# Issues in the measurement of sleep-related noise events in road traffic streams

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## ABSTRACT

The sleep literature reports that integrated measures of road traffic noise levels by themselves (eg $L_{night}$) do not account for all of the observable effects of traffic noise on human sleep, and that level and numbers of noise events in road traffic streams need to be measured. Each of the END and the Night Noise Guidelines for Europe refer to both integrated energy descriptors and noise event descriptors as measures relevant to assessment of human sleep disturbance. At Griffith University we are investigating the occurrence and nature of noise events arising from road traffic streams. Here we examine, based on the literature of experimental and field sleep disturbance studies of road traffic noise, the noise event stimuli utilised in that sleep research. While the notion of an "event" in a noise stream is conceptually unambiguous, there are issues with the application of the noise event concept to streams of road traffic noise, vis-à-vis air and rail traffic noise, that need further consideration.

## INTRODUCTION

While there has been interest in the concept of events in road traffic noise signals for many decades, noise events remain largely peripheral to the current paradigm of road traffic noise measurement, prediction, assessment and management. Management, in practice, is almost completely based on noise metrics that integrate the time-varying road traffic noise signal over some period (eg, $L_{eq}$, $L_{dn}$, $L_{den}$, or $L_{night}$) or metrics which report a statistic of the distribution of the time-varying signal (eg, the exceedance level, $L_{10}$). These pay little or no attention to much of the dynamics of the signal of A-weighted levels of road traffic noise heard by receivers, including the events in the road traffic noise signal.

Our focus in this paper is on road traffic noise, and examining the characteristics of road traffic noise events (as distinct from aircraft noise events or railway noise events) that have been utilized by researchers as the stimuli in road traffic noise and sleep studies.

This is one component of a broader study by the author into the nature of noise events in road traffic streams, looking at how events can be identified and the relationships between these and the conventional traffic noise metrics such as $L_{eq}$. Our longer-term aim is to provide the foundations for a more rigorous approach to the measurement of noise events in road traffic, and to identify the situations in practice where information about noise events provides additional useful information—beyond that provided by conventional measures—for road traffic noise management.

We have looked at the different metrics of noise events included in the sleep disturbance literature, and examples of the magnitudes, and ranges, of these metrics in the noise event stimuli of experimental, and field sleep studies. We wanted to identify how these stimuli might represent the noise-event exposure of urban populations living near roadways. Different levels and numbers of events would occur, in reality, as a result of different combinations of traffic flow, mix of vehicle types, vehicle speeds, distances between the sources and the dwellings, and attenuation by building envelopes.

However, it quickly became apparent that this was not simple. For while the notion of an "event" in a noise stream is conceptually unambiguous—a noticeable increase in sound level related to the passage of an individual loud vehicle or succession of vehicles, or even the passage of a not particularly loud vehicle but heard against a quieter background—the application of the concept to streams of road traffic noise is not always unproblematic.

## NOISE EVENTS AND SLEEP DISTURBANCE

Aasvang et al. (2011) note that both field and laboratory studies have shown that transportation noise disturbs sleep. Various authors (Aasvang et al., 2011; Basner and Samel, 2005; Marks et al., 2008; Griefahn et al., 2008; Brink et al., 2009; Pirrera et al., 2010) have concluded that noise events in transportation noise streams relate directly to some aspects of sleep disturbance. The 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, when the noise is not of a continuous nature. Some researchers have investigated the effect on sleep outcomes of event dimensions other than maximum level and number.

To describe single events, the Night Noise Guidelines for Europe (WHO, 2009) refers to both $L_{Amax}$ (maximum outdoor sound pressure level) and SEL (sound exposure level) – with the latter in use for aircraft noise. For different health end points, the guidelines suggest different indicators could be chosen. "*Long-term effects such as cardiovascular disorders are more correlated with indicators summarizing the acoustic situation over a long time period, such as yearly average of night noise level outside at the facade ($L_{night, outside}$) while instantaneous effects such as sleep disturbance are better with the maximum level per event ($L_{Amax}$), such as passage of a lorry, aeroplane or train*" (see Table 1). The Environmental Noise Directive (Council Directive, 2002) requires assessment of $L_{den}$, and $L_{night}$, but additionally allows the use of noise events as supplementary noise indicators: "*$L_{Amax}$, or SEL (sound exposure level) for night period protection in the case of noise peaks*".

**Table 1**. WHO (2009) reports sufficient evidence is available linking the following indicators to different instantaneous effects on sleep.

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

The Night Noise Guidelines for Europe (WHO, 2009) do note that, "*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*".

The Guidelines (WHO, 2009) also note that events should be measured, not just by average $L_{Amax}$ or average SEL, but by combination of a number of events and their level. However "…*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 (2004) notes that the use of $L_{night}$ that summarizes the complex nocturnal time pattern of exposure into a single value, 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.

There is thus a need to be able to reliably describe and measure noise events, both their level and number, arising from transportation sources.

## DIFFERENT DIMENSIONS OF NOISE EVENTS IN SLEEP DISTURBANCE STUDIES

Different dimensions of the noise events that have been reported in sleep studies are listed below, together with some examples of the magnitude of that dimension when the source of the events was road traffic noise. The indicated magnitudes are an illustrative sample from a few studies and, because of space limitations in this paper, the contexts of source, propagation and sleeper are not described:

- the *maximum sound level* of the event indoors: range 44 to 74 dB(A) in laboratory; 45, 50, 55 and 60 dB(A) in laboratory; mean 45 dB(A) with std. dev. 9 dB(A) in field; mean 61 dB(A) with range 50 to 70dB(A) in field
- the *Sound Exposure Level* of the event: none reported for road traffic noise
- the *slope* or *rise time* of the event: range 1.5 to 8.4 dB/s (measured from emergence from the background at 32 dB(A) to the occurrence of the maxima) with mean 4.8 dB/s and std. dev.1.9 dB/s, in field
- the *duration* of the event: range 3 to 92 s with mean 56 s and std. dev. of 8s in field; 9 s in laboratory; range 9 to 38 s with mean 21 s and std. dev. of 8s in laboratory
- the *emergence* of an event above the background or some other specified level (also referred to as the *audibility* of an event, measured as the bandwidth-adjusted signal-to-noise ratio): range 12 to 42dB(A) emergence above background of 32 dB(A), in laboratory
- the *number of noise events* (NNE) in the measurement period: range 40 to 120 in whole of night, in laboratory; range 6 to 73 rail events in whole of night, road events not able to be counted, in field
- the *temporal distribution* of the number of events within the (sleeping) hours of interest; also termed event order position (Brink et al., 2009)
- the duration of the *noise-free intervals* between events (gaps, respite): range 3 to 21 min, in laboratory; range 0.4 to 7 min with mean 1.7 min and std. dev 1.6 min, in laboratory.

Marks et al. (2008) provide a binary categorisation of these event-related metrics as being part of the *microstructure* or *macrostructure* of the acoustical stimulus:

- *acoustical microstructure*: maximum, rise time, duration, SEL, emergence
- *acoustical macrostructure*: NNE, noise free intervals, temporal distribution.

In practice these depend on quite different drivers. The *acoustical microstructure* is a function of vehicle type and source strength, speed, and distance from source to receiver. The *acoustical macrostructure* is a function of traffic volume. The dimension of emergence is more complex, depending on the source strength of the individual vehicle, but also on traffic flow volume, as higher flow rates increase the background level, reducing the emergence.

We will, in the course of our work, be able to examine the interrelationships between these different metrics, and in particular how well the event-based exposures, or doses, included in sleep disturbance studies may represent the range of levels, numbers (and other metrics) of road traffic noise events experienced by populations living near roadways in urban areas. But for the present we turn to several problematic issues associated with the application of noise event concepts to road traffic streams.

## ISSUES WITH MEASUREMENT OF NOISE EVENTS FROM ROAD TRAFFIC

There have been more studies on sleep disturbance and noise events utilising aircraft sources (and rail sources) than there have been for road traffic sources. It is not surprising then that approaches to noise event measurement may have been shaped primarily by the protocols of aircraft noise overflight measurement and by the sequence of arrival/departure patterns of aircraft overflights. There are issues in the measurement of both the maximum level of the noise event, and the number of events, that arise when the same approaches are applied to noise events in road traffic noise. In making these observations, we are not criticising the experimental and field sleep disturbance work that has been performed to date, but are identifying matters that need to be considered because of the different nature of noise event signals from different modes of transport. These are more apparent as field studies of sleep disturbance increase, there having been (Pirrera et al., 2010) a lesser number of field studies in comparison to laboratory experiments for road traffic noise in the past.

There are two issues that are discussed here:

- time weighting of the measurement of the maximum level of the event
- the difficulty in identifying and counting road traffic noise events at higher traffic flows.

### Time Weighting in Measurement of the Maximum Level of the Noise Event

Measurement of the maximum sound level generated by the overflight of aircraft, usually with the A frequency weighting, is conventionally undertaken using a 1 s time constant (S response) – correctly described as $L_{ASmax}$. Sleep disturbance studies that use aircraft overflights as the stimulus, either in the laboratory or the field, have followed this practice – so commonly that the maximum level of events has sometimes been reported without reference to the time weighting utilised. Given the nature of the signature of most aircraft overflights (that arises from the large distances between source and receiver resulting in longer duration, and relatively smooth and rounded, peaks to the events) the difference between $L_{Amax}$ measurement with S and F (.125 s) response would be minimal. To some extent, this may be similar for the noise events generated by many passing rail sources (other than high speed trains). However, the difference between levels using F and S time weightings for the maxima of many passing road vehicles is not insignificant (Figure 1). Conventionally, measurements of road traffic noise are always conducted using the F response—for example, in their detailed sleep field study on the effects of noise events of rail and road traffic, Aasvang et al. (2011) measured the maxima of both road and rail events as $L_{AFmax}$.

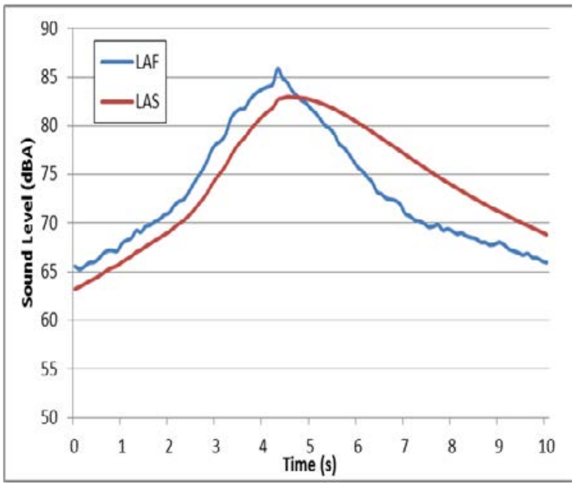


**Figure 1.** Differences between F and S time-weighted measurements of the pass-by of a truck ($L_{AF}$ is the line with the higher maximum), 80 km/h, accelerating, 9m from source, $L_{AFmax} – L_{ASmax}$ = 2.9 dB.

The issues are that, to avoid misinterpretation in comparisons of the level of events between studies and between different modes, the time constant used in measurement of noise event maxima always need to be reported, and standard measurement procedures need to be adopted, at least within the one transport mode.

### The Difficulty in Identifying and Counting the Events at Higher Traffic Flows

Depending on source strengths and distances to receivers, the noise event of an aircraft flyover and the noise event of a passing road vehicle can have the same maximum noise level—though such equi-maximum events from different transport modes will be quite different on other dimensions of their acoustical microstructure - such as duration and rise time. However the differences between the event signals of different modes is also in terms of their acoustic macrostructure, and this impacts the identification and counting of events.

At low traffic volumes of any of aircraft, trains or road traffic, the passages of vehicles result in clearly-distinguishable noise events (situations described (Griefahn et al., 2008) as "intermittent noise i.e. aircraft, railway and low density traffic noise"). As more vehicles pass, each aircraft and trains will still be clearly distinguishable events. However for road traffic, identifying individual events eventually becomes problematic as the traffic volumes increase (Figure 2). This results from differences between the transport modes in terms of minimum headways (the time between successive vehicles passing). Operationally, minimum headways for aircraft and trains will most often result in clearly identifiable, and temporally separated, noise events. By comparison, minimum headways for motor vehicles are very short. Further, roadways generally have two-way flow, and often multiple lanes in each direction. For all but the lowest traffic flows on most roadways of interest, the noise events no longer remain temporally separated.

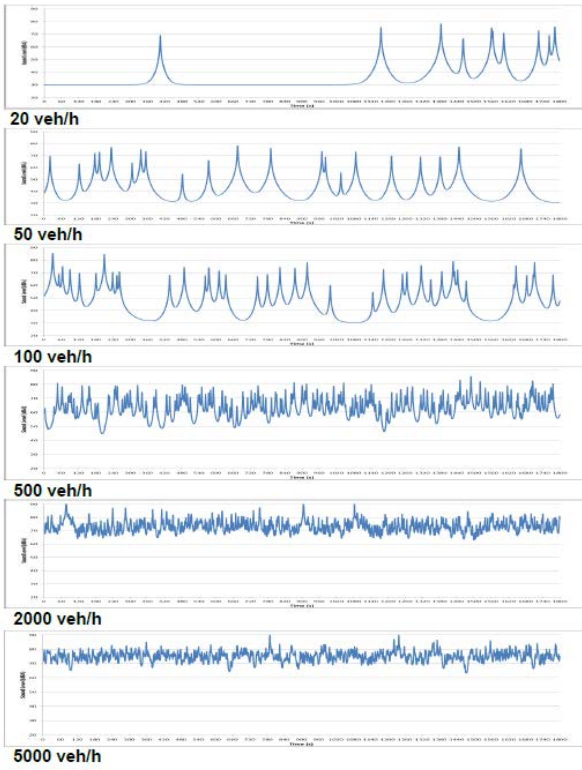


**Figure 2**. 30 minute simulations of $L_{AF}$ at 15m from a 100 km/h two-lane two-way roadway, for vehicle flow rates of 20 to 5000 veh/h. For each of the six plots of sound level generated by traffic streams with different flow rates: the x axis represents time ranging from 0 to 1800 seconds; the y axis shows the sound level $L_{AF}$ with a range of 20 to 90 dB. Individual events are difficult to distinguish as traffic flow rates increase. While the maxima remain the same, the emergence of events decreases as the background fills in.

Laboratory studies generally utilise a small number of vehicle pass-bys against a reasonably low background level—and there is no difficulty then in counting the number of noise events over any period. Similarly, in aircraft field studies where the background noise level is steady, discrete events arise from the overflights of individual aircraft will nearly always be identifiable because of the minimum headways on the flight path. Road traffic streams at very low flow rates are the same, but at higher flow rates, particularly for multi-lane roadways, the events overlap. There is also in-fill of the background levels, and events will consequently emerge less than at lower flow rates. The difference between rail and road is illustrated in a field study of road and rail sleep disturbance (Aasvang et al., 2011) where noise levels were continuously logged at 1 s intervals throughout the night. Train noise events were able to be identified and counted, but events for road traffic noise were not always discernible despite the full time history of noise levels being available, and thus not able to be counted.

As both level and number of events are important in assessing sleep disturbance, where each individual event is not clearly distinguishable, some protocol is required for event definition. As yet there is no agreement on such a protocol, and different protocols (De Coensel et al., 2012) (one based on the number of times that the sound level exceeds $L_{A50}$ + 3 dB(A) for at least 3 seconds; the other triggered by levels being above 60 dB(A) but with additional requirements in terms of prior- and post-event history) have been shown to result in quite different counts of events. A third example protocol for identifying and counting events in traffic streams is based on the sound level exceeding $L_{A05}$ +10 dB(A) for two consecutive seconds (Aasvang et al., 2011).

Further illustrating the problem, an entirely different way of counting noise events was used in a road traffic noise field study (Pirrera et al., 2011). The number of noise events reported was the number of 30 s epochs in which the noise level reached particular levels (three different levels: 30 to 40 dB(A), 40 to 55 dB(A), and > 55 dB(A)) within the night. They were also reported as a percentage of the total number of epochs over a complete night.

Clearly, more work is needed in understanding how to identify and count noise events in road traffic streams.

## DISCUSSION AND CONCLUSIONS

The 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 (rise time of the events, emergence, and the event-free intervals between the events may also be important). There is thus a need for agreed, unambiguous, and replicable, measurement of both level, and count, of noise events arising from transportation sources.

While there is little ambiguity with respect to the concept of a single noise event, there are differences and difficulties in applying this across all transport modes over the range of traffic flows likely to be met in practice. In particular, application to road traffic noise is problematic in terms of measurement of the maximum level of the event and in terms of the counting of the number of events.

The time constant used to measure noise event maxima should always be reported to allow comparisons of the levels of noise events across different studies and across different transport modes. It would also be useful to adopt standard measurement procedures for maximum levels of events, at least within the one transport mode.

The primary dimension of the acoustic macrostructure of transport noise exposures is the number of events (distribution throughout the night, and periods of respite, are others). If noise events could always be readily identified, then measurement of the number of events would be straightforward. Such would generally be the case for aircraft noise and rail noise because of the significant headways utilised in these transport modes, and for low traffic volumes of the road traffic mode. However, as traffic volumes increase, major differences appear in the acoustical macrostructures of the event signals between aircraft flight paths and beside roadways. Identification and counting of events becomes complex in anything other than low traffic volumes for roadways. Where individual events are not clearly distinguishable, a protocol is required for event definition. While several algorithms for event identification have been suggested, further work is required.

Finally, Gestland has noted (quoted in van Kamp (2011)), that while energy equivalent levels are currently used to assess human response to noise, the number of events is also relevant. He suggests it is unknown at present as to where use of the equivalent level should be supplemented, by consideration of individual events. It is tempting to speculate that this breakpoint, if such exists, may somehow be related to observations in the previous paragraph with respect to the changing nature of noise events in traffic stream as traffic volumes increase.

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## REFERENCES

Aasvang, G.M., Øverland, B., Ursin, R. and Moun, T. (2011) A field study of effects of road traffic and railway noise on polysomnographic sleep parameters. *Journal of the Acoustical Society of America* ,129 (6) 3716-3726.

Basner M and Samel, A. (2005) Effects of nocturnal aircraft noise on sleep structure. *Somnologie,* 9, 84-95.

Brink, M., Basner, M., Schierz, C, Spreng, M., Scheuch, K. Bauer, G. and Stahel, W.A. (2009) Determining physiological reaction probabilities to noise events during sleep. *Somnologie,* 13, 236-243.

*Council Directive (EC) 2002/49/EC of 25 June 2002 Relating to the Assessment and Management of Environmental Noise.*

De Coensel, B., Brown, A.L., Tomerini, D. and Botteldooren, D. (2012) Modeling road traffic noise using distributions for vehicle sound power level. *Internoise 2012,* New York, pp 2957-2966.

European Commission (2004) *Position paper on dose-effect relationships for night time noise.* Working Group on Health and Socio-Economic Aspects.

Griefahn, B., Basner, M., Bröde, P. and Robens, S. (2008) Development of a sleep disturbance index (SDI) for the assessment of noise-induced sleep disturbances. *Somnologie,* 12, 150-157.

Marks, A., Griefahn, B. and Basner, M. (2008) Event-related awakenings caused by nocturnal transportation noise, *Noise Control Engineering Journal, 56, 52-62.*

Pirrera, S., De Valck, E. and Cluydts, R. (2010) Nocturnal road traffic noise: A review on its assessment and consequences on sleep and health, *Environment International,* 36, 492–498.

Pirrera, S., De Valck, E. and Cluydts, R. (2011) Nocturnal road traffic noise assessment and sleep research: The usefulness of different timeframes and in- and outdoor noise measurements. *Applied Acoustics,* 72, 677–68

van Kamp, I. (2011) The role of noise events in noise research, policy and practice (peaks, events or both): Report of an expert meeting 25 and 26 October 2010, Utrecht. RIVM, Report Number 815120005.

WHO (2009) *Night Noise Guidelines for Europe*. WHO Regional Office for Europe, Copenhagen**.**