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# A review of transport noise indicators

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**Abstract**
The different approaches to noise impact assessment adopted by the individual countries and the scientific community have led to the development of a certain amount of indicators, mainly focused on specific transport modes. However, in practice, technicians and decision- makers alike may fail to identify the most appropriate indicators, if they have not a specific expertise on environmental noise.
The paper presents a review of the main transport noise indicators, both the general acoustic ones and those used for specific transport modes. A critical analysis of the strengths and weaknesses of those indicators is provided, as well as a section discussing the framework in which they work, and suggestions for their best use, aimed at assisting decision-makers to ascertain their role in the evaluation process of the transport systems. To this extent a classification is proposed supplemented by the DPSIR approach (Driving forces, Pressures, States, Impacts, Responses), in an effort to assess the cause-effect relationship between society and the environment. Decision-makers will also gain insight in prioritising the use of existing indicators in accordance to their own needs, as well as advice into the joint use of socio-economic variables to fully support their decisions.
**Keywords**
Noise indicators, transport, sustainability, SEA

## 1. Introduction

Noise pollution from transport activities is an endemic problem in modern societies and has become a critical issue in the assessment of transport system sustainability.

Noise induces social and behavioural effects, notably annoyance and sleep disturbance; from a medical point of view, the effects of noise on human health are also well known: hearing impairment, speech intelligibility, physiological dis-functions, mental illness, performance reduction, cardiovascular diseases (WHO, 1999; WHO, 2011). Many of these effects are assumed to result from the interaction of a number of auditory and non-auditory variables.

The need to safeguard the quality of life and health of the population calls for more efforts for transport noise abatement as regards to the increasing demand of mobility. To reconcile these conflicting needs, the EU 6th Action Programme "Environment 2010: Our Future, Our Choice" has set up the target to reduce the number of people regularly affected by long-term high levels of noise from an estimated 100 million people in the year 2000 to around 10% reduction in the year 2010 and in the order of 20% by 2020. The difficulty to attain those targets is that 80% of people live in the urban areas, where transport infrastructures represent the most important source of noise. In fact, today 115 million people are exposed to noise levels *Lden* higher than 55 dB(A), and, at night time, 80 million people are exposed to *Lnight* higher than 50 dB(A) (EEA, 2011). All over the world, a total of 2 billion citizens are subject to road traffic *Lden* of over 55 dB (De Vos and Van Beek, 2011).

The social costs of rail and road noise in Europe was recently estimated to €40 billion a year (90% related to passenger cars and goods vehicles) (EC, 2011a). The noise costs, including health care, represent about 0.4% of total EU GDP (den Boer and Schroten, 2007) and, according to the Commission (EC, 2011a; SEC, 2011a,b), the noise-related external costs of transport would increase to roughly 20 billion € by 2050 (+40%).

Thence, lawmakers are paying growing attention to adopt reliable and homogeneous instruments for monitoring and evaluating transport noise emissions. In some cases, the national norms establish rules to preserve the sound quality of specific areas (e.g. parks, hospitals, schools, etc.) and to reduce people noise exposure, recommending the adoption of noise indicators and setting the thresholds to be complied with.

In Europe, the need to define guidelines to set common noise legislation led to the Environmental Noise Directive 2002/49/EC, also known as the "END". This Directive urges the monitoring of the main European cities and the biggest transport infrastructures, assessing the number of exposed people and mapping sound levels, using specific noise indicators.

The study of transport noise emissions kicked off in the 50's in the United States to tackle the significant problem of the aircraft emissions (Kryter, 1959), and continued over the years with the research of good dose-response relationships (FICON, 1992; Miedema and Vos, 1998; Miedema and Oudshoorn, 2001; Fidell, 2003).

Various noise indicators have been proposed for different objectives, but, in practice, technicians and decision-makers alike may fail to identify the most appropriate ones if they lack a specific expertise on environmental noise.

This paper reviews the main transport noise indicators, proposing a classification of those according to their nature, to the transport mode to which they are related, and to their field of application. After the review of the general and mode-related noise indicators, a section is devoted to critically analyse their strengths and weaknesses. Finally, the framework in which those have to work is discussed, suggesting their best use. The ultimate goal is to assist decision-makers to distinguish the role of the different indicators in the evaluation process of the transport systems. However, what it is more significant is to highlight what is missing today and to propose an operational approach to properly evaluate the impacts of the transport systems on the exposed population.

## 2. General acoustic indicators

The general acoustic indicators describe noise emissions in terms of the physical characteristics of the sound pressure. They represent the physical-mathematical basis on which all the other noise indicators were developed and are the simplest tools for acoustic noise analysis. Their use in the assessment of transport noise pollution revealed them inadequate or even useless to describe the phenomenon, for example when assessing long-term noise impacts. In addition, their relationship with people annoyance has

indeed been challenged. These indicators include the Equivalent Level, the Maximum and Minimum Level, the Statistical Levels, and the Sound Exposure Level. They were defined in the standard ISO 1990/1-2003.
The best known energy noise indicator is the *"Equivalent Level" Leq*, used to describe sound fluctuation over time. It represents the average noise level varying its pressure level during a period *T* of observation, expressed in dB(A).
The *Maximum and Minimum sound Level, Lmax* and *Lmin*, are, respectively, the highest and the lowest time-weighted sound level measured expressed in dB(A). These indicators depend on typology and location of the source. They are generally used to describe the source in terms of acoustic power.
The *statistical noise levels Lxx* represent the pressure level exceeded the "xx"% of the recording time, measured in dB(A). The statistical levels usually considered are *L5*, *L10*, *L50*, *L90*, *L95*. *L90* and *L95* are typically used to describe the "background noise". Some of those levels are used to calculate other indicators or in traffic noise models. Well established examples are the models: CSTB (CSTB, 1991), Griffith and Langdon (Schultz, 1972), Burgess (Burges, 1977), and C.R.T.N. (Department of Transport and the Welsh Office, 1998).
The *"sound exposure level SEL"* (or "*LAE*" or "*LAX*" or "*SENEL*") is used to describe a single noise event in a particular context (e.g. a passage of a train or of a single vehicle in an empty street). The evaluation of the indicator on a base time period of one second (t0) allows to compare *SEL* values coming from different sources, where t2 – t1 is the interval of the event where the noise level LA(t) > LAmax -10:

$$SEL = L_{AE} = 10\, log\left[\frac{1}{t_0}\int_{t_1}^{t_2}\frac{p_A^2(t)}{p_0^2}dt\right]$$

In Italy, this indicator is typically used for railway noise evaluation (D.M., 1998). During an observation time period (TR) the measure of the *SEL* of each event allows calculating the corresponding *Leq* generated by the source.
In aircraft noise it is common to speak about *SENEL* for the evaluation of single airplane operations (take-off and landing). The formulation of *SENEL* (EPA, 1971) is the same as *SEL*, but it is generally preferred for the definition of the integration time (t2-t1) (California Department of Aeronautics, 1971).

### 3. Road traffic noise indicators

Road traffic is the main responsible for noise in urban areas and is characterized by fluctuations of the traffic flow during the day, due to the evolution of its kinematic
characteristics, notably speed, acceleration, deceleration. For this reason, road traffic is treated like a pseudo-casual source, where the energy characteristics of the noise are very important. These noise indicators are recorded over a long time period to describe the average condition at source, the most important of those being: the "*traffic noise index TNI*", the "*noise pollution level NPL*", the "*CRTN Indicator L10,18h*".
The *"traffic noise index TNI"* was proposed by Griffiths and Langdon in the 1968 (Schultz, 1972). The index was developed in the UK using statistical noise levels *Lxx*:

$$TNI = 4(L_{10} - L_{90}) + L_{90} - 30 \quad \text{or} \quad TNI = 4(L_{10} - L_{90}) + L_{eq}$$

The indicator takes into account the difference between the noisiest events (*L10*) and the background noise (*L90*); however changes of the base-line sound are weighted with a similar emphasis as those in the noise peaks (Graf et al., 1980). This is the reason why the indicator is not widely used, since it becomes representative only when the traffic is flowing, risking to be misinterpreted in a different situation. In fact, in some cases, when the traffic flow increases, the *TNI* decreases (Berglund and Lindvall, 1995). Furthermore, when the difference between the *L10* and *L90* declines, the attenuation loss over distance can change significantly (Schultz, 1972).
The *"noise pollution level NPL"* was developed by Robinson in the late 60´s (Schultz, 1972). The *NPL* formulation sums k*σ (constant k = 2.56 and standard deviation) to *Leq*:

$$L_{NP} = L_{eq} + k \cdot \sigma$$

When the distribution of the instantaneous A-weighted sound level is Gaussian, the noise pollution level could be expressed in function of some statistical noise levels:

$$L_{NP} = L_{eq} + (L_{10} - L_{90})$$ and $$L_{NP} = L_{50} + (L_{10} - L_{90}) + \frac{(L_{10} - L_{90})^2}{60}$$

Like the *TNI*, the *NPL* is made up by two terms: the first one is the "average" noise level, or "energy mean"; the second represents the fluctuation of that level during the emission time.
Moreover, in the first formulation, the parameter *σ* is influenced by the background noise: for a lower background noise, the fluctuation and the variability of the events are higher.
The above indicator has not been widely used because of the difficulty to define the parameter *σ* correctly. Some examples of its application are presented in Rice (1975) and Langdon (1976, part I and II).
The *"CRTN Indicator L10,18h"* is the most common indicator of traffic noise used in the UK and in Ireland, named *LA10,18h*. It comes from the Calculation of Road Traffic Noise (CRTN) prediction method, and it was first introduced in the 70's (Abbott and Nelson, 2002).
This indicator is the arithmetic average of eighteen *LA10,1h* values (i.e. the noise level exceeded for 10 % of the hourly period) from 06:00 to midnight:

$$L_{A10,18h} = \frac{1}{18}\sum_{t=6}^{23} L_{A10,t}$$

It does not take into account the noise emission in the night period. When traffic flow is low, the variation of the *LA10,1h* depends on the individual passing vehicle and not on the global traffic parameters. In some cases the indicator shows a high correlation with other statistical indexes and with *Leq* (Langdon and Griffiths, 1982).
The indicator is used in the UK in the context of National Insulation Regulations; in that case the value of noise contains a correction factor of +2.5 dB for the reflection from façades (O'Malley et al., 2009). In accordance with the END, it is possible to transform the CRTN indicator into *Lden* (Abbott and Nelson, 2002).

**4. Railway noise indicators**

There are few examples of "noise indicators" specific for rail transport in the state-of-the-art literature. This may be due to the fact that, historically, railway infrastructure has been perceived as less intrusive than roads and airports, representing a lower risk and a lower impact on the population.
From an acoustic point of view, railway noise is easier to study: the sound events are better defined and identifiable, the kinematic characteristics of the traffic being less variable than those of road traffic. Of course, the individual emissions from each moving train are energetically higher than those from road vehicles; this issue is acknowledged, in some national legislation, where noise limits are set higher than those adopted for road traffic.
The best known indicators are the *"transit exposure level TEL"* and the "*railway rating levels Lr"*. The *TEL* is used to describe the noise emitted by railway traffic taking into account the "train pass-by" duration (Tp) expressed in seconds (train length divided by the train speed). Its formulation is given by the EN ISO 3095:2005 (EN ISO, 2005):

$$TEL = 10\,log\left[\frac{1}{T_p}\int_0^T \frac{p_A^2(t)}{p_0^2}dt\right]$$

The *TEL* is related to the *SEL* and to the *Leq,T*; it is not a pure energy level like *SEL*, but it adds the equivalent level of the pass-by to a correction term. This last is the ratio between the length of the measuring time T and the pass-by duration Tp. This implies that a 100 m long train would reach about the same *TEL* as a train 200 m long of the same type:

$$TEL = SEL + 10\,log\left(\frac{T_0}{T_p}\right) \text{ [dB(A)]} \quad \text{and} \quad TEL = Leq_{,T} + 10\,log\left(\frac{T}{T_p}\right) \text{ [dB(A)]}$$

The *"rating levels Lr"* are calculated affecting the average noise level by corrections due to specific noise characteristics. When legal limits are applicable to both road and rail traffic, a "rail bonus" is subtracted from the average railways noise level. This reduction reflects the lower annoyance caused by rail noise as compared to that generated by road traffic (Danneskiold-Samsoe, 2002).

In Europe there are some examples of "rail bonus": in Austria and Germany the railways rating level is computed as *Lr=Leq-5dB*, in France *Lr=Leq-3dB* (I-INCE, 2009). In Switzerland (Swiss Federal act 814.41, 2010) the rating level is calculated increasing the average noise level with factors taking into account noise events related to the infrastructure; in that case the rating level includes noise from trains (*Lr1*) and shunting noise (*Lr2*):

$$L_r = 10\,log\left(10^{0,1L_{r1}} + 10^{0,1L_{r2}}\right)$$

**5. Aircraft noise indicators**

The presence in the literature of several indicators and studies related to the aircraft noise shows that impact assessment has historically been an important issue in airport design and management. Aircraft traffic noise became a big problem when, in the early 50's, the jet-propelled aircrafts were introduced in the civil aviation. The aircraft noise during take-off and landing is characterized by very high peak values with different spectrums depending on the operation phases.

Studies conducted over the years on people exposed to the noise produced both by air traffic and by aircraft ground operations, have led to the definition of different noise indicators, geared to describe human perception and the impact caused by different noise characteristics: spectrum, impulsiveness and high levels. The main indicators reported here are described below.

The *"Composite Noise Rating method CNR"* was proposed and developed for the first time in the USA by Rosenblith and Stevens in 1952 (Bradley, 1996) and later revisited, as cited by Goodfriends (1977). The indicator is based on the principle that people's perception is different at different frequencies and, for this reason, measurements have to record the equivalent sound pressure level in octave bands. The measured spectrum and noise levels are superimposed to a set of octave band contours and some corrections are subsequently added to the spectrum to take into account the presence of pure tones, impulsive sounds, repetition of the sound, background noise levels, time of day, and expected people's accommodation to the noise.

The adjusted *CNR* level rank is represented by the highest contour penetrated by the spectrum after the corrections. The reaction of annoyed people, resulting from the analysis of eleven different surveys, is associated to each *CNR* rank. People's reaction was expressed on a six levels scale, from the first degree "No annoyance", to the sixth degree "Vigorous legal action".

Following the introduction of jet engines, the *CNR* method was, initially, modified and adapted by Kryter (1959), in order to express the *CNR* value as a function of the perceived noise level, more akin to this type of aircraft. The final version of the *CNR* value adds a term including the number of day-time (Nd,ij) and night-time (Nn,ij) events for the aircraft typology *i* and flight path *j* to the *PNLij*, subtracting a constant (Raichel, 2006):

$$CNR_{ij} = PNL_{ij} + 10\,log(N_{d,ij} + 16.7N_{n,ij}) - 12$$

The total *CNR* value was obtained by an energy summation of the single *CNR* values:

$$CNR = 10\,log \sum_i \sum_j 10^{\frac{CNR_{ij}}{10}}$$

This method was used for a short period and replaced by the *NEF* indicator (see below).
The *"Perceived Noise Level PNL"* was developed by Kryter (1959) and adopted by the Federal Aviation Administration (1985) for noise certification. It is used to describe the noise emitted by a single overflying aircraft, and is based on the "total Noy" index (linear unit of annoyance) of the event *Nt*:

$$PNL = 40 + 10\,log_2\, N_t$$

*Nt* is calculated taking into account the spectrum of the event expressed in third-octave-bands: the pressure level of every band is compared to a normalized annoyance curve to get the term *Ni* for the i-th band (Hassall and Zaveri, 1979). The Ni value for that band represents the "Noy curve" expressed in dB. The equal noise contours are developed to take into account the high-pitched jet engine noise (Nelson, 1987).
An evolution of the *PNL* is the "*Effective Perceived Noise Level EPNL"* (Schultz,1972). It introduces a penalty F, depending on the duration of the highest levels, to take into account the modulation of the noise value over time, which creates different annoyance in people. In fact, sounds including distinct whistles and whines and/or having longer duration proved to be more annoying in respect to what measured by *PNL*:

$$EPNL = PNL + 10\,log_{10}\left(\frac{\Delta t}{T_0}\right) + F$$

Δt = time interval where PNL > PNLmax-10; T0 = 15 seconds.
*EPNL* is mainly used in the USA; some specifications about the indicator are reported in the ICAO Annex 16 (Jones and Cadoux, 2009).
The *"noise number index NNI"* was developed in the UK and used for thirty years up until 1990, when it was replaced by *Leq* (Jones, and Cadoux, 2009). The index is based on the *PNL* and the number of aircraft operations (Schultz, 1972; DORA, 1981); it was developed during a social survey in the 1961 in the vicinity of London (Heathrow) Airport in order to estimate the total annoyance on people due to airport activities. The *NNI* takes into account only noise levels greater than 80 PNdB during the day-period (I-INCE, 2009), the average level of the peak noise (*LAPN*) and the number of events (N):

$$NNI = L_{APN} + 15\,log_{10}\, N - 80$$

This indicator was discontinued since it does not take into account night events and because it is not effective in describing people's annoyance related also to aircraft low noise emissions (Brooker et al., 1985).
The *"Noise Exposure Forecast NEF"*, is a global aircraft noise indicator developed by the US Federal Aviation Administration for the evaluation of commercial aircraft noise (Schultz, 1972). This indicator was developed on the basis of the *EPNL* and it takes into account the aircraft typologies (*i*), the different flight paths (*j*), and the exposure period – day (7.00-22.00) or night (22.00-7.00) – through the number of day (nD) and night (nN) operations:

$$NEF_{ij} = EPNL_{ij} + 10\,log_{10}\left(\frac{n_{D,ij}}{20} + \frac{n_{N,ij}}{1.2}\right) - 75$$

This indicator, as mentioned in I-INCE, (2009) is used in China, in Greece, and in Canada.

Australia uses a modified version of *NEF*, called *ANEF,* contained in the Australian Standard 2021-2000 (I-INCE, 2009); it weights the values in the period 19:00-7:00, to better correlate noise and community reaction (Australian Dept. of Transport and Regional Services, 2000).

The *"Community Noise Equivalent Level CNEL"* was developed in the 70s and it was recommended in the California technical law for airport noise impact (California Department of Aeronautics, 1971). The indicator takes into account the duration and number of flights and the frequency response of human ear. It is expressed in dB(A), to avoid the complex calculation of other indicators like *EPNL* (EPA, 1971), and it does not contain any pure tone correction. The *CNEL* takes into account the occurrence of the noise events using weighting factors. In particular, researchers observed that one flight at night time was equivalent to ten equally noisy flights in the day-time or three in the evening.

The *CNEL* adds a term considering the total or average number of flights per hour during the day and the night period (*NC*) to *SENEL* (EPA, 1971):

$$CNEL = \overline{SENEL} + 10 Log N_C - 49{,}4$$

The formulation proves the *CNEL* is very similar to other noise indicators, namely the Italian *LVA* (D.M. 31/10/1997*)* or the *Lden* adopted in the END. *CNEL* is related to the sheer number of noise events and their recorded values during three periods of the day. The *SENEL* is used to calculate *CNEL* as well as *SEL* is used to calculate *LVA*, but without weighting the factors, unlike *Lden*.

The *"weighted noise exposure forecast WECPNL"* is an evolution of *EPNL*, proposed by International Civil Aviation Organisation in 1971 (Changwoo et al., 2007). The *WECPNL* (or *LWECPN*) represents an index for describing the noise emitted during a time period by different numbers of flights, taking into account the different annoyance and noise impact in various day periods. The computation involves three steps (Bennet and Pearsons, 1981). First of all an index called Total Noise Exposure Level (*TNEL* or *LTNE*) is calculated and used to normalize every noise event along 10 second time intervals.

At a second step all the different *LTNEs* are converted into another index, the Equivalent Continuous Perceived Noise Level (*ECPNL* or *LECPN*). This conversion is necessary to weight every noise level in function of the reference period.

Finally, at the third step, the *WECPNL* is calculated through an equation incorporating a weighting for noise emitted during evening and night periods, to reflect the significantly different annoyance in respect to the day period (as for *Lden*).

In some cases, like in Korea, the national Noise and Vibration Regulatory Law 1991 (revised in 2004) suggests adopting indicators as a function of the number of flight operations and their distribution throughout the day (I-INCE, 2009).

The *WECPNL* has been used in Japan, China, and Korea for few years, but it is being gradually replaced with other general purpose indicators, such as *Lden*.

The *"Isopsophic Index I"* was developed in France by the "Commission de Bruit of the Secrétariat Général à l'Aviation Civile" (ICAO, 1974) to assess the total noise exposure of populations living in the vicinity of airports.

At the outset, the index was calculated separately for day and night periods and, over the years, different formulations were developed until the definition of a single noise index for the whole day. The hypotheses used during the development of the index are that global people's annoyance is a function of the number of overflying aircrafts of each type (n,p) – but unrelated to the duration of those flights – and the peak noise level (LD,LN). Instead, the night flights are considered ten times more annoying than day flights for the same type of aircraft (Collet and Delol, 1980):

$$I = 10 Log \left[ \sum_{i=1}^{n} 10^{\frac{L_{Di}}{10}} + 10 \sum_{j=1}^{p} 10^{\frac{L_{Nj}}{10}} \right] - 32$$

The index was used until 2002 and replaced by *Lden.*

The *"Time Above Threshold, TAX"* represents the time over which a threshold level X is exceeded by aircraft noise, during a defined reference time period, and it is expressed in seconds or minutes (ECAC, 2005). The indicator was developed by the Federal Aviation Administration (FAA, 2007) like a secondary metric for assessing airports impact; the typical threshold value was set up at 60 or 65 dB. While, admittedly, some compulsory specific regulations require the use of this indicator, other technical documents simply suggest its adoption in certain contexts; for example, Fighter Conveyer (FICON, 1992) suggests to use *TA* for describing communication interference.

Similar to *TA* the *"Number Above Threshold"*, *NATX* or *NAxx*, represents the number of events exceeding the threshold level X during specific periods (ECAC, 2005). This indicator is barely used; however some technical documents refer to it (WHO, 2007), and countries like Germany have adopted it (Isermann, 2008). A frequently used NATX is NA70, representing the number of events exceeding 70 dB(A).

The *"Störindex Q"* is a German indicator used for aircraft traffic. Its formulation is similar to the *Leq*, but some corrections were introduced to take into account the duration of the noise event and the day period. The indicator was discontinued and replaced with the German regulation Air Traffic Noise Act 2007, where the equivalent level is evaluated on sixteen hours *LAeq,16h* (I-INCE, 2009).

The *"Kosten method B"* is used in the Netherlands, and specified by the National Aviation Act. It was developed by the Kosten Committee in 1963 and described in the document "Adviescommissie geluidhinder door vliegtuigen. Geluidhinder door vliegtuigen Delft" by the Netherlands Organisation for Applied Scientific Research (TNO) in 1967 (Franssen et al., 2004). The indicator, sometimes referred also as "total noise load" (Nelson, 1987), is related to noise emitted during a 24-hour period, taking into account the different impact of noise emitted in the night period.

The *"indicator LVA"* is used in Italy for aircraft noise description around airports and described in the Italian norm D.M. 31/10/1997:

$$L_{VA} = 10\,log\left[\frac{1}{N}\sum_{j} 10^{\frac{L_{VAj}}{10}}\right]$$

This indicator is an energy mean of the representative aircraft noise emission (LVAj) during a year time observation: the measurements have to be taken in three periods of the year (1/10 to 31/01; 1/02 to 31/05; 1/06 to 30/09). For each of those periods the busiest week is considered, up to a total of N=21 days.

**6. General environmental noise indicators**

Most of the previous indicators have been developed to formulate a synthetic description of the noise emissions produced by the different transport modes; they are often good energy noise indicators. Over the years the scientific community has opted to develop the "general environmental noise indicators". Both in project evaluation and environmental assessment, decision makers and technicians need indicators easy-to-calculate and to deal with, when confronted to the general public. Furthermore, the need to evaluate people disturbance has prompted the development of indicators able to describe the noise emissions in relation to people annoyance: the *"Day-Night equivalent level LDN or DNL"*, and the *"Day-Evening- Night equivalent level Lden or DENL"*.

The "*LDN*" is used for different noise sources: road, railway and aircraft, proposed by the U.S. Environmental Protection Agency (Langdon, 1976, Part II). The *LDN* is an A-weighted average noise level apt to take into consideration the different noise impacts according to the day-time (6:00-22:00) and night-time (22:00-6:00). The night level, considered a sensitive
time where people need to be safeguarded, is increased by10 dB(A):

$$L_{DN} = 10\log\frac{1}{24}\left(16\cdot 10^{\frac{L_D}{10}} + 8\cdot 10^{\frac{L_N}{10}}\right)$$

The *"Lden"* and the *"Lnight"* are the most recently developed general indicators. *Lden* is an A-weighted average level of the noise emitted in three periods – day (7:00-19:00), evening (19:00- 23:00), and night (23:00-7:00) – with a penalty of 5 dB(A) and 10 dB(A), respectively, for the evening and the night-time, to allow for the different people's sensitivity to noise exposure. This indicator was proposed in the END, where it is recommended that all European countries have to use, for all transport systems, *"Lden"* to assess annoyance, and *"Lnight"* for sleep disturbance.
L*den* has been used in some studies to assess the relationship between noise and annoyance (Miedema and Oudshoorn, 2001; Klæboe et al., 2004). Corrections of the value of *Lden* have been incorporated depending on the typologies of sound, presence of low frequencies and tonal components, in order to reduce the scatter on the dose-response relationship (Schomer, 2002).
In general, for the traffic noise, no corrections are added to the noise levels, but some analyses show that the presence of low frequencies are significant in the assessment of annoyance and, in some cases, the use of the A-weighted curves could be inappropriate (Nilsson, 2007).

**7. Strengths and weaknesses of the current noise indicators**

The noise emitted from transport infrastructures contains several acoustic characteristics, important for the impact assessment, and, hence, indicators must properly record this feature, but also give a synthetic evaluation of noise. The indicator that better suits this last requirement is *Leq*; however, special types of noise, emitted by diverse sources in various ways (constant or impulsive), can be differently perceived by people, even if recording the same *Leq*. Shortening the time period to a specific time lapse, for example each hour (*Leq,h*), might help to track important noise variations that could be concealed by *Leq* calculated on day-time or night-time basis. In fact, during the night or in low-traffic corridors, the emission of an individual vehicle as opposed to overall traffic noise becomes significant. In such situations as well as when the traffic is discontinuous, notably near intersections and at traffic lights, the *Leq* is inappropriate to describe the noise variation (Can et al., 2008).
Conversely, some energy indicators can be applied to the study of certain short-term interventions. For example, a public transport operator, or a railway company, could use indicators such as the *SEL* for assessing the noise from new vehicles.
The *L50*, computed during a specific period of the day (e.g. day or night or 24h), has been used to assess road traffic noise and environmental noise (Omiya et al., 1997), but it is barely used nowadays. In some cases the *L10* over 24, 18, and 12 hours has been used to predict annoyance in residential locations (Langdon, 1976, part I and II), but the results show a low correlation between values of the indicator and people disturbance.
In some cases, such as the evaluation of annoyance from low noise emissions by aircraft, a good correlation is observed between the *SEL*, expressed on dB(C), and the people's annoyance (Hodgdon et al., 2007).
The general acoustic indicators are useful when it is just important to quantify the noise produced and, for this reason, both road and rail noise indicators stem from *Leq*, *SEL* and *Lxx*. This aspect influences the use of mode-related indicators for planning purposes. For example, *TNI* was used to determine an optimum distance between dwellings and the road axis (Langdon and Scholes, 1968). Some examples of its use are presented in Langdon (1976, part I and II); a drawback due to its origins from *Leq* and *Lxx* is that it becomes representative only when the traffic is flowing. Furthermore, both *TNI* and *NPL* are not sufficiently sensitive to assess the diversity of urban contexts and the different traffic kinematic characteristics, showing a feeble correlation with residents' annoyance (Banerjee et al., 2009). These reasons, as well as the specificity of the traffic conditions in which they have been calibrated, make them inadequate for the assessment of the infrastructures impact and make it impossible to generalize their usability. Moreover, their computation requires a complex data collection, made difficult also by the acoustically complex environments – characterised by multiple sources of sound – in which the infrastructures are located. This may cause uncertainty in attributing to the infrastructure only the noise levels generated by its own traffic, making the building of noise maps more difficult. The same weakness is associated to the railways, notably in the urban stretches.
Another important setback in railway noise assessment is the lack of a technical and normative framework. Railway infrastructure is considered to include both track and the train stations. The noise emitted in the railway stations stems from sundry activities (rails shunting, manoeuvring, train departure and arrival, and

communication equipment) that become significant in urban areas where the stations are located; but, for most of those, specific noise indicators and related limits are not defined in literature. In general, specialists go around this problem by considering railway stations as industrial sites, bridging the normative gap in a practical, but not quite scientific way.
Concerning the ability of indicators to describe the disturbance, an unsatisfactory statistical correlation between road and rail indicators and people's annoyance is observed, unlike for air transport indicators. The main difference lies in the weighting system, *A* or *PNL*. *PNL* weighting lies one third octave band sound pressure level to better consider the different perception at different frequencies and it suits better the annoyance evaluation. As showed in figure 1, most air indicators stem from *PNL* – except those based on A-weighting system – that represent high sound energy spectra related to specific sounds. This has implied a complexity in their formulation, requiring many specific data, sometimes not easy to find, especially when forecasting is needed. However, that complexity allows a detailed description of the phenomenon, as in the case of *WECPNL*.
Figure 1 depicts the relationships among the indicators, showing how road, rail, and some air indicators (*CNEL*, *LVA*, *Störindex Q*, and *Kosten method B*) stem from general acoustic ones. The aircraft indicators derive mostly from event-related noise indicators, both A-weighting and PNL-weighting.
We can also observe how there are few basic indicators on which all the other have been built: for the A-weighting, *Leq*, *SEL*, and *Lmax*; while, for PNL-weighting, *PNL*.
The difference between road and rail indicators stems also from their origin: the first are based on *Leq* and *Lxx*, while the second on *Leq* and *SEL*. This makes rail and air traffic more similar, being characterised by events, while road traffic has pseudo-random variability over time. However, rail traffic has been always considered less intrusive than other modes (see *Lr*). Road and rail transport have been lately considered an important source of annoyance in respect to airports, but their sprawl and density over the territory rendered their study and control more complicated and expensive to conduct.
A last aspect to be highlighted, comparing the indicators in figure 1, is that the weighting according the day-periods has been largely anticipated by the air indicators (*NEF*, *CNEL*, *WECPNL*, *Isopsohic Index*, *Störindex Q*, *Kosten method B*, and *LVA*) that show analogies with *Lden*, that was selected by the END to assess annoyance. Also *LDN* has been used to describe the annoyance: Martin et al. (2006) reported that it relates well to the annoyance when considering the "highly annoyed" people, but they show that also the *Lmax* relates well with the "average annoyed people".
The END, according to studies on the subjective characteristics of the response to annoyance, suggested considering the dose-response relationship. Some researchers have found a strong dose–response relationship between *Ldn* or *Lden* and annoyance (Ohrström et al. 2006; Miedema and Oudshoorn, 2001;). However, forecasts have often been found inaccurate as large variations in the dose-response relationships as well as in individual annoyance reactions to the same noise exposure level were observed (Miedema and Oudshoorn, 2001; Ouis, 2001). This stems from the long term nature of *Lden*: it cannot describe the nature of the noise in terms of short term variations, presence of tonal components, etc., but these issues are often considered more disturbing and generate more complaints (Murphy and King, 2010).
In addition, *Lden* describes the average day–evening–night *Leq* over a year; the current prediction methods used to calculate *Lden* do not use the same approach to account for meteorological conditions that vary along the year, and this affects its calculation. Even though this comes from the lack of models standardization, the use of long term indicators accentuates the problem (Murphy and King, 2010). Likewise, for specific sources like airports, *Lden* proves inadequate to describe annoyance, especially in terms of sleep disturbance (Vallet, 2008).
Conversely, *Lmax* is a useful indicator to evaluate instantaneous effects, notably sleep disturbance (Pirrera, et al., 2010), and in some cases a good relationship with annoyance is observed (Sato et al., 1999). Furthermore, mainly during the night-time, the number of noisiest events caused by the intermittent traffic is related to the quality of sleep (WHO, 2007). The reason is that sleep disturbance is more often related to individual events than to average noise levels over the night, and Murphy and King (2010) suggest indicators as *Lmax* or *SEL* as most appropriate. When the measurement shows high noise levels, Paunovic et al. (2009) observed that night-time *Leq* might be as good as *Lden* in predicting noise annoyance in noisy urban areas. Thus, the general acoustic indicator is accurate enough to take decisions when a high noise is recorded; instead, it is not suitable to predict annoyance in the quiet areas (Paunović et al., 2009), where

the single noise events become relevant in absence of a high background noise, typical of congested transport infrastructures.
Presently, the European Commission (EC, 2000) supports the *Lnight* indicator arguing that *Lmax* or *SEL* do not consider the number of events, and a common method to calculate an average long-term *Lmax* or *SEL* is still missing.
A synthesis of strengths and weaknesses of the described indicators is provided in tables 1,2,3 as well as suggestions about their use. Tables 2,3 allow to observe that the mode-related indicators are hardly able to predict annoyance as too many endogenous variables, related to the personal sphere of individuals are involved, playing a confounding effect on annoyance.
The general acoustic indicators reveal a good performance for single event evaluation and in case of noisy areas, where they can assist decision-makers in implementing proper interventions, while the *Leqshort* can be used to track important noise variations and shed light on people's reaction to disturbance in quiet areas. Event-related indicators as *Lmax*, *SEL* or *NATx* and *TAx* should be more used, aside *Lden* and *Lnight*, to better support decisions when people disturbance is a key aspect.

## 8. Discussion and conclusions

The definition of common approaches to compare the transport environmental assessment and policy formulation in different countries deems necessary. The proposal of common indicators suitable for calculation, using national data and harmonized computation methods (Nijland and Van Wee, 2005) has been stressed by the END, and the EC decided to prepare Common NOise aSSessment methOdS for road, railway, aircraft, and industrial noise in order to improve the reliability and the comparability of results across the EU countries (EC, 2012).
The indicators were at first conceived to assess the effect of noise from an energy point of view, but more recent research has progressively addressed people's perception of noise. In fact, even though some characteristics of noise exposure (noise sources, type of traffic, number of events, frequency and time of exposure) allow calculating the noise levels, too many issues of people wellbeing are related to the soundscape and to the subjective noise sensitivity, expectations and attitudes toward noise, personality traits, social status, housing and working conditions. These elements are independent from noise exposure and strongly influence annoyance (Paunović et al., 2009).
Noise levels are, arguably, the objective element to understand the noisiness of an area, and they work well to predict annoyance in very noisy urban areas. Instead, the less noisy areas and the quiet zones, where the exposure to noise is secondary, should be approached investigating residents in terms of the afore-mentioned social and psychological aspects. A further element to consider is the background noise level in the studied areas: the construction of a new infrastructure will have a stronger impact in quiet zones than in noisier areas. The "differential noise" approach can help to better understand the change of disturbance in those zones and, actually, neither current indicators nor decisional process take into account this aspect.
A step forward is the three-dimensional approach – environmental, social, and economic –adopted by the research on transport environmental sustainability, even though solutions based also on technical, operational, and institutional dimension are still preferred (Janic, 2006). However, policy makers need indicators to support their decisions about infrastructures (construction, location, alignment); to this extent a four categories classification is proposed (figure 2):

1. noise Level Indicators, describing noise in terms of energy and physical characteristics;
2. noise Exposure Indicators, describing the noise effect on the exposed people in terms of magnitude and territorial extension;
3. noise Annoyance Indicators;
4. noise Strategic Indicators.

If the goal is the simple noise definition, useful, for example, to improve vehicle technology and infrastructure, an energy-based indicator should do. Public transport operators or railway companies could use indicators such as the *SEL*: a lower noise level in terms of *SEL* of the single vehicles means a lower overall noise level caused by the infrastructure. The introduction in the vehicle fleet of new electric or hybrid vehicles may be characterised through indicators such as *Lmax*, *Lmin*, *SEL* and *Leq*, even though they would be inadequate to describe their noise impact. In fact, their low noise emissions will require a different consideration to pedestrian perceptions and, in particular, to some categories as the blind, to properly consider the safety issues (Yamauchi et al., 2011). Considering the psycho-acoustic characteristics of the noise should allow provide pedestrians with information on the kinematic behaviour of the vehicles.

The noise Exposure Indicators allow quantifying the impact at territorial level. They can be successfully used to understand the number of people exposed to different noise levels. Noise maps are used to this extent and general environmental noise indicators, such as *Lden* are appropriate. Some indicators, as *CRTN* for road traffic, have been converted to *Lden* to allow the drawing of comparable noise maps. The problem is that different countries use time series measured according to indicators other than *Lden*, or not easily convertible to it; the analysis of the relationships between those indicators and *Lden* is important not to waste previous work. Moreover, carrying out measurements is a very expensive exercise and, to meet the Directive requirements properly, long time measurements are necessary. The possibility to use short-time measures to calculate *Lden* is critical for a good use of past efforts and to reduce monitoring costs. However, the scope of this exercise is purely informative and decision-makers should not use the noise maps results to assess people's annoyance. To this extent the measurement techniques are important to distinguish between potential (*Lden*) and real disturbance. The ongoing studies on environmental dosimetry could help (Neitzel et al., 2012). The alternative is an extensive use of simulation models, but their accuracy need to be improved, also in terms of a more precise source description, mainly in the case of road traffic, more difficult to describe not being event-related. The traffic micro-simulation models, more suited to apprehend the kinematic characteristics, can help (Chevallier et al., 2009; Beuving and Hemsworth, 2006, but costs are high as regards the potential improvements. Specialised software for source recognition and noise directivity would create a good synergy with measurements to better understand the annoyance. Of course, simpler methods are welcome and better measured data will allow a good trade-off between simplification and precision, also because measurements remain essential to calibrate the models (e.g. for the evolution of the vehicle fleets). The HENNAH-project (http://www.ennah.eu/home?lang=en) and ongoing COST Actions TU1105 and TD0804 (http://www.cost.eu/domains_actions/tud/Actions) deal with these issues.

The lessons learned from the difficulties encountered by the member countries in applying the Noise Directive using the available data and considering country specificities should help to understand the most suitable approach to follow and find a trade-off between simplification and significance. After a first revision of Annex II of the END, the Commission is considering a possible revision of the Annex II in 2012, focused on the strategic mapping (EC, 2011b).

However, the research has showed the risks to compromise the understanding of the people disturbance using a long term indicator as *Lden*. The use of more indicators to better support the understanding of disturbance could benefit decision-makers in taking proper actions to reduce noise. But, the need of an indicator more able to understand people noise perception and allowing also to give a strategic support in decision making seems urgent.

The noise Annoyance Indicators include those taking into account people perception and disturbance. To this extent, several indicators have been developed; some of them were designed for air transport, as *WECPNEL*, but are difficult to compute, while others are more general and simple, as *Lden*, recommended for all the infrastructures. Actually, this category of indicators covers those used to define the noise impacts, but as argued above, they should be used to understand the "potential" but not the "real" annoyance. The difference between them is explained by several variables, according to the studies of numerous researchers:

- subjective characteristics and personality traits: attitudes towards environmental noise (Lam et al., 2009; Miedema, 2007; Van Kamp et al., 2004; Miedema and Vos, 2003); attitude towards traffic, notably heavy vehicles and public transport at night-time (Paunović et al., 2009); level of awareness the people get about the noise problems (Pronello, 2006); subjective noise sensitivity, showed as the strongest common indicator of annoyance in both noisy and quiet urban areas (Paunović et al., 2009); self-reported noise annoyance at workplace (Jakovljevic et al., 2009); neuroticism (Ohrström et al., 1998); introversion (Belojevic et al., 2001); current mood (Vastfjall, 2002);
- health status: the physical and psychological status and the presence of some illnesses (Pronello, 2006);

- social factors: socio-demographic parameters as the social role, family relations, the kind of life (active or not) (Paunović et al., 2009; Pronello, 2006);
- acoustical environment in which people work and live (Pronello, 2006); duration of stay at home during the day (Paunović et al., 2009); housing conditions as orientation of living room and bedroom windows towards the street (Paunović et al., 2009; Ohrström et al., 2006; Rylander and Björkman, 2002).

Those researchers and, notably, Paunović et al. (2009) proved that noise-related characteristics are less relevant in predicting annoyance than personal and social characteristics. This does not render meaningless all the described noise indicators, but points out to use them just to understand the magnitude of the phenomenon and its objective characteristics.

The noise Strategic Indicators are proposed to tackle the afore-mentioned remarks and seek to consider the cause-effect framework for describing the interactions between the society and the environment and quantify the noise damages.

This category represents a step forward in the classification of noise indicators provided by the authors in Folkeson et al. (2010; p,167), where the first three categories defined before were matched with the DPSIR (Driving forces, Pressures, States, Impacts, Responses; EEA, 2009) approach (Table 4). This approach allows to understand both the nature of indicators in the chain of casualties and how strategic they are in the decision making process. This is essential in transport policy and within the Strategic Environmental Assessment, where transport plans and sustainable urban mobility plans are analysed in terms of sustainability.

That classification reveals how the current indicators do not allow measuring the impact (I) and how much the assessment of annoyance is important, albeit not exhaustive, in assisting decision-makers to develop a sustainable transport policy.

Several researchers have studied these issues and suggested typologies of indicators (Marsden, 2005; Litman, 2007; Calderón et al., 2009; Joumard and Gudmundsson, 2010). In fact, even though indicators like *Lden* could meet the needs of strategic planning, considering the percentage of people exposed to different noise levels, this impact has to be “filtered” through the subjective noise sensitivity. To this extent, the END has stressed the need to ascertain the true correlation between noise emissions and people’s annoyance, requiring each country to define its own dose-response relationship. However, the research has showed that “dose–response” relationships are still far from being able to determine the acoustic impact of transport systems if subjective variables are not included in the analysis. In addition, the building of one curve per country would clash with the current research outcomes, averaging the many and different characteristics of people. Thence, we propose to build one curve for each category of individuals. Thus, the market segmentation, largely used in other branches of transport research, would be the way to individuate a number of groups, homogeneous in terms of the subjective, personal, and social characteristics as well as health status, acoustical environment in which people live and work, and noise exposure.

What emerges from the above analysis is that there is little margin for the development of new noise indicators. We propose the Strategic noise Indicators, formed by the aggregation of the first three classes plus the social and economic variables, to allow decision-makers to implement policies guaranteeing the health of the population, but also taking into account the real perception and the economic constraints. This leads to the definition of a new index, namely the “index of real sustainable development”, to be used by decision makers for strategic transport noise evaluation (figure 2). The use of Factor Analysis to define latent variables, on which applying the cluster analysis, has been successfully used in transport users market segmentation (Redmond, 2000; Anable, 2005; Hunecke et al., 2010; Pronello and Camusso, 2011); here it is proposed to segment different categories of population characterised by their own dose-effect curve. This curve will allow to monetise the disturbance according to the dose-response method (Pronello, 2010), and define an index useful to implement policies to attain a real sustainable development.

While in Europe the use of *Lden* and *Lnight* indicators for the economic evaluation of noise effects is now common, this paper shows that decision-makers should jointly use noise and socio-economic variables to fully support their decisions.

**References**


Abbott, P.G., Nelson, P.M. (2002) Converting the UK traffic noise index LA10,18h to EU noise indices for noise mapping. TRL Project Report PR/SE/451/02.

Anable, J., (2005) 'Complacent Car Addicts' or 'Aspiring Environmentalists'? Identifying travel behaviour segments using attitude theory. Transport Policy 12(1), pp. 65–78.

Australian Dept. of Transport and Regional Services, (2000) Expanding Ways to Describe and Assess Aircraft Noise. Discussion Paper.

Banerjee, D., Chakraborty, S.K., Bhattacharyya, S., Gangopadhyay, A., (2009) Attitudinal response towards road traffic noise in the industrial town of Asansol, India. Environmental Monitoring and Assessment vol. 151, pp. 37–44.

Belojevic, G., Slepcevic, V., Jakovljevic, B., (2001) Mental performance in noise: the role of introversion. J. Environ. Psychol., 21, pp. 209–213.

Bennet, R.L., Pearsons, K.S., (1981) Handbook of aircraft noise metrics. NASA contract report 3406 N81-21871.

Berglund, .B, Lindvall, T., (1995) Community noise. Document prepared for the WHO. Archives of the Centre for Sensory Research, 2: 1-195.

Beuving, M., Hemsworth, B. (2006) Improved Methods for the Assessment of the Generic Impact of Noise in the Environment, IMAGINE Final Synthesis Report.

Bradley, J.S., (1996) NEF Validation Study: (2) Review of Aircraft Noise and its Effects. Institute for Research in Construction, National Research Council. Contract Report A-1505.5.

Brooker, P., Critchley, J.B., Monkman, D.J., Richmond, C., (1985) United Kingdom Aircraft Noise Index Study (ANIS): main report. DR report 8402, CAA, London.

Burgess, M.A., (1977) Noise prediction for urban traffic conditions, related to measurements in the Sydney metropolitan, Area, Appl.Acoust. vol.10, issue1.

Calderón, E., Pronello, C., Goger, T., (2009) Integrated assessment of environmental impact of traffic and transport infrastructure. Univ. Politécnica Madrid, 405 p.

California Dept. of Aeronautics, (1971) Supporting Information for the Adopted Noise Regulations For California Airports. Final Report to the California Dept. of Aeronautics.

Can, A., Leclercq, L., Lelong, J., Defrance J., (2008) Capturing urban traffic noise dynamics through relevant descriptors. Applied Acoustics, 69, 1270-1280.

Changwoo, L., Jaehwan, K., Jiyoung, H., Scoogab, L., Soojoo, L., (2007) The relationship between civil aircraft noise and community annoyance in Korea. J. of Sound and Vibration, 299, pp. 575-586.

Chevallier, E., Can, A., Nadji, M., Leclercq, L. (2009) Improving noise assessment at intersections by modelling traffic dynamics. Transp Res Part D-TR E 14, pp.100–110.

Collet, F., Delol, J., (1980) The French method (Of representing noise annoyance). Nasa technical memorandum 75833.

CSTB, Centre Scientifique et Technique du Batiment (1991) Etude théorique et expérimentale de la propagation acoustique, Revue d'Acoustique n.70, 1991.

D.M. 16/03/1998 Tecniche di rilevamento e di misurazione dell'inquinamento acustico. Published on Gazzetta Ufficiale n°76 on 1 April 1998, Roma, Italy.

D.M. 31/10/1997 Metodologia di misura del rumore aeroportuale. Published on Gazzetta Ufficiale n°267 on 15 November 1997, Roma, Italy.

Danneskiold-Samsoe, U., (2002) A study of European priorities and strategies for railway noise abaetment. Annex I Retrieval of Legislation Final Report, February 2002.

den Boer, L.C., Schroten, A. (2007) Traffic noise reduction in Europe Health effects, social costs and technical and policy options to reduce road and rail traffic noise. CE Delft.

Department of Transport and the Welsh Office (1998) Calculation of Road Traffic Noise"(CRTN), HMSO.

De Vos, P., Van Beek, A., (2011) Environmental Noise. Encyclopaedia of Environmental Health, pp. 476–488.

DORA, (1981) The noise and Number Index. DORA Communication 7907, 2nd ed., Dir. of Operational Res. and Anal., Civil Aviation Authority, London.

ECAC, (2005) Report on Standard Method of Computing Noise Contours around Civil Airports. Volume 1: Applications Guide. ECAC.CEAC Doc 29, 3rd Edition.

EC, (2012) Environment noise, common noise assessment methods. http://ec.europa.eu/environment/noise/cnossos.htm.
EC, (2011a) WHITE PAPER. Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system.
EC, (2011b) Report from the Commission to the European Parliament and The Council. On the implementation of the Environmental Noise Directive in accordance with Article 11 of Directive 2002/49/EC. Brussels, 1.6.2011.
EC, (2000) Position paper on EU noise indicators. Belgium: European Communities.
European Directive 2002/49/EC of the European parliament and of the council of 25 June 2002 relating to the assessment and management of environmental noise.
EEA , (2009) Glossary. http://glossary.eea.europa.eu/EEAGlossary/D/DPSIR
EEA, (2011): Laying the foundations for greener transport. TERM 2011: transport indicators tracking progress towards environmental targets in Europe. EEA Report n°7.
EN ISO, (2005) Railway applications-acoustics-measurement of noise emitted by rail-bound vehicles - EN ISO 3095-2005. Technical Report, UNI, Milano, Italy.
EPA, (1971) Community noise. U.S. Environmental Protection Agency, Washington DC.
FAA, (2007) Environmental desk reference for airport actions. FAA report.
FAA, (1985) Aviation noise effects. Technical report n° FAA-85-2. Department of Transportation FAA, Office of Environment and Energy, Washington D.C.
FICON, (1992) Federal agency review of selected airport noise analysis issue. Report for the Department of Defence, Washington DC.
Fidell, S. (2003) The Shultz curve 25 years later: A research perspective. J. Acoust. Soc. Am. 114 (6), pp. 3007-3015.
Folkeson, L., Boughedaoui, M., Joumard, R., Ortega Pérez, R., Waeger, P., Camusso, C., Pronello, C., Arapis, G., Karkalis, K., Goger, T., Chiron M., Dimopoulou, S. (2010). Assessment of some indicators within an impact. In: Indicators of environmental sustainability in transport. An interdisciplinary approach to methods. Editors: Joumard R., Gudmundsson H. RECHERCHES. © Les collections de l'INRETS. Réf. : R282, 422 pp.
Franssen, E.A.M., van Wiechen, C.M.A.G., Nagelkerke, N.J.D. Lebret, E., (2004) Aircraft noise around a large international airport and its impact on general health and medication use. Occupational Environmental Medicine 2004;61, pp. 405–413.
Goodfriends, L.S., (1977) Range of Sound Levels in the Outdoor Environment. In Heisler, Gordon M.; Herrington, Lee P., eds. Proceedings of the conference on metropolitan physical environment; Gen. Tech. Rep. NE-25. Upper Darby, PA: U.S., pp. 172-182.
Graf, P., Mueller, R., Meier, H.P, (1980) Socio-psychological airplane noise investigation in the districts of three Swiss airports, Zurich, Geneva and Basel. National Aeronautics and Space Administration. Washington DC, 359 p.
Hassall, J.R., Zaveri, K. (1979) Acoustic noise measurement. Brüel & Kjær, 4th edition.
Hodgdon, K.K., Atchley, A.A., Bernhard, R.J., (2007) Low Frequency Noise Study. PARTNER project final report.
Hunecke, M., Haustein, S., Böhler, S., Grischkat, S., (2010) Attitude-Based Target Groups to Reduce the Ecological Impact of Daily Mobility Behavior. Environ Behav 42(1), 3–43.
ICAO, (1974) Noise assessment for land-use planning. CIRCULAR 116-AN186.
I-INCE, (2009) Survey of legislation, regulations, and guidelines for control of community noise. I-INCE publication: 09-1- Final Report of the I-INCE technical study group on noise policies and regulations (tsg 3).
Isermann, U., (2008) The DLR Project "Quiet Air Traffic". ODAS 2008 9th Onera-DLR Aerospace Symposium, 22nd to 24th October, 2008, Chatillon, France.
ISO 1996-1, (2003) Acoustics - Description, measurement and assessment of environmental noise -- Part 1: Basic quantities and assessment procedures.
Jakovljevic, B., Paunovic, K., Belojevic, G., (2009) Road-traffic noise and factors influencing noise annoyance in an urban population. Environ. Int. 35, pp. 552–556.

Janic, M., (2006) Sustainable Transport in the European Union: A Review of the Past Research and Future Ideas. Transport Reviews, Vol. 26, No. 1, pp. 81–104.
Jones, K., Cadoux, R., (2009) Metrics for aircraft noise. Environmental Research and Consultancy Department. Civil Aviation Authority , ERCD Report 0904.
Joumard, R., Gudmundsson, H., (2010) Indicators of environmental sustainability in transport. An interdisciplinary approach to methods.. Les collection de l'INRETS, 422 p.
Klæboe, R, Amundsen, A.H., Fyhri, A., Solberg, S., (2004) Road traffic noise – the relationship between noise exposure and noise annoyance in Norway. Appl. Acoust. vol. 65, pp. 893–912.
Kryter, K.D., (1959) Scaling human reactions to the sound from aircraft. J. Acoust. Soc. Am., 31(11), pp. 1415-1429.
Lam, K.C., Chan, P.K., Chan, T.C., Au, W.H., Hui, W.C., (2009) Annoyance response to mixed transportationnoise in Hong Kong. Appl. Acoust. 70, pp. 1-10.
Langdon, F.J., Griffiths, I.D., (1982) Subjective effects of traffic noise exposure, II: comparisons of noise indices, response scales, and the effects of changes in noise levels. J. Sound Vibrat. 83(2), pp. 171-180.
Langdon, F.J., Scholes, W.E., (1968) The Traffic Noise Index: A Method of Controlling Noise Nuisance, Building Research Station Current Papers 38168. pp. 2-3.
Langdon, F.J., (1976) Noise nuisance caused by road traffic in residential areas: Part I. J. Sound Vibrat. 47(2), pp. 243-263.
Langon, F.J, (1976) Noise nuisance caused by road traffic in residential areas: Part II. J.Sound Vibrat. 47(2), pp. 265-282.
Litman, T., (2007) Well Measured: Developing Indicators for Comprehensive and Sustainable Transport Planning, Victoria Transport Policy Institute (www.vtpi.org). Marsden, G., (2005) Appraisal of Sustainability: Environmental Indicators, Institute for Transport Studies, University of Leeds.
Martin, M.A., Tarrero, A., Gonzalez, J., Manchimbarrena, M., (2006) Exposure-effect relationship between road traffic noise annoyance and noise cost valuations in Valladoid, Spain. Appl. Acoust., 67, pp. 945-958.
Miedema, H.M.E., (2007) Annoyance caused by environmental noise: elements for evidence-based noise policies. J. Soc. Issues, 63, pp. 41–57.
Miedema, H.M,E., Vos, H., (2003) Noise sensitivity and reactions to noise and other environmental conditions. J. Acoust. Soc. Am. 113, pp. 1492–1504.
Miedema, H. M. E., Vos, H., (1998) Exposure-response relationships for transportation noise. J. Acoust. Soc. Am. 104 (6), pp. 3432-3445.
Miedema, H.M.E., Oudshoorn, C.G.M., (2001) Annoyance from Transportation Noise: Relationships with Exposure Metrics DNL and DENL and Their Confidence Intervals. Environ. Health Persp., vol. 109, 4, pp. 409-416.
Murphy, E., King, E.A. (2010) Strategic environmental noise mapping: Methodological issues concerning the implementation of the EU Environmental Noise Directive and their policy implications Environment International, 36, pp. 290–298.
Neitzel, R.L., Gershon, R.R.M., McAlexander, T.P., Magda,L.A., Pearson, J.M., (2012) Exposures to Transit and Other Sources of Noise among New York City Residents. Environ. Sci. Technol., 46, pp.500–508.
Nelson, P.M., (1987) Transportation noise reference book. Butterwoth & Co.(Publishers).
Nijland, H. A., Van Wee, G.P., (2005) Traffic Noise in Europe: A Comparison of Calculation Methods, Noise Indices and Noise Standards for Road and Railroad Traffic in Europe. Transport Reviews, Vol. 25, No. 5, pp. 591–612.
Nilsson, M.E., (2007) A-weighted sound pressure level as an indicator of short-term loudness or annoyance of road-traffic sound. J. Sound Vibrat. 302, pp.197-207.
O'Malley, V., King, E., Kenny, L., Dilworth, C.,( 2009) Assessing methodologies for calculating road traffic noise levels in Ireland - Converting CRTN indicators to the EU indicators (Lden, Lnight). Appl. Acoust., 70(2), pp. 284-296.
Ohrström, E., Skanberg, A., Svensson, H., Gidlof-Gunnarsson, A., (2006) Effects of road traffic noise and the benefit of access to quietness. J. Sound Vibrat., 295, pp. 40–59.
Ohrström, E., Björkman, M., Rylander, R., (1998) Noise annoyance with regard to neurophysiological sensitivity, subjective noise sensitivity and personality variables. Psychol. Med., 18, pp. 605–613.

Omiya, M., Kuno, K., Mishina, Y., Oishi, Y., Hayashi, A., (1997) Comparison of community noise ratings by L50 and LAeq. J. Sound Vibrat. 205(4), pp. 545-554.
Ouis, D., (2001) Annoyance from road traffic noise: a review. J. Environ. Psychol., 21, pp.101–120.
Paunović, K., Jakovljević, B., Belojević, G. (2009) Predictors of noise annoyance in noisy and quiet urban streets. Sci. Total Environ. 407, pp. 3707–3711.
Pirrera, S., De Valck, E., Cluydts, R., (2010) Nocturnal road traffic noise: A review on its assessment and consequences on sleep and health. Environ. Int., 36, pp. 492–498.
Pronello, C., Camusso, C., (2011) Travellers' profiles definition using statistical multivariate analysis of attitudinal variables. Journal of Transport Geography 19, pp. 1294–1308.
Pronello, C., (2010) The monetary evaluation of the transport noise social cost: the use of the continuous attribute-based SC method, Rivista Italiana di Acustica 34(3), pp. 27–34.
Pronello, C., (2009) Tools and models overview for analysis and evaluation of the transport-related environmental conditions in: Integrated assessment of environmental impact of traffic and transport infrastructure. ETS, Madrid. Spain, pp. 121-163.
Pronello, C., (2006) The holistic approach for low noise transport solutions, INTERNOISE 2006, 3-6 December 2006, Honolulu, Hawaii, USA.
Raichel, D.R., (2006) The science and applications of acoustics. Second ed. (Ed.) Springer.
Redmond, L., (2000) Identifying and Analyzing Travel-related Attitudinal, Personality and Lifestyle Clusters in the San Francisco Bay Area. Master Thesis, Institute of Transportation Studies, University of California, Davis.
Rice, C.G., (1975) Subjective assessment of transportation noise. J. Sound Vibrat., 43(2), pp. 407-417.
Rylander, R, Björkman, M., (2002) Road traffic noise annoyance and window orientation in dwellings. J. Sound Vibrat., 249, pp.828–831.
Sato, T., Yano, T., Bjorkman, M., Rylander, R., (1999) Road traffic noise annoyance in relation to average noise level, number of events and maximum noise level. J. Sound Vibrat., 223(5), pp. 775-784.
Schomer, P.D., (2002) On normalizing DNL to provide better correlation with response. Sound and Vibration, December 2002, pp. 14-23.
Schultz, T.J., (1972) Community noise ratings. Applied Acoustics Supplement n°1, Applied Science, (Ed.) Peter Lord, London.
SEC (2011a) 358 final, Commission staff working paper impact assessment. Accompanying document to the White Paper.
SEC (2011b) 391 final, Commission Staff Working Document. Accompanying document to the White Paper.
Swiss Federal Act 814.41, (2010) Ordinanza contro l'inquinamento fonico (OIF) 814.41, (1987) updated at 1st August2010. http://www.admin.ch/ch/i/rs/c814_41.html.
Vallet, M., (2008) Airport noise policies in Europe: The contribution of human sciences research. 9th ICBEN 2008, Foxwoods, CT.
Van Kamp, I., Soames Job, R.F., Hatfield, J., Haines, M., Stellato, R.K., Stansfeld, S.A., (2004) The role of noise sensitivity in the noise–response relation: a comparison of three international airport studies. J. Acoust. Soc. Am. 116, pp. 3471–3479.
Vastfjall, D., (2002) Influences of current mood and noise sensitivity on judgments of noise annoyance. J. Psychol., 136, pp. 357–370.
WHO, (1999) Guidelines for community noise. Edited by B. Berglund, T. Lindvall, D.H Schwela, WHO report, Geneva.
WHO, (2007) Night Noise Guidelines (NNGL) for Europe. Final implementation report.
WHO, (2011) Burden of disease from environmental noise - Quantification of healthy life years lost in Europe.
Yamauchi, K., Menzel, D., Fastl, H., Takada, M., Nagahata, K., Iwamiya, S., (2011) Cross-cultural study on feasible sound levels of possible warning sounds for quiet vehicles. Inter-noise 2011, Osaka, Japan 4-7 September.

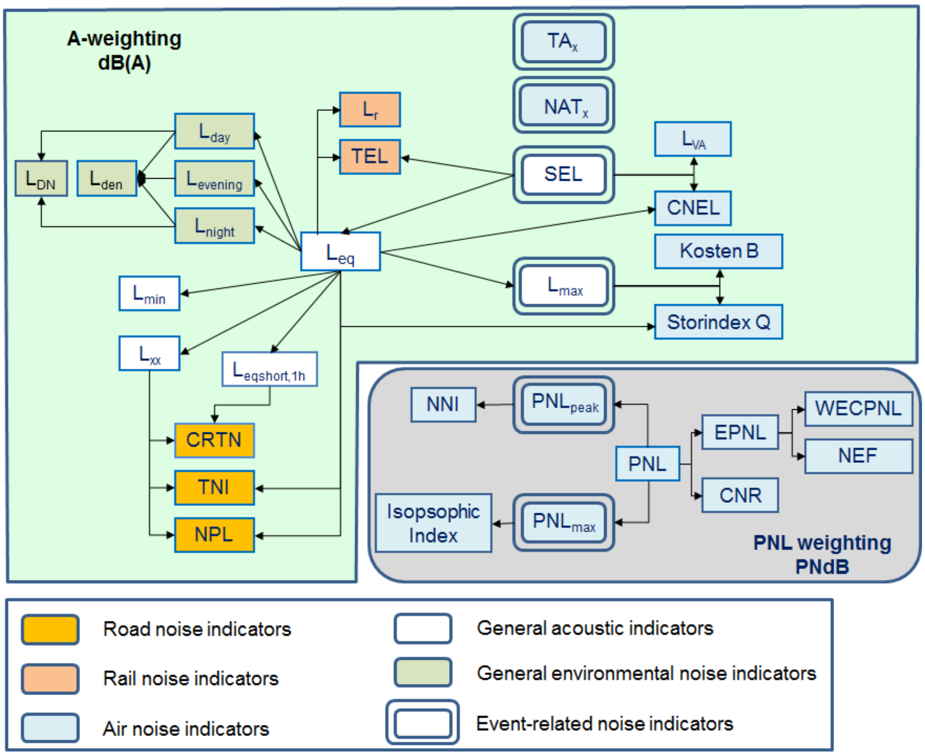


Figure 1 Relationships among the noise indicators

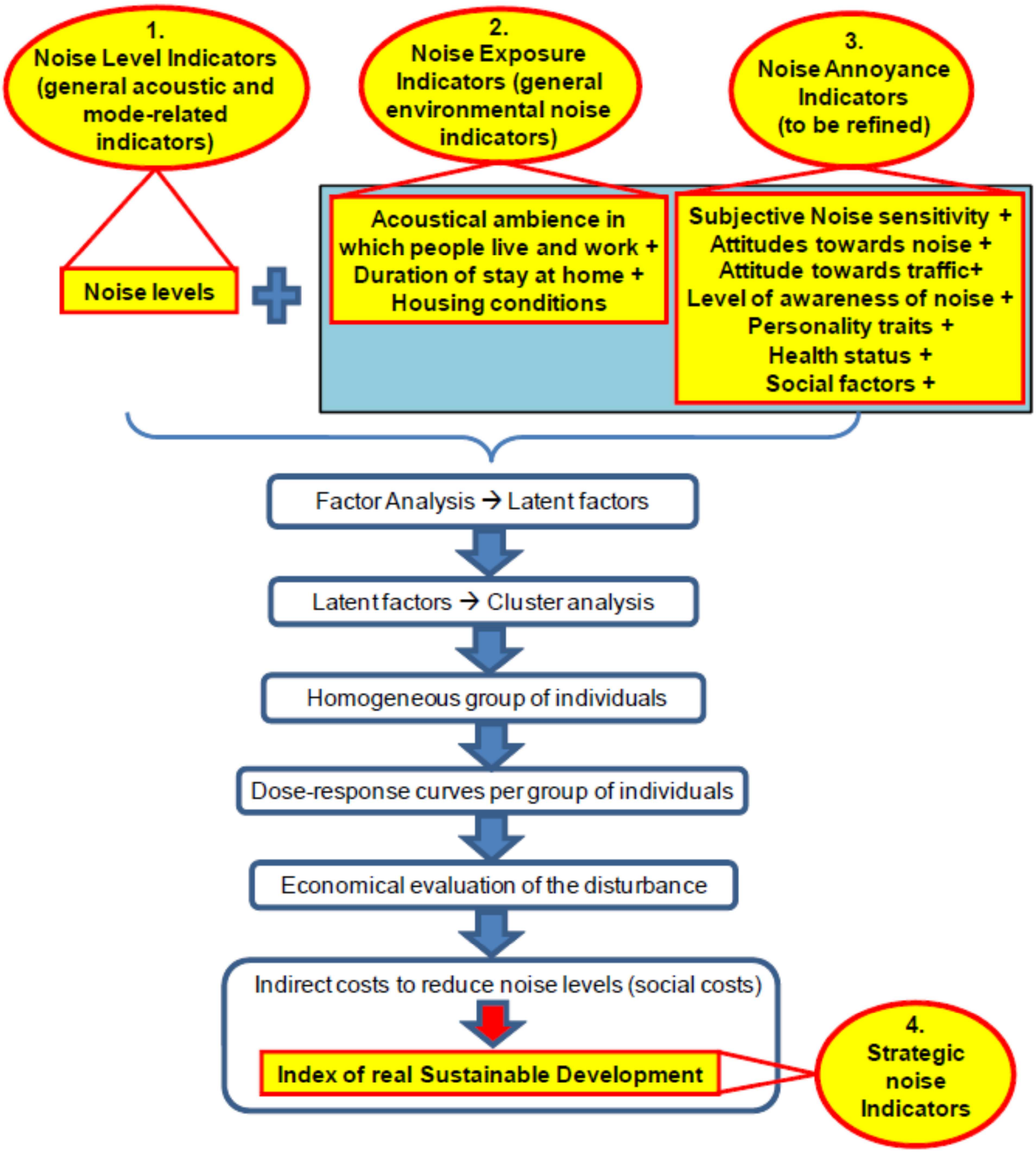


Figure 2 Classification of indicators and the process to individuate strategic noise indicators

Table 1 Synthesis of strengths and weaknesses and use of general acoustic and general environment noise indicators

| Indicator typology | Indicator name | Strengths | Weaknesses | Possible/typical use | Suggestions |
|---|---|---|---|---|---|
| General acoustic indicators | $L_{eq}$ | It is easy to calculate<br>It gives a synthetic evaluation of noise<br>It is suitable for automatic measures<br>It is correlated with long term effect of noise | It does not evaluate noise variations<br>It is influenced by the highest values of noise<br>It shows low correlation with annoyance | It is useful to generally describe the noise when an easy and synthetic noise event description is needed | $L_{eq}$ calculated during the night – $L_{night}$ – is a good indicator of annoyance, only in noisy areas<br>$L_{eqshort}$ can be used to track important noise variations |
| | $L_{max}$, $L_{min}$ | It is easy to calculate<br>It evaluates instantaneous effects | Difficult to assign to a specific source if the measurement is not assisted by an operator<br>It shows low correlation with annoyance | Suitable to analyses on well identifiable sources or to describe single noise events | $L_{max}$ can evaluate sleep disturbance, even if an average long term $L_{max}$ would be more appropriate |
| | $L_{xx}$ | They represent noise distribution<br>They give information on soundscape | It shows low correlation with annoyance | Suitable to describe background noise and evaluate noise increase due to noise source introduction | $L_{xx}$ can support in evaluating the acoustical climate and the background noise |
| | SEL | It is easy to calculate<br>It allows to calculate $L_{eq}$ summing single SELs<br>It allows to compare different noise events (two trains, buses, etc.) | In automatic measure it is difficult to select the event on which calculate the SEL<br>It shows low correlation with annoyance | Suitable to single events evaluation<br>Suitable to evaluation of noise emitted by vehicle fleets (public transport, trains, etc.) | SEL can evaluate sleep disturbance, even if an average long term SEL would be more appropriate<br>SEL can evaluate annoyance from low noise emissions by aircraft |
| General environmental noise indicators | $L_{DN}$ | It weighs differently the noise according to day and night period<br>There is a good correlation between noise level and annoyance of very disturbed people<br>It is quite easy to calculate, also in case of automatic measurements<br>It can be represented through maps | It is unable to describe annoyance for all the levels of disturbance<br>It does not take into account all the acoustical differences of the sources | It is used to evaluate the acoustical impact of all the infrastructures | It has been substituted by $L_{den}$ |
| | $L_{den}$ | It weighs differently the noise according to three periods: day, evening, and night<br>It allows the comparison among different infrastructures<br>It is easy to understand from general public<br>It can be represented through noise maps | It needs continuous monitoring for long periods (even one week)<br>It needs average yearly data to take into account the meteorological conditions<br>It is not suitable to describe the disturbance during the night-time | It is used to evaluate noise impact on the long term for all the infrastructures | It is the most popular indicator used for annoyance description and some recent dose-response curves are based on it. However, it is better to use it only for understanding the potential impact, not filtered by subjective people characteristics |
| | $L_{night}$ | It is easy to calculate<br>It allows a better representation of the impact in function of the perceived disturbance<br>It can be represented through noise maps | Some studies show that other information as the number of events and their noisiness could be used to describe night-time disturbance | It is used to evaluate night-time noise disturbance for all the infrastructures | It can be used to evaluate night annoyance in noisy areas jointly with event-related noise indicators (SEL and $L_{max}$) |

Table 2 Synthesis of strengths and weaknesses and use of road and rail noise indicators

| Indicator typology | Indicator name | Strengths | Weaknesses | Possible/typical use | Suggestions |
|---|---|---|---|---|---|
| Road traffic noise indicators | TNI | They take into account traffic fluctuations | It is suitable only to be exported to contexts similar to those where they have been developed<br>It is representative only when the traffic is flowing<br>It shows low correlation with annoyance | It is used for planning purposes to determine the distance between roads and dwellings | It can be used to describe the acoustical impact of road infrastructures when traffic is flowing |
| | NPL | | It is suitable only to be exported to contexts similar to those where they have been developed<br>Some parameters as σ are difficult to calculate<br>It shows low correlation with annoyance | They are used to describe the acoustical impact of road infrastructures | They can be used to describe the acoustical impact of road infrastructures, but they are too difficult to calculate |
| | CRTN | It is easy to calculate, based on specific $L_{eq}$ values | It is suitable only to be exported to contexts similar to those where they have been developed<br>It does not take into account night time noise<br>When traffic flow is low, the noise levels depend on individual passing vehicle<br>It shows low correlation with annoyance | | |
| Railway noise indicators | TEL | It is related to the single noise event, described by SEL and to $L_{eq,T}$ | It takes into account only the passing vehicles and not station operations<br>It doesn’t give any information on the global impact of the infrastructure<br>It shows low correlation with annoyance | It is used to describe the single passing of trains | It is useful to compare different trains noise |
| | $L_r$ | It takes into account both the passing vehicles and some specific station operations<br>It can be represented through maps | Some parameters used to calculate $L_r$ come from a qualitative approach, being the corrective terms difficult to define<br>It shows low correlation with annoyance | It is used in some countries where the laws provide a unique indicator for roads and railways | It is useful to give a global evaluation of emissions, but it needs a clear definition of the station activities as well as of the correction terms (in function of the perceived annoyance) |

Table 3 Synthesis of strengths and weaknesses and use of air noise indicators

| Indicator typology | Indicator name | Strengths | Weaknesses | Possible/typical use | Suggestions |
|---|---|---|---|---|---|
| Aircraft noise indicators | CNR | It takes into account the different people perception of the noise spectrum<br>It can be represented through maps | They are difficult to calculate, they need many data and parameters | They are specific for a global evaluation of the airport noise | They can be used to evaluate annoyance around airports, but the risk is the reliability of the results, as they were calibrated mainly using data coming from several US surveys |
| | PNL | It takes into account the different aircraft typologies<br>It can be represented through maps | | | |
| | EPNL | Similar to PNL, it takes into account also the duration of the different noise events<br>It can be represented through maps | | | |
| | NNI | Based on PNL, it has a simpler structure<br>It can be represented through maps | It does not take into account the night-time noise<br>It only considers the very noisy events<br>It is not suitable to annoyance description | | They can be used to represent the emissions in relation to the airport service, depending on the number of flights.<br>However, NNI cannot be used for the evaluation of the global impact because it does not take into account the night-time noise |
| | NEF/ANEF | Based on EPNL, it takes into account the aircraft typologies and different paths<br>It differently weigh the night time noise<br>It can be represented through maps | It is difficult to calculate | | |
| | CNEL | More simple than EPNL<br>It takes into account the duration and number of events and the people perception of different frequencies<br>It can be represented through maps | It considers only two periods: day and night | | It can be used also for the noise evaluation of other infrastructures, different from airports<br>It is similar to $L_{VA}$ or to $L_{den}$ |
| | WECPNL | Based on EPNL, it takes into account the noise impact in different day periods<br>It can be represented through maps | It is difficult to calculate, it needs many data and parameters | | It is accurate in describing all noise characteristics of the infrastructures, but it is very difficult to calculate and it is not practical for decision makers.<br>It shows analogies with the simpler $L_{den}$. |

Table 4. Classification of noise indicators

| Indicators | Noise level indicator | Noise exposure indicator | Noise annoyance indicator | DPSIR |
|---|---|---|---|---|
| Leq,h | x | | | P/S* |
| $L_{max}$ | x | | | P/S* |
| $L_{min}$ | x | | | P/S* |
| $L_{xx}$ | x | | | P/S* |
| SEL | x | | | P/S* |
| TNI | x | | | P/S* |
| NPL | x | | | P/S* |
| CRTN | x | | | P/S* |
| TEL | x | | | P/S* |
| PNL | x | | x | P/S* |
| EPNL | x | | x | P/S* |
| NNI | x | | x | P/S* |
| NEF | x | | x | P/S* |
| WECPNL | x | | x | P/S* |
| $L_{VA}$ | x | | | P/S* |
| $L_{DN}$ | x | | x | P/S* |
| $L_{den}$ | x | | x | P/S* |
| $L_{night}$ | x | | x | P/S* |
| $km^2$ of the territory with $L_{den}>L_{den,limit}$ | | x | | S |
| km of the infrastructure with $L_{den}>L_{den,limit}$ | | x | | S |
| $km^2$ of the territory with $L_{night}>L_{night,limit}$ | | x | | S |
| km of the infrastructure with $L_{night}>L_{night,limit}$ | | x | | S |
| % of people exposed to $55<L_{den}<65$ dB(A) | | x | | S |
| % of people exposed to $65<L_{den}<75$ dB(A) | | x | | S |
| % of people exposed to $L_{den}>75$ dB(A) | | x | | S |
| Population having access to quiet areas (within 500 m of residence) | | x | | S |

*the indicator represents a Pressure (P) if measured as "emission" value near the source; a State (S) if measured as "immission" value close to the receptor. (Folkeson et al., 2010, p. 167).