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Considerations to Establish Groundborne Noise Criteria to Define Mitigation for Noise Sensitive Spaces

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Abstract

The Federal Transit Administration (FTA) provides guidance for the evaluation of impacts to a variety of noise and vibration specific uses along a rail transit system. Included under the category of special buildings are concert halls and sound recording facilities, and auditoriums. The impact criteria for groundborne noise from the transit systems into such spaces are maximum noise levels of 25 or 30 dBA, respectively, which are far more restrictive than any other category considered in the FTA "Guidance Manual". Conformance with these impact criteria is necessary to avoid "significant" impact during environmental analysis, but this is not a sufficient evaluation of the effect of the transit systems. In fact, for professional and world class facilities the FTA thresholds may be inadequate. This paper discusses some special parameters that should be considered for any rail transportation project that seeks to become a close neighbor of such facilities.

Introduction

As urban areas are redeveloped and filled-in, civic spaces and transit are naturally paired. Out of necessity, innovations in rail transit structure design and building isolation design over the latter part of the 20th century have made it possible for these important community resources to be close neighbors, in particular, rail transit and performing arts facilities are co-existing successfully in close proximity. For some of these performing arts facilities, a low level sound caused by groundborne vibration would not interfere with the enjoyment of a performance or a recording. For others, the tightly controlled background noise conditions within the facility would seem to disallow any intrusion from any source.

Table 1 summarizes information about many world class performing arts facilities in close proximity to rail transportation facilities. For concert halls, a resident orchestra will often use their home space for making recordings which will be made available for commercial sale. The facilities are ordered chronologically in Table 1, according to the latest renovations or changes made to the building or rail system. Generally speaking, since the early 1990s with the Birmingham Symphony Hall in the U.K., world class performing arts facilities (concert halls, opera and multi-use) near existing rail transit facilities have been designed and constructed with vibration isolation systems. New rail transportation systems and track renovations near these important cultural facilities have likewise been built with vibration isolation.

Where known, Table 1 includes the background noise criterion used during design or information on the existing background noise condition, and in many cases these criteria were also used to evaluate the impact of groundborne noise from nearby transportation sources. The criteria shown were originally developed specifically to evaluate continuous noise sources such as HVAC. There are several criterion methods used around the world, discussed in more detail later in this paper. The most restrictive is the “N-1”, which essentially follows the normal threshold of hearing.

Evaluation of transient groundborne noise from transportation sources is not standardized or well defined. As of this writing, an ISO technical committee is working on a standard to measure and evaluate complaints of groundborne noise from rail systems (1). The potential impact of subway noise on cultural institutions and commercial businesses should be better understood so that transit agencies, stakeholders and their communities can more easily have shared expectations.

Table 1 Selected World Class Performing Arts Facilities within 300 ft. of Transportation Sources

Facility (city)	**Resident Group(s)**	**Year open; Renovated**	**Closest Transit Source**	**Horizontal Distance to Building[8]**	**Vibration Isolation**	**Background Noise Design Goal**
Concertgebouw (Amsterdam)	Royal Concertgebouw Orchestra	1866	surface trams	50 ft.	None	Note 7
Carnegie Hall (New York)	none	1891	subway shares wall	0	None	Trains Audible; Estimated RC-30[2]
Grosser Tonhalle (Zurich)	Tonhalle-Orchester Zurich	1895	Surface trams	80 – 280 ft.	Unknown	Note 7
Symphony Hall (Boston)	Boston Symphony Orchestra; Boston Pops Orchestra	1900	light rail (surface and subway)	60 ft.	None	Note 7
Avery Fisher Hall (New York)	New York Philharmonic	1962	subway	Shallow subway	None[1]	Unknown
Abravanel Hall (Salt Lake City)	Utah Symphony	1979	Surface light rail	90 ft.	Unknown	Unknown
Palais Garnier (Paris)	none	1875; 1989	subway	<50 ft.	None	Unknown
de Doelen (Rotterdam)	Rotterdam Philharmonic Orchestra	1934;1966; 1990	surface light rail	130 ft.	Unknown	Unknown
Birmingham Symphony Hall (UK)	Birmingham Symphony Orchestra	1991	commuter rail subway	0	Building	N-1*
Francis Winspear Centre for Music (Edmonton)	Edmonton Symphony Orchestra	1997	surface streetcar	50 ft.	Building	N-1*
New Jersey Performing Arts Center (Newark)	New Jersey Symphony Orchestra	1997	surface light rail	280 ft.	floating slab at track	N-1*
Sangnam Hall - LG Gangnam Tower (Seoul)	none	1997	Subway	50 ft.	Building	N/A
Benaroya Concert Hall (Seattle)	Seattle Symphony	1998	freight rail in tunnel subway and adjacent light rail subway	0	Building; main hall	NC-10 to 15 for HVAC N-1* for trains
Grosser Musikvereinssaal (Vienna)	Vienna Philharmonic Orchestra	1870; 2001+	subway; light rail	100 ft.	None[2]	Unknown
Kimmel Center (Philadelphia)	Philadelphia Orchestra	2001	subway	<50 ft.	Building	N-1*
Roy Thomson Hall (Toronto)	Toronto Symphony Orchestra	1982; 2002	streetcar; subway	100 ft.; 300ft	standard floating slab for subway	Unknown

Facility (city)	Resident Group(s)	Year open; Renovated	Closest Transit Source	Horizontal Distance to Building[8]	Vibration Isolation	Background Noise Design Goal
Walt Disney Concert Hall (Los Angeles)	Los Angeles Philharmonic	2003	subway	30 ft[5]	none[4]	NC-15
Jazz @ Lincoln Center	none	2004	Subway	70 ft.	Building	N/A
Four Seasons Centre for the Performing Arts (Toronto)	Canadian Opera Co; National Ballet of Canada	2006	Streetcar with crossover; subway	20 ft.; 40 ft.	Building	N-1 (Main Hall)
Bartok Concert Hall (Budapest)	Hungarian National Philharmonic	2006	surface light rail; commuter	500 ft.; 90 ft.	Building	PNC15-20*
Harman Center for the Arts (Washington, DC)	Washington, DC Shakespeare Theatre Co	2007	Subway with crossover	300 ft.	Acousticall y Isolated Constructio n for Theatre and Stagehous e	RC-20
Suzanne Roberts Theatre (Philadelphia)	Philadelphia Theatre Co	2007	Subway	<50 ft.	Building	N/A
Stadtcasino (Basel)	Basel Symphony Orchestra, Basel Chamber Orchestra, Basel Sinfonietta	1876	surface trams	25 ft.	floating slab track added in 2007	Unknown[9]
Maison Symphonique (Montreal)	Montreal Symphony Orchestra; Metr opolitan Orchestra	2011	Rubber tired vehicles in subway	0 ft.	Building	N-1
Alice Tully Hall (New York)	Julliard School of Music	1969; 2013	subway	50 ft.	track on soft fasteners; floors and walls isolated on rubber bearing pads[1,3]	NC-15
Polonsky Shakespeare Center (Brooklyn)	Theatre for a New Audience	2013	Subway	<50 ft.	Building	N/A
Xiqu Cultural Center (Hong Kong)	none	Under construction	Subway; surface traffic	0; <25 ft.	Floating slab track; Building isolated for surface traffic	NR-15

Facility (city)	Resident Group(s)	Year open; Renovated	Closest Transit Source	Horizontal Distance to Building[8]	Vibration Isolation	Background Noise Design Goal
* We are unaware of post-construction measurements to confirm the design goal Note 1: Buildings constructed around this time used lead or cork asbestos pads for vibration isolation, but they provide little effect for rail transportation; recent trackwork improvements by NY MTA at nearby Alice Tully Hall have been extended to AFH. Note 2: Per reliable source, based on site visit to the facility Note 3: Per reliable source, acoustical consultant for renovations Note 4: The Roy and Edna Disney CalArts Theater was isolated from the building to minimize impact of the parking garage in which it is located. The isolation also serves to reduce structureborne noise from its productions on the Main Auditorium Note 5: At its closest point the new LA Metro Regional Connector will be 30 ft. away from the parking structure. Note 6: The track will include a high performance floating slab system Note 7: There was no practice of using noise criteria to evaluate background noise during the original construction; for the case of renovations, we are not aware of any criteria that were used. Note 8: In many cases the horizontal distance is based on review of aerial photo and estimating the near track/tunnel to the building envelope. Note 9: The new floating slab provides significant reduction. (2)						

For these facilities, professional sound recording can be an important and vital part of the intended purpose, but by and large, these are not commercial recording facilities; public performances and rehearsals generally dominate the schedules, with some time allotted for recordings. Discussion of the impact and appropriate mitigation for commercial recording facilities is beyond the scope of this paper.

Vibration to Sound

Vibration is generated where the vehicle interfaces with the running surface, whether this is steel wheel and rail or rubber tire and pavement. The small irregularities at this interface and the magnitude of the irregularities can vary. As the vehicle travels the irregularities cause the "unsprung mass" (i.e., portions of the transmission or truck below the primary suspension such as the wheels and axles) to move up and down. Maintenance of rail and wheels or the pavement is the primary means by which to minimize the effect of irregularities by keeping them under control.

Once the vibration travels though the ground and enters the building it propagates through the building where it excites large building surfaces to vibrate such as floors, walls and ceilings. The vibration of large building surfaces generates sound inside the various spaces (rooms) of the building. This sound is called groundborne noise since its path to the building is through the ground. However, once it enters the building it can also be referred to as structure-borne noise. Groundborne noise inside rooms is also affected by the amount of acoustical absorption in the room. A highly reverberant room will have higher levels of groundborne noise than one with a substantial amount of acoustical absorption, other things being equal.

The groundborne noise inside a room consists of a range of sound frequencies, and there are several ways of characterizing the sound energy over the normal range of human hearing. The frequency spectrum can be divided up into bands. Octave bands, in which each frequency band is twice the adjacent lower band, are most common for characterizing sound in buildings. A combination of all the octave bands is called the "overall" sound level. In the case of typical transit systems, the dominant frequency range of groundborne noise is generally from 31.5 to 125 cycles per second (Hz). Compared to other environmental sound, this is low frequency sound. If the groundborne noise in this range of frequencies is audible, it would be perceived as a "rumble." The 63 Hz octave band is typically the controlling frequency (highest predicted level in frequency spectrum) for groundborne noise from rail transportation sources.

Another common measure of noise is the "A-weighted" metric. A-weighting in decibels (dBA) is used to combine sound energy from all frequencies into a single number, by simulating how the human ear hears the "loudness" of different frequencies. The ear is most sensitive to mid-range frequencies (e.g., 1,000 Hz), which are not decreased by A-weighting, whereas low and high frequency sounds, which the ear is less sensitive to, are decreased in the A-weighting process. The FTA recommended criterion for groundborne noise in concert halls and recording studios is 25 dBA (3).

As an example, the approximate threshold of hearing (4) at 63 Hz frequency is 36 decibels (dB). If a sound at this frequency were <u>the only sound present</u>, the A-weighted level would be 10 dBA, which is 15 dBA below the FTA criterion. High quality performance facilities can make a case that the FTA criterion will result in a situation that will impact them, in particular when making recordings.

Ambient Noise

Ambient noise is defined as a combination of noise from all sources and by nature is transient. As a measure of the transient nature of ambient noise, it is common practice to use "statistical levels" (Ln), which are defined as "the level exceeded n% of the time." The L90 (level exceed 90% of the time) is typically considered to define the "background" noise level. The L1 is commonly considered to be the level characterizing infrequent, but repeating maximum events. Depending on the speed, train length and operating schedule, rail transit operations during peak operations could conceivably contribute groundborne noise in an adjacent building, say, 5 to 20% of the time. A busy light rail system could potentially generate groundborne noise for 5 to 8 seconds per train, and with 2-minute headways in both directions this system would potentially have an effect on an adjacent concert hall for 480 seconds in any hour, or 13.3% of the time.

Ambient noise in any performing arts facility is generated by both internal as well as external sources. Internal sources of ambient noise typically include the building's heating, ventilation and air conditioning (HVAC), human activities and, in particular at the relevant groundborne noise frequencies, elevator machinery and movement of vehicles in adjacent parking structures, etc.

External sources of groundborne ambient noise typically include motor vehicle traffic in the area, in particular heavy trucks and buses. Larger HVAC equipment in nearby buildings and structures may also produce groundborne noise.

Performance vs Recording

During performances, the probability of a train occurring at the same time as a quiet passage during a performance would vary depending on the program music; the probability of a train passing during the peak commute period (say 60 trains at 8 seconds each, or 14%) combined with the probability of a quiet moment during a 2-hour program, perhaps up to 540 seconds of quiet at the beginning of movements and during quiet moments in the music (up to 7.5%, 540 seconds/7200 seconds). The combined probability would be 1% or less. The ambient environment for a live performance also includes the effects of the audience.

However, during a recording session a quieter background environment can be required compared to what is typically acceptable for a performance. Anecdotal information from recording engineers indicates that audible sounds can affect the recording, and if a subway train was detectable at a quiet moment in the music, it might require that passage to be re-recorded, depending on the intended quality of the recording and ultimate use. Alternatively it might require the recording engineer during post-production mixing to edit the recording to eliminate the train sound, and many recordings require some editing during the normal course of post-production. Frequent intrusions probably render a recording space less than ideal. Another comment from recording engineers is the relation between intruding sounds, the artist and the creative muse; again, frequent intrusions can interfere with the creative process. The key here is detection, not audibility, which at extremely low levels is a complex and very subjective process, and which would depend on the individual and the acoustic activity preceding the transient event. Thus, this paper assumes that recording activities are more sensitive than performances.

Groundborne Noise Predictions

Groundborne noise from vehicle vibration is predicted using an empirical model, which relies on data from several measurements. This is the prediction method described in the FTA "Guidance Manual" (3) for the evaluation of rail transit systems. The prediction model is based on experience of many past transit projects and has been in use for 30 years (5; 6; 7; 8).

The noise model includes the following:

- The transit vehicle and the track structure it operates on under normal operating conditions.
- The transmission path from the transit guideway (e.g., tunnel) – propagation through the ground.
- The transmission path into and through the potentially impacted building to critical spaces within.

Predictions for any new rail transit project are typically based on measurement data for system specific vehicles and data from similar vehicles. The groundborne noise model typically includes field measurement data obtained in the area adjacent to the noise sensitive spaces. The transmission path into the building and through the structure is not typically included for typical environmental studies; some engineering studies do measure this during preliminary or final engineering. The predicted levels of groundborne noise from modern rail transit vehicles typically cover the frequency range of 20 to 160 Hz, with some older systems can generate frequencies up to 300 Hz.

Design and Mitigation Criteria

In addition to the single number, A-weighted criteria used by the FTA, there have been many frequency band criteria curves that have been developed that established a basis for the design of continuous noise sources within a space. These are alluded to in Table 1. These continuous sources are typically related to heating, ventilation and air-conditioning systems (HVAC), and they were originally developed to design for environmental comfort.

The Noise Criteria (NC) curves were one of the earliest developed. Proposed in 1957, the original NC curves were designed to determine the potential for speech interference caused by a continuous source and the perceived loudness of that noise source; the NC curves have been formalized by the American National Standards Institute (ANSI). Since then, two other criteria have found broad support for the design of music performance facilities, including the Noise Rating (NR) curve that was developed by the International Organization for Standards (ISO) which is widely used in Europe (9), and the Preferred Noise Criteria (PNC) curves which were introduced in 1971 as a modification of the original NC curves to bring it in line with speech interference curves and to take into account possible broadband low frequency effects of modern HVAC systems. A fourth criteria family, the Room Criteria (RC) curves, was adopted by ASHRAE[1] in 1981. (10) (11)

In addition to these families of curves, it became the practice of one leading acoustical consultant, and his firm, to use a curve which was very similar to the threshold of hearing, and termed the “N-1” curve[2]. Since that time, many of the pre-eminent world class facilities have been designed to this industry standard. The choice of which criteria curve typically depends on the sensitivity of the project, the acoustical design consultant’s preference and the project owner’s goals. There is no universally accepted practice, although there may be some general consensus among acoustical consultants.

As mentioned above, these curves were originally developed to evaluate continuous noise; they have been adapted by acoustical consultants to determine the level of quietness within a space above and beyond the need to minimize speech (or music) interference. While these criteria have been applied to evaluate the potential intrusion of transient sounds on a performance or recording event, the practical effect of transient sounds on such facilities has not been broadly studied.

It is the authors’ understanding that building isolation was designed to control the intrusion of groundborne noise to the “N-1” level from existing rail transit into many of the performance halls for which the “N-1” criterion has been used, as listed in Table 1. In some cases, the “N-1” criterion was used as guidance to evaluate the merits of different building isolation options. In some cases, the concept that “a few” trains could exceed the “N-1” criterion was acceptable, and in others, the building isolation was designed to eliminate all incursions above “N-1”.

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[1] Formerly known as the American Society of Heating, Refrigeration and Air-Conditioning Engineers.
[2] Frederick Russell Johnson was the originator of the “N-1” curve, and his firm, Artec Consultants, founded in 1970, used this criterion curve for many world class and high profile projects around the world.

Background Noise vs. Transient Noise

It is possible that the use of such "background noise" criteria to evaluate the impact of transient sounds may be overly conservative for most facilities; transient sounds can be very short and the human ear is less sensitive to sounds shorter than 100 milliseconds (12). As illustrated in Figure 1, a tone burst of 100 ms duration is perceived to be 2 dB less loud than the same tone burst sounded for at least 400 ms. For shorter durations, the human ear treats those shorter sounds as quieter events, as shown in Figure 1, where a 10 ms duration sound is about 10 dB less loud than the same sound at 400 ms duration. A train passby can last from a few seconds to almost 30 seconds, but groundborne noise from a passing train is not a continuous noise. The random irregularities generate time-varying vibration and groundborne sound, as shown in Figures 2 and 3. Figure 2 shows the groundborne noise in the 63 Hz octave band measured inside a building for a normal passage of a heavy rail subway train[3]. Figure 3 shows a passby for a light rail train moving through a surface crossover. In both cases, note how there are many maximum events during the passby that are less than 100 ms duration. (12). Thus, the maximum measured level at any moment (e.g., Lmax) may have little meaning on the way groundborne noise from a train is perceived, but perhaps an aggregation of the maximum events through statistical analysis, or an average (e.g., Leq over a given time period or the energy average of several events) would be a more useful measure that correlates to the effect that the passby has within the receiving space.

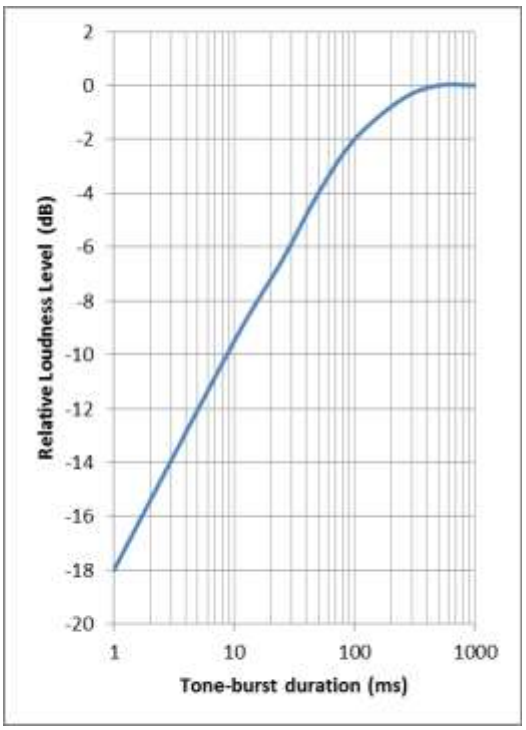

Figure 1 Effect of sound duration on perceived loudness, after Zwicker (12)

[3] The specific conditions of the wheel and rail are not documented for these measurements, and the measured sound is somewhat affected by the rooms in which they are measured.

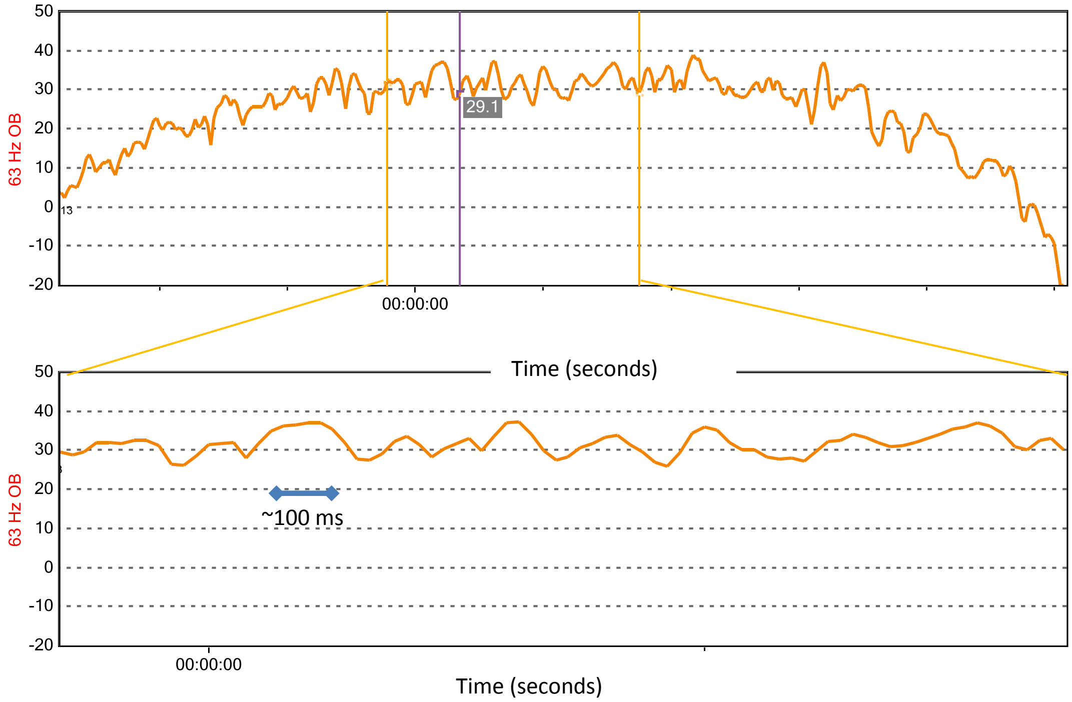

Figure 2 Groundborne noise time series from subway train passby - tangent track (25 ms sampling)

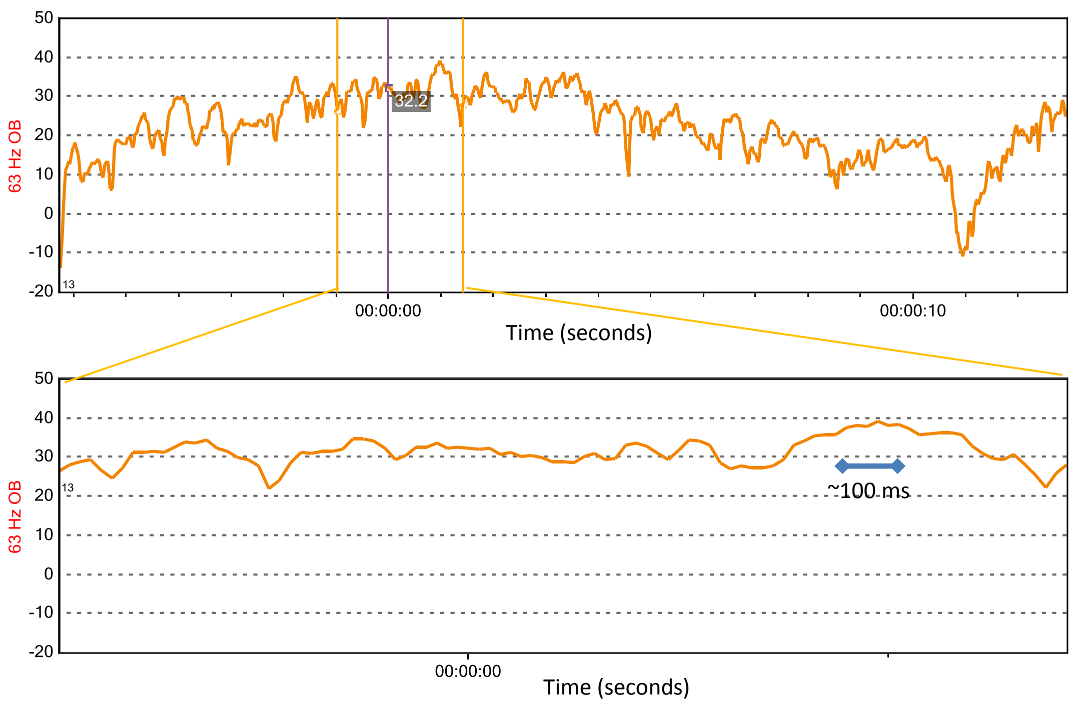

Figure 3 Groundborne noise time series from surface light rail train passby - crossover track (25 ms sampling)

For the case where the groundborne noise is very low, and difficult to distinguish from the prevailing noise environment, the prevailing ambient will influence the sound measurement at any point in time.

Thus, one way to measure the effect of the transportation source would be to measure some basic statistical metrics for the ambient condition with and without the transportation events.

Reliance on the basic FTA criteria alone would be insufficient for world-class facilities because some of these facilities, particularly those constructed in recent decades, have a very low ambient, attained through careful design and construction. While 25 dBA is the lowest criteria value within the FTA schedule, a “rumbly” train could be well below 25 dBA within such a space and still be audible. If audibility is viewed as the basis of impact, this can be a problem. See Figure 4, which shows predicted values at the main hall of Four Seasons Performing Arts Center in Toronto, without building isolation (7). The upper range is 42 dBA, and the lower range is 28 dBA; the typical train value is 37 dBA. These predicted values all would have exceeded the most stringent FTA criterion of 25 dBA for a special use facility. These estimates were prepared during building design for a new performing complex adjacent to existing rail transit tracks. It is not difficult to imagine, then, that the low end of the range, reduced by 3 dBA to comply with the FTA criterion, would still be more than 10 dBA higher than the threshold of hearing. The isolated spaces were constructed on rubber bearing pads, and post construction, the measured results at the Four Seasons main hall are shown in Figure 5; the range shown is 19 to 21 dBA (7).

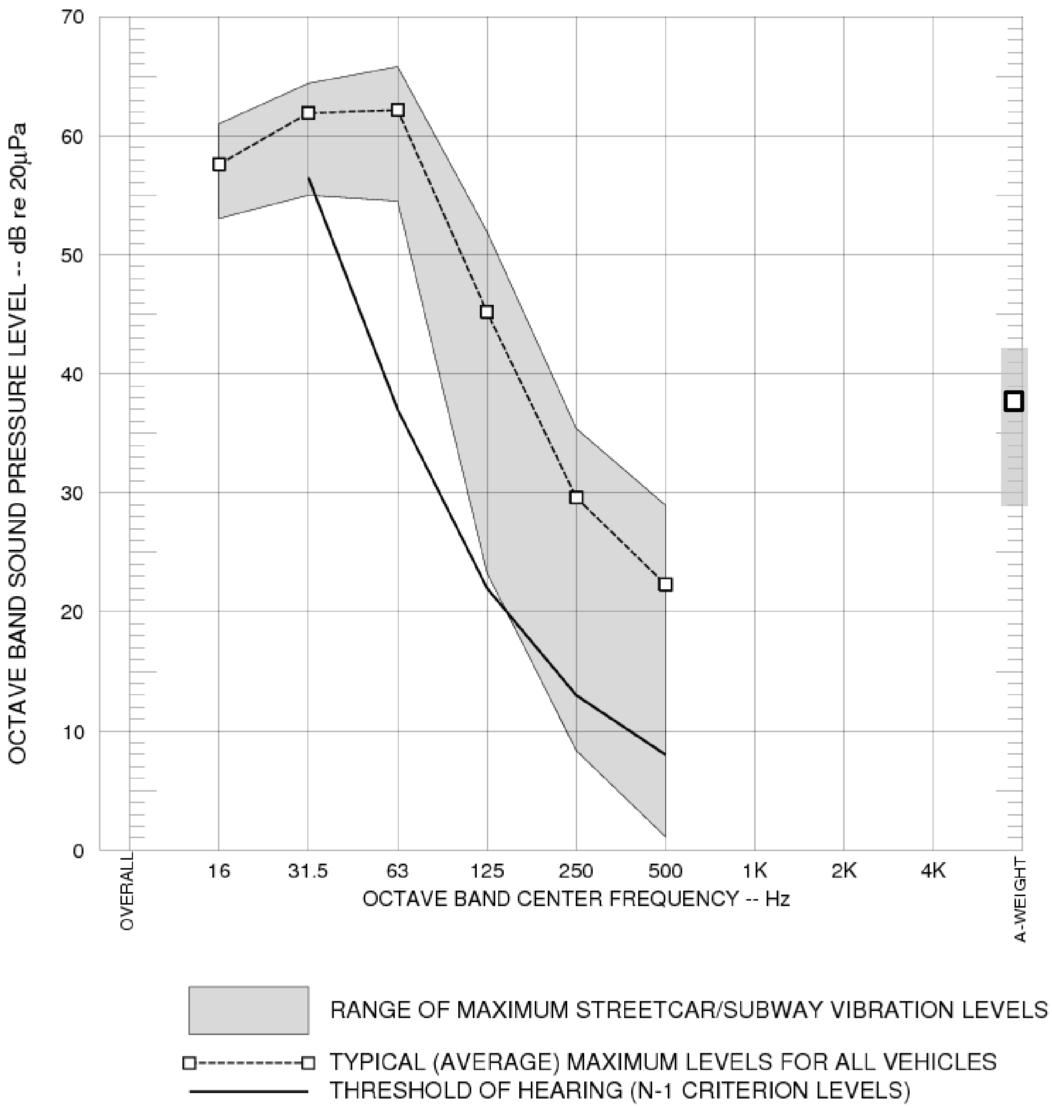

Figure 4 Range Of Maximum Estimated Radiated Noise Levels Inside Main Hall (Four Seasons, Toronto)

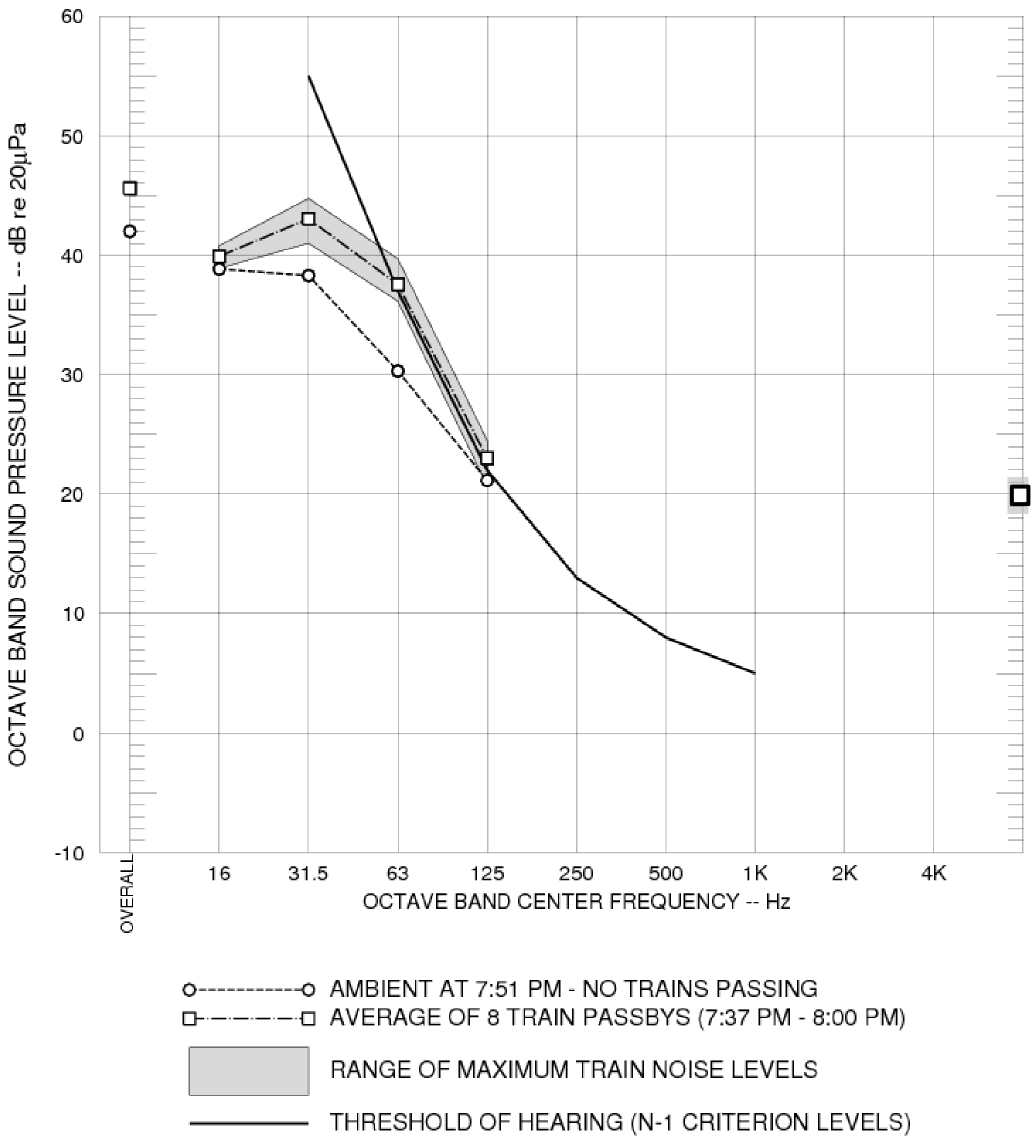

Figure 5 Measured Noise Levels Inside Main Hall (Four Seasons, Toronto)

Recommended Considerations

- Use additional information other than basic building category to determine the appropriate impact criteria. This could include cultural significance of the building to the community and whether professional recordings are conducted within the facility. Typical recording and performance schedules and their relation to the future transit system operations can also be important considerations.
- Document the existing ambient during typical use or most noise sensitive use, as appropriate. The ambient conditions must be controlled, or not, as they are during normal use. The threshold

of transit system impact should be based on the intrusive effect above and beyond the normal range and frequency of intrusions the facility currently experiences during those typical or most noise sensitive uses.

- Develop a Transit Design Criterion for a single train passby that takes into account the existing ambient (and future non-project ambient) and the cultural sensitivity of the affected facility. For instance, a possible hierarchy, from most restrictive to least restrictive:
    - Transit Design Criterion selected to match the background noise acoustical design criterion (e.g., "N-1"). This may be a necessary consideration for a high cultural value facility that was already designed with stringent criteria. This may be the only option that the stakeholder will accept.
    - Statistical combination of the Transit Design Criterion under any operation schedule and the existing conditions to result in
        a. No increase to the ambient conditions, as defined by statistical metrics (L1, L10, L20, L50) or the equivalent sound level, Leq.
        b. Some increase allowed in the ambient during peak hour operations (which typically do not coincide with most performances)
        c. Some increase allowed in the ambient up to the industry standard for comparable performance spaces. For an existing performing arts facility that enjoys an exceptionally low ambient condition, any substantial degradation of their ambient may be difficult for the stakeholder to accept.
- Any of these scenarios can have far-reaching effects on the feasibility of any new vibration source (i.e., new rail transit), and this issue should be explored as soon as possible so that alternate plans can be considered during the planning and environmental phases.

Conclusions

The Federal Transit Administration provides guidance for the evaluation of impacts to a variety of noise and vibration specific uses along a rail transit system. The impact criteria for groundborne noise from the transit systems into special buildings such as concert halls and auditoria are maximum noise levels of 25 or 30 dBA which are still potentially audible and would interfere with professional recordings. Conformance with the FTA impact criteria is necessary to avoid a "significant" impact during environmental analysis, but this is not a sufficient evaluation of the effect of the transit systems on these facilities. In fact, for professional and world class facilities the FTA thresholds may be inadequate.

Noise regulations around the world impose maximum limits on noise, and in the case of groundborne noise generated by a transportation source it may seem obvious to impose a maximum limit on the intruding groundborne noise. However, it is not clear how that limit should be defined, and what obligation the transportation agency has to protect a cultural resource. Rail transportation operators in urban areas are balancing and juggling many parameters every day to move thousands of people on schedule. Even with best practices in place to maintain the wheels and rails, and monitoring systems to alert operations when anomalous conditions arise, it seems that it would be difficult for a transportation agency to provide any guarantee with regards to any maximum limit. Statistical trends, on the other hand, could be more meaningful, providing some flexibility for a few higher value events above the typical range. Additional study would be useful to clarify appropriate metrics and methodologies to characterize the existing ambient noise conditions in such spaces, and to develop further guidance and appropriate design criteria for mitigation design.

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