event* concept warrants further evaluation. Overall, there remains sufficient evidence to continue to examine the measurement and prediction of events from surface transport schemes, and to examine their role in determining human response to transport noise exposure.

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