Understanding Speech Intelligibility and the Fire Alarm Code

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Summary

Major International, European, and North American fire alarm codes now require that voice alarm systems meet minimum levels of speech intelligibility. The new codes and standards have spawned the need for education about the basics of intelligibility, and for tools to ensure that voice alarm systems are designed for good intelligibility, can be measured for compliance at the time of commissioning, and can be periodically tested during the life of the system.

The basics of speech intelligibility are reviewed here, including the factors that affect intelligibility in typical situations. In addition, the various methods for measuring speech intelligibility are discussed, together with techniques for predicting intelligibility in advance of building construction or equipment installation. Finally, many of the practical considerations fire alarm professionals will face in managing the intelligibility requirement are presented.

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0. Introduction

Voice alarm systems are meant to inform and instruct building occupants in the event of an emergency. Their use is based on strong evidence in two areas: 1) occupants often ignore audible and visual alarms but will obey a voice command, and 2) alarms have extremely limited information content (on or off) whereas voice can be used to deliver a wide range of potentially life-saving information.

For a voice alarm system to be effective, it must be intelligible. In fact, it is fair to argue that good intelligibility is the single most important requirement for a voice alarm system. It is unlikely that occupants will act as desired if the intelligibility of the system is poor. They may panic when they should remain calm, or evacuate when they should remain in place, for example.

For many, however, the subject of speech intelligibility is a relatively new one. Fortunately, the field of speech intelligibility has been a very active one both scientifically and commercially for the past 25 years. There are today a number of proven methods for quantifying intelligibility. There are tools for predicting intelligibility in the design stage of a project, and for measuring it after installation is complete. All of this know-how is immediately applicable and available to the fire alarm industry.

This paper draws on the years of scientific research and commercial experience in an effort to give the reader a basic appreciation of speech intelligibility. The goal is to provide a theoretical (but not overly technical) foundation, together with a discussion of the practical considerations fire alarm professionals will encounter as they address the speech intelligibility requirement in their work.

1. Factors Affecting the Intelligibility of Voice Alarm Systems

Speech intelligibility is not a physical quantity like Amperes, Volts, or BTU's. It is a measure of the degree to which we understand spoken language, and as such is a complex phenomenon affected by many variables.

1.1 Audibility does not imply intelligibility

Speech is not necessarily intelligible simply because it is audible. Having enough speech level is a necessary, but not sufficient condition for good intelligibility. Just like adding more light to blurry text doesn't make it more readable, adding more sound level to speech that has been blurred by reverberation, echoes, or distortion does not make it more intelligible. A loud enough, but overly reverberant speech signal can be almost completely unintelligible, to which users of many airports, train stations, and places of worship can easily attest.

This fundamental fact – that audibility does not imply intelligibility – explains why the NFPA and other organizations throughout the world have taken the important and appropriate step of creating a separate requirement for speech intelligibility.

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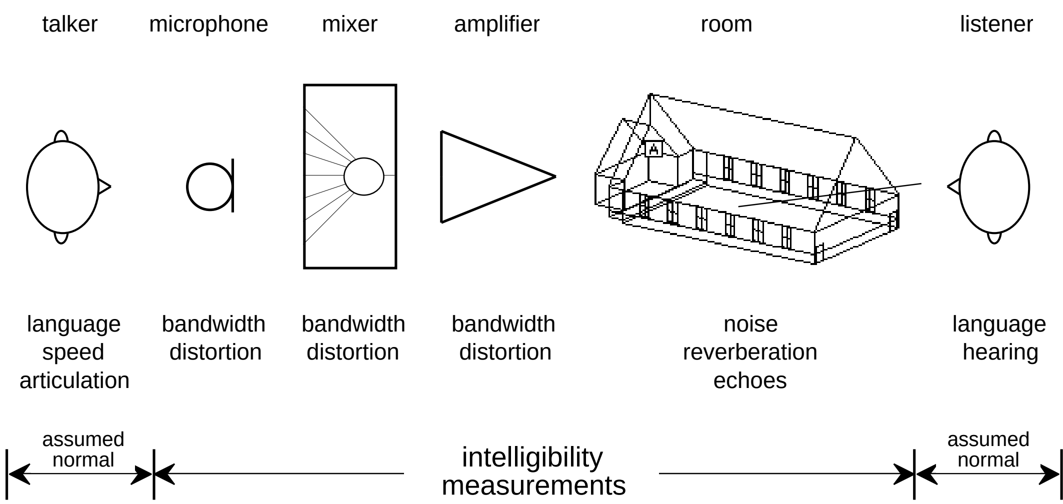
1.2 Talker-to-listener transmission path

To understand the major variables that affect intelligibility, it is helpful to consider the talker-to-listener transmission path as a system, as shown graphically in the figure below.



In standardized speech intelligibility testing the talker-to-listener transmission path is measured with certain assumptions made about the talker and listener. For example, it is assumed that the talker speaks without accent or speech impediment. It is assumed he or she speaks at a normal speed and with normal emphasis of words. Similarly, it is assumed that the listener has normal hearing ability, and does not have any language-based disorders.

This approach is similar to how cars are tested for their published mileage ratings. Assumptions are made about the road conditions, driver ability and more. These variables are fixed in the interest of measuring the performance of the car itself. In the case of intelligibility, talker and listener variables are fixed in the interest of measuring the performance of the transmission path from talker to listener. In both cases, the actual performance (mileage or intelligibility) will vary, especially if the assumptions made about the talker and listener can not be met in practice.

There are situations where it is known *a priori* that not all listeners will share the language of the talker as their first language – an international airport for example. Similarly, there are situations where the normal loss of hearing with age (presbyacusis) can be assumed, as in the case of an assisted living facility. In these situations, and others like them, special considerations must be made in order to ensure an acceptable level of speech intelligibility. (This subject is addressed in Section 6.) But for the vast majority of situations, it is sufficient to assume normal talker and listener performance and a common first language.

1.3 Message content and delivery

The subject of speech intelligibility does not include the content or intent of the message itself, which is nevertheless an important variable affecting the overall effectiveness (but not the intelligibility) of a voice alarm system. Fire industry professionals are justifiably

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concerned about the messages themselves. A perfectly intelligible voice alarm system will do nothing to produce the desired occupant behavior if the message is inappropriate or is delivered in an inappropriate manner. The issue of message content and delivery, while outside the scope of this paper, is vital to the effectiveness of voice alarm systems, and deserves the same level of attention as the subject of speech intelligibility.

1.4 Factors related to the talker-to-listener transmission path

To review, talker and listener abilities are assumed to be normal in standardized speech intelligibility testing in order to focus on the variables within the transmission path from talker to listener. Second, message content and delivery is a major determinant of the *effectiveness* of a voice alarm system, but not the *intelligibility*.

Thus the variables, or factors affecting speech intelligibility are those that affect the voice signal just after it has left the talker, through to the moment just before it enters the ear canals of the listener. The factors that can corrupt the integrity of a voice signal on its path from talker to listener are summarized below:

- Speech-signal-to-noise ratio. Noise has the effect of masking or obscuring the voice signal. Remarkably, we are able to tolerate a great deal of noise before intelligibility diminishes appreciably, but once it begins to diminish, it diminishes rapidly.
- Reverberation. Most are familiar with how difficult it can be to understand speech in a reverberant environment such as a cathedral or gymnasium. Reverberation is made up of sound reflections that have the effect of smearing, or blurring speech, making it less clear and distinct and therefore more difficult to understand.
- Echoes. If echoes arrive much later in time than the first arrival of sound, they can harm intelligibility. In continuous speech, the echo from a previously uttered syllable masks or obscures the sound of subsequent syllables, making speech more difficult to understand. The time delay and level of the echo are key variables in determining the impact of echoes on intelligibility.
- Distortion. If one of the electrical or electro-acoustical components in the sound system is distorting, it is generating a form of noise that masks the original speech signal. Severe amplifier clipping, for example, can make an otherwise perfect speech signal at the input to the amplifier more difficult to understand at the output.

To accurately account for the effect of these factors, they must be measured in at least octave-band resolution. A single broadband measurement is insufficient and more than octave band resolution is almost always unjustified.

2. Methods of Measuring Speech Intelligibility

A number of methods for quantifying the speech intelligibility of a talker-to-listener transmission path have been approved for use by major international organizations, and are referenced in the appendix of the fire alarm code (NFPA 72). Some of these methods are based on the measurement of physical quantities such as speech and background noise levels, and others are based on subject-based testing where specially-designed word lists are read and subjects write down what they think they heard. The former class will be called *quantitative methods*, and the latter *subject-based methods*. Below is a summary of the major methods.

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- Speech Transmission Index (STI): This is a quantitative method. Its measurement is covered in the International Electrotechnical Commission (IEC) standard 60268-16. Note that several timesaving methods for measuring the STI are given in the standard.
- Articulation Index (AI): This is a quantitative method. Its measurement is covered in the American National Standards Institute publication ANSI S3.5-1969 (R 1986).
- Articulation Loss of Consonants: This is both a quantitative method, and a subject-based method. The quantitative method has been published, but neither the quantitative nor the subject-based measurement has been standardized.
- Phonetically Balanced Word Scores: This is a subject-based method. Its measurement is covered in the American National Standards Institute publication ANSI S3.2 (1989) and the International Organization for Standardization publication ISO/TR 4870.
- Modified Rhyme Test: This is a subject-based method. Its measurement is covered in the American National Standards Institute publication ANSI S3.2 (1989).

2.1 Subject-based methods

The subject-based methods are used mainly in academic research, or in rare cases, to resolve a dispute over the performance of an installed audio system. Researchers trying to develop new insight into how a particular variable affects speech intelligibility would, for example, use one of the subject-based methods.

The subject-based methods are difficult, tedious, and expensive to carry out. For example, hundreds, even thousands of words must be used in a single test location before a reliable result can be obtained. Trained talkers and listeners must be used. Great care must be taken to avoid experimenter or subject bias. And the environment in which the test is given has to be carefully controlled, which is often difficult or impossible to accomplish in an operating facility. In general, conducting subject-based tests requires a skill level not often present outside of the sciences.

Finally, these methods can not be used at all when the task is to predict the intelligibility in advance of building construction or equipment installation; if there's no building constructed yet, or no equipment installed, there's nothing to which subjects can listen.

2.2 Informal subject-based methods

It should be stressed that an informal approach to subject-based testing will lead to inaccurate results at best, and wildly misleading results at worst. One cannot quantify the speech intelligibility of a voice alarm system, for example, by reading the newspaper over the emergency microphone and asking people to say, or write down, what they hear. There are numerous problems with such approaches, chief among them the following:

- A robust subject-based method controls the variables that are known to affect intelligibility. For example, the talker in a subject-based test should not be known to the subjects, and vice versa, since that condition can't be expected during normal use of the sound system. If the talker is known to the subjects, the intelligibility scores will be unrealistically high simply because of the listeners' familiarity with the talker's diction, cadence, accent, etc.

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- Enough subjects must be used to accurately represent the population at large. Using one or two subjects does not meet this requirement.
- Enough words must be used to ensure that an accurate and precise result is obtained; to use results from an informal test that uses only a few words is to ignore the basics of using data that are inherently statistical in nature.
- Because the variables that affect intelligibility are not controlled in informal subject-based tests, the results are not repeatable. A good subject-based test must produce the same result (or very nearly the same result) when conducted under similar conditions at a different time or place. Informal methods fail to meet this most basic requirement.
- Bias almost always enters into informal tests. The talker, subjects, or both usually have a stake in the outcome, and even with the best intentions of remaining objective, humans act differently and different results are therefore obtained under such conditions. As numerous scientific studies have shown, bias far subtler than what would be encountered in an informal test of speech intelligibility has been found to significantly skew results. To ignore these effects in the case of speech intelligibility testing is to ignore overwhelming evidence about the distorting effect of bias on experimental results.

Having said this, the intent here is not to discourage informal listening to voice alarm systems. To the contrary, these listening sessions build valuable intuition, experience, and insight. But informal subject-based testing should never be used as a means to quantify speech intelligibility in a repeatable and legally defensible manner. If a subject-based test is to be used, a standardized method should be employed by skilled professionals following the rules established for obtaining bias-free results.

2.3 Quantitative methods

Because subject-based tests are so difficult to conduct, and because informal subject-based tests fail in fundamental ways to produce reliable, repeatable, and unbiased results, researchers have worked since at least the middle of the twentieth century to develop methods of measuring speech intelligibility that are based on the measurement of acoustical quantities, rather than the use of subjects. For example, scientists at Bell Laboratories wanted a method to test the intelligibility of telephone equipment quickly and repeatably without the need to carry out expensive subject-based tests. Eventually, the quantitative method now known as the Articulation Index was proven effective.

The basic idea behind any of the quantitative methods is to attempt to correlate measurements of physical quantities varied under experimental conditions to speech intelligibility scores obtained using subjects. If good correlation can be found over a range of situations that cover the intended application, then that same physical quantity can be measured in some new situation and the correlation used to determine the speech intelligibility. For example, experimenters found that they could measure the speech signal and background noise in telephone systems and from this measurement accurately predict what subjects would score on one of the standardized subject-based tests.

The appendix of NFPA 72 points to the use of three quantitative methods: the Speech Transmission Index (STI) method, the Articulation Index (AI) method, and the Articulation Loss of Consonants (Alcons) method. The first two have well-documented

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standards that specify how the measurements are made. The third has a journal article but no standard.

The AI method was developed for situations where signal and background noise levels are the dominant factors affecting intelligibility – telephone systems, for example. The AI method, however, does not account for the effects of room acoustics, such as reverberation or echoes, or the effects of non-linear distortion, say from an overloaded amplifier. For these reasons, it is probably not a good general-purpose choice for voice alarm systems, since reverberation, echoes, and distortion are all factors that can easily exist in typical environments.

The AI method has recently been updated, and the name of the quantity measured changed to reflect the enhancements made. It is now called the Speech Intelligibility Index (SII) and is documented in an ANSI standard (S3.5-1997). The SII method accounts for several of the factors that the AI ignored, such as reverberation.

In part as a result of the weaknesses in the Articulation Index method, the military and others began funding the research and development of a quantitative method of measuring speech intelligibility that was more comprehensive – one that could measure a system that had virtually any combination of the factors commonly found to affect speech intelligibility. The work that eventually led to what is now called the Speech Transmission Index method was started in the 1970's at a well-known research laboratory called TNO in the Netherlands, mainly under NATO funding.

The STI method is based on a fundamental insight about how speech can be deconstructed into component parts and the effect of virtually all factors seen in one single type of measurement. The method proved robust under a wide array of conditions – from a talker in a room, to a telephone system, to a large PA system. The STI method has been implemented in a number of commercially available devices, and is today an international standard used extensively throughout the world.

2.4 The Common Intelligibility Scale (CIS)

Regardless of which speech intelligibility measurement is used, subject-based or quantitative, there are times when it is valuable to relate the results obtained from one measurement to those that would be obtained from another. For example, if an STI value of 0.50 were measured, what would the corresponding score be if the Phonetically Balanced Word List method had been used? To answer questions like these, and to recognize the value of the different methods for measuring speech intelligibility, the International Electrotechnical Commission (IEC), which publishes the speech intelligibility standard referred to in the appendix of NFPA 72, contains a graph relating most of the measurements to a single scale called the Common Intelligibility Scale, or CIS.

A reproduction of the graph relating the various measures of speech intelligibility from IEC 60849 is shown below.

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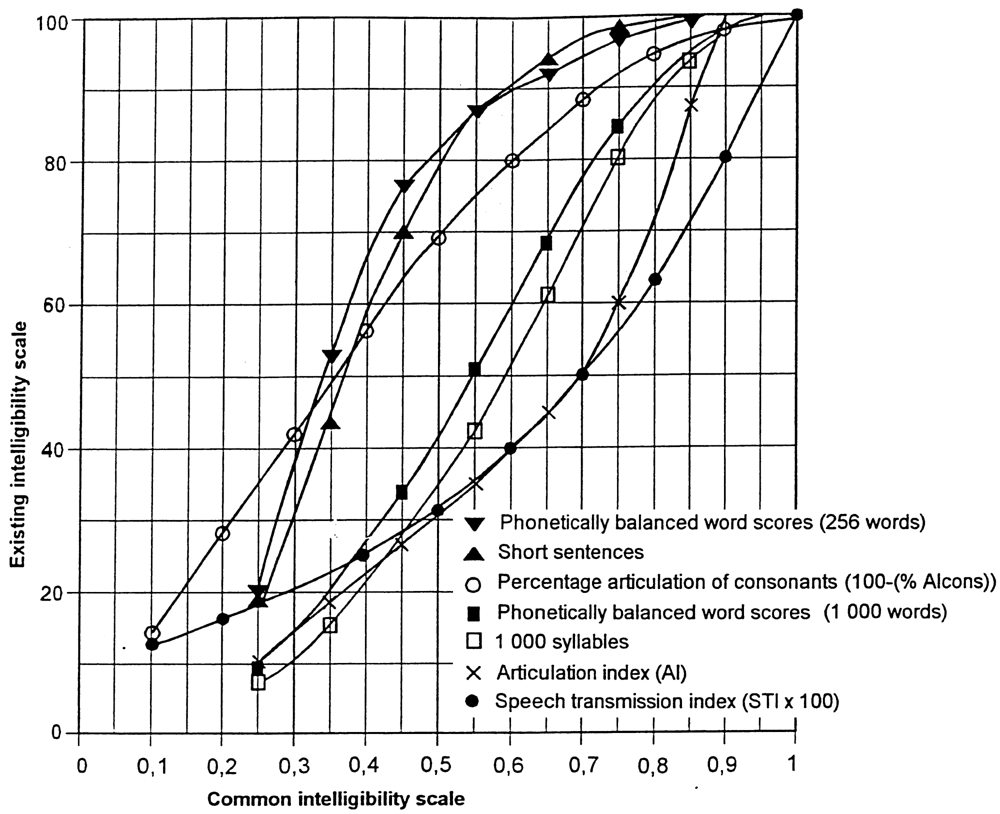

3. Understanding the Speech Transmission Index (STI)

Of all the methods for measuring speech intelligibility, the STI has an advantage in that it correctly accounts for all of the factors in the talker-to-listener transmission path that affect intelligibility, and is relatively straightforward to carry out. The method is based on the idea of replacing speech with a repeatable signal that has the same characteristics of speech insofar as intelligibility is concerned, and then measuring the corruption of that speech-replacement signal by the transmission system. In the section that follows, a basic explanation of the STI method is given.

3.1 Critical elements of real speech

Speech is composed of (among other things) two spectra. The first is the *audible spectrum* – the speech sounds we hear. The audible spectrum occupies a wide range of frequencies from about 100 Hz to 10 kHz, which can be represented by the seven octaves whose center frequencies range from 125 Hz to 8 kHz. The audible spectrum of speech is not flat; there is more energy in the lower-middle frequencies, for example, than the higher frequencies.

Speech, however, is not composed only of sound over the seven octave bands from 125 Hz to 8 kHz. The sound we hear in speech is organized into language packages – words, or the even smaller packets that make up words, called phonemes. Our rate (frequency) of

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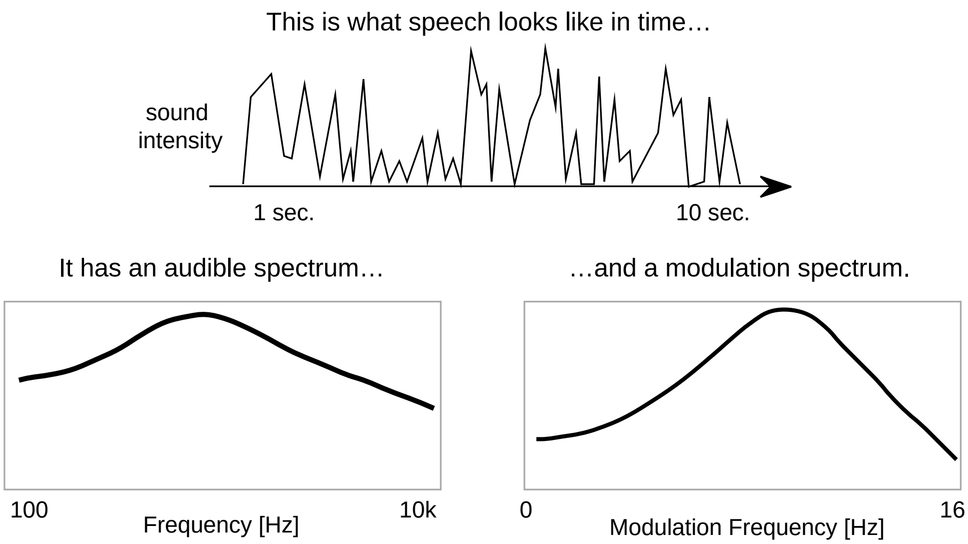
phonemic production is much lower than the audible frequency range. It turns out we can only utter a few phonemes per second, which corresponds to a few Hertz.

The audible sounds from our vocal chords and mouth, organized into packets of phonemic information, can be modeled by amplitude modulating a wide-band signal. Thus the second spectrum in speech, the low-frequency spectrum that defines the rate at which we utter phonemes, is called the *modulation spectrum*. The modulation spectrum can be represented by fourteen frequencies spaced at one-third octave intervals ranging from 0.63 to about 16 Hz. This spectrum is also not flat. We tend to say phonemes more at the middle modulation frequencies rather than the very low or very high frequencies.



3.2 Simulating speech

The fact that real speech can be decomposed into two spectra, the audible spectrum and the modulation spectrum, can be used to construct an artificial speech signal that has the same properties. The audible spectrum can be modeled using a wide bandwidth noise signal comprised of the seven octave bands from 125 Hz to 8 kHz, each octave having a level that matches that of real speech. The individual octave bands of noise can then be modulated according to the fourteen frequencies in the modulation spectrum.

To see how this works, consider just one of the octave bands from the audible spectrum – say the 1 kHz band – and one of the frequencies from the modulation spectrum – say 4 Hz.

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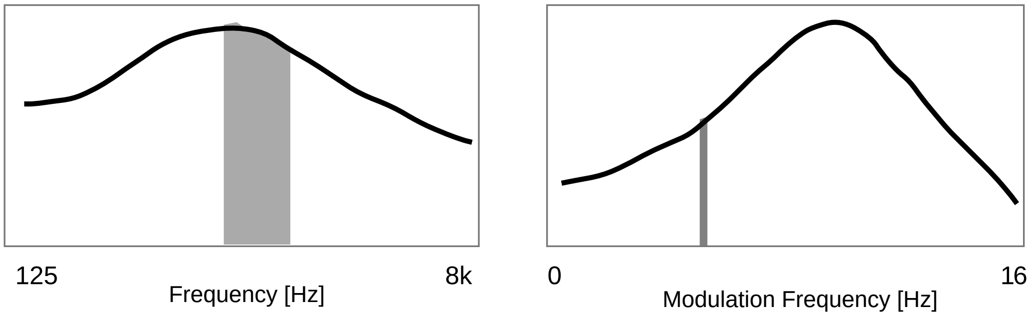
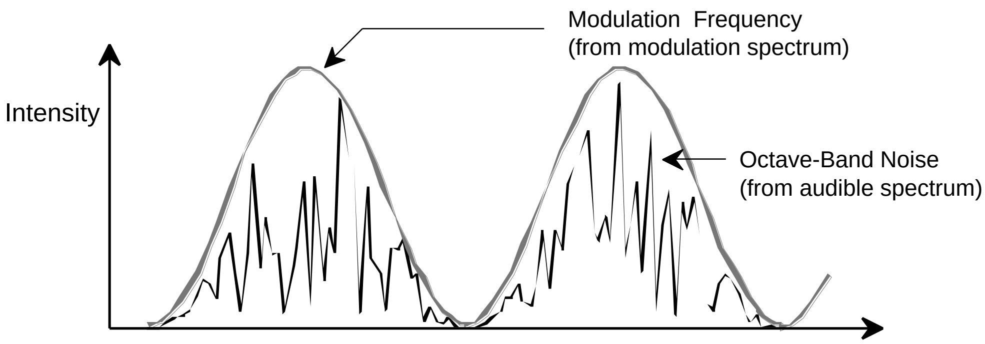


① Take one octave band from the audible spectrum…

② and one frequency from the modulation spectrum…

③ Then use ② to amplitude modulate ①.



To fully represent speech, not only this combination is needed, but all of the various combinations: seven octave bands from the audible spectrum times fourteen frequencies from the modulation spectrum for a total of 7 x 14 = 98 different combinations. To test a system, these modulated octave bands are used as the test signal instead of speech.

3.3 Corruption of speech

There are a number of factors that can corrupt speech intelligibility (see section above). These corruptions occur as the speech signal is passed from the input of the system through any electronics and then through the acoustical space to the listener's ears. Just as these distortions occur on real speech signals, they also occur when the artificial speech signal consisting of the modulated octave bands is substituted. These distortions, such as background noise and reverberation, have the effect of diminishing the amount of modulation present in the original speech signal or in the artificial speech signal, and this modulation reduction is a measure of the loss of speech intelligibility.

Consider, for example, the effect of background noise. Background noise in the transmission path between talker and listener has the effect of filling in the troughs of the originally modulated signal. The reduced modulation at the output is a measure of how much the speech has been corrupted by the background noise.

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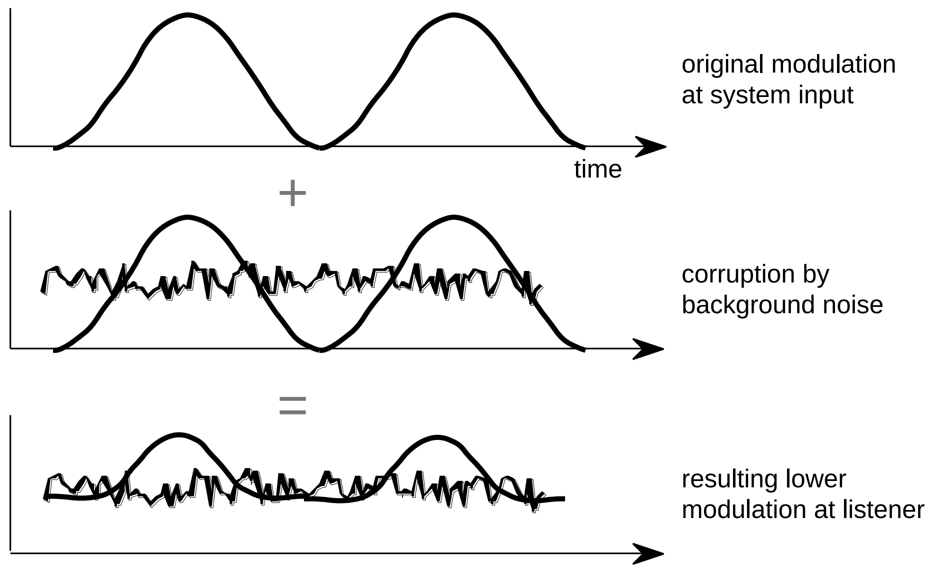
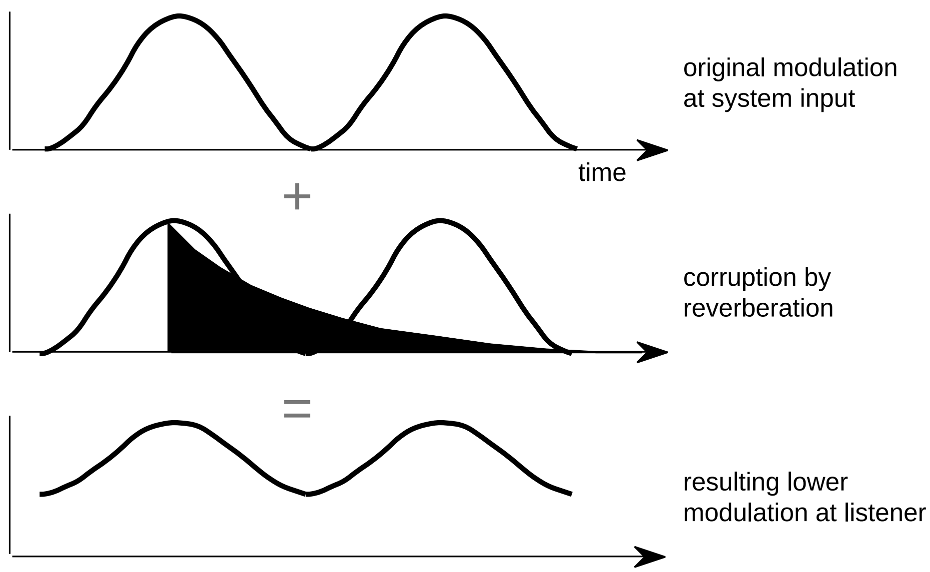


Reverberation also has the effect of diminishing the amount of modulation originally present at the input to the system.



3.4 Other forms of speech corruption

In the examples above the effect of background noise and reverberation on the original modulation in uncorrupted speech was shown. The same thing occurs when a speech signal, or the artificial speech signal made up of the modulated octave bands, is corrupted by most forms of non-linear distortion.

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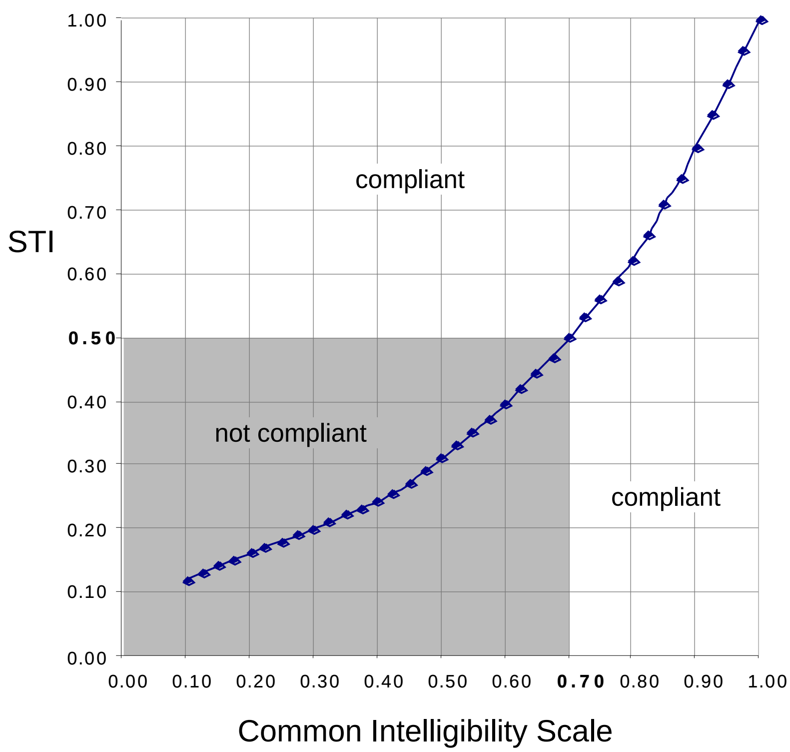
3.5 The Speech Transmission Index & the Common Intelligibility Scale

The Speech Transmission Index, or STI, refers to the amount of modulation preserved in the transmission of the artificial speech signal through a system. It is a single number between zero and one and accounts for the modulation preserved over all of the combinations of octave bands from the audible spectrum and modulation frequencies from the modulation spectrum. In many cases, not all of the 98 combinations (seven octave bands times fourteen modulation frequencies) need be measured to obtain an accurate measurement of speech intelligibility. The IEC standard for measuring the STI (IEC 60268-16) specifies a number of ways to limit the number of combinations under typical conditions. The STI is computed by performing a specially weighted average of the remaining modulation in the various combinations of octave bands and modulation frequencies.

An STI of 0.00 means that none of the original modulation remains; it has been completely obliterated by some combination of background noise, reverberation, and other forms of distortion. This corresponds to speech intelligibility of zero. An STI of 1.00 means that all of the modulation present at the input of the system has been preserved, and speech is perfectly intelligible.

The STI can be related to any of the other measures of speech intelligibility through the Common Intelligibility Scale. That relationship is shown in the figure below.



The appendix of NFPA 72 calls for a minimum intelligibility of 0.70 on the CIS scale, which corresponds to an STI of 0.50. A voice alarm system performing at or above either

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of these values constitutes a compliant system. It should be noted that a CIS of 0.70 is far from perfect intelligibility. It corresponds to about 80% word intelligibility, and about 95% sentence intelligibility, which has been shown to be slightly higher than what is required to reliably and accurately transmit an emergency message.[1] The same level of intelligibility for a sound system used for non-emergency purposes would often be considered barely acceptable.

4. Putting Speech Intelligibility into Practice

At this point, it is hoped that the reader has a basic understanding of speech intelligibility, of how speech intelligibility is measured, and of the most comprehensive and commonly used of the various measurement methods: the Speech Transmission Index. Most readers by now may also have a number of unanswered questions about how the new speech intelligibility requirements are met and measured in practice. In this section, therefore, we examine issues of practical importance to members of the fire alarm industry – voice alarm system engineers, system contractors and local fire officials – when it comes to the every day use of speech intelligibility in their work.

4.1 Design tools

Designing sound systems for sufficient intelligibility has been a focus in the professional and commercial sound industries for at least fifty years. Numerous journal articles over this period describe how factors encountered in real-world situations affect intelligibility, and have defined design strategies proven to produce higher intelligibility scores.

As a result of this large body of work, a number of commercial tools have been developed to aid the sound system designer wishing to achieve a certain level of intelligibility. In addition, a number of training seminars exist both from manufacturers and from independent educational institutions that address the subject of designing for acceptable speech intelligibility. All of this information and all of these tools are suitable with little or no modification to the purpose of designing intelligible voice alarm systems.

Readers who wish to learn more about the various tools and educational seminars are encouraged to contact the National System Contractor Association (NSCA), the leading organization for manufacturers and contractors concentrating in the field of commercial and professional sound.

4.2 High intelligibility does not require high fidelity loudspeakers

A concern expressed by some in the voice alarm industry is that the new speech intelligibility standards will mean that more expensive, higher fidelity loudspeakers will be required. Intelligibility, however, is not the same as fidelity. A telephone, for example, has a very limited bandwidth (approximately 300-3,000 Hz) that means it is far from high fidelity. And yet the telephone is almost 100% intelligible. Similarly, the limited bandwidth speakers currently used in voice alarm systems are also of sufficient bandwidth to achieve high intelligibility, if not high fidelity. The sound of fire alarm

[1] See, for example, ISO Technical Committee 159, Sub-Committee 5, Working Group 3 draft standard, available on request.

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speakers may not be very pleasing because of their relatively poor fidelity, but that doesn't mean they can't be effective in conveying a message.

It is the misapplication of speakers – regardless of their fidelity – that usually leads to poor intelligibility. For example, the use of small non-directional cone speakers in a large reverberant room is unlikely to lead to acceptable intelligibility. Similarly, voice alarm speakers placed too far apart in a large meeting room may not meet the minimum requirement, nor would speakers that are badly overdriven by excessive amplifier power.

This is not to say that there will be no circumstances when the design required to meet the intelligibility standard is more expensive than what would have been designed in the past to meet only the audibility requirement of NFPA 72. There may be cases, for example, where closer speaker spacing is required. But these are the cases where added expense is entirely justified since by definition the design for audibility alone would have been insufficient to reliably warn and inform occupants in an emergency.

4.3 Measurement tools

There are a number of general-purpose acoustical measurement tools that have as one of their functions one of the standard speech intelligibility measurements. Again, the National System Contractors Association (NSCA) is a good source of information on these tools.

These general-purpose measurement tools are powerful because they can be used to make many different kinds of measurements, not just speech intelligibility. They also require a substantial amount of skill and training on the part of the user to set up and use properly. Moreover, these tools represent a significant investment for the users, typically several thousand dollars for the computer, several thousand dollars more for the software, and perhaps a thousand dollars more for the cost of training.

At least one instrumentation manufacturer has announced the introduction of a measurement tool designed to make accurate and reliable measurements of speech intelligibility in about 10 seconds, based on the Speech Transmission Index method. The CIS score called for in NFPA 72 can be obtained by standing at the test location with the instrument, and pressing one button to start the test. The instrument does not need to be attached to the system input, freeing the user to roam anywhere within the protected space to make a measurement. The goal of such an instrument is to allow users untrained in acoustical measurements to test a system for compliance with the code, in much the same way that a dB meter is used today to test the audibility requirement.

A schematic of how a simple-to-use speech intelligibility meter would be used is shown in the following diagram.

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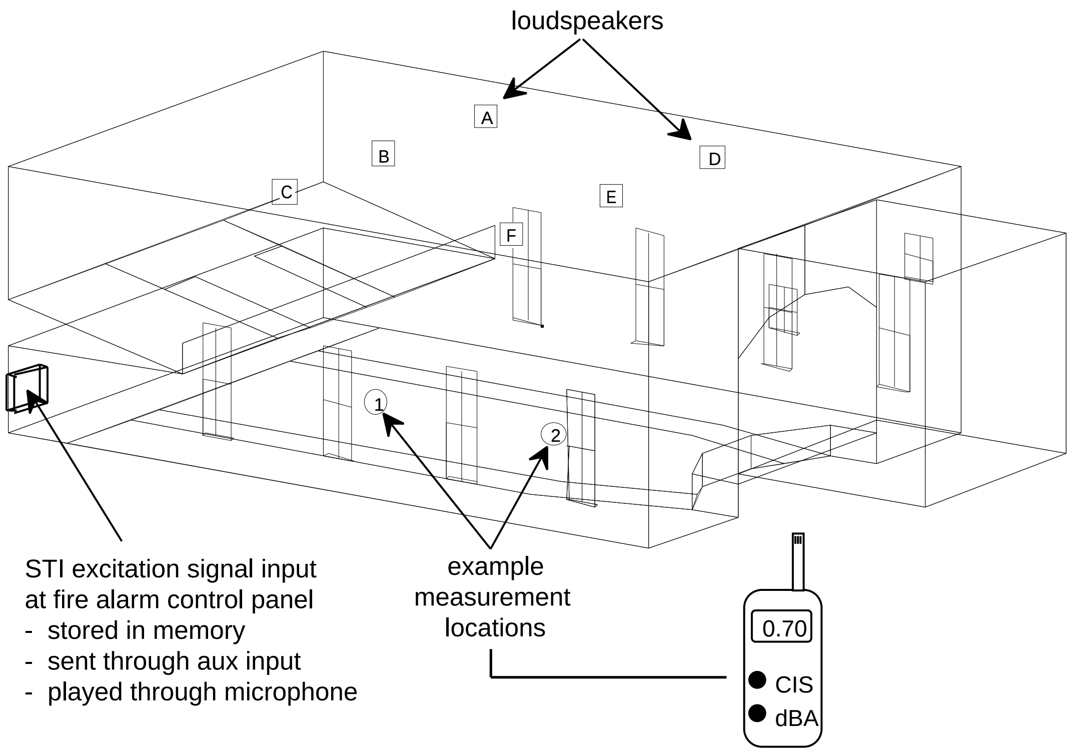

4.4 STI measurement tool calibration

While minimum or better speech intelligibility is now required by codes and standards throughout the world, and while instruments exist to make reliable and accurate speech intelligibility measurements, there exists no standard for the instruments themselves. Just as it took several years for such a standard to emerge for sound level meters (ANSI S1.4-1983 R 1997) the same can be expected for speech intelligibility measurement tools. Until then, instrument manufacturers and users must share the burden and responsibility for ensuring that their instruments are capable of making accurate and reliable measurements. There are two basic means for accomplishing this important goal.

First, the measurement tool manufacturer can supply pre-made audio signals that represent speech intelligibility under various conditions of noise, reverberation and distortion. These calibrated situations can be input directly to the measurement tool to test whether the expected speech intelligibility is in fact obtained. If it is not, the tool is known to be out of calibration and should be returned to the manufacturer for repair.

Second, a program whereby speech intelligibility measurement instruments are regularly returned to manufacturers for maintenance, upgrades, and calibration is highly recommended. Such a program can often prevent future failures by correcting problems long before they affect the reliability and accuracy of measurements. Similar programs for other critical test instruments such as oscilloscopes have worked well for decades.

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4.5 Where to measure intelligibility

Until such time as more explicit code language is written, common sense must guide us in the matter of where within a protected space to measure intelligibility. In many cases, the same logic used already in measuring the audibility requirement of the fire alarm code serves as a useful guide for making intelligibility measurements.

The issue can be split into two parts: 1) how many areas, or zones, need to be measured, and 2) within a given zone, where should the measurements be taken?

For the purposes of measuring intelligibility, a facility protected by a voice alarm system can be broken into zones using the following logic.

- A different room is always a different zone. Hallways, corridors, and stairways should be considered rooms.
- In general, a room has only one zone.
- Occasionally, within a room, more than one zone can exist if more than one loudspeaker type is used or if the ceiling height changes by more than about 20%. For example, in an outdoor stadium, the part of a single seating area under a balcony or deck would be one zone because it is serviced by one type of loudspeaker and has one ceiling height. The part of the same seating area open to the sky would be a second zone if serviced by a second type of loudspeaker, but also because the ceiling height has changed. Similarly, an atrium with a high-ceiling area in the center surrounded by a low ceiling area around the perimeter should be considered two zones even if a single type of loudspeaker is used to service both areas.

As to how many measurements should be made within a zone, and where they should be made:

- A good rule of thumb is to make measurements on approximately a twenty-foot grid. Thus a hotel room or any room less than 20’ x 20’ (6m x 6m) would require only one position to be measured.
- In spaces larger than 20’ x 20’ feet, multiple measurements on a 20’ x 20’ grid should be made.
- Edges and corners of rooms need not in general be measured as they are rarely occupied.
- It is unfair to only measure near to, or directly under loudspeakers.
- Areas where sonic quality is judged to be relatively inferior should be measured.
- Seams between two zones within a single room should be measured, again using the 20’ rule of thumb.
- Caution should be taken not to mistake a ‘zone’ for a ‘loudspeaker coverage area’. It is of course possible to cover only a portion of a zone with a loudspeaker coverage area while leaving the other parts unprotected. Measure the whole zone, not simply the loudspeaker coverage area.

In some facilities, there may be many rooms built and equipped identically or very nearly identically. Hotel rooms and hotel meeting rooms are examples. In the case of a 1,000-room hotel, should each room be measured? Here are some recommendations:

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- How do you handle the same situation in the case of meeting the audibility requirement? The same approach is probably good for speech intelligibility.
- Do not automatically lump all hotel rooms together. Usually, there are a few classes of rooms, ranging from ‘economy’ to ‘deluxe’ to ‘suite’, for example. Measure several rooms within each class.
- Actively look for exceptions.
- In the case of meeting rooms, use caution to not automatically lump all similar-looking rooms together. Only rooms that are built *and* equipped the same should be lumped together into a single class. Measure several rooms within each class.

4.6 When to measure speech intelligibility

Again, until more explicit code language is developed, common sense must be our guide in addressing the issue of when to measure speech intelligibility. A set of basic guidelines and recommendations follow:

- For new construction or major renovations, a zone should be measured when ready for occupancy. Dominant acoustical finishes (wall, floor, and ceiling materials) should already be in place, as should the major furnishings such as office partitions. Noise-emitting equipment should already be installed and operating.
- An existing zone should be retested when major renovations have occurred. When wall, ceiling or floor materials have changed substantially – say from carpet to tile – a zone should be retested. Testing could be triggered by the granting of a building permit.
- An existing zone should be retested if the sound system has been changed.
- An existing zone should be retested if for any reason the sound system fails the audibility requirement of the code.
- An existing zone should be retested if the primary purpose of the room has changed. For example, if a machine shop has been added to a room and the noise from the machinery is substantially higher than before, the zone (or zones) should be retested.

4.7 Setting the gain of a sound system for intelligibility testing

Each time an intelligibility test is conducted, the special artificial-speech signal must be played through the system. Care must be taken to ensure that the level of the speech-like signal has been adjusted to the same level as the speech that will be used with the system. This is an important issue since the level of the speech compared to the background noise can affect the intelligibility. Here are some guidelines and suggestions for accomplishing this goal.

- Most, if not all, fire alarm control panels contain solid-state memory for the purpose of storing voice messages. Additional solid state memory could be used to store the special speech-like signal used in STI measurements. If used for this purpose, the issue of gain calibration can be addressed at the place of manufacture and ceases to be a field issue. This is by far the most attractive scenario.

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- A dB-meter can be used to measure the level (dB-A) of the speech to be used. Adjust the level of the speech-substitute signal can then be adjusted to the same dB-A level.
- For systems where the special speech-like excitation signal is not stored internally within the voice alarm control panel, assume that the system is a 70 Volt design, meaning 70 Volt amplifiers are used with speakers whose maximum output is obtained when driven with 70 V_{rms}. The master gain of the system should be gradually increased until at least one of the amplifiers in the system has reached 70 V_{rms}. Then speech intelligibility testing should begin. In the case of a 25V design, the above numbers should all be changed from 70V to 25V.
- Occasionally, a low-impedance system will be used. In such systems, amplifiers can have a wide range of maximum voltages, and loudspeakers are driven to their maximum level at a wide range of maximum Watts as given by the manufacturer's long-term power-handling specifications. In these situations, the master gain should be increased until one of the two following conditions are met:

  1) One or more amplifiers reaches its maximum output capability, computed as $V_{rms,\max} = \sqrt{P_{amp} \times Z_{amp}}$ where P_{amp} is the manufacturer's stated power output into Z_{amp} ohms, or

  2) One or more speakers has reached its stated power handling limit, computed as $P_{spkr} = V_{rms}^2 / Z_{nom}$ where V_{rms} is the voltage driving the speaker and Z_{nom} is the nominal impedance of the loudspeaker.

4.8 Testing a system that includes a microphone

Only in extreme cases of abuse will a microphone alone be the cause of a significant loss of intelligibility. Microphones commonly employed in voice alarm systems may not be studio grade in their fidelity, but they are nearly 100% intelligible and have passed stringent requirements as defined by Underwriters Laboratories.

Occasionally, however, a microphone may be suspect due to improper handling or abuse. Or there may be concern that microphone users are so unfamiliar with their use that they may use an inappropriate distance from the microphone. If the talker is too far away, the intelligibility may be diminished because the signal level drops below the ambient noise in the protected areas. If the microphone user shouts at very close proximity, the microphone element or some other part of the sound system electronics may distort, which is known to be another factor that diminishes speech intelligibility.

In the unusual situation where the microphone must be included in the intelligibility test, an apparatus is needed to simulate the talker. This apparatus consists of a loudspeaker whose on axis response when excited by the standard artificial speech signal matches that of an average talker. These levels have been standardized in IEC 60268-16 and ISO 9921-1. With such an apparatus, a wide range of different talker conditions can be simulated, including a talker that's very soft, very loud, too far from the microphone or too close.

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4.9 Estimating speech intelligibility in high noise environments during off hours

In some facilities, it is not possible to measure speech intelligibility (or audibility) during operating hours because the testing would be considered too obtrusive. In situations where high noise can be expected, it may be necessary to predict the final intelligibility from measurements made with the building unoccupied.

Two approaches can be used. One approach is to simulate the background noise expected during high occupancy using a loudspeaker near the measurement microphone as a noise source. Random noise or speech babble recordings can be used and adjusted to achieve the desired octave band noise spectrum at the listener locations. Measurement of speech intelligibility can then proceed as usual.

The second approach is analytical and can be automated using the following process:

1) Measure the STI during low or no occupancy.
2) Enter the seven octave band noise values into the instrument that correspond to the expected higher noise levels.
3) Automatically recalculate the STI based on the higher noise values entered.

5. Cost of Speech Intelligibility

Whenever a new requirement is set forth, there is understandable concern about the costs involved. In the case of the new speech intelligibility requirement there are bound to be some additional costs. However, in the discussion that follows, these costs will be shown to be rather modest.

5.1 Cost of poor intelligibility

No discussion of the cost of meeting a minimum intelligibility requirement can begin without a reminder of the cost of *not* having acceptable intelligibility. Voice alarm systems are designed *by definition* to inform and instruct occupants in the case of an emergency. If the system is unintelligible the voice alarm system cannot perform its most fundamental duty and tragedies are simply waiting to happen. These are costs that we would prefer to consider only in the abstract.

Voice alarm systems were always *meant* to be intelligible. They just didn’t always turn out that way. The fire alarm industry now has a requirement and a variety of methods for validating the intelligibility of a voice alarm system. Therefore, it can be argued that the modestly higher costs are those necessary to ensure that the fundamental purpose of a voice alarm system can in fact be carried out.

5.2 Cost of designing intelligible systems

Given that speech intelligibility is a *de facto* requirement in the professional and commercial sound system market, we can rely on a rich body of experience from that industry when it comes to the additional effort required to achieve the desired intelligibility on a particular project.

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To be sure, designing for intelligibility requires some additional work to be undertaken, but it is a relatively small percentage of the total design effort. On projects where there is a normal amount of reverberation and background noise, the additional effort is probably less than 1%. In projects where reverberation and background noise are likely to interfere with speech communication, such as in large places of worship, auditoriums, and sports facilities, experience has shown that the additional effort to achieve a desired level of intelligibility is in the 1-3% range of the total design effort. The incremental increase to the *total* system cost is of course even lower since design effort only makes up a portion of a system's total cost.

In addition to the variable costs of designing intelligible systems, there are the fixed costs of training staff engineers and designers, and the cost of equipping designers with tools capable of accurately predicting speech intelligibility before construction or equipment installation begins. Training costs may amount to $100-500 per designer per year. Prediction programs average $1,000-3,000 with 0-10% annual maintenance and upgrade fees.

5.3 Cost of measuring intelligible systems

The cost of measuring speech intelligibility can be very small if it is done at the same time as audibility testing. There is no reason that a person capable of using a SPL meter can not also make intelligibility measurements. System installers and fire authorities alike will be able to make these measurements easily and effectively just as they do today in the case of the audibility requirement. In at least one case, a single instrument can be used to make both measurements, and there is no reason to suspect that other instruments with similar capability won't be available in the near future.

5.4 Cost of acoustical experts

Some have expressed concern that acoustical experts will now be needed on every project. This is simply not the case. In some very complex projects, where there is a high degree of concern that background noise or reverberation (or both) will interfere with speech communication, an acoustical expert may be justified. But these projects represent a very small fraction of the total voice alarm market. Moreover, there is every reason to expect that voice alarm system engineering firms will obtain the skill necessary to provide expert service in the area of speech intelligibility, obviating the need for outside experts.

6. Special Considerations for Unique Environments

In some facilities, the normal assumptions made about talker and listener abilities in speech intelligibility testing are likely to be poor ones. For example, in an international airport, the assumption that the talker and listener share the same first language is clearly not a good one. Similarly, in an assisted living facility, the assumption that listeners have hearing the same as the population at large is also incorrect.

In addition to situations where the assumptions about talker and listener abilities are unlikely to be good ones, there are situations where the planned use of the sound system is for both emergency *and* non-emergency use. In such situations, the minimum

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intelligibility required for emergency purposes may be judged not high enough for daily non-emergency use. For example, a single system may be used in an airport or convention center for both emergency and non-emergency use, but a higher minimum could be set to meet the requirements of everyday use.

In situations like these, a different method of measuring intelligibility is *not* what is needed. Instead, a higher minimum intelligibility level should be required. For example, a minimum of 0.80 on the CIS scale might be appropriate for an international airport or assisted living facility. The ISO has recently ratified a standard that addresses this issue,[2] and North American code organizations are encouraged to use as much of this work as possible as they strive to enhance their codes with respect to speech intelligibility.

7. Recommended Enhancements to Codes, Standards, and Practices

Any successful effort to integrate a major subject like speech intelligibility into the fire alarm industry must be viewed as a multi-year effort. The industry has taken the most important first step – unambiguous language stating that systems must be intelligible. Significant effort has been expended since the 1999 edition of NFPA 72 to educate the industry on the basics of speech intelligibility, and manufacturers have begun to respond to the challenge of integrating speech intelligibility design and measurement into their operations.

At the same time, there are a number of current needs which in this author's opinion require effort in the next period in order to strengthen the long-term goal of improving the effectiveness of voice alarm systems.

- The language in NFPA 72 could be strengthened to require a minimum CIS score of 0.70. Currently this language is contained in the Appendix.
- A reasonable speech intelligibility testing approach could be added to Chapter 7 of NFPA 72. Currently the code offers no specifics on when and where to test. Appendix and Handbook material to support the testing requirement will greatly strengthen the code's adoption and consistent use.
- Code work could be harmonized with the ISO/IEC and the European Community. At the moment there is a significant amount of duplicate effort, and some areas of conflict. Harmonization will result in better codes everywhere, and in higher efficiency in the marketplace.
- Fire alarm industry training courses could be developed and handbooks written for the major players, including authorities having jurisdiction, voice alarm system engineers, and voice alarm installers.
- The National Systems Contractors Association is an excellent source of expertise in the area of speech intelligibility design and measurement tools. The fire alarm industry is encouraged to use the NSCA as a valuable resource in the area of speech intelligibility.

[2] ISO Technical Committee 159, Sub-Committee 5, Working Group 3.

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- The subject of voice message content and effectiveness should be given the same amount of scientific and industry attention as has been, and is being, given to the subject of speech intelligibility. It makes no sense to have a perfectly intelligible sound system if the voice message is incapable of producing the desired response from occupants.
- Standards are needed for speech intelligibility measurement instruments. Currently, any manufacturer can claim that their instrument measures intelligibility. The industry could specify the conditions under which a measurement instrument had to produce accurate readings.

8. Conclusion

Sufficient scientific and engineering know-how exists today to accurately and reliably design for, and measure speech intelligibility in virtually every environment. Tools exist to aid the voice alarm engineer in the design of systems that will pass the minimum intelligibility requirement, and easy-to-use instruments are now appearing for measuring intelligibility according to international codes and standards. The costs associated with meeting the speech intelligibility requirement are not zero, but they can also fairly be described as modest or even negligible when compared to total system cost.

Given that the most fundamental function of a voice alarm system is to convey language-based information to building occupants, the National Fire Protection Association has taken the important first step of requiring intelligibility in every voice alarm system. As with any new requirement – especially when that requirement is related to a human variable (our ability to understand speech) – it will take time to assimilate the required detail into the codes, standards, and practices of the fire alarm industry.

With this in mind, there are a number of near-term steps the industry can take which will greatly accelerate and strengthen the adoption of intelligibility as a vital performance parameter in voice alarm systems. There now exists a code-based mechanism that ensures that when a voice alarm system is used, there can be certainty that its effectiveness will not be compromised because of poor speech intelligibility. This can be considered a major step forward. Ultimately, adherence to the speech intelligibility requirement of the fire alarm code means that building occupants will be better protected, which, it is safe to say, is the principal purpose of an alarm system.

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