Technical Council

Technical Document AESTD1007.1.20-05

Understanding and managing sound exposure and noise pollution at outdoor events

May 2020

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Technical Document

Understanding And Managing Sound Exposure And Noise Pollution At Outdoor Events

2020-05-22

Prepared by the Working Group on Sound Exposure and Noise Pollution due to Outdoor Entertainment Events

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1. Overview

Sound exposure and noise pollution due to outdoor entertainment events carry implications spanning public and private life. This isn't a new issue. The AES library contains papers published over 50 years ago discussing these issues, although judging by the continued discussion and debate, it's clear that the industry has yet to produce a universally-accepted solution (or even a robust understanding) of the relevant problems.

In the UK alone, live music contributed to around £1 billion in gross added value to the economy and employed over 28,000 people in 2017. Furthermore, 29 million people enjoyed live music in the UK that year. This occurred in parallel with a decline in the recording industry brought about by the digital age of free streaming and downloads. Artists now tour as their primary source of income rather than touring to advertise an album. This has resulted in a greater demand for tours and festivals which has in turn significantly increased the number of events and the adoption of new venues – all of which increase the potential risk of audience sound exposure and environmental noise disturbance.

There has been a significant amount of recent work, largely carried out by the World Health Organization (WHO), to develop a comprehensive set of objectively-derived community noise regulations [1]. These guidelines present advice for understanding, monitoring and controlling noise from roads, rail, air travel and wind turbines. The section dedicated to leisure noise (which outdoor entertainment events fall under) highlights the lack of unbiased objective research carried out, resulting in no new guidelines presented. The 2018 guidelines instruct readers to continue to use the 1999 guidelines for community noise [2] as well as the 2009 night noise guidance [3]. It is disappointing, to say the least, that this is the present level of understanding of leisure noise, considering the problem has been discussed for at least half a century.

A recent working group called Live DMA (a European network of live music associations including venues, clubs and festivals) set out guidance for the drafting of a good urban policy in relation to live music in mid-2019 [4]. The overarching message in this guidance is that "music is not noise," and therefore should not be treated as such in regard to regulations for both audience sound exposure and community noise (where they imply that minimal or light-touch regulation is appropriate). There is certainly truth in treating music as separate to noise, but it should be stressed that one person's music is likely to be another person's noise. Diminishing attention to audience safety and community well-being on account of a supposed greater social value of live music is a counterproductive and dangerous stance to take.

The stance set out in Live DMA's white paper demonstrate the danger of not consulting a wide range of audio engineering and electroacoustic professionals with experience in the live event industry when developing such guidelines. The majority of such professionals (who this AES working group consists entirely of) strongly support properly designed and implemented regulations.

The key message that is presented throughout this report is that the problems/ambiguities with current regulations are due to a lack of unbiased, scientifically-based research, which is in line with the WHO's findings [1]. As will be shown in this report, it is possible to deliver acceptably high sound levels to audience members in a safe manner (minimizing risk of hearing damage) while also minimizing annoyance in local communities. It is the view of this working group that solutions to the on-site and off-site problems should begin with a well-informed sound system design. Only with a properly designed sound system can sound/noise regulations be realistically applied. This working group aims to cooperate with regulating bodies and live music associations to ensure the delivery of high-quality and enjoyable live entertainment while keeping audiences safe and minimizing annoyance in the local communities.

This report is intended to present the current state of affairs surrounding the issue of outdoor event-related sound and noise. The two principal areas of investigation are sound exposure on-site and noise pollution off-site. These issues are different in nature and require distinct approaches to mitigate the associated negative short-term and long-term effects.

In this report, a distinction is made between on-site sound and off-site noise. On-site, the audience and performers (and to an extent the staff) are actively engaged listening to the event, hence on event grounds the issue is referred to as *sound exposure*. Off-site, members of the local community aren't actively engaged in listening to the event, therefore outside the event grounds the issue is referred to as *noise pollution*. This convention is sustained throughout the report.

The report begins in Section 2 by focusing on audience experience, specifically on expectations (in terms of sound quality/delivery) and issues related to sound exposure (with a focus on hearing damage, but also covering cardiovascular, neurological and psychological disorders).

Section 3 gives an abbreviated overview of system design procedures for high-quality audience experiences with minimal health risks (with an extended discussion on the appropriateness of using ground-based subwoofer systems at large-scale events, due to the unsafe sound pressure levels experienced by members of the audience and event staff closest to the stage).

Having covered the audience experience, Section 4 moves on to community noise pollution where environmental noise regulations across the globe are summarized, covering international, national and local noise laws. The takeaway from this section is that there is little consensus on what level of noise is appropriate in residential areas. There are few examples of regulations that specifically consider information-carrying noise (i.e. music and speech) and even fewer regulations that aren't based on A-weighting. The use of A-weighting largely ignores low-frequency noise even though this is typically the principal noise issue stemming from live events.

Since noise levels received within a community from an outdoor event are generally short-lived and low in level, direct physical health issues aren't necessarily a problem. The issue is annoyance caused by pulsing/beating low-frequency noise (and occasional broadband signals, due to specific atmospheric situations) which could lead to certain mental health issues. The focus of entertainment-related noise should be on limiting annoyance; something that is addressed in few existing regulations (although there are some good examples where the issue is addressed in a reasonably robust manner), especially in terms of information-carrying noise.

Section 5 builds upon the findings in Section 4, where a brief overview of noise measurement/monitoring regulations is given, followed by a summary of noise monitoring, management and prediction practices. This section also includes insight into how to work with local noise regulations and instances where following such regulations is unlikely to solve the problem. This is followed by examining both standard and state of the art noise monitoring practices (ranging from sound level meter-based approaches to more "intelligent" software-based methods) to highlight how primary noise sources can be identified for straightforward noise control. The section also discusses what's known about quantifying annoyance due to information-carrying noise in order to better understand how such noise pollution may be addressed. A selection of case studies is presented for illustrative purposes.

Finally, Section 6 details methods for noise pollution suppression. This section includes good practice for venue configuration to limit noise spill and information on recent advancements in so-called *secondary* sound systems, which are deployed on an event's perimeter in an attempt to cancel low-frequency content from permeating off-site. A discussion on maintaining a high-quality audience experience while simultaneously controlling off-site noise pollution is presented to complete the section.

The report is concluded in Section 7, not with a set of recommendations for control of sound exposure and noise pollution from outdoor entertainment events, but with a set of questions to be answered before a definitive set of recommendations or guidelines can be produced. These questions will inform the remaining work of this group, but more importantly should focus the wider audio engineering and acoustics community on what work is necessary to resolve the current ambiguities in these areas.

In particular, a suggestion to form an event noise initiative, provisionally termed the Healthy Ears, Limited Annoyance (HELA) Initiative, is detailed at the end of Section 7. This is drawn out of necessity, as it is improbable that this (or any) work in this area will result in sound exposure and noise pollution regulations changing on an international scale (at least in the near future). An initiative which allows relevant parties (event promoters, production teams, musicians, venues, etc.) to join would allow wide-scale adoption of best practice while still adhering to local and national regulations. Such an initiative would give events the ability to clearly indicate to the audience and local community that they are committed to providing a safe, sustainable and unobtrusive event. This approach would allow work derived from this report to progress in a more efficient and effective manner as compared to pursuing a regulatory route (although this remains a longer-term goal).

Though commercial products are referenced at various places throughout this report their inclusion should not be interpreted as an endorsement or recommendation.

2. Audience experience

The public has enjoyed attending live events for many centuries, although it hasn't been until relatively recently (the past century or so) that these events have included electronically-amplified sound (as opposed to naturally-amplified sound). With the ever-increasing capabilities of sound reinforcement systems in terms of power, efficiency and bandwidth, audiences have been subjected to increasingly greater sound pressure levels (over wider bandwidths), which consequently pose a risk to the health and safety of event attendees.

This section focuses on issues related to delivering a high-quality audience experience while simultaneously preventing audience exposure to harmful sound pressure levels over long durations. The discussion begins with an analysis of typical audience expectations in terms of audio quality followed by how this relates to recreational sound exposure. The section is concluded with a survey of regulations pertaining to current audience sound exposure limits and measurement protocols.

2.1. Perception and expectations

Audiences typically pay to attend live events for entertainment and enjoyment. A central focus of sound engineers and system designers is therefore to deliver a high-quality and enjoyable listening experience to the audience. It follows, then, that a clear definition is necessary regarding what an audience classifies as a high-quality listening experience.

There have been a handful of studies investigating this issue, conducted predominantly over the past twenty years [5-14]. Many of these studies investigate aspects related to amplified sound's frequency response, time response, overall level and "punchy-ness". Much of this work has found that, as expected, the listening experience is far from objective and in some cases the sound is used more for facilitation of social interactions than for an enjoyable listening experience.

There currently exists no agreed standard for high-quality sound. A study conducted in 2013 investigated eight different indoor live event venues in an attempt to determine key indicators for high-quality sound using a combination of measurements and audience surveys [6]. In each venue at least nine measurements were taken from within the audience area, with results showing that there was typically a variation in mean SPL of ±5 dB across an audience area. In most cases there was a strong boost in low-frequencies below 100 Hz, which is typical of modern-day popular music sound reinforcement, both indoor and outdoor. The measured systems generally exhibited roll-offs below 40 Hz and above 12.5 kHz. This is assumed to be the typical spectrum of popular music throughout this report.

The key finding in the 2013 study [6] was that audience perception of sound quality was strongly influenced by Early Decay Times (EDT) at low-frequencies. The best performing venues showed low-frequency EDTs of around half a second while the poorly-rated venues had low-frequency EDTs above one second. The researchers noted, though, that it's difficult to make reliable comparisons between venues due to the varying topology and musical content. A separate study found that 75% of the overall impression of concert sound is related to bass clarity and that venues should be as dry as possible in the low-frequency region, especially around the 63 Hz octave band [7, 11]. It is important to note that the studies in [6], [7] and [11] were conducted in internal venues where reverberant properties are key – this is not the case outdoors, therefore further investigations are required ensure both indoor and outdoor scenarios are considered.

The central perceptual attribute could be a reinforced sound's "punchy-ness", which has recently been studied in [12], where a metric is proposed for quantification. In this study, low-frequency content was found to heavily influence the perceived "punchy-ness" of a sound system. Further work is needed to confirm how significant this perceptual attribute is in relation to the previously described bass clarity and low early decay times (in indoor venues). It is likely that these attributes are strongly correlated.

Drawing upon the findings in [6] and the widespread practice of large low-frequency boosts in recorded popular music and sound reinforcement [13, 15], it is important to understand the motivation for strong low-frequency, especially in terms of the psychoacoustical and physiological effects the enhanced low-frequency has on audience members.

A study conducted in 2008 looked into the importance of bass clarity in popular music venues [7]. An interesting note within this study's introduction is that strong low-frequencies are known to stimulate the part of the brain that controls basic instincts such as sexual desire and hunger. This is supported by an extensive study from 2017 in which a general investigation was carried out (in nightclubs) to try to understand why people like loud sound [8]. This work identified (through a survey of audience members) four themes explaining why people like loud music:

1. High sound levels induce feelings of arousal and excitement

2. High sound levels mask unwanted external sound and/or thoughts (allowing audience members to tune-out of their lives for a short period of time)

3. High sound levels facilitated increased social interaction (requiring closer proximity to people to have a conversation as well as increased confidentiality – it being difficult to overhear a conversation in such an environment)

4. High sounds levels emphasized and enhanced audience members' personal identity

The above list has less to do with sound quality and more to do with masking effects and brain stimulation as a result of experiencing sound at very high levels. The study in [8], however, focuses on sound reproduction in nightclubs, not large-scale outdoor live events, which tend to be different in terms of level, dynamic range and bandwidth, not to mention audience attention. Further work is needed to determine if the same findings hold true for large outdoor events.

Recent research suggests a link between the saccule, part of the vestibular system in the inner ear (primarily responsible for maintaining balance), and the enjoyability/preference for loud music [14, 16, 17]. The research shows that the saccule is most sensitive between 200 – 400 Hz and can be strongly excited in environments above 90 dBA. The acoustically-evoked saccular response will then provide a similar sensation of going on a roller coaster (or similar), making the experience as "sound as force," rather than the classical "sound as text" [18], due to the vestibular, not cochlear, origin of the response. Clearly, the experience at popular music live events isn't solely auditory – all senses should be considered when addressing audience expectations.

In terms of playback level, the measurements from [7] highlight a trend in data from many studies: that sound level steadily increases as the event progresses. One reason for this is that the headline act of the event usually requires their set to be louder than any support act set (although this requirement is rarely written or spoken – it's more commonly an unspoken understanding), but there exist further factors that cause this behavior.

First, as an event progresses the audience and sound engineer's hearing will experience a Temporary Threshold Shift (TTS) resulting in lower sensitivity to sound. To maintain the same perceived sound level over the course of the event, the objective sound reinforcement level must be boosted as compensation for TTS. Additionally, there has been research carried out regarding alcohol consumption's effect on sound level [9]. This work showed a direct relationship between the amount of alcohol consumed and preferred sound level. What's interesting is that the relationship works in both directions: drinking more results in the desire for louder sound as well as louder sound results in audience members drinking more.

This is closely related to research carried out on the topic of background music in restaurants (faster paced and louder music results in patrons eating quicker) [19, 20]. The effect of alcohol on preferred sound level (and the reverse) was found to have the strongest effect on males and in rural areas. What wasn't explored in this study was any relationship between this behavior and musical genre preference. Again, it must be noted that this study took place in nightclubs, rather than at large-scale live music events, so further work is necessary to determine if the findings translate to large outdoor events (especially considering that at high-profile events it's becoming increasingly rare to find sound engineers drinking excessively).

Returning to the point of sound level creep over the duration of an event, most prior studies have collected data from indoor music venues. At large outdoor events, sound level monitoring is commonly used at the mix engineer's position. Sound level restrictions are typically in place and often vary between support acts and headliners. These restrictions serve to keep any natural level creep (due to TTS, alcohol consumption or any other factor) in check. This was shown clearly in a case study from a large American music festival [21], where there was no significant statistical link between set time during the day and overall mix level. A detailed analysis of sound level monitoring and management at live events will be presented in Section 5 of this report.

Ultimately, modern day audiences expect sound to be delivered to them with minimal effort on their own part and can be described as sonic "couch potatoes" [10]. Therefore, the expectation is for strong, high quality sound delivered to every seat in the house. This includes (but is not limited to) excellent intelligibility, clarity, broadband magnitude response (not necessarily flat) and wide dynamic range [13]. Additionally, most audiences at modern pop music concerts have come to expect a strong tactile response, primarily delivered with large and powerful subwoofer systems [22]. Whether this is something that audiences actually prefer or have simply become accustomed (or addicted) to is open to debate [14].

The high expectations of modern audiences were illuminated by the recent Spice Girls reunion tour, where audience members complained of poor intelligibility during the first number of concerts [23]. The poor intelligibility was likely related to the very high audience noise (i.e. screaming and singing along) in addition to lighting and video taking precedence over audio, restricting speaker placement, the movements of the performers (often in front of the sound system) and the often poor acoustics of large sports stadiums. Based on the audience reaction, the label of sonic "couch potato" seems appropriate. It should be noted, though, that the issues from the Spice Girls' tour was potentially blown out of proportion as the number of complaints were relatively few, compared to the total number of audience members.

The vast majority of audience expectations can be achieved with modern day sound reinforcement technology (although there certainly isn't a one-size-fits all solution and the sound will never please everyone in attendance due to its highly subjective nature). This isn't a problem, although it's still a challenge for system designers. What's problematic are the health and safety (and noise pollution) implications that come along with the above-mentioned audience expectations. Common-sense measures should be taken to protect everyone on- and off-site and there's little reason why this can't be achieved with minimal impact on the audience (and performer) experience. The underlying health and safety issues are the focus of the remainder of this section.

2.2. Recreational sound exposure

Members of the public attend events of the type concentrated on in this report for entertainment purposes. Currently, only a minority of attendees will be conscious of the risks they are exposing themselves to and an even smaller minority will take preventative measures to protect themselves.

This was made clear in a survey conducted in 2002, where over 600 attendees of a festival in Switzerland were surveyed to gather data on their use of hearing protection at such events [24]. It was found that 5% of the surveyed attendees always wore ear plugs during the show and a further 34% wore ear plugs occasionally. The remaining 61% of the surveyed attendees took no protective measures against hearing damage due to sound exposure. Of those surveyed, 36% reported issues with tinnitus due to their attendance at the festival. It should be noted that sound exposure was strictly monitored at this particular festival, so all sound pressure levels were within legal limits – the mean exposure of 10 volunteers who wore noise dosimeters was 95 dBA with only 8% of the total festival duration exceeding 100 dBA.

These findings were supported by a thorough summary of previous research into music-related noise exposure and hearing disorders in 2009 [25]. In this review, issues related to music-based noise exposure were discussed in regard to musicians, venue staff and attendees. The general findings for all three categories of individuals were a high incidence of tinnitus (mostly temporary for the attendees, but permanent for many of the musicians and members of staff) and a worryingly sparse use of hearing protection. In a specific study covered in this work, 29 concert attendees were given noise dosimeters, with results showing a mean sound intensity of 99.8 dBA with a peak of 125.6 dBA [26]. Again, the majority of the concert adhered to the generally accepted mean audience level limit of 100 dBA, but there is clear evidence of potentially damaging exposure in terms of peak levels.

2.2.1. Measuring hearing damage

A study conducted in 2015 at a festival in Amsterdam monitored Temporary Threshold Shifts (TTS) of 86 volunteers after attending a festival with a duration of 4.5 hours [27]. Half of the group was given ear plugs while the other half of the group received no hearing protection. The TTS tests indicated that 8% of the group with hearing protection experienced a noticeable TTS, while 42% of the group without any hearing protection experienced TTS. A separate study found that 80% of surveyed festival goers have experienced TTS and/or tinnitus [68].

It should be noted that separate research findings indicate that TTS is an unreliable measure for such scenarios and point to Octoacoustic Emissions (OAE) as a more reliable measure of the effects of sound exposure to audience members [29, 30]. Furthermore, research has demonstrated that TTS (as well as Permanent Threshold Shift – PTS) is not a reliable indicator of hearing damage on the whole [31-33]. What TTS/PTS do not directly relate to is Sensorineural Hearing Loss (SNHL – also known as hidden hearing loss). TTS/PTS can be measured with audiometric thresholds, but these tests do not always reflect reported hearing difficulties [14, 32, 34]. Most commonly, difficulty hearing in noisy environments is reported, even when audiometric tests reveal no problems [31].

Recent research gives indication (although not inarguable proof) that the tectorial membrane in the cochlea plays an important role in returning hearing to normal after noise exposure [33]. It is thought that this membrane is used as storage for calcium ions that contribute to the regulating function of sensory cells (which are responsible for relaying auditory information from the inner ear through the auditory nerve to the brain) [33]. Upon exposure to high levels of noise, the calcium ions store is drained, causing the sensory cells to cease their function. Normal hearing resumes after the calcium ion supply is restored. This is thought to relate to temporary and permanent SNHL.

While PTS is a strong indicator of damage to the outer hair cells in the inner ear, it does not give any meaningful indication of damage to Inner Hair Cells (IHC, which are connected to the sensory neurons) until the neural loss is in the region of 80 – 90% [32]. Studies on lab animals indicate that the most vulnerable parts of the inner ear are these synaptic connections between the IHCs and the sensory neurons. An improved understanding of this mechanism is essential, as the health implications for humans could be profound. Although early experimental results conflict in places, there is some indication that such damage may be reversible through various means, which is encouraging [32].

In terms of sound exposure at large live events, further research is required to determine what level/duration of exposure will result in SNHL. Past lab-based experiments on animals have been conducted at extremely high sound pressure levels and durations, which is not representative of real-world live events. The need for specific research for such recreational sound exposure is already noted in the reviewed work [31, 32].

Returning to audience sound exposure, the overall trend observed is that (at least in Europe) sound system operators are adhering to local/national audience exposure guidelines (discussed in Section 2.3). The problem is that event attendees seem to be either unaware of the sound exposure risks or are ambivalent towards the risk. A driving issue in this area is the problem that sound exposure (especially in the low-frequency band) has a cumulative effect [35] and hearing damage tends to not reveal itself until the event has concluded (where permanent damage can take many years to be revealed) [8]. Looking at the situation from a young person's perspective, the immediate social/emotional rewards from attending a loud concert will outweigh any consideration towards the long-term costs of the sound exposure [14].

2.2.2. Low-frequency sound exposure

While the effects of long term and/or high intensity sound exposure in the high frequency range (above approximately 200 Hz) is relatively well-known and covered in regulations pertaining to occupational noise exposure, audience sound exposure and community noise pollution, there is significantly less knowledge (and consensus) on the effects of such exposure in the low-frequency band (especially in the infrasound region, below 20 Hz). There have been a handful of studies on the effects of low-frequency sound exposure over the past few decades, with varying degrees of agreement between published work [35-39].

Early research into the area of low-frequency noise exposure (primarily infrasound) was carried out by NASA when developing their launch vehicles as part of the Apollo program [36]. In general, their findings were that there was no serious health risk to noise exposure of this kind, although this was in terms of highly-trained and monitored astronauts, which isn't necessarily representative of the general public, who are unlikely to actively monitor their noise exposure and/or take preventative measures.

At the time of writing this report, a large American technology firm introduced a noise monitoring app for their devices which "helps users understand the sound levels in environments such as concerts and sporting events that could negatively impact hearing" [40] using WHO noise exposure guidelines [1]. This is certainly a step in the right direction, although it's unclear whether microphones within such smart devices can handle the sound pressure levels typically encountered at live events (especially in regard to low frequencies).

Beyond the early studies into low-frequency noise exposure, there seems to be little knowledge of high-intensity low-frequency sound exposure on the order experienced at typical entertainment events. Most reviewed studies in this report focus on exposure only up to 100 dB [36]. Some of the earlier studies tested well beyond this level (in some cases approaching 170 dB peak [39]), but it's unlikely that such studies will be feasible/ethical nowadays due to health and safety considerations of test subjects. The lack of data is problematic, since audiences are exposed to significantly higher levels of low-frequency sound at events (often exceeding 130 dBC peak [21]). This is addressed in the UK's Purple Guide to Health, Safety and Welfare at Music and Other Events [68] and will be discussed in detail in the proceeding section.

In the research that is available on the effects of low-frequency sound exposure, there are some key points to keep in mind. As will be mentioned throughout this report, the vast majority of regulations and measurement methods for noise utilize the A-weighting curve. This weighting is an approximation of the 40-phon equal loudness contour, which isn't representative of levels experienced by audiences at entertainment events [36]. Furthermore, the reality of the A-weighing curve is that it doesn't actually approximate the 40-phon equal loudness contour and was instead designed to fit within the limitations of analog electronics of the day.

In recent years, there have been updates to some regulations to include peak level limitations using C-weighting, but these currently are the exception not the rule. Peak equivalent C-weighted sound pressure level ($L_{Ceq,peak}$) has been part of European law since 2003 with 10/EC/2003 [41] which handles occupational noise exposure. This has subsequently influenced various event noise regulations across Europe (highlighted in Section 4) and certain pieces of monitoring software (highlighted in Section 5).

It has been proposed in previous work that the difference between dBC and dBA or dBZ and dBA be used as a simple indicator of a potential noise exposure (or off-site annoyance) issue at low-frequencies. If either of these differences is beyond 20 dB, then the low-frequency region must be examined in more detail to avoid an unmeasured risk to audiences (and workers). If the primary issues are identified to exist in the infrasonic region, then ISO 7196 (1995) [42] describes the G-weighting curve which is centered in this frequency range. It has been cautioned, though, that G-weighting can't be used in isolation, as it underemphasizes content between 30 – 80 Hz, which is often significant in modern music [36].

The physiological and psychological effects of exposure to low-frequency noise are interesting and conflicting between certain studies. A comprehensive review is presented in [36], indicating that certain exposure will cause heightened alertness, while a different variety of exposure will cause drowsiness and decreased cognitive function. Certain studies on lab animals have given proof of clear neurological impairments after significant exposure to infrasound over long durations [35, 39]. Recovery times are on the order of days for sound exposure similar to that of a typical multiple day music festival, which should lead to some concern about sound engineers and musicians who are exposed to such levels on a nearly daily basis [36]. As infrasound is becoming increasingly common at live events [43], this is a problem that must be better understood in the context of this industry to ensure risks to permanent hearing damage aren't being inflicted on both audiences and working personnel. It must be noted that considering the intensity and duration of low-frequency sound exposure to audience members at large events, standard ear protection is ineffective at low frequencies. This will be discussed in Section 3.2.1 in relation to ground-based subwoofer systems.

In addition to audience exposure, considerations must be made in regard to infrasound propagation. In this spectral region, propagation will be both through the air and through the ground and nearby structures, which has been well documented in the specific context of live events [44-46]. This will be discussed in Section 4 in relation to noise regulations and Section 5 in regard to noise prediction, measurement and monitoring.

2.2.3. Noise vs. music induced hearing loss

Lastly on the subject of recreational sound exposure, a handful of researchers have questioned whether noise exposure is the appropriate focus [14, 47-51]. Most regulations and recommendations give guidelines focused on the prevention/limitation of Noise Induced Hearing Loss (NIHL). This is in line with the vast majority of studies on noise exposure, as lab-based tests use broadband noise and/or pure tones to evaluate the effects of noise exposure. For many years, though, a small group of researchers has emphasized the point that the characteristics of noise and music are very different, especially in terms of temporal properties.

A study published in 1994 examined listeners who were exposed to 96 dBA of pink noise followed by 96 dBA of music [47]. The pink noise was rated as unpleasant by listeners, while the music (at the same measured level) was judged to be too quiet for a rock concert. This led to the question of whether music exposure is as damaging as noise exposure. Unfortunately, no further noteworthy work has been done in this area since this publication and the published results leave more questions than answers (and the method of the experiment itself is questionable).

A review of previous literature in the 1994 study gave some indication that music is not as damaging as noise. In one study where participants were exposed to one hour of noise or music, the measured TTS of the participants exposed to music was 9 dB less than those exposed to noise. Another study showed that risk of TTS from music exposure was less than noise exposure from factory work by a factor of between 4 and 5. The question was raised of whether pleasurable sounds are less physically damaging than unpleasant sounds. This, of course, has yet to be proven either way and is a contested point due to the lack of scientific evidence supporting it. As noted above, the fact that TTS isn't related to SNHL also leads to the assertion here to be called into question, pointing towards necessary further research into this area.

More recent work looking into NIHL vs. Music Induced Hearing Loss (MIHL) indicate that perhaps a separate set of regulations/recommendations is required based on MIHL for entertainment events due to the known differences between signal characteristics and physiological/psychological effects [48, 49]. Much of the existing regulations (detailed in Section 2.3) are based on industrial noise exposure [29], which isn't necessarily appropriate to apply to leisure-sound exposure, especially if such exposure occurs infrequently. This is supported findings from an experiment comparing TTS and recovery after energy-equivalent exposure to industrial noise and classical music [52]. The classical music resulted in significantly lower TTS than the equivalent energy noise. Of course, classical music is extremely different from popular music, but the findings at least point to further research required: "…the conventional approach of rating sound exposures exclusively by the principle of energy equivalence can lead to gravely misleading assessments of their actual physiological costs" [52]. A later study [53], however, did investigate the difference in TTS between classical and popular music exposure and found a significant difference (as expected).

Again, more scientific and unbiased research is needed in this area. Based on published research, the nature of hearing damage due to music is likely to be different to that of noise, indicating that a focus is required on MIHL for this work rather than NIHL (although this is not to say all work on NIHL is irrelevant to this study – it should be considered, but with the understanding that findings may differ when replacing noise with music). The effect of high levels of harmonic distortion in the reproduced sound should also be considered, as this will likely result in great hearing damage. This is particularly an issue for smaller indoor venues (where sound system are more likely to be overloaded, introducing distortion), but still must be kept in mind for larger outdoor applications.

Overall, audience members (especially those closest to the stage) are potentially exposed to dangerous amount of sound energy, where low-frequency exposure is particularly problematic and not addressable using conventional hearing protection. The next section will focus on existing regulations in this area, with analysis provided pointing to further research and development that is necessary to ensure live events are safe places for members of the public to enjoy listening to music, without any danger of developing lasting and life-altering hearing damage.

2.3. Level and measurement regulations

Audience level regulations, recommendations or guidelines are few and far between across the world, with significant variation in practice. Table 2.1 contains current audience sound exposure regulations across Europe [49], which is the furthest progressed in this area as compared to the rest of the world.

Location	Limit 1 (dB)	Weighting	Integration time	Limit 2 (dB)	Weighting	Integration time	Ref.
Austria	100	A	1 min				[55]
Belgium (Brussels)	100	A	60 min	115	C	60 min	[56-58]
Belgium (Flemish region)	100	A	60 min	102	A	15 min	[59]
France	102	A	15 min	118	C	15 min	[60]
France (children < 6 y.o.)	94	A	15 min	104	C	15 min	[60]
Germany	99	A	30 min	135	C	35 ms (peak)	[61,62]
Netherlands	103	A	15 min	140	C	35 ms (peak)	[63]
Netherlands (children < 13 y.o.)	91	A	15 min				[63]
Netherlands (children 14-15 y.o.)	96	A	15 min				[63]
Netherlands (children 16-17 y.o.)	100	A	15 min				[63]
Norway	99	A	30 min	130	C	35 ms (peak)	[55]
Sweden	100	A	event duration	115	A	125 ms (fast)	[55]
Sweden (children < 13 y.o.)	97	A	event duration	110	A	125 ms (fast)	[55]
Switzerland	100	A	60 min	125	A	125 ms (fast)	[64,65]
Switzerland (children < 16 y.o.)	93	A	60 min				[66,67]
United Kingdom	107	A	event duration	140	C	35 ms (peak)	[68]
WHO	100	A	240 min (4 times/year)				[69]

Table 2.1 Audience sound exposure limits in European countries [49]

There is no consensus or standard practice concerning audience level regulations, although Table 2.1 indicates that there is some generally shared practice across a number of European countries. All published regulations give primary limits using A-weighting, which fails to address the typical spectral balance of a modern pop music event and, more importantly, isn't representative of the characteristics of the human hearing system at such levels (C-weighting provides a more accurate measure of perceived loudness, but even this isn't representative of the standardized equal loudness curves detailed in BS ISO 226:2003 [54]).

The conjecture that A-weighting is unsuitable for on-site measurements is supported by a significant amount of previous research [24, 30, 55, 70], particularly pointing to the fact that audiences at pop music events are exposed to high sound pressure levels, causing A-weighting measurements to grossly underestimate exposure [21]. Furthermore, as discussed above, modern day live music is rich in low-frequency content, where A-weighting significantly underestimates the low-frequency contribution to sound exposure. This is especially important considering that research has shown low-frequency sound exposure to cause hearing damage at high frequencies [71-73]. It is relevant, then, to consider adopting C- (or Z-) weighted measurements (for both long and short integration times) for regulating audience sound exposure.

Integration time for the primary limits range from 1 minute to 240 minutes. Interestingly, the minimum (Austria) and maximum (WHO) integration times have exactly the same limit (100 dBA). Considering the transient and changing nature of a music event, it seems more reasonable to integrate over a longer period to better represent the noise dose received by the audience, rather than risking data being skewed by a particularly (but infrequent) loud portion of the musical event. On the other hand, integrating over too long a time period may have the damaging effect of sound level limit transgressions earlier in the event making it impossible to meet the long-term averaged limit, even if the sound system is turned off for the headliner's set. A compromise must be reached. In most cases in Europe, a 15-minute integration time is applied in practice along with real-time monitoring.

Most of the secondary limits detailed in the European regulations focus on peak levels, with C-weighting measured over 35 ms in a number of cases. This may be reasonable, although considering the emphasis on low-frequencies in modern sound reinforcement systems perhaps the integration time is too short. Research has indicated that at low-frequencies the hearing system's integration time is around 170 ms [74]. Nonetheless, levels of 140 dBC are significant and should be avoided to prevent serious hearing damage. It should be noted that a few of the secondary limits do take C-weighted readings over longer integration times (up to 60 minutes). It may be that this sort of monitoring practice is more useful than the primary A-weighted approach as it will closer represent the actual perception of the audience, although it must be stressed that such long integration times are likely to make the job of the front of house (FOH) engineer very difficult, especially towards the end of an event when most of the "loudness capital", so to speak, has been spent.

As an aside, NASA's technical standards for human factors, habitability and environmental health during space flight [75] adopts ACGIH's infrasound exposure limits which state that sound pressure levels for frequencies between 1 – 80 Hz (in 1/3 octave bands) can be no higher than 145 dBZ (peak) and no more than 150 dBZ (peak) measured over the entire spectrum [76]. No integration times are specified. Additionally, if low-frequency sound is centered in the region that causes chest resonance (roughly 50 – 60 Hz); this has the potential to cause whole-body vibration which can lead to annoyance and/or discomfort. In such cases, a reduction in sound pressure level is necessary [76]. Such sound levels aren't unheard of at live events (especially for the audience members standing directly in front of a large subwoofer array [21]). NASA's primary focus is the wellbeing of their astronauts and they've adopted unweighted measurements to best quantify low-frequency noise exposure. In the live event industry, A-weighting is still used, which (as stated earlier) largely ignores low-frequency content. There is a serious disagreement in practice here, where although the two industries are greatly different, the nature of the sound/noise exposure isn't as dissimilar as one would imagine.

It isn't out of the realm of possibilities to implement a dynamic weighting curve that adjusts depending on the received unweighted sound levels according to equal loudness contours. This would ensure accurate readings of noise exposure for dynamic, ever-changing entertainment events. Modern day devices should have little problem providing adequate computing power to achieve this, although such an approach will need to be formalized though technical standards and be included in revised noise regulations before wide adoption could be expected. A change such as this would take many years to achieve. At present, it's important to work with existing measurement standards/regulations and equipment to achieve a reasonable and realistic approach to ensure audiences are kept safe at entertainment events. However this by no means indicates that the industry shouldn't strive to update current measurement procedures, looking towards the future. There's no benefit of an unwavering devotion to long-used measurement procedures if there's evidence that said procedures are inadequate (although it's much easier to stick with the old – and familiar – practice).

It should be noted that it's encouraging to see stricter limits in place for children's events. While there is no conclusive research to show that children's hearing systems are more sensitive to noise exposure and thus more susceptible to damage, it is known and agreed that hearing loss at an early age will detract from an individual's quality of life and accelerate the onset of age-related hearing loss [77-80]. Furthermore, research has shown that individuals with existing hearing loss requiring hearing aids are much more susceptible to further hearing loss by attending live events, with the study showing that this prevents such people (especially youths) from attending events, thus missing out on important and enjoyable social interactions [81].

2.3.1. Measurement and monitoring procedures

In terms of measurement procedures for audience sound exposure, there appears to be no consensus between countries. Some countries specify a measurement location at the front of house mix position (FOH), while others allow readings to be taken anywhere accessible to the public. In the UK, it is recommended that sound exposure be measured at the loudest area of the audience at head height [28]. Germany and France also specify measurement at the loudest position in the audience. A relatively arbitrary measurement location in the audience is problematic, as research has shown that in-situ measurements at music festivals exhibit differences in SPL horizontally across an audience of upwards of 13 dB (or more) [24]. Also, due to the impracticality of such a monitoring location, correction values can be implemented by measuring the relative difference between the loudest location in the audience and a practical monitoring location (usually FOH).

While efforts should be made to achieve a consistent energy distribution across the audience (as will be discussed in Section 3), this highlights the problem of specifying a single measurement point for monitoring audience exposure. A recent study has given indication that if a single measurement location is necessary/unavoidable, that the FOH mix position tends to give good estimates of overall audience exposure [55]. This assumes that the sound system has been designed so that the received response at FOH is representative of the response across the audience and that crowd noise won't overpower the sound reinforcement system. This goal is a primary focus in Section 3 of this report.

DIN15905-5 from Germany (a technical standard, not a law [61, 62]), raises an interesting issue in audience sound level monitoring. It requires compliance to the stated limits (99 dB $L_{Aeq,30\ min}$ and 135 dBC peak) at the loudest point in the audience. There have been legal cases brought based on hearing damage suffered due to attendance at large-scale outdoor events, which in part cites DIN15905-5. A listing of key legal cases can be found in [82].

As mentioned above, the front of house mix position (FOH) is most commonly the monitoring location during an event, but this poses an issue. During pop music events, crowd noise can easily exceed stated limits, even without the sound system active [83]. If the measurement microphone is placed at FOH, crowd noise will result in limit infractions that have nothing to do with the sound system. It has been suggested, therefore, that the measurement microphone is placed near to the sound system to avoid influence of the audiences [83]. This also has issues, as monitoring a single sub-system can give a false reading of what the full system is providing to the crowd. Also, the high sound pressure levels experienced near to a large sound system can cause the measurement microphone to malfunction, rendering the measurements useless (this is clearly expressed in DIN15905-5). A straightforward solution is to have a FOH measurement location, where the monitoring software has knowledge of the input signal to the sound system to ignore sound level limit infractions due to crowd noise. This method is implemented (to an extent) in existing sound level monitoring software and is discussed in Section 5.

Overall, it is clear that much work is required in the area of audience sound exposure regulation. There exist some regulations which are likely to be close to something appropriate for the reality of the situation at modern day live events, but there is no accepted standard practice across the world. While the broadband spectrum should be considered in terms of potential noise or music related hearing loss, low-frequencies may pose the greatest risk due to common system design practices, whereby subwoofer systems are often ground-based only a few meters from the nearest audience members (while line arrays are suspended well above an audience), resulting in sound exposure exceeding many recommended limits. As discussed in this section, such levels expose the audience to potential temporary or permanent hearing loss, as well as additional (potential) neurological and sociological impairments over extended periods of time. More research and practical experiments are needed in this area. This will be discussed further in Section 3.2.1.

2.3.2. Preventative measures

Numerous pieces of published research have given strong indication that a public education program is necessary to assist the avoidance of hearing damage due to regular attendance at live events [28, 77, 84-87]. In one study, participants took part in a six-month education program on the risks of high-level sound exposure at live events [85]. After the program, 12% more of the participants used hearing protection at events, although this result can’t be conclusively pinned to the education program. It was noted that younger participants seemed less influenced by the program.

What most studies related to public education on sound exposure risks suggest is that if sound levels are expected to exceed accepted regulations/recommendations for audience exposure, there should be clear signs in the venue stating there is a risk of hearing damage due to sound exposure. It is also suggested that in such cases, hearing protection (in the form of ear plugs) is provided either free of charge [86] or for a small cost [87]. The availability of hearing protection (as well as clear notifications of dangerous sound levels) at venues is likely to result in greater caution by audience members.

The effectiveness of standard hearing protection to limit damage from low-frequencies must be questioned, though, due to bone/tissue conduction transmission paths. The issue is well-known by individuals working on aircraft carriers [88-90] as well as by NASA who clearly state in their flight technical standards [75] that hearing protection can never be used to satisfy requirements for low-frequency noise exposure. In the case of high levels of low-frequency sound exposure, therefore, there is no reasonable hearing protection device that will provide adequate (or any) protection in this area.

2.3.3. Approach to sound exposure regulations

Ultimately, the worry is (and has been within the AES since the 1970s) that if those responsible for the design and operation of large-scale sound reinforcement systems don't actively contribute to the development of reasonable and accurate audience sound exposure regulations, it is almost certain that governments will step in and impose unrealistic/impractical regulations that the live event industry will have no choice but to adhere to. This has already begun to happen.

The problem was emphasized in 1976 in an AES paper [91]: "If we ourselves do not come up with some guidelines, some government agency will step into the void." Another study from the same year [92] expresses a similar sentiment: "It is not good enough to provide means for the generation of louder and louder noises without any consideration for the possibility of proven harmful effects." Again, this statement was specifically targeting AES members.

A later study in 1980 [84] made it clear that it's the responsibility of members of the AES to protect the public from the risk of serious hearing damage due to live events, pointing out that if we don't address the problem it's almost certain that governments will over-regulate: "Our civil liberties would be eroded by any government dictation or control of our leisure life styles, but this intervention can definitely occur sooner or later unless an aroused citizenship assumes the initiative to counteract the tidal wave sweeping our civilization into the insidious undercurrent of aural incapacitance… It is hoped that the profession can hear the whispered hint. If it is not yet deafened into insensibility."

While this working group fully supports the research and development of suitable and effective sound exposure regulations and guidelines for audiences at live events, this activity on its own is insufficient. Management of audience sound exposure must begin with appropriate sound system design. With this in place, regulations can then be realistically applied without compromising the high-quality listening experience of the audience members. It is critical to understand that for both on-site and off-site sound/noise issues, the solution has to start with the sound system design. This point appears to be absent in much of the discussion surrounding these issues in published literature. Sound system design is therefore the focus of the next section.

3. System design

Sound system design and optimization has progressed significantly over the past half-century. With technological innovations such as Meyer Sound's Source-Independent Measurement (SIM) system in the 1980s [93], which gave sound system engineers the ability to inspect detailed time, frequency and phase data from in-situ measurements, to the advent of the modern day line array by L-Acoustics in the early 1990s [94], and the current developments of source-oriented (a.k.a. hyper-realistic immersive) sound reinforcement systems such as L-Acoustics' L-ISA [95] and d&b's Soundscape [96], the goal of homogeneity of listening experience across a wide audience is closer to becoming a reality.

There exist a number of textbooks focused on sound system design and optimization [10, 97, 98], written by well-respected and highly-experienced engineers. This section will not attempt to cover all aspects of system design and optimization, as this wouldn't be useful in regard to the purpose of this report. Instead, core principles will be briefly highlighted, pointing to key references for further reading, with a more detailed focus on recent developments in system design which aim to further the quest towards uniform high-quality coverage across an audience with minimal energy leakage into noise-sensitive areas.

The focus on uniformity in coverage is central to this report's focus on audience sound exposure. Uniform audience coverage allows engineers and acoustic consultants to precisely track audience sound levels without the need for many monitoring locations (as alluded to in Section 2). This makes audience sound exposure monitoring and management more practical and accurate, while simultaneously ensuring all audience members receive a high-quality listening experience.

For the remainder of this report, systems labeled as *primary* will refer to the sound reinforcement system designed to deliver audio content to the audience as well as musicians on stage. Systems labeled as *secondary* will refer to active noise cancellation systems decoupled from the primary sound system with the purpose of limiting off-site noise pollution. Primary sound systems will be the focus of this section while Section 6 will detail recent work on secondary sound systems.

3.1. Main PA

The majority of modern-day large-scale sound reinforcement systems consist of flown broadband Variable Curvature Line Sources (VCLS), commonly referred to as line arrays [99], although it must be noted that for some applications point source technology will more adequately meet the sound reinforcement requirements. The most common configuration of such line source systems is in a spaced left/right system, where identical arrays are flown symmetrically at the sides of a stage. While such systems are technically capable of stereo reproduction, most program material sent to the system is center-panned, resulting in multiple-mono system behavior.

The reason for this multiple-mono approach is dictated by audience configuration. At large events, the audience is spread in front of and off to the sides of a stage. Employing stereo mixing practices will result in (1) the audience located to the side of a venue not receiving adequate signal level from instruments hard-panned to the opposite side of the system and (2) the stereo effect being lost on everyone other than a relatively narrow area of audience central to the main PA [10, 43]. The benefits of mixing in stereo are outweighed by the drawbacks in most cases.

This leads to an issue in terms of sound reinforcement uniformity across a wide audience. If the left and right line arrays are fed identical signals, then coherent interference will occur. At high frequencies, this can manifest itself as the perception of "phaseyness" as one moves their head even slightly from side to side (or when the wind causes varying temperature gradients in the acoustic signal path, resulting in varying propagation times for system elements). This presents no issue in terms of audience sound exposure, however, so won't be discussed further here.

At lower frequencies (below 200 Hz), however, coherent interference causes areas of the audience to suffer from a complete lack of acoustic energy over specific (position-dependent) narrow frequency bands. While these effects may not be noticeable to the general concert-goer, who may not move significantly during the course of an event, it does hinder a system engineer's aim of achieving democracy of sound (i.e. the same high-quality objective listening experience to all audience members) as well making it more difficult to accurately track audience sound exposure.

There already exist solutions to the low-frequency coherent interference problem (although these aren't necessarily widely adopted, as of yet). Three possible approaches are detailed here.

3.1.1. Center arrays

Center arrays avoid coherent interference because the main sound source is coming from a single line array (or a cluster of multiple, coupled arrays). It is unlikely to be a suitable option, though, for wide audiences unless the individual elements in the array (or cluster) exhibit wide horizontal coverage.

This approach has limitations in terms of interfacing with the lighting and video systems, where a center hang could potentially block important sightlines. Most large-scale productions require a letter-box/landscape view of the stage, unimpeded by obstructions such as loudspeakers. In general, a stage of 18 m (60') x 12 m (40') x 1.8 m (6') is standard, with a requirement that there be 12 m (40') clearance between the stage surface and any overhead structure. These requirements are focused on the "look" of an event, where sound requirements are currently less of a priority (something which this working group hopes to see changed in the near future). Barring any adjustment to production priorities, center-hung arrays would have to fit within this existing framework in order to be widely adopted.

Nonetheless, it is well documented that a centrally-flown main sound system is capable of delivering a homogeneous listening experience to large audience areas [10, 99]. This is particularly possible for cases where a central array is rigged high for sightline purposes, thus providing more even front-to-back coverage. Additionally, this single source of sound potentially makes easier the role of secondary systems in cancelling sound energy traveling off-site.

In situations where stereo sound reinforcement isn't important (remembering that use of multi-mono systems is currently widespread) and there exist no serious sightline or rigging issues, a center array is quite a good option.

3.1.2. Signal decorrelation

If a multiple-mono system is implemented which has the capability of reproducing the low-frequency range (some large-scale main systems currently available extend down to 50 Hz) and is used in conjunction with a subwoofer system, low-frequency coherent interference can be mitigated by decorrelating the left and right line array drive signals (over the broadband spectrum or focusing solely on the low-frequency range, below 200 Hz).

A rudimentary application of this sort has been used in the industry for many years, primarily for left/right subwoofer decorrelation [100]. In this approach, an independent equalizer channel is applied to the left and right signals individually. Different EQ is applied to each channel so that the phase relationship between the left and right signals varies by frequency, thus partially randomizing the location of strong peaks and dips in the acoustic response due to comb filtering. Alternatively, consultants installing permanent systems into venues have regularly employed separate allpass filters to each sub-system to achieve a certain level of decorrelation [101]. The authors of this report don't recommend these approaches, as they have the potential of reducing the sound quality delivered to audience members and are commonly unacceptable to sound engineers.

A more robust solution for decorrelation is known as Diffuse Signal Processing (DiSP) [74, 102-104]. DiSP operates by convolving the audio stream going to the left and right arrays with different temporally diffuse impulse responses (TDIs). The TDIs exhibit a full-scale impulse at time zero, followed by an exponentially decaying noise tail, generated with random phase noise exhibiting frequency-dependent decay. TDIs can be synthesized to provide decorrelation over the full frequency spectrum or for select frequency bands. In most cases, broadband decorrelation is unnecessary, with a focus instead on the low-frequency band or crossover region(s).

As long as TDIs are generated to ensure transparency [74], the result will be a reduction in coherent interference effects, resulting in a more homogeneous response across the audience. Additionally, transient preservation can be embedded in the algorithm to ensure audiences receive the expected impact from the sound system while still benefiting from sufficient decorrelation [74, 102].

For indoor venues, it is possible to implement dynamic DiSP to decorrelate not only the direct sounds from each other but the early reflections from the direct sounds using time-varying TDIs (in other words, for every audio frame received by the signal processor, that frame will be convolved by a different TDI than its predecessor and successor) [102]. Experiments have shown that this process significantly improves objective listening response homogeneity across an audience for systems with even only a single sound source and increasing in performance as more degrees of freedom (sound sources) are included [105].

In terms of practical implementation of DiSP (or similar), it must be kept in mind that there exists minimal time for system tuning for most touring productions. Such a system would need to be easily incorporated into the system, without a lengthy calibration procedure. DiSP is designed specifically to meet this requirement, where the algorithm can be applied in its own networked device (or be built into an existing piece of equipment such as a mixing desk or system processor) and requires no calibration measurements. It functions as a turn-key solution, requiring little to no extra time on-site.

DiSP's ability to improve consistency in audience sound coverage along with its ease of implementation and flexibility can directly contribute to ensuring audience sound exposure can be accurately tracked and managed while ensuring the best-possible high-quality listening experience for everyone in attendance. Front-to-back coverage inconsistencies, though, can't be resolved using any form of decorrelation and therefore still pose a potential issue for audience sound exposure.

3.1.3. Source-oriented systems

The past few years have seen the emergence of what some term *source-oriented sound reinforcement systems*, largely owing to work carried out by L-Acoustics and d&b audiotechnik. Such systems strive to deliver identical immersive listening experiences to every audience member [43, 95, 96]. This is achieved with multiple horizontally-distributed line arrays (at the front of the venue with the possibility of expanding the system to the sides and rear of the venue as well) with individual elements exhibiting wide horizontal coverage patterns. Mixing is done using an object-based approach, whereby the engineer specifies where each individual instrument/voice should be localized within the venue (along with the apparent source width).

Such systems' design philosophy, though, is in opposition to conventional wisdom. Traditionally, the approach to sound system design is to avoid significant overlap between decoupled loudspeakers to minimize spectral and ripple variance [10]. Spatial crossover regions between elements should be made as narrow as possible so that time alignment can be meaningfully and effectively applied to maintain low variance in listening experience in these regions. Object-oriented sound systems often (but not always) deploy loudspeakers with wide horizontal coverage patterns with the aim of covering as much of the audience as possible. This means that significant inter-element overlap usually will occur. As ideally the line arrays will be closely spaced, there is the possibility to have the arrays coupled at low-frequencies, thus limiting the issue of coherent interference causing inconsistent coverage below around 200 Hz in the audience. It is common to have a centrally flown subwoofer array in such systems, which can provide very consistent audience coverage (as discussed in Section 3.1.1).

In order for increased uptake of object-oriented sound reinforcement systems, it will be essential for live event production to refocus on the importance of audio, instead of the current situation where loudspeaker placement is restricted based on the needs of lighting and video, causing main line arrays to be pushed outwards and upwards into non-ideal locations – especially for adequate sonic imaging (in terms of audio-visual fusion) [43].

While there are greater requirements in terms of equipment and rigging, there are likely to be benefits from such systems beyond those of immersive audio. One such benefit is due to the distributed nature of the sound system, comprising of many small line arrays/point sources. This may require less output from each individual component in the system, which is likely to avoid exposing audience members closest to the system to unreasonable and dangerous sound pressure levels as well as potentially reducing sound energy traveling off-site, thus reducing noise pollution. The distributed nature of the system also has the potential to provide consistent audience coverage horizontally and front-to-back, thus making audience sound exposure monitoring and management easier. As such systems are relatively new to the market, further research is needed to provide clear conclusions on these points.

It is still open to debate, however, whether such systems can and will be adopted by the touring side of the live event industry. As stated earlier, time- and equipment-efficiency is central to most touring operations, which is why only a limited number of productions have taken such systems on the road to date.

3.1.4. Design objectives

A key contributor to audience satisfaction is the "democracy of sound." This phrase has recently been adopted by at least one major manufacturer [312] and reflects a growing movement among engineers and system designers to achieve nearly uniform high-quality coverage over the entire audience area. This ideal has only been achievable relatively recently as understanding of line array physical deployment has matured, including effective optimization through DSP-based optimization.

There are four variances that should be minimized [10]:

1. Level variance

   Difference in sound pressure level across the audience area.

2. Spectral variance

   Difference in spectral characteristics across the audience area.

3. Ripple variance

   Differences in spectral characteristics across the audience area due to coherent interference between system elements and reflections (i.e. comb filtering).

4. Sonic image variance

   Differences in spatial impression of sound reinforcement across the audience. Emphasis given to agreement between aural and visual cues.

The primary issues related to level variance come down to loudspeaker make/model, source physical deployment (position, trim height, aiming, splay angles), source electronic settings (frequency response, processing) and global system layout (frontal, distributed, in the round). It is important to understand that absolute minimization of level variance is unreasonable in most venues. It should be accepted that there will exist a certain degree of level attenuation towards the rear of a large audience area (but ideally no more than 6 dB).

The important aspect of main PA design in regard to noise pollution relates to the coverage pattern of the overall system. The challenge to system engineers/designers is to optimize audience coverage for minimal variance while simultaneously avoiding unacceptable sound levels in noise-sensitive areas (such as the stage, on-site quiet areas, and surrounding communities). With conventional line arrays, the primary focus should be on configuring the system, using manufacturer-provided software, to ensure the coverage ends where the audience ends.

Many modern processors manipulate the input signal for each individual speaker component to help the system achieve a homogenized response over the audience area. This has several advantages in terms of noise concerns. Effective use of FIR processing means that, for a large system, level variance can be minimized over the audience area and between the mix position and the audience area.

A potential issue arises from line arrays capable of reproducing strong low-frequency content (many modern arrays are marketed to operate downwards of 50 Hz). An extended main array frequency response means that since more low-frequency content is being distributed via the main arrays, fewer auxiliary subwoofers are required. This is good for audience members close to the stage (as there will be reduced sound pressure levels from ground-based subwoofers) and audience members further from the stage (since there will be more even front-to-back low-frequency coverage) but such systems, if implemented in a typical left/right configuration, will reintroduce a power alley of low-frequency energy, as well as comb-filtering horizontally across the audience, and therefore should be processed to decorrelate the left and right signals. This has already been mentioned in Section 3.1.2, but will be covered in greater detail in Section 3.2, especially in relation to subwoofer systems.

Main line array length must also be considered in terms of audience coverage and noise pollution. It is not the case that bigger is always better. Implementing too long of a line array (resulting in either a very long throw or an array that physically extends almost to the stage/ground or both) is likely to cause more problems than it solves (it is generally recommended that a line array be flown at three times its length to achieve the desired and predicted performance). Too long of an array can result in great difficulty in controlling the throw of the system due to limitations of array curvature. Additionally, it will likely result in poor front-to-back audience coverage consistency. While in some cases, individual elements can be addressed within the array to adjust their drive signal to avoid some of these issues, it is better practice to implement an array that is suitable to the venue and event. In certain cases, smaller line arrays or short-throw distributed elements may be advantageous over large line arrays. Analysis must be carried out for each event where a cookie-cutter style approach should be avoided. Careful analysis to ensure appropriate system design and implementation will help to ensure a good audience experience while minimizing annoyance caused in surrounding communities.

Overall, main PAs should be designed to deliver the majority of the spectral content to the majority of the audience with minimal sound energy spillage beyond the defined audience area. The physical deployment of a source (location, aiming, precise splay angles settings for a line source) should be optimized first. It minimizes the need for electronic processing that would otherwise be used to correct poor design choices and could degrade sound quality or even create secondary lobes outside of the audience coverage. Manufacturer software is essential in achieving this – both during the design stage and during deployment, in addition to on-site measurements when tuning the system with an appreciation for how environmental factors can significantly distort the predicted system response.

3.2. Subwoofer systems

Due to the limited transducer size and array length of main PA line arrays, a subwoofer system is usually required to reinforce/reproduce the lower range of the frequency spectrum (below 100 Hz). Such systems can be deployed as flown arrays, generally in close proximity to the main PA (to allow for coupling), or as ground-based systems (in many cases in a horizontal array). There are advantages and disadvantages to each approach, which are detailed below.

3.2.1. Ground-based

Ground-based subwoofer systems may be viewed as a holdover from the days when sound systems consisted of stacked point sources on either side of the stage. Usually the main PAs embedded subwoofers within their design, alternating broadband boxes and subwoofers. When flown point source arrays became common, the broadband loudspeakers moved above the stage, often leaving the subwoofer system alone on the ground [22]. Initially, subwoofers were kept in left/right configurations, which caused coherent interference issues described in Section 3.1. Such a configuration results in a strong *power alley* down the center of an audience (assuming a symmetrical subwoofer layout) surrounded by areas of significantly lower amplitude low-frequency (the precise location of these dead spots is frequency dependent), along with sidelobes which will stretch off to the sides of the stage. If the individual subwoofers are omnidirectional in nature, then this pattern will be mirrored in the backwards-facing direction (i.e. the stage).

This results in significant spectral variance across the audience as well as propagation into noise-sensitive areas. The only practical way to avoid this issue is to apply a form of decorrelation to the left/right system, by using individual EQ/allpass filters for each side of the system (which has the potential of perceptible signal distortion) or using a more robust (and perceptually transparent) approach such as DiSP. This has already been discussed in Section 3.1.

If free space exists in front of the stage, then the subwoofer system can be deployed as a horizontal array. There are some benefits to this approach, primarily based on the improved control of the system's sound radiation pattern over the traditional left/right systems. Steering and optimization techniques for ground-based horizontal arrays are well-known and researched [10, 22, 106-108]. In general, electronic delay, polarity and/or amplitude can be adjusted for each element in the array in order to produce the desired polar response with as little deviation across the subwoofer frequency band as possible.

As with main PA line arrays, subwoofer arrays such as this necessitate a considerable length/depth in order to accurately control directivity at the lowest frequencies (stretching into the infrasonic range in some cases [43, 106, 109]). In general, the array will be able to control frequencies with wavelengths equal to or less than the overall array width (although based on practical experience, this limit can overestimate effectiveness at such low frequencies) [110].

In regard to noise pollution, ground-based subwoofer arrays do not limit off-site low-frequency noise levels due to acoustic absorption in the audience (as is commonly claimed). There should therefore be minimal difference in noise pollution off-site between ground and flown subwoofer systems (assuming the systems are properly configured). It's important to note, though, that these systems, even if designed for even horizontal coverage, can suffer from some spectral variance within the audience due to low-frequencies reflecting at the boundaries of the audience due to impedance mismatches. The effect is most pronounced with dense audiences that terminate abruptly. Gradual audience density roll-offs avoid this issue [111], but this is impossible to arrange for in practice.

While horizontal ground-based subwoofer arrays can easily achieve tightly controlled coverage of the audience area (with minimal radiation into noise-sensitive areas) – at least horizontally, but perhaps not from front-to-back – there exists a serious health risk from such systems that has been brought up in past publications [21, 49, 68], but little seems to have been done to address the issue.

Such ground-based systems are typically placed in between the stage and the crowd barrier, often leaving only a meter or two between the first row of audience and the subwoofers. Inspecting manufacturer-provided datasheets, many professional-grade large-scale subwoofers are capable of producing peak levels of 140 dB (or more) at 1 m [112-115]. In regard to the audience sound exposure, such systems will almost certainly be in breach of all regulations and recommendations detailed in Section 2.1. Considering that audience members at the front of an audience are usually the biggest fans of the performers on stage, it can be reasoned that they will attend more concerts than the average member of the public. This means that the biggest fans of a popular music group will be put at significantly more risk of permanent hearing damage due to this activity (where they have absolutely no control of the system).

As detailed in Section 2, there is ample evidence in published research showing that conventional hearing protection is of minimal use at low frequencies, since sound not only travels through the ear, but also through bone and tissue in the body. Blocking the ear canals only removes one transmission pathway, leaving all others open (although previous research indicates that these remaining pathways are less efficient at transmitting airborne noise into the body and through to the inner ear [14]). Unless a similar methodology deployed on aircraft carriers is implemented for audience members near ground-based subwoofers – where full body suits and helmets are worn to decouple a person from the surrounding acoustic environment (which is clearly impractical for live events) – there is no way to avoid such sound exposure from these subwoofer systems. There is an element of duty of care from the system engineers and operators in this case that shouldn't be taken lightly (but usually is ignored).

In addition to this, recent research has given clear evidence that ground-based subwoofers fail to provide minimal level variance from front-to-back of an audience due to the significant difference of propagation paths between the front row and back row of audience [99]. In the tested cases, a front-to-back difference of over 30 dB was regularly observed. This is unacceptable in terms of low-frequency level variance. In terms of spectral variance, if the main PA exhibits no more than 10 dB level variance from front-to-back, the problematic subwoofer level variance would result in up to 20 dB spectral variance for the overall sound system across the audience (which is unacceptable).

Furthermore, a ground-based subwoofer system proves challenging in terms of time alignment with the main PA. Assuming the main PA and subwoofers are fed coherent signals, proper time alignment is necessary in terms of spectral variance as well as transient response (assuming that the audience receives similar sound pressure levels in the subwoofer crossover region from the subwoofer system and other system elements). A misalignment will result in comb-filtering in the spectral crossover region as well as smearing of the transient response in the low frequency range. Considering the evidence presented in Section 2 regarding sound quality being closely linked to bass clarity and accuracy, this is sure to detract from the listening experience.

Unfortunately, with such a configuration there is no way to time align the subwoofers to the main PA so that all audience areas are properly aligned. Alignment can only be performed in one location and the further away from this location, the further misaligned the received response will be. Research is ongoing, however, to identify the most effective time-alignment approach for such systems [116].

Considering the above-mentioned concerns over ground-based subwoofers, it would seem suspicious why such systems are so commonly deployed at large-scale live events. Likely reasons for this are the ease of implementation (stage roof rigging capacity, time requirements, associated costs, etc.) and potential for higher sound pressure levels at the mix position (which isn’t necessarily the case). Ground-based systems require no rigging and therefore are much quicker (and cheaper) to deploy. Central ground-based systems largely avoid coherent interference issues, giving the audience (from left to right, at least) a consistent listening experience. Front-to-back, although experiencing significant level differences, benefit from tonal consistency (minimal spectral variance) in the subwoofer range. Additionally, if a horizontal ground-based array of omnidirectional subwoofers is used, there will likely be significant issues on stage (unacceptable low-frequency sound level, feedback problems, etc.). In such cases, the array should consist of (or be configured to replicate) cardioid subwoofers.

3.2.2. Flown

Considering the analysis presented in the previous section on ground-based subwoofer systems, it would seem logical that flown subwoofer systems are a more sensible choice for large-scale sound system design. In many respects, this is true, but there are also drawbacks that must be carefully considered when designing a system.

The most common implementation of flown subwoofer systems is in the form of vertical arrays flown just beside or behind the main PA. The key benefit to this is that the subwoofers will now directly couple to the main PA, avoiding the tricky issue of time alignment experienced with ground-based systems. This coupling can also be beneficial in terms of rear rejection, allowing to create a cardioid type behavior of the coupled flown broadband line source array and subwoofer system in the shared bandwidth. This is the approach taken by L-Acoustics using combinations of large scale K1 or K2 line source arrays with K1SB flown arrays and applying end-fire processing as an alignment strategy. The relative positioning of the subwoofer array against the broadband source further allows choosing the direction of cancellation.

Unfortunately, left/right configurations suffer the same coherent interference issues as main left/right PAs, giving rise to significant spectral variance across an audience. As discussed earlier, this can be (at least partially) mitigated using a form of decorrelation such as DiSP (which can be implemented in a perceptually-transparent manner only in the frequency band(s) where decorrelation is necessary) [102]. Rudimentary forms of this are sometimes put in place in industry, but signal processing such as DiSP should be more seriously considered, especially in the subwoofer region, as it is likely to allow for a more consistent audience listening experience (with minimal/no perceptual artifacts), hence more accurate monitoring and management of sound exposure levels.

Research looking into flown subwoofer arrays share the same conclusion: a centrally-flown subwoofer array is the best possible option in regard to all of the above-mentioned considerations [22, 43, 99, 106, 117, 118]. Central flown subwoofer arrays achieve consistent frequency-independent coverage across the audience, both from left-to-right and front-to-back. The only area of concern in terms of audience coverage is time alignment with the main PA (assuming it is still in a typical left/right configuration). This problem will be somewhat easier to solve, though, since the difference in propagation distance from the subwoofers to audience and main PA to audience isn't as severe as with a ground-based system. There is still unlikely to be a perfect time alignment solution.

One commonly-held belief regarding flown subwoofer systems is that they will be 6 dB less efficient than ground-based systems due to lack of the Waterhouse effect (coupling between the direct sound and ground reflection [360]). It is unlikely that ground-based horizontal subwoofer arrays consisting of stacked units will benefit from a full 6 dB boosted output, due to the distance between the ground and the top transducer in the stack. The supposed loss in efficiency for flown systems was shown to be untrue in recent research [99]. Through a series of electroacoustic models and mathematical analysis, the researchers found that the 6 dB loss in efficiency can in reality be as little as 1 dB. In certain configurations, such as a centrally-flown array, it was shown that a 6 dB boost in efficiency was achieved (where they considered efficiency not in terms of absolute output of the sound system, but in terms of sound energy delivered throughout the audience). Considering the improved front-to-back consistency (flown arrays showed a loss which is roughly in line with main PA behavior, while ground-based systems exhibited greater than 30 dB loss over the length of the audience), any small loss in efficiency is justifiable.

The work resulted in a useful metric known as DHER (Distance-to-Height Efficiency Ratio), which is the ratio of the listening distance at which the flown system is within 1 dB of the equivalent ground-based system (which approximates to two times the subwoofer height) and the height to the lowest flown subwoofer. DHER can be used to either specify a minimum listening distance at which full subwoofer system efficiency is observed or to determine the maximum allowable height of the subwoofer array to ensure good efficiency. An example given in the paper is for a 50 m deep venue with a standing audience (DHER = 5). In this case, the subwoofer array can be flown up to 10 m off the ground without losing any efficiency at the back of the audience (front to back reduction is 12 dB lower than with an equivalent ground-based system).

Another perceived drawback to flown subwoofer arrays is the issue of ease of propagation off-site due to no absorption (other than negligible effects of air absorption) in the direct sound's path or due to meteorological effects [119]. This is why in Amsterdam flown subwoofer arrays are outlawed (a case study is given in Section 5). For a flown system this *may* pose a noise pollution risk, although current published research into this area is inconclusive. In any case, a straightforward solution to this problem, which for unknown reasons isn't universally adopted as standard practice, is to apply line array directivity control to the flown subwoofer arrays. Some production companies physically angle the arrays so that they point downward towards the audience, but this may place unacceptable loads onto rigging points. Instead a solution well within the reach of modern-day live sound technology is to electronically steer the array towards the audience (and away from neighboring communities or on-site performance stages) [22, 106, 118].

The effectiveness of array steering at low frequencies is a direct function of the array length. For example, if the array was 8 m long, accurate beam width steering can be expected down to around 45 Hz. Amplitude tapering can be applied to the array so that side lobes are reduced (which otherwise could cause noise pollution problems) [97, 120, 121]. This means that the lowest frequencies in the subwoofer band may still cause issues off-site, but the extent of the issue may be similar in scale to ground-based systems due to low levels of audience or ground absorption at such frequencies [111]. Steering the main beam of a flown subwoofer array towards the audience and ground does run the risk of causing a strong ground reflection, which may result in noise pollution problems due to environmental effects on sound propagation. Aspects related to this will be discussed in Section 5, but it should be mentioned here that further research is needed in this area. It's worth noting that the effect of a low-frequency ground reflection is well-known to researchers working with wind-turbine farms [122].

It must also be re-emphasized that many main PAs are regularly operated down to 70 Hz and in some cases to 50 Hz and below. This results in a significant spectral crossover between the main PA and the subwoofer system, making low-frequency steering a challenge that can't be limited in scope to subwoofer array processing – the main PA must also be considered in order to get acceptable results. As the subwoofer system is generally driven on an auxiliary send, separate to the main PA sends, the subwoofer and main arrays will be partially correlated, again increasing the challenge of effective low-frequency steering. Research investigating this subject in the context of the main PA and subwoofer system is needed, as most previous work treats on the two systems in isolation.

3.2.3. Performance quantification

There is a distinct lack of accessible methods for practitioners to quantify live sound system performance (although there is indication in recent releases of manufacturer system design software that this may be changing [123]). What system designers do in lieu of clear performance metrics is to inspect spatial and spectral plots of predicted system performance in manufacturer-supplied software. While this is likely to be sufficient for experienced system engineers, individuals with less experience may struggle to meaningfully and reasonably interpret the displayed data. Such human-centered analysis leaves the door open to human error/misunderstanding.

Two recent pieces of research [99, 121] have put forward methods to quantify various aspects of subwoofer system performance. It is likely that some of these metrics can be adapted to allow for broadband analysis of system performance, but work is required to confirm this.

The first paper published on the topic [121], proposes three central objectives for subwoofer system performance at live events:

1) Tonal consistency across an audience
2) Acceptable system headroom
3) Minimal difference between the mix position and mean audience level

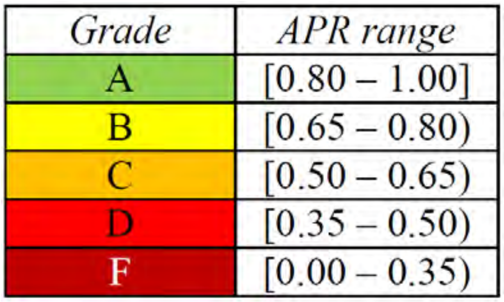
In the conclusion of this work, a fourth objective is identified which should be included in further work on the subject:

4) Minimal noise spill into noise-sensitive areas

The second paper [99] made improvements on the recommendations in [121], where instead of acceptable system headroom (which was originally calculated based on the difference between the target and achieved SPL at FOH) used to determine system efficiency, a far-field SPL efficiency criterion, labeled *L-Eff*, was proposed, which is the difference between the mean SPL at the rear of the audience with the full system and the mean SPL at the rear of the audience with a single subwoofer. The higher *L-Eff*, the better "return on investment."

Additionally, instead of basing the FOH to audience consistency (3) on mean audience level, the paper [99] recommends using the 95% interval of audience SPL to better capture the full range of sound energy across a large area (especially paying attention to audience members at close listening positions).

The work in the first paper [121] went a step further to combine all relevant metrics related to system performance into a single value, termed Array Performance Rating (APR), which exists on a scale between 0 – 1. Each individual metric can be weighted depending on the design requirements and the overall system performance can be mapped to a letter grade for simple communication to clients and other non-technical interested parties (Figure 3.1).



Grade	*APR range*
A	[0.80 – 1.00]
B	[0.65 – 0.80)
C	[0.50 – 0.65)
D	[0.35 – 0.50)
F	[0.00 – 0.35)

Figure 3.1 APR letter grading scale for subwoofer system performance quantification [121]

An additional metric that must be investigated for inclusion in something like APR is a measure of a subwoofer system's waveform fidelity (or impulse integrity). In light of the audience subjective preferences outlined in Section 2, the transient performance (accuracy) of a subwoofer system is equally (if not more) important than the steady-state response. The inclusion of such a time domain-based metric within APR (or similar) would ensure the overall metric effectively enables the design of a subwoofer system that achieves a high-quality listening experience when incorporated with the other PA elements. It also should be noted that if a wide-bandwidth main PA is used (which can extend down in frequency to the subwoofer band) both the subwoofer system and main PA must be analyzed with APR (or similar) to ensure consistent low-frequency coverage with full system operation.

Regardless of the metrics used, both papers redefine efficiency in regard to subwoofer systems. For many years, system engineers talked about system efficiency in terms of electrical power sent to the loudspeakers, which is why amplitude tapering has been strongly resisted by many professionals (since it requires attenuating signals towards the outside of the array, thus wasting power amplifier resources). While it's true that amplitude tapering won't use all available amplification resources, it has been shown in many cases to allow for a more even sound distribution across a wide area and result in higher SPL in the audience [121, 124] due to the elimination of side lobes. It should be clear that such a system would be far more efficient than without amplitude tapering. It uses less power and delivers more sound energy to the audience in a more consistent manner. Further research is required, however, to inspect the effects of amplitude tapering on a realistic subwoofer system, where compression/limiting within the processors/amplifiers and power compression in the loudspeakers is considered. There is the possibility that such nonlinearities could limit the effectiveness of amplitude tapering (which is typically modeled as a linear time-invariant system). Due to these unknowns most manufacturers currently don't recommend amplitude tapering of subwoofer arrays.

3.3. Additional sound sources and other considerations

Aside from the main PA and subwoofer system, large-scale sound reinforcement systems may also contain (depending on the venue) front-fills, out-fills, in-fills, down-fills and delay towers/units. These subsystems are generally included within a PA to ensure adequate coverage of areas beyond what is considered the main audience area.

Front-fills, in-fills and down-fills are intended for coverage of the front-most center portion of the audience that can't be covered by a standard left/right main PA. It has been emphasized by a number of sound engineers that it's essential to get these systems configured correctly, since the audience members in these areas are typically the biggest fans of the performers for general admission events (or the highest payers for tickets at seated events – these two groups aren't necessarily related to each other) [43]. As these systems only require modest levels and don't reproduce significant low-frequency content (due to the lower directionality of the subwoofer system), they won't be major contributors to sound exposure on-site or noise pollution off-site and won't be discussed further in this report.

Out-fills are usually placed in close proximity to the main PA and are typically in the form of a smaller line array than the main PA. Due to this close proximity, the out-fill arrays can be considered coupled to the main PA (at least in the low- and low-mid frequency ranges). As these sub-systems are pointed outward from the stage to cover side areas, it is important to design the arrays to avoid overshooting the audience area to limit risk of unintended noise pollution. In practice, it is often found that out-fills are the source of noise pollution issues, in many cases due to a symmetric system design implemented when symmetry wasn't appropriate considering the layout of the event grounds or where the out-fills were radiating sound onto large reflective surfaces such as fencing, tour busses or trucks. The same level of attention must be paid to out-fill coverage on- and off-site as with the main PA.

Delay towers are commonly implemented to counteract sound attenuation of mid- and high-frequencies over long distances, which will have negative effects on speech intelligibility, and also attenuation of low-frequencies when subwoofers are ground-based. When flown subwoofers are used, delay systems aren't required to produce significant low-frequency content, since the acoustic energy from the subwoofers is likely to encounter limited attenuation across an audience. The same considerations must be made for delay towers as with out-fills: careful design to avoid unintended noise pollution.

One aspect of sound reinforcement systems that is often ignored when considering noise pollution is the stage monitoring system. While monitor wedges are usually pointed towards standing musicians and have limited low-frequency content, side-fills and drum/DJ-fills usually resemble a sound system that could be found at a small to medium sized indoor venue and have the potential to emit considerable low-frequency (and in some cases high-frequency) content into the crowd and beyond. Such systems should be considered in regard to time alignment of the overall sound system [10] as well as potential noise pollution issues [119].

While considerable effort is usually made to achieve adequate directionality of the audience-facing PA to avoid spill into noise-sensitive areas, the stage monitoring system is commonly overlooked. Stage monitors have been shown in recent studies to be a significant contributor to off-site noise [119] and will be discussed further in Section 5.

Lastly, a common element separate from the sound system can prove to be extremely problematic for both audience coverage and noise pollution on site: temporary "soft" structures (tents, marquees, etc., consisting of frames bounded in taut fabric). Such structures will act as large radiating surfaces (especially at low frequencies), causing inconsistent audience coverage inside and unpredictable noise pollution outside. To the knowledge of the authors of this report, no in-depth study has been conducted on such structures. Such a project is essential to gain a better understanding of the acoustic excitation and radiation properties of these structures. This knowledge will allow a more focused and informed approach to implementing sound reinforcement systems within and around them to simultaneously give the audience a good listening experience and limit annoyance in the neighboring community.

3.4. PA shoot-outs

It is often the case that multiple sound systems are directly compared in what are known as “PA shoot-outs” to help engineers and management decide which system to use for an event or to invest in for their company. While such shoot-outs have been taking place for many years, both indoor and outdoor, it is often the case that the test procedure isn’t completely transparent and the results are ambiguous [125].

While there have been standardized methods of testing loudspeakers using a double-blind approach for quite some time now, it is often difficult to apply these principles to large-scale sound reinforcement systems due to the physical size of such systems and limitations in terms of rigging. Additionally, it is rare to have access to a large indoor venue for such testing purposes, therefore many of these shoot-outs take place outdoors.

Attempting to run such tests outdoors is fraught with problems, principally dynamic meteorological conditions. Since these systems are often tested for audience coverage and rejection in noise-sensitive areas (on-site and off-site), measurements and subjective evaluations must be carried out at great distances from the sound systems. Any change in wind speed, temperature or humidity during the tests can largely invalidate the results [116, 125].

An additional issue with PA shoot-outs is lack of comparability of the systems under inspection. This may be due to vastly different system designs and sizes, but more often comes down to vastly different placement of the systems. This can result in one system being placed more favorably than another, thus skewing the measurements and subjective evaluations [125].

It is imperative, therefore, that large-scale loudspeaker testing and evaluation (a.k.a. PA shoot-out) is standardized. A bespoke standard for larger-scale systems is needed which takes the various practical limitations into account and specifically addresses the numerous problems associated with testing outdoors. At the time of writing this report, initial work looking into this issue has already commenced [125]. Until this happens, it is likely that most PA shoot-outs will lead to highly-contested results and potentially poor choices in sound system design as a result.

4. Noise regulations

This working group has striven to present a broad and comprehensive an overview of noise pollution in order to highlight areas of good and poor practice throughout the world. The collection of regulations presented in this section are to be viewed as wide-reaching, but not entirely comprehensive as there are over one thousand regulations across the globe on the international, national, regional and local levels. Nonetheless, trends are clear and areas of good practice stand well-apart from many of the other examples.

4.1. Motivation

There has been considerable work over the past couple of decades on modernizing noise pollution regulations at all levels (international, national, etc.). The majority of this work has focused on road, rail, wind turbine and occupational noise. Significantly less attention has been paid to entertainment/leisure noise, although (as will be highlighted in the following section) this is largely due to a serious lack of objective research in the area [1]. Consequently, most noise regulations relating to leisure noise are based on occupational noise exposure (although some exceptions exist). It must, therefore, be a central focus of this working group to critically examine existing regulations in the context of noise from live events and point towards necessary further research to lead to better-informed, accurate and suitable regulations.

There are three primary groups that are directly impacted by noise pollution regulations: event audiences, event staff/volunteers, and members of the local community in the vicinity of the outdoor event in question. This report focuses on two of the three groups: the audience and the local community. Members of staff at events are covered by various national occupational noise regulations, although volunteers are not [68]. The question of whether volunteers should fall under regulations for the audience or staff needs to be addressed.

In terms of the audience, a selection of existing regulations have already been detailed in Section 2 of this report and won’t be repeated here, although it should be re-emphasized that there is significant work to be done in this area to ensure audiences are sufficiently protected at outdoor entertainment events. Aspects of system design (covered in Section 3) are highly relevant in this regard.

Turning to members of the local community, there is clear motivation for ensuring regulations are fit for purpose. Residents living near a large outdoor event effectively have no control over the noise emitted from such an event, aside from the ability to raise a complaint. It is necessary, then, to ensure noise control and monitoring procedures are as effective and realistic as possible (but not overly-restrictive) to ensure such individuals don’t have an unwanted intrusion affecting their quality of life. As such outdoor events are becoming increasingly common in heavily populated areas (for business purposes) [43], the situation has become sensitive, where great care must be taken in system design and operation to ensure all parties involved are happy. In this section, the existing regulations are presented, while Section 5 contains a discussion on the application of regulations including a number of instructive case studies.

The remainder of this section inspects current regulations, highlighting those that demonstrate good practice while equally illustrating examples of poorly-informed practice. It is important to note that the majority of regulations presented in this section were not developed with temporary/infrequent outdoor music events in mind. In the absence of a bespoke regulation for such events, however, these regulations are often what event organizers must abide by, hence their inclusion in this report. The hope is that with this review, a clearer picture of what can and should be done to avoid unacceptable noise pollution into local neighborhoods becomes clearer than it is at present.

Satisfying the regulation requirements shouldn't be the focus here; satisfying the local community is what's really important.

4.2. World Health Organization

The World Health Organization (WHO) released their Environmental Noise Guidelines for the European Region [1] in 2018. These guidelines build upon previous guidelines, namely the WHO Guidelines for Community Noise [2] and WHO Night Noise Guidelines for Europe [3]. The 2018 work specifically made a point to ensure all guidelines were based on unbiased objective studies, giving evidence-based recommendations. As part of this work, systematic reviews were carried out on subjects including: transport noise interventions and their impacts on health [126], environmental noise and adverse birth outcomes [127], environmental noise and annoyance [128], environmental noise and cardiovascular and metabolic effects [129], environmental noise and cognition [130], environmental noise and effects on sleep [131], environmental noise and permanent hearing loss and tinnitus [132], and environmental noise and quality of life, wellbeing and mental health [133]. In the context of this working group, the reviews on annoyance [128] and hearing loss [132] are of particular relevance, as the other topics are more applicable to long-term sound exposure from permanent sources in the environment rather than the temporary nature of outdoor live events (although even these reviews predominantly focus on persistent noise sources, not infrequent noise encountered from outdoor events).

The 2018 WHO guidelines are based around four principles [1]:

1) Reduce exposure to noise, while conserving quiet areas.
2) Promote interventions to reduce exposure to noise and improve health.
3) Coordinate approaches to control noise sources and other environmental health risks.
4) Inform and involve communities potentially affected by a change in noise exposure.

A number of different metrics are discussed in the guidelines, all serving different purposes. A central metric used in the guidelines is the day-evening-night weighted sound pressure level, L_{den}, which is in accordance with ISO 1996-1:2016 [134]. This is an adjusted measure of $L_{Aeq,24h}$, to account for different sensitivities to noise from day, to evening, to night. L_{den} is calculated using Eq. 4.1.

$$L_{den} = 10\log_{10}\left[\frac{1}{24}\left(12\cdot 10^{\frac{L_{day}}{10}} + 4\cdot 10^{\frac{L_{evening}+5}{10}} + 8\cdot 10^{\frac{L_{night}+10}{10}}\right)\right] \tag{4.1}$$

Typically, the daytime range is defined as either between 07:00 – 19:00 or 06:00 – 18:00 and carries no penalty imposed to the level limits. The evening time range is defined as either between 19:00 – 23:00 or 18:00 – 22:00 with a +5 dB penalty imposed on the level limits. The nighttime range is defined as either between 23:00 – 07:00 or 22:00 – 06:00 with a +10 dB penalty imposed on the level limits. Measurements should be taken at the façade most exposed to the noise (outdoors).

The guidelines expand upon this to give correction values to relate outdoor measurement to indoor levels. When windows are fully closed, half open or fully open, the indoor-outdoor difference will be 25 dB, 15 dB and 10 dB, respectively. The WHO guidelines note, though, that a more accurate estimation is covered in a previous study, which includes frequency-dependent data [135]. Figures 4.1 and 4.2 show a sampling of the indoor-outdoor level relationships for overall L_{Aeq} and frequency, respectively. The lack of data below 50 Hz in Figure 4.2 should be noted as well as the high variance of results across the frequency bands (observe that in some cases the indoor noise was at a higher level compared to the outdoor noise at low-frequencies, which is likely due to room modes).

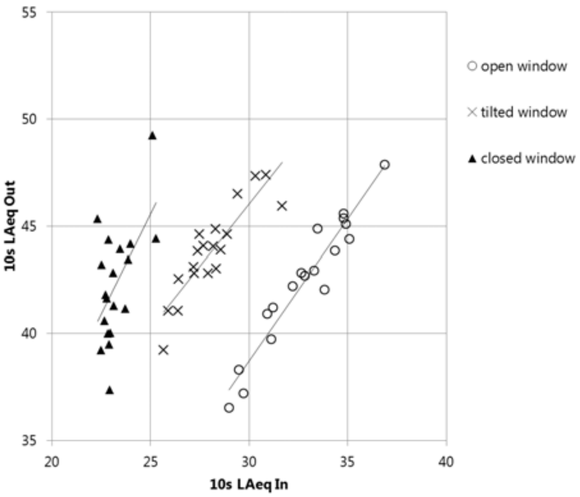


Figure 4.1 Sample of data comparing $L_{Aeq,10s}$ for indoor and outdoor measurements [135]

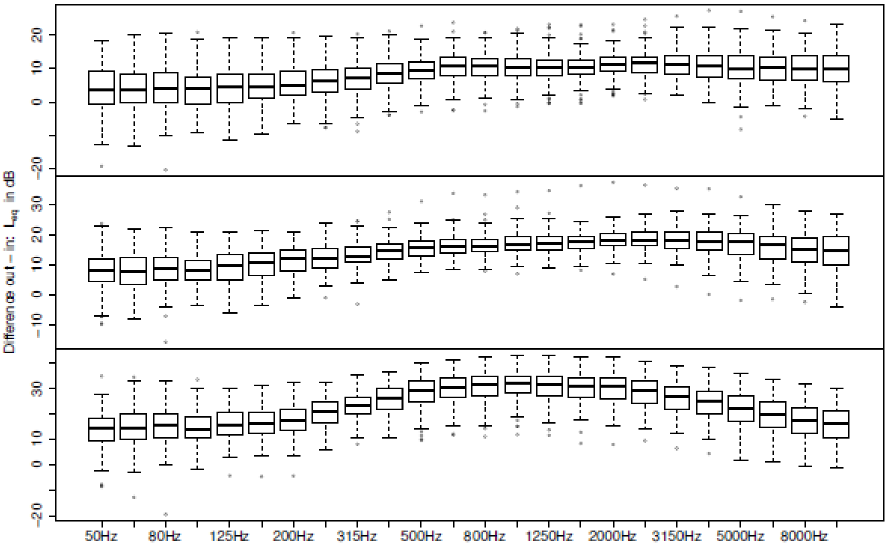
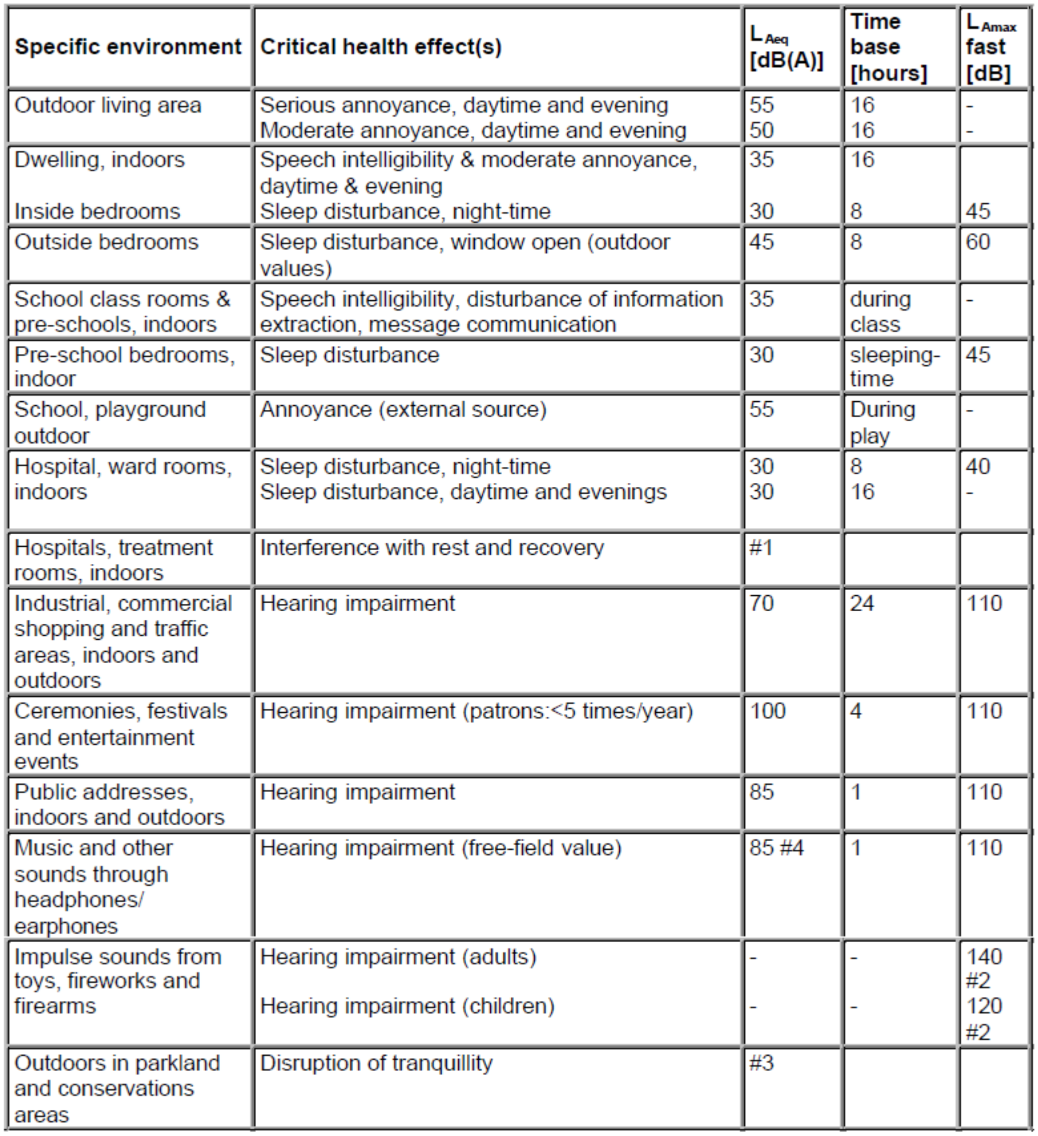


Figure 4.2 Analysis of outdoor-indoor differences over frequency. The top, middle and bottom plots represent data for the open, tilted and closed windows, respectively [135]

There are some important practical aspects of using L_{den} for live event noise monitoring. As the metric utilizes different limits between day, evening and night (which immediately switch over at the defined times), problems have been known to arise when an act's set at an outdoor event spans two of these time ranges. The change in limit during a performance makes on-site and off-site noise monitoring problematic in practice, due to a requirement for a quick cut in sound level (to the detriment of the audience experience). Additionally, it has been observed that the +5/10 dB penalties for night/evening times were arbitrary figures, not necessarily based on any robust scientific underpinnings. The use of L_{den} is therefore currently being questioned by professionals in terms of its suitability for environmental noise monitoring.

Although the 2018 WHO guidelines are meant to supersede the 1999 Community Noise Guidelines [2], due to the insufficient reliable data to present updated limits for leisure noise, the 1999 guidelines are still viewed to be valid, with live event-specific guidelines given in Table 4.1.



Specific environment	**Critical health effect(s)**	**L_{Aeq} [dB(A)]**	**Time base [hours]**	**L_{Amax} fast [dB]**
Outdoor living area	Serious annoyance, daytime and evening Moderate annoyance, daytime and evening	55 50	16 16	- -
Dwelling, indoors	Speech intelligibility & moderate annoyance, daytime & evening	35	16	
Inside bedrooms	Sleep disturbance, night-time	30	8	45
Outside bedrooms	Sleep disturbance, window open (outdoor values)	45	8	60
School class rooms & pre-schools, indoors	Speech intelligibility, disturbance of information extraction, message communication	35	during class	-
Pre-school bedrooms, indoor	Sleep disturbance	30	sleeping-time	45
School, playground outdoor	Annoyance (external source)	55	During play	-
Hospital, ward rooms, indoors	Sleep disturbance, night-time Sleep disturbance, daytime and evenings	30 30	8 16	40 -
Hospitals, treatment rooms, indoors	Interference with rest and recovery	#1		
Industrial, commercial shopping and traffic areas, indoors and outdoors	Hearing impairment	70	24	110
Ceremonies, festivals and entertainment events	Hearing impairment (patrons:<5 times/year)	100	4	110
Public addresses, indoors and outdoors	Hearing impairment	85	1	110
Music and other sounds through headphones/ earphones	Hearing impairment (free-field value)	85 #4	1	110
Impulse sounds from toys, fireworks and firearms	Hearing impairment (adults) Hearing impairment (children)	- -	- -	140 #2 120 #2
Outdoors in parkland and conservations areas	Disruption of tranquillity	#3		

Table 4.1 Community noise guidelines values from 1999 WHO Community Noise Guidelines [2].

The indicated limit of 100 dB L_{Aeq} (over 4 hours) and peak of 110 dB $L_{A,max}$ is what many of the audience exposure limits presented in Section 2 are based on. In practice, a 4-hour integration time is problematic, as over the four-hour period there are likely to be multiple performers on stage, each with a different mix engineer. Should an engineer early on in the event exceed the stated limits, this could result in engineers later in the day effectively being required to turn off the sound system to ensure the 4-hour level reading is at or below the 100 dBA limit. This is clearly unreasonable.

A potential solution to this issue could be to introduce a three-tier level guideline for live events. The first limit will be for peak-levels, the second limit for inter-set levels (15 minutes, covering at most two or three songs) and the third limit spanning the duration of the event. This will ensure that reasonable adjustments can be made throughout the day, where engineers won’t be penalized for transgressions of other engineers. This approach will be discussed in more detail in Section 5, pointing towards necessary further research.

Lastly, on the subject of WHO guidelines, there is considerable information contained within the 2018 report which builds upon what was initially presented in the 2009 WHO Night Noise Guidelines for Europe [3]. Nearly all of these guidelines (1999 and 2018) are focused on road, rail and other non-live event related noises. They look at long-term exposure to such noise in terms of health effects (hearing damage, cardiovascular effects, sleep disturbance, psychological disorders, annoyance, etc.). While impulsive noises are covered in the guidelines, these can't be seen to directly relate to noise pollution from live events, as virtually none of the noise sources covered in these documents contain information.

In this case, information can be viewed as musical content in the noise. It is more likely that individuals exposed to this variety of noise will have lower annoyance thresholds, while adverse health effects from the relatively short and infrequent exposure is unlikely. The problem that must be addressed, therefore, is minimization of annoyance to reduce the risk of formal complaints from the local community, which could easily cause the festival to no longer be allowed to operate at a given site. This topic will be expanded upon in Section 5.

Overall, the WHO guidelines present a step in the right direction and ensure that limits are based on objective and unbiased research. What's clear, though, is that there exists a significant lack of unbiased scientifically-derived knowledge in the area of leisure noise, especially noise stemming from outdoor live events.

4.3. North America

In general, North American countries each have their own federal guidelines regarding noise, with the ability for states/provinces/municipalities to use these to formulate appropriate noise codes/ordinances. This section will highlight some (but not all) of such laws.

4.3.1. Canada

Out of the three countries in North America, Canada appears to be most forward-thinking in terms of defining both indoor and outdoor noise limits, with adjustments based on the impulsiveness of the noise, the time of day, and (in some cases) the specific frequency content and information contained within the noise.

Noise codes are typically set out by the provinces and further defined within municipalities. A selection of noise regulations across Canada is given in Table 4.2.

Location	Year	Measurement method	Indoor (day/night)	Outdoor (day/night)	Impulse?	Events?	Octave bands?	Notes	Ref.
Toronto (advisory)	2015	dBA	50/45	85/60	✓	✓		Clear misunderstanding of what dBA and dBC represent.	[136]
Toronto (law)	2009	LAeq, 5 min		/85		✓		Measured 20 m from event site property line.	[137]
Montreal	2012	LAeq	45/38	60/50	✓	✓		Lower limits for information bearing sound (speech or music).	[138]
Ontario	2013	LAeq, 1 hr	45/40	45/40	✓			Logarithmic Mean Impulse Sound Level (LLM) dBA used for impulsive sounds (industrial).	[139]
Nova Scotia	2005	dBA		65/55				Municipalities still responsible for nuisance noise (music).	[140]
Quebec	2006	LAeq		45/40					[141]
Yukon	2002							Between 11pm - 7am nuisance noise not tolerated.	[142]
Calgary	2004	LAeq or LCeq, 1 hr		/65		✓		Measured level must be at least 5 dB over ambient noise level. 85 dBC limit for night.	[143]
Edmonton	2018	LAeq		75/65				Adjustments detailed for duration of noise.	[144]
Halifax	2005							Prohibited times defined. No limits given.	[145]
Vancouver	2018			60/55		✓		Some measurements in dBA (Leq, 5 min), most are undefined.	[146]
Victoria	2015	LAeq		60/55	✓	✓	✓	Adjustments for tonality in specific frequency bands. Also considers intermittency.	[147]

Table 4.2 Selection of noise regulations in Canada

With the exception of Calgary, all noise regulations surveyed across Canada impose limits based on A-weighted measurements over a defined duration (ranging from 5 minutes to however long the noise persists). As discussed in Section 2, A-weighting is unlikely to capture the primary noise components that will cause annoyance due to outdoor events (usually centered in the 63 or 125 Hz octave band).

In terms of noise limits, there is great variability between provinces/cities. Outdoor daytime limits range from 45 – 75 dBA, where outdoor nighttime limits range from 40 – 85 dBA (note that the 85 dBA limit is specifically for permitted outdoor events and doesn’t represent the noise limit for everyday occurrences [137]).

One of the most comprehensive noise regulations identified across Canada are those of the city of Victoria [147]. Although still using A-weighting, which can cause issues (as will be discussed in Section 5), they provide information to allow for measurements to be adjusted based on tonality and intermittency. This sort of approach is moving in the right direction in terms of converting basic measurements into something that reflects perception. Similar procedures are present in Montreal, where legal noise limits can be adjusted if noises contain information (such as speech or music) [138].

Overall, Canada appears to have some examples of good practice in the area of noise regulations, but there are a few of examples of ill-informed regulations, most commonly due to the misuse of A-weighting, where in one particular case there seems to be a misunderstanding of what the weighting curves represent [136].

4.3.2. Mexico

While there exists considerable information on occupational noise regulations in Mexico, there is very little in the way of regulations focused on noise pollution. The single example identified is the Official Mexican Standard NOM-081-SEMARNAT-1994, which establishes the maximum permissible limits for noise emission of fixed sources and a method of measurement [148]. This law gives ordinary people a chance to defend themselves from "acoustic terrorism."

All measurements are specified as A-weighted, with only outdoor limits given (55 dBA and 50 dBA during the daytime and nighttime, respectively, in residential areas). The standard specifies that for special events, the limit should be 100 dBA on -site over 4 hours, which is directly in line with the 1999 WHO Community Noise Guidelines [2]. Table 4.3 shows the limits described in the standard (translated from Spanish).

Zone	Timetable	Max. permissible limit (dBA)
Residence (outside)	6:00 to 22:00 22:00 to 6:00	55 50
Industrial & commercial sites	6:00 to 22:00 22:00 to 6:00	68 65
Schools (outdoor play areas)	During recess	55
Ceremonies, festivals & entertainment events	4 hours	100

Table 4.3 Noise pollution limits from Mexican Standard NOM-081-SEMARNAT-1994 [148]

It is encouraging that Mexico has taken on board the WHO on-site guidelines for live events (which can't be said for most countries), but like Canada, they still are fixated on using A-weighting which may be missing the primary offending noises due to live events. As mentioned previously, the 4-hour integration time is unreasonable for live event engineers as it makes it extremely difficult to compensate for transgressions earlier at the event.

4.3.3. United States

Within the United States there are three tiers of noise regulations: federal, state and local. The federal regulations are largely used as a framework for states and local communities to write their own laws. The basis of most of this stems from the Environmental Protection Agency's (EPA) Model Noise Ordinance in 1975 [149]. The ordinance makes clear that assessment of unwanted sound (specifically *not* referred to as noise) should be completely objective, requiring no additional subjective assessment. All limits are defined based on measurements taken at property boundaries.

The EPA's 1975 ordinance gives some general guidance regarding what levels pose health risks, considering both continuous and impulsive sounds (Figure 4.3).

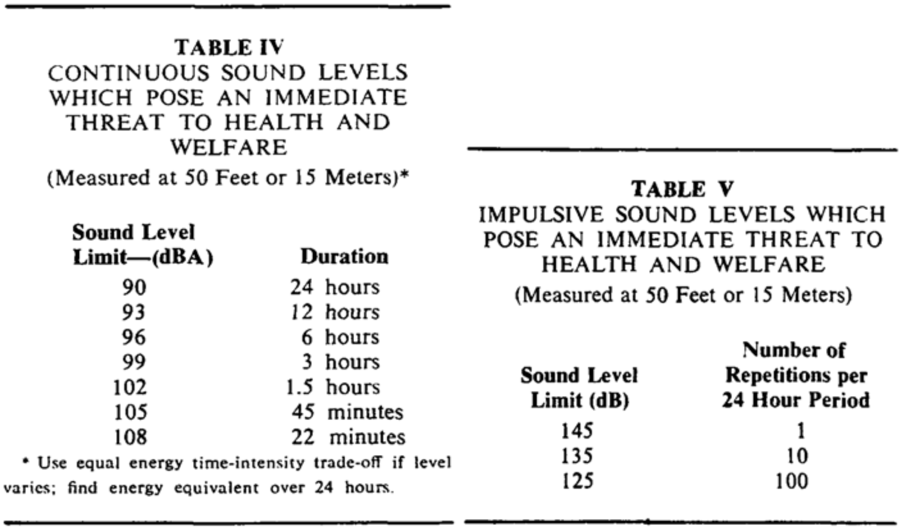


TABLE IV
CONTINUOUS SOUND LEVELS WHICH POSE AN IMMEDIATE THREAT TO HEALTH AND WELFARE
(Measured at 50 Feet or 15 Meters)*

Sound Level Limit—(dBA)	Duration
90	24 hours
93	12 hours
96	6 hours
99	3 hours
102	1.5 hours
105	45 minutes
108	22 minutes

* Use equal energy time-intensity trade-off if level varies; find energy equivalent over 24 hours.

TABLE V
IMPULSIVE SOUND LEVELS WHICH POSE AN IMMEDIATE THREAT TO HEALTH AND WELFARE
(Measured at 50 Feet or 15 Meters)

Sound Level Limit (dB)	Number of Repetitions per 24 Hour Period
145	1
135	10
125	100

Figure 4.3 Levels for continuous (left) and impulsive (right) sounds that pose health risks [149]

An earlier document from the US Department of Housing and Urban Development (called the Noise Guidebook, 1971) sets out acceptable noise levels for various settings in the community (Figure 4.4) [150]. Note that L_{dn} is as described by Eq 4.1, while NEF (Noise Exposure Level) is a coefficient used to represent noise exposure, which was primarily used in the 1970s and 80s, but has since been largely replaced by L_{dn} (or similar metrics).

It may have been possible for clearer federal noise regulations, but the office responsible for regulating and enforcing noise, the Office of Noise Abatement and Control (ONAC) at the United States Environmental Protection Agency (EPA), was defunded by the Reagan administration in 1981. Despite the funding cut (and subsequent closing of the ONAC), the Noise Control Act of 1971 was never repealed, meaning that it exists to this day with no method of enforcement aside from assuming that the individual states will regulate themselves. No replacement has ever been created to fill this void. This is the primary reason why the United States is significantly lagging behind the rest of the Western world in noise regulation and management. It is generally seen as a public policy failure [151].

The existing federal guidelines now only serve to inform the formulation of state and local guidelines. Following this, and considering the size of the United States, it shouldn't be surprising to find that there exist hundreds of noise ordinances/regulations within even a single state (such as California) (Table 4.4). Note that the data in Table 4.4 is taken from a 1997 survey [152], so it should be considered fairly out of date, but still provides a good representation of the complexity of noise law in the United States. It is therefore difficult to formulate an overall impression of noise regulations across the entire country. Instead, a selection of noise regulations will be presented here to provide a general idea of the current situation.

With the exception of Wyoming (the least populous state in the USA), all states have at least one noise law on the books. A sizeable minority of states have regulations which feed into local regulations. A smaller number of states give model ordinances for local governments to adopt for their own regulations. Few regulations give any information on limits for impulsive sound. Fewer still make any mention of outdoor entertainment event noise.

A selection of current noise laws at the federal, state and local levels is presented in Table 4.5.

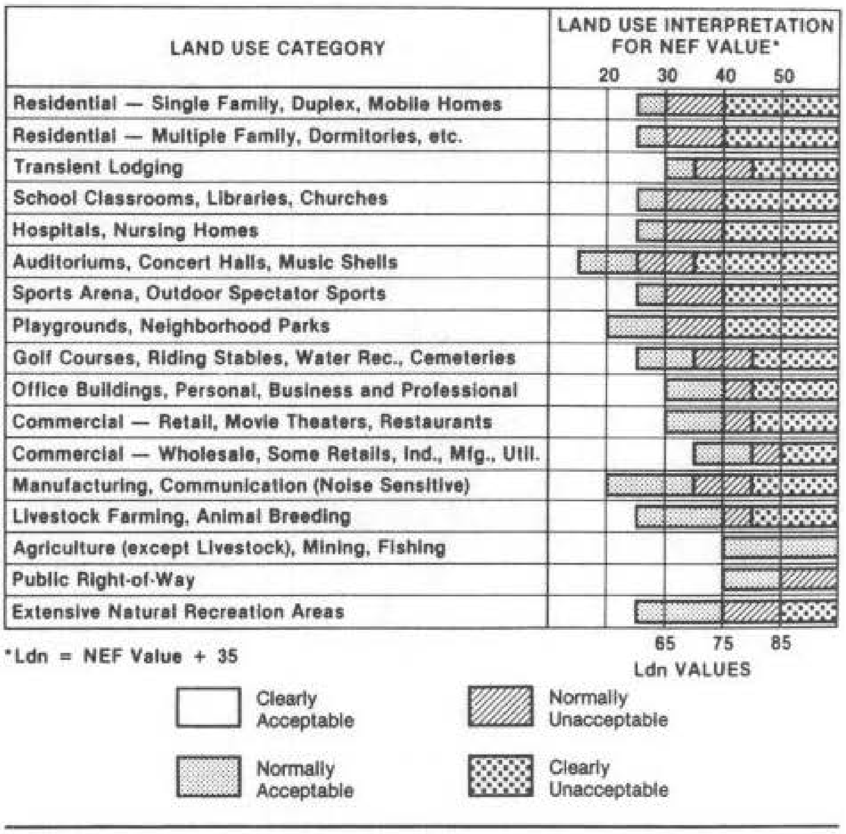


Figure 4.4 Acceptable noise levels for various locations within the community [150]

State	State reg.	Local regs.	Impulse	Model Ord.
AK		1		
AL		6		
AR		5		
AZ		12		
CA		124		✓
CO		15		
CT	✓	8	✓	✓
DC	✓	1		
DE	✓	1	✓	
FL		34		
GA		11		
HI	✓	1	✓	
IA		6		
ID		3		
IL	✓	18	✓	✓
IN		11		
KS		6		
KY	✓	2		✓
LA		6		
MA	✓	13		
MD	✓	5	✓	✓
ME	✓	2		
MI		17		
MN	✓	7		✓
MO		9		
MS		2		
MT		2		
NC		14		
ND		1		✓
NE		2		
NH		2		
NJ	✓	46	✓	✓
NM		4		
NV		5		
NY		19		
OH		9		
OK		6		
OR	✓	12		✓
PA		7		
RI		5		
SC		5		
SD		2		
TN		6		
TX		51		
UT		9		
VA		12		
VT		1		
WA	✓	14		
WI		14		
WV		1		
WY		0		

Table 4.4 1997 survey of noise regulations across the United States [152]

Location	Year	Measurement method	Indoor (day/night)	Outdoor (day/night)	Impulse?	Events?	Octave bands?	Notes	Ref.
EPA	1975	LAeq, 24 hr			✓			Only guidelines for setting up specific limits + info on hearing loss/damage.	[149]
Delaware	1982	LAeq, 24 hr		65/55	✓	✓		Noise must exceed ambient noise level by 10 dBA.	[153]
Illinois	2003	LAeq		Various	✓	✓	✓	Limits based on octave bands. Very specific.	[154]
California	2009	LAeq, 24 hr		50/45	✓			Various corrections for noise characteristics/location.	[155]
Colorado		dBA		55/50	✓			10 dB increase in limits allowed for noises occurring no more than 15 mins/hr.	[156]
Hawaii	1996	dBA (fast)		55/45		✓			[157]
Maryland	2010	LAdn		65/55					[158]
Massachusetts	1990	LA,90						Violation of noise regs if 10 dB above ambient noise.	[159]
Minnesota	2017	dBA (fast)		65/50 (L50)	✓			L10 values also given.	[160]
New Jersey	2012	dBA		65/50	✓		✓	Impulsive sound allowed up to 80 dBA.	[161]
Oregon	2018	dBA		50/45 (L50)	✓	✓	✓	L10 and L1 values also given.	[162]
New York City	2005	dBA					✓	Indoor noise limits (unclear whether day or night).	[163]
Chicago	2006					✓		Can't have sound over conversational level 100' away (unless permit holder).	[164]
Chicago	2019					✓		Must submit noise control plan for approval.	[165]
Los Angeles	2013	dBA		50/40	✓		✓	Corrections: duration, impulsive, steady, time of day. Map sound level to octave bands. Incl. ambient noise level.	[166]
Las Vegas	2017				✓		✓	Limits given for octave bands. Gaming Enterprise District exempt. Limits can be exceeded by 10 dB < 15 mins.	[167]
IFC	2007	LAeq, 1 hr		55/45				3 dB max. increase beyond ambient noise level.	[168]
ASHRAE	2009	NOT dBA					✓	Thorough noise guidelines for HVAC including annoyance quantification.	[169]

Table 4.5 Selection of noise regulations in the United States

With the exception of New York City [163], there is no mention of indoor noise limits (only outdoor values are given). There appears to be less variation in the outdoor limits as compared to Canada, ranging from 50 – 65 dBA during the day and between 40 – 55 dBA at night. Again, all measurements are A-weighted, which can pose an issue in terms of quantifying annoyance due to outdoor events. The guidelines for Los Angeles are particularly detailed, giving correction values for most aspects of a sound (steady/impulsive, frequency content, time of day, ambient noise level, etc.) [166].

While many states give exemptions to these guidelines for permitted outdoor events, very few place stipulations on the requirements of said events in terms of noise pollution. One notable exception is Chicago, which regularly holds large-scale events in its downtown area in the summer. Event organizers must provide details within the permit application covering what the sound system will consist of and how they will control the noise pollution to surrounding areas (with further information required as to how they can further limit noise should it pose a problem as the event progresses) [165]. This should be viewed as an area of good practice, where the local government is placing the noise coordination responsibility on the event organizers, where they must submit in writing their noise control plan (and they will be held to it).

A number of the state ordinances indicate that if no clear local ordinances are available to refer either to the International Finance Corporation (IFC) noise guidelines [168] or the ASHRAE Noise and Vibration Control Guidelines [169]. The IFC guidelines are very brief, stating only that the outdoor noise levels can be no higher than 55 dB and 45 dB during the day and night, respectively. Also, they indicate that noise can cause no more than a 3 dB increase beyond the background noise in residential areas. This relative noise limit is similar to what is increasingly implemented across Western Europe. All measurements are to be taken over one hour with A-weighting.

The ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) guidelines, while seemingly unrelated to outdoor live event noise, are in fact quite useful in terms of mapping noise measurements to annoyance. It is one of the very few published sets of guidelines to recommend against using A-weighting, as it makes clear that most offending noises are in the low-frequency range and therefore not accurately represented by A-weighting. It goes further, stating that single metric noise monitoring isn't useful, as sound propagates in a frequency-dependent manner. It recommends using either one octave or one third octave band measurements of the sound source (or preferably sound power level) and sound level at a distance to better gauge noise pollution issues. This is in line with research findings from a long-term study conducted in Sweden [170].

The ASHRAE guidelines don't go so far as to identify a single method of noise measurement, but they do highlight a small selection of potential metrics, such as NC, RC (Mk 2), NCB and RNC. Many of these methods, though, are focused on rating in-room noise (ASHRAE are interested in HVAC system noise, not leisure noise). It isn't clear whether these metrics would be appropriate for noise originating at outdoor live events (especially due to the infrequent nature of these events).

Of all the noise guidelines/standards/laws reviewed across North America, it appears that the ASHRAE guidelines take the most common-sense and informed approach to quantifying and dealing with noise and should be considered when developing any new and revised noise guidelines specifically for live events.

4.4. Central America

Although nearly every country in Central America has occupational noise exposure regulations, very few countries have any law related to noise pollution and only two countries (Nicaragua and Panama) make any mention of music-related noise [171, 172]. Table 4.6 details the available noise regulations in Central American countries.

Location	Year	Measurement method	Indoor (day/night)	Outdoor (day/night)	Impulse?	Events?	Octave bands?	Notes	Ref.
Belize	2003	dBA		70/45	✓			Limits given based on duration, 3 hr duration given here.	[173]
Costa Rica	2015	dBA		65/45	✓			Adjustments for impact + intermittent noise.	[174]
Nicaragua	2006	Unclear	30	45	✓	✓		Adopted from WHO recs. 110 dB limit on event sites. 45 dB limit for impulsive sound.	[171]
Panama	2002	dBA	50/45	55/50		✓		Ambient noise must be considered. Music sources = 65 dBA max.	[172]

Table 4.6 Selection of noise regulations in Central America

While there aren't nearly as many laws in place to control noise pollution as there are in North America, the Central American laws are all relatively new, indicating that these countries are only beginning the process of addressing these issues. Of the identified regulations, half of them specify both indoor and outdoor limits as well as considerations for outdoor events (generally indicating that permits can be granted for exemptions from regulations within certain times). Like all of the North American regulations, dBA is used exclusively.

In Panama's regulations, music-based noise is allowed up to 65 dBA, but only in non-residential areas. Presumably, this is to ensure commercial establishments can have live music or music playback for their customers. Nicaragua gives an on-site limit for event sites at 110 dB, which is in line WHO guideline's peak limit. It is unclear what weighting is to be used when making measurements and whether the 110 dB is a peak limit measured with C-weighting. If so, this would be in line with the WHO guidelines, but the ambiguity in the regulations here makes it likely that it will be used incorrectly.

4.5. South America

The situation in South America is similar to that in Central America, where it appears that work has been taking place in recent years to develop suitable noise regulations beyond the existing occupational noise laws. Table 4.7 details the surveyed noise regulations in South American countries.

Of the South American countries, Argentina and Brazil have the most extensive noise codes, with many large cities in these countries possessing detailed laws which expand upon the national laws. Only Rio de Janeiro in Brazil has any regulations focusing on noise within living environments (in this case focused on ensuring people's comfort) [175].

Of the examined regulations, only Colombia's has any information on frequency-specific limits/adjustments. All others primarily use A-weighted measurements. The limits across countries are generally in agreement (typically 50 or 55 dBA during the day and 45 dBA at night), but there are some exceptions. For example, Guyana allows 75 dBA during the day and 60 dBA at night [176], which seems to be entering the territory of hearing damage with long-term exposure. Virtually no attention is paid to event-based noise in any of the reviewed regulations.

Location	Year	Measurement method	Indoor (day/night)	Outdoor (day/night)	Impulse?	Events?	Octave bands?	Notes	Ref.
Argentina	2012	dBA		55/45	✓			Adjustments for zone, impulse, holiday.	[177]
Rosario, Argentina	2012	dBA		/45	✓			65 dBA for frequent peaks, 70 dBA for infrequent peaks.	[177]
Party de La Plata, Argentina	2012	dBA		60/	✓				[177]
Brazil	2003	LAeq		50/45	✓			Evaluation of noise in inhabited areas, aiming at the comfort of the community.	[178]
Rio de Janeiro, Brazil	1992	dBA + NC	45/35					Noise limits for comfort (indoor values only).	[175]
Curitiba, Brazil	1995	dBA		55/45					[179]
Sao Paulo, Brazil	2016	dBA		50/45					[180]
Chile	2011	NPC dBA		55/45				Or 10 dB over ambient noise.	[181]
Colombia	2007	LAeq		65/55	✓		✓	Adjustment values for duration, frequency content, impulsiveness. Very thorough.	[182]
Guyana	2000	Unknown		75/60		✓			[176]
Peru	2003	LAeq		60/50					[183]
Venezuela	1992	LAeq		55/45	✓			Or 10 dB over ambient noise.	[184]

Table 4.7 Selection of noise regulations in South America

4.6. Europe

Of all the regions in the world, Europe is most forward-thinking in terms of noise regulation for entertainment events (and general consistency of environmental noise regulations). This is in large part thanks to the clear guidelines developed by the WHO over the past twenty years focused on community noise in Europe.

This is not saying that the noise regulations in Europe are perfect. There is room for improvement and expansion. Tables 4.8 – 4.10 give a collection of general environmental noise regulations from countries in the European region. The vast majority of regulations here are based on LAeq measurements, meaning that annoyance due to low-frequency musical content will be missed by such approaches and may not give a clear indication of the true situation regarding noise pollution from outdoor entertainment events.

An emerging trend in the European regulations (which can be seen elsewhere in the world, but not to the same extent) is setting noise limits relative to ambient noise levels (typically allowing for somewhere between 3 – 15 dB of noise above the ambient level). This seems to be very reasonable, as background noise levels vary significantly from region to region and city to city. There exist numerous studies on this, but aren't presented here, as this would be beyond the scope of this work.

Most EU countries have adopted the use of L_{den} for noise monitoring, where individual limits for day, evening and night are presented in their respective regulations (only day and night limits are given in this report's tables). Counties such as Denmark, France, Ireland, Slovakia and the UK have separate limits for the low-frequency bands (typically defined as 63 and 125 Hz, but extended to 32 Hz for some city limits, such as in parts of London).

Out of the 37 European countries surveyed, only 16 make specific reference to entertainment/event noise in their national (Tables 4.8 – 4.9) or local regulations (Table 4.11). These counties include: Austria, Belgium, Croatia (Zagreb), France, Finland (Tampere), Germany (Munich), Greece, Hungary, Ireland (Dublin), Italy (Florence and Turin), Netherlands (Utrecht and The Hague, as well as most other cities), Norway, Portugal, Spain, Sweden (Stockholm), Switzerland and the UK (national and London and Manchester).

Of the specific entertainment event regulations, there is a moderate amount of variation across those surveyed, but the general trend is that higher-profile events tend to be granted more leeway in terms of noise pollution (upwards of 85 dBA in residential areas), usually up to 11pm. Similar noise curfews exist in cities across the world, where breach of the curfew can result in heavy fines and revocation of an event's permits.

The improved consistency of the European regulations as compared to the rest of the world should be attributed to the work of the WHO in publishing their clear guidance for community and night noise [1, 3, 2]. While there still exists variation between countries (especially on the local level), outliers are few and far between, with the trend being that of caution rather than negligence.

Despite the continued work in Europe to appropriately address the issue of community noise, there still appears to be more work needed in the area of outdoor entertainment events, largely focused on appropriate characterization of the music-based noise and how it specifically relates to annoyance, which will be the primary reason for complaints from the community.

There is a fair amount of evidence indicating that communication with the local community prior to an event goes a long way in limiting complaints [185, 186, 187, 188], as they will have the understanding of the time limits of the noise and what is being done to minimize any intrusion into their lives. Additionally, steps have been taken in certain cases where a noise hotline is put into place, allowing residents to phone in concerns about noise as an event progresses, giving them a certain sense of control over the noise. These aspects of noise management will be addressed in Section 5.

Location	Year	Measurement method	Indoor (day/night)	Outdoor (day/night)	Impulse?	Events?	Octave bands?	Notes	Ref.
Albania	2007							Limits according to WHO guidelines (1999 CNR).	[189]
Armenia	2002	LAeq		55/45				Max limits (LAmax) = 70/60 dBA.	[190]
Austria	2000	LAeq		80/60		✓		Normal limits = WHO. Levels for permitted events (decrease with freq. of events/year). Guidelines for sound system design.	[191]
Austria	2010	LAeq		50/40	✓			Various adjustments indicated. Focused on road/rail noise.	[192]
Azerbaijan	2008	LAeq		55			✓	<63 Hz considered vibrations (different limits).	[193]
Belgium	2018	LAeq, 1hr	33/28	45/35	✓	✓		Normal limits = WHO. Above 100 dBA LEQ 1hr forbidden. Peak given for LAeq, 1s, max.	[59]
Bosnia and Herzegovina	2012	LAeq		55/45				Normal limits = WHO. Peak limits also given (L10 = 65A dB, L1 = 70 dBA).	[194]
Bulgaria	2006	LAeq	35/30	55/45	✓			Normal limits = WHO. +5 dB for impacts. Ordinance 9/2010 gives infrasound limits.	[195]
Croatia	2004	LAeq		55/40				Normal limits = WHO.	[196]
Cyprus	2006	LAeq		50/35				Also following WHO guidelines (1999 CNR).	[197]
Czech Republic	2006	LAeq		50/40				Corrections details for music (-5 dB).	[198]
Denmark	2012	Lr, LAeq	30/25	45/40	✓		✓	5 dB penalty for impulse and tonal noise. Correction also given for noise duration. Limits for infrasound are also given (Lael + LGeq).	[199]
Denmark	2001	LAeq, LGeq	25/20 85/85					Focus on LF noise and infrasound.	[200]
Estonia	2016	LAeq		50/40	✓		✓	Corrections for tonality/impulsiveness. Focused on traffic/industrial noise.	[201]
Finland	1992	LAeq		55/45	✓		✓	5 dB penalty for impulse and tonal noise.	[202]
France	2017	LAeq				✓	✓	Leq or indiv. bands = no more than 3 dB above ambient noise for music-based signals at night. 7 dB excess allowed for 125/250 Hz bands.	[203]
France	1998	LAeq, 30 min	22			✓	✓	Limitation a LF (66 - 75 dB sound insulation required in venues). No more than 3 dB above ambient noise 125 Hz to 4 kHz.	[204]
Germany	1998	LAeq	35/25	55/40	✓			Short duration peaks can't go more than 10 dB above state limits.	[205]
Greece	2012	LAeq		55/45		✓		Limits to avoid disturbance of sleep due to recreation activities.	[206]
Hungary	2007	LAeq		50/35	✓	✓		Correction equation for leisure noise.	[207]
Iceland	2016	LAeq	30/25	50/40					[208]

Table 4.8 Selection of general noise regulations in Europe – part 1

Location	Year	Measurement method	Indoor (day/night)	Outdoor (day/night)	Impulse?	Events?	Octave bands?	Notes	Ref.
Ireland	2016	LAeq		55/45	✓		✓	Corrections for tonality based on frequency band. Specific emphasis on addressing LF noise. 5 dB penalty for impulsive noise.	[209]
Italy	1997	LAeq		50/40				Mostly focused on traffic noise.	[210]
Italy	1997	LAeq, 1min	25	40				Outdoor value for open window. No more than 3 dB above ambient noise.	[204]
Latvia	2014	LAeq		55/45	✓		✓	Corrections for impulsiveness and tonality.	[210]
Lithuania	2011	LAeq	45/35	55/45	✓			Corrections for impulsive noises.	[210]
Luxembourg	1990	LAeq		55/40				Based on German laws.	[210]
Malta	2013	LAeq		55/45				No formal limits set, but recommendations for traffic noise given.	[210]
North Macedonia	2015	LAden	40/30	50/40	✓			Based on EU DIRECTIVE 2002/49/EC.	[211]
Norway	1997	Lael	/25	35				Max values = 30 dBA, 45 dBC. Entertainment venue limits also given (95 dBA Leq, 110 dBA fast, 130 dBC peak).	[204]
Poland	2002	LAden		55/45				Based on EU DIRECTIVE 2002/49/EC.	[212]
Portugal	2007	LAeq		55/45				Does not apply for outdoor ambient levels below 45 dBA or indoor levels below 27 dBA.	[213]
Portugal	2000	LAeq, 22h-7h				✓		Music-based noise no more than 3 dB above ambient level.	[214]
Romania	2014	LAeq	35/30	55/45					[215]
Serbia	2009	LAeq	35/50	55/45	✓			Based on EU DIRECTIVE 2002/49/EC.	[216]
Slovakia	2006	LAeq, 24 hr	40/30	55/45	✓		✓	Also includes infrasound limits (G-weighted), various corrections for noise characteristics.	[217]
Slovenia	2004	LAeq		55/45					[218]
Spain	2007	LAeq	40/30	65/55	✓	✓	✓	5 dB penalty for transients. Indoor limits of 35/25 dBA for adjacent premises activities.	[219]
Sweden	1998	LAeq	/30	50/40	✓			Largely focused on traffic noise. 5 dB allowance for occasional noises at night.	[220]
Switzerland	1986	LAeq		55/45	✓		✓	Corrections for impulsive noise and music.	[219, 220]
Switzerland	1999	LAeq, 10s	34/24	44/34	✓	✓	✓	Corrections for impulsiveness and tonality.	[204]
Turkey	2010	LAeq		60/50				Mostly focused on industrial noise.	[221]

Table 4.9 Selection of general noise regulations in Europe – part 2

Location	Year	Measurement method	Indoor (day/night)	Outdoor (day/night)	Impulse?	Events?	Octave bands?	Notes	Ref.
United Kingdom	2011	LAeq, 15 min		75,65 +15		✓	✓	For concerts (based on number of events per year and location, +15 dB above LA90 is absolute limit). 63/125 Hz = 70 dB OK, 80 dB causes disturbance. Overnight events can't be audible in bedrooms with open windows. No more than 15 dB above ambient level for concerts. See Table 5.2 for further details.	[185, 203, 222]
United Kingdom	2014	LAeq, 15 min			✓		✓	Details correction values for impulsive + tonal noises.	[223]
United Kingdom	2009	LAeq		65/45	✓	✓		Focused on construction site noise. Adjustment of limits + times based on ambient noise.	[224]

Table 4.10 Selection of United Kingdom noise regulations

Location	Year	Measurement method	Indoor (day/night)	Outdoor (day/night)	Impulse?	Events?	Octave bands?	Notes	Ref.
Zagreb, Croatia	2011	LAeq		50/40		✓		Predominantly commercial zones limits = 65/50 dB.	[203]
Tampere, Finland	2011	LAeq, 10 min		/75		✓		Special exception limits = 85 dB.	[203]
Munich, Germany	2011	LAeq, 1 or 2 hr		65, 55		✓		First limit between 20:00 - 22:00, second limit after 22:00.	[203]
Dublin, Ireland	2011	LAeq, 15min		/75		✓		Noise curfew = 11pm. Limited number of events allowed per venue.	[203]
Florence, Italy	2011	LAeq, 15min		70/60		✓		Special exception limits = 80/75 dB. Maximum event length = 3 days.	[203]
Turin, Italy	2011	LAeq, 30min		/70		✓		If traffic noise > 65 dB (1 hr Leq), limit raises to 73 dB. Big-named concerts have limit of 80 dB.	[203]
Utrecht, Netherlands	2011	LAeq, 2 min LCeq, 2min		80, 90		✓		Measured at closest house to event or 100m from source (inner city), 200 m from source (outer city).	[203]
The Hague, Netherlands	2011	LAeq, 10 min		75		✓		Very large concerts limit = 85 dB. Noise curfew = 11pm. Limited number of events per venue.	[203]
Stockholm, Sweden	2011	LAeq, 15/30min		50/40		✓		Specifically for outdoor events.	[203]
Manchester, UK	2015	Leq	47, 41			✓	✓	Unweighted Leq for 63/125 Hz (music noise). Makes clear existing standards are not appropriate for LF noise evaluation. Limits given for 63 Hz and 125 Hz bands.	[225]
London, UK	2008	Leq, 15min		80		✓	✓	London Borough of Lambeth. Unweighted measurements at any octave band from 32 - 125 Hz can't be above 80 dB. Called Bass Music Noise Level (BMNL).	[226]

Table 4.11 Selection of entertainment event specific noise regulations for selected cities in Europe

It is instructive to inspect the work carried out in the UK over the past 25 years. In 1995, the Noise Council published its Code of Practice on Environmental Noise Control at Concerts [222]. The recommendations contained in this document are reflected in the first entry for the UK in Table 4.10

and are used extensively by UK acoustic consultants for noise control and monitoring of outdoor events as well as by local councils for setting noise limits for infrequent outdoor events.

The Noise Council Code of Practice is used to this day in the UK for noise control purposes. The Council was dissolved shortly after publication of the document, resulting in no updates based on new knowledge. This means that it should be used with caution and it should be seriously considered whether an updated code of practice is required, nearly twenty five years after the original code's publication. It is important to note that the code gives information based on one-octave frequency bands, but in industry this is often misrepresented as one-third octave bands, resulting in poorly informed (and ineffective) methods of noise pollution control from large outdoor events.

Currency and misinterpretation of the code aside, it has been the basis of a number of in-depth studies into entertainment noise pollution, largely supported by DEFRA in the UK. This will be discussed in detail in Section 5.1. There is also an interesting historical regulation from Edinburgh, Scotland which was based on inaudibility of music-based noise in residences. This will also be highlighted in Section 5.1 as a cautionary tale of overly-restrictive noise regulations.

At the writing of this report, a working group within the UK's Chartered Institute of Environmental Health was in the process of drafting a "Good Practice Guide for Noise Control at Outdoor Concerts and Similar Events." This work has the potential to bring outdated practice contained within the 1995 code of practice up to date to allow for more effective noise monitoring and management at events.

4.7. Asia

Tables 4.12 and 4.13 present a survey of regulations across Asian countries. Interestingly, most of these regulations were discovered through official environmental impact reports from mining and construction companies bidding for projects in these countries (the regulations were extremely difficult to find through official governmental channels). It appears than many Asian countries based their environmental noise laws on the recommendations of the World Bank Group (which correspond to the IFC recommendations [168]) (Figure 4.5).

An example of good practice in Asia can be seen in the regulations of Taiwan [227]. Taiwan considers both traffic noise and entertainment noise and splits limits between wideband noise and low-frequency noise. Dubai imposes strict indoor noise limits (30 dBA during the night) [228], where these limits are based on British Standard BS8233:1999 [229], although caution must be exercised here as these regulations are not based on infrequent entertainment noise. Kuwait, Mongolia and Tajikistan have similar limits.

Location	Year	Measurement method	Indoor (day/night)	Outdoor (day/night)	Impulse?	Events?	Octave bands?	Notes	Ref.
Afghanistan	2007	dBA		65/45					[230]
Armenia		dB		40/30					[231]
Azerbaijan	2008	dBA		55				65 dBA allowed for road vehicles.	[232]
Bahrain				55/45				Same as WHO 1999 CNR.	[233]
Bangladesh	1997	LAeq		50/40					[234]
Bhutan	2010	dBA, max		55/45					[235]
Cambodia	2000	dBA		60/45					[236]
China	2011	dBA		55/45				Unclear if these are current regulations.	[237]
India	2000	LAeq		55/45		✓		Sound from loudspeakers can't be any more than 5 dB about ambient level. Permits allow relaxation of limits.	[238]
Iraq	2015	dBA		55/45					[239]
Israel	1990	LAeq		45/35	✓		✓	Time-based limits. Tonality + impulsive corrections. Limits to level above BG noise.	[240]
Japan	1998	dB		55/45				Noise control must be applied if night time levels exceed 73 dB.	[241]
Kazakhstan	1997	dBA		70/				Focused on road noise.	[242]
Kuwait	2001	dBA	40/30	50/45				Ultrasonic limits given by frequency band (unweighted), for occupational noise.	[243]
Kyrgyzstan	1994	Leq		55/45				Maximum values = 70/60 dB.	[244]
Laos	2009	LAeq, 24hr		55/45					[245]
Lebanon	1996	LAeq		50/45					[246]
Malaysia	2007	LAeq		55/45					[247]
Maldives	2018	LAeq		55/45				Follows World Bank Group guidelines.	[248]

Table 4.12 Selection of noise regulations in Asia – part 1

Location	Year	Measurement method	Indoor (day/night)	Outdoor (day/night)	Impulse?	Events?	Octave bands?	Notes	Ref.
Mongolia	2016	LAeq	/30	55/				Unclear if limits are law or based on other recommendations.	[249]
Myanmar	2015	dBA		55/45				Maximum 3 dB increase to ambient noise levels.	[250]
Oman	2001	LAeq		55/45				Higher limits for road and aircraft noise.	[251]
Pakistan	1997	dBA		55/45				Limits are recommendations. Currently not part of the environmental law.	[252]
Philippines	1976	dB		55/45					[253]
Qatar	2002	dB		55/45					[254]
Russia	2019	LAeq		55/45	✓		✓	Maximum limits = 70/60 dBA. Octave bands for steady and impulse noises. Infrasound limits included.	[195]
Saudi Arabia	2015	LAeq		55/45				Metrics to predict annoyance and sleep disturbance.	[255]
Singapore	2018	LAeq, 15 min		65/55	✓		✓	Focused on HVAC systems. Corrections for tonality, impulsiveness, LF noise (using LCeq) and intermittent noise.	[256]
South Korea	2010	dBA		65/60		✓		Different limits based on where sound is generated (outdoor given, indoor = 55/45). Applies to music venues.	[257]
Sri Lanka	1996	LAeq		55/45	✓		✓	Noise no higher than 3 dB above ambient noise. Corrections for impulsive/tonal noise.	[258]
Taiwan	2008	LAeq		37/27 57/47		✓	✓	Separate LF and WB limits (LF+WB given here). Limits for entertainment noise. Evening levels over 40 dBA must implement noise control.	[227]
Tajikistan	1996	dBA	40/30	55/45	✓		✓	Octave band limits also given. Impulsive/tonal corrections provided.	[259]
Thailand	2007	LAeq, 24hr		70				Maximum limit = 115 dBA. Avoid 10 dB over ambient noise to prevent annoyance.	[260]
Timor-Leste	2002	LAeq		55				Based on World Bank Group guidelines. 3 dB above ambient noise allowed.	[261]
Turkey	2010	LAeq		60/50				No more than 5 dBA above background noise.	[228]
Dubai, UAE	1999	LAeq	35/30	50/40	✓		✓	Based on BS8233:1999.	[262]
Uzbekistan	1996	dBA	65/60	75/75				Level can't be more than 3 dB over ambient noise.	[263]
Vietnam	2010	LAeq		70/55				Follows ISO 1996-2:2007.	[264]
Yemen	2008	dBA		55/45					[229]

Table 4.13 Selection of noise regulations in Asia – part 2

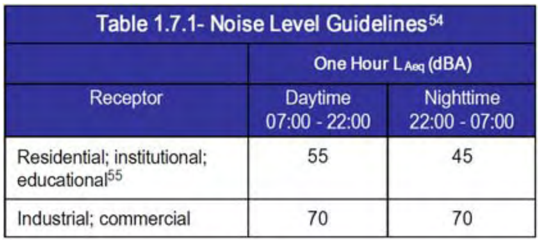


Table 1.7.1- Noise Level Guidelines[54]

	One Hour L_{Aeq} (dBA)	
Receptor	Daytime 07:00 - 22:00	Nighttime 22:00 - 07:00
Residential; institutional; educational[55]	55	45
Industrial; commercial	70	70

Figure 4.5 IFC/WBG noise level guidelines [168]

On the other side of the spectrum, countries such as Kazakhstan, Vietnam and Thailand have noise limits that are either based on extremely high ambient noise levels or are simply unfit for purpose [242, 263, 260]. In the case of Kazakhstan and Vietnam, the former may be the case, as all regulations seem solely focused on road noise. In Thailand, however, this does not seem to be the case. The 24-hour LAeq limit is 70 dBA with a maximum limit of 115 dBA. Additionally, the regulations state that 10 dB over the ambient noise should be avoided to minimize annoyance. The relative limit seems roughly sensible, but allowing for 70 dB across the entire 24-hour day appears to be very generous and may not help to mitigate any noise problems.

Overall, Asian noise regulations are much more consistent than in the Americas, largely thanks to the guidelines set out by the World Bank/IFC. Only India, South Korea and Taiwan give any indication of limits for entertainment-based noise, so there is more work to be done to ensure live events can take place without causing serious disruption to local communities.

4.8. Africa

A selection of environmental noise regulations across the countries of Africa can be seen in Table 4.14. Only 18 out of the 52 countries in Africa are represented in the table, as there were no regulations identified for any of the other countries.

Of the countries surveyed, there exists consistency between regulations, largely due to most regulations being based on the WBG recommendations [168] or the 1999 WHO community noise guidelines [2], which are around 55 dBA and 45 dBA for daytime and nighttime, respectively.

The countries of Liberia, Nigeria and Uganda have regulations specifically targeting entertainment (music) based noise. The regulations for these three countries [265, 266, 267] are identical and appear to have originated with Uganda's 2003 regulations [267]. They limit noise coming from entertainment venue or event to 60 dBA during the daytime and 40 dBA during the nighttime. All values are set for outdoor measurements in residential areas.

With the exception of a few countries where weighting isn't specified, all African countries use A-weighting. Integration time for Leq is only mentioned specifically for Cameroon [268], where 1-hour measurements are required. Additionally, the Cameroon regulations specify a relative noise limit of no more than 3 dB above ambient noise. While no entertainment-specific regulations are given, Cameroon's regulation for relative noise level is in line with trends seen in European regulations of recent years and should be considered an example of good practice (along with the three countries identifying limits for entertainment-based noise).

Location	Year	Measurement method	Indoor (day/night)	Outdoor (day/night)	Impulse?	Events?	Octave bands?	Notes	Ref.
Algeria	1993	LAeq		70/40				Information on façade sound insulation requirements.	[269]
Cameroon	1998	LAeq, 1 hr		55/45				Follows World Bank Group guidelines (1998). No more than 3 dB above ambient noise.	[268]
Congo, Democratic Republic of the	2007	dBA		45/40					[270]
Egypt	1994	LAeq		60/50					[271]
Eritrea	2010	LAeq		55/45				Based on World Bank Guidelines. No more than 3 dB above ambient noise.	[272]
Ghana	2008	dBA		55/48					[270]
Kenya	2009	LAeq + NR	45/35	50/35				NR limits = 35/25 indoor, 40.25 outdoor.	[273]
Liberia	2017	LAeq		50/35	✓	✓		60/40 limits for noise from entertainment venues.	[274]
Mauritius	2007	LAeq		60/50					[270]
Nigeria	2009	LAeq		50/35	✓	✓		60/40 limits for noise from entertainment venues. Identical to Uganda's 2003 limits.	[266]
Rwanda	2014	dB, max	55/45	55/45	✓				[274]
Senegal	2001	dB		55/40					[275]
Seychelles	2007	LAeq		60/55	✓				[270]
Sierra Leone	2015	dB		35-40					[276]
South Africa	2008	LAeq		50/40	✓		✓	In line with WHO CNR 1999.	[277]
Tanzania	2015	LAeq		50/35					[239]
Uganda	2003			50/35	✓	✓		60/40 limits for noise from entertainment venues.	[267]
Zimbabwe	2002	LAeq		55/35				Based on WHO guidelines. Permits available for events.	[278]

Table 4.14 Selection of noise regulations in Africa

4.9. Australia and Oceania

Of the countries in the Australia and Oceania region of the world, only Australia and New Zealand's regulations were identified in this study (Table 4.15). The regulations between these two countries are consistent, calling for LAeq, 15min measurements and outdoor residential limits of around 55 dB and 45 dB for daytime and nighttime respectively.

Interestingly, Australia's national guidelines specify penalties to the published limits for each "characteristic" contained in the noise, which can be taken to refer to information carried within the noise (such as is the case with music). One characteristic results in the limits dropping by 5 dB, two characteristics give a drop of 8 dB and 3 or 4 characteristics result in 10 dB subtracted from the limits [279]. A separate document specifies what's required for outdoor event noise in Australia [280].

In New Zealand, there aren't penalties due to noise characteristics, but there are adjustments to the limits based on level in each octave band as well as based on the duration of a noise [281]. The national regulations are clearly designed to allow scope for setting local noise limits. An example is given in Table 4.14 with Auckland's noise regulations [282]. These regulations build upon the national regulations by specifying octave band noise limits for indoor measurements with an overall outdoor limit given based on Ldn.

While Australia and New Zealand are more advanced than many countries in the world in terms of noise regulations, the complete lack of regulations for the remainder of the countries in the region point to the need for further work in this area (although most of these countries are classed as micro-nations, so it may be the case that they don't host large-scale outdoor events, making well-defined entertainment-related noise limits unnecessary). Australia and New Zealand's regulations, though, should be seen as examples of good practice, with sensible and clearly-defined noise limits/guidelines. The potential issue of measuring with A-weighting is avoided with octave band limits (or similar).

Location	Year	Measurement method	Indoor (day/night)	Outdoor (day/night)	Impulse?	Events?	Octave bands?	Notes	Ref.
Australia	2007	LAeq, 15min		52/45	✓	✓		Noise with 1, 2, 3/4 "characteristics" = 5, 8, 10 dB penalty, respectively. Event instructions in separate document [280].	[279]
New Zealand	2008	LAeq, 15min		55/45			✓	Noise duration adjustments. LAFmax = 75 dB. Adjustments for tonality by freq. band. Guidelines for setting local limits.	[281]
Auckland, NZ	2013	LAeq, 15min	45/35	50			✓	Octave band limits given (for internal measurements). Outdoor limit is Ldn.	[282]

Table 4.15 Selection of noise regulations in Australia and New Zealand

4.10. Discussion

As demonstrated in this section, noise regulations vary widely across the world. In some regions, such as Europe, the regulations have been going through a refinement process for many years, while in other regions, such as parts of Asia, the regulations are in the formative stages with high variability from country to country. In large countries such as Canada and the United States, national noise regulations aren't very prescriptive, but instead provide guidance for formulating regulations on the state/province or local level. While a reasonable approach on the surface, due to the varying requirements and characteristics of localities across these vast areas, the differing regulations from city to city in some instances can cause a great deal of confusion, especially for touring acts. The American state of California, for instance, has well over 100 local noise ordinances in place. In this instance the approach could be seen as counterproductive, where a state-wide regulation may be more appropriate for ease of implementation and enforcement (especially in the case of entertainment events).

Looking specifically into entertainment event noise-related laws, the countries possessing these are in a small minority across the world. Countries such as (but not limited to) France, The Netherlands and Australia demonstrate good practice in this area, but their approaches are widely different. This stems from the lack of thorough research into the area of noise pollution from such events. It is still encouraging, though, that countries such as these are attempting to address the growing issue.

The majority of countries with noise regulations specify measurements using the A-weighting scale over a specified time interval (Leq). While A-weighting may be suitable for general environmental noise monitoring, it is clear that such measurements will miss potentially annoying low-frequency noise. A few countries (such as Denmark and The Netherlands) give additional limits for C-weighting and/or G-weighting (infrasound) to account for this. A more focused discussion on the suitability of the various weighting curves in terms of noise annoyance will be given in Section 5. Time intervals range from 10 seconds to 24 hours. The extremes of this range are unsuitable for the dynamic nature of outdoor events. Looking through event-specific regulations, a 15-minute integration time appears to be favored, which roughly corresponds to three songs in a band's set.

Looking at the bigger picture across the world, histograms can be generated to view the trends in residential noise limits between daytime and nighttime and indoor and outdoor (Figure 4.6).

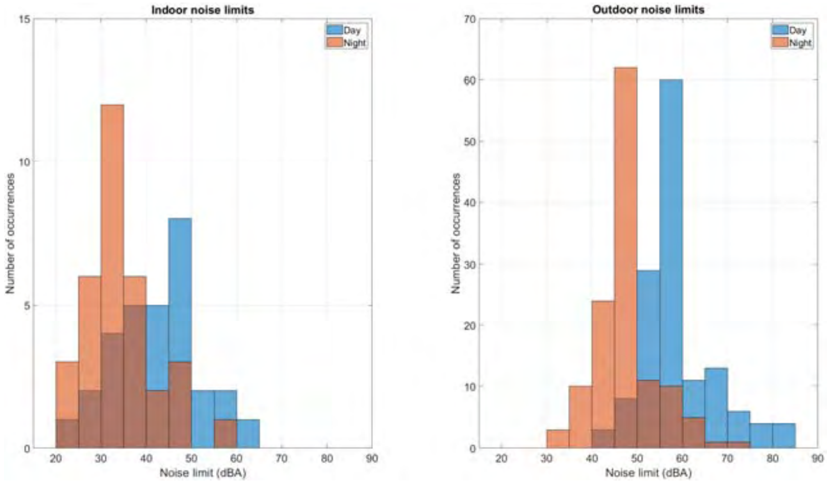


Figure 4.6 Histograms of indoor and outdoor residential noise limits from countries across the world

While the spread of limits is quite wide (45 dB and 55 dB for indoor and outdoor limits, respectively), the general consensus and the moment is for indoor day/night limits of 50/30 dBA and outdoor day/night limits of 60/50 dBA. Although it's potentially dangerous to follow general trends in data, in this case it can be assumed that at least some of these noise regulations are rooted in a certain level of scientific understanding. The data is therefore indicative of what's deemed acceptable levels of environmental noise in residential areas across the globe (though perhaps not a good indicator of acceptable levels of entertainment event-derived noise).

5. Noise prediction, measurement, monitoring + management

Considering the complexities involved with setting effective and practical noise regulations, as discussed in Section 4, it may be surprising to find that defining noise limits is relatively easy compared to predicting and monitoring in-situ noise. This section looks into current capabilities in terms of noise prediction, measurement and real-time monitoring as well as noise management techniques.

A question affecting all of Section 4 (on noise regulations) is what level of entertainment event-derived noise is problematic in residential areas? It is unlikely that such noise will pose significant health risks due to the infrequent nature of outdoor events. The likely effect of event noise in residential areas is annoyance. As the issuance of many event permits are dependent on the potential for annoyance (to minimize complaints from nearby communities), it is essential to understand what constitutes an annoying sound.

This section begins with a broad overview of published literature on noise-based annoyance. With a general understanding of the likely offensive levels of noise, consideration can be given on how to best approach regulation. This is essential, as it is often the case that meeting local/national noise regulations does not adequately limit the level of noise-based annoyance. The result is neighbor complaints will persist and cause issues for event organizers. We then present an overview of the differing regulations for measuring and monitoring environmental noise.

The second half of this section will focus on noise prediction, monitoring and management practices. A few software packages for these purposes will be highlighted. A selection of case studies is presented to illustrate how noise monitoring can be used in a pragmatic way to mitigate problems stemming from noise pollution from outdoor events.

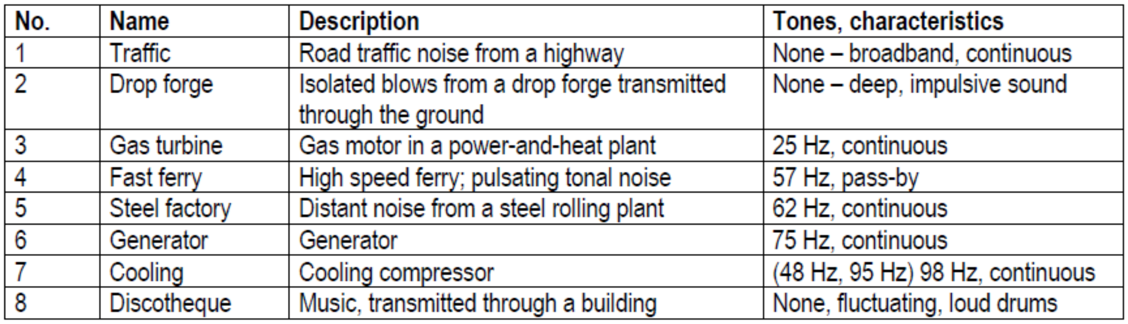
5.1. Annoyance due to entertainment-derived noise

Annoyance is defined as: *A feeling of displeasure associated with any agent or condition believed by an individual to adversely affect him or her* [283]. There exists a considerable body of research on noise-related annoyance [36, 170, 185, 222, 284-295, 299]. Most of this work focuses on industrial- and transportation-based noise, rather than music-based noise, but there are some exceptions.

5.1.1. Music-derived noise

One of the most comprehensive reviews on noise-derived annoyance [36] specifically states in its introduction that all noise sources are considered in the review *except* music. Considering the infrequent nature of outdoor entertainment events, this is a reasonable approach to such research, as traffic and industrial noise can be persistent and result in lasting negative effects to a community's health and wellbeing. The purpose of this report is to consider noise from outdoor entertainment events, so it is necessary to review information on annoyance due to noise from musical sources.

One relatively recent study was conducted on behalf of the Danish Environmental Protection Agency in 2002 [284]. This study devised a series of lab-based listening tests focused on noise annoyance due to eight different noise signals. All but one of these signals were from industry/HVAC/traffic. The one non-standard noise signal was music, recorded outside a local entertainment venue. A list of the considered noises is given in Figure 5.1.

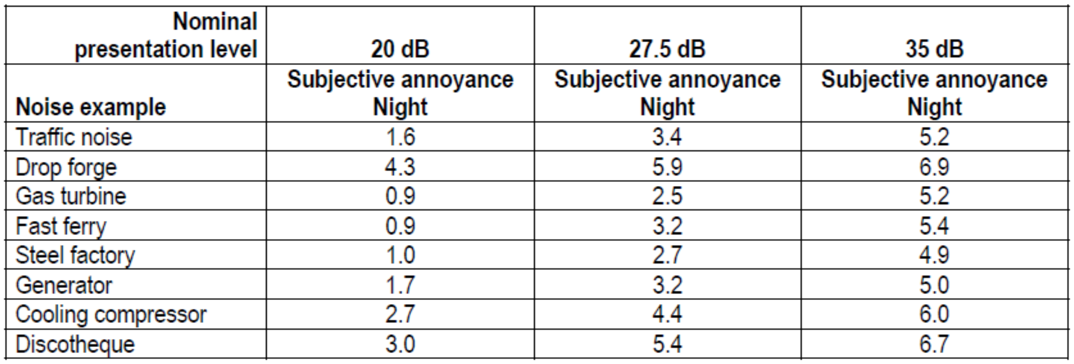


No.	Name	Description	Tones, characteristics
1	Traffic	Road traffic noise from a highway	None – broadband, continuous
2	Drop forge	Isolated blows from a drop forge transmitted through the ground	None – deep, impulsive sound
3	Gas turbine	Gas motor in a power-and-heat plant	25 Hz, continuous
4	Fast ferry	High speed ferry; pulsating tonal noise	57 Hz, pass-by
5	Steel factory	Distant noise from a steel rolling plant	62 Hz, continuous
6	Generator	Generator	75 Hz, continuous
7	Cooling	Cooling compressor	(48 Hz, 95 Hz) 98 Hz, continuous
8	Discotheque	Music, transmitted through a building	None, fluctuating, loud drums

Figure 5.1 List of noises used in the noise annoyance study from [284]

In the study, the noise samples were recorded indoors or filtered to simulate indoor reception (using a filter approximating outdoor to indoor transmission loss). The signals were additionally filtered to remove strong resonances due to room modes. Annoyance was rated by participants on a 10 point scale and tested at three levels: 20 dB, 27.5 dB and 35 dB (measured with A-weighting between 10 – 160 Hz).

The results from the test were interesting, since the two most annoying noises were (by far) the drop-forge and the popular music. The primary results are shown in Figure 5.2.



Nominal presentation level	20 dB	27.5 dB	35 dB
Noise example	Subjective annoyance Night	Subjective annoyance Night	Subjective annoyance Night
Traffic noise	1.6	3.4	5.2
Drop forge	4.3	5.9	6.9
Gas turbine	0.9	2.5	5.2
Fast ferry	0.9	3.2	5.4
Steel factory	1.0	2.7	4.9
Generator	1.7	3.2	5.0
Cooling compressor	2.7	4.4	6.0
Discotheque	3.0	5.4	6.7

Figure 5.2 Subjective annoyance (out of 10) for noises at the three tested levels [284]

The drop forge and popular music signals were quite different in nature (as shown by their 1/3 octave band spectra in Figure 5.3). In terms of the low-frequency noise limits analyzed, the popular music signal was most regularly in breach of 1/3 octave band limits in the 80 and 125 Hz bands. It was found through statistical analysis of how well existing low-frequency noise regulations predicted the annoyance levels found in the tests that the Danish method was most accurate [296], where a best fit line to the data was derived to predict annoyance based on how much a given noise exceeds the published 1/3 octave band limits (Equation 5.1).

$$y = 1.61 + 0.26x \tag{5.1}$$

where the predicted annoyance (out of 10), *y*, is based on how much a noise exceeds a given 1/3 octave band limit, *x* (dB) [284]. The excess value can either be taken as an average over all analyzed octave bands or inspected based on the worst offending band. Based on the data, every 1.5 dB above a stated threshold resulted in a 2/10 increase of annoyance at low-frequencies.

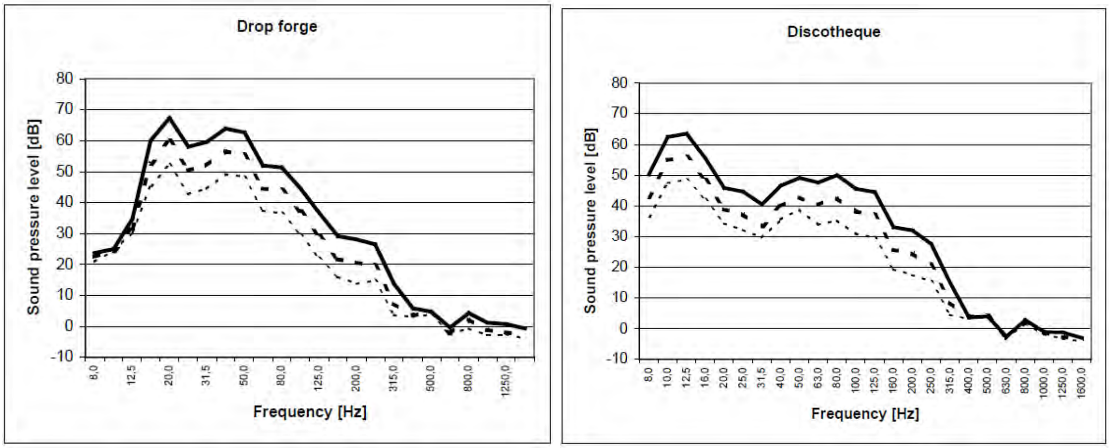


Figure 5.3 1/3 octave band spectra of the drop forge (left) and music (right) noise samples [284]

A selection of criteria for low-frequency noise annoyance is shown in Figure 5.4. Again, it was the Dutch curve that was found to be the best predictor of low-frequency noise annoyance in this study.

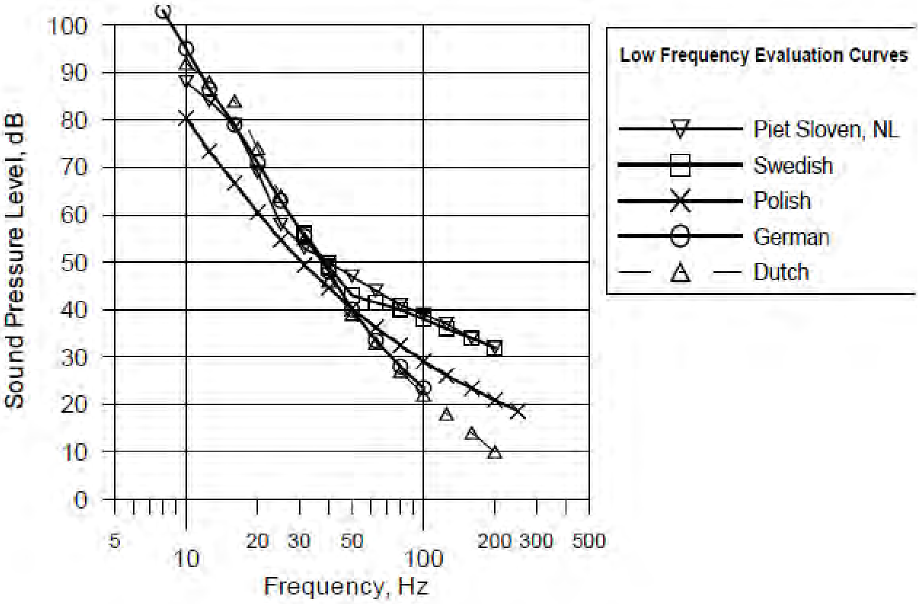


Figure 5.4 Low-frequency noise criteria curves inspected in the annoyance tests from [284]

When comparing the two worst offending signals, the drop forge and the music, there are clear differences (aside from spectral). When the music noise was measured with A- and C-weighting, it resulted in the lowest measured noise levels over all analyzed signals and playback levels. Furthermore, the subjective loudness ratings for the music signal were rated close to average of the loudness for all signals. These metrics won't accurately predict music-based annoyance.

The percentages of participants who were annoyed by the music were 47.2%, 80.6% and 94.4% for 20 dB, 27.5 dB and 35 dB playback, respectively. These were closely in line with the drop forge ratings and were greater than any of the other noise sources. Participants also rated the noise annoyance based on a combined day/night scenario and a nighttime-only scenario. There was an observed downward shift in the annoyance thresholds of 5 dB between day and night.

While the results in the study from [284] indicate that the Dutch low-frequency noise annoyance criteria is most accurate for annoyance prediction, the authors of the study suggest that perhaps this isn't the most reliable method (using hearing thresholds) and that a loudness growth analysis would be more appropriate, especially for intermittent noises. They note, though, that this process is much more time consuming and not entirely straightforward at low-frequencies.

The results from the Danish study [284] are reflected in a study conducted the following year by a team of Swedish researchers [170]. In this study, the focus was on the effectiveness of Sweden's community noise guidelines, which were adopted in 1996. These guidelines specify noise limits based on 1/3 octave band readings, rather than a single A-weighted metric (which was used in the old guidelines). Thirty-seven local Environmental Health Authorities (EHA) were surveyed (out of a total of 289 EHAs in Sweden). 62% of the surveys EHAs reported a decrease in noise complaints after implementation of the new guidelines, while only a single EHA reported an increase in complaints. Other EHAs didn't report a noticeable change in complaints received due to noise.

From the survey, a list of the worst offenders for noise complaints was compiled. The worst offenders were as follows (expressed as a percentage of total complaints received): 21% air handling systems, 18% music, 17% compressors, and 16% laundromats. Low-Frequency Noise (LFN) accounted for 35% of the total complaints received. As this particular study investigated complaints over a 14 year period, it was identified that there is a steady and significant increase in low-frequency noise-related complaints over time. Whether the LFN is objectively increasing or whether people are becoming more sensitive to LFN is left unanswered here.

5.1.2. Time relationship

Looking into the time relationship between loudness and annoyance, a recent study [286] found that perceived loudness and annoyance don't change with time in the same manner. At low frequencies (below 50 Hz), annoyance may rise over the first few minutes of exposure, while perceived loudness decreases. After a few minutes, though, both annoyance and perceived loudness decrease, just at different rates (perceived loudness decreases faster than annoyance) [286]. Even if a low-frequency noise isn't perceptible, it has been shown that it can trigger a fight or flight response in people (inducing a nervous, hormonal and/or vascular change) [283]. This sort of effect has even been observed when people are asleep, although this has been due to continuous industrial noise and may not be relevant to short and infrequent exposure to event-based noise.

NASA also has investigated how noise-related annoyance varies over time as well as how it can be influenced by other noises/sounds [297]. The purpose of their research was to assess how astronauts on deep-space missions will react to persistent noise over long periods. The work details how habituation to noise annoyance is a form of coping mechanism, where annoyance tends to decrease over time if a certain offending noise persists for a long duration. Interestingly, in one reported study 16 seconds of noise played back at 78 dB was rated significantly more annoying than the same 16 seconds of noise at 78 dB being followed directly by 8 seconds of noise at 66 dB. This seems to indicate that the perceived annoyance of a noise source is relative to additional environmental noise. This supports the trend in many European countries (as discussed in Section 4) to set noise limits based on an offending noise's relative level to the background noise. It also gives some level of indication that a short period of loud noise from an outdoor event may be tolerable to local residents if it is followed by lower level noise (or the most serious offending noises being short in duration and spaced widely throughout an event).

5.1.3. Small indoor venue noise

A two-phase research project looking into noise annoyance from clubs and pubs in the UK was carried out from 2005-2006 [290, 298]. The commonly-quoted outcome of this work was that absolute LAeq was conclusively proven to be the ideal metric for measuring and monitoring off-site noise from entertainment sources. Looking at the two phases of the work in detail, though, it would appear that this is a weak conclusion.

Phase two of the work [298] aimed to identify the best metric for quantifying noise issues from entertainment sources. Two tests were conducted: a highly-controlled laboratory experiment and a field test with real-world venues. The laboratory-based testing was carried out in two houses at Building Research Establishment Ltd. (BRE), where the noise was monitored in three upstairs bedrooms. The sound system was representative of that found in a small club. For half of the tests, the system was placed downstairs in the houses while the other half of the tests, the system was placed outside. Results from 30 participants gave strong statistical evidence that absolute LAeq was the best predictor of annoyance due to the received noise (which was musical in nature).

The field tests were carried out at 10 venues around the UK. A similar test procedure was followed in collecting data from participants, except this time they were tested with the actual noise coming from the venues. From these tests, the best predictor of annoyance was the LA10-LA90, although there was a greater margin of error, indicating that these results were less conclusive.

The fact that the conclusions of phase 2 of the DEFRA-backed work state in no uncertain terms that absolute LAeq should be exclusively used for measurement and monitoring of night time noise from pubs and clubs is misleading. The results from the two experiments don’t agree, and therefore a clear conclusion is impossible. Interestingly, this point is briefly mentioned in the summary of the second phase of the work [298], but is contradicted in the next section of the same summary. The recommendations, nonetheless, have been applied to monitor/manage noise from clubs and pubs with good levels of success, but it must be stressed that pub/club noise is characteristically different from noise emitted from large-scale outdoor entertainment events.

There are a number of issues in applying the findings from [290, 298] to large-scale outdoor entertainment events, principally because the study was focused on night time noise from pubs and clubs. First, in the laboratory experiment, the system used is not representative of what is used at large outdoor events, especially in terms of low-frequency reproduction capabilities. Second, the placement of the sound system, while possibly realistic for clubs and pubs (which was the focus of the study), is far from realistic for large outdoor events where the sound system will be significantly further away from residences. More work is needed to inspect noise annoyance predictors specifically for large-scale events. Until this happens, there is no evidence to support any single metric being ideally suited for measuring and monitoring event stemming from large outdoor events.

Even though most existing literature (aside from the examples discussed above) focuses on industrial and traffic noise rather than music, there are some interesting conclusions can be made. It has been shown that annoyance is significantly greater when a noise contains strong low-frequency components. This is confirmed in the reviewed music-based noise studies. Additionally, if noise is intermittent rather than continuous, the noise is more annoying (which is reflected by many noise regulations imposing a 5 dB penalty on limits for impulsive noise [285]).

5.1.4. Factors unrelated to audio

A different DEFRA-backed a study into local resident’s attitudes towards environmental noise from concerts was carried out in 2011 [185]. The key findings from this work focused on the importance of effective communication between event organizers and local residents. Of those pre-warned of an event taking place, only 14% were annoyed by the resulting noise. Of those not notified in advance, 35% reported annoyance. Households with children under the age of nine or individuals with hearing-impairment were statistically more likely to complain (at first glance, it may be surprising that the hearing-impaired group is more annoyed by noise than the average person. Considering that most entertainment-based noise pollution is rooted in the low-frequency range, and that a significant portion of hearing loss is in the high frequency range (along with a reduced auditory dynamic range), this finding is believable.

A similar piece of research from the Netherlands [289] found that three groups of people showed greater sensitivity to specifically low-frequency noise: women, the elderly, and people who were unhappy. The explanation for increased sensitivity of the elderly was the same in both studies, with no commentary provided for the other two groups.

What is clear from the work in [185] is that effectively managing the attitudes of the local residents to the event taking place can significantly lower annoyance (often to the point where few complaints will be made). In many cases, when the public was aware of the event, noise was heard but perceived as positive. This effect will be revisited later in this section, as this aligns closely with findings from independently-conducted research, including that of NASA in [297], where subjects without any perceived control of an annoying noise often became angry, while this was not the case when subjects had some *perceived* level of control of the annoying noise.

An individual’s degree of annoyance can be influenced by a number of factors such as: time of day, unpleasant characteristics in the noise, duration/intensity of the noise, meaning associated (i.e. information contained within) with the noise, and nature of the person’s intended activity that is being disrupted by the noise (i.e. work, sleep, etc.) [283]. In terms of a person’s sensitivity to noise (threshold for annoyance), this can be affected by: fear of the noise source, conviction that the noise could be controlled by a third party, the degree of personal control over the noise, whether the noise originated from important economic activity, and whether the noise is predicable or not [283].

Another influential factor on sensitivity to noise is an interesting one: whether the noise originated from important economic activity. There are a number of local noise regulations that allow for heightened noise limits during evening hours for outdoor events (where especially large events are allowed more noise pollution than smaller events) [203]. Whether on purpose or not, these regulations take into account that residents of the neighboring community may be more accepting of entertainment-based noise if the event is seen to be beneficial to the local economy. This is directly in line with the previously-mentioned findings from [185].

The primary author of this report, as it turns out, grew up in such a neighborhood. The city of Highland Park, Illinois, USA has had a well-known outdoor music venue, Ravinia Festival (the oldest outdoor music festival in the US), located within Highland Park for most of the city’s history. It is accepted that during many evenings each week over the summer months there will be noise from the venue (ranging from classical to pop music). To the author’s knowledge there are relatively few noise complaints (as compared to similar venues) and, in fact, many residents see it as pleasant background noise (especially for barbeques). The community regards these events as part of what defines the city and contributes significantly to the local economy. The relationship has developed over the past 100+ years, so this isn’t something that can happen overnight, but demonstrates how noise annoyance can be mitigated through continued development of positive relationships with local residents.

5.1.5. Prediction methods

One model developed for predicting noise-related annoyance was developed by Zwicker and was investigated in [287]. The model predicts noise nuisance, based on loudness, sharpness, roughness and fluctuations in strength of a noise. The analysis is performed for each critical band of the human hearing system (24 in total) and generates a nuisance level in each band on a 100-point scale. Each of the four contributing metrics feeding into the nuisance rating is subjectively-based (rooted in subjectively-defined metrics that are more precise than simple A- or C-weighting). In this specific study, as with some of the other reviewed research in this report, outdoor measurements were taken and a filter was applied to the results to mimic indoor measurements.

It is interesting to observe that such a model exists and has been verified to be accurate [287], but it is completely absent in any of the reviewed pieces of regulation or recommendations. It may indeed be found to be useful for noise-based music annoyance quantification and prediction, but may have been overlooked due to its perceived complexity of implementation (it can't easily be measured using industry-standard noise monitoring equipment).

On the matter of conventional noise measurement techniques, there is a growing body of evidence that A-weighting is unsuitable for noise when considering annoyance [36, 288, 289]. While A-weighting is generally suitable (and *roughly* approximates human hearing) at low noise levels, the weighting curve (as standardized in ISO 226:2003) doesn't extend into the infrasonic region (note that the music spectrum from the [284] study in Figure 5.4 shows significant energy below 10 Hz).

A study into annoyance due to continuous and modulated noises (focused on HVAC systems) found that unmodulated noise annoyance is best predicted using C- or Z-weighting, but modulated noise is best predicted using C-weighting [288]. Further work supports this finding, which was focused more on music-based noise and found that C-weighting was most appropriate out of the available weighting curves [285]. This work makes clear that averaging of measurements over time can be counterproductive as much of the annoyance is rooted in the time-varying properties of the noise, which is included as part of Zwicker's model [285].

Some regulations take a 20 dB (or so) difference between C- (or Z-) and A-weighting measurements to indicate a low-frequency noise issue. However this may be over-simplifying the situation and missing some of the crucial information in the actual noise that is causing an annoyance [285, 289]. The work in [285] recommends that to account for fluctuations in the noise any time an overall fluctuation of 10 dB or more is observed, 5 dB should be taken away from the noise criteria. LC10 and LC90 can be used to ascertain the maximum and minimum values for the noise over time.

The focus on C-weighting for more accurate assessment of noise annoyance was indicated by a DEFRA-sponsored report, where it makes clear that if there are any prominent low-frequency components in a noise, then A-weighting measurements are inappropriate [36]. The findings from the survey in [36] resulted in criteria and procedures for assessing low-frequency noise disturbances [300, 301], although these were based on industrial and traffic noise, without any consideration of music-based noise [36]. The key findings in the DEFRA documents, which can be seen as relevant to music noise, is that single number measurements aren't appropriate. Spectrum-based criteria and measurements are required for accurate noise monitoring and prediction. If any 1/3 octave band is found to have noise exceeding the given criteria, annoyance due to the noise is likely [289].

In contrast to the bulk of the previously reviewed work included in this section, a recent study calls into question the culpability of low-frequency noise as the primary source of annoyance [283]. The research, based on formulating a set of indoor low-frequency noise annoyance thresholds for noise originating from live music events, suggests that the key factor of residents' annoyance is misappropriated to the subwoofer/infrasonic range and the more problematic spectral range is 160 – 315 Hz. While the work didn't conduct any subjective evaluations of its own, it uses data from a set of well-regarded studies alongside new measurements of façade isolation. Interestingly, when the in-room noise is modeled to reflect lightly- or heavily-compressed music (as is common with popular music), the resulting annoyance thresholds are largely in line with existing regulations and guidelines, notably those put forward by the WHO [1-3].

The finding that the subwoofer/infrasonic spectral range is less important in terms of annoyance is supported by a Danish study [287] which found that low-frequency noise sources aren't usually obvious and the true noise source is often unknown (even to the person making the complaint). The research concluded that existing criteria have no simple relationship to the complaints surveyed in the study. Clearly, there is more work required to resolve the ambiguities exposed here in relation to low-frequency noise and annoyance.

5.1.6. Inaudibility criteria

A historic noise regulation focused on annoyance minimization is an excellent example of significant problems arising due to an overly-restrictive limit being imposed by local authorities. It should be clear by this point that accurately predicting annoyance from music-based noise is an extremely difficult task due to the many influential psychological factors. From a regulatory point of view, it would be much easier to place a blanket ban on any audible noise stemming from music venues.

This is precisely what occurred in the city of Edinburgh, Scotland starting in the late-1990s. In Planning Advice Note PAN 56 (1999) Planning and Noise, states in clause #6 [302, 303]:

> *A noise limit that is close to the background level will be difficult to monitor. Conditions that seek to safe- guard levels of amenity by ensuring that noise resulting from a proposed development is inaudible in adjacent noise sensitive premises may be appropriate in cases where the noise lends itself well to fine tuning (e.g. amplified music) although should be used sparingly. In every case, conditions should be considered in terms of the six tests set out in Circular 4/1998.*

This policy was adopted within the City of Edinburgh bylaws, where noise policy simply became: if a resident can hear any noise from an entertainment event there is a breech in the regulations. The rise of inaudibility as policy clearly stems from the inability to accurately measure offending/annoying noises since they were low-frequency in nature. As A-weighting was (and still is) the most commonly used measurement method, there is no way to accurately measure a low-frequency music noise in the heart of a large city where other noise sources such as traffic and weather will easily mask or corrupt the measurements [302].

This policy (which many experts viewed as draconian) resulted in over-enforcement of entertainment noise from local venues, even resulting in some venues to close. This eventually sparked a heated debate within the UK's Institute of Acoustics (IoA), where arguments were made for the inaudibility policy [304, 305] and against [302, 306]. All of the referenced arguments are from industry professionals or academics with many years of experience. Ultimately, professional and public pressure resulted in Edinburgh relaxing their nuisance criteria in 2016, removing the inaudibility requirement, bringing the city in line with the rest of the UK [307]. Unfortunately, during the time of the inaudibility policy, many live music venues were forced to shut their doors in

Edinburgh. It is still the case in the UK (and elsewhere) that such venues are under an ever-increasing threat of closure due to noise complaints from local residents, where cities are becoming increasingly dense and housing prices are reaching levels well beyond what was previously typical in the neighborhoods home to well-established live music venues.

5.1.7. Summary

Overall, annoyance due to music-derived noise is certainly problematic, which is demonstrated in the work from [284]. The difference between industrial/traffic noise and entertainment noise is that while the former tends to be present in the long term, the later only occurs in the short term, generally only a handful of time each year. This means that health effects due to long-term noise pollution aren't necessarily important here (although residents living near permanent indoor venues may have issues, this report is focused on temporary outdoor events). It is annoyance that should be the central focus in this instance, where significant (and in some cases not-so-significant) annoyance levels (likely stemming from large amounts of low-frequency energy) will result in formal complaints, which can in turn put the future of a given outdoor event in jeopardy.

Much more research is needed in this area. Unbiased scientific studies are required which specifically look into music-based noise (especially in regard to large outdoor events), including how to best predict, quantify and measure such annoyance (and how to minimize it, of course). One aspect that was largely avoided in the reviewed research is the effect of room modes on low-frequency noise. While living rooms won't support room modes in the infrasonic region, they will have room modes at frequencies above approximately 40 Hz which, as has been shown, is a prominent component of most music-based noise. This is compounded by the fact that long-distance propagation of noise will exhibit significant attenuation of high-frequency components on top of further high-frequency attenuation from transmission through building materials. Depending on where a resident is located within a room, the noise can be greatly exaggerated due to room-modes (potentially a 20 dB boost or more). This would make noise that is measured as insignificant outdoors to be problematic indoors. This is another area that requires more research, although a current technological solution to this problem is discussed in Section 6.2.3.

5.2. Approach to noise regulations

As discussed in the preceding sections, noise regulations are relatively well-suited for persistent environmental noise from traffic or industry, but generally not fit for purpose for noise control and monitoring of outdoor entertainment events (although at least two studies disagree [293, 298]). Nevertheless, until any changes are made to specify regulations for music-based noise, practitioners should ensure everything is done to comply with local/national regulations that are in place and being enforced. Otherwise, the future of an event may be placed in jeopardy or fines could be levied.

Considering that the overall goal for an outdoor event is to please the event organizers, crew and attendees with high-quality listening experiences while simultaneously appeasing local residents [308], a pragmatic approach must be taken. Of course, if noise control was the solitary goal, the easiest solution would be to not hold an event in populated areas. If audience experience was the solitary goal, then sound systems would be designed to deliver what the audience expects without consideration of directionality, perhaps with the exception of towards the stage area. In reality, both goals must be considered.

The truth of the situation is that many existing noise regulations that are particularly detailed (and tend towards the academic side) can make it difficult for event organizers, managers and engineers to fully understand the requirements to appropriately address the situation [309]. Additionally, when an event is in progress, most of the technical staff will be busy with providing for the musicians and audience with little attention paid to noise pollution. An increasingly common solution at large-scale events (at least in Europe) is to bring in a separate technical staff to monitor and manage noise pollution both on and off-site. This can either be instigated by the local authorities or event organizers – or both. At multi-stage festivals, noise pollution can be problematic between stages, which further complicates the issue as in such cases engineers much avoid sound spilling into other stage/audience areas as well as avoid noise pollution in the local community. Methods of addressing this in an informed manner are highlighted in Section 5.5.

At permanent venues in Brussels, for example, regulations state that there should be a “decibel officer” on staff for all entertainment events, whose role is to monitor and control noise [309]. This officer would go through training so that they are fully aware of how to interpret the regulations and carry out appropriate measurement and control practices. Additionally, they must ensure forgery-proof data logging [309]. Software such as 10EaZy includes a log file validation function for just such purposes [310].

Whatever method is deemed appropriate for noise management, monitoring and control, it is important to understand that keeping to the regulations won’t guarantee local residents won’t be annoyed. Keeping to regulations will ensure (in most cases) that there will be no serious repercussions. In all cases, a clear written Noise Management Plan (NMP) should be produced in advance of the event.

5.3. Measurement regulations

The noise regulations surveyed in Sections 2 (audience sound exposure) and 4 (community noise) detail a wide range of measurement procedures. A comprehensive discussion of all of these wouldn’t be useful for the purpose of this report. Instead, this section will be kept brief, only highlighting important aspects of a selection of regulations and standards that will help inform best practice for measurement and monitoring of music-derived noise from outdoor entertainment events.

In the UK, BS7445-1:2003 [311] details description and measurement of environmental noise. This standard is identical to ISO 1996-2:1987. The standard opens with a general statement alluding to the complexity of noise regulations at present [311]:

> *Extensive research concerning the way in which human beings are affected by noise from a single kind of source such as rail or road vehicles, aircraft or industrial plants, has led to a variety of measures for assessment of different kinds of noise, many of which are in common use. Conversion from one measure to another is often beset with serious uncertainty. If an acoustical environment were always dominated by a single kind of noise, the confusion caused by the existence of different measures would not be so severe. But often environmental noise is a composite of the sounds from many sources, and the distribution of the different kinds of noise is likely to change from moment to moment.*

The standard goes on to suggest that due to the complexities and confusion resulting from the various proposed and implemented measures that equivalent continuous A-weighted sound pressure level should be adopted for all noise measurements. Considering the discussion earlier in this section, this suggestion is not suitable for music-based noise, as the most common problem associated with such noise is annoyance. Interestingly, researchers at one of the contributing institutions to this standard expressed the view that A-weighting is completely inappropriate for noise containing significant low-frequency components [36]. These documents were published in the same year, indicating a worryingly mixed message coming from researchers working within the same department. It must be noted that the British Standard was only adopted in 2003 and is identical to the ISO from 1996. Nevertheless, the lack of consensus among professionals is reason for concern considering the growing complexity of the noise situation worldwide.

Disregarding the issue with A-weighting in the standard [311], there is some instructive information (even though the standard isn't specifically focused on entertainment event-based noise). One of the central challenges in noise measurements is that there is rarely a single noise source present in an environment. Multiple simultaneous noises cause confusion with single measurements. The challenge, then, is to identify the *specific noise* from the offending source while discarding the *residual noise*. According to the standard (page 3), this should be carried out via acoustical means (with the possibly incorrect assumption that this means using a measurement). On the other hand, on page 8 of the standard it indicates that the individual taking the measurements should strive to log the source(s) of offending noises. The text is ambiguous at best, contradictory at worst.

For the example of an event taking place near a residential area, how can people monitoring noise be sure that the measurements prove the offending noise came from the concert or from another unrelated source? This common challenge has been emphasized by practitioners and researchers [308, 43]. BS7445-1:2003 [311] only indicates that care must be taken by the individual taking the measurements to document the most probable source of noise. LAeq measurements give no information in this regard.

While highlighting this conflict is a step in the right direction, placing the burden of noise source identification on an individual opens up the possibility of human error. In the case where there is a multiple stage festival taking place, how is the responsible person to identify where the offending noise source? It is unlikely that accurate assessments will be made. Technological solutions to this problem are discussed in detail in Section 5.5.

In terms of measurement location, BS7445-1:2003 [311] represents the general consensus of the noise regulations across the world. Outdoor measurements should be taken 1 – 2 m from the façade of a building and 1.2 – 1.5 m off the ground. Indoor measurements should be taken 1 m from any wall, 1.2 – 1.5 m off the floor and around 1.5 m from any window [311]. No instruction is given on how to deal with room-mode effects. This is not surprising since low-frequency noise is largely ignored by the standard. Additionally, outdoor measurements should be taken in stable meteorological conditions to ensure accuracy and repeatability. Fluctuating noise is classified as noise that differs by more than 5 dB during the course of the measurement. Guidelines are given in the standard on how to use averaging to avoid skewing data, but the fluctuating nature of the noise should be recorded by the measurement taker. Again, this is (at least quantitatively) ignoring the time-variant nature of the noise, which is clearly a strong factor in annoyance and potential physiological effects from noise. While a 5 dB penalty can be imposed on set noise limits due to such fluctuations in the noise, it should be seriously questioned (through further research) whether this is sufficient.

Lastly, measurement integration time should be considered, specifically in regard to annoyance. The audience sound level limits discussed in Section 2 highlight grossly varying practice (even across Europe) in terms of integration time (ranging from 1 minute to 4 hours). Even taking a moderate integration time of 15 minutes as "standard", this may be too long to properly relate to annoyance due to noise pollution. Contributors to this report have noted that music-based noise pollution causing annoyance is best measured with short integration times (around 3 minutes). If the on-site sound level monitoring is operating over 15 minutes, this will allow the mix engineer to have multiple loud peaks (L10 – L90) without breeching any limits. Off-site, though, these peaks often can result in annoyance. It has been suggested that Leq integration times be synchronized between on-site and off-site, where precedence is always given to the shorter duration [21]. At present, this issue isn't addressed in any known standard, regulation, or law. Further work is needed to develop and validate idea solution.

5.4. Noise prediction

Environmental noise propagation models have existed for many years and are used extensively in atmospheric and underwater acoustics. In the context of this report, a special noise propagation model is required. Unlike standard noise analysis where individual noises are incoherent, noise from outdoor entertainment events comes from multiple loudspeakers which output approximately coherent signals. Consequently, complex summation (as opposed to energy summation) is required to accurately predict noise levels at receiver positions. Until recently, no publicly available software existed for such purposes.

5.4.1. Modeling approaches

German loudspeaker and amplifier manufacturer d&b audiotechnik [312] set out to provide such software, through a partnership with the makers of industry-standard noise modeling software, SoundPLAN [313]. The aim was to bridge the divide between the work of the sound system designer and the environmental consultant by linking system design software, ArrayCalc [314] and terrain data from Google Earth [315]. This work resulted in the freely-available software NoizCalc [316-318].

NoizCalc includes modified implementations of ISO 9613-2 and Nord2000 propagation models. ISO 9613-2 is the most commonly used model in environmental acoustics. This model is empirically-derived and is generally agreed to be acceptably accurate over 1 km. The ISO model aims to give a worst-case prediction of noise (using the meteorological conditions that best favor noise propagation) [317]. In general, ISO 9613-2 predicts noise propagation using Equation 5.1.

$$L_r = L_w + D_c - A \tag{5.1}$$

where the noise level (dB) at the receiver, L_r, is calculated based on the sound power level of the source (dB), L_w, the source directivity factor (dB), D_c, and the total attenuation from the source to the receiver (dB), A. The attenuation factors include geometric divergence, atmospheric absorption, ground effect, attenuation due to barriers and any additional attenuation (such as foliage).

Nord2000 is more advanced than ISO 9613-2, as it includes more accurate modeling of ground effects, surface reflections and scattering. This provides acceptably accurate noise predictions up to 3 km from a source. The Nord2000 calculation is carried out using Equation 5.2 [317].

$$L_r = L_w + \Delta L_d + \Delta L_a + \Delta L_t + \Delta L_s + \Delta L_{re} \tag{5.2}$$

where the noise level (dB) at the receiver, L_r, is calculated based on the sound power level of the source (which includes a correction for source directivity), L_w (dB), and the attenuation due to geometrical divergence, air absorption, ground effects and barriers, scattering, and reflections from obstacles, ΔL_d, ΔL_a, ΔL_t, ΔL_s, and ΔL_{re}, respectively (all in dB).

To overcome the inherent limitation due to the assumption of incoherent noise sources in both standards, complex summations were carried out for frequencies of 160 Hz and below. Higher frequencies were allowed to maintain the usual energy summations, as coherent interference is less problematic in this portion of the spectrum [317].

The makers of NoizCalc recommend that system designers inspect noise propagation not only due to the worst-case scenario, but for other likely meteorological conditions that could arise during the event, to allow for quick on-site adjustments to be made to limit noise pollution due to a known weather condition. The better prepared a system operator/technician is in this area, the smoother an event will run with turn-key solutions at hand [317].

The environmental noise propagation model used in NoizCalc was verified using measurements from three outdoor music festivals [318]. The validation was performed in a slightly different way to what would be normally done in practice, as the exact weather conditions at the events were known before running the model (the simulations were conducted after the events). Overall, the model was shown to be in good agreement with the measurements, generally erring on the side of safety (1 dB overestimate of noise levels compared to reality). To improve confidence in the model, further work is needed to compare predictions made prior to an event to measurements, as all practical scenarios for noise management don't allow for tuning of the model after an event.

The interlinked sound system design and noise control software provided by d&b should be seen as a step in the right direction in terms of overall sound system design for a large outdoor event. It brings environmental noise prediction in line with the realities of entertainment events, which typically use coherent sources. In large multi-stage festivals, however, such software is still of limited use, as it can't handle numerous sound emission points (stages, tents, buildings, etc.) and is therefore not accepted as evidence of noise pollution management planning in certain jurisdictions (such as Rotterdam, Netherlands).

It has been found by some practitioners that currently available commercial software packages (free or otherwise) struggle to accurately predict low-frequency propagation in heavily built-up areas. Firms such as Rocket Science and SPLtrack (who employ two of the contributors to this report) have developed their own proprietary modeling software for this reason, which has been shown to provide more accurate predictions in these cases [319]. In general, it was found that noise propagation models based on Nord2000 or ISO 9613-2 don't sufficiently take into account interference from coherent sound sources and reflections or diffraction from large objects/structures. The general recommendation from the Rocket Science report (which analyses most available sound propagation modeling approaches) is to consider BEM or FDTD for low-frequency noise propagation modeling purposes [319]. SPLtrack augments classical noise modeling with empirical data to continuously update their model. This will be discussed in greater detail later in this section.

5.4.2. Meteorological effects

Despite any achieved accuracy in existing noise propagation prediction software, there are meteorological effects that can be difficult to predict using current software and these potential issues should be well-understood by those involved with the sound system's operation at an outdoor event. The first primary issue, which is generally well-known among practitioners, is that of sound refraction. Refraction is due to the sound wave encountering a temperature gradient (which can be due to a number of factors such as the wind or a large group of people). As the speed of sound is directly related to air temperature, as a sound wave encounters a temperature gradient, it will tilt towards the cooler region of the gradient. This is illustrated in Figure 5.6. Similarly, refraction due to wind-caused temperature gradients is illustrated in Figure 5.7.

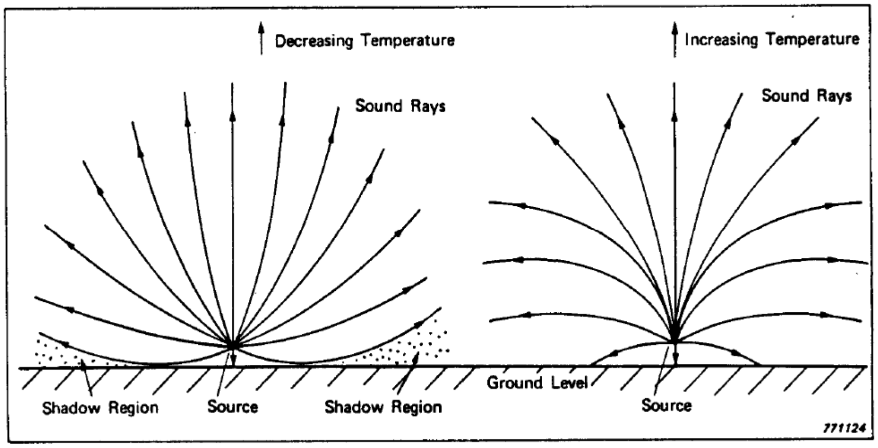


Figure 5.6 Illustrations of sound refraction due to temperature gradients in the air [320]

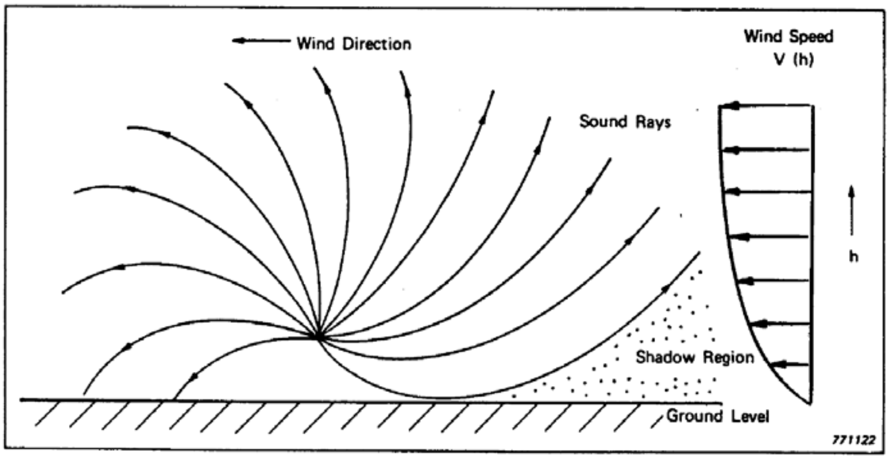


Figure 5.7 Illustration of sound refraction due to wind-based temperature gradients [320]

Considering that at large outdoor events there will be a densely-packed audience which generates heat (especially later in the day when there will be more people present for the headliner's set), there is likely to be a strong temperature gradient which bends the sound from the event upwards towards the cooler air at night. With increasing altitude, though, wind speed is typically greater than at ground-level [276]. This has the potential to cause the sound to curve back down towards the ground away from the event site (due to the corresponding temperature gradient), resulting in strong noise pollution in neighboring communities. Should noise complaints start to occur (or monitoring equipment detects a rise in noise level), this is potentially what is causing the issue. In terms of correcting for this effect, though, it is hard to say what can be done other than turning down the offending frequency bands on site. The problem is complicated by the fact that such temperature gradients are regularly observed to vary (and in some cases completely reverse) during the course of an event. Most noise prediction software doesn't currently consider this.

An additional consideration is low-frequency noise propagation over long distances. It is commonly assumed that in the far field of a loudspeaker array sound will propagate spherically (-6 dB per doubling of distance). It has been found in research related to wind turbines [122], however, that this is not necessarily the case. In this area, low-frequency noise propagation beyond 200 m is modeled as cylindrical propagation (-3 dB per doubling of distance) due to the combined effects from temperature inversion and low-level jets.

Additionally, noise from wind turbines is known to be influenced by ground reflections. This is approximated as a corrective value applied in noise propagation predictions. A corrective value of +1.5 dB, +3 dB, or +6 dB is used, depending on which guideline is followed (Danish, Swedish, and field observations, respectively) [122]. The Swedish guideline is specifically focused on the 63 Hz octave band, which is directly relevant to low-frequency noise from music events. Comb-filtering due to ground reflections often isn't an issue. Assuming a propagation distance of 800 m, a source height of 75 m, and a microphone height of 1.5 m, (the first comb filtering frequency is 625 Hz. Lower source heights (as used at outdoor events) will be even less sensitive to comb-filtering at low-frequencies. Due to these influences, experts on wind turbine noise caution that in certain scenarios it is possible to observe no significant attenuation of low-frequency noise over long distances.

It may also be useful to consider any noise transmission by vibrations through the ground or surrounding structures of an event. This is a low-frequency (including infrasonic) issue and could cause unexpected problems far from the source. In one instance, a building's engineer informed the sound system engineers that unsafe low-frequency vibrations were reaching the building's foundation (it was a very old building). As a consequence, the subwoofer system had to be bandlimited and slightly reduced in level to avoid any structural issues to the venue. While this was not a large outdoor event, it demonstrates a less-discussed transmission path for noise. While there is currently no published guidance in this area for music-based noise, BS5228-2 [321] specifically addresses noise and vibration control on construction and open sites. Whether ground- or structure-based noise transmission poses a serious risk in the context of outdoor music events remains unclear and requires further investigation.

Lastly, there is a lesser-known effect that is directly related to sound refraction and can cause noise to propagate extremely long distances with minimal attenuation. This is known as acoustic tunneling or channeling. Little research has been done on this in the field of atmospheric acoustics, but there has been significant research carried out in the field of underwater acoustics [322-324].

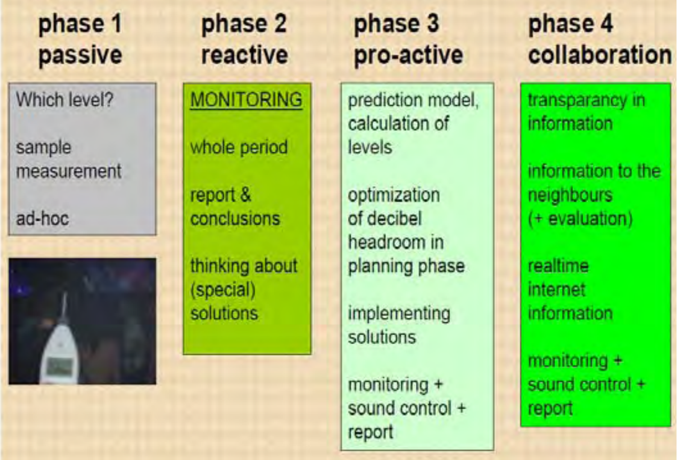
In underwater acoustics, this effect is known as a sound fixing and ranging channel (SOFAR). Initial tests to confirm its existence were carried out in 1943 by detonating 1 pound of TNT underwater in the Bahamas. The blast was easily detected over 2000 miles away off the coast of West Africa [279]. Most published research was done in the 1960s and 70s when the US Navy was exploring its use for long-range submarine detection and monitoring [324].

It is now known that the long-range low-attenuation propagation is due to the laws of refraction, where the underwater sound is trapped (so to speak) in a channel where the speed of sound is at a minimum. This is due to fluctuations in pressure and temperature with depth in water. The effect can be thought of as a sound waveguide. Professionals working in atmospheric acoustics have come across such SOFAR-like effects in air, where sound is trapped in a stream of cool air surrounded by warmer air, thus trapping the sound in a narrow channel, allowing it to propagate for significantly longer distances than would be expected. This has caused unexpected issues with some outdoor events. Even with knowledge that this is a possibility, such occurrences are extremely difficult (if not impossible) to predict or control for. At the very least, if noise levels are suddenly found to be above expectations at very far distances from an event, environmental noise consultants can have an explanation ready. Informally speaking to consultants as part of the research for this report, most had encountered such effects on at least one occasion in their careers.

In response to all of the above issues (noise propagation model accuracy/reliability, sound system model accuracy, meteorological effects), engineers at SPLtrack developed an empirical noise pollution model which uses real-time data acquired from field sensors to continuously update the model. This model, known as SPæL, is used in the construction, motorsport and live event industries. The model's accuracy has been shown in tests to predict noise pollution levels to within 1 dB accuracy (where competing models showed greater than 10 dB of error). Aside from accounting for meteorological effects, it was found that a common source of error for the competing models was due to inaccurate sound system prediction when line arrays were flown too close to the ground (so that they wouldn't exhibit their intended behavior when deployed in the real-world). This is why the recommendation of flying line arrays no lower than three times their length is important when relying on modeling to predict behavior on- and off-site. The accuracy of SPæL demonstrates the importance of noise propagation models supporting tuning functions using field data to ensure accuracy. Without this, there is no practical method for handling the ever-changing meteorological effects as well as non-ideal sound system configurations.

5.5. Noise monitoring

Noise monitoring has become indispensable over the past couple decades at large outdoor (and indoor) entertainment events. This includes monitoring at the front of house mix position (FOH) as well as in selected locations in the community (where specific locations are chosen according to their noise sensitivities). A number of contributors to this report have significant experience in noise monitoring of outdoor events, primarily in Europe. One group member set out phases for sound level management at events in a recent publication [325], as reproduced here in Figure 5.8.



phase 1 passive	phase 2 reactive	phase 3 pro-active	phase 4 collaboration
Which level? sample measurement ad-hoc	MONITORING whole period report & conclusions thinking about (special) solutions	prediction model, calculation of levels optimization of decibel headroom in planning phase implementing solutions monitoring + sound control + report	transparency in information information to the neighbours (+ evaluation) realtime internet information monitoring + sound control + report

Figure 5.8 The so-called "phases" of sound level management at events [325]

In the working group's opinion, sound level management at outdoor events is inconsistent across the world and generally can be classified as phase 1, 2, or 3. A select few live events have recently made efforts to move towards a phase 4 approach to sound/noise level management. Some examples will be discussed here as well as in Section 5.6.

The primary author of this report has been responsible for designing and operating sound systems at large-scale festivals in the American Midwest since the early 2000s. In his experience, most of these festivals can be classified as Phase 1 (Figure 5.8). No clear limits are set prior to the events and generally the event management hastily agrees on limits about five minutes after the first band begins to play. At this point it becomes obvious that these individuals have minimal knowledge of sound measurement protocols. For example, one festival manager imposed a limit of 90 dBC, fast response, at FOH. This limit was unrealistic. The main sound system was briefly muted to demonstrate that the limit was still exceeded due to sound coming from the stage monitoring system and the band's instruments. Generally, at such events the only noise control specified is the noise curfew (time(s) at which the sound system must be turned off).

This is not to say that all outdoor events in the US are in such a poor state for noise control. Large cities such as New York or Los Angeles do specify limits (as seen in the noise regulations survey in Section 4). The issue is whether these limits are enforced. This usually falls to the local fire station, where (from experience) it is evident that the individuals tasked with noise monitoring are insufficiently trained.

Fortunately, many touring engineers have adopted various pieces of sound level monitoring software to ensure they adhere to specified on-site local limits. Such engineers will confirm their SPL limit at FOH upon arrival and input this into their monitoring software to ensure they keep to the stated limit for the duration of the show. This good practice is already widespread.

5.5.1. Front-of-house (FOH) monitoring software

One of the most commonly used pieces of software for this purpose is 10EaZy [310]. The software provides engineers with real-time data covering aspects of sound level including time-averaging in reference to a defined limit, full graphical history of the sound level, and a comprehensive warning system (Figure 5.9), indicating when (and what) action must be taken to resolve a sound limit breech. Similar functionality is available in other software of this variety.

In Europe, it can be said that most large-scale professional outdoor entertainment events are more noise-conscious, falling into Phase 3 and possibly Phase 4 of Figure 5.8. It is standard practice for most festivals (or local authorities) to employ noise consultants to monitor levels in the surroundings areas during the festival. In most cases, any issues identified can be immediately corrected by liaising with the FOH engineer at the stage under question.

Aside from 10EaZy, which is focused on monitoring sound level from the mix position at an event, there are other pieces of software which incorporate community noise monitoring on top of on-site monitoring, such as MeTrao [326], SPæL [327], Wavecapture RT-Capture 3 [328] and Horecasense [329]. Regardless of the specific software package chosen, there are some similarities in functionality. Multiple monitoring locations can be set up and fed either to a base station or to the cloud (for analysis online). In most cases remote monitoring is readily available, so that consultants don't have to be on site at all times, allowing for professional advice available to a greater number of simultaneous events.

WARNING!!

Risk of limit violation

Please respond immediately to suggested reduction in dB!

REDUCTION REQUIRED

-3,0 dB

Dialog will close in: 76 Seconds

102,9

Current dB limit: LAeq 15 min @ 103dBA

System information: Dialog will aid in reaching Limit-0.2dB in 2 minutes.

Figure 5.9 10EaZy user interface – warning example

One of the most useful features of these advanced noise monitoring platforms is the ability to precisely identify the source of noise, in many cases down to the 1/3 octave band. This is especially useful at a multi-stage festival (Figure 5.10). For monitoring off-site it’s essential to know which stage is contributing to the noise pollution and at what frequency band(s). Without this, noise control would be largely left to a series of educated guesses.

All of the monitoring information can be seen at all times by users of the system (including FOH engineers), which meets the transparency of information criteria of Phase 4. Additionally, such software can generate noise reports on demand, which is useful for post-event reporting. This is highly recommended in order to deal with any subsequent complaints [325] and is useful in dealing with complaints during the event.

Figure 5.10 User interface for MeTrao Super-Correlator, used to identify source and frequency bands of noise issues at multiple stage festivals and to predict potential problems with noise pollution

5.5.2. Effectiveness of FOH monitoring software

An important caveat to using such monitoring software should be noted. During the review of available software for this report, user testimonials were examined. These testimonials fell roughly into two groups. The first group was as expected: the user expressed gratitude for helping them ensure that the audience got the experience they came for while making sure the local residents weren’t overly annoyed by ensuring the noise stayed within legal limits.

The second group of users appears to use the software in a different manner. These users expressed gratitude for allowing them to get their mix as loud as possible. One particular engineer who expressed this sentiment was mixing for what would be considered a soft folk rock act, yet he was boasting that the software allowed him to ensure his mix was the loudest out of all the bands on the bill that night.

While the software companies advertise the two forms of testimonial in equally positive light, the second form of testimonial should trigger caution within the industry. A recent research project confirmed this [330, 331]. The work looked at whether introducing sound level monitoring (in this case 10Eazy software) into music venues would help limit sound exposure to staff and attendees.

The investigation was split into two stages. The first stage (labeled A) involved monitoring the sound levels for a number of concerts, but not giving the FOH engineer access to the readings during the show. The second stage (labeled B) was the same as the first stage, but this time the FOH engineer could see the meter readings and where his/her mix was sitting relative to the set level limit. The results are reproduced here in Figure 5.12 and Table 5.1. The complete set of data is available in a paper that was published at the time this report was being finalized [331].

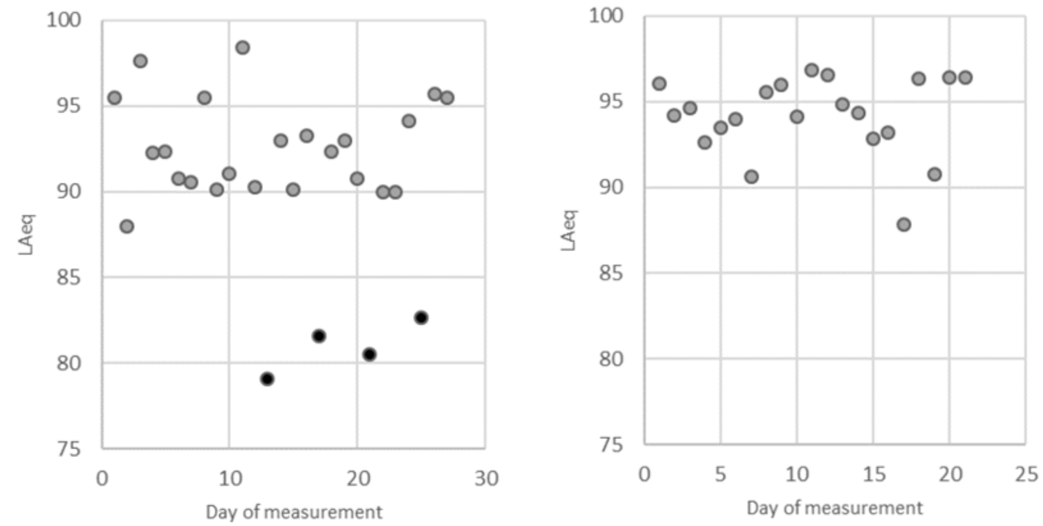
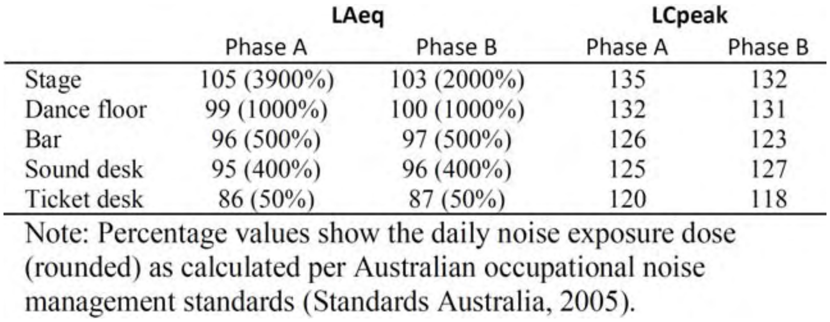


Figure 5.12 LAeq measurements for each individual concert measured where the engineer couldn't (left) and could (right) see the sound level monitor software. The black circles represent data points that were omitted from the study due to various issues [330]



	LAeq		LCpeak	
	Phase A	Phase B	Phase A	Phase B
Stage	105 (3900%)	103 (2000%)	135	132
Dance floor	99 (1000%)	100 (1000%)	132	131
Bar	96 (500%)	97 (500%)	126	123
Sound desk	95 (400%)	96 (400%)	125	127
Ticket desk	86 (50%)	87 (50%)	120	118

Note: Percentage values show the daily noise exposure dose (rounded) as calculated per Australian occupational noise management standards (Standards Australia, 2005).

Table 5.1 Noise dose and peak level readings for the investigation in [330]

The authors identified that the worst offenders of the noise limit were brought under control using the sound level monitoring software, but a worrying trend also appears in the data that the researchers also took note of. It seems to be that once the engineers could see their mix level relative to the limit, they naturally increased the level until they were at the limit (in other words, using the monitoring software to set a target rather than a limit). This is evidenced by the data in Figure 5.12 showing all events clustered around the set limit for the venue. As the 10EaZy software uses a Maximum Average Manager interface, it is clear that achieving the maximum allowable mix level is the goal, which is roughly seen in the results from [330]. The data in Table 5.1 gives some indication of this where the measured level at the sound desk on average increased by 2 dB when the engineer could see the level monitoring software. Note that a direct comparison of the data between phase A and B in Table 5.1 isn't possible since these readings only took place on one night for each phase.

While certainly an interesting trend, the data did not indicate this as a statistically significant finding. Further work is needed in this area to better understand how sound level monitoring software affects sound engineering practice. This should include the exploration of different sound level monitoring interfaces that don't focus on level maximization, but on a less "louder is better" approach.

In terms of noise dose for everyone in the venue, there was no significant effect due to the software, but the question must be asked whether this is a universal trend – will engineers who see that they are mixing below the maximum sound level limit naturally increase the level of the mix (whether it's artistically relevant or not) until they reach the limit? Is monitoring software doing more harm than good in certain situations? Additionally, in light of these findings we must ask which is worse:

- avoiding any breach of the set sound level limits but having all events increase in level due to access to the level monitoring software?, or
- allowing the occasional event to go above set limits but maintain the natural level of all other events (which will likely be below the limit)?

User interface design for existing monitoring software has the potential to result in the former scenario.

Further work is needed to determine if this is a significant problem with such software and, if so, what can be done to rework the user interface to avoid, or reduce, this issue. As the study in [330, 331] was based on indoor venues, further work is required to see if the observed trends hold for large outdoor events. A recent case study repeated the indoor music venue experiment from [330] at a large-scale outdoor music festival [21]. This research is detailed as a case study in Section 5.6.6 and provides early indications regarding the effect of sound level monitoring software at large-scale outdoor entertainment events.

5.5.3. Communication

After many years of noise monitoring, Dutch company dBcontrol [332] found that every problem with sound/noise levels could be traced to communication errors (many of which occurred in the preparatory phase of the event). They have championed a human-centered augmentation to noise monitoring in the form of "Sound Guards" [325]. This is similar to the "decibel" officers recommended in Brussels, but in this case the "Sound Guards" can be hired for one-off events. They are meant to be a means of communication between all stakeholders at an event. Figure 5.11 highlights the key responsibilities of such a position.

Figure 5.11 Communication channels tended by the dBcontrol "Sound Guards" [325]

The use of software like 10EaZy, SPæL and MeTrao, along with qualified personnel to act as intermediaries between stakeholders at events must be viewed as good practice in the industry. With this in mind, noise control operations at European outdoor events should be taken as a model to draw upon for noise control and monitoring purposes across the globe. SPæL specifically allows local residents to send messages using a simple mobile phone app or web browser directly to the FOH mix position and noise consultants, allowing for real-time communication between the engineers responsible for sound levels and local residents. This provides a strong sense of control over potentially annoying noise for residents, which as discussed earlier in this report is a well-known method of annoyance mitigation. A direct communication approach such as this should be regarded as good practice.

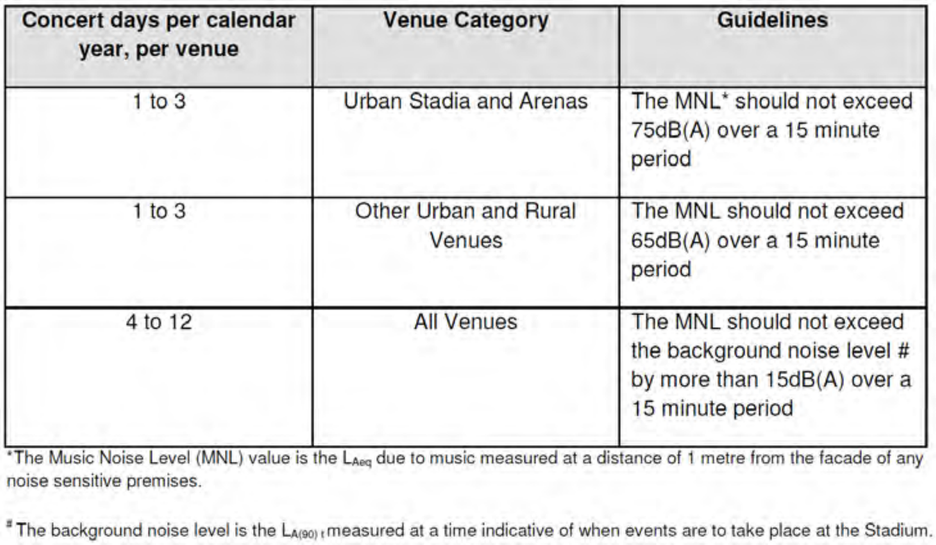
5.6. Case studies

A collection of case studies is presented in this section in order to demonstrate various consultants' approach to noise control for outdoor entertainment events. A particular emphasis on good practice will be made within each case study, to make clear what approaches are most effective and practical.

5.6.1. Emirates Stadium (London, UK)

While the primary purpose of Emirates Stadium is for soccer (a.k.a. football) matches, the stadium is also designed to be able to host live music a limited number of times per year. The local council must approve all concerts in the stadium since the stadium is in very close proximity to residential areas. All information in this case study is taken from the acoustics report put together by the UK-based consultancy, Vanguardia [186, 333].

The council follows the UK's Noise Council Code of Practice (1995) [222] with limits given in Table 5.2 (the same as discussed in Section 4).



Concert days per calendar year, per venue	Venue Category	Guidelines
1 to 3	Urban Stadia and Arenas	The MNL* should not exceed 75dB(A) over a 15 minute period
1 to 3	Other Urban and Rural Venues	The MNL should not exceed 65dB(A) over a 15 minute period
4 to 12	All Venues	The MNL should not exceed the background noise level # by more than 15dB(A) over a 15 minute period

*The Music Noise Level (MNL) value is the L_{Aeq} due to music measured at a distance of 1 metre from the facade of any noise sensitive premises.

The background noise level is the $L_{A(90)\,t}$ measured at a time indicative of when events are to take place at the Stadium.

Table 5.2 Allowable concert limits in the UK, followed for the noise control planning in [222]

As the stadium in question was in an urban location, up to three concerts were allowed per year, which is what the council was prepared to approve. In addition to the limits given in Table 5.2, there are additional recommendations for the low-frequency bands of 63 Hz and 125 Hz. Measured levels up to 70 dB are considered acceptable, while anything over 80 dB is likely to be problematic. Note that these assumptions are those of the consultants, which are not necessarily shared by all contributors to this report.

An additional issue raised by the council is that there are high-rise buildings in the vicinity of the stadium, which due to their height may experience more noise than lower altitude dwellings. To avoid any issues, the council required sound insulation to be installed in the buildings if internal levels (in the residencies) were expected to exceed 57 dB (LAeq, 15min) according to BS 8233:1999 [229]. If this condition could be met, then any form of concert would be allowed. If it couldn't be met, then only "soft" music will be permitted (i.e. not rock or pop).

In order to comply with the local council, the event organizers must submit a feasibility study no less than 28 days before a concert, which should include noise predictions. Additionally, a noise management plan must be in place, which should include clear liaison with local residents and a hotline for the residents to call during the event if there is an issue.

Tests were carried out before any concerts were booked into the stadium to ensure it could comply with the council's requirements. The consultancy firm did on-site testing using a popular rock track as well as pink noise. The resulting measurement data is reproduced here in Table 5.3.

No	Site	Source	Internal LAeq	External LAeq	Maximum Allowable Mixer LAeq based on 75LAeq external
1	Northern Triangle (ground)	Music	105	79	101
		Pink	102	77	100
2	Drayton Park	Music	105	67	113
		Pink	102	65	112
3	Hornsey Road	Music	105	73	107
		Pink	101	71	105
4	Northern Triangle (7th Floor)	Music	104	78	101
		Pink	101	76	100
5	Northern Triangle (8th Floor)	Music	105	79	100

Table 5.3 Measurement data from consultancy-led testing at Emirates Stadium [222]

The measurement data shows that in certain areas around the stadium the noise levels are in breach of the stated 75 dBA limit. Based on these findings, the consultancy advised that a FOH limit of 98 dBA must be set to ensure all community noise is kept within legal values. Low-frequency noise was found to be around 90 dB in many places, but the consultant advised that from experience this shouldn't be a problem as the regulations are aimed at distances of 2 km from a source, not in close proximity. Whether this is accurate or not is hard to say, as there is no scientific evidence to support the claim. In addition to the recommended FOH limits, the report also suggests that additional acoustical treatment be applied to the stadium to further reduce noise spill into the community.

Based on this work and the following high-profile concerts, sound levels at FOH needed to be reduced further to between 95 to 96 dBA which made the stadium difficult to use as a concert venue. Options were reviewed for a temporary noise barrier to be installed in the large gaps at all four corners of the stadium, however the cost of implementing such a solution was not supported by the income from such concerts. There would also be additional effort required to rig and de-rig the barriers each time such an event was held.

Good practice within this case study includes the Noise Management Plan (NMP) in regard to interfacing with local residents, including a noise hotline during the event. This would give residents a perceived level of control over the noise, which has been shown to go a long way in reducing the high levels of annoyance. Additionally, the pre-event testing in the surrounding areas allows for accurate prediction of expected noise levels in local residences, which can inform limits at the mix position in the venue. Unfortunately, the measurements all use A-weighting, which has the potential to miss the most problematic noise components in the low-frequency range. The notion that the problem changes in nature based on proximity to the noise source doesn't agree with published research covered in previous sections of this report.

5.6.2. BAT Test (Amsterdam, Netherlands)

The city of Amsterdam regularly holds outdoor entertainment events within its densely populated city center. To ensure the best practices are put into place to control noise pollution from events within the city, Amsterdam commissioned Event Acoustics to carry out a detailed investigation. The lead engineer on the project is a contributor to this report. All information in this section comes from [119].

The test intended to identify the Best Available Techniques (BAT) for limiting noise pollution from outdoor events and was conducted on the outskirts of the city, near the airport and a motorway. Testing consisted of four sound systems, supplied by local companies. All sound systems consisted of line arrays (in a left/right configuration), a separate subwoofer system and a DJ monitoring system on stage. Four separate stages were set up, side by side at the end of the test field (Figure 5.13).

The aim of the test was to determine if there is a preferable configuration for a sound system that minimized off-site noise while delivering a consistent high-quality listening experience for the audience. All measurements were taken using C-weighting (which is in line with Amsterdam's local regulations) and each system was calibrated to deliver a standard 100 dBA at FOH (120 dBC). The DJ monitors were required to reach 105 dBA at a distance of 2 m. As noise pollution issues are generally low-frequency in nature, the tests only considered frequency content at 630 Hz and below.

Figure 5.13 Photo of the test layout for the experiments in [119]

Each sound system provider was told that their PA must evenly cover from 12.5 m to 50 m in front of the stage edge over a width of 35 m while minimizing noise pollution to the surrounding areas. SoundPLAN 8 [313] was used to create a reference (ideal) system design and noise prediction which represented the ideal scenario (Figure 5.14). Note that SoundPLAN 8 includes complex summation, which is essential for sound system-based noise predictions, as discussed in Section 5.4.

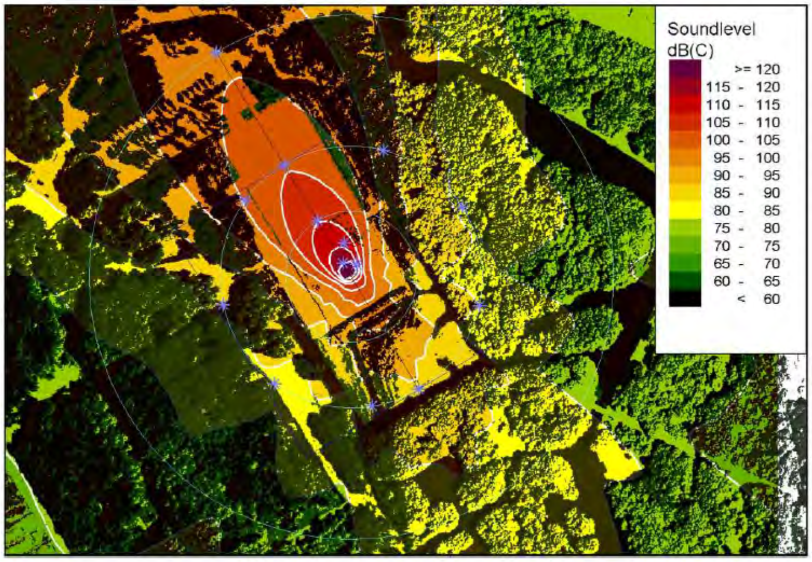


Figure 5.14 Ideal sound system coverage from reference model [119]

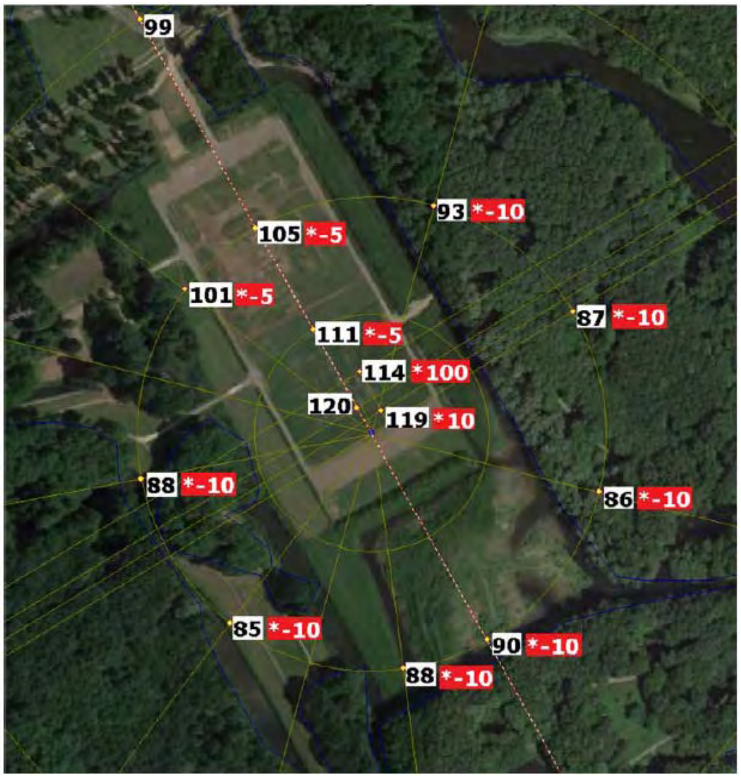
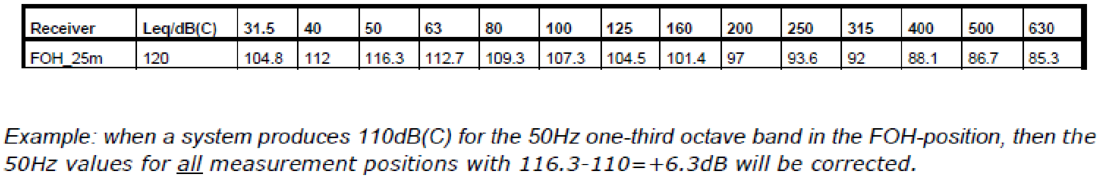


Figure 5.15 Reference point locations with corresponding weighting values [119]

A points-based system was derived to rate the performance of each system. Reference measurement points were given weightings (Figure 5.15) so that high- and low-priority areas could be defined. As a starting point, the audience consistency was given a high weighting, indicating that this was an important aspect of this exercise, not to be overlooked. The point rating for each system was calculated using Equation 5.3.

$$PTS = \sum_{i=1}^{N} \left(meas_i - ref_i \right) weighting_i \tag{5.3}$$

The points-based rating (*PTS*) is calculated based on the difference between the measured system responses (*meas*) and the reference response (*ref*, from SoundPLAN), both at point *i*, multiplied by the weighting factor at the i^{th} point. All individual measurement points are summed to get the overall rating. Before calculating the ratings, each measurement was corrected based on a flat magnitude response at FOH to ensure consistency of analysis between systems (Figure 5.16). The analysis was repeated a number of times using different approximated music spectrums to simulate different varieties of events.



Receiver	Leq/dB(C)	31.5	40	50	63	80	100	125	160	200	250	315	400	500	630
FOH_25m	120	104.8	112	116.3	112.7	109.3	107.3	104.5	101.4	97	93.6	92	88.1	86.7	85.3

Example: when a system produces 110dB(C) for the 50Hz one-third octave band in the FOH-position, then the 50Hz values for all measurement positions with 116.3-110=+6.3dB will be corrected.

Figure 5.16 Example of measurement corrections (based on FOH) applied prior to analysis [119]

All measurements were taken over 1/3 octave bands (Leq, 1 s) at 28 measurement points, where five separate trials were run for each sound system:

1) Full system (tops, subs, DJ)
2) Full PA (no DJ)
3) Tops only
4) Subs only
5) DJ only

To avoid negative influence due to weather conditions, each trial was measured for 2 minutes using intermittent pink noise with a 20 – 250 Hz sine sweep superimposed onto the signal. The signal possessed a crest factor of 4.5 dB. It is unclear whether this test signal was based on any prior research findings or if it is proprietary. Additionally, to ensure correct tracking of background noise, the test signal would be on for 20 s and off for 10 s. If any more than 3 dB of corrections were required to take the background noise into account, then that specific measurement would be deemed unreliable. Over the course of the tests, only frequency bands above 1 kHz encountered this issue, but these bands weren't used within the analysis. The wind was reported as fairly constant throughout the day at around 6 m/s blowing 250° relative to the stage. The temperature was a consistent 20° C.

All systems were roughly the same (in terms of using line arrays and ground-based subwoofers), but they differed in physical size (length of arrays) and layout. System 1 included stacks of shipping containers directly behind the line arrays to shield rear-going sound propagation (which is moderately common practice and is usually part of the stage structure), although none of the other systems used this. This poses an issue in terms of direct comparability of the systems as this approach prevents like-for-like comparisons. This should be kept in mind when analyzing the results. Current issues surrounding large sound system evaluations – a.k.a. shoot-outs – are discussed in Section 3.4.

The staff from Event Acoustics reserved the right to reconfigure any of the systems for further trials to inspect whether any optimization could be achieved. Make and model information for the loudspeakers was deemed irrelevant and not disclosed. It was assumed that professional-grade sound systems are at a high enough standard that sound coverage is largely a function of configuration.

The principal conclusions of the test are reported here as quotations alongside comments from regarding areas with limited evidence available. The conclusions regarding flown subwoofers have been discarded as no flown subwoofer arrays were considered during the test.

- *Size matters.* "The best performing system during this test according to the predefined conditions is also the largest system in terms of dimensions. This is not accidental; it is a fact that larger dimensions lead to greater control at lower frequencies." [119]

- *Height matters*. "During the process of taking measurements at 200 meters distance, wind influence causes up to approx. 10dB(C) difference between lower and upper wind points on the transfer. The wind speed during the process of taking measurements was approx. 6m/s. This influence caused by the wind in the transfer is greater than the current applied calculation models predicted. The biggest influences are on the line-arrays, the influences on the sub-layer systems are smaller. The reason for this has not been demonstrated, but it is probably because the wind speed on the ground is lower than at the height of the line-arrays… In these tests, there is no direct correlation between the height of the sound systems and the test scores. This measure appears to be especially important if the sound system is not well-directed (straight ahead). However, it appears that the wind influences on the systems in the air are greater than on the systems on the ground. This calls for this measure." [119]

  Author's note: Looking closely at the published results of this study, this finding doesn't appear to be conclusive. The vagueness of the data can largely be attributed to coarseness of the angular sampling resolution (45 degrees). Earlier in the report it remarks that "[t]he reason all systems are influenced by the wind to varying degrees is unclear for the time being." This points to further research needed before any conclusion on height of a sound system (especially concerning subwoofers) can be made. It is likely that height can't be considered on its own. Height as well as physical speaker orientation and electronic steering (if used) most likely have to be considered together instead of in isolation.

- *Ground-based horizontal subwoofer arrays are preferable.* "The measurements show that the emission with overhead subs in the 90-180 degree area is about 10dB worse than with a cardioid sub-array. In addition to this, it appears that the wind influence on the overhead subs is much greater than on sub-arrays on the ground... The measurements show that overhead subs have a negative influence on the sound. This is because all line-arrays have significantly less direction in the dB(C) values compared to the sub-arrays. It also appears that systems that are higher up from the ground are more subject to wind influences." [119]

  Author's note: A flown subwoofer array wasn't tested as part of this study. This recommendation is in opposition to the analysis from Section 2 on audience sound exposure. Further research is necessary to make a clear conclusion regarding ground versus flown subwoofer arrays. Considering the relevant research detailed in other sections of this report, the conjecture that ground-based subwoofer systems are easier to control in terms of noise pollution is questionable. As flown subwoofer systems are currently banned in Amsterdam (on the supposed fact that they result in greater noise pollution), it is very important to resolve this ambiguity to avoid ill-informed regulations.

- *Cardioid subwoofer arrays are essential.* "The use of a cardioid sub-array is clearly better than when the array is not cardioid or when a left-right sub-arrangement is used. Compared to the left-right setup tested here, the tested cardioid sub-array is 9 to 15 dB(C) quieter on the sides and rear of the stage. The recommendation is to apply a cardioid sub-array at all times when control of the emission is important. The array must continue uninterrupted." [119]

  Author's note: This isn't supported in the published results. Only rear-propagating sound radiation was reduced. It must also be noted that a cardioid polar response at low frequencies can be achieved by positioning a flown subwoofer array in close proximity to the main line array, creating an end-fire or gradient loudspeaker configuration for the spectral region of overlap between the two arrays.

- *Extreme far-field source behavior:* "The measurements show that a cardioid sub-array in the direction of play from 100 meters away simply behaves as a point source and declines by 6dB/ doubling of the distance. The idea that these systems "reach further" than other systems is therefore incorrect. These effects only occur in the nearby field up to about 50 meters (depending on the array size)." [119]

  Author's note: Further research is required here, as this finding is in direct opposition to what is known (from extensive research) about noise propagation from wind turbines [122].

- *Higher crossovers are preferable.* "In systems where a measurement difference x-over between sub-array and line-arrays was made at 80Hz or at 40/60Hz, the higher x-over points were found to score better each time. The sub-layer systems are also clearly less affected by the wind. This measure can therefore be considered effective." [119]

  Author's note: At stated above, this finding is open to debate as the published results are unclear on this point, where in some cases there is no observable difference between the tested crossover points. Further work is needed and should be linked to additional investigations looking into sound radiation control of ground versus flown subwoofer systems. At present there is insufficient evidence to make a clear recommendation.

- *The DJ fill matters.* "The test shows that DJ monitoring can contribute significantly to total emissions. As a result, the following 2 recommendations regarding the DJ monitoring can be made: 1 - If subwoofers are used, these must be implemented as cardioid stack behind the DJ. 2 - The DJ monitoring must be controlled by the FOH sound table at all times." [119]

These findings are already used to inform system design for large outdoor entertainment events taking place in Amsterdam. Contributors to this report have noted that Amsterdam already has a ban on flown subwoofer arrays to limit noise pollution. As this approach is in opposition to the discussion on audience sound exposure, an investigation is necessary to resolve this conflict. The results presented in this case study are inconclusive on this point.

5.6.3. National Bowl (Milton Keynes, UK)

An interesting case study can be drawn from an event at the National Bowl in Milton Keynes in 2010 [188]. The Bowl, which is a permanent structure, with a stage and hard standing areas, was originally classified by the local council as a "Other Urban and Rural Venue", using the terminology from the Noise Council's *Code of Practice on Environmental Noise Control at Concerts* (1995) [222]. This resulted in a maximum noise level being imposed of 65 dBA. Interestingly, the council didn't set clear off-site limits for this venue (unlike other major venues in the UK). Instead, an internal limit was set at the edge of the bowl, focused exclusively on low-frequency noise, as this was what most residents complained about. A survey of UK venue noise limits is given in Figure 5.17, for comparative purposes.

Venue	Internal Condition	Off-site Condition	Low frequency limit
Lancashire County Cricket Club	None	80LAeq	No
Heaton Park, Manchester	None	80LAeq	No
Hyde Park, London	None	75LAeq	No
Victoria Park	None	75LAeq	No
RDS Showground, Dublin	None	75LAeq	No
Twickenham Stadium	None	75LAeq	No
Hampden Park, Glasgow	None	75LAeq	No
Ricoh Stadium, Coventry	101LAeq	75LAeq	No
Don Valley, Sheffield	None	75LAeq	No
Portman Road, Ipswich	None	75LAeq	No
Madejski Stadium, Reading	None	75LAeq	No
St Marys, Southampton	None	75LAeq	No
Rosebowl, Southampton	None	75LAeq	No
Stadium of Light, Sunderland	None	75LAeq	No
The National Bowl	***Yes***	***No***	***Yes***

Figure 5.17 Survey of major UK venue noise limits [188]

Due to the noise limits imposed by the local council, the venue gained a reputation as being unusable by major touring acts. This came to a head when The Prodigy was booked to play the venue in 2010. The event would be the band's largest show ever and there was significant incentive to make it as good an experience for the audience (and band) as possible. UK-based consultancy, Vanguardia [333], was brought in to contribute to a legal case against the local council to get the venue reclassified with conventional noise limits [188].

The outcome of the case was that Vanguardia was able to prove that the venue should be reclassified under the "Urban Stadia and Arenas" label, which would raise the allowable noise limit from 65 dBA to 75 dBA. The council's argument that their venue was similar to those of Glastonbury and Knebworth was disproven, as Glastonbury operates all day, thus necessitating stricter noise limits, while Knebworth (and Glastonbury, for that matter) aren't stadia or arenas, but open fields in rural areas.

It was stressed that care must be taken not to confuse industrial noise limits with leisure noise limits, as industrial noise tends to be persistent throughout the year, thus imposing a potential health and safety risk as well as ongoing annoyance. Concerts are infrequent events, where there is no health and safety concerns for the local residents. The potential issue (as stated earlier in this report) is annoyance, which can be (and is regularly) managed through effective communication with local residents in the run up to the event. Experience dictates that with these communication measures in place (as well as the infrequency of such events), local residents are much more accommodating than if the noise were originating from a permanent industrial source.

Ultimately, the local council had to adjust the venue's noise limits to be in line with UK regulations and standard practice. The restrictive low-frequency limit was removed and replaced with off-site noise monitoring in sensitive areas, as is standard for such venues hosting large events. Although the recommendations (and resulting changes) adopted an LAeq limit – justified based on the DEFRA Pubs and Clubs study [290, 298], which is in opposition to other research reviewed in this report – the outcomes should still be seen as positive where the venue's overly-prescriptive limits were normalized to match practice across the UK.

5.6.4. Victorious Fest 2014 (Portsmouth, UK)

Another example of noise assessment and management at UK festivals from UK-based consultancy, Vanguardia, was from Victorious Fest, held in Portsmouth in 2014 [187]. The festival consisted of a main stage, a big top tent stage and a smaller local act stage. The event was planned to run for two days from 10am until midnight.

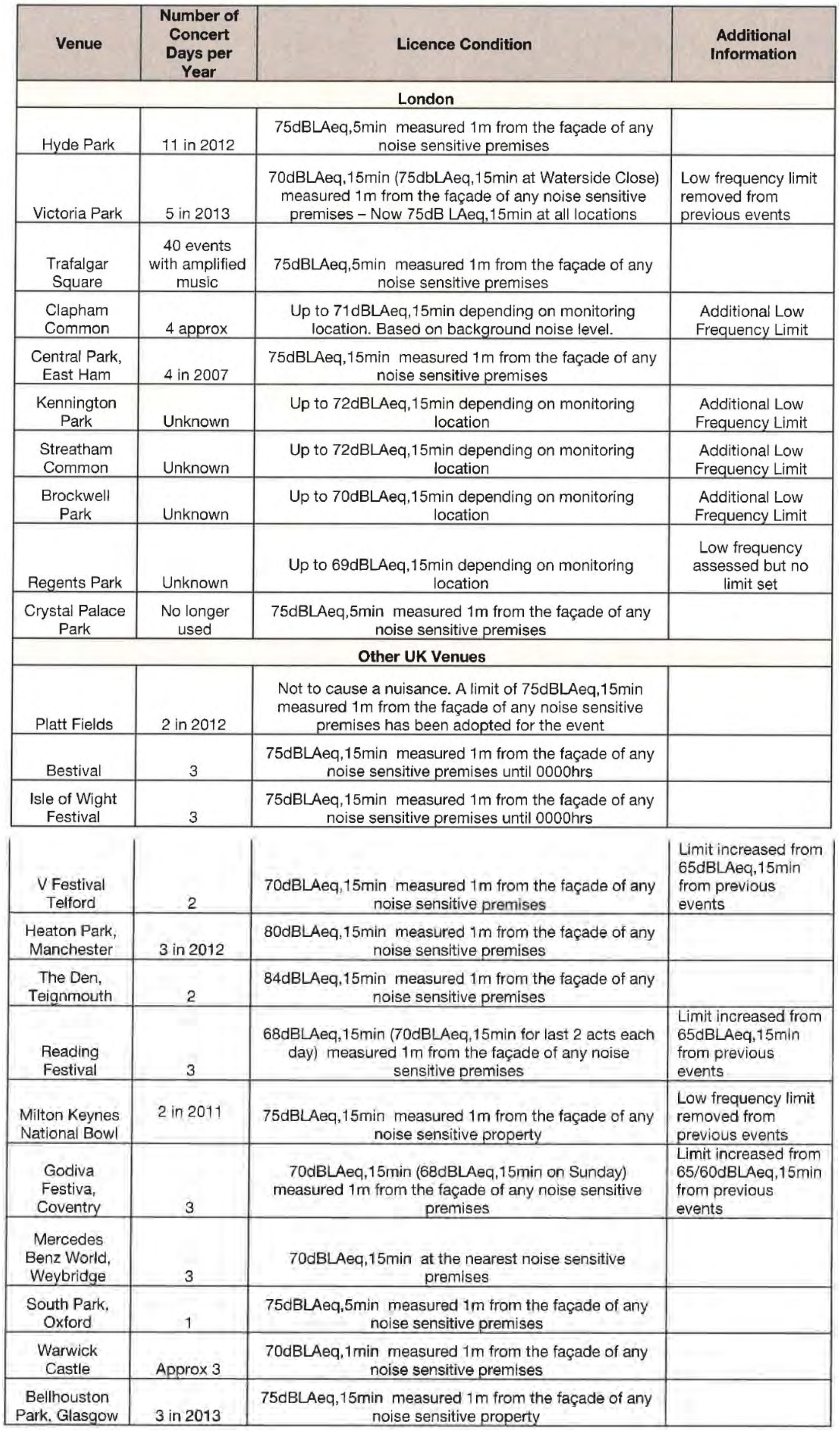
Drawing again from the Noise Council's 1995 Code of Practice, it was clear that after 11pm the noise as measured externally to a noise-sensitive property must be no more than 45 dB (LAeq, 15 min) so that the music-based noise will be completely inaudible in the dwelling with the windows open for ventilation purposes. Other than during this last hour of the event, the limit was 65 dBA (LAeq, 15 min) as the venue was classified as "Other Urban and Rural Venue." The report gives a nice summary of noise limits at similar venues across the UK (reproduced in Table 5.4).

For the noise predictions, there was an assumed maximum level of 98 dBA at FOH (where 95 dBA at FOH was considered to be unacceptable for such events). The corresponding noise predictions for a worst-case scenario for all stages operating simultaneously are reproduced here in Table 5.5.

Victorious Festival	Main Stage (dBA)	Stage 2 (dBA)	Stage 3 (dBA)	Total (dBA)
9 Clarence Parade	57.3	58.6	46.8	**61.2**
Palmerston Court	64.8	63.4	51.7	**67.3**
53 Clarence Parade	69.0	64.1	56.1	**70.4**
Lennox Mansions	74.0	63.2	59.0	**74.4**
27 South Parade	72.2	59.2	54.1	**72.4**

Table 5.5 Worst-case scenario noise predictions with all stages operating simultaneously [187]

In this scenario, all but one measurement location is in breach of the 65 dBA limit, while all locations are well-above the 45 dBA post-11pm limit. Note that the data in Table 5.5 doesn't consider any attenuation effects from the surroundings, so these levels are unlikely to occur in reality.



Venue	Number of Concert Days per Year	Licence Condition	Additional Information
London			
Hyde Park	11 in 2012	75dBLAeq,5min measured 1m from the façade of any noise sensitive premises	
Victoria Park	5 in 2013	70dBLAeq,15min (75dbLAeq,15min at Waterside Close) measured 1m from the façade of any noise sensitive premises – Now 75dB LAeq,15min at all locations	Low frequency limit removed from previous events
Trafalgar Square	40 events with amplified music	75dBLAeq,5min measured 1m from the façade of any noise sensitive premises	
Clapham Common	4 approx	Up to 71dBLAeq,15min depending on monitoring location. Based on background noise level.	Additional Low Frequency Limit
Central Park, East Ham	4 in 2007	75dBLAeq,15min measured 1m from the façade of any noise sensitive premises	
Kennington Park	Unknown	Up to 72dBLAeq,15min depending on monitoring location	Additional Low Frequency Limit
Streatham Common	Unknown	Up to 72dBLAeq,15min depending on monitoring location	Additional Low Frequency Limit
Brockwell Park	Unknown	Up to 70dBLAeq,15min depending on monitoring location	Additional Low Frequency Limit
Regents Park	Unknown	Up to 69dBLAeq,15min depending on monitoring location	Low frequency assessed but no limit set
Crystal Palace Park	No longer used	75dBLAeq,5min measured 1m from the façade of any noise sensitive premises	
Other UK Venues			
Platt Fields	2 in 2012	Not to cause a nuisance. A limit of 75dBLAeq,15min measured 1m from the façade of any noise sensitive premises has been adopted for the event	
Bestival	3	75dBLAeq,15min measured 1m from the façade of any noise sensitive premises until 0000hrs	
Isle of Wight Festival	3	75dBLAeq,15min measured 1m from the façade of any noise sensitive premises until 0000hrs	
V Festival Telford	2	70dBLAeq,15min measured 1m from the façade of any noise sensitive premises	Limit increased from 65dBLAeq,15min from previous events
Heaton Park, Manchester	3 in 2012	80dBLAeq,15min measured 1m from the façade of any noise sensitive premises	
The Den, Teignmouth	2	84dBLAeq,15min measured 1m from the façade of any noise sensitive premises	
Reading Festival	3	68dBLAeq,15min (70dBLAeq,15min for last 2 acts each day) measured 1m from the façade of any noise sensitive premises	Limit increased from 65dBLAeq,15min from previous events
Milton Keynes National Bowl	2 in 2011	75dBLAeq,15min measured 1m from the façade of any noise sensitive property	Low frequency limit removed from previous events
Godiva Festiva, Coventry	3	70dBLAeq,15min (68dBLAeq,15min on Sunday) measured 1m from the façade of any noise sensitive premises	Limit increased from 65/60dBLAeq,15min from previous events
Mercedes Benz World, Weybridge	3	70dBLAeq,15min at the nearest noise sensitive premises	
South Park, Oxford	1	75dBLAeq,5min measured 1m from the façade of any noise sensitive premises	
Warwick Castle	Approx 3	70dBLAeq,1min measured 1m from the façade of any noise sensitive premises	
Bellhouston Park, Glasgow	3 in 2013	75dBLAeq,15min measured 1m from the façade of any noise sensitive property	

Table 5.4 Noise limits set by various similar venues across the UK [187]

Additional predictions were generated for more likely scenarios (with attenuation sources included), showing that most measurement locations will be within the stated limits. To ensure the noise impact is limited the consultancy advised that all sound systems be flown and directed down towards the audience with as narrow as possible horizontal dispersion pattern (while still adequately covering the audience area). It is assumed that this includes the subwoofer system, which is in direct contrast to the case-study from Amsterdam where flown subwoofers were strongly discouraged, due to the likelihood of low-frequency noise propagation due to varying meteorological conditions (although it must be re-emphasized that the results from the Amsterdam study were inconclusive on this point).

The key recommendation is how to effectively communicate with local residents. This is a feature of all of Vanguardia's work, where residents are notified in advance of the event and given information about a hotline to call during the event to report any issues. This process (and how it feeds back to those controlling the sound system) is reproduced here in Figure 5.18. Adopting such practice has shown at past events to significantly reduce complaints, allowing for large-scale outdoor events and local residents to exist in relative harmony (provided the events are infrequent, of course).

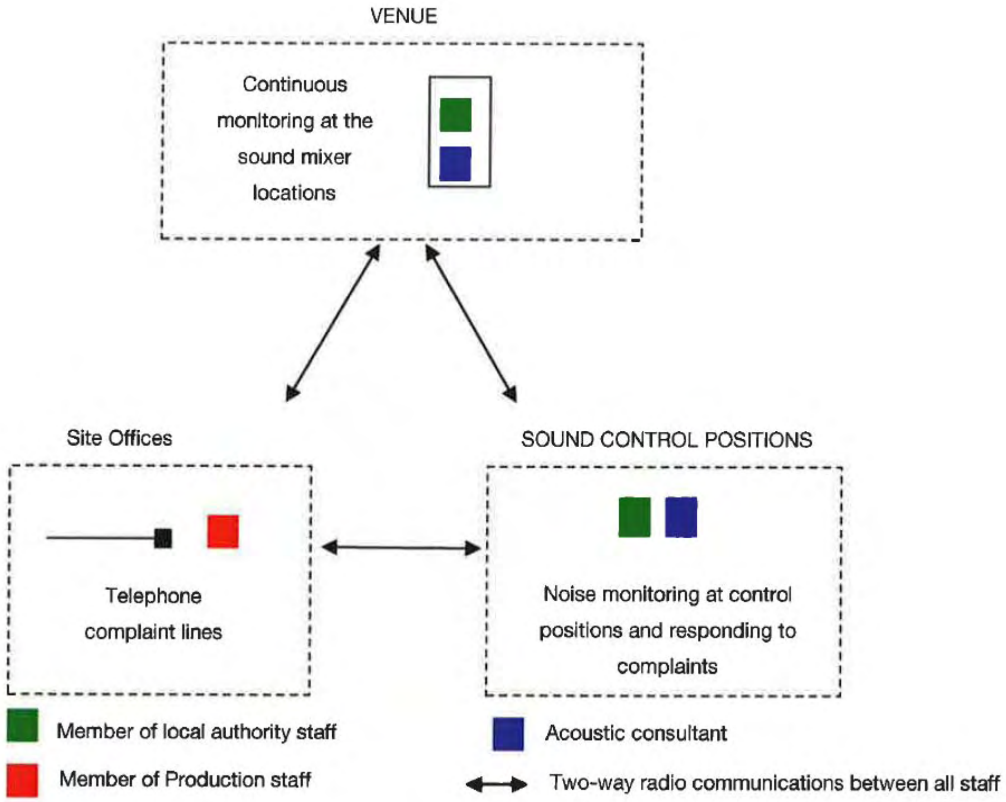


Figure 5.18 Diagram of communication channels during the event [187]

5.6.5. Colorado State University (Fort Collins, CO, USA)

Colorado State University planned to build a new football (a.k.a. American football) stadium on their campus in 2014 and conducted a study of the potential noise pollution that could arise due to the new stadium. All information in this section is taken from their published report [334].

Noise predictions were carried out using SoundPLAN [313] for both sporting event and concert scenarios. While the sporting events won't be discussed here, it should be noted that they had planned to install a distributed sound system to avoid noise pollution in local residential areas (the closest of which is directly across the street). The proposed stadium is a horseshoe shape (it has one closed end and one open end), meaning that any residences in the path of sound emitting from the open end of the stadium could receive problematic noise levels.

The university wasn't legally required to follow local Fort Collins noise limits but, in an effort to be good neighbors, would do their best to abide by the regulations. For Fort Collins, residential areas should be exposed to no more than 55 dBA and 50 dBA during the day and night, respectively. This is roughly in line with regulations reviewed in Section 4 of this report.

The consultants also noted that the US Department of Housing and Urban Development's (HUD) recommended noise limit was 75 dBA during the day (L_{dn}). This highlights the disjunctive nature of US noise regulations, whereby local communities impose strict limits (in line with most of the world), but the federal government's published limits are extremely relaxed.

For the noise predictions, the consultants assumed an average of 22 dB outdoor-to-indoor attenuation, which resulted in a worst-case scenario of 53 dBA inside a residence due to a concert at the stadium (corresponding to roughly 75 dBA at the property line). The predictions over the event duration as well as the entire day (L_{dn}) for both possible stage locations in the stadium are reproduced in Figures 5.19 – 5.22.

The primary finding from the predictions is that for concerts, the stage should always be positioned facing away from the open end of the stadium to avoid excessive noise levels in the surrounding areas. The conclusion of report, though, is slightly ambiguous as it states that the predicted noise levels are in clear breech of the local regulations (and reiterates that the university is committed to being a good neighbor). It states that it is expected that the local residents will grow accustomed to the events at the stadium over a year or so of operation and it will become part of local life and points out that the noise predictions are roughly within the US HUD guidelines. This is a good example of the issues with US noise regulations. In this case, the authors of the report may well be correct that the noise from the stadium won't be seen as a problem, but it is a risky approach.

Near the end of the report, however, the author does note that if concerts are deemed to be an issue, a system can be implemented where each concert has to apply for an individual operating permit, which then allows for the local community to prohibit a proposed event. Even if this doesn't come to fruition, the recommended approach is to limit the number of concerts at the stadium to a handful per year (similar to the UK guidelines).

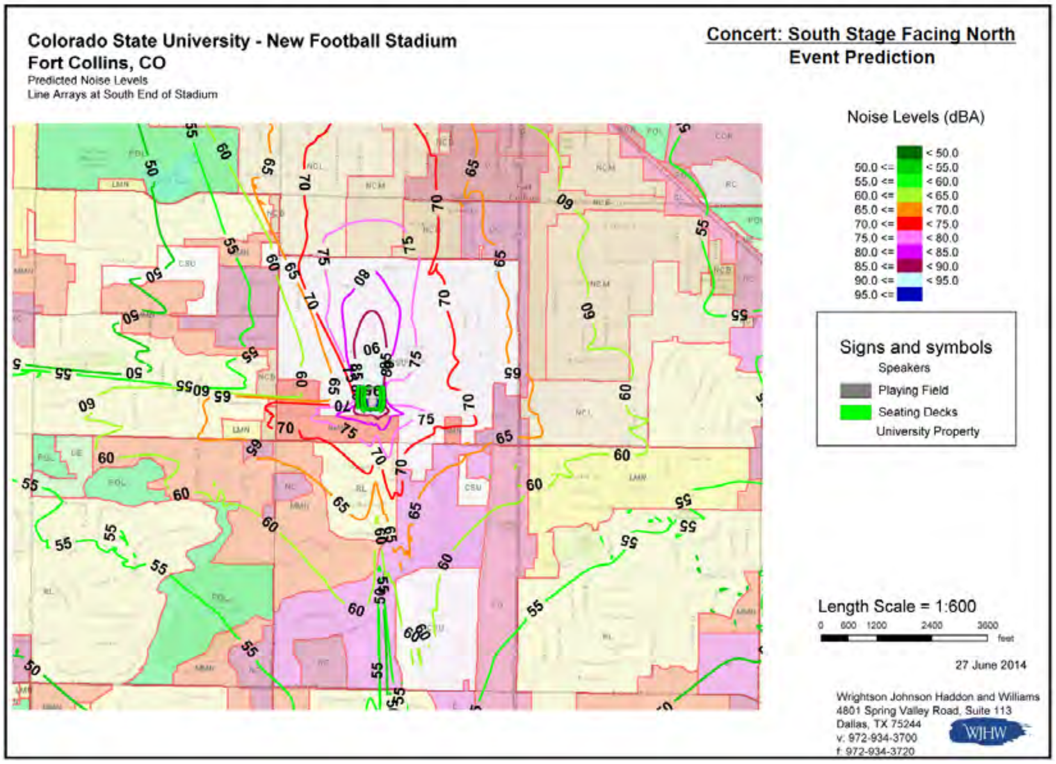


Figure 5.19 Noise prediction over a concert duration with a south stage location, facing north [334]

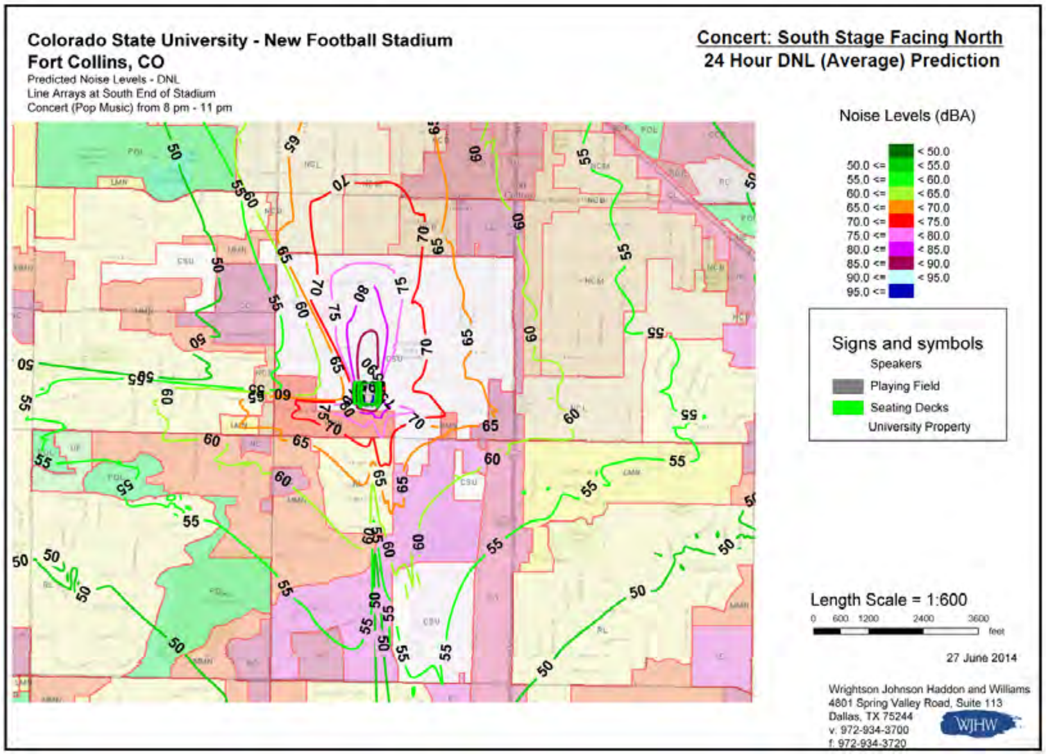


Figure 5.20 Noise prediction over a day (Ldn) with a south stage location, facing north [334]

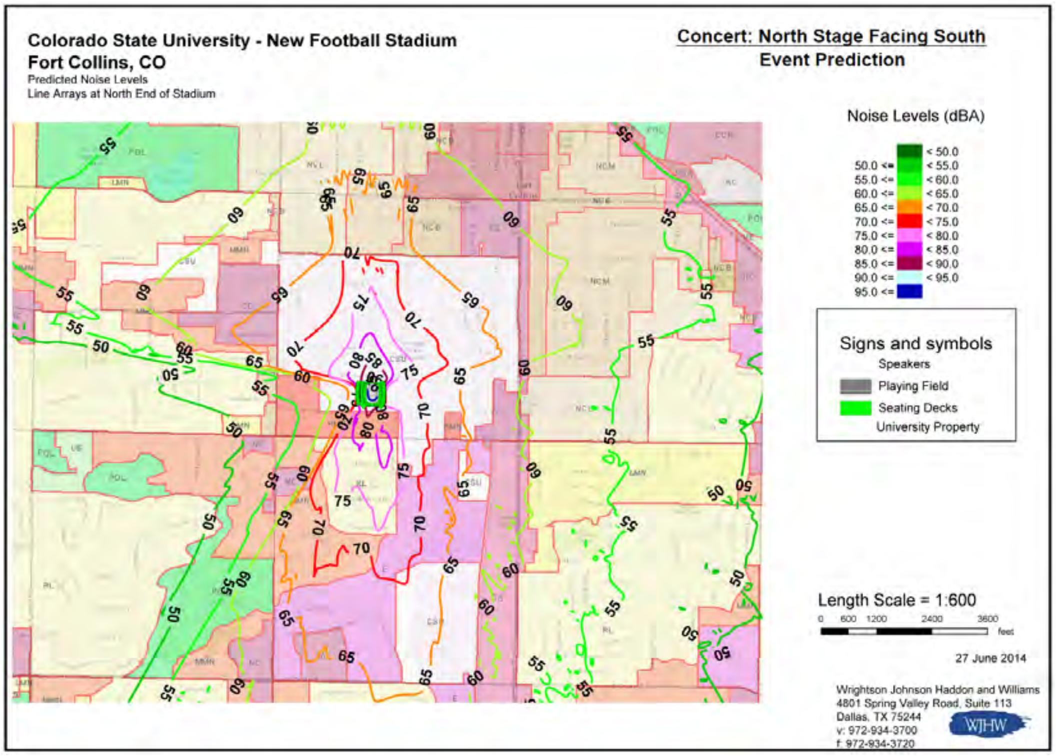


Figure 5.21 Noise prediction over a concert duration with a north stage location, facing south [334]

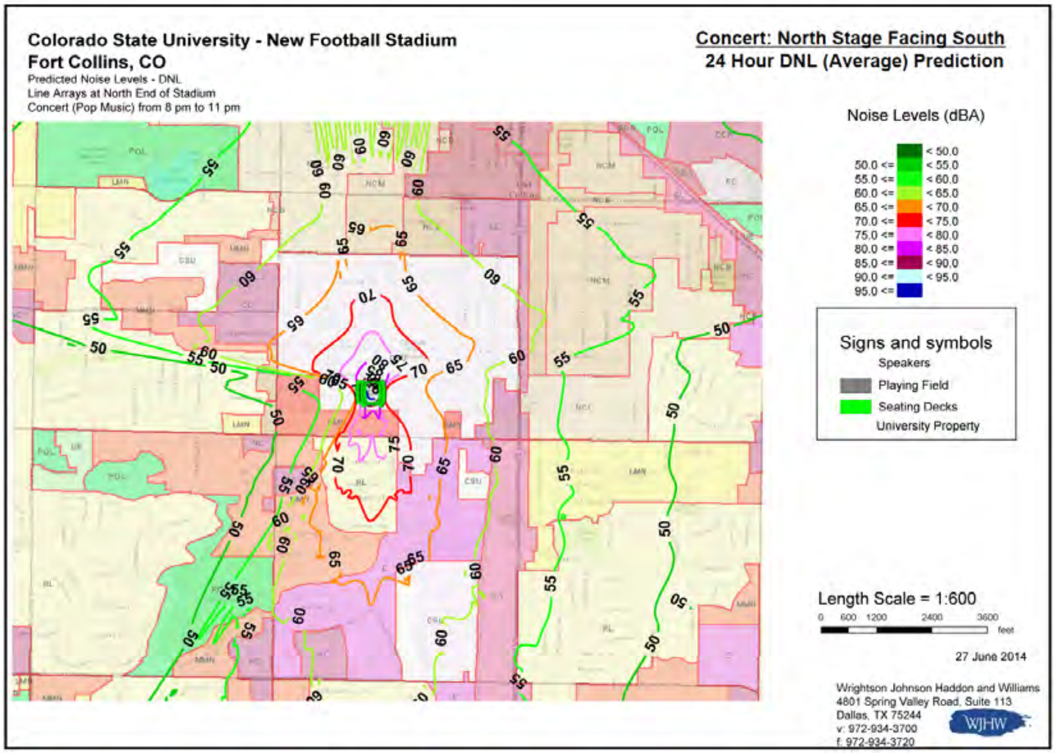


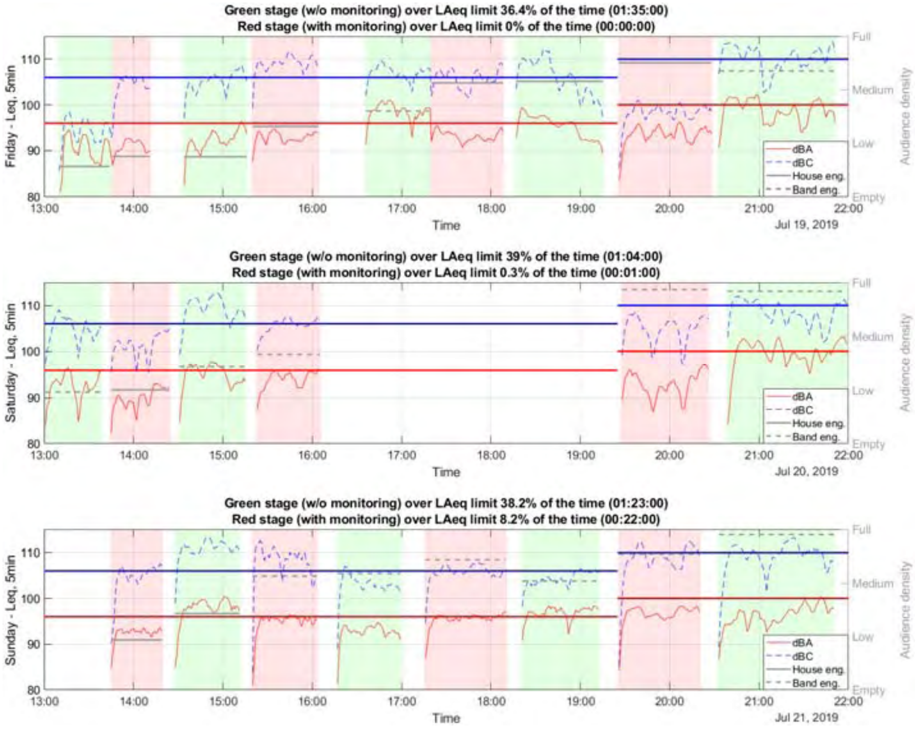
Figure 5.22 Noise prediction over a day (Ldn) with a north stage location, facing south [334]

5.6.6. Pitchfork Music Festival 2019 (Chicago, IL, USA)

A recent case study conducted by some of the contributors to this report focused on applying the experimental technique used in the Australian indoor music venue study in [330, 331] to determine if similar trends would be observed at a large outdoor music festival [21]. The experiment took place on the two main stages at Pitchfork Music Festival in Chicago, Illinois, USA near the end of July, 2019. On one of the stages (labeled the Red Stage), sound engineers had sight of sound level monitoring software (10EaZy) giving information on the current mix level in comparison to the set festival limits (96 and 100 dBA LAeq, 5 min for support acts and headliners, respectively). The other stage (labeled the Green Stage) had no sight of the sound level monitoring software, but the software still logged data from that stage with the same level limits.

Both stages had nearly identical sound systems (with the exception of different subwoofer models used in the ground-based subwoofer arrays) allowing for acceptable comparisons between the measurement data. In addition to the front-of-house (FOH) sound levels, audience distribution and density were tracked along with music genre and engineer type (house or band engineer). Measurements at various positions in the audience were taken prior to the start of the festival to allow for indirect tracking of audience sound pressure levels throughout the event. This data would be critical in determining the extent of audience sound exposure at such an event.

The raw FOH sound level data is reproduced in Figure 5.23. The data shows that with sound level monitoring, the level limits were exceeded roughly 3% of the total "live" time on the stage, while without the software, the level limits were exceeded roughly 38% of the time.



Green stage (w/o monitoring) over LAeq limit 36.4% of the time (01:35:00)
Red stage (with monitoring) over LAeq limit 0% of the time (00:00:00)

Green stage (w/o monitoring) over LAeq limit 39% of the time (01:04:00)
Red stage (with monitoring) over LAeq limit 0.3% of the time (00:01:00)

Green stage (w/o monitoring) over LAeq limit 38.2% of the time (01:23:00)
Red stage (with monitoring) over LAeq limit 8.2% of the time (00:22:00)

Figure 5.23 FOH sound pressure level data over the course of the festival [21]

An interesting consequence of engineers mixing to the limit with the sound level monitoring software was that the dynamic range (quantified as LA10 – LA90 averaged over 1 second) decreased by more than 3 dBA (Figure 5.24). C-weighted dynamic range showed no significant change. The A-weighted change was due to two primary factors: first, that the level monitoring used A-weighting therefore changes to low-frequency content would have less impact on the measured levels. Second, the subwoofer system was driven by a mono auxiliary send from the mixing console. When engineers saw they were in breach of the level limits, it was observed that they always decreased the level of the main left/right send and never touched the separate subwoofer send. This would therefore impact the A-weighted levels, but leave the C-weighted levels untouched. The impact this had on the audience listening experience is at present unknown. Further research is required to determine the just noticeable difference in dynamic range at such events (for A- and C-weighted measurements) before the audience notices a change in sound quality).

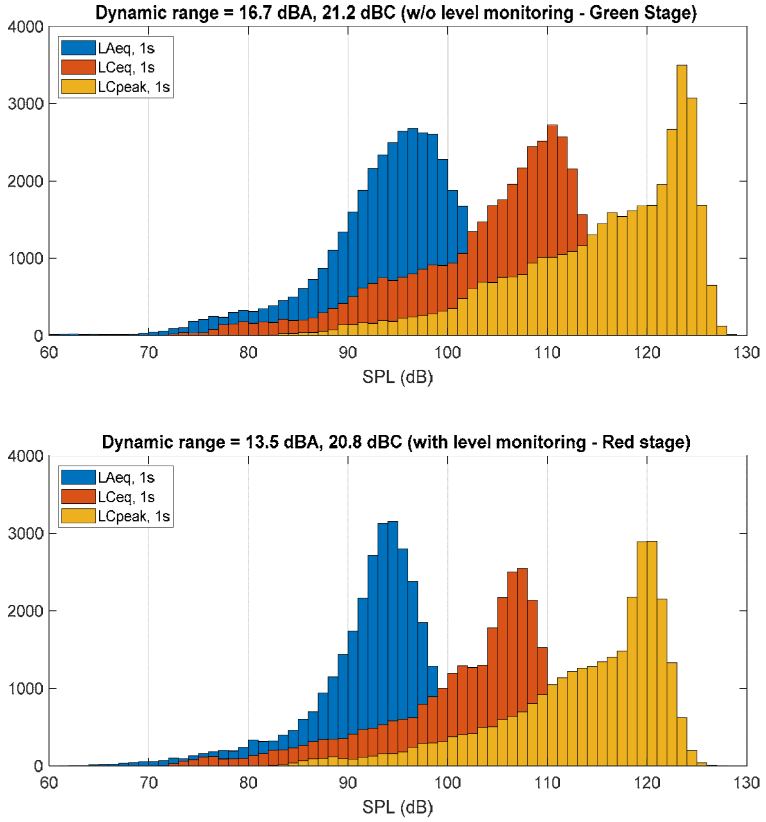


Figure 5.24 Calculated dynamic range for the Green Stage (top) and Red Stage (bottom) [21]

The audience exposure throughout the festival was tracked using the pre-festival audience measurements (relative to FOH) where the front-center audience location was estimated for sound exposure. Peak C-weighted values (averaged over 1 second and 5 minutes) were determined and are reproduced here in Figure 5.25. The data shows that the front center portion of the audience regularly was exposed to peak C-weighted sound pressure levels between 120 – 130 dBC (5-minute moving window average) and experienced absolute peaks of approximately 140 dBC (1-second averaging) each day of the festival. Based on the discussion in Section 2 of this report, such levels are beyond safe limits for low-frequency sound exposure, where foam ear plugs can’t provide any meaningful protection. This data (not the first to show this, it must be noted) should be viewed as a warning sign that ground-based subwoofer systems are indeed exposing portions of the audience to dangerous sound levels and therefore pose a health and safety risk.

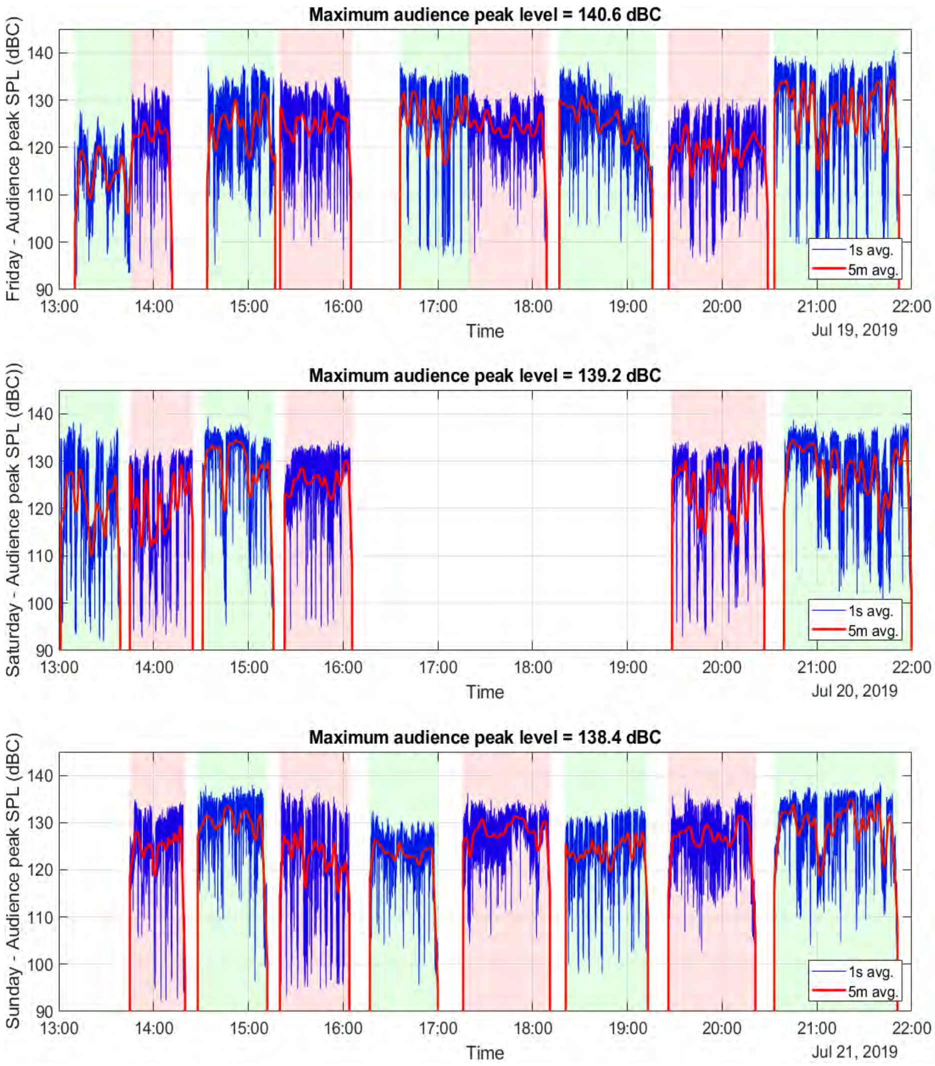


Figure 5.25 Estimated peak audience levels (dBC) during the festival [21]

The data showed that use of noise monitoring software caused a statistically significant reduction on sound level (relative to the set limits) of approximately 2 dB. Crowd size and engineer type (house or band) produced a statistically significant effect on absolute sound level. No factor showed a statistically significant impact on dynamic range (although the use of sound level monitoring software came very close). No statistically significant interaction between factors was identified.

As this is a case study involved a single festival, the findings should be used with caution. Nevertheless, the results suggest further work is needed to inform ways to simultaneously provide a safe festival experience for both audience and staff members while minimizing annoyance in the local community.

5.6.7. Case studies summary

This review reveals the extent of the problem with management of sound exposure and noise pollution from outdoor entertainment events. Practice varies greatly over the included case studies with some of the implemented solutions directly in opposition to the research detailed in the previous sections of this report. The differences primarily concern the use of A-weighting in regard to low-frequency noise pollution as well as with aspects of system design for limited noise pollution.

Common to some of the case studies is the emphasis on importance of effective communication. The process of pre-warning local residents of upcoming outdoor events, with the inclusion of a noise hotline they can call during events if there is an issue, goes a long way in limiting complaints. This ties into the previously-discussed research in this area showing that noise is perceived as less annoying when the listener believes they have some control over the offending noise [185]. In this case the noise hotline gives residents a direct line of communication to the event staff. While it's not guaranteed that phoning the hotline with result in any change to the event's sound system operation, it is likely that the simple act of listening to concerned residents will go a long way to limit annoyance and the corresponding complaints.

While noise regulations and measurement and monitoring practice aren't yet based on unbiased scientific evidence, this human-centered approach to managing noise pollution issues can and should be adopted by organizers of large events. This will be discussed further in Section 6.

6. Noise suppression techniques

Previous sections of this report have focused on national and local noise regulations, audience sound exposure levels, prediction/measurement/monitoring practices, and illustrated these using a collection of case studies. Techniques for actually suppressing noise pollution in surrounding areas (or at nearby stages at music festivals) will now be considered. Simply turning down the level is currently a common approach to dealing with the problem (often targeting specific 1/3 octave bands), but it must be stressed that this isn't the only option. In many cases it isn't the best solution. The dual goal here is to minimize noise propagating to local residential areas and delivering consistently high-quality and appropriate listening experiences for all audience members.

This section will first discuss venue configuration options for limiting noise pollution, some of which have already been highlighted previously in this report. This will be followed by an extended discussion on cutting edge developments into so-called secondary sound systems which are usually set up on the perimeter of outdoor entertainment events for the sole purpose of cancelling low-frequency sound before it exits the event grounds. Lastly, it is critical that any deployed noise suppression technique doesn't degrade the audience experience. This will be the focus near the end of this section. Noise control solutions that negatively impact the audience experience can't be considered appropriate.

6.1. Venue and sound system configuration

A considerable number of noise pollution issues can be resolved by intelligently configuring an outdoor venue. Accurate computer modeling of the sound system design during planning stages is critical. Without this, it will be nearly impossible to efficiently and effectively control noise on-site and off-site during an event.

Common practice dictates experimenting with stage orientation within computer models in order to achieve four primary goals for multiple stage music festivals:

1. Minimize noise pollution to surrounding noise-sensitive off-site areas.
2. Minimize noise pollution to other stages and designated quiet areas on-site.
3. Maximize allowable sound levels at FOH.
4. Ensure all audience members are protected from over-exposure to sound.

Items (1), (2) and (3) can be largely controlled by proper orientation and location of performance stages and suitable sound system configuration. Point (4) is only dependent on the sound system configuration.

Stage orientation must be considered for addressing points (1) and (2) on the above list, as this will affect noise off-site (annoying residents) and on-site (annoying the audience, staff and musicians and other stages). Simply rotating the stage 90° can mitigate noise issues in a particular area, although care must be taken that addressing noise in one area doesn't negatively affect another area. This situation was encountered by the consultant working on Reading Festival in the UK [335], where the 90° rotation caused more issues that it solved.

Stage orientation alone can't address noise issues. Sound system configuration is essential in this area. Various aspects of this have already been addressed in Section 3 of this report. Straightforward design considerations such as physically or electronically steering flown systems so that coverage terminates at the back of the audience area are achievable for most medium- to large-scale scenarios, provided the line arrays can be flown sufficiently high that loudspeakers don't radiate parallel to the ground plane. It is essential to understand that a sound system's throw will vary throughout the course of an event due to dynamic meteorological conditions, so system design based on idealized conditions will never be completely impervious to noise issues.

The underlying control factor for sound systems used at outdoor events is the sound power level used to achieve the required audience sound level and coverage pattern. Sound power level refers to the absolute energy output of the sound system, with no consideration of propagation distance. The sound power level required for a given event will largely depend on the effectiveness of the system design. A sound system that directs the majority of its energy at the audience and away from noise-sensitive areas will require less overall sound power than a system that is less directive, wasting much of the energy on non-audience areas. It is therefore essential to focus on minimization of sound power level when designing a system. This will result in lower off-site noise pollution and in general a more efficient and effective sound system design.

Advanced signal processing functions can be useful here, such as d&b audiotechnik's Array Processing [312] or L-Acoustics Soundvision (including Autosplay, Autofilter and Autoclimate functions) [123]. With these (and similar) approaches, various audience distribution and weather conditions can be pre-set or continuously adjusted to suggested settings on the system. With a press of a button the system can be reconfigured electronically to restore the intended frequency response and coverage pattern. For example, this could be due to the audience only filling the first half of a field early in the day (therefore deeming the top half of the line array unnecessary) or temperature and humidity shifts causing changes in sound propagation (including effects due to sound refraction from temperature gradients). Such functions are becoming increasingly used in practice.

It should be noted that most loudspeaker manufacturer-provided software will only be reliable within the limits dictated by the geometry of the audience plane and the sound system elements' rigging height and dimensions. A rule of thumb used by some in industry is that the rigging point for any line array should be at least three times the length of the array to ensure the software-based predictions are within an acceptable margin of error. The software will often recommend attenuating the bottom loudspeakers in a long array flown at a low height to give an even audience coverage. This may be acceptable in the near field, but such a configuration causes a significant amount of energy to propagate parallel to the ground plane. Refraction due to temperature gradients is likely to cause this sound to curve upwards, resulting in poor audience coverage at the rear of a venue and off-site noise pollution issues.

In many cases the solution is to use a shorter line array to ensure precise sound field control is achievable in practice. This precision of sound field control is particularly important when holding events in large marquee structures, to avoid directing significant sound energy towards the structure, which will result in problematic reflections inside and re-radiation of particular low-frequency bands outdoors.

One additional option that has been used for indoor and quasi-outdoor venues in recent years is using variable acoustic technology in the form of low-frequency absorption [336]. Large inflatable thin plastic membrane tubes can be installed in venues to increase low-frequency absorption. The membranes can be inflated or deflated, depending on how much absorption is required. An example application for the Eurovision Song Contest in 2014 is given in Figure 6.1.

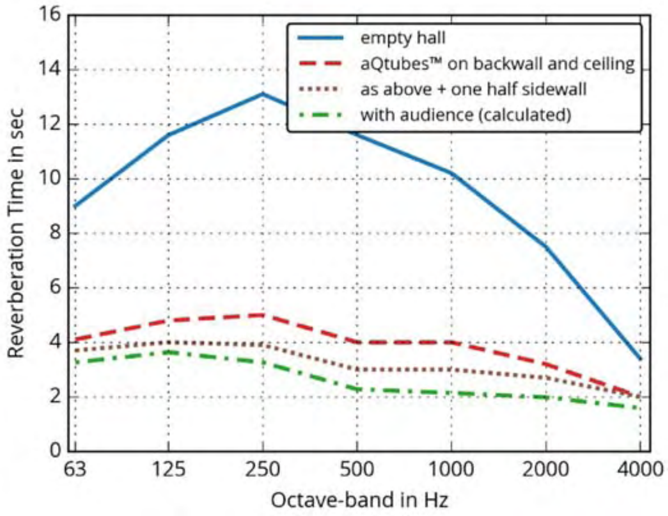


Figure 6.1 Reverberation time due to inclusion of variable acoustic technology for low-frequency absorption (applied to roof, rear wall and half of the side walls) [336]

Placement is usually on the roof, but they have been deployed on rear and side walls as well as behind stages to minimize rear-radiation to empty areas of a stadium. One deployment was for a popular music concert at Amsterdam Arena, where the arena has a partial glass roof that can be opened. The tube absorbers were installed in the roof areas surrounding the glass roof as well as behind the stage to minimize sound propagation into the empty (and highly reflective) portions of the arena (Figure 6.2). Application of the technology in this instance was shown to reduce low-frequency reverberation times by 50% or more from their original peak values (when the venue is empty) (Figure 6.3).

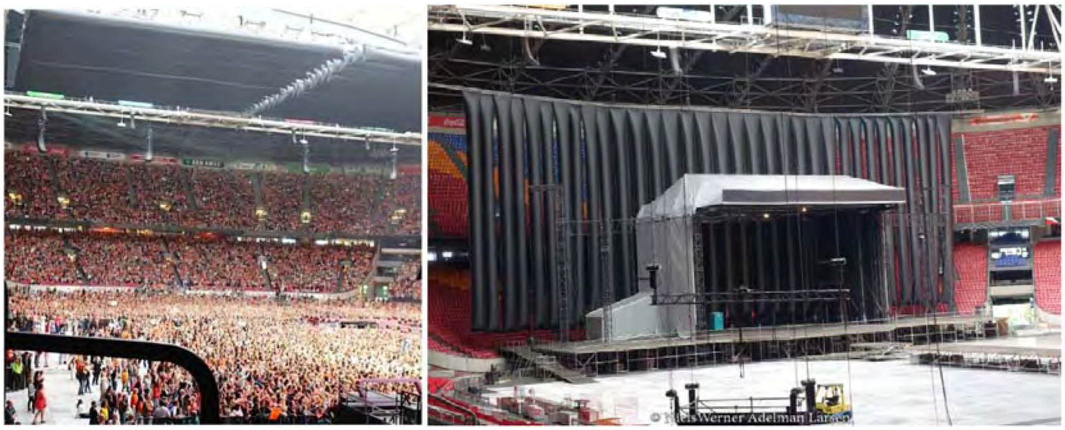


Figure 6.2 Example application of low-frequency tube absorbers at Amsterdam Arena [336]

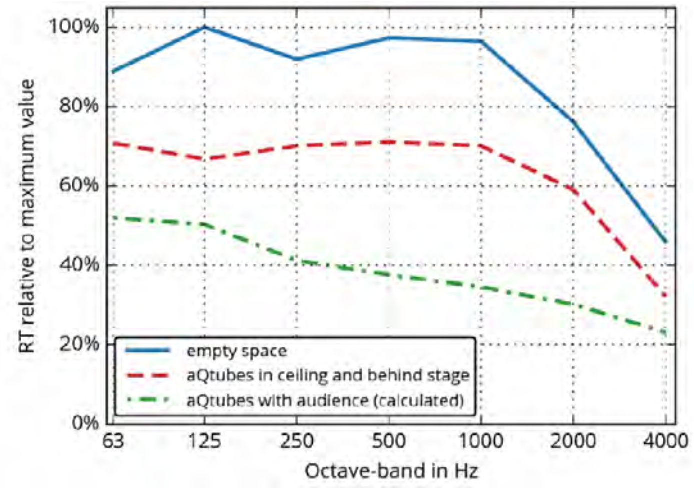


Figure 6.3 Resulting reverberation time reduction (based on original empty arena measurements) in Amsterdam Arena with the additional low-frequency absorbers installed [336]

While this technology is focused on indoor venues, there are some suggestions that it can assist with noise issues for at least quasi-outdoor venues (such as with the previous example). Limiting low-frequency reverberation in large venues will ultimately limit noise spilling out of the venue into the local environment (as well an increase the perceived quality of sound on-site – as discussed in Section 2). With reverberation under control, attention can be devoted to the direct sound, where the task will be much more straightforward to avoid radiation off-site. For completely outdoor events, though, the issue of wind is likely to prevent adoption of this technology, as it would be expected that the tubes would act as large sails, placing unsafe loads onto temporary structures.

The stage structure itself can play a large role in sound propagation. Experience by the primary author of this report has found that non-acoustic transparent stage skirts can degrade a ground-based subwoofer system’s cardioid response, causing greater sound levels in noise-sensitive areas or in some cases diminished levels in the audience. A similar effect (in terms of loss of cardioid response) can be caused by subwoofer placement underneath a stage. This has been investigated in previous research [337] with results independently replicated in [338] and [339], where the work in [338] makes clear that stage “catwalks” will also result in a similar loss of directionality. The key experimental findings are reproduced in Table 6.1 and Figure 6.4. The findings from [338] are also reproduced in Figure 6.5.

An important question has been posed by an industry expert on this subject, asking if the stage structure diminishes the subwoofer system’s directivity in the audience area – is the same effect seen off-site or is it more of a local effect? This question requires further research to answer.

Additionally, it was demonstrated in a case study included in Section 5.6.2 that providing shielding to the rear-moving sound energy from flown line arrays (in this example with shipping containers) can provide improved noise control. In reality, this can be achieved with part of the stage structure in combination with use of a cardioid pattern line array, such as Nexo Geo-T [340] or d&b SL-series [341] with cardioid subwoofers or alternatively a combination of a standard broadband line source and a subwoofer array such as an L-Acoustics K1 and K1-SB [342].

In the case of using shipping containers to control off-site noise in the rearward direction to the sound system, care must be taken to avoid any significant acoustic slap-back (reflection) propagating back through the stage area to the audience, thus interfering with sound coverage consistency. Alternatively, it has been found that straw bales and trackway baffles can provide a level of acoustic absorption/insulation when placed in appropriate areas to avoid sound propagation off-site. These methods tend to be most effective at higher-frequencies, but can have a modest effect at low-frequencies provided they are deployed appropriately.

Configuration	Small stage		Large stage	
	39 – 110 Hz	20 – 300 Hz	39 – 110 Hz	20 – 300 Hz
Under stage	-5.43 dB	-6.06 dB	-6.40 dB*	-5.63 dB*
On top of stage	-6.40 dB	-3.97 dB	-3.28 dB	-3.15 dB
In front of stage	1.34 dB	1.41 dB	0.92 dB	2.78 dB

Table 6.1 Mean front-to-back sound pressure level difference for each tested configuration (using the no stage configuration measurements as a reference) (* modeled data due to stage height restrictions) [337]

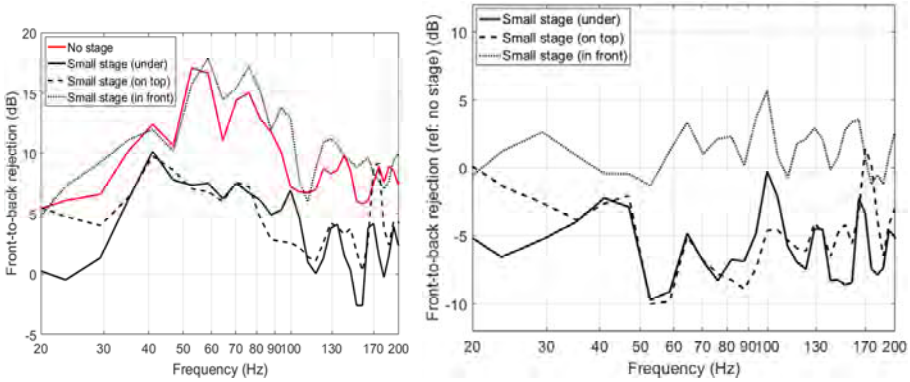


Figure 6.4 Comparison of front-to-back rejection for each of the subwoofer locations (left = direct comparison to stage-less configuration, right = deviation from the stage-less configuration) [337]

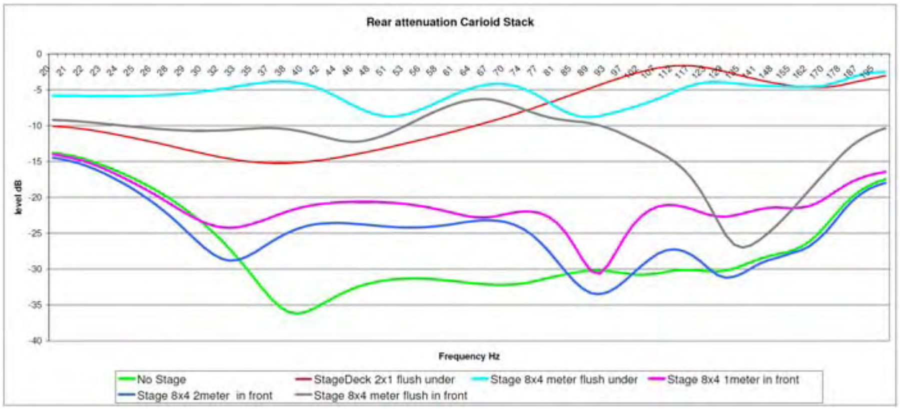


Figure 6.5 Modeled front-to-rear rejection of a cardioid subwoofer for various configurations [337]

As an extension to the case-study presented in Section 5.6.2 (from Amsterdam), further study of the effectiveness of shielding materials behind a sound system was conducted using BEM software. The key findings are shown in Figure 6.6 [338].

Figure 6.6 Frequency-dependent effectiveness of the three tested shielding materials from the BEM-based study in [338]

The use of shipping containers was shown to be most effective across the subwoofer band (tested from 40 – 315 Hz in this instance), followed closely by 18mm wood paneling affixed to the stage structure directly behind the PA. Proprietary modular low-frequency baffling [343] was found to be least effective, although it should be noted that the deployment of these baffles doesn't detract from the look of the stage (the baffles fit around the sound system and are colored black).

In all cases it was found that placing the shielding as close to the sound system as possible will maximize effectiveness. It should be noted that this data is based on a BEM model, therefore material properties (especially in terms of reactance) may not be accurately modeled. The aforementioned slap-back issue must also be considered. The research in [338] was focused only on the geometry of the various shielding materials. Further work is needed in this area to confirm the results in Figure 6.6 are accurate.

Some additional observations from the study in [338] should be noted. First, is the diffractive effect of the edges of shielding materials. In all cases, sound radiation to the sides of the stage area was increased, while the rear-moving sound radiation was decreased. One solution to this issue would be to deploy shields with rounded edges, although in terms of practicality this isn't necessarily possible as shipping containers with rounded edges don't exist. Alternative shielding structures may be more suitable for such applications.

The study in [338] also notes the destructive interference effect of the reflection off the shielding structures in the forward-moving direction, resulting in lower sound pressure levels in the audience area (thus lowering system efficiency). This has the potential to significantly impact sound quality in the audience and should be carefully considered when choosing noise shielding methods.

If using cardioid subwoofers (or clusters to achieve a cardioid pattern), it must be understood that (as with placing subwoofers underneath a stage), placing such sources very close to a large shielding structure will result in the loss of the cardioid pattern [338]. In this study, it was shown that a cardioid subwoofer system placed in front of a shielding material resulted in a polar response nearly identical to that of an omnidirectional subwoofer system. As most noise pollution complaints arise due to low-frequency content, this raises a problem. In terms of system design, cardioid subwoofers are regularly used to limit sound levels on stage, but if a large shield is put into place, this may negatively impact this (especially where the subwoofers are flown, where they will be closer to the shield, resulting in a more pronounced degradation of the cardioid pattern).

Similarly, if subwoofer arrays are to be flown along with the main line arrays, electronic steering can be used to direct the sound energy to the audience, avoiding forward radiation off-site. In this instance, cardioid subwoofers would be appropriate. This is simply demonstrated in Figure 6.7. If possible, the absorbing tubes from [336] can be installed, if the stage structure permits it, to further minimize rear-going sound radiation.

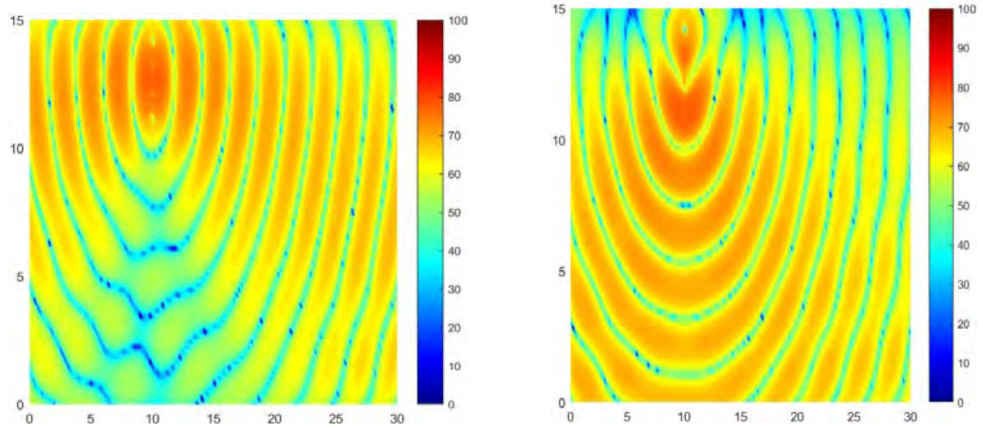


Figure 6.7 Vertical coverage pattern of a flown vertical array (four omnidirectional units with one meter spacing) without steering (left) and with steering – focused at 20 m into the audience (x- and y-axes are length and height of the venue (m), respectively) [117]

By implementing these relatively straightforward techniques during the planning stage of an outdoor event, there will be a much higher likelihood of a smooth-running event with few noise complaints from local residents or engineers/musicians at other on-site stages.

6.2. Bandwidth extension

An unconventional approach to noise suppression due to large-scale outdoor entertainment events is based on current trends in the industry to incorporate subwoofers capable of infrasound reproduction into primary sound systems [43, 106, 109]. The question posed was whether bandwidth extension (in the downward direction with the use of infrasound-capable devices) results in a perceived increase in loudness. If this were shown to be the case, then the overall subwoofer system could be operated at a lower level while maintaining (and possibly enhancing) the audience's listening experience (which includes a strong tactile element). This would alleviate pressure on the FOH engineer to keep within the specified sound level limits, as the subwoofer system would be operating with lower output.

This hypothesis was investigated through a series of in-situ listening tests conducted during the European leg of The Prodigy's 2017 tour, by the band's FOH engineer, Jon Burton (who is a contributor to this report). The findings were reported in [106, 109] and will be summarized here.

The listening tests were carried out at three sites, all 10,000+ capacity arenas with the tour's L-Acoustics V-Dosc system [94] and d&b audiotechnik subwoofer system (consisting of B2 subwoofers [334] and J-Infra subwoofers [345]). The system is depicted in Figure 6.8.

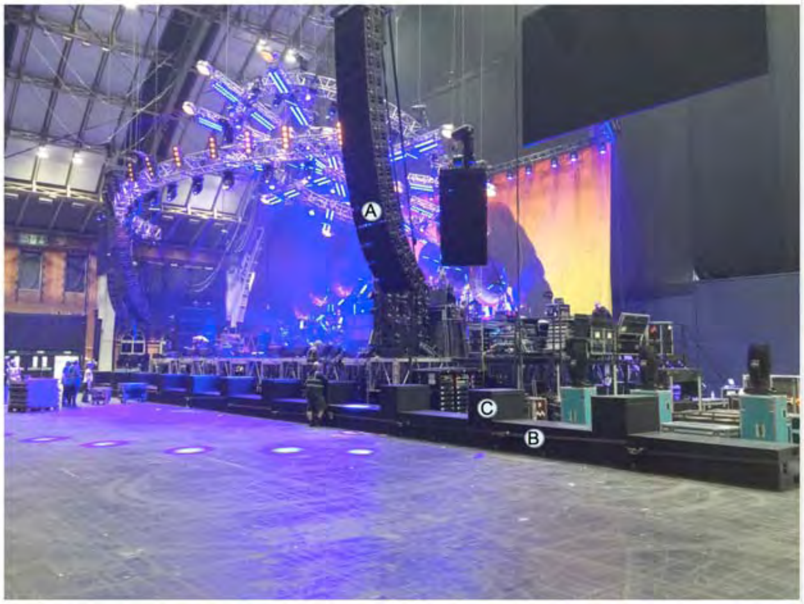


Figure 6.8 Primary sound system used for the listening tests including the main line arrays (A), the standard bandwidth subwoofers (b) and infrasound subwoofers (C) [109]

The standard bandwidth subwoofers had a lowpass filter applied at 90 Hz while the infrasound subwoofers were low-passed at 54 Hz with a 6 dB boost applied at 35 Hz. The overall subwoofer array was optimized to give a consistent coverage pattern horizontally across the audience area using d&b's ArrayCalc software [314]. All subwoofers were located at ground level. Magnitude responses for the three separate system elements are reproduced in Figure 6.9.

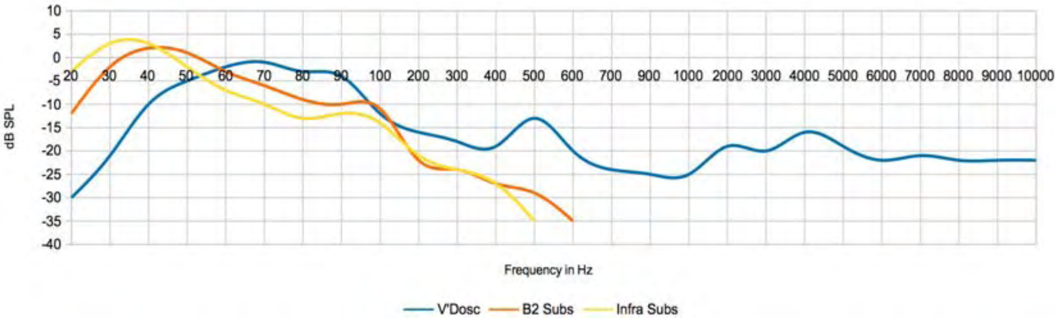


Figure 6.9 Magnitude responses for the main line arrays (blue), standard bandwidth subwoofers (orange) and infrasound subwoofers (yellow) [109]

The listening tests were conducted in two stages. In both stages, participants were told to listen to playback of one out of three selected test tracks (of popular music) and adjust the subwoofer system level until they were happy with the playback level. The participants were only presented with a single control for this purpose and there was no indication given of the corresponding measured sound pressure level (which was tracked using 10EaZy [310]).

The first stage of the test included only the standard-bandwidth subwoofers activated. The second stage of the test included all subwoofers (standard-bandwidth and infrasound). The preferred listening levels were then compared between the two stages. The results from the test (separated by music genre of the test signal) are reproduced in Figure 6.10.

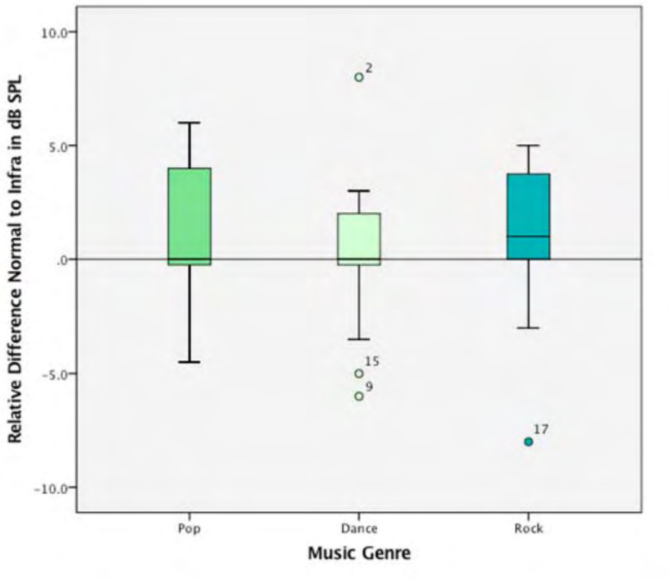


Figure 6.10 Listening test results for extended bandwidth subwoofer system investigation in [109]

Data in Figure 6.10 indicate the difference in preferred playback levels between the standard-bandwidth and extended bandwidth systems. Positive values indicate that the extended bandwidth system (with the infra subwoofers) was played back at a lower level than the standard bandwidth system.

The results from this study give indication that there may be a trade-off between perceived loudness and bandwidth. In this case, the subwoofer system could be operated at lower SPL if the bandwidth was extended by roughly 10 Hz in the downward direction (towards infrasound). In actuality, there was still little infrasound present in the infra-enabled system, just more frequency content in the 20 Hz region, which isn't always reinforced by modern day large format subwoofers. The addition of very low-frequency content using this approach does open the possibility of an increase in off-site noise pollution (and annoyance) since such low frequencies can experience very low absorption as they propagate from on-site to off-site and pose the risk of causing vibration of off-site structures.

The highly variable results indicate that further work is required in this area. These findings should prompt a more focused effort by practitioners to consider bandwidth extension as a viable option for control of sound exposure on-site and noise pollution off-site of large-scale outdoor events.

6.3. Psychoacoustically-based suppression

One FOH level monitoring software provider, Event Acoustics (makers of MeTrao), offers an additional solution to low-frequency noise pollution: BassCreator [347]. BassCreator is similar in functionality to MaxxBass (now a Waves plugin) [348], where virtual bass is used to subjectively boost the perception of low-frequencies without an increase in low-frequency energy. This is a similar approach used in a different research project focused on small-room room-mode correction [349].

Virtual bas synthesis is well-known [349] and won't be covered here. The effect maintains high-quality audience experiences while simultaneously limiting noise pollution. If a certain low-frequency band needs to be attenuated to comply with local noise regulations, the system attenuates the offending spectral content and replaces it with virtual bass content, resulting in a subjectively-similar listening experience. Overuse of this effect can result in synthetic sound which lacks impact, a critical component of live sound [349].

6.4. Secondary sound systems

In this report, a *primary sound system* is responsible for delivering consistent high-quality and appropriate sound to the audience. A *secondary sound system* is responsible for preventing as much sound energy as possible from the primary system propagating off-site to noise-sensitive areas.

There are two groups currently leading development of secondary sound systems for outdoor entertainment events: Rocket Science GmbH (Switzerland) [350] and the Acoustic Technology Group at the Technical University of Denmark as part of the MONICA project [351], although there are other groups also exploring such technology. Both groups' work will be discussed in this section. Note that there are patents describing technology which limits outdoor noise propagation to sensitive areas [346, 352].

6.4.1. Active noise cancellation (ANC) systems

Rocket Science [353], whose founder is a contributor to this report, focuses on minimizing sound propagation off-site in a direction on-axis to the primary sound system. The reasoning is that the primary system (focusing on the subwoofers) should be designed to equally cover the audience area with minimal noise spill into non-audience areas (as well as minimal side lobes off-axis). Information on how to best achieve this (in terms of the primary system) is given in [353] and briefly summarized in Section 3 of this report.

Noise from the primary system is prevented from propagating off-site by an Active Noise Cancelling (ANC) array near the perimeter of the event site. In this case, the secondary system is only focused on the subwoofer range. The ANC array is required to reproduce the coverage pattern of the primary system as accurately as possible over the entire subwoofer range in order to be maximally effective. The arrays operate on a filtered-X LMS approach using a single in, single out (SISO) DSP unit.

To properly calibrate the filtered-X LMS process, the transfer function of the secondary path is required. The secondary path transfer function is that defined between the secondary sound system and the error microphone (typically placed a distance in front of the secondary system). The calibration is usually performed before the event commences by injecting low-level pink noise through the secondary system and measuring the response at the error microphone (although the calibration can be repeated during the event, providing the pink noise signal isn't disruptive to the event and provides enough signal-to-noise ratio for an accurate reading). With calibration completed (and using wirelessly transmitted real-time knowledge of the FOH signals), the ANC array operates according to Figure 6.11.

The ANC array's performance is directly related to the distance between the primary and secondary arrays and the desired silent zone. Cancellation efficiency is ideal for a given distance away from the secondary array and then loses its effectiveness due to atmospheric effects. Figure 6.12 illustrates this clearly, as reproduced from [353].

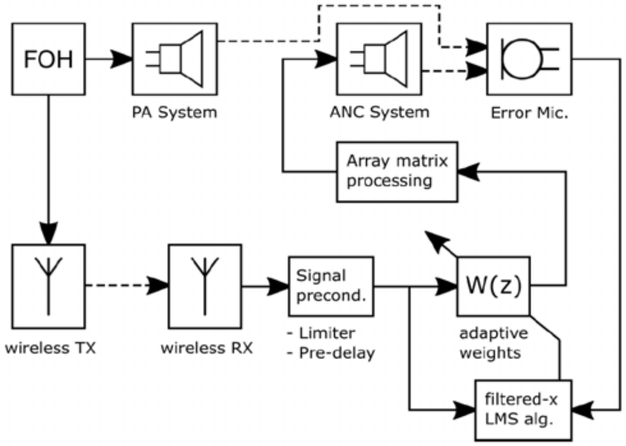


Figure 6.11 Block diagram of ANC array Filtered-X LMS process for noise cancellation [353]

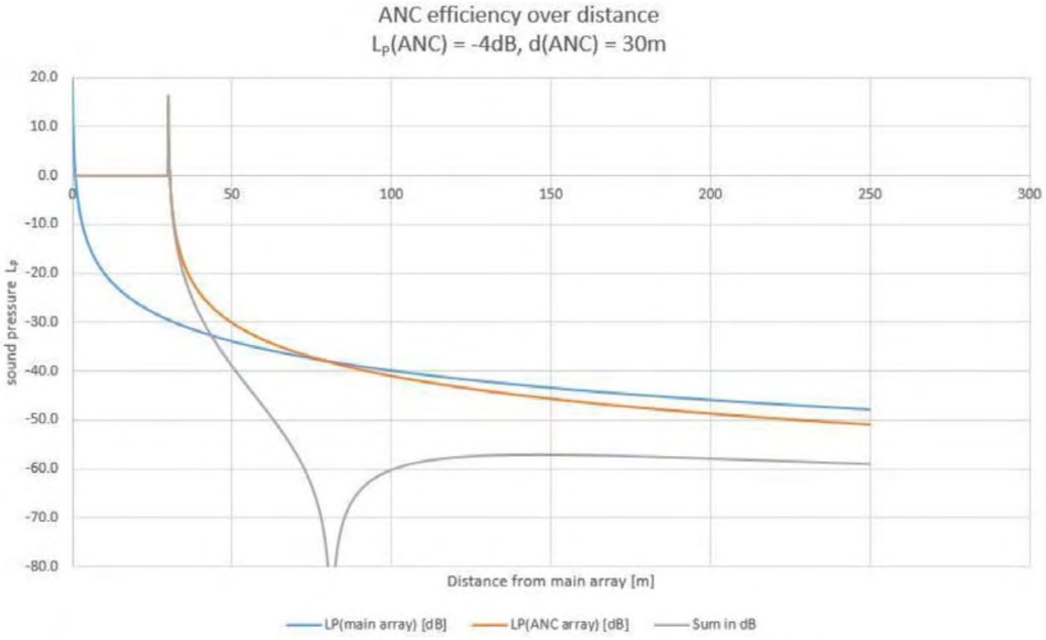


Figure 6.12 ANC array effectiveness over distance (simulated results) [353]

Practical implementations of such a system have been carried out at a number of music festivals in Europe. An example scenario is reproduced here, where the simulated results are given in Figure 6.13 and the measured results are given in Figure 6.14. This specific application included a primary subwoofer system of 14 elements and a secondary subwoofer system of 20 elements (located 65 m from the primary system).

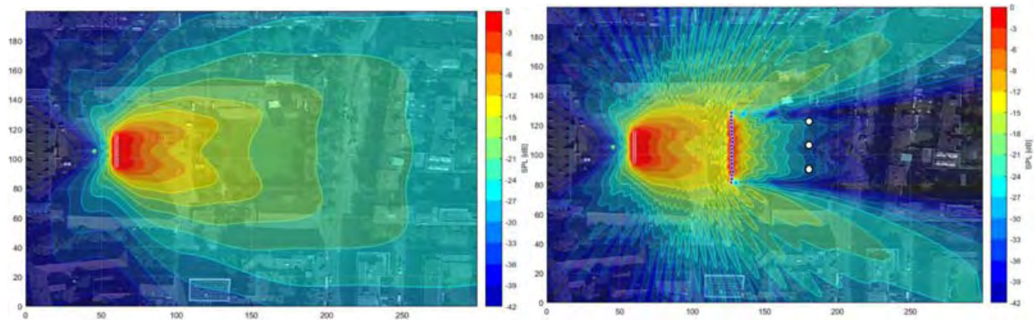


Figure 6.13 Simulated results of sound pressure level distribution over a festival site and off-site for the primary system only (left) and the primary + secondary systems (right) [353]

Figure 6.14 Measured results of sound pressure level distribution at three test points off-site, but on-axis to the primary system. The magenta, pink and dark blue traces are the primary system on its own, while the pink, light blue and orange are with the secondary system applied [353]

Both the simulations and measurements show an attenuation of off-site low-frequency noise between 15 – 18 dB. The best results in the measurements are seen around 50 Hz, with efficiency inversely proportional to frequency. This is expected due to the increasingly-complex propagation characteristics with increasing frequency. This is an encouraging result and one which is likely to bring any noise infractions under control in a local community in the direct path of the primary system. Significant energy is still expected to propagate to off-site locations.

As with any engineering challenge a compromise needs to be made between system effectiveness and practicality. The performance could likely be improved with many more subwoofers in the secondary system, but this would cost more and consume more space. When the secondary system is already larger than the primary system, this would be a difficult proposal to justify. The practicality is a central focus of the engineers as Rocket Science and should be seen as an area of good practice.

6.4.2. MONICA project

The other group researching secondary systems highlighted in this report is the Acoustic Technology Group at the Technical University of Denmark (DTU), as part of their involvement with the MONICA project [351]. MONICA is a European Union-based project focused on using the internet of things (IoT) to manage sound and security for outdoor events. The idea is to use a cloud-based network of sensors to monitor noise in real-time to reduce low-frequency noise outside venues while maintaining a good audience experience (and potentially allowing for a quiet zone within the concert site) [308]. The secondary system research at DTU is a significant component of the noise control aspects of the MONICA project. A number of publications are available covering this aspect of the project [354-357], which will be summarized here.

In [354] a proposed noise cancellation system is investigated using Pressure-Matching Acoustic Contrast Control (PM-ACC). The assumption is that the secondary system will be completely independent from the primary system (unlike with the Rocket Science filtered-X LMS approach). The goals of the work are exactly the same as with Rocket Science: minimize noise off-site (termed “dark zones” here) and cause minimal audible impact in the audience area (termed “bright zones” here).

The algorithm uses regularization to ensure the optimization solution is insensitive to any noise present in the measurements and applies a weighting factor to prioritize the optimization between noise minimization in the dark zones and minimizing impact in the bright zones. The use of weighting for assignment of priorities is similar to the case-study from Amsterdam in Section 5.6.2. The mathematics behind the algorithm are explained in [354] for those interested.

In this work, two metrics are used to judge performance of the secondary system. Insertion loss (IL) quantifies how much the secondary system reduces SPL within the dark zone (the sensitive area). Primary to Secondary Ratio (PSR) quantifies the ratio of sound energy coming from the primary system to that coming from the secondary system within the bright zone (audience area). Both metrics are calculated in decibels, where larger values indicate better performance.

Three experiments were conducted using this technology. The first was a highly-controlled test in an anechoic chamber. The primary and secondary systems consisted of 6 and 12 loudspeakers, respectively, where the secondary system required twice as many loudspeakers as it was a dual-layer implementation with one layer facing the primary system and one layer facing the dark zone. If the loudspeakers are cardioid over the targeted frequency range, then the secondary system can be a single layer, thus requiring half the loudspeakers.

To calibrate the system for the anechoic experiment, 700 transfer functions were measured (one between every loudspeaker and microphone), where the measurement locations were split between the bright and dark zones. The results show an IL of around 10 dB (up to 1 kHz) and a PSR of at least 18 dB (up to 1 kHz). There were severe dips in PSR at 400 and 800 Hz which were due to the physical spacing of the dual-layer secondary system (40 cm). This issue could be avoided if cardioid loudspeaker were used. The results from this experiment are reproduced in Figure 6.15.

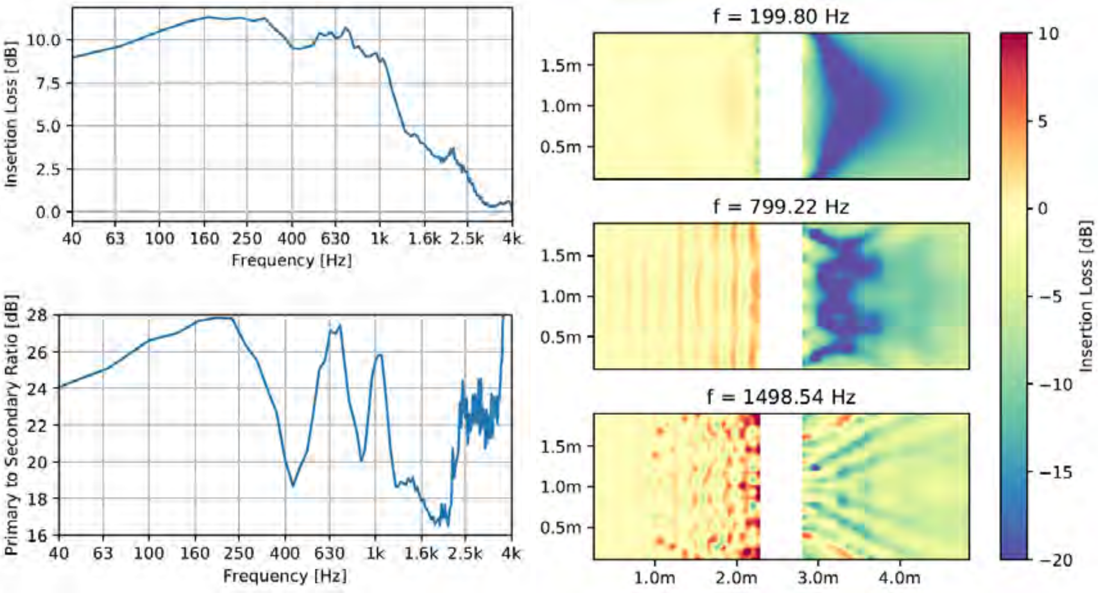


Figure 6.15 Anechoic experimental results from DTU showing measured IL (top left), PSR (bottom left) and insertion loss distribution between the bright and dark zones (right) [354]

The anechoic experiments were followed by a large-scale outdoor experiment, closely resembling conditions for a medium-scale event. In this experiment the primary and secondary systems consisted of 10 and 20 subwoofers, respectively, where the secondary system was implemented with a dual-layer approach. The subwoofers were cardioid between 37 – 115 Hz and it was found that there was a negligible difference between a dual- and single-layer implementation, confirming the theoretical analysis.

The transfer functions were measured as before, but this time over 100 points, split between the bright and dark zones. IL was estimated to be 12 – 14 dB, but the measured results weren't as good. PSR was greater than 15 dB over the entire targeted frequency range (45 – 85 Hz). Using the single-layer secondary system, PSR increased by 2 – 10 dB over the frequency range. The results from this experiment are reproduced in Figure 6.16.

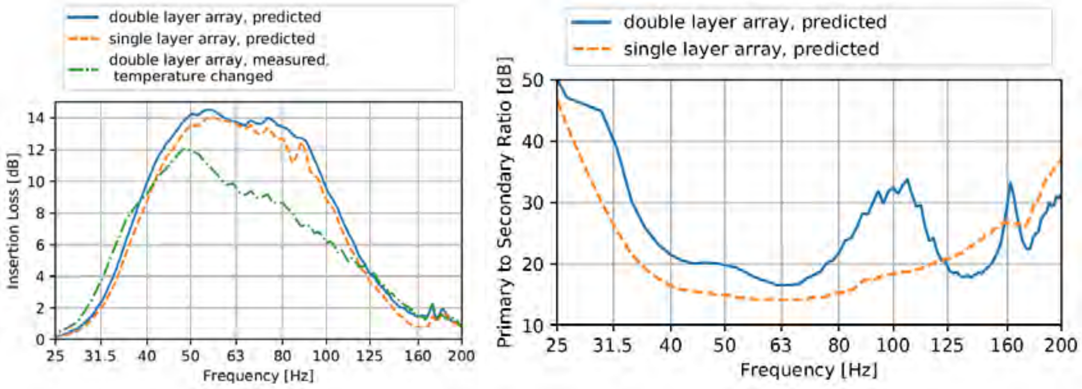


Figure 6.16 Predicted and measured results of the large-scale experiment from DTU for IL (left) and PSR (right) [354]

Finally, the PM-ACC system was implemented at a music festival in Turin, Italy. In this scenario, the primary system consisted of 20 cardioid subwoofers, while the secondary system consisted of 16 cardioid subwoofers facing the primary system. The layout is reproduced here in Figure 6.17. 50 measurement points were used for transfer function measurements. The measured results are given here in Figure 6.18, where overall it was found that IL was around 6 dB.

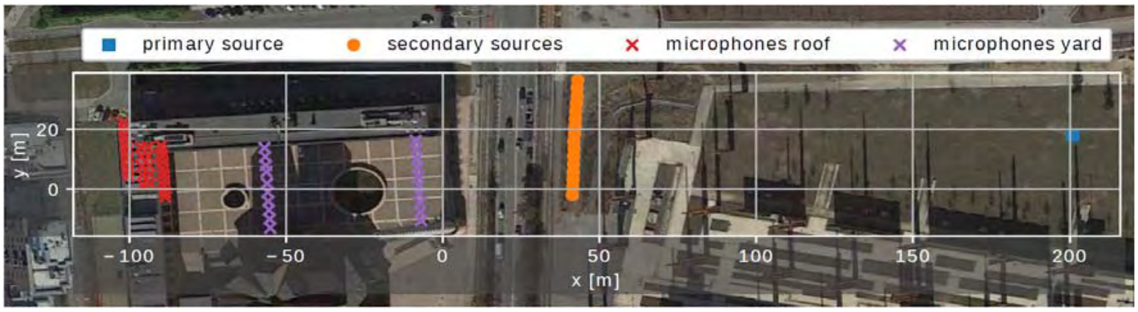


Figure 6.17 Real-world implementation of DTU system [354]

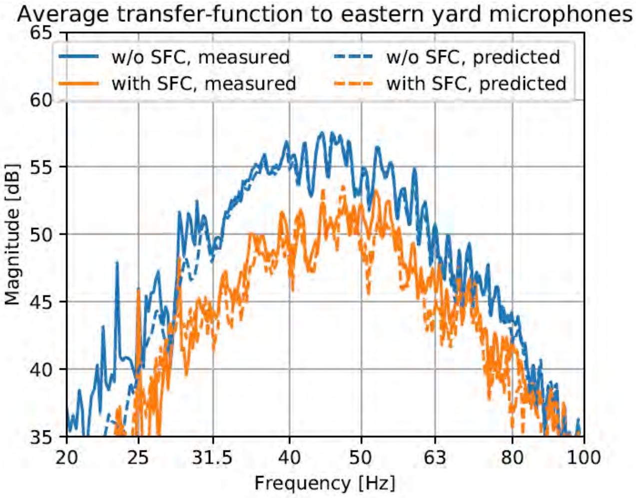


Figure 6.18 Predictions and measurements for the real-world application of the DTU system [354]

The results from the real-world application of the DTU approach indicates that the PM-ACC algorithm needs further work or another approach is necessary. A suggestion near the end of the paper is to use an acoustic model to generate transfer functions. This would save considerable time on-site and allow for adjustments due to weather fluctuations (which was found in the large-scale experiment to diminish system effectiveness).

DTU has also been exploring using a filtered-X LMS solution to the problem, similar to Rocket Science [355]. This work won't be elaborated on here, as the solution and results are very much in line with the Rocket Science findings presented earlier in this section. It should also be noted that DTU are investigating an adjoint-based time domain approach to sound field control with the aim to intelligently control the radiation pattern of the sound system to evenly cover an audience while minimizing noise pollution to sensitive areas [356]. Whether this sort of approach would be acceptable to sound system designers and engineers has yet been addressed in the work.

6.4.3. In-home noise cancellation

A different approach to noise control in residential areas has also been developed by Rocket Science. In this case, the secondary system isn't located on the event site, but in the bedrooms of local residents [350]. This can be considered a distributed secondary system. An image of the required hardware is given in Figure 6.19.

6.19 Rocket Science's in-room distributed secondary system hardware [350]

In terms of noise control fundamentals, this isn't ideal (as noise should be controlled at the source, ideally), but it can be seen as a worst-case scenario solution. If the sound can't (or won't) be controlled by the event, this will allow residents to control the noise from within their own homes. Interestingly, this approach could also address room-mode problems, where certain low-frequency noise components have the potential to be greatly amplified, causing more disturbance/annoyance. At the time of writing this report, there was no published data available on the effectiveness of this system – only anecdotal evidence.

6.5. Automated sound level control

A final example of a possible noise suppression technique is automated sound level control. This approach was investigated in a recent research project [358] which primarily considered audience sound exposure, but is equally relevant to off-site noise pollution control. A first-order prediction model for daily noise exposure was implemented and fed into a dynamic range limiter (in line with the main PA) to ensure that an audience isn't exposed to a dangerous amount of sound at an event. The prediction was based on mixing desk output levels along with a necessary acoustic calibration measurement. This approach was chosen due to practical issues involved with audience members or staff wearing noise dosimeters and reporting the data back to the base station in real-time.

This system was tested in a lab-based experiment, using popular music tracks as test signals. The system showed good results in predicting sound exposure approximately two minutes into the future (based on the previously observed audio signal) and required the sound system to be attenuated by roughly 1 dB at worst.

In reality, this system is unlikely to be easily accepted. Sound system designers and operators are generally weary of automated controls in a system, especially if such automation is based on predicting what will come in the future. There are also problems with multi-act events, where such a system may require the headline act to be limited to a lower SPL due to prior transgressions. This is effectively an automated version of the issue encountered with long integration times used for sound level monitoring. The project researchers note that their intention is to introduce imperceptible attenuation to the output of a sound system. However, it is likely that much more robust practical experimentation is required before practitioners will accept such an approach to sound exposure/noise pollution suppression, especially at large-scale outdoor events.

6.6. Audience impact and practical issues

As discussed earlier, a goal for all secondary sound systems (in addition to limiting noise pollution off-site) is to ensure there is minimal to no impact on the audience's listening experience. This is critical, as secondary system-based approaches to noise control are unlikely to see wide-scale adoption if they negatively affect the audience experience.

Of the systems described above, the filtered-X LMS approach currently appears to be the best option to ensure minimal audience impact. This is due to the use of an error microphone to continuously adapt the noise cancellation algorithm. This ensures weather changes and effects of an audience will be taken into account to give consistent performance. Also, these systems have cardioid subwoofers facing away from the audience area, further reducing the chance that there will be a noticeable impact on the listening experience. This assumes the secondary array is properly configured to avoid strong side-lobes, which can be accomplished with amplitude tapering.

It should be noted that if local residents see a large subwoofer array aimed at their homes, complaints could increase due to perceived annoyance (which has been shown to be irrespective of actual received level in many cases). If such systems are used, a robust public communication/education campaign (such as those described in many of the case studies earlier in Section 5) must be implemented to ease concerns.

One aspect of such systems that hasn't yet been explored (or at least published) is noise control with secondary systems that aren't in line with the primary system. Can these systems operate covering a wider area? Of course, there are practical limitations here, such as budget and space for a large additional subwoofer array, likely placed within public areas. The possibilities need to be explored to see how far the secondary system approach can be pushed.

Secondary systems are ground-based and therefore can do little to limit noise pollution due to sound refraction (or any noise not travelling off-site at ground level). It must be investigated whether such ground-based systems have the potential to cause additional noise away from the ground-plane. To date, there is no clear published research in this area. The effective height of secondary systems is an interesting question that is partially explored in some of the referenced DTU research, but results indicate that the effective control height is usually much lower than where people may be living in built-up areas. More research is needed before a clear conclusion can be reached. It is unlikely that flown secondary systems would be a practical alternative.

7. Conclusions

The challenges surrounding sound exposure and noise pollution due to outdoor entertainment events are numerous and extremely complicated. The duality faced by the audio engineer at such events is problematic. On the one hand, the engineer strives to design a sound system that delivers uncompromising, consistent, high-quality audio to all audience members. This requires wide-bandwidth sound reinforcement/reproduction and (usually) high sound pressure levels. On the other hand, the engineer must strive to limit noise pollution to the surrounding areas. This requires precise control of the sound system's directivity (which can be especially problematic at low-frequencies) and careful planning for possible weather conditions. In summary, the audience wants to hear the music clearly and loudly and residents usually don't want to hear anything.

This report presents no definitive solutions. It does offer a number of potential solutions, all of which require further research to validate and refine. We have presented a broad overview of the variables at play at outdoor entertainment events, including existing research to support various practices and understandings. Most sound exposure and noise pollution research is focused on industrial- or traffic-based noise, which tends to be persistent year-round. Music-based event noise is short-lived and infrequent, so it's not surprising that it is rarely addressed in the literature. When it is, it plays a minor role in the overall focus of the research.

The research identified here that does specifically examine music-based noise presents findings that are often contradictory. In some cases, this can be attributed to difficulty in designing adequate experiments. In a few cases, it appears that conclusions have been pre-determined, where results were analyzed to fit expectations. Following the WHO's lead in their current set of community noise guidelines, it is essential that any research used to inform policy must be unbiased and objective in nature. Not all work covered in this report meets this requirement, which is why the 2018 WHO report couldn't provide updated guidelines for leisure noise [1]. Clearly, much more scientific, unbiased research is required in this area.

While no definitive solutions have been identified, there are clear questions that have arisen through the course of this work. These can be broadly split into three categories of stakeholders at outdoor live events: audience, community, and engineers. The key questions arising within this report are presented here, with all instances of "further research required" given in Appendix A.

7.1. Audience-focused questions

1) What is the best approach to measuring and monitoring audience sound exposure?

   Would it be possible to take measurements at various points within the audience area before an event to generate transfer functions between the measurement locations and the chosen monitoring location (roughly similar to DIN15905-5)? This would allow the data to be inputted into appropriate monitoring software to give real-time audience sound exposure values, based on the monitoring location (where it is essential to choose an appropriate monitoring location).

2) What is an appropriate sound exposure limit for the audience?

   Is it possible to achieve a consensus on level limits, including integration time, peak limits and appropriate weighting? Integration times must be practical (15 minutes seems to currently be favored by engineers, while 60 minutes is favored by regulators and health experts. Both could be too long when considering off-site annoyance). A-weighting is inappropriate for the levels present in audience areas. However, much is known about hearing damage in terms of A-weighted measurements – so perhaps A-weighting should be maintained for these purposes until more data using alternative weightings becomes available. Should C- or Z-weighting be used? Or would 1/3 octave band criteria be more appropriate and useful? One-third octave band criteria, while more specific, might pose a challenge for the bodies responsible for noise monitoring, due to the current lack of appropriate equipment and training. Nonetheless, examples exist of favorable responses from local authorities after the introduction of such methods.

3) Does Noise-Induced Hearing Loss (NIHL) correspond to Music-Induced Hearing Loss (MIHL)?

   The majority of literature informing many audience limits is based on NIHL. If MIHL doesn't possess the same triggers and characteristics as NIHL, then what are appropriate sound exposure limits based on MIHL? As music is dynamic in nature (and variable across genres) is it even possible to create limits based on MIHL? It must be noted that the human ear does not discriminate between noise and music (as far as is currently known), so noise-based limits shouldn't be discarded. There is currently a significant amount of research focused on hearing loss from personal listening devices, which may provide key information on this topic.

4) Are audience members (and staff) situated near ground-based subwoofer systems receiving dangerous noise doses?

   Considering that most large-format subwoofers are capable of producing 140 dB (or more) at 1 m, which is in some cases is the distance to the first audience members (and also security, video crew and pit photographers), this is an extremely serious question. Is it a dereliction of duty on the part of the system designer to place such high-powered sources in close proximity to audience members (who have no control over the system)? Should limits be imposed on how close these systems can be placed to audience members?

5) What are the physiological and psychological effects of high-levels of infrasound (at the level/duration experienced at a typical outdoor event)?

   All available research on this topic is lab-based and not focused on this industry. It needs to be determined if there is any risk (beyond hearing damage). Considering that subwoofer systems are continuously extending their range downward (many now operate well into the infrasonic region), this must be investigated.

6) Considering (5), does standard hearing protection available at events (typically foam plugs) do anything to protect from hearing damage at low frequencies?

   Drawing on what's known by the military and NASA on protecting their crews, the answer appears to be no. Bone/tissue conduction (which is significant at low-frequencies) can bypass the sound's standard route to the inner ear and can cause damage. It must be determined whether the military knowledge is applicable to this industry. It is likely that it is and will be especially relevant for audience members located nearest to any ground-based subwoofer system.

7) What should be done to best educate audiences of the risks of sound-exposure at large events?

   A number of reviewed studies in this report have indicated that an educational program targeting concert-goers can be at least somewhat effective in increasing the use of hearing protection. This can go a long way in preventing temporary and permanent hearing loss. What should such educational programs consist of? How can they be delivered to achieve maximal effectiveness? Can some of this be provided at events? What's the best practice in terms of warning signs posted at events? This should be seen as a critical set of questions, as it appears (based on the research detailed in this report) that audience members are generally oblivious or ambivalent to the serious risk of hearing damage due to high levels of sound exposure. This is a public health issue and must be taken seriously.

7.2. Community-focused questions

8) What is best practice to achieve high-quality audience listening experiences while minimizing off-site noise?

   Can community annoyance be managed through public relations campaigns, where residents are pre-warned about the event, informed about the logistics and how to register a complaint during the event, and reminded of the positive economic impact of the event. Past experience has shown this to be extremely effective. This should be considered alongside any system design approaches. Opinions appear to be split on best practice for system design and calibration. It is clear that current noise monitoring and control methods used in Europe are effective and practical.

9) Is there an opportunity to standardize entertainment event noise regulations?

   Through the review conducted for this work, it was found that relatively few countries possess clear entertainment event noise regulations. The regulations that do exist are predominantly based on industrial and traffic noise regulations. Is there an opportunity here (through some in-depth unbiased objective research and consultation with industry) to devise practical and effective regulations that can be promoted as best practice? Looking over past attempts at this, the answer would appear to be no, as all previous work seems to end in groups dissolving into factions, but this shouldn't rule out a fresh effort, if it were deemed appropriate. Perhaps an industry-driven initiative would be more appropriate in the short- to mid-term, as this could be implemented much more quickly as compared to pursuing the regulatory route. This is discussed in more detail at the end of this section.

10) When analyzing acoustic models for noise prediction, should it be standard practice to include the stage monitoring system?

    One of the case studies in this report measured DJ fills on stage as part of an in-depth study of noise pollution due to sound system configuration. The DJ fills were found to strongly contribute to the noise pollution in the community. It would seem reasonable to include such systems when modeling noise. Without these elements, can the noise predictions cannot be considered accurate.

11) When planning noise control measures, is there any practical method to predict and correct for the effects of sound refraction (especially if SOFAR-like long-distance propagation is encountered) or is this uncontrollable?

    Sound refraction due to temperature gradients in the air causes a great deal of variability in sound propagation over long distances. In extreme cases, the propagation can span multiple miles with minimal attenuation of low-frequencies. Is there any way to deal with this aside from simply having a broad understanding of the effects? The answer to this is likely to be no, but at the very least, system designers and operators as well as acoustic consultants need to made aware of the potential effects of such meteorological conditions. It may be useful to take cues from the wind turbine industry, as they have recently been dealing with such issues and have amassed a fairly sizeable relevant knowledge base.

12) What is the most accurate and practical method for predicting noise annoyance in the community?

    Community noise regulations (whether for music events or otherwise) tend to focus on annoyance rather than serious health effects, as the received noise levels are usually low. Most noise pollution that causes annoyance is low-frequency. The vast majority of measurement regulations dictate the use of A-weighting, although there is little research identified that suggests A-weighting is appropriate. Should a different weighting be used (such as C- or Z-weighting) for identifying low-frequency noise? What about 1/3 octave band noise criteria? How can fluctuations in the noise be included in measurements and monitoring? Are flat decibel penalties appropriate? What experiments are necessary to identify the appropriate approach in this area?

13) Is it possible to standardize noise monitoring practices at large-scale outdoor events?

    There appears to be a wide variety of practices, ranging from little to no consideration of noise, to ill-informed monitoring, to highly-transparent, informed and coordinated efforts. Events encountering the least amount of problems with noise pollution all share the fact that they have benefitted from proper consideration of noise control during the planning stages. Many employ professionals to monitor noise during the event itself. Communication between all relevant stakeholders has been demonstrated to be key. A robust noise management plan is key. How can these practices be encouraged on a wider scale?

14) How problematic are room-modes in domestic environments that receive music-based low-frequency noise pollution?

    Most reviewed literature sidesteps this issue, but it appears that room-modes can cause a significant increase in received sound level in the low-frequency range. Typical living room or bedroom sizes are likely to support room-modes spanning the 63 Hz and 125 Hz bands, which are generally the worst offending noise components. Can this effect be adequately predicted from outdoor measurements? It is unlikely without knowledge of the receiving space's topology which varies between residences.

15) How effective are in-room noise cancellation devices?

    There exist commercially-available devices that aim to cancel low-frequency noise received in domestic settings. It is unclear how effective these devices are and how sensitive they are to placement. If such devices are proven to be effective in limiting noise annoyance, would it be worth considering distributing these to residences near event sites in an effort to minimize annoyance?

7.3. Engineer-focused questions

16) Do flown subwoofer systems generate greater noise pollution off-site? If so, what can be done to avoid this issue while still using flown systems?

    In some of the reviewed literature, flown subwoofers were (at least loosely) identified as serious contributors to community noise pollution due to their height above the ground (although the data leading to this conclusion contains many ambiguities). Can mechanically or electronically steering flown array(s) towards the audience mitigate the (potential) problem? It is unclear how often this approach is currently implemented, but it seems to be a logical solution to the problem (and would improve system efficiency). It also needs to be confirmed if the use of flown subwoofer arrays actually poses a greater risk of noise pollution off-site as compared to ground-based systems.

17) Can the same audience experience achieved with a ground-based subwoofer system be delivered with a flown subwoofer system?

    Some professionals have argued that ground-based systems are necessary to achieve the sound pressure levels and horizontal consistency required and that flown arrays would severely limit headroom. This is contradicted by recent research into this area explored in this report. The work found flown systems lost 1 dB in some cases and were 6 dB more efficient than ground-based subwoofer arrays in others. It should be noted that flown arrays achieve greater front-to-back consistency. The inherent problem with flown systems is that if a left-right array is required, then coherent interference will degrade the horizontal consistency. In such cases, can the two sides of the system be effectively decorrelated to limit these effects? Existing solutions in this area were discussed in this report, but it is yet to be seen whether these are practical.

18) Do source-oriented systems result in lower audience sound exposure levels?

    Considering the increasing use of such systems and their distributed nature (many small elements distributed around the stage area – and sometimes to the sides and rear of the venue), would the lower drive levels of the individual components make for a safer listening environment? Can these systems be practically deployed at large-scale events (including touring productions)? How would this work if implemented at a music festival? Early work is being done in this area, but more information is needed to determine if such systems are practical for wide adoption in the industry.

19) Should greater use of virtual bass be recommended to mitigate noise issues?

    Virtual bass can be used to enhance or replace certain low-frequency components in musical signals for on-site sound. There exist products in this area that are aimed at live events. More research is needed to see how much these systems help in noise control off-site (and possibly audience exposure) and whether or not they degrade the audience listening experience through over-use.

20) Is it possible to exchange sound level for system bandwidth?

    Recent in-situ experiments have shown that allowing subwoofer systems to extend to the infrasonic range results in a slightly lower preferred listening level. Do the potential reductions in level make this effect worth exploring in greater detail? Considering the case studies included in this report, any SPL reduction without any discernable effect on the audience experience would be beneficial for noise control. The problematic lack of absorption in the infrasonic range, however, must be considered with this approach, as this has the potential to increase annoyance in the local community.

21) If a stage structure causes the degradation of a subwoofer system's cardioid pattern in the stage and audience area, is this effect seen in the extreme far-field (i.e. the community)?

    Past research indicates that poor cardioid subwoofer placement (generally too close or under a stage) results in the subwoofer displaying omnidirectional characteristics. The question is whether this effect transfers to off-site noise propagation or is it local to the stage and audience areas?

22) How effective are secondary sound systems?

Secondary sound systems attempt to cancel low-frequency noise propagating off-site. Recent research (both lab-based and practical) has shown mixed results. To date, these systems seem to be potentially capable of providing around 10 – 15 dB of attenuation at low frequencies, which is significant in terms of noise pollution. As practical issues dictate that these systems are ground-based, what is the maximum effective height that they can control? Will this affect residents in high-rise towers? Will sound refraction allow noise to bypass such systems? Are there issues with cancelling semi-correlated signals (such as low-frequencies from main PAs and subwoofers, which are driven separately at the mixing desk)? Can these systems be deployed to limit noise in all directions relative to the stage or are they only practical operating in the on-axis direction? This may be an important point to address for multiple stage events.

23) Is it worth exploring more widespread use of low-frequency absorbing tubes at live events?

    These absorbers are becoming popular for indoor arenas in Europe to limit low-frequency reverberation. Are there any practical applications for outdoor (or quasi-outdoor) events or will wind issues make deployment impossible?

24) Is automatically mixing to the sound level limit practical?

    Some research showed that when engineers had sight of sound level monitoring software, they tended to mix to the given sound level limit, even though a louder mix may not have been appropriate. This research was performed on smaller indoor venues, though other research at a large-scale outdoor event didn't show this trend. More work is needed, as this was limited to a single outdoor event. Research should be conducted to determine if FOH mixes naturally gravitate to the stated limits if engineers can see how much headroom they have available.

25) How can large-scale PA shoot-outs be conducted to guarantee reliable and unbiased data? Is it worth standardizing this?

    There are numerous examples of large-scale PA shoot-outs where the results are either highly biased or unusable due to various factors (meteorological effects tending to be the most significant issue as well as equivalent spacing of the sound systems under inspection). Would it be worth exploring the possibility of standardizing a loudspeaker test procedure for large-scale sound reinforcement systems, similar to how standardized testing exists for smaller-scale loudspeakers? The significant variability in test procedure and data analysis leads to incompatible data between (and even within) tests.

It must be emphasized that the authors of this report are not the noise police. Many of us have designed and operated live sound systems for many years and are more focused on audio engineering than environmental noise. The aim of this work was to review the current state of sound exposure and noise pollution at large-scale outdoor entertainment events and to identify sensible questions that need to be answered to improve the current situation.

If this report raises awareness of key issues relating to live sound exposure and noise pollution, this would justify the effort invested in its drafting. It is hoped, though, that the work leads to a renewed effort in focused, unbiased research to address the questions it has raised. The ultimate goal is for the live sound sector to routinely deliver a high-quality listening experience to every seat in the house while avoiding annoying the neighbors or giving the audience and staff a dangerous noise dose, and to achieve this using practical, effective, and efficient solutions.

In conclusion, we present a proposal for the formation of a live event sound/noise initiative to address these issues. We acknowledge that any regulatory change, while worth pursuing, faces a long hard road to fruition. Nevertheless, existing knowledge identified within this report can be used to good effect in the near-future.

7.4. The Healthy Ears, Limited Annoyance (HELA) Initiative

This report makes clear the complex international regulatory climate surrounding sound exposure and noise pollution from outdoor events. This is in large part due to the lack of unbiased scientifically-based research needed to create unambiguous, practical and effective regulations in these areas. Much of this is identified in the WHO's 2018 community noise guidelines [1]. At present, while some regulations appear to be roughly sensible and practical, the confusion stemming from the contradictory data identified in this report has resulted in poor sound/noise control practices at many large-scale live events.

This working group supports the pursuit of updated and better-informed regulations on an international scale. We realize that such ambition and effort must be sustained over many years before substantive change will occur. Sound exposure on-site and noise pollution off-site should be viewed as critical to the health and well-being of everyone involved. Something needs to be done aside from waiting for the research and regulations to catch up.

We propose that a live event sound/noise management initiative be created, focused on the dual-nature of the problem: on-site sound exposure and off-site noise pollution. Such an initiative would detail current best practice in these areas and would allow venues, events, manufacturers and even possibly performers to pledge voluntary compliance. This could be marketed through a logo on their websites and other materials. Use of the logo would signal commitment to the well-being of all on-site individuals (musicians, technical staff, volunteers, vendors, security, press, and – most importantly – the audience members) as well as residents in the off-site surrounding community.

Participating in such an initiative would allow members of the public to understand what a given event or venue has done to promote the health of all stakeholders. The initiative would encompass current best practice in all areas discussed in this report, and would be updated periodically as new information becomes available. Members of the initiative would implement accepted and informed standard practices.

In addition to the primary goal of standardizing practice at large outdoor live events, the initiative would also support and take the lead on key research required to answer the many questions raised here (and others that will inevitably come up). Such research would eventually inform work on new regulations and standards. Bringing together professionals committed to achieving these goals would gather the expertise and drive research to insure on-site and off-site experiences of outdoor events are as safe and enjoyable as possible.

The working name for this initiative is The Healthy Ears, Limited Annoyance (HELA) Initiative. *Healthy Ears* indicates a commitment to preserving healthy hearing of all individuals on an event site (whether they are working, volunteering or in attendance). *Limited Annoyance* focuses on the off-site community, striving to avoid excessive annoyance due to noise pollution from an event. The word *limited* is used as it is understood that it is impossible to avoid all annoyance. Limiting noise-based annoyance as much as practical must be the target. The acronym, HELA, is a play on a common slang term used in California, "hella", meaning *very*. In this case, any member of the initiative would be considered *HELA-compliant* (read: very compliant).

Such an initiative will not be successful without input and sustained participation from organizations outside of the Audio Engineering Society. Groups such as the World Health Organization (WHO) – which is championing safe listening practices through their Make Listening Safe initiative [359], the

Institute of Acoustics, (IOA) and the Acoustical Society of America (ASA), to name but a few, should be included.

7.5. Closing remarks

The information contained within this report should be seen as an informed starting point on the journey to achieve a healthy and sustainable environment surrounding large-scale outdoor live events. Key questions have been raised, stemming from conflicting conclusions in previously published research, pointing to numerous required areas of further research, spanning many different disciplines. The authors of this report plan to contribute to the necessary research highlighted in this report, but a sustained effort by many individuals and organizations is required to adequately address each of these questions and satisfy the corresponding research needs.

Discussion and feedback on the points raised in this report are welcomed and encouraged. This can be through meetings of the Audio Engineering Society Technical Committee on Acoustics and Sound Reinforcement (AES TC-ASR), held at every AES convention, or by contacting this report's primary author, Adam Hill (a.hill@derby.ac.uk). Regular updates on work stemming from this report will be published on the AES TC-ASR webpage [361] and through panel sessions at AES conventions.

The working group hopes that this report will spur a well-informed and sustained discussion and debate focused on the best way forward. We hope the live event sector will embrace and support local communities to help them grow their local economies, protect their residents from harmful effects of sound exposure and noise pollution, and deliver awe-inspiring (but safe) experiences to audiences at outdoor events.

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9. Appendix A – Areas for further research

All instances where the authors believe further research is necessary are listed below, organized by the core report sections. Many of these topics are reflected in the 25 core research questions highlighted in the conclusion of this report. There are additional topics listed in this appendix which also merit attention from researchers to provide the best possible knowledge base covering the topics relevant to sound/noise exposure management at outdoor live events.

9.1. Audience experience

1. **Punchy-ness as a metric for perceptual quantification of LF content:** "Further work is needed to confirm how significant this perceptual attribute is in relation to the previously described bass clarity and low early decay times (in indoor venues). It is likely that these attributes are strongly correlated." (p.8)
2. **Reasons for enjoying loud music playback – the same at outdoor events as in clubs?** "The study in [8], however, focuses on sound reproduction in nightclubs, not large-scale sound reinforcement of live music, which tends to be different in terms of level, dynamic range and bandwidth, not to mention audience attention. Further work is needed to determine if the same findings hold true for large outdoor events." (p.8)
3. **Link between alcohol/drug consumption and preferred listening level (for both the audience and engineer):** "Again, it must be noted that this study took place in nightclubs, rather than at large-scale live music events, so further work is necessary to determine if the findings translate to large outdoor events (especially considering that at high-profile events it's becoming increasingly rare to find sound engineers drinking excessively)." (p.9)
4. **Question of whether strong tactile LF response at live events:** "Whether this is something that audiences actually prefer or have simply become accustomed (or addicted) to is open to debate [14]" (p.9)
5. **Hidden hearing loss (SNHL):** "In terms of sound exposure at large live events, further research is required to determine what level/duration of exposure will result in SNHL. Past lab-based experiments on animals have been conducted at extremely high sound pressure levels and durations, which is not representative of real-world live events. The need for specific research for such recreational sound exposure is already noted in the reviewed work [31, 32]." (p.11)
6. **NIHL vs. MIHL:** "The question was raised of whether pleasurable sounds are less physically damaging than unpleasant sounds. This, of course, has yet to be proven either way and is a contested point due to the lack of scientific evidence supporting it. As noted above, the fact that TTS isn't related to SNHL also leads to the assertion here to be called into question, pointing towards necessary further research into this area." (p.14)
7. **THD vs. hearing damage:** "The effect of high levels of harmonic distortion in the reproduced sound must also be considered, as this will likely result in great hearing damage. This is particularly an issue for smaller indoor venues, but still much be kept in mind for larger outdoor applications." (p.14)
8. **Dynamically-weighted noise measurement devices:** "Modern day devices should have little problem providing adequate computing power to achieve this, although such an approach will need to be formalized though technical standards and included in revised noise regulations before wide adoption could be expected." (p.16)
9. **Audience sound exposure regulations:** "Overall, it is clear that much work is required in the area of audience sound exposure regulation. There exist some regulations which are likely to be

close to something appropriate for the reality of the situation at modern day live events, but there is no accepted standard practice across the world." (p.17)

9.2. System design

1. **Effect of source-oriented systems:** "One such benefit is due to the distributed nature of the sound system, comprising of many small line arrays/point sources. This may require less output from each individual component in the system, which is likely to avoid exposing audience members closest to the system to unreasonable and dangerous sound pressure levels as well as potentially reducing sound energy traveling off-site, thus reducing noise pollution. The distributed nature of the system also has the potential to provide consistent audience coverage horizontally and front-to-back, thus making audience sound exposure monitoring and management easier. As such systems are relatively new to the market, further research is needed to provide clear conclusions on these points." (p. 22)
2. **Effect of ground-reflection from flown subwoofer array:** "Steering the main beam of a flown subwoofer array towards the audience and ground does run the risk of causing a strong ground reflection, which may result in noise pollution problems due to environmental effects on sound propagation. Aspects related to this will be discussed in Section 5, but it should be mentioned here that further research is needed in this area." (p.28)
3. **Interaction between main PA and flown subwoofer system for steering:** "This results in a significant spectral crossover between the main PA and the subwoofer system, making low-frequency steering a challenge that can't be limited in scope to subwoofer array processing – the main PA must also be considered in order to get acceptable results. As the subwoofer system is generally driven on an auxiliary send, separate to the main PA sends, the subwoofer and main arrays will be partially correlated, again increasing the challenge of effective low-frequency steering. Research investigating this subject in the context of the main PA and subwoofer system is needed, as most previous work treats on the two systems in isolation." (p.29)
4. **Metric for waveform fidelity:** "An additional metric that must be investigated for inclusion in something like APR is a measure of a subwoofer system's waveform fidelity (or impulse integrity). In light of the audience subjective preferences outlined in Section 2, the transient performance (accuracy) of a subwoofer system is equally (if not more) important than the steady-state response." (p.30)
5. **Effect of system nonlinearities on array amplitude tapering:** "Further research is required, however, to inspect the effects of amplitude tapering on a realistic subwoofer system, where compression/limiting within the processors/amplifiers and power compression in the loudspeakers is considered. There is the possibility that such nonlinearities could limit the effectiveness of amplitude tapering (which is typically modeled as a linear time-invariant system). Due to these unknowns most manufacturers currently don't recommend amplitude tapering of subwoofer arrays." (p.30)
6. **Acoustic excitation and radiation properties of large marquees:** "Lastly, a common element separate to the sound system can prove to be extremely problematic for both audience coverage and noise pollution on site: temporary "soft" structures (tents, marquees, etc., consisting of frames bounded in taut fabric). Such structures will act as large radiating surfaces (especially at low frequencies), causing inconsistent audience coverage inside and unpredictable noise pollution outside. To the knowledge of the authors of this report, no in-depth study has been conducted on such structures. Such a project is essential to gain a better understanding of the acoustic excitation and radiation properties of these structures in order to develop a more focused and informed approach to implementing sound reinforcement systems

within and around them to simultaneously give the audience a good listening experience and limit annoyance in the neighboring community." (p.32)

7. **Standardized method for PA shoot outs:** "It is imperative, therefore, that large-scale loudspeaker testing and evaluation (a.k.a. PA shoot-out) is standardized similar to that of smaller-scale loudspeakers. A bespoke standard for larger-scale systems is needed which takes the various practical limitations into account and specifically addresses the numerous problems associated with testing outdoors" (p.32)

9.3. Noise regulations

1. **Volunteers at events:** "The question of whether volunteers should fall under regulations for the audience or staff needs to be addressed." (p.33)
2. **Potential for a three-tier limit:** "A potential solution to this issue could be to introduce a three-tier level guideline for live events. The first limit will be for peak-levels, the second limit for inter-set levels (15 minutes, covering at most two or three songs) and the third limit spanning the duration of the event. This will ensure that reasonable adjustments can be made throughout the day, where engineers won't be penalized for transgressions of other engineers. This approach will be discussed in more detail in Section 5, pointing towards necessary further research." (p.37)

9.4. Noise prediction, measurement, monitoring + management

1. **LFN vs. annoyance:** "The finding that the subwoofer/infrasonic spectral range is less important in terms of annoyance is supported by a Danish study [294] which found that low-frequency noise sources aren't usually obvious and the true noise source is often unknown (even to the person making the complaint). The research concluded that existing criteria have no simple relationship to the complaints surveyed in the study. Clearly, there is more work required to resolve the ambiguities exposed here in relation to low-frequency noise and annoyance." (p.64)
2. **Room-modes' influence on indoor LF noise issues:** "One aspect that was largely avoided in the reviewed research is the effect of room modes on low-frequency noise. While living rooms won't support room modes in the infrasonic region, they will have room modes at frequencies above approximately 40 Hz which, as has been shown, is a prominent component of most music-based noise (especially considering that long-distance propagation of noise will exhibit significant attenuation of high-frequency components on top of further high-frequency attenuation from transmission through building materials). Depending on where a resident is located within a room, the noise can be greatly exaggerated due to room-modes (potentially a 20 dB boost or more). This would make noise that is measured as insignificant outdoors to be highly problematic indoors." (p.66)
3. **Predicting music-based noise annoyance:** "Unbiased scientific studies are required which specifically look into music-based noise (especially in regard to large outdoor events), including how to best predict, quantify and measure such annoyance (and how to minimize it, of course)." (p.66)
4. **Suitability of 5 dB penalty for fluctuating noises in measurements:** "Again, this is (at least quantitatively) ignoring the time-variant nature of the noise, which is clearly a strong factor in annoyance and potential physiological effects from noise. While a 5 dB penalty can be imposed on set noise limits due to such fluctuations in the noise, it should be seriously questioned (through further research) whether this is sufficient." (p.69)
5. **Leq integration time for on-site and off-site:** "It has been suggested that Leq integration times are synchronized between on-site and off-site, where precedence is always given to the shorter

duration [21]. At present, such an issue isn't addressed in any known standard/regulation/law/etc. Further work is needed to develop and validate this idea." (p.69)

6. **Sound level monitoring software + interface:** "Further work is needed in this area to better understand how sound level monitoring software affects sound engineering practice. This should include the exploration of different sound level monitoring interfaces that don't focus on level maximization, but on a less "louder is better" approach." (p.79)
7. **Similarity between noise monitoring trends indoor and outdoor:** "Further work is needed to determine if this is a true problem with such software and, if so, what can be done to rework the user interface to avoid this issue. As the study in [330, 331] was based on indoor venues, further work is required to see if the observed trends hold for large outdoor events." (p.79)
8. **System height vs. propagation/wind effects:** "This points to further research needed before any conclusion on height of a sound system (especially concerning subwoofers) can be made. It is likely that height can't be considered on its own. Height as well as physical speaker orientation and electronic steering (if used) most likely have to be considered together instead of in isolation." (p.85)
9. **Ground vs. flown subwoofer array sound propagation:** "Further research is necessary to make a clear conclusion regarding ground versus flown subwoofer arrays. Considering the relevant research detailed in other sections of this report, the conjecture that ground-based subwoofer systems are easier to control in terms of noise pollution is questionable." (p.85)
10. **LF noise propagation (6 or 3 dB):** "Further research is required here, as this finding is in direct opposition to what is known (from extensive research) about noise propagation from wind turbines [122]." (p.86)
11. **LF noise propagation vs. crossover point:** "Further work is needed and should be linked to additional investigations looking into sound radiation control of ground versus flown subwoofer systems. At present there is insufficient evidence to make a clear recommendation." (p.86)
12. **Just noticeable difference in dynamic range at live events:** "Further research is required to determine the just noticeable difference in dynamic range at such events (for A- and C-weighted measurements) before the audience notices a change in sound quality)." (p.95)

9.5. Noise suppression techniques

1. **Stage degradation of cardioid response in far-field:** "An important question has been posed by an industry expert on this subject, asking if the stage structure diminishes the subwoofer system's directivity in the audience area – is the same effect seen off-site or is it more of a local effect? This question requires further research to answer." (p.101)
2. **Use of shielding materials near PAs:** "In all cases it was found that placing the shielding as close to the sound system as possible will maximize effectiveness. It should be noted that this data is based on a BEM model, therefore material properties (especially in terms of reactance) may not be accurately modeled. The aforementioned slap-back issue must also be considered. The research in [343] was focused only on the geometry of the various shielding materials. Further work is needed in this area to confirm the results in Figure 6.6 are accurate." (p.103)
3. **Extended bandwidth subwoofers/SPL trade-off:** "The high variability in the results indicate that further work is required in this area, but these findings should prompt a more focused effort by practitioners to consider bandwidth extension as a viable option for control of sound exposure on-site and noise pollution off-site of large-scale outdoor events." (p.106)

4. **Secondary sound system's effective coverage:** "One aspect of such systems that hasn't yet been explored (or at least published) is noise control with secondary systems that aren't in a straight line. Can these systems operate covering a wider area?" (p.114)
5. **Effective height of a secondary system:** "It must be inspected whether such ground-based system have the potential to cause additional noise away from the ground-plane. To date, there is no clear published research in this area. The effective height of secondary systems is an interesting question that is partially explored in some of the referenced DTU research, but results indicate that the effective control height is usually much lower than where people may be living in built-up areas. More research is needed before a clear conclusion can be reached. It is unlikely that flown secondary systems would be a practical alternative." (p.115)