# STI Measurement in The Car

## Assignment One - Measurement and Analysis Report

Audio Systems and Measurement – DESC9090, Architecture Design and Planning, University of Sydney, *Semester Two 2018*

### Introduction and the Aim of Measurement

In modern car industries, the intelligibility of sound inside the cabin of vehicles has been known as a factor of comfort [6]. One of the known objective methods for evaluating speech intelligibility inside cars is the speech transmission index STI which is the main subject of this report. The measurement aim is to predict the STI in a running car as a factor of speed (background noise). For this purpose, a series of audio- acoustical measurements have been conducted inside a five-door car (Mazda) based on the European standard IEC 60268-16 [4]. As the harshness of background noise in different speeds, compartment reverberation time and speech level are accounted for in the STI calculation, the resulting data can be interoperated as the quality of sound in the car [6]. Further investigations have been done for better understanding the effect of source spectrum and direction on the transmission index and finally the direct measurement method in aarae has been compared with a similar method in Arta (Audio Measurement and Analysis Software) in the room space.

### Audio System Description

This system consists of an acoustic part (the cabin of car) and audio measurement instruments as follows:

- B&K calibrator type 4231
- B&K speech source type 4720
- Measurement microphone (Earthworks, type M30)
- RME audio interface with two physical inputs and outputs
- Laptop computer equipped with aarae and RME driver software
- Handmade Dummy Head (mouth simulator) with internal 4-inch active driver (3W)

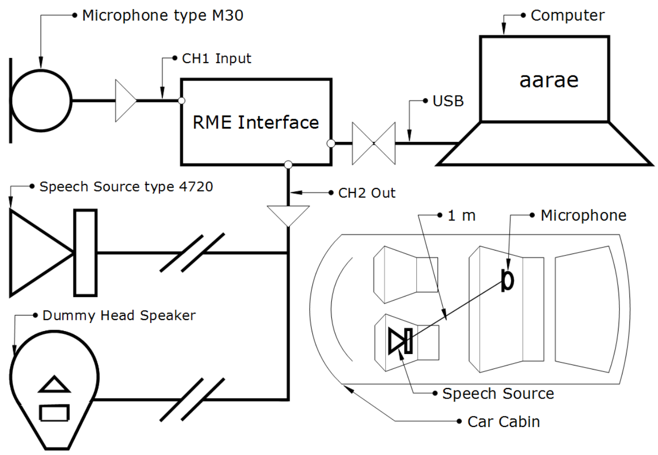


Figure 1. *Audio measurement schematic implemented inside the car. The speech level has been produced by the internal standard noise generator of 4720 as the reference and other external equalized speech signals are generated by aarae (STIPA-signal) for playing through 4720 and the Dummy Head.*

The speech source type 4720 has been used as the calibrated reference for STI measurements. The analysis of the recorded in-built calibrated MLS signal at 1m (far enough from reflective surfaces) has shown about 60dBA equivalence level for the pink spectrum in the octave bands. The spectrum of the recorded octave band levels was not compatible with the recommended spectra by IEC 60268-16 [4,1] for male speech spectrum in high frequency octave band. So, the signal with adjusted spectra (arrae STIPA-signal) has been derived externally to 4720 and the results are represented for comparison.

## Measurement Methods and Limitations

In a cavity the size of the car compartment, opening the windows can change the measurement results due to wind intrusion which refracts the sound waves and generates extra noise. Such a system can tend toward a time variant system that is not applicable for indirect STI measurement [1]. For this reason, all car windows have been closed throughout the measurements and the air-conditioning system has been off at all times. Apart from the signal to noise of the system, the size, positioning, spectrum and level of sources can affect the results. Car resonance frequencies and high frequency reflections from the windows can affect the spectrum of speech and noise. As the background noise in some speeds is higher than the speech level, measuring the STI by a direct method suggested by aarae can produce higher error due to level and spectrum variation of the background noise along time. Furthermore, the direct method is time consuming and cannot be practical when we need to measure STI inside a running car. In contrast, by indirect measurement it is possible to measure the three involved components (background noise, speech level and impulse response) separately that can be compatible with linear time invariant systems [1,3]. As the car impulse response has not been affected with the variation of background noise and other external interferences, the introduced system *(figure 1)* can be considered as LTI and the STI can be calculated from an indirect method according to [1].

To account for the acoustical effects of the human torso in the measurements (diffraction & reflections), a dummy torso has been made (dense foam covered with artificial leather) for speech generator (4720) and the dummy head (4-inch active speaker box surrounded by polyurethane foam and aluminum foil). The source has been placed in the talker's place on the front-left seat and the measurement microphone has been located at the ear level on the rear-right back seat *(Figure 2)*. The distance between source pivot and the mic is about one meter.


Figure 2. *The positioning of speech source (4720) and receiver (Earthwork M30) inside the car*

## Background Noise

The background noise has been recorded on five different occasions *(figure 3)*. The microphone is calibrated by using the calibrator type 4231 according to the suggested procedure by arrae and the calibration offset has been accounted for and analyzed by *octave_band_leve_barplot*. For more accuracy the calibration procedure has been repeated several times. As the background noise source in the running car is a combination of mechanical vibrations and road noise with variation in time, the recording time for each session has been considered as long as 60s which can enhance the accuracy of the averaged equivalence level for each octave band center frequency [2]. The accuracy of car speed along the recording sessions has been kept as tight as ± 5km/h.

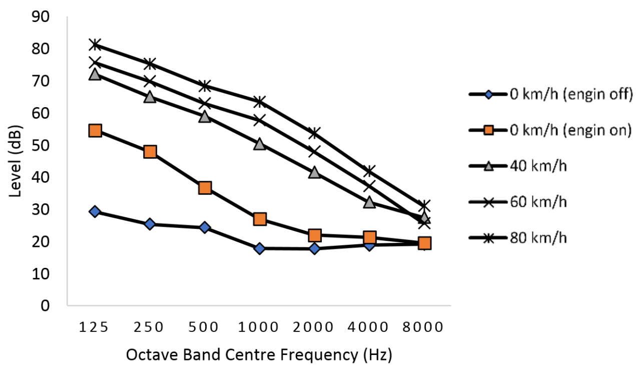


Figure 3. *Octave band background noise inside the stationary and running car. For the speeds less than 40km/h the low frequency noise is more dominant but in higher speeds the noise has been increased in the entire band with the same ratio.*

### Speech Level

Based on the indirect method [6], the speech level has been recorded for three different stimuli in the stationary car (engine off, quiet area). The first stimuli were the standard in-built pink MLS signal (60dBA) of speech source (4720) and in the second experiment, the speech source has been fed externally by the default STIPA-signal in aarae with the spectra suggested by IEC60268. As the source (4720) has a calibrated output level, its level has been used as the reference for adjusting the speech level for external STIPA signal in the car. The third speech level has been produced by the dummy head. The spectrum of the artificial mouth has been adjusted according to the standard IEC 60268-16 (male weighting) and has been compared to the speech source (4720) when stimulated with the same signal for on axis octave band levels. The measurements have been repeated on 90 degrees source direction for accounting the source directionality in the STI calculations. The resulting spectrums of the three different sources (at 0 degree) have been shown in the *figure 4*.

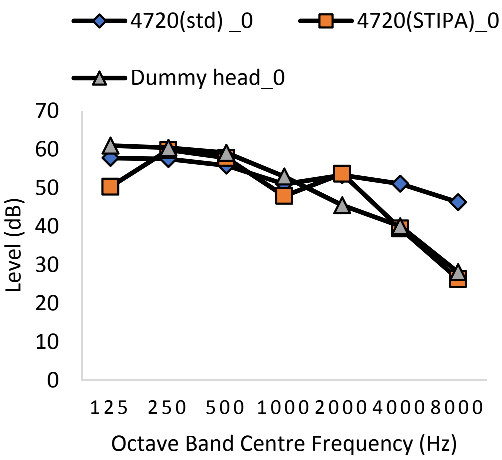


Figure 4. *Speech level spectra at the position of receiver for speech source (4720) and dummy head.*

Figure 5. *Dummy head (artificial mouth prototype-talker)*

### Impulse Response

The IR has been measured by stimulating the speech sources (4720 and dummy head) by an Exp sweep from 63Hz to 16kHz generated by aarae. Selecting the wider frequency band can reduce the fade in/out filtering and ripples effects on the 125Hz and 8kHz octave frequencies and result in higher quality impulse response. The length of the sweep has been adjusted to 60s for creating higher SNR on low frequencies. Accordingly, the swept signal has been recorded through the omni-directional mic according to the standard [4]. The impulse response has then been calculated by convolution of the recorded signal with its inverse filtering [3] and properly zero padded for covering up the lowest frequency of interest (125Hz). For enhancing the accuracy, the measurements were repeated three times and the parameters adjusted properly. Then the IR was processed with the octave filter-banks and analyzed to see if the peak to noise ratio is fine for the all octave band frequencies. The resulting SNR has been measured between 70dB to 90dB from 125Hz to 8kHz octave band frequency.

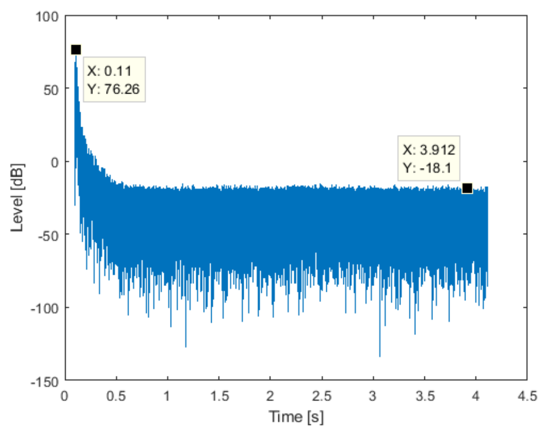


Figure 6. *Car cabin impulse response measured in a quiet area for neutral car (source: B&K 4720, Receiver: Earthworks M30)*

| Octave band f (Hz) | 125 | 250 | 500 | 1k | 2k | 4k | 8k |
|---|---|---|---|---|---|---|---|
| Reverberation time T30 (s) | 0.46 | 0.32 | 0.17 | 0.06 | 0.05 | 0.05 | 0.05 |
| Early decay time (s) | 0.23 | 0.07 | 0.03 | 0.07 | 0.06 | 0.05 | 0.06 |
| Clarity index C50 (dB) | 19.5 | 26.2 | 34.8 | 41.4 | 51.1 | 55.7 | 51.8 |

Table 1. *$RT_{30}$, EDT and $C_{50}$ calculated from the car impulse response. The low reverberation in mid and high frequencies is due to the size of the cabin and absorptive boundaries.*

## Analysis and Discussion

The octave band speech and noise levels have been analyzed through *STI-IR* (aarae) analyzer for calculating the indirect STI inside the car. The zero amount for STI has been calculated for some of the low octave band frequencies due to low frequency masking at higher background noises for higher speeds. The highest octave band STI has been calculated for 2kHz due to the highest weighting factor (alpha). *Figure 7* has depicted the calculated indirect STI in the four different situations. The STI amounts have shown a linear declination in respect to car speed increment. The measured STI for speech source in-built signal (pink MLS) has been overestimated by a factor of 0.1 at noisy situations but for steady car with engine-on the all STI amounts are close to one due to more than 15dB signal to noise in the important octave band frequencies (500Hz, 1KHz and 2KHz) for STI [4]. The experiment has also shown that turning the source by 90 degrees toward the receiver position can slightly improve the STI (~ 0.04) due to the directionality of the source.

A study conducted by *Parma University* [5,6] has shown a similar trend for the STI amount in the cars which have been measured with *noise free IR*. According to the *figure 8*, only the *noise free IR* method has depicted a linear regression compared with the derived STI amounts in *figure 7*. The overestimated STI amounts in figure 8 [6] can be due to lower background noise inside the car as the car has been run over the steady roller.

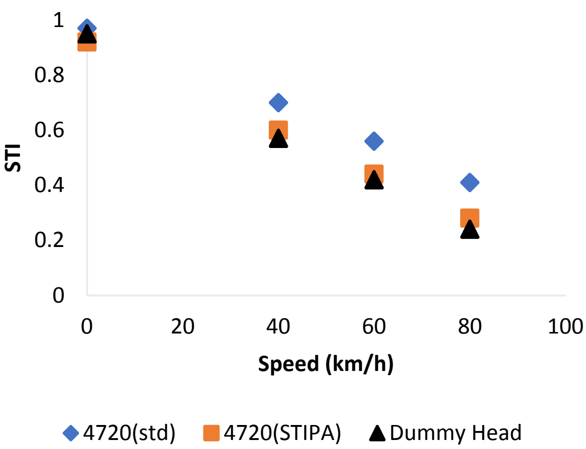


Figure 7. *The calculated indirect STI mapped for different car speeds*

| Speed/STI | Neutral | 40km/h | 60km/h | 80km/h |
|---|---|---|---|---|
| 4720 (std) | 0.97 | 0.7 | 0.56 | 0.41 |
| 4720 (STIPA) | 0.92 | 0.6 | 0.44 | 0.28 |
| Dummy Head | 0.95 | 0.57 | 0.42 | 0.24 |

Table 2. *Typical STI amounts calculated by Modulation Transfer function (MTF) method (aarae) [1]*

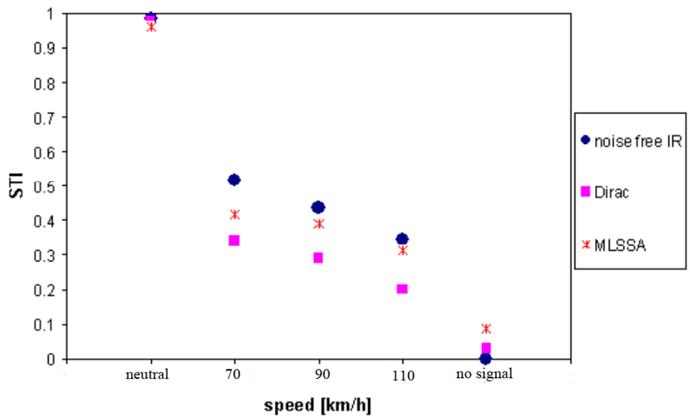


Figure 8. *The comparative STI measurement methods in the car conducted by Parma University [6]*

The measured transfer function between the source and receiver inside the car have shown similar peaks and nulls for the dummy head and 4720 speech sources except in 221Hz and 643Hz. in comparison, the dummy head has shown better linearity in frequency response (250Hz to 4K) but 4720 has shown a flatter low frequency due to high compliance in its driver.

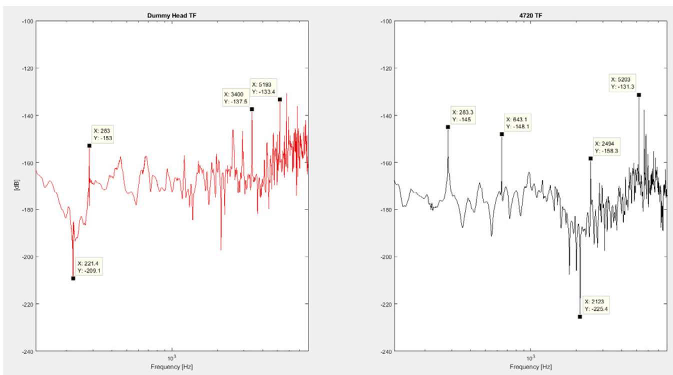

Figure 9. *Transfer function between the sources and receiver inside the car. The peaks and nulls are reviling the standing wave and resonance frequencies effects in the car cabin. The TF has been derived for a 60s Exp sweep from 50Hz to 16kHz and the convoluted IR has been truncated to 4s.*

The effect of raised level (Lombard) is not shown in the STI calculation. Obviously, increasing the level from 60dBA to 72dBA can improve the STI substantially. The noise spectrum for higher speeds has shown more power at low frequencies rather than high frequencies. So, raising the speech level and changing the formant can be helpful for improving the speech intelligibility in the cars. Higher insulation in the car cabin also can reduce the overall background noise and enhance the intelligibility and comfort inside the cars.

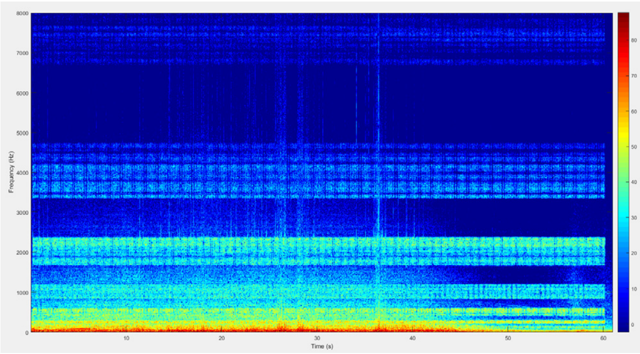

Figure 10. *Background noise masking for Lombard speech level (4720) inside the running car (0-45s) and steady car (45-60s) at 60km/h. The masking for frequencies under 500Hz is high.*

**Aarae vs Arta**

The comparative results of direct STI measurement of the following system *(figure 11)* between two software aarae and Arta [7] has been shown in *table 3*.

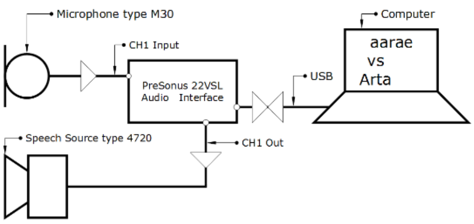


Figure 1. *Direct STI measurement schematic in a hall room (~ 100 m^3).*

Both systems have been measured under similar conditions using the method suggested by IEC 60268 [4]. According to [4] the STI method cannot produce similar results by repetition as the test signal is band-limited random or pseudo noise like signal. The STI direct test signal in arrae has been created by generating 7 STIPA like signals (option 0, fast calculation) and the test signal in Arta is a spectrum adjusted noise like signal. According to the results *(table 3),* the STI amounts are overestimated by Arta at low and high frequency octave bands due to variation in background noise or different calculation methods but the calculated STI male for both methods are very close to each other. In comparison Arta is much faster for direct method, probably because it is a computer-based software and arrae is based on Matlab.

| Octave band frequency / STI | aarae | Arta |
|---|---|---|
| 125 | 0.26 | 0.65 |
| 250 | 0.78 | 0.82 |
| 500 | 0.87 | 0.87 |
| 1000 | 0.86 | 0.87 |
| 2000 | 0.9 | 0.89 |
| 4000 | 0.87 | 0.89 |
| 8000 | 0.87 | 0.73 |
| STI male | 0.8529 | 0.8518 |

Table 4. The results of direct STI measurements in the same situations for aarae and Arta (Audio measurement and analysis software)

In conclusion the STI in the car can change from excellent to poor due to increasing the background noise by speed and road factors. The precision of STI methods are not absolute and the randomness in the test signals and background noise can affect the STI ratings.

**References**

[1] Cabrera, D. (2018). *Audio Systems and Measurement – DESC9090 (Week 3- Speech Transmission Index)*- Power point slides

[2] Cabrera, D. (2018). *Audio Systems and Measurement – DESC9090 (Week 6- Measuring Noise and Time-variance in Audio Systems)*- Power point slides

[3] Cabrera, D. (2018). *Audio Systems and Measurement – DESC9090 (Week 5- Linear Time-Invariant (LTI) Audio System Measurement)*- Power point slides

[4] CODE, P. (2003). Sound system equipment–Part 16: Objective rating of speech intelligibility by speech transmission index.

[5] Farina, A., & Bozzoli, F. (2002). Measurement of the speech intelligibility inside cars. *PREPRINTS-AUDIO ENGINEERING SOCIETY.*

[6] Farina, A., Bozzoli, F., & Strasser, P. (2003). Comparative study of speech intelligibility inside cars. *EuroNoise03*.

[7] Mateljan, I. (2018). Audio Measurement and Analysis Software (Version 1.9.1) [Windows]. ARTA.