Automotive Speech Intelligibility Measurements

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Speech communication from the front seat to the rear seat in a passenger vehicle can be difficult. This is particularly true in a vehicle with an acoustically absorptive interior. Speech transmission index (STI) measurements can quantify speech intelligibility, but they require specialized signal processing. The STI calculations can be simplified if it is assumed that reverberation and echoes play an insignificant role in an automobile. A simplification of a STI measurement is described that uses a stationary reference speech signal from a talker mannequin in the driver's seat to create a signal at rear passenger positions. On-road noise measurements are used for the noise level, and the calculated signal-to-noise ratio is used to calculate a simplified STI value that tracks closely to a full implementation of the STI method for sedans. In fact, this method is very similar to the techniques described in the articulation index (AI) and speech interference index (SII) standards. Those standards provide for the use of a talker mannequin, though that is rarely done. The use of all three measurement techniques is considered.

In an attempt to make vehicles quieter, it is tempting to add a great deal of acoustic absorption to the interior. However, this may cause speech intelligibility to become worse. For many years the ability to communicate easily in a vehicle has been considered a key attribute contributing to the perception of a comfortable acoustic environment and a high-quality vehicle. The ability to hear and understand speech is obviously important for all vehicle occupants but can be a particular issue when the driver communicates with passengers in the rear of the vehicle. Vehicles with acoustically absorptive interiors can be particularly problematic, and vehicles with third row seats provide even bigger challenges.

The three most common measurements to assess intelligibility are articulation index (AI), speech intelligibility index (SII), and speech transmission index (STI). Each of these measures provides a method for generating a signal at the talker's position, measuring the response at the listener's position, and judging the ability to understand speech based on the speech-to-noise level at the listener position.

However, this is not the way the articulation index is used in the automotive industry. The articulation index is generally not used to calculate an actual speech intelligibility rating but rather a "speech-weighted" noise level. The articulation index is calculated by computing the speech-to-noise level, but an idealized speech spectrum in the articulation index standard is generally used in place of actually measuring the received speech level at the listener's position. Though the speech intelligibility index is a more recent measure and contains updates and refinements to the articulation index standard, it has not been widely adopted. Both of these measures are considered in more detail below.

In recent years there has been quite a bit of interest in using the speech transmission index to gage speech intelligibility. This method cannot be implemented without simulating talker levels. STI accounts for the drop in level as the sound travels from the talker to the listener, the background noise level at the listener's position, and reverberation and echoes in the environment. STI requires the measurement of a modulation transfer function between the talker and listener, which accounts for the effects of reverberation, echoes, and background noise. While the AI and SII computations are relatively simple, the STI method is somewhat more complicated. It will be shown that the STI method yields results that are similar to simpler AI/SII style measurements in a vehicle where echoes and reverberation are not significant.

All of these measures, AI, SII, and STI, assume a single receiving microphone. For automotive measurements, however, there can be large differences between measurements at the inboard and outboard ears of a rear passenger. In general, the intelligibility will be much higher for the inboard ear. This is because the received talker level is higher at the inboard ear, and the vehicle noise is somewhat lower at this location. Though there have been studies of binaural STI in larger architectural spaces, no work has been done to investigate binaural effects in automobiles. That will be considered.

Articulation Index and Speech Intelligibility Index

Procedures to quantify an articulation index have existed since at least 1929,[1] when the term was used to describe a juried method with talkers, listeners, and lists of words. This method was primarily intended for communication systems (telephone and radio), but its use for other applications was also considered.

An objective measurement technique was standardized in ANSI S3.5-1969, American National Standard Methods for the Calculation of the Articulation Index.[2] That standardized measurement technique is based on an assessment of the ratio of measured or "idealized" speech and the background noise level at the listener's position. The 1969 standard has been superseded by ANSI S3.5-1997, American National Standard Methods for the Calculation of the Speech Intelligibility Index.[3] The 1997 standard provides a method that is similar in principle to the earlier standard but contains enough differences that the authors choose a new name for the measured quantity. Some of the many differences include the use of different standardized talker levels, an expanded frequency range, and updated band importance factors. Note that the original 1969 standard had a single-talker level. The updated standard has four talker levels: normal, raised, loud, and shouting.

Both the 1969 and 1997 standards rely on a computation of the speech-to-background noise difference at the listener's position. This ratio is computed in bands: octave, 1/3-octave, or bands that contribute equally to the intelligibility of speech. (The 1997 standard also includes critical bands.) The speech-to-noise difference in these bands is multiplied by a band importance factor, and the results are summed over all the frequency bands. A speech-to-noise difference of 30 dB at all bands results in an articulation index of 1, while a speech-to-noise difference of 0 at each band results in an articulation index of 0. To keep the articulation index from exceeding 1 or becoming less than 0, speech-to-noise differences

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Nomenclature

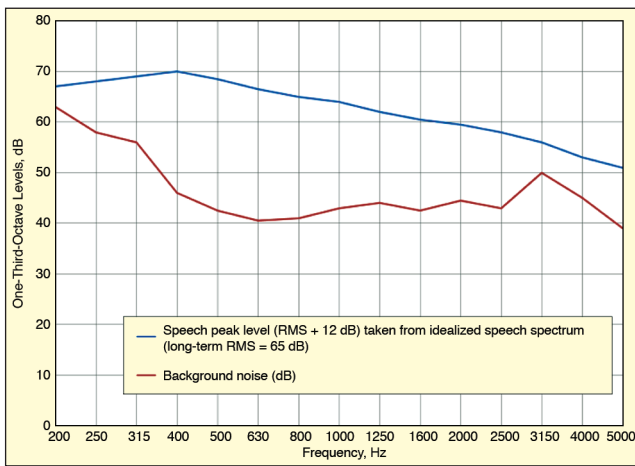|	
f	Modulation frequency index (0.63 - 12.5 Hz)
k	Octave-band signal frequency index (125 Hz - 8k Hz)
$m(F_{f,k})$	Modulation transfer function
m_i	Source modulation level
m_o	Receiver modulation level
MTI	Modulation transfer index
$SNR_{k,f}$	Signal-to-noise ratio, dB
TI	Transmission index
T	Reverberation time, sec
α_η	Octave weighting factor for STI
β_η	Adjacent-band correction factor for STI

Figure 1. Peak speech level and background noise from an example calculation in ANSI S3.5-1969; speech levels are peak levels in a speech signal with a long-term RMS average of 65 dB.

are capped at a maximum of 30 dB and a minimum of 0 dB. This range defines the limits from perfect speech intelligibility to no intelligibility at all.

An example AI calculation from ANSI S3.5-1969 is shown in Table 1, and the peak speech levels and the background noise from this example are shown in Figure 1. Note that the RMS speech levels are assumed to be 12 dB lower than the peak levels.

The differences between AI and SII are not large, but can be significant in cases where the AI is being used as a vehicle development target. In one study, vehicle level measurements indicated that the SII values are about 3 - 4% less than the AI values during a vehicle acceleration.[4]

Note that many automotive OEMs and suppliers have created their own talker levels and band importance functions. An additional complication is that the newer ANSI speech intelligibility index standard has not been widely adopted in the automotive industry. Though ANSI S3.5-1969 (the AI standard) has been out of print since it was replaced by ANSI S3.5-1997 (the SII standard), AI is still more widely used as compared to SII.

As already noted, the AI and SII standards provide for a measurement of the talker's speech level at the listener's position, but this is not the way these standards are generally used for automotive work. It can be cumbersome (or at least an extra measurement step) to mount a speaker at the talker's position and measure the levels at the listener position. For this reason, the standardized speech levels in the standards are often used as the signal in the signal-to-noise difference calculations. The resultant AI and SII

values are, therefore, a "speech-intelligibility-weighted" noise level rather than an actual assessment of the speech-to-noise ratio at the listener's position.

Speech Transmission Index

The speech transmission index was developed by Steeneken and Houtgast in the late 1960s to measure speech intelligibility in VHF radio systems and is now standardized by the International Electrotechnical Commission (IEC).[5] Speech transmission index measurements are similar to AI and SII measurements in that they require the generation of a signal at the talker's position and a measurement of that signal at the listener's position. As with AI and SII, STI measurements use a test signal with a frequency spectrum equal to the long-term frequency spectrum of speech. STI measurements differ in that they use a modulated noise source. For a male speaker, octave-band noise from 125 Hz to 8000 Hz (seven bands) is used, and each octave band is modulated with a periodic signal in such a way that the intensity envelope is a modulated sinusoidal. For a female speaker, the 125-Hz octave-band is not used. The modulation frequencies range from 0.63 Hz to 12.5 Hz in 1/3-octave steps (14 frequencies). This is a total of 98 measurements for a male speaker.

The measured signal is influenced by its travel through the acoustic environment (including a drop in level as well as reverberation and echoes) and by the background noise at the listener's position. The STI technique is fundamentally different as compared to the AI or SII methods in that it assesses the temporal degradation of the speech signal as well as the speech-to-background noise ratio.

The change in the modulation is the modulation transfer function, $m(F_{k,f})$, where:

$$m\left(F_{k,f}\right) = \frac{m_o}{m_i} \tag{1}$$

and m_o is the modulation of the signal at the listener's position, m_i is the modulation of the signal at the talker's position, k indicates one of the seven octave bands (125 Hz to 8 kHz) and f designates one of the 14 modulation frequencies (0.63 Hz to 12.5 Hz). This is determined for all 98 cells as shown in Figure 2. Note that Equation 1 and all the following equations related to STI measurements can be found in the STI standard.[5]

Though STI could be determined by measuring all 98 modulated sounds, STI measurements are generally implemented by measuring the frequency response function from the talker to listener position and calculating the impulse response function. The modulated sound at the speaker's position can then be determined from the impulse response.

The modulation transfer function can be interpreted as an apparent signal-to-noise ratio (SNR). This ratio includes factors related not only to the difference between the speech and background noise levels, but also the effects of reverberation and echoes:

$$SNR_{k,f} = 10\log\left(\frac{m\left(F_{k,f}\right)}{1 - m\left(F_{k,f}\right)}\right) \tag{2}$$

Note that the apparent SNR in the STI calculations is a little different as compared to the signal-to-noise ratio as it is used in the AI and SII calculations. For the AI and SII calculations, it is just the difference between the speech level at the listener's position and the background noise. For AI and SII calculations, a signal-to-noise ratio of 30 dB would indicate 100% intelligibility, and a signal-to-noise ratio of 0 dB would lead to 0% intelligibility. The apparent SNR in the STI calculations is similar to the signal-to-noise ratio in AI and SII calculations in that there is a linear relationship between the SNR and intelligibility. The apparent SNR in the STI calculation spans a range from −∞ to +∞ with a SNR of 0 dB corresponding to a modulation of 0.5. The apparent SNR is truncated outside the range of −15 to +15, which corresponds to intelligibility scores from 0 to 1. Differences in the way the SNR is calculated are accounted for by the transmission index, which is described below.

This apparent SNR is calculated for each of the 98 cells in Figure 2. The SNR is converted to a transmission index, $TI_{k,f}$:

Table 1. Example of articulation index calculation from ANSI S3.5-1969; speech spectrum consists of peak levels based on assumption of 65 dB long-term RMS idealized speech level at listener position.

Freq.	Peak Speech Level*	Bkgnd Noise, dB	Peaks Minus Bkgnd noise, db	Weighting Factor	
200	67.0	63.0	4	0.0004	0.0016
250	68.0	58.0	10	0.0010	0.0100
315	69.0	56.0	13	0.0010	0.0130
400	70.0	46.0	24	0.0014	0.0336
500	68.5	42.5	26	0.0014	0.0364
630	66.5	40.5	26	0.0020	0.0520
800	65.0	41.0	24	0.0020	0.0480
1000	64.0	43.0	21	0.0024	0.0504
1250	62.0	44.0	18	0.0030	0.0540
1600	60.5	42.5	18	0.0037	0.0666
2000	59.5	44.5	15	0.0037	0.0555
2500	58.0	43.0	15	0.0034	0.0510
3150	56.0	50.0	6	0.0034	0.0204
4000	53.0	45.0	8	0.0024	0.0192
5000	51.0	39.0	12	0.0020	0.0240
				AI =	0.5357

* RMS + 12 dB, taken from idealized speech spectrum, long-term RMS = 65 dB/
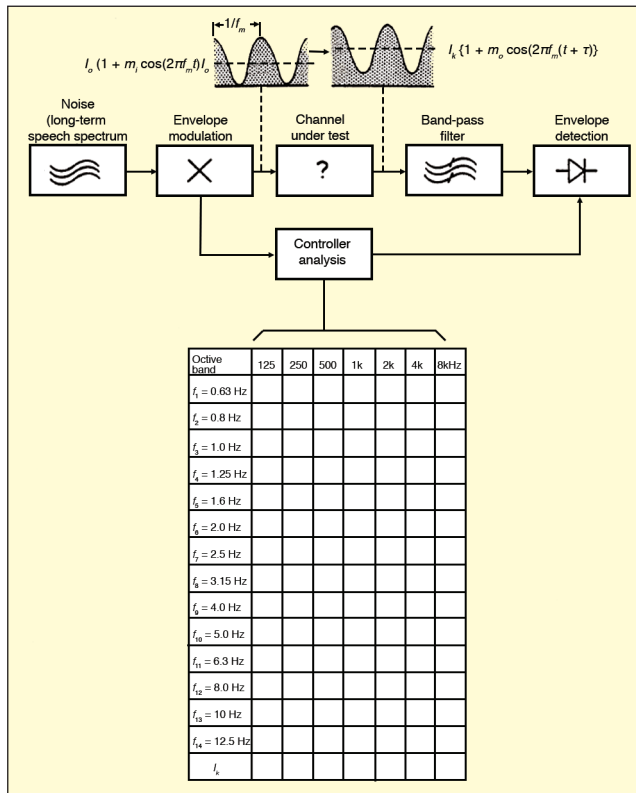
Figure 2. Schematic of STI measurement process; octave-band sound from 125 Hz to 8 kHz is modulated at 14 frequencies, from 0.63 Hz to 12 Hz, and the modulation transfer function is measured from source to receiver positions.[5]

$$MTI_f = 10\log\left(\frac{SNR_{k,f} + 15}{30}\right) \qquad (3)$$

where the shift is 15 dB and range is 30 dB. The modulation transfer index, MTI_k, is the average of all transmission indices for a given octave band frequency:

$$MTI_k = \frac{1}{14}\sum_{f=1}^{14} TI_{k,f} \qquad (4)$$

Finally, the overall STI value is obtained by multiplying the modulation transfer matrix indices by a frequency-dependent weighting factor:

$$STI = \sum_{f=1}^{7} \propto_f MTI_f = \sum_{f=1}^{6} \beta_f \sqrt{MTI_f * MTI_{f-1}} \qquad (5)$$

where $\propto_n$ is the octave weighting factor and β_n is a correction term related to the contribution from adjacent frequency bands.

Though this method is more complicated than AI or SII, it includes the talker-to-listener path, the acoustic environment, and the background noise. It has, therefore, been proposed as a better way to measure speech intelligibility for automotive applications.[6,7,8,9]

For automotive applications, the STI can be measured while the vehicle is in motion (see Figure 3). This includes the total effects of the transmission of sound from the talker to listener. In some cases, however, this is not practical (for instance, if it is desired to have the speaker in the driver's position). In those cases, it is possible to measure the STI while the vehicle is stationary and in a quiet environment. This measurement will include all the transmission effects except the background noise. The background noise can be measured separately and combined with the stationary STI measurement to calculate the overall STI for the moving vehicle.

Influence of Decay Time on Automotive STI

The reverberation time in vehicles is extremely short.[10] An earlier study compared methods of measuring the reverberation time in a mid-sized sedan. Depending on the analysis method, the reverberation time in the 125 Hz octave band was determined to be between 140 and 260 msec. The reverberation time at 250 Hz was found to range from 80 to 140 msec. Above 250 Hz, the reverbera-
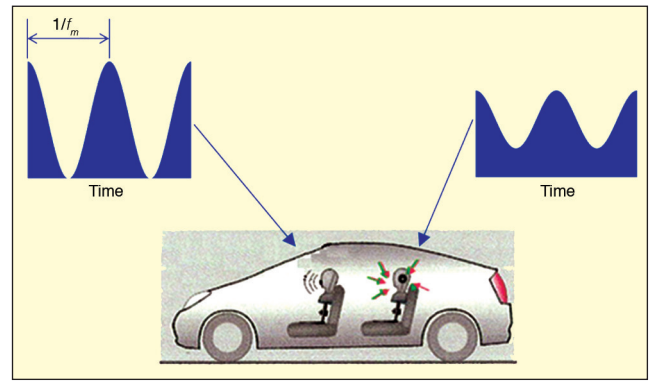

Figure 3. Measuring STI in vehicle consists of placing talker and listener mannequins in vehicle, generating modulated sound at talker position and measuring response at listener position. This includes effects of acoustic environment, drop in level from source to receiver positions, and background noise.
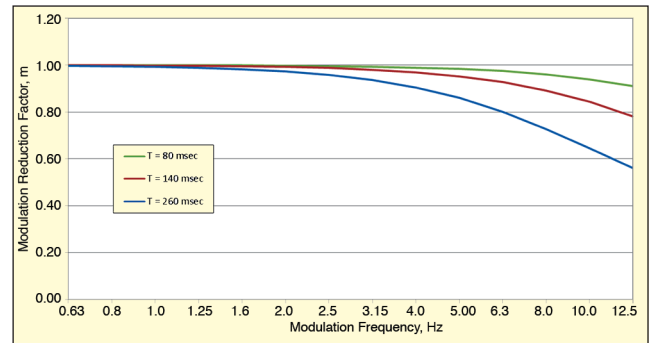

Figure 4. Modulation reduction factor, m, as a function of modulation frequency for octave-band noise at 125 Hz, 250 Hz, and the octaves above 250 Hz.
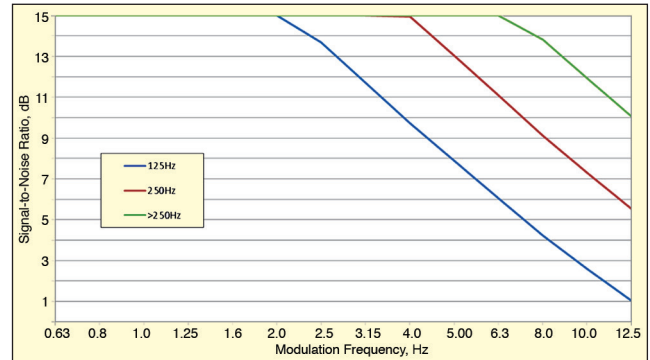

Figure 5. Apparent signal-to-noise ratio for mid-size sedan, assuming reverberation only.

tion time was relatively constant as a function of frequency and was found to range from 40 to 80 msec.

Assuming that the background noise and echoes are negligible, the modulation transfer function is:

$$M(F_k) = \sqrt{1 + \frac{2\pi F_k T}{13.8}} \qquad (6)$$

where F is the modulation frequency and T is the reverberation time in seconds.

Assuming the worst-case reverberation times from the earlier sedan study leads to the modulation reduction factors shown in Figure 4. Since a modulation reduction factor of 1 indicates no degradation in the modulation as the signal travels from source to receiver, there appears to be very little degradation for the higher signal frequencies (above 250 Hz) and at the lower modulation frequencies (below 2 Hz). The apparent signal-to-noise ratio is calculated from the modulation reduction factor by using Equation 2, and the results are shown in Figure 5.

Next the modulation transfer index is calculated using Equation 4. This index is nearly 1 for all values except those at the lowest
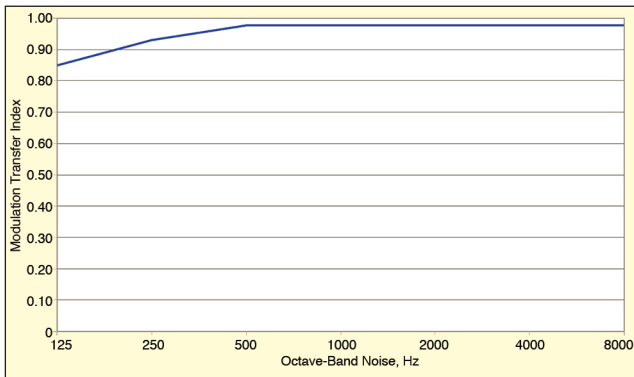
Figure 6. Modulation transfer index shows reverberation has minor influence on modulation; most influence is below 500 Hz, a range less important to speech intelligibility.
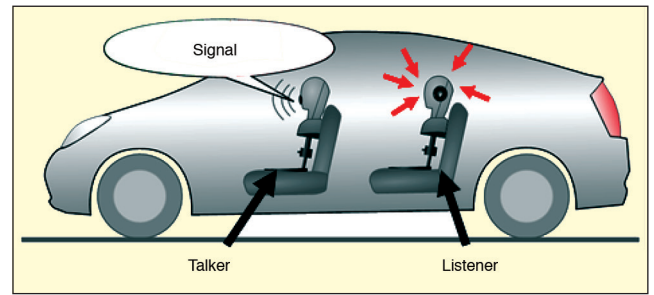

Figure 7. Talker head positioned in driver seat, and listener mannequin positioned in rear on both driver and passenger side. STI system measured modulation transfer functions from talker to listener position. Measurements conducted in hemi-anechoic room. Signal levels at listener position were also measured and used with previously measured on-road data to calculate SNR.

frequency bands, 125 and 250 Hz, and those bands are not as critical for good speech intelligibility (see Figure 6). As previously noted, a value nearly equal to 1 indicates very little degradation to the signal modulation.

Finally, the STI value is calculated from Equation 5, and that value is 0.97. Reverberation appears, therefore, to be a very minor part in the STI calculations for a sedan.

Influence of Background Noise on STI Measurements

Assuming that reverberation and echoes are negligible, the modulation transfer function can be calculated from the apparent SNR alone:

$$M(F_k) = \left[1 + 10^{\frac{-SNR_k}{10}}\right]^{-1} \quad (7)$$

Note that the modulation transfer function is now independent of the modulation frequency, and instead of having a 7 × 14 array of modulation values, the matrix is only 7 × 1. In addition, since Equation 7 is just a rewritten version of Equation 2, the SNR values can be inserted directly into Equation 3.

Note that if these SNR values are taken from a vehicle measurement in which the signal is the speech level and the noise is the background noise in the vehicle, this SNR ratio can be input into Equation 3 using a shift of 0 dB and a range of 30 dB. In addition, the MTI is equal to the TI, and the TI values can be used directly in Equation 5 to calculate the STI. An example is shown in Table 2 for a situation in which the SNR is 20 dB at all frequencies, and the shift in Equation 7 is 0.

Note that this very simple procedure will provide the same results as a full STI measurement if reverberation and echoes are not significant. As previously noted, this appears to be true for a passenger sedan.[11]

Comparison of STI with a Simplified Version

Tests were conducted to see if it is possible to duplicate STI results by simply using the SNR at the listener's position. STI measurements were carried out with a commercial STI system. The excitation was provided by a talker head in the driver seat and the speech signal was measured up by a listener head in the rear seat. Two measurements were made: one with the listener head on the driver side and a second measurement with the listener head on the passenger side. These measurements account for all octave-band excitations and modulation frequencies specified by the STI

standard. These measurements, however, were carried out with the vehicle in a hemi-anechoic chamber and did not simulate the SNR found at the listener position during normal driving conditions. The STI system includes a provision to enter this SNR so that it is included in the STI calculations. The procedure for calculating the SNR is described in the next paragraphs.

Prior to the STI measurements, a calibration procedure was carried out to determine the difference in sound pressure level from a chin microphone located close to the talker head's artificial mouth and a location 1 m on axis from the mouth in an anechoic environment. This was done because the level at 1 m from the speaker in an anechoic environment is what is specified for the talker level in the STI standard. This procedure consisted of placing a microphone at the chin of the talker head and a second microphone at 1 meter on axis in an anechoic environment. The level difference between the two locations was measured for each of the octave bands and used as a calibration for the in-vehicle measurements:

$$L_{Cal} = L_{Chin-anechoic} - L_{1m-anechoic} \quad (8)$$

For the in-vehicle measurements the talker level was measured with the chin microphone. From this level the equivalent 1 m anechoic level was calculated:

$$L_{1m-equivalent} = L_{Chin-ln vehncle} - L_{Cal} \quad (9)$$

It was assumed that the vehicle provided a linear environment and that any increase in sound level at the talker head would produce an equal increase at the listener head. Therefore, instead of adjusting the output of the talker head to match the speech level specified by the STI standard, differences between the equivalent 1 m level and the STI standard speech level were used as a correction factor:

$$L_{Correction} = L_{Standardized talker} - L_{1m-equivalent} \quad (10)$$

and

$$L_{Corrected listener level} = L_{Measureded at listener level} - L_{Correction} \quad (11)$$

This "corrected listener level" is the level that would have been measured if the talker head had been adjusted to provide the equivalent 1 m anechoic level that is specified in the STI standard. That adjustment could have been made, for instance, with a graphic equalizer. Finally, the background noise measurements were taken from a smooth-road cruise at 120kph.

$$SNL = L_{Corrected listner level} = L_{On-roadnoise at 120 kph} \quad (12)$$

This signal-to-noise ratio was calculated for each octave band and fed into the commercial STI system for a full calculation of the STI considering both the SNR and the reverberation and echoes in the vehicle. This procedure was carried out for four full-sized sedans as shown in Figures 7 and 8. Figure 7 shows the measurement of the impulse response between the talker and listener mannequins and the measurement of the source level. Figure 8 shows the measurement of the on-road background noise.

The STI using the full standardized procedure will always be lower than the STI calculated from the speech-to-background noise ratio. This is seen in Figure 9, where the full STI calculation is

Table 2. Sample calculation of STI assuming no reverberation or echoes and a signal-to-noise radio of 20 dB (male talker assumed).

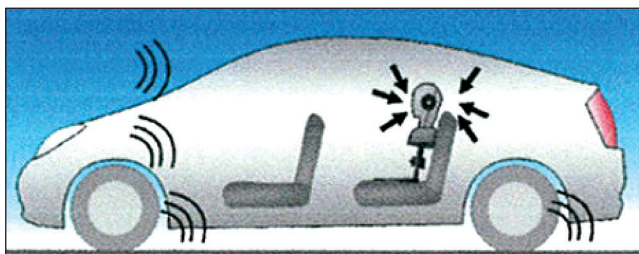| Frequency	125	250	500	1000	2000	4000	8000	
SNR	20	20	20	20	20	20	20	
TI, MTI	0.67	0.67	0.67	0.67	0.67	0.67	0.67	
Alpha	0.085	0.127.0	0.23	0.233	0.309	0.224	0.173	
Beta		0.085	0.078	0.065	0.011	0.047	0.095	
Alpha*MTI	0.057	0.085	0.153	0.155	0.206	0.149	0.115	0.921
Beta*SQRT		0.0570	0.052	0.043	0.007	0.031	0.063	0.254
							STI	67%

Figure 8. Noise at listener position measured previously. It was more convenient to use previously measured data and impossible to position the talker mannequin in driver seat for full on-road implementation of STI procedure.

shown as solid bars, and the "SNR Only" calculations are shown as shaded bars. Note that values are shown for the inboard and outboard ears with the mannequin in both rear the driver side and passenger side for the four tested sedans. The talker head was in the front driver seat. Though the full STI value is always lower than the STI calculated using only the SNR, the differences are relatively small (within 97% to 99% of the full STI values). The maximum difference for these four vehicles is 2.5%.

The simplified STI values are slightly higher than the full STI values, but a correction term could be developed to account for the small reverberation in the vehicle. Based on the average for these four sedans, it appears that the simplified STI should be lowered to a level 98% of the calculated value. This correction would certainly change for different classes of vehicles, with larger vehicles having more significant correction terms.

Note that this correction is nearly equal to the STI that was computed in the section of this article that considered the influence of the decay time on the STI. That section used decay values from a different sedan, yet the STI values are almost identical to those found on these four vehicles. The similarities in these values are not a coincidence, but are due to the fact that the reverberation time in the earlier sedan study and in the sedans considered in this study must be very similar. The correction factor for a given vehicle can be determined by measuring the reverberation time in the vehicle.

Use of AI and SII with a Talker Head

Since the effect of the reverberation has a relatively small effect on the STI, additional calculations were performed to assess the performance of the four sedans using the procedures described in the AI and SII standards. Though these procedures use the talker and listener heads and account for the actual speech level at the listener position, the AI and SII procedures are simpler computationally.

As previously mentioned, the AI and SII results will be slightly different relative to each other and as compared to the STI results. Because of slight differences in the band importance weighting coefficients, the different source levels in the three standards and other details, the differences were within a few percent for these four sedans.

Note that the results of these AI or SII calculations can be expressed in one-third-octave bands showing the contribution of each one-third octave to the overall AI or SII (see Figure 10). This type of plot can indicate the frequency bands that need to be improved to improve the overall AI or SII. This can provide more diagnostic information and guide the selection of materials to enhance speech intelligibility.

Binaural Speech Intelligibility

For these four sedans, there is a difference between the inboard and outboard ear STI. For some of these vehicles, this difference is more than 10%, with the inboard ear always providing a higher STI (see Figure 11).

STI is a monaural measurement, and additional research is needed to understand the overall intelligibility when there is a significant difference in the STI at two ears. A study of architectural spaces[12] indicates that single-number STI measurements underpredict the speech intelligibility for binaural listening and that a significant improvement in the assessment of speech intelligibility will result by taking the STI from the higher of two ears. But this
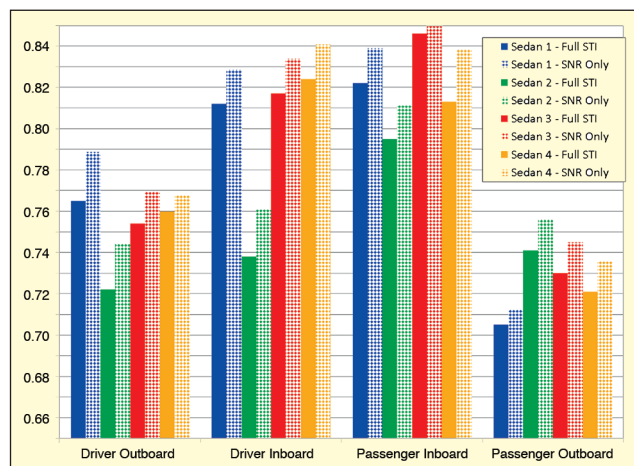

Figure 9. Comparing full STI calculation to one that only uses ratio of the speech level to the background noise. Full STI calculation always produces lower STI value, but maximum difference for the four tested vehicles is relatively small, 2.5%.
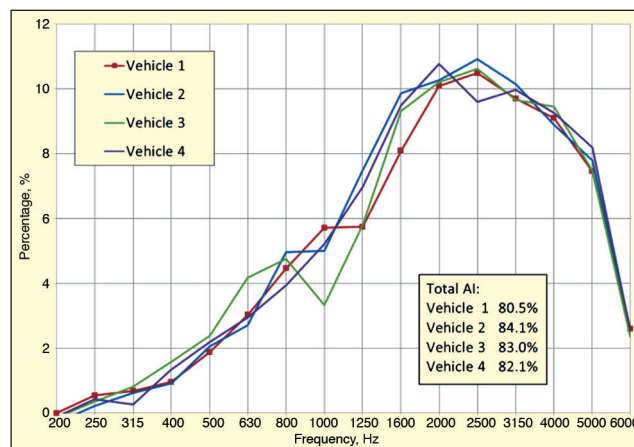

Figure 10. Breakdown of AI contributions for inboard ear measurements showing percent contribution from each of the 1/3-octave bands. For an AI calculation, these values are obtained by multiplying band importance factor by difference between speech and noise levels. Note: "raised" speech level was used for these calculations.
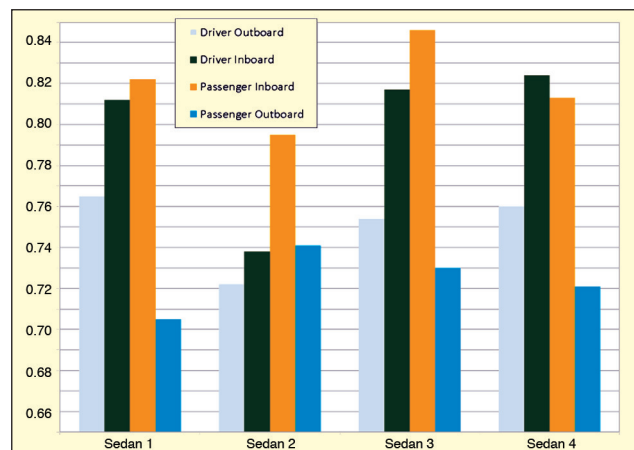

Figure 11. STI for inboard and outboard ears of four full-sized sedans; talker head is in front driver seat. Note: STI significantly higher for inboard ear

will still likely under-predict that actual intelligibility.

Summary/Conclusions

A method has been shown that simplifies the procedure used to measure STI. This method is appropriate for situations where reverberation and echoes are not significant. This method has been shown to provide results that are within 97% to 99% of the results obtained from a full implementation of the STI procedure when measuring full-size sedans. The additional volume found in

minivans and SUVs may provide more reverberation and degrade the performance of this simplified technique. This will be examined in a future study. The authors would like to acknowledge Josh Russell and Ryan Klobucar from the Toyota Technical Center for assisting with the measurements.

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