ASHRAE Journal's
Practical Guide

Controlling Noise From Large Rooftop Units

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Member ASHRAE

Rooftop HVAC equipment provides enticing features for the design engineer and cost advantages for the owner. Fans, ventilation equipment, a heat source, compressors, condenser, and controls are assembled in a compact unit ready for installation on a roof curb. Manufacturers assemble, test, and rate the entire package as a system. Moreover, locating the unit on the roof frees up floor space in the building.

Despite these benefits, large (40 tons [140 kW] and larger) rooftop units sometimes generate enough noise to make the spaces they serve unusable. Ironically, these units can condition theaters, recording studios, and other sound-sensitive areas without complaints. The success of rooftop HVAC installations on acoustically critical jobs hints at the importance of system design in acoustics. It also leads to the premise of this article:

From an acoustical perspective, using a fixed set of design practices on every job unnecessarily inflates the cost of some jobs and under attenuates others. A better approach is to include at least a simple acoustical analysis early in the design process.

The discussion that follows:

• Reviews the acoustical fundamentals of large rooftop HVAC application.

• Illustrates how an acoustical analysis affects design decisions and helps the installation succeed in terms of first cost and occupant satisfaction.

Defining an Acoustical Model

Following prescriptive methods is better than "doing it like we did the last one," but understanding *why* particular practices are used allows greater flexibility and could reduce costs. Therefore, understanding acoustic fundamentals is a prerequisite to making sound decisions for rooftop HVAC installations. A simple acoustical model consists of a:

• **Source**, where the sound originates.

• **Receiver**, where a person hears the sound.

• **Path**, the route the sound travels from the source to the receiver.

Source: Large rooftop units contain a number of sound sources, including compressors, condenser fans, supply fans, return fans, and exhaust fans. Each source has a unique sound quality and level. All play a role in determining the sound the receiver hears. Manufacturers provide information about these sources in their sound ratings.

Receiver: The receiver is simply the location where you are concerned about the sound. This could be the conference room, an open office area, a theater, etc. A given sound source may have several receivers.

Path: Most acoustical variability lies in the path. For that reason, it deserves particular attention. Sound from a single source may take more than one path. For example, sound from the supply fan follows the ductwork and enters the room through the diffuser. Sound also travels through the wall of the duct and the ceiling into the room.

Since minimizing cost is the overriding theme for most rooftop HVAC installations, the unit is usually situated to provide short duct runs. Often this decision places the unit directly above occupied space.

Acoustical Analysis, Step by Step

An acoustical analysis consists of five basic steps:

Step 1: Set acoustical goals for the finished space.

It is critical to establish the acoustical goals for the finished space at the outset of any HVAC project. There are always implicit, often subjective, expectations for the acoustics of occupied spaces. It is much easier to produce a successful installation if you understand these expectations *before* designing the installation.

This step is sometimes overlooked based on the reasoning that "it's the way we did it on the last job, and it was okay." The risk involved in waiting until the unit is installed is considerable because the cost of quieting an installed unit always exceeds the cost of applying the same treatment during installation.

Sound goals will vary depending on how the space is used. Once the sound goals are understood they can be stated using an appropriate descriptor such as NC or RC. Remember these three points

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when defining desired sound levels:

1. As a general rule, lower sound levels cost more to achieve.
2. The entire building does not have the same sound requirement. Bathrooms and hallways do not need to be as quiet as executive offices and conference rooms. A low-cost, quiet installation takes advantage of this point.
3. Successful acoustics requires a team effort. The team should include the owner, engineer, architect, equipment manufacturer, and contractor.

Step 2: Identify each sound path and its elements.

Large rooftop HVAC installations have four types of paths (*Figure 1*):

1. Airborne sound follows the airflow path. Supply airborne sound travels the same direction as the supply air. Return airborne sound travels against the airflow direction.

2. Breakout sound passes through duct walls into the plenum space, then through the ceiling and into the room.

3. Roof transmission sound passes through the roof deck (either within or outside the roof curb), plenum space, and ceiling into the room.

4. Structure-borne sound differs from the other sound paths in that it describes energy transmitted through the framework of the building. This energy may come directly from the vibration of the sound source, or may be airborne sound transferred to the structure.

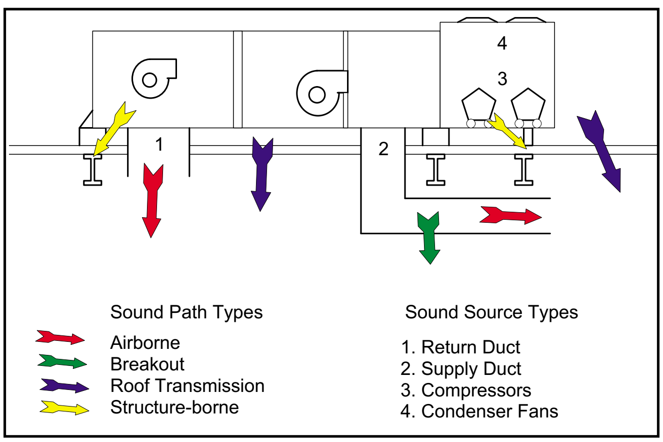

Figure 1: Rooftop unit sound paths.

Step 3: Perform a path-by-path analysis.

Once each path has been identified, individual elements can be analyzed for their contribution. For example, the supply airborne path includes various duct elements (e.g., elbows, straight duct, junctions, diffusers) and a room-correction factor. Algorithms available from ASHRAE can calculate the acoustical effect of each duct element. The effect of changing an element (e.g., removing the lining from a section of ductwork) can be calculated. Software tools make these algorithms easier to use.

On a rooftop installation there often isn't much to the path, especially when the unit is located directly over occupied space.

It is possible to change the components of a particular path, but this rarely can be done without adding cost to the installation. Changing the path after the unit is installed certainly will be much more expensive.

This step typically entails at least two iterations for each path. The initial pass establishes the acoustical performance of the initial design. Subsequent passes calculate the effect of adding various acoustical treatments.

Step 4: Sum the results to determine the acoustical performance of the installation.

After the contributions of the individual paths are calculated, they must be added together to determine the total sound at the receiver. If the sum exceeds the goal, another round of path attenuation calculations is required.

Step 5: Compare the summations with the acoustical goals in the context of the project budget.

Once a design meets the acoustical goals for the project, everyone on the team must understand the work and costs required to implement the design. It may also be prudent to review the cost of meeting the acoustical goals and reconsider equipment options that were initially rejected due to cost.

The following example walks through an acoustical analysis for a rooftop unit. Some details have been left out, but the analysis is typical for this type of unit.

Assume the design for a rooftop HVAC installation calls for placing a 60-ton (211 kW) rooftop unit over an open-plan office area. The acoustical goal for this space is RC 40-45(N). The manufacturer has provided the following sound power data taken in accord with ARI 260:[1]

- Supply data for sound leaving the unit via the discharge duct,
- Return data for sound leaving the unit via the return-duct opening, and
- Outdoor-radiated data for sound emanating from the outdoor portion of the unit.

Each acoustical path must be modeled separately, then added to the others to determine the total sound reaching the receiver. In this "worst case" (loudest) example, the receiver is directly below the unit.

Once each path and its elements have been identified, ASHRAE algorithms are used to calculate the contribution of each element. For brevity, calculations for individual elements are not included in this article. Assumptions in the example about individual elements follow typical engineering practice.

Return Sound

Return Airborne Sound

Assume the unit return connection is open to the plenum (no return duct). The path consists of a transmission loss for the ceiling and a room-correction factor. The path calculations look something like this:

Octave band, Hz	63	125	250	500	1000	2000	4000
Return sound power	90	89	81	82	80	79	68
Acoustical tile, TL	–4	–8	–8	–12	–14	–15	–15
Room correction	–9	–9	–8	–9	–10	–11	–13
Result, RC 57(N)	77	72	65	61	56	53	40

As shown in *Figure 2*, this path alone exceeds the acoustical goal. Comparing the result above with an RC 40 curve, the difference by octave is:

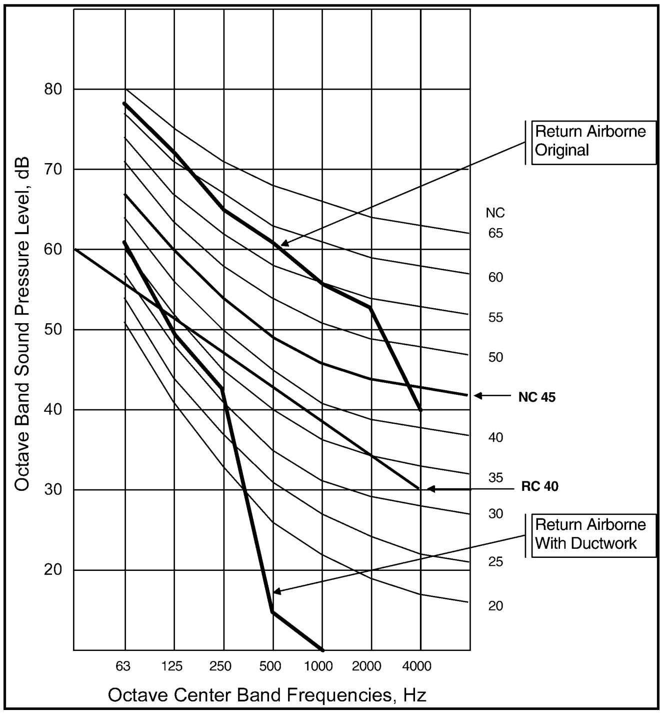

Figure 2: Return duct noise.

Result minus RC 40	17	17	15	16	16	18	10

The difference represents the amount of attenuation needed. Fortunately, inexpensive methods of reducing return airborne sound are available.

The required attenuation could be achieved by adding two layers of 0.5 in. (13 mm) gypsum board on top of the acoustical tile—but only if no gaps exist between the edges of the sheets. Such an installation would be difficult and would hinder access to the area under the unit.

A second solution is to add lined return ductwork. There are multiple acoustical benefits to adding a return duct:

1. The duct transfers the sound away from the other sound sources.
2. The return duct provides some attenuation.
3. Best of all, the end of the duct provides an end reflection loss attenuation.[2]

Duct end reflection increases as duct size decreases. Installing a tee also increases end reflection and further separates the sound sources. For example, the attenuation associated with a tee-junction, 20 ft (6 m) of duct with 2 in. (50 mm) lining, a duct end reflection loss, and the increased distance to the receiver is:

Return duct credit	14	11	21	43	43	41	39

Notice that attenuation of the upper bands drops the total to RC 11(RH) or NC 44.

As shown in *Figure 2*, the return airborne path is now at the upper range of where it needs to be to meet the sound criteria. Adding another tee-junction to the end of each return run (forming an H-shaped duct as shown in *Figure 3*) would reduce return sound even further. The added tee-junction takes advantage of further duct end reflection at low frequency. With the additional tee-junction, the duct lining could be reduced to one inch.

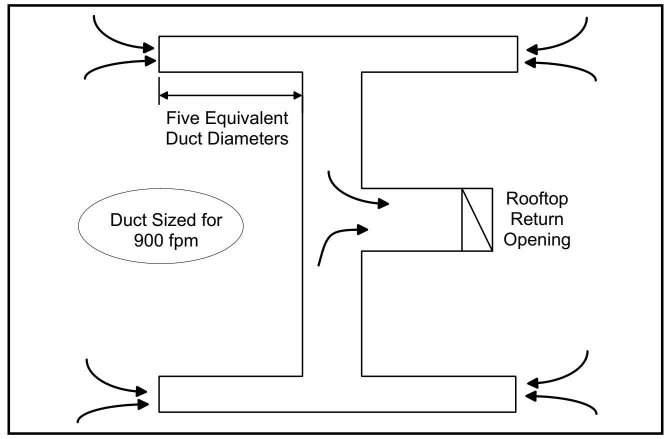

Figure 3: H-shaped return duct.

Return Duct Breakout

Adding ductwork to the rooftop-unit return opening creates a new sound path—the return duct. A portion of the sound traveling down the return duct breaks through the duct wall into the plenum area. From there, the sound travels through the ceiling into the occupied space.

The only thing new in this path is the "duct breakout" reduction, which is the transmission loss that occurs when sound passes through a duct wall. Duct breakout for a 15-ft (4.6 m) length of 22-gauge 25×50 duct is:

Return duct breakout	–5	–8	–11	–14	–18	–24	–30

When added to the other components, the return-duct-breakout path results in a space sound level of RC 11(RH) or NC 43. In general, increasing mass increases transmission loss. If need be, using a heavier gauge duct would increase the duct breakout transmission loss. But, for now, the return breakout path is near our acoustical target.

Supply Sound

Supply Duct Airborne

The supply-duct airborne sound path considers the sound traveling with the supply air from the unit, through the ductwork, out the diffuser, and into the room.

For this scenario, assume that 15 ft (4.6 m) of unlined, rectangular duct is attached to the discharge opening of the unit. A junction feeds a duct with secondary junctions at 10-ft (3 m) intervals to short runs that end at diffusers.

This path contains many more components than the return path. As a result, it is subject to additional variability and compounding of error. Nevertheless, as a starting point the ASHRAE algorithms yield an estimate of NC 49 or RC 59(H).

The RC (H) rating indicates that high frequencies predominate in this sound path. Therefore, a simple solution is to line the ductwork. Applying a 2 in. (50 mm) fiberglass lining to just the last 10 ft (3 m) of each runout to the diffusers yields NC 42 or RC 39(H) as shown in *Figure 4*.

If this were a VAV design, the VAV-box sound contributions would have to be included, too. VAV boxes add sound to the supply airborne path plus sound is radiated from the box casing. Moving the VAV box away from the rooftop unit would help reduce the sound directly below the unit.

Supply Duct Breakout

Duct breakout also occurs in the supply duct. For rooftop installations, supply duct breakout is often the critical (loudest) sound path. Path components are similar to the return breakout path except that the source is now the supply sound, which is typically louder than the return sound.

The manufacturer's supply data for the unit in this example are:

Supply sound power	99	95	91	91	89	87	82

If the supply duct has an elbow after it drops through the roof and continues as a single 25×100-in., 22-gauge unlined duct, the breakout transmission loss is:

Supply duct breakout	–3	–6	–9	–12	–18	–24	–30

Adding this loss to the other path components yields a supply breakout path of RC 41(R) or NC 65. Clearly, something must be done to attenuate the sound from this path. A reduction of 10 to 15 dB is required in the 63-Hz octave to approach the acoustical target.

A reduction of 10 to 15 dB is a considerable undertaking, but an even greater reduction might actually be required. As stated on Page 74 of ASHRAE's *Application of Manufacturers' Sound Data:*

> *These products are tested and rated under controlled laboratory conditions in a configuration specified by the applicable ARI test standard using in-line ductwork without elbows or tees, which differs from the typical configuration in field installations.*

and

> *Therefore, laboratory performance ratings of airflow, static pressure, and sound power will not usually be duplicated in a field installation unless the configuration of the inlet and discharge connecting ductwork approaches the laboratory conditions.*

The paragraph goes on to say that discharge effects can result in a 5 to 15-dB increase over the performance ratings. Mock-up tests and field surveys indicate that a very disruptive flow path is required to cause a 10-dB increase. Nevertheless, installation effects must be considered in the analysis.

Supply duct breakout is often the dominant sound path when rooftop units are placed over occupied spaces, since this is the shortest route from the source to the receiver. We can analyze some of the common approaches and the predicted results for attenuating the first three octave bands. The first is to add mass to the path by using heavier wall duct, lagging the duct, and using heavier ceiling tile. In the critical first three octaves:

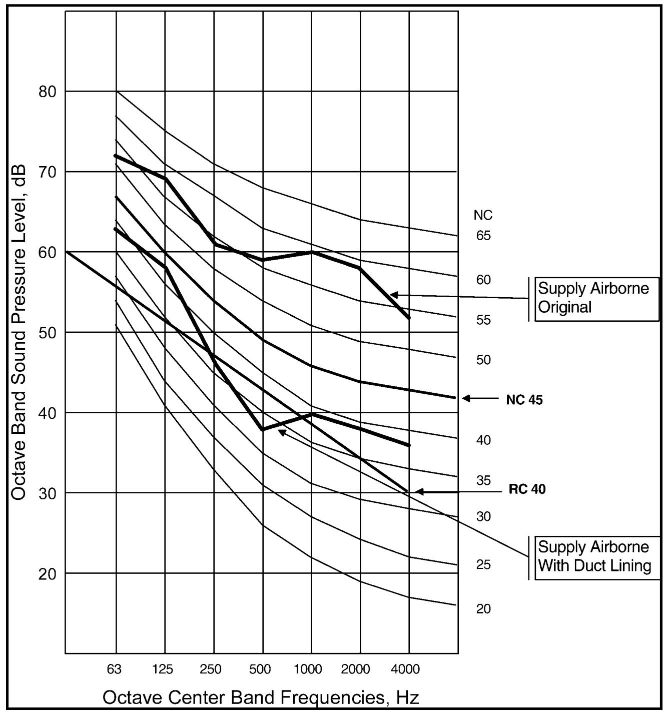

Figure 4: Supply duct noise.

Acoustical benefit by octave band	63	125	250
Increasing duct thickness from 22 to 16 gauge	–1	–6	–6
Lagging with two layers of 0.5 in. (13 mm) gypsum board over a 1 in. (25 mm) fiberglass blanket	–9	–4	–14
High-density acoustical ceiling tile	–1	–1	–2
Total reduction	–11	–11	–22

It is easy to see how frustrating sound attenuation can be. According to manufacturers' data and reasonable prediction methods, making all the changes listed earlier (at considerable cost) should bring the discharge breakout sound into the target range. However, when we account for the installation effects, the actual sound could still be unacceptable.

Another approach, using multiple runs of round duct, yields:

Acoustical benefit by octave band	63	125	250
Duct breakout for a single 25-in. (63 cm), 22-gauge spiral-wound round duct	–35	–35	–23

The reduction decreases if there is more than one duct because each duct is a sound source. In this example, the single rectangular duct is replaced by three round ducts. The two additional ducts add about 5 dB. Running the ducts in different directions could reduce this effect.

The results of the original and two alternate supply duct breakout analyses are shown in *Figure 5*.

A word of caution: Round duct reduces breakout by keeping the sound inside the duct. This may transfer a potential sound problem to a different location. If round duct is used, the supply airborne path should be recalculated. Using lined round duct can help, but it increases the size of the duct.

The transition to round should occur very close to the discharge opening of the unit, preferably at the discharge. If a rectangular duct with an elbow is used to drop through the roof and make the transition to the horizontal plane, these should be treated as separate sound paths.

Another way to reduce supply airborne sound in a rooftop HVAC installation is to add silencers. Silencers attenuate by absorption, so silencers typically remove more sound from high frequencies than low frequencies. Since low frequencies dominate the spectra for rooftop units, it is important to focus on the ability of a silencer to remove sound from the low-frequency octave bands.

Obviously, a silencer cannot attenuate ductwork upstream of itself. That duct should be checked for breakout. To reduce breakout from this upstream ductwork, the tendency is to place the silencer as close to the unit as practical. However, placing the silencer close to the unit introduces another problem: Silencer rating data (both insertion loss and pressure drop) are based on laboratory conditions that are rarely repeatable in an actual installation. Consequently, the acoustical effectiveness and the pressure drop of the silencer may be degraded.[3]

Adding silencers to a rooftop unit is rarely an effective way to reduce sound in the space directly below the unit. Fan sound increases when a silencer is used because the fan speed must be increased to overcome the pressure drop of the silencer. This, coupled with the limited effectiveness of silencers at low frequency, can even increase low-frequency sound in the occupied space.

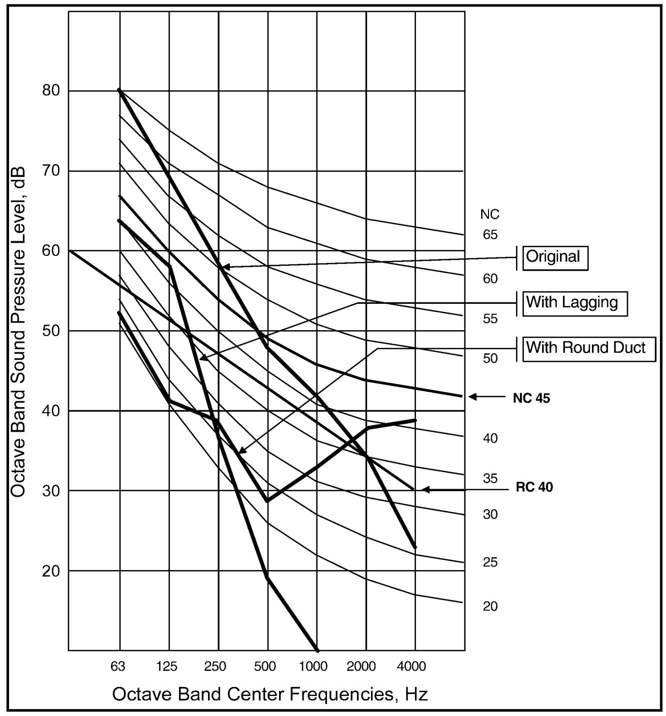

Figure 5: Supply duct noise with round ducts.

Roof Transmission Sound

Two roof-related sound paths must be considered in large rooftop HVAC installations:

• Sound radiated from the outdoor portion of the unit, which is transmitted through the roof deck, plenum, and ceiling into the occupied space.

• Sound radiated from the bottom of the unit, which is transmitted through the roof deck (or openings) under the unit, plenum, and ceiling into the occupied space.

Sound Radiated from the Outdoor Portion of the Unit

Analyzing this path begins with the outdoor-radiated sound power data from the manufacturer. The problem with determining how much of this radiated sound penetrates the roof is twofold: (1) A good algorithm to predict how much of the radiated sound from the unit reaches the roof does not exist, and (2) transmission loss data for lightweight, built-up roof decks is not readily available.

One way to model sound radiated from the outdoor section of the unit is to treat the outdoors as a large room and use the equipment-room-wall algorithm. The first step of this process predicts how much of the sound radiated from the rooftop unit reaches the roof deck. The second step accounts for the transmission loss through the roof.

Most of the sound that radiates from the unit travels into space and does not reach the roof deck. This part of the sound is approximated by modeling the outdoors as a very large room with absorptive surfaces.

Transmission loss values for the roof deck can be used directly if they are known, or approximated by determining the average mass per unit area and thickness.

The path is completed by adding a transmission loss for the ceiling and applying a room-correction factor. Using octave-band sound power and the method described earlier results in a sound level of NC 45 or RC 23(R). As shown in *Figure 6*, this path is low-frequency-driven. At this point, the roof transmission path is not out of line with the other paths; however, the potential error in these calculations is greater than for the other paths. If this path is to be attenuated, it is best done by adding mass to one of the path components. Gypsum board can be added above the ceiling tile, but this is difficult and reduces access. If the need to attenuate this path is known ahead of time, mass can be added by pouring a concrete pad around the unit. In general, the pad should extend at least 1.5 times the width of the unit.

Sound Radiated from the Bottom of the Unit

This path is not very complicated, but it is difficult to predict because identifying the strength of the source is difficult. It is not included in any of the three rated sound source components (outdoor, supply, and return). The sources of this sound are inside the unit cabinet. The sound is then transmitted through the bottom of the unit.

If the installation is done poorly, the entire roof area within the roof curb is cut out to provide easy access when attaching supply and return ducts. In this case, the only acoustical barrier between the bottom of the unit and the occupants is the ceiling.

In a better installation, a minimum amount of roof is cut away and the remaining cracks are caulked with an acoustical mastic. Additional mass can be added inside the curb to provide an even greater sound barrier.

To illustrate the importance of sealing cracks, let's review the equation that describes the average transmission loss of composite panels:

$$TL_c = 10 \log (1/\tau_{ave})$$

where,

$\tau_{ave} = (S_1\tau_1 + S_2\tau_2) / (S_1 + S_2)$
TL_c is the transmission loss of the combination
τ_{ave} is the average transmission coefficient
τ_1 is the transmission coefficient of Area 1
τ_2 is the transmission coefficient of Area 2
S_1 is the size of Area 1 (ft^2)
S_2 is the size of Area 2 (ft^2)

Suppose the roof deck beneath the unit is concrete and that openings will only be cut for the supply and return ducts. Concrete supplies a transmission loss of 35 dB in the 63-Hz band. If a 0.25 in. (6.5 mm) crack is left around each of the ducts:

$$\tau_{concrete} = 0.000316$$
$$S_{concrete} = 147\ ft^2$$
$$\tau_{opening} = 1.0$$
$$S_{opening} = 0.9\ ft^2$$
$$\tau_{ave} = [(147 \times .000316) + (0.9 \times 1.0)] / (147 + 0.9) = .0064$$
$$TL_c = 10 \log (1/0.0064) = 22\ dB$$

The example shows that a leakage area of less than 1% results in nearly a 40% reduction in the effectiveness of the barrier! When curbs are filled with several layers of gypsum board, it is critical to stagger and seal the joints between pieces and to seal the joints around the duct and between the duct and the curb.

Because the magnitude of the sound source inside the curb is unknown, it is difficult to predict the contribution of this path. Sound radiated from the bottom of the unit is probably less than that radiated to the outdoors. A conservative approach would be to treat the area under the curb in the same manner as the area surrounding the unit (e.g., if concrete is used outside, it should also be used inside). On every installation, it is critical to only cut away enough roof to accommodate the supply and return ducts and to seal all cracks with acoustical mastic.

Structure-Borne Sound

This path is unique because the source of the sound is structure-borne vibration. Vibration from the unit is transmitted to the building structure and then re-radiated into the occupied space. The fans and compressors generate vibrations that are transmitted to the frame of the unit. This energy can be transmitted to the structure of the building, where it follows various paths. Problems result when this energy vibrates a portion of the structure, causing audible sound.

Structure-borne vibration paths are difficult to assess. For most airborne paths, we can predict what is required to meet the established sound criteria. In the case of the vibrational path, it is best to install vibration isolation on every job.

ASHRAE's publication, *A Practical Guide to Noise and Vibration Control for HVAC Systems*, contains a list of design guidelines, including:

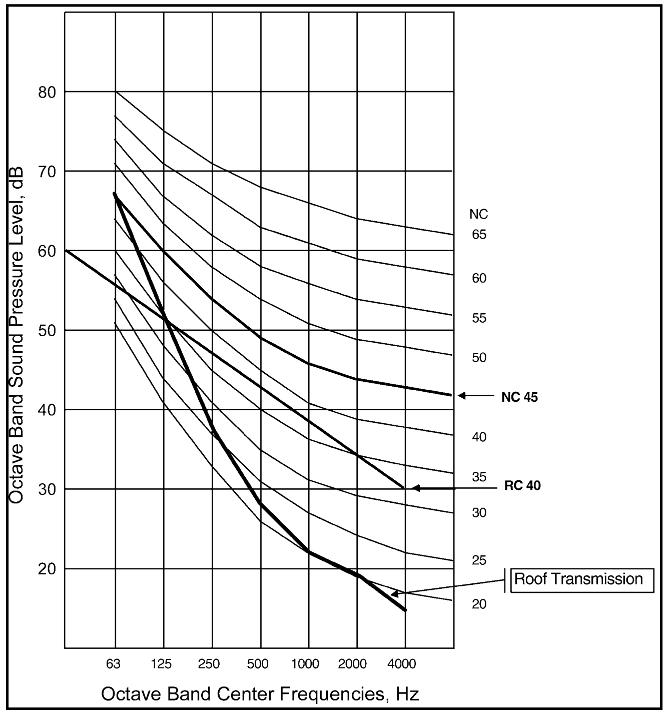

Figure 6: Rooftop unit outdoor noise.

The roof structure should be stiff enough to deflect no more than ¼ inch under the combination of the dead load and the operating load of the unit. This may require 20-foot column spacing in the vicinity of the unit.

And for units with cooling capacities of 20 tons (70 kW) and larger:

For installations over noise sensitive areas, mount the unit on high-deflection spring isolators resting on grillage that is supported 2 to 3 feet above the roof line by extensions of the building columns.

An ASHRAE paper, "Sound and Vibration Considerations in Rooftop Installations," suggests the following static deflections for the springs:

A rooftop unit, mounted on a good stiff roof, can use an isolation system with 1 or 2 inch static deflection on the springs. But a unit on a flimsy roof may require 3 to 5 inches of static deflection to achieve adequate vibration isolation because of the lower natural frequency of the flimsy roof.

Proper installation of the springs is just as important as properly specifying them. Spring effectiveness can be virtually eliminated by any of the following:

- Attaching an electrical conduit or a pipe to the unit and to the roof or curb.
- Placing any material (roofing tar, scraps of wood, etc.) between the bottom of the unit and the top of the curb.
- Applying horizontal pressure to the unit (misalignment) that causes the spring guides to make contact.
- Attaching ductwork to the unit without flexible connectors.

Summing the Paths

Suppose the example unit was properly isolated and that the area under the curb was installed so structure-borne and inside-the-curb sound paths can be ignored. If we sum the remaining paths, the result is:

Octave band, Hz	63	125	250	500	1000	2000	4000
Return airborne sound	61	59	43	15	9	8	5
Supply airborne sound	63	58	46	38	40	38	36
Return breakout sound	66	57	40	15	11	7	5
Supply breakout sound	52	41	39	39	33	38	39
(Roof) transmission sound	67	52	37	28	22	19	15
Sum	71	63	49	39	41	41	41

Note that this addition is performed with the procedure for combining decibels. The transmission losses, breakout losses, and other reductions calculated previously represent power reductions, so were added arithmetically.

The result is NC 50 or RC 40(RH) as shown in *Figure 7*. So, despite having added the following acoustical treatments…

- a tee and two 20-ft (6 m) runs of lined return duct
- round (rather than rectangular) supply duct
- lining on portions of the supply duct
- a well-sealed and filled curb
- carefully installed spring curb

…we are still considerably above our acoustical target for this job. If we were determined to place this unit above the occupied space, the next steps would be to: compare the "sum" listed above to the target RC 40(N) curve and note the difference, then compare octaves with the greatest difference to the individual paths to see which paths need to be addressed first.

Given enough iterations (and money), the acoustical goal for this installation could be met. At some point, the cost to meet the acoustical target should be reviewed to see if there is a more cost-effective way to achieve it.

As a side note, imagine if the unit was installed without regard for acoustics, and it was necessary to make the unit meet the acoustical goal. The expense required to retrofit the required solutions could exceed the cost of the unit!

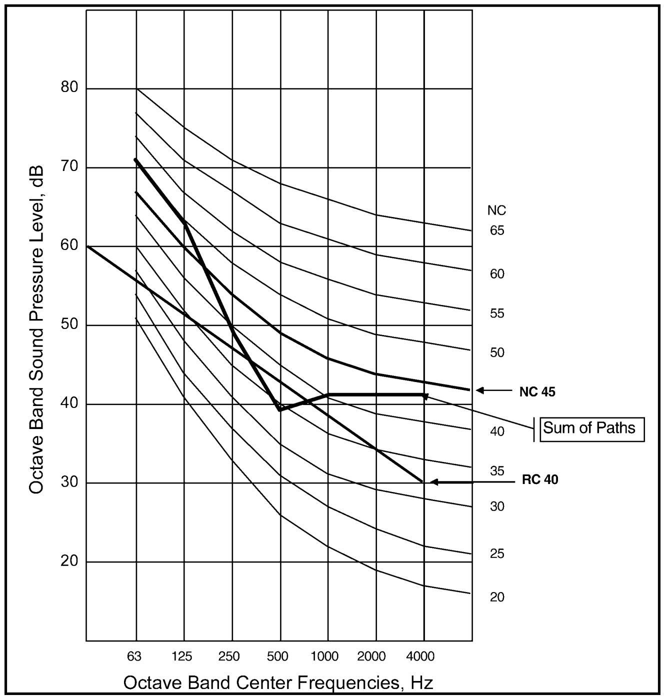

Figure 7: Sum of rooftop unit noise paths.

Closing Thoughts

Our example demonstrated that the cost-effective location for a large, commercial rooftop unit is *not* over a sound-sensitive area. The money saved in ductwork is more than offset by the cost of acoustical treatment. The unit in the example was of medium size. Rooftop units with more than twice as much capacity (that output considerably more sound) are available. Since they are a concentrated sound source, *it is best to place rooftop units away from areas where sound is a concern*. Several ways exist to incorporate this precept when designing rooftop HVAC installations. The following suggestions are roughly ranked in descending order from better acoustical effect/lower cost to less acoustically effect/higher cost:

- **Locate units over utility areas, service areas, bathrooms** and other areas where sound is not a concern. Run supply ducts (lined if necessary) over these areas before entering areas where sound is a concern. Split the supply duct into multiple ducts and take off in different directions from the noncritical area.
- **Elevate the unit on a structure supported by the building steel** if the unit must be over a sound-sensitive area. This approach: 1) moves the compressor and condenser-fan sound sources away from the roof deck; 2) there is no "area under the curb;" 3) some of the low-frequency sound breaks out of the supply duct above the roof; 4) structure-borne paths are less often a problem; and 5) perhaps most important, the straight run of supply duct from the bottom of the unit lets some of the fan-generated air turbulence settle before any duct elbows are encountered.

In some cases, an extended-height acoustical curb can be used. This curb not only moves the unit farther from the roof, but includes lined plenums that absorb sound and permit some of the turbulence to settle. The solid bottom of these curbs also provides an additional barrier to sound transmission through the bottom of the unit.

- **Run supply and return ducts on top of the roof in lined, thin-walled duct before penetrating the roof.** This allows areas under the unit to be completely sealed. It moves the supply and return duct sound sources away from the roof and minimizes curb-transmitted noise. The straight runs above the roof also allow air turbulence to settle, while the lining and thin duct walls provide attenuation and low-frequency breakout, respectively.

It is virtually impossible to provide a list of design practices that always yield an acoustically successful rooftop HVAC installation…there are simply too many variables. It would most likely result in more money being spent than necessary, too.

Caveats are the difficult-to-predict paths for vibration transmission and under-curb sound. The benefits of proper isolation and good roof treatment on the original installation far outweigh the cost of adding these treatments after the unit is installed.

For the other sound paths common to all large rooftop jobs, use an acoustical analysis to find the least expensive method for meeting the acoustical goals.[4] Techniques for quieting each sound path can be found in various references, including ASHRAE publications, and publications and support provided by the manufacturers of rooftop products.

Notes

1. It is critical to start with good sound data. Two key points are to know the type of data (sound power or sound pressure) and how the data were derived. The difference between sound power and sound pressure is described in many publications. A particularly good reference is the ASHRAE *Application of Manufacturers' Sound Data* (Chapter 2, page 13). Chapter 6 provides additional information on sound ratings for rooftop units and recommends how to use the data.

2. Duct end reflection loss describes a phenomenon that can significantly reduce the low frequency sound leaving a section of straight duct. Additional information can be found in Chapter 46 of the *1997 ASHRAE Handbook—Applications*.

3. Chapter 7 of *Application of Manufacturers' Sound Data* provides a complete description of these effects and includes tables that can be used to estimate their impact.

4. ASHRAE provides the equations needed to make these calculations in *Algorithms for HVAC Acoustics*. The algorithms can be entered in a spreadsheet or purchased in a commercial software application.

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