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Investigation of in-vehicle speech intelligibility metrics for normal hearing and hearing impaired listeners

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INVESTIGATION OF IN-VEHICLE SPEECH INTELLIGIBILITY METRICS FOR NORMAL HEARING AND HEARING IMPAIRED LISTENERS

By

Nikolina Samardzic

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INVESTIGATION OF IN-VEHICLE SPEECH INTELLIGIBILITY METRICS FOR NORMAL HEARING AND HEARING IMPAIRED LISTENERS

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DECLARATION OF PREVIOUS PUBLICATION

This dissertation includes 8 original publications (6 journal publications and 2 conference publications) that have been previously published, accepted or submitted for publication in peer-reviewed journals and conferences, as follows:

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Chapter 2, 3, 4, *Section 6.1.2*	Samardzic, N. and Novak, C. (2011) ‘Sound source signal parameters in vehicles for determining speech transmission index’, *J. Audio Eng. Soc.*, Vol. 59, No. 10, pp.1-10.	*Published*
Chapter 2, 3, 4, *Section 6.1.3*	Samardzic, N. and Novak, C. (2011) ‘In-vehicle application of common speech intelligibility metrics’, *Int. J. Vehicle Noise and Vibration*, Vol. 7, No. 4, pp.328-346.	*Published*
Chapter 2, 3, 4, 5, *Section 6.2.1*	Samardzic, N., Novak, C. and Gaspar, R. (2012) ‘The Evaluation of Speech Intelligibility in a Simulated Driving Environment Using the Hearing in Noise Test (HINT)’, *Int. J. Vehicle Noise and Vibration*, Vol. 8, No. 4, pp. 318-336.	*Published*
Chapter 2, 3, 4, *Section 6.1.4*	Samardzic, N. and Novak, C. (2011) ‘In-vehicle speech intelligibility for the hearing impaired using speech intelligibility index’, *Society of Automotive Engineers*, Paper No. 2011-01-1681.	*Published*
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ABSTRACT

The effectiveness of in-vehicle speech communication can be a good indicator of the perception of the overall vehicle quality and customer satisfaction. Currently available speech intelligibility metrics do not account in their procedures for essential parameters needed for a complete and accurate evaluation of in-vehicle speech intelligibility. These include the directivity and the distance of the talker with respect to the listener, binaural listening, hearing profile of the listener, vocal effort, and multisensory hearing.

In the first part of this research the effectiveness of in-vehicle application of these metrics is investigated in a series of studies to reveal their shortcomings, including a wide range of scores resulting from each of the metrics for a given measurement configuration and vehicle operating condition. In addition, the nature of a possible correlation between the scores obtained from each metric is unknown. The metrics and the subjective perception of speech intelligibility using, for example, the same speech material have not been compared in literature. As a result, in the second part of this research, an alternative method for speech intelligibility evaluation is proposed for use in the automotive industry by utilizing a virtual reality driving environment for ultimately setting targets, including the associated statistical variability, for future in-vehicle speech intelligibility evaluation. The Speech Intelligibility Index (SII) was evaluated at the sentence Speech Receptions Threshold (sSRT) for various listening situations and hearing profiles using acoustic perception jury testing and a variety of talker and listener configurations and background noise. In addition, the effect of individual sources and transfer paths of sound in an operating vehicle to the vehicle interior sound, specifically their effect on speech

intelligibility was quantified, in the framework of the newly developed speech intelligibility evaluation method.

Lastly, as an example of the significance of speech intelligibility evaluation in the context of an applicable listening environment, as indicated in this research, it was found that the jury test participants required on average an approximate 3 dB increase in sound pressure level of speech material while driving and listening compared to when just listening, for an equivalent speech intelligibility performance and the same listening task.

DEDICATION

Драга моја дјецо, Стефане и Ана, овај рад посвећујем вама.

Ви сте мој највећи дар од Бога, а године проведене с вама завршавајући овај рад су биле најљепше у мом животу.

My dear children, Stefan and Ana, I dedicate this work to you.

You are my greatest gift from God, and the years I spent with you while completing this work were the best years of my life.

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I would like to thank my husband, Igor, for his love, support and understanding, to my sister Irena, for her support and friendship, and to my parents, for all their love, support and sacrifices throughout my life.

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NOMENCLATURE

AI	Articulation Index
SII	Speech Intelligibility Index
STI	Speech Transmission Index
α	Octave weighing factor used in STI calculations
β	Correction for the contribution of adjacent frequency band used in STI calculations
HINT	Hearing in noise test
HL	Hearing level
I_i	Input signal with a sinusoidal intensity modulation
I_o	Output signal with a sinusoidal intensity modulation
SNR	Signal to noise ratio
MTI	Modulation transmission index
MTF	Modulation transfer function
TI	Transmission index
$m(F)$	Modulation transfer function
m_i	Modulation index of the source signal
m_o	Modulation index of the receiver signal
F	Modulation frequency
$h_f(\tau)$	Impulse response
L_{noise}	Sound pressure level of background noise

L_{signal}	Sound pressure level of signal
n	Index
NVH	Noise, vibration and harshness
$\overline{X_i}$	Subgroup average
$\overline{\overline{X}}$	Subgroup grand average
s_i	Subgroup standard deviation
$\bar{s}$	Average subgroup standard deviation
sSRT	Sentence speech reception threshold
i	Data index
j	Data index
k	Data index
A_3	Control chart factor
B_3	Control chart factor
B_4	Control chart factor
LCL	Lower control limit
UCL	Upper control limit
W_i	Frequency weighing factor for AI calculations
L_{si}	Speech spectrum level for AI calculations
L_{p_i}	Background noise spectrum for AI calculations
I_i	Band importance function for SII calculations
A_i	Band audibility function for SII calculations

E_i	Speech spectrum level for SII calculations
D_i	Disturbance level for SII calculations

CHAPTER 1: Introduction

Our sense of hearing is undeniably essential for fully experiencing the physical changes of the world that surrounds us. The ability to hear these changes enhances our quality of life and drives the need to communicate with other individuals, most often through speech. Speech communication is one of the fundamental mechanisms of human interaction. In addition to being audible, effective speech communication needs to be intelligible, or capable of being understood.

Generally, the effectiveness of speech communication depends on the parameters associated with the talker, or sound source, the listener, or sound receiver, and the surrounding environment in which they are located. Often, these parameters are used in order to evaluate the objective or subjective effectiveness of speech communication. The results of this evaluation may be obtained through a variety of methods, standardized or unstandardized, and are all termed “speech intelligibility”.

Using the currently available evaluation methods, the assessment of these parameters is often incomplete or inapplicable to a variety of practical listening situations. A complete assessment of all the parameters affecting speech intelligibility in the context of a particular listening environment is essential for an accurate evaluation of speech intelligibility. For the example of speech intelligibility inside an operating vehicle in the presence of background noise, these parameters can include the directivity of the talker with respect to the listener, the distance between the talker and the listener, binaural listening, hearing profile of the listener, vocal effort, and multisensory hearing. Currently, there are no published methods for speech intelligibility evaluation to account for all of these parameters. In addition, there are no available methods for quantifying the statistical variability associated with the evaluation of speech intelligibility. The lack of these is the main motivation for the work presented in this dissertation.

In today's society, a vehicle interior has become a common communication environment. The intelligibility of in-vehicle communication can potentially influence the overall comfort of the occupants and their perception of the overall quality of the vehicle. Such communication may involve either the use of the many currently popular in-vehicle communication systems or person-to-person communication. Despite the technological advancements that provide alternative ways of communicating, the person-to-person communication is still the most basic means of human interaction. For the increasing number of senior aged drivers, the ability to hear speech sounds clearly permits individuals to converse and, consequently, provide an increased sense of independence and quality of life. For many families, the conversations during the daily commute to and from work or school can be important opportunities to remain connected. In addition to facilitating social interaction, in-vehicle person-to-person communication may also carry important safety information. Cheesman and Jennings (2009) found that despite an awareness of speech communication difficulties in cars, little research on interpersonal speech communication exists in the literature. There is though a large and growing body of research focused on in-vehicle machine to human communication and automated speech recognition systems, which are direct applications for vehicle navigational and control systems. For example, McKeown and Isherwood (2007) investigated speech, environmental sounds, auditory icons and abstract synthetic warnings as candidates for within-vehicle interfaces and found that speech and auditory icons produced both the fastest response times and greatest accuracy. Although the focus of this research is for person to person communication, the methodology presented in the upcoming chapters related to in-vehicle speech intelligibility evaluation, including the evaluation of the statistical variability, may be applicable to any other speech communication situation and the communication environment.

Speech intelligibility may be evaluated subjectively using listening tests or objectively using speech intelligibility metrics. The objective approach is often preferred, as it is often more practical, but a good correlation with subjective speech intelligibility measures is critical and not always found.

All objective speech intelligibility metrics require that a speech signal associated with a particular level of vocal effort to be specified in their analysis. The results from these metrics are presented in terms of a score ranging from zero to one and interpreted based on the subjective descriptions of scores associated with a particular evaluation method or a standard, if such descriptions are available. An alternative presented in this work to using a particular vocal effort in the evaluation and later interpretation of objective speech intelligibility scores is to consider the sentence speech reception threshold, as routinely used in the fields of audiology and speech audiometry. The sentence speech reception threshold (sSRT) is defined as “the minimum hearing level for speech at which an individual can recognize 50% of the speech material” (ASHA, 1988). Utilizing the sSRT eliminates the need for the subjective interpretation of scores by, instead, characterizing the human speech hearing ability in the presence of noise, and the associated variability. For sentence-type tests typically used to measure sSRT, there is a point (a sound pressure level) after which the speech is understood in its entirety. Below that point, it is not fully understood. This speech intelligibility evaluation method is easy to understand, simple and universally applicable. The speech and background noise conditions at sSRT may then be used to calculate the objective speech intelligibility metric of choice and the associated variability.

In this context, the basis of this work is to evaluate the decrease of in-vehicle speech intelligibility within a simulated driving environment using acoustic perception jury testing to set targets for future in-vehicle speech intelligibility evaluation. In addition, a simulated driving environment may also be used to account for multisensory listening and to investigate whether or not, when presented with the same listening task, a listener would require a change in sound pressure level of the speech material while driving and listening compared to when just listening for an equivalent speech intelligibility performance. Consequently, the associated potential increase in sound pressure level could also be quantified. The multisensory context of the driving experience and its impact on the in-vehicle speech intelligibility would be evaluated in the presence of combined stimuli, including the background noise as well as driving tasks including steering, throttle control, braking and visual stimuli.

Meston et al (2011) suggested that with an aging population, the number of older drivers would continue to increase, with their many health related factors, such as hearing loss, vision loss, cognitive changes, and central processing deficits that can affect driving. Consequently, as individuals get older they may rely more heavily on passengers while driving to help with various driving tasks. In addition, car-buying demographics now include an increasing population of the hearing impaired individuals, regardless of age. Therefore, it is important to incorporate the effects of hearing profiles changes due to hearing loss in the investigation and the evaluation of in-vehicle speech intelligibility, so that both normal and hearing impaired individuals are included in any acoustic perception jury testing.

Background noise is one of the most significant contributors to decrease of speech intelligibility inside a vehicle. Due to this, the inside of the vehicle can be a challenging communication environment for both normal hearing and hearing impaired individuals. The sound pressure levels of background noise at different locations inside the vehicle depend on the magnitudes and directions of the various structure-borne and air-borne sources of excitation. These excitation sources can include road noise, engine noise, transmission noise, intake and exhaust noise as well as aerodynamic noise sources. The resulting background sound pressure levels are also influenced by the amount of attenuation provided by the vehicle noise control components from these sources of excitation to the receivers inside the vehicle. The attenuation is directly related to the sound propagation and the sound absorption and transmission loss characteristics of the individual vehicle noise control components. The results of this work provide a possibility to explore the effect of the individual sources and transfer paths of sound to the vehicle interior sound, specifically their effect on speech intelligibility, thus offering a potential for vehicle sound package design changes for improving the effectiveness of in-vehicle communication.

The objectives of this dissertation are to:

- Quantify in-vehicle speech intelligibility using the most comprehensive objective speech intelligibility metric - the Speech Transmission Index (STI) - for a variety of vehicle operating conditions, road surface profiles and talker and listener configurations (Section 6.1.1).

- Investigate the effects of sound source signal parameters associated with vocal effort and various measurement techniques used to evaluate the STI (Section 6.1.2).
- Quantify the effectiveness of in-vehicle communication using the better known objective speech intelligibility metrics, compare the metrics’ results, and identify any shortcomings associated with each metric to lay the ground for developing an alternative, novel method for a complete and accurate speech intelligibility evaluation (Section 6.1.3).
- Investigate in-vehicle speech intelligibility using the Speech Intelligibility Index (SII) and the hearing profiles associated with common hearing impairments (Section 6.1.4).
- Quantify the effect of multisensory hearing on speech intelligibility by incorporating visual stimuli and performing tasks such as controlling the vehicle steering, throttle and brake as found in an actual driving situation, using a hearing in noise test within the simulated driving environment.
- Develop a novel method for a complete and accurate speech intelligibility evaluation for the automotive industry using a virtual reality driving environment and acoustic perception jury testing to ultimately set targets. This will include investigating the associated statistical variability for future in-vehicle speech intelligibility evaluation (Chapter 5, Section 6.2). For this the background noise measurements used in creating the simulated driving environment were obtained using a vehicle dynamometer.

- Develop a second driving simulator model for use with jury test participants having various hearing profiles and on-road interior sound measurements so as to include the effects of vehicle wind noise. Using the proposed novel method, evaluate in-vehicle speech intelligibility.
- Quantify the effect of the individual automotive sources of sound to the resulting vehicle interior sound, specifically their effect on speech intelligibility in the context of the above speech intelligibility evaluation method (Section 6.2.4).

Table 1 provides an overview of the research.

Table 1: Research Overview

Section			6.1.1	6.1.2	6.1.3				6.1.4	6.2.1	6.2.2	6.2.3
Objective Speech Intelligibility Metrics/Methods			STI	STI	STI	SII(nve[1])	SII(m[2])	AI	SII	sSRT	SII at sSRT[3], Statistical Variability (Control Limits)	SII at sSRT
Background Noise Signal	Vehicle Dynamometer, Roll Surface	Smooth	X	X	X	X	X	X	X	X	X	
		Rough	X		X	X	X	X	X			
	On-road											X
Speech Signal	Measured	60 dBA	X	X	X		X					
		68 dBA		X								
		Hearing in Noise Test								X	X	X
	Fixed	60 dBA				X						
		82 dBA						X				
Assumed Common Listener Hearing Impairements									X			
Acoustic Perception Jury Test within a Driving Simulator	Normal Hearing Jurors									X	X	X
	Hearing Impaired Jurors											X

[1] normal vocal effort

[2] measured speech signal

[3] sentence speech reception threshold

It should be noted that the jury evaluation components of this study underwent a rigorous review and were approved by the University of Windsor Research Ethics Board.

CHAPTER 2: Literature Review

The following is a literature review of the existing objective and subjective speech intelligibility evaluation methods as they apply to the evaluation of in-vehicle speech intelligibility. The evaluation methods associated with each of the objective metrics considered are reviewed in order to expose the absence of consideration of some or all of the critical parameters necessary for a complete and accurate in-vehicle speech intelligibility evaluation. As indicated in Chapter 1, these parameters include the directivity of the talker with respect to the listener, the distance between the talker and the listener, affects of binaural listening, hearing profile of the listener, vocal effort and multisensory hearing. A rigorous search failed to find any published methods for speech intelligibility evaluation which account for all of these parameters. In addition, no published studies were found on the statistical variability associated with in-vehicle speech intelligibility evaluation. A suggested alternative to the current state of art, as presented in this work, is the development of a driving simulation to measure the ability to hear speech in the presence of noise using a popular speech test common in the fields of audiology and speech audiometry known as the hearing in noise test (HINT). As such, an overview of research supporting the potential benefits of incorporating a driving simulation in the evaluation of in-vehicle speech intelligibility is presented. The background noise measurement considerations required for the development of a driving simulation, including the effects of wind noise and the effect of vocal effort on the objective evaluation of in-vehicle speech intelligibility are also presented. In addition, an overview of the vehicle acoustics applications of statistical variability analysis is provided. It includes a discussion of the potential benefit of using control charts in quantifying variability associated with in-vehicle speech intelligibility evaluation. Also, an overview of past research related to in-vehicle speech intelligibility for hearing impaired individuals is presented. Lastly, it should be noted that another aspect of speech communication quality assessment is speech privacy. Due to its lesser significance for automotive acoustics applications, it is not being considered in this research.

2.1 Objective Evaluation of In-vehicle Speech Intelligibility

Articulation index (AI), speech intelligibility index (SII) and speech transmission index (STI) are the most common objective speech intelligibility metrics used. These metrics involve values with a range from zero, indicating unintelligible speech, to one, indicating excellent speech intelligibility. Data requirements vary depending on the type of metric and the calculation method. All three methods account for the effects of the speech signal to background noise ratio on the reduction of speech intelligibility, and therefore, all three methods utilize background noise measurements in their calculations. The AI method also utilizes a fixed speech spectrum. The SII method allows for both a fixed and measured speech spectrum in the procedure, as described in the ANSI S3.5-1997 standard. The STI method based on the IEC 60268-16:2003 standard utilizes a measured speech signal. This method also accounts for the effects of the enclosure on the resulting reduction of speech intelligibility from reverberation and echoes. However, a recent study showed that for in-vehicle applications, this effect is indeed negligible (Samardzic and Novak, 2011b). The main factor influencing a decrease in the apparent signal to noise ratio responsible for the loss of speech intelligibility is due to background noise in the vehicle interior at different vehicle operating conditions. Qatu et al (2009) classified the vehicle interior noise according to its various sources, mainly the powertrain, road, tire and wind noise, and provided an overview of vehicle design issues related to vehicle interior sound quality. Samardzic and Novak (2009) quantified the contributions of engine radiated sound and mount vibration to the overall vehicle interior sound and vibration using transfer path analysis. This contribution is often strongly dependent upon the vehicle's vibroacoustic attenuation characteristics, including the damping package design of the vehicle's sheet metal (Samardzic and Sergiyenko, 2008, 2009).

Although the same level and spectrum of background noise can be used in the calculations of the three metrics, each method has its own calculation algorithms, frequency band weighing factors and usually speech spectra as well and, as a result, may yield different predictions for speech intelligibility. For example, although the SII and AI methods both utilize a fixed speech spectrum, the former accounts for the distance between the talker and the listener but does not account for the effects of directivity and binaural listening on the perception of speech intelligibility, much like the AI method. Bozzoli et al (2005) showed that the directivity of the talker inside a vehicle has a significant impact on the STI calculation results. The study suggested that for room acoustics applications the impact of the directivity of the talker is not critical for STI calculations due to, typically, a relatively large distance between talker and listener and, typically, a large amount of reflections. Similarly, in telecommunications acoustics, the proximity of the receiver microphone is associated with only the near field impact on speech intelligibility. For in-vehicle applications, as for small room applications, the distances between talker and listener are less than two meters but more than a few centimeters, and the whole directivity pattern of the talker is significant for in-vehicle STI evaluation.

Genuit (2004) acknowledged that binaural signal processing is essential for speech communication in a noisy environment, such as a vehicle interior; the two auditory channels allow for spatial discrimination essential for pattern recognition, as well as directional hearing, selectivity and suppression of noise. The study also suggested that, in contrast to a typical measuring microphone with linear, frequency independent response for all directions of sound incidence, the outer ear is a directional filter which is able to change the sound pressure level at the ear drum by +15 to -30 dB, depending on the frequency and direction of sound incidence. According to the same study, the filtering is due to the ear pinna, head, shoulder and torso geometry, which is dependent on the direction of sound, and resonances, which are independent of the direction of sound. This emphasizes the importance of binaural measurements using, for example, a head and torso simulator. In addition, Shinn-Cunningham (2003) stated that for a target (speech) signal near threshold, binaural spatial processing, i.e. combining information across the two ears, provides a performance improvement equivalent to increasing the speech audibility.

A systematic evaluation of speech intelligibility for a variety of applicable configurations of the talker and listener's locations inside a vehicle, considering binaural speech and background noise measurements has not been found in literature. Such evaluation would also require a consideration for a variety of the available speech intelligibility metrics' calculation methods. For example, in addition to speech and background noise measurements, depending on the selected measurement procedure, the STI metric calculation may require impulse response measurements to account for the effect of reverberation on the reduction of speech intelligibility.

2.1.1 Articulation Index

Articulation index was originally developed by French and Stenberg (1947) in order to predict speech intelligibility. It was later modified by Kryter (1962). The best known method for calculating articulation index is based on the ANSI S3.5-1969 standard. It requires a measurement of the C-weighted speech signal, and adjusting the idealized speech spectrum by the difference between 65 dB (standard speech spectrum overall level) and the measured C-weighted overall level. Examples of additional corrections include non-anechoic conditions and maximum allowed overall level. There were no published studies found on the implementation of this method in the automotive industry. Instead, the work by Beranek (1947) is often referenced in many automotive noise, vibration and harshness (NVH) software packages to describe the articulation index calculation procedure, although references regarding the origin of the reference idealized speech spectrum and the frequency band weighing factors used in the calculations are not provided. The reference idealized speech spectrum and the frequency band weighing factors are also quite different from those specified in the ANSI S3.5-1969 and ANSI S3.5-1997 discussed in the next section and appear to be customized for vehicle applications. In addition, no published studies were found to describe the correlation of intelligibility scores to subjective speech intelligibility measures. In comparison, these correlations are available in both the ANSI S3.5-1997 and IEC 60268-16:2003 standards describing the SII and STI metrics, respectively.

Articulation index is the most commonly used speech intelligibility metric in the automotive industry, however, due to its simplicity, there are several limitation associated with its application. The reference idealized speech spectrum has an overall level of 82 dBA, presumably referring to a free field measurement at a one meter distance from the talker’s mouth. This value is significantly higher compared to 60 dBA used in the ANSI and IEC standards describing the SII and STI metrics also used in this study. In addition, the AI spectrum is fixed, without considerations for the effects of the directivity or the distance between the talker and the listener in different locations, all having a significant impact on speech intelligibility, particularly for in-vehicle applications. The same spectrum is assumed for both male and female speech. Also, the method does not account for binaural listening, i.e. any difference in speech spectra at the receiver locations between the left and the right ears, also potentially influencing the perception of speech intelligibility. Still, this method was frequently used in publications related to the automotive industry over the years as one of the measures of vehicle NVH performance and, more specifically, the performance of vehicles’ acoustic package and its components. For example, Block (2001) used AI to compare the performance of the polyester acoustic absorbing materials in various applications in a sport utility vehicle relative to conventional absorbers. Connelly et al (2005) calculated AI to compare the performance of three vehicles tested on a chassis dynamometer. Hilyard and Cunningham (1991) used AI to rank the acoustic performance of foam backed automotive carpet systems. Lu (2008) used AI results to illustrate the improvements in speech intelligibility performance associated with acoustic windshields.

2.1.2 Speech Intelligibility Index

The SII metric calculation is based on ANSI S3.5-1997 standard and it is an update to the ANSI S3.5-1969 standard. As the new standard is a major revision, the name has changed from the Articulation Index to the Speech Intelligibility Index. Ebbitt (2009) found that the differences between ANSI S3.5-1969 and ANSI S3.5-1997 calculation results are small but potentially significant for a vehicle sound package development program. Jiao et al (2006) performed subjective listening tests and multivariate linear regression analysis to find that SII "exerts a major effect on car interior noise quality". Despite this, SII is infrequently used as a speech intelligibility metric in the automotive industry. According to the new ANSI S3.5-1997 standard, it is possible to use either a standard or user-defined speech spectrum to calculate SII. There were no published studies found in literature on the comparison of the two methods for in-vehicle speech intelligibility evaluation. The standard, fixed speech spectrum is based on a distance of one meter from the talker's mouth. As such, for in-vehicle applications, corrections would be required for the different distances between the talker and the listener inside the vehicle. For the standard speech signal there are four available spectra depending on the required vocal effort, including 'normal', 'raised', loud' and 'shout', with overall levels of 59 dBA, 67 dBA, 74 dBA and 82 dBA, respectively. For in-vehicle applications, the method utilizing user-defined spectra should be based on the speech spectrum measured binaurally at the listener's location. There were no published studies found in literature describing such application. The same speech measurements acquired for the STI calculations may also be used to calculate SII using the user-defined speech spectra method. Coincidentally, the overall level of 60 dBA associated with the STI speech measurements is similar to the 59 dBA specified for the SII standard speech spectrum overall level for normal vocal effort. Therefore, it is possible to compare the SII and STI metrics using the same speech spectrum measured at the listener's location, as well as the SII metric using the fixed speech spectrum method, all with approximately the same overall level. Again, no published studies on this type of a comparison have been found in literature.

The SII method may also account for special cases with variations in hearing threshold levels of a listener (Samardzic and Novak, 2011a) and insertion gain for hearing-aid devices worn by a listener.

Rhebergen and Versfeld (2005) developed a method to predict SII in nonstationary noise by partitioning both speech and noise signals into small time frames to calculate SII and predict the amount of speech information available to the listener at that time frame.

2.1.3 Speech Transmission Index

The STI metric was developed by Steeneken and Houtgast (1980) and was shown to be well correlated to speech intelligibility. Anderson and Kalb (1987) showed that the STI method is a valid method for testing the speech transmission of communications channels for use with the English language; previously the method has been validated only for the Dutch language (Steeneken and Houtgast, 1980). The STI method is standardized as described in IEC 60268-16:2003. Its previous uses were in the telecommunications industry and in studies of building acoustics. It has more recently been introduced to automotive applications (Farina et al, 2003; Granat, 2008; Viktorovitch, 2005) given the growing interest of in-vehicle communications. In previous studies, only selected combinations of talker and listeners locations inside a vehicle and operating conditions were used to investigate intelligibility using the STI metric (Viktorovitch, 2005), and to also study the effect a talker mouth’s directivity for a given vehicle trim components at the in-board ear (Granat, 2008).

The STI calculation method is more involved compared to the other two methods. It postulates that the reduction of speech intelligibility in an environment can be associated with the decrease of intensity of modulations from the source signal to the receiver signal. The conventional method based on IEC 60268-16:2003 standard is described in the next chapter. An alternative known as the impulse response method is used to calculate the modulation transfer function, resulting in increased repeatability and reduced measurement effort (Farina et al, 2003). The impulse response is obtained in noise-free measurement conditions. The noise-free impulse response method is used in this research for all STI calculations. In this method, the modulation transfer function, $m(F)$ at the modulation frequency F is defined at each octave band frequency as:

$$m(F) = \frac{\int_0^\infty h_f^2(\tau)\exp(-j2\pi Ft)d\tau}{\int_0^\infty h_f^2(\tau)d\tau} \frac{1}{1+10^{\left(\frac{L_{noise}-L_{signal}}{10}\right)} \qquad (2.1)$$

Here, $h_f(\tau)$ is the impulse response and L_{noise} and L_{signal} are the sound pressure levels of background noise and the signal at a particular octave band, respectively; The modulation transfer function is required for each octave band frequency used to calculate the STI. Farina et al (2003) also compared STI calculations using the impulse response measured in noise-free conditions as well as in background noise. The noise-free impulse response method resulted in a lower standard deviation of the STI, particularly at low signal-to-noise ratios typically associated with in-vehicle listening environment.

The modulation frequency, F, ranges from 0.63 Hz to 12.5 Hz in one third octave intervals, and octave band frequency , k, ranges from 125 Hz to 8000 Hz for male speech signal and 250 Hz to 8000 Hz for female speech. The above expression accounts for the effects of both reverberation (first term) and background noise (second term) on reducing the speech intelligibility. For in-vehicle applications, the impact of the reverberation term on the STI should be quantified; in case it is found that the impact is negligible, likely due to the highly absorptive automotive interiors and their small volume, the first term of the above equation can potentially be neglected in order to reduce the measurement effort, and to only consider the effects of background noise.

Another alternative to evaluating STI and reducing the measurement effort was proposed by Li and Cox (2001) who used the convolutions of anechoic speech signals and impulse responses of rooms to train an artificial neural network. A multi-layered feed forward neural network trained by back-propagation was used to estimate STI received by a microphone in rooms. It was also acknowledged that the current neural network could not effectively identify the spectral difference caused by different speech signals.

Balasubramanian et al (2011) used the virtual ray tracing simulation method for predicting in-vehicle STI and identifying the effect of change in acoustic properties of high contribution components to STI. However, a good correlation between the simulated and measured STI impacts was shown only for a limited number of components.

Humes et al (1986) suggested that a potentially important difference between the SII and STI is that the latter is only an octave-band procedure. This may be a drawback during abrupt changes in signal spectrum, including abrupt changes in audiometric configuration for the hearing impaired listeners.

2.2 Subjective Evaluation of Speech Intelligibility in an In-vehicle Environment

A couple of recently published studies described below dealt with the subjective evaluation of in-vehicle speech intelligibility. The second study provided the basis for developing the evaluation method for speech intelligibility in a simulated driving environment presented in this research.

Balasubramanian et al (2011) compared the STI predictions with the ratings for the ease of conversation for four test vehicles from 1 (best) to 4 (worst) as rated by twelve panelists. This kind of a comparison is in contrast to the method used in the IEC 60268-16:2003 standard where the intelligibility scores from the subjective intelligibility measures are compared and correlated to the STI calculations. In this study, word lists from the Modified Rhyme Test (MRT) utilizing similar-sounding monosyllabic English words in a carrier sentence were used. Prior to this study, the results of the MRT have not been compared to any of the standards or publications associated with the common objective speech intelligibility metrics, including the STI. A head and torso simulator used as the talker was positioned in the passenger, front, right location and the panelist was in the passenger, rear, left location with the vehicle being driven at 120 km/h on a smooth road. There was no data reported either for the sound pressure level of the speech material played inside the vehicle or, from the performance of the panelists in terms of their intelligibility scores from the MRT.

In another recent study, Sudirga et al (2011) used the Hearing in Noise Test (HINT) to quantify in-vehicle speech intelligibility. The test setup and vehicle operating conditions described in previous studies (Samardzic and Novak, 2011a, 2011b, 2011c, 2011d), utilizing a mid-size sedan in a semi-anechoic dynamometer test cell was replicated in

Sudirga’s study which used the same test vehicle and operating conditions. Each of the nine jury participants was positioned in the driver’s seat and a Bruel and Kjaer (B&K) 4128 Head and Torso Simulator (HATS) was used to present speech sounds from the various passenger positions (front right, rear right and rear left). The necessarily sentence recognition task associated with the HINT was performed on both smooth and rough dynamometer rollers, at 50 km/h and 100 km/h.

In this research, in-vehicle speech intelligibility associated with person-to-person communication was evaluated by implementing the HINT in a driving simulator. This provided the means of comparing the results to the HINT test from the previously mentioned study by Sudirga et al (2011).

2.3 The Use of a Driving Simulator in the Evaluation of In-Vehicle Speech Intelligibility

Vehicle driving simulators provide a variety of purposed uses: drivers’ training, research of drivers’ response to different driving conditions, vehicle design and verification, including NVH aspects, or simply entertainment. Norfleet et al (2009) investigated three driving simulators in terms of their ease of use, user-interface, motion/vision agreement, vehicle dynamics, haptic feedback, traffic scenarios, realism, mobility, and programmability. The same study provided examples of various driving simulator applications including vehicle development, in-vehicle system design, psychology and human factors research, education and training, traffic control improvements and entertainment. Bhise and Bhardwaj (2008) compared driving behavior and performance of drivers in two different fixed-base driving simulators while performing the same set of distracting tasks under geometrically similar freeway and traffic conditions. Kolich (2003) used a driving simulator for the automotive seat comfort development.

For the automotive industry, the NVH driving simulator provides a means to evaluate the vehicle interior sound quality as one of the main factors affecting the customers' perception of the overall vehicle quality. The traditional subjective evaluation of the vehicle interior sound consists of jury testing in quiet listening rooms using pre-recorded sounds replayed in exactly the same manner for each juror through the headphones. In reality, the sound perceived in an operating vehicle is a function of continuously changing parameters such as the throttle position, steering, the physical environment such as the weather and traffic, the visual and vibration stimuli, listener's attitude and expectations and others. Therefore, the main advantage in creating a simulated driving environment for evaluating the speech intelligibility would be to account for the multisensory context of the driving experience and to, therefore, more accurately evaluate the vehicle occupants' perception of speech intelligibility in presence of the vehicle interior background noise. Qatu et al (2009) classified the vehicle interior noise based on the root cause of the NVH phenomenon into powertrain, road, tire, wind, brake, chassis, squeak and rattle and electromechanical noise.

According to Genuit and Fiebig (2007), the consideration of combined stimuli that affect various senses is imperative for properly capturing the perception relevant phenomena. Genuit (2004) also stated that speech communication in a noisy environment is only possible through binaural signal processing. Ellermeier and Legarth (2006) found there was a moderate but a significant visual bias in an experiment in which sounds submitted for sound-quality evaluation were accompanied by pictures showing suggestive images of the supposed sound source. This visual bias effect was equivalent to a level change by 2-3 decibels. For this research, a simulated driving environment was created using a B&K Desktop NVH Simulator at the University of Windsor. The desktop simulator used in this research did not capture the influence of vibration on the perception of sound; however, this influence is not significant. According to Amman et al (2005), there is little evidence that vibration can significantly affect the perception of sound; some studies show that the judgment of sound is not dependent on perceived vibration while others do not. The same study also concludes that any existing evidence indicates that at low levels of vibration, the sound caused a reduction in vibration annoyance while at high vibration levels, sound increased the level of vibration annoyance. For this research, the assumption is that the physical vibration present during constant city and highway speed driving on a smooth road that does not manifest as airborne excitation would not affect the perception of sound or the speech intelligibility. Therefore, at these driving conditions, the Desktop NVH Simulator would be an adequate sound evaluation tool for in-vehicle speech intelligibility in the presence of combined stimuli, including the background noise, steering, throttle, braking and visual stimuli.

There are several published studies from the automotive industry involving applications of the particular NVH simulator used in in this research. Allman-Ward et al (2003) explained the need for interactive NVH simulation using sound decomposition and synthesis and interactive sound replay. This work described the early development of the NVH Simulator used in this study for the evaluation of design alternatives under realistic driving conditions using both the engineering specialists and non-specialists, such as customers, for jurors. Williams et al (2005) used the NVH Simulator for powertrain, sound quality, target setting and the evaluation of concept Computer Aided Engineering (CAE) models. Dunne et al (2007) also used the NVH Simulator by modifying acoustic features interactively in order to instantly subjectively evaluate their effect on the overall character of the target sounds. Quinn et al (2009) used the NVH Simulator approach to obtain the target sound generated by a secondary air intake system.

The method proposed by Crewe et al (2003) for decomposing component sounds from a single operating measurement can provide an accurate sound synthesis of the sounds for use in driving simulators. The sound decomposition method is an alternative to combining multiple test results where influence of one source is enhanced while the other sources are suppressed. This is the case of towing the test vehicle on a rough surface for road noise to eliminate the affects of the engine noise or measuring noise interior wind noise by putting the vehicle in a wind tunnel. These all may provide inaccurate results and at a higher cost (Crewe et al, 2003).

In the field of psychology, the results from a study published on the subject of driving and speech intelligibility by Becic et al (2010) are particularly relevant. In this study, the participants, drivers and their conversation partners, were engaged in a story-retelling task using a driving simulator. They found that language production and comprehension are less accurate when one is driving. The decline in accuracy included the driver's storytelling and their memory for stories related to them by their non-driving partners. However, the loss of intelligibility was not quantified by any physical acoustic parameters such as the known objective metrics or the subjective methods for the evaluation of speech intelligibility. There are no published studies on the use of the NVH

Simulator, or any other simulated environment, for the evaluation of in-vehicle speech intelligibility.

2.3.1 Background Noise Measurements Including the Effects of Wind Noise

The reduction of in-vehicle speech intelligibility can be caused by numerous sources of noise including wind, road, tire, powertrain, intake and exhaust system noise as well as its operating conditions and the overall design of the vehicle. Background noise measurements obtained from previous studies by Samardzic and Novak (2011a, 2011b, 2011c, 2011d) and Samardzic et al (2012) were conducted using a small sized sedan in a semi-anechoic vehicle dynamometer test cell which did not account for the contribution to the vehicle interior wind noise and the reduction of in-vehicle speech intelligibility. Qatu et al (2009) showed that at high speeds above 90 kph the wind noise is a dominant source to the vehicle interior background noise. According to Her et al (1997), wind noise reaches the vehicle interior through aerodynamic excitation of the exterior surfaces of the vehicle, acoustic transmission through door seals, including gaps and glass edge leaks, and also from airborne transmission of noise generated by wind interaction with body panels. The characterization of the impact of wind noise on the vehicle interior sound quality is a popular research topic in the automotive industry, as seen from the studies listed next. However, there are no published studies to describe the impact of wind noise on in-vehicle speech intelligibility. Hoshino and Katoh (1999) developed an objective method to evaluate wind noise levels in the vehicle passenger compartment by considering the human hearing properties of auditory masking and sound localization. Coney (1999) showed that the air flow under the vehicle chassis and wheel wells as well as radiation from the roof and seal aspiration are significant contributors to the vehicle interior noise. Li et al (2006) investigated the distribution of wind noise sources and its generation mechanisms experimentally and using computational fluid dynamics (CFD). Jeong et al (2007) investigated roof rack and cross bar design parameters and their influence on wind noise. Calcada and Moncao (2009) measured the sound transmission loss of different glass types and vehicle interior noise due to wind noise for proposed acoustical performance improvements and lower mass. Callister and George (1993) used statistical energy analysis (SEA) modeling to analytically predict the noise level transmitted to the passenger by using an empirical expression for the fluctuating wall pressure on the window of an automobile. Peng (2011) analyzed two SEA wind noise load cases and evaluated the results against vehicle measurements. Graf et al (2011) coupled an unsteady computational fluid dynamics (CFD) solver for the wind noise excitation to a SEA solver for the structural acoustic behaviour to predict the noise the green house region for different yaw conditions, and then validated the predictions against the wind tunnel test measurements.

In this research, a driving simulator model was created using both the vehicle dynamometer and on-road measurements to include the impact of wind noise, as well as various hearing profiles of the listener.

2.3.2 The Effect of Vocal Effort on Objective Evaluation of In-vehicle Speech Intelligibility

The sound pressure level of speech delivered by the human talker is associated with the necessary effort required to communicate intelligible speech to the listener. Inside the vehicle, the sound pressure level is influenced by the talker’s location with respect to the listener, the level of background noise, the vehicle interior acoustics, as well as the talker's individual speaking style. A previous study of speech sound pressure level inside a vehicle found 74 dBA (measured at one meter in front of the talker's mouth in free field) to be a realistic value for the situation when a talker positioned behind the driver was asked to speak "normally" (Bozzoli and Farina, 2004a, 2004b). This value is significantly higher than the 60 dBA specified by the current IEC standard for calculating STI (IEC 60268-16:2003). The previous version of the IEC standard (IEC 60268-16:1998) specified a level of 68 dBA at a "normal speaking distance". As in previous studies related to automotive STI applications utilizing this version of the standard (Viktorovitch, 2005; Granat, 2008; Bozzoli and Farina, 2004a, 2004b; Farina et al, 2003), this distance was assumed to be one meter.

The 74 dBA corresponds to a "loud" vocal effort according to the ANSI standard for calculating the SII (ANSI S3.5:1997). The same standard assigns 66 dBA for a "raised vocal effort" and 59 dBA for a "normal" vocal effort. These overall A-weighted values can be calculated from the fixed spectral density levels assumed for each vocal effort, as provided in the standard, using appropriate conversions. The overall levels reported in the standard were expressed in terms of linear sound pressure levels. Given a fixed vocal effort of the talker, however, the signal perceived by the listener may be quite different for different configurations of the talker and the listener due to the effects of the directivity and the distance between the talker and the listener, especially inside a vehicle. For this reason, the speech signal should be measured as described, for example, in the STI standard (IEC 60268-16:1998 and IEC 60268-16:2003), as opposed to assumed, for each configuration of the talker and the listener. In addition to the procedure utilizing fixed speech spectrum signals, the ANSI standard also describes a procedure using user-defined or measured speech signals.

Lastly, the AI calculation most commonly used in the automotive industry assumes speech signal spectrum level of 82 dBA. It also assumes a fixed speech signal level and does not account for the effects of the directivity or the distance between the talker and the listener associated with in-vehicle applications.

All of the different available options for speech spectra point to a need for standardizing speech level for in-vehicle speech intelligibility investigations. Ultimately, a subjective study, currently not found in published literature, seems appropriate to determine the speech sound pressure level for different talker and listener configurations and different vehicle operating conditions under which speech communication is expected to be intelligible. This is another motivation for developing the speech intelligibility evaluation method presented in this research. In addition, a study on the effect of different source signal types and levels to obtain for the calculation of objective speech intelligibility metrics such as the STI seems appropriate. Figure 1 illustrates the speech spectra associated with the various, previously mentioned, objective speech intelligibility metrics' standards.

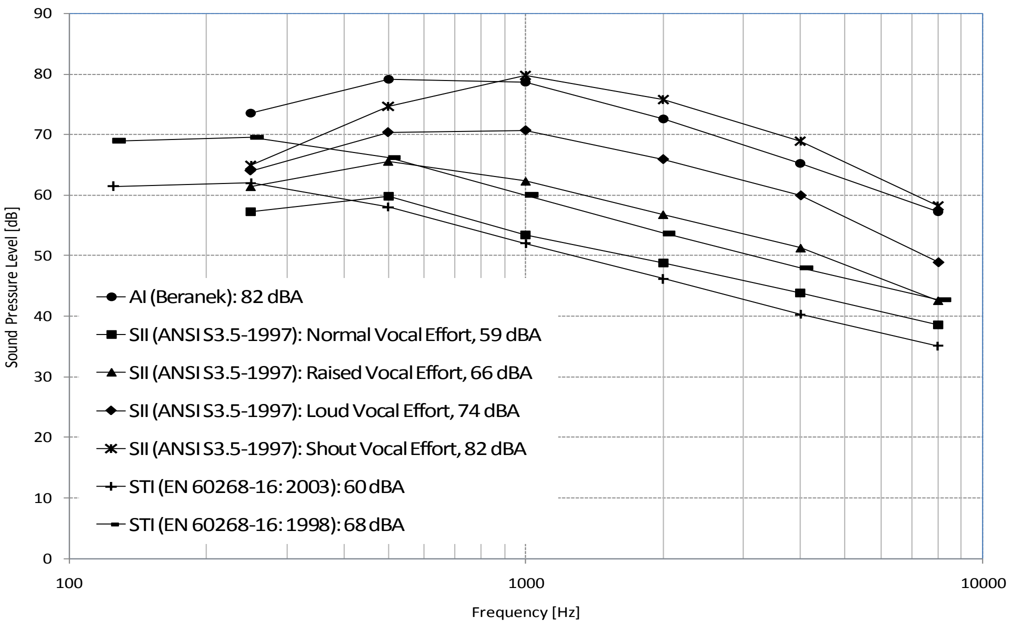


Figure 1: Speech Spectra Associated with Various Objective Speech Intelligibility Metrics.

2.4 Hearing in Noise Test (HINT)

The HINT used in this research is a popular test used in the fields of audiology and speech audiometry to measure the ability to hear speech in noise. The HINT may allow more regular and reliable assessment of the effects of noise on word recognition (Debonis and Donohue, 2007) and is one of the most common tests using sentence length stimuli (Katz et al, 2009). Nilsson et al (1994) developed the HINT by creating a large set of sentence materials selected for their uniformity in length and representation of natural speech in order to quantify the sentence speech reception threshold (sSRT). The sentences were derived from the Bamford-Kowal-Bench British sentence materials, rewritten in American English, and equated for intelligibility, uniformity in length and naturalness of speech. The resulting test consists of recordings of 250 sentences, subdivided into 25 phonemically matched and balanced lists with ten sentences per list. The SRT (speech reception threshold) is defined as the presentation level required for a listener to recognize the speech materials correctly for a specified percentage, usually 50%, of the time. Since speech materials become less difficult as they are repeated or reused, each test condition in this study included 20 unique HINT sentences, or two 10-sentence lists. Below is an example sentence list. The permitted word variations from the listeners' response are indicated in brackets; the underlined words were used in the recordings in this study.

1. *(A/the) boy ran down (a/the) path.*
2. *Flowers grow in (a/the) garden.*
3. *Strawberry jam (is/was) sweet.*
4. *(A/the) shop closes for lunch.*
5. *The police helped (a/the) driver.*
6. *She looked in her mirror.*
7. *(A/the) match fell on (a/the) floor.*
8. *(A/the) fruit came in (a/the) box.*
9. *He really scared his sister.*
10. *(A/the) tub faucet (is/was) leaking.*

The derivation of the sSRT uses an adaptive procedure where the level of presentation of the speech material is increased or decreased by a fixed amount, depending on the listener's ability to repeat the sentence correctly. Nilsson et al (1994) justifies the many advantages of the HINT compared to the other available subjective speech intelligibility tests.

Despite these advantages the results of the HINT have not previously been compared to any of the other objective speech intelligibility metrics mentioned above. In addition, they have not been mentioned in the standards associated with these metrics, mainly the IEC 60268-16:2003 and ANSI S3.5-1997 for the STI and the SII metric, respectively. For example, the IEC 60268-16:2003 provides a relationship between the intelligibility scores from several subjective intelligibility measures including the phonetically balanced (PB) words test, Consonant Vowel Consonant (CVC) words test and sentence intelligibility based on the SRT test. The reference for the SRT test, however, is not provided in the standard. For that reason, it cannot be associated with the HINT method that also involves determining the SRT. The ANSI S3.5-1997 standard provides band importance functions for various nonsense syllable tests, PB words tests, Diagnostic Rhyme Test, short passages of easy reading material and SPIN monosyllables. No published studies were found on the derivation of the HINT band importance function, or its application to any other objective speech intelligibility metric with the exception of the study by Eisenberg et al (1998) who used HINT in speech-shaped noise to compare subjective judgments of clarity and intelligibility for the same speech material and experimental conditions. The clarity and intelligibility ratings were highly related but differed in magnitude. As such, caution is needed when substituting clarity for intelligibility. Nevertheless, according to the ANSI S3.5-1997, the band importance function for average speech provides accurate predictions across different communication situations and for communications situations where contextual, linguistic, semantic and syntactic constraints vary within a situation. Therefore, for studies utilizing HINT for SII calculations, it seems appropriate to use the band importance function for average speech, as specified in the ANSI S3.5-1997 standard. Nevertheless, the impact of different band importance functions in the evaluation of the SII using the HINT in a driving simulator should be investigated to determine the sensitivity of the SII to the band importance function particularly for constant background noise conditions associated with driving vehicle at a constant speed as presented in this research.

2.5 Vehicle Acoustics and Statistical Variability Analysis

An accurate measure of speech intelligibility should be able to quantify the statistical variability of speech intelligibility for a complete objective assessment of speech intelligibility between passengers in a vehicle. None of the traditional objective speech intelligibility metrics accounts for the variability associated with the hearing ability of normal hearing or hearing impaired individuals and the influence of multi-sensory hearing on the perception of in-vehicle speech intelligibility. In addition, an exhaustive search failed to find any published studies on the analysis of statistical variability associated with any particular measure of in-vehicle speech intelligibility.

The statistical variability is critical for an accurate evaluation of the impact of any proposed vehicle design modification on in-vehicle speech intelligibility. The design modification may involve improvements to the performance of a noise control package or general troubleshooting and correction of a vehicle interior noise issue. If the difference in the selected speech intelligibility measure, for example caused by a proposed design modification or a noise issue, exceeds the amount of variability associated with the measure, then the change would be considered significant. For example, a design change of an inner dash silencer, a common automotive noise control component, may alter the baseline levels and spectra of vehicle background noise. If an inherent variability of the AI calculation, based on background noise measurements at a particular vehicle operating condition is +/-0.06 for example, the change (preferably an increase) in AI due to the design change would need to exceed 0.06 for this design change to be considered significant, in a positive sense. This example emphasizes the importance of quantifying the variability associated with a selected speech intelligibility measure and any other sound quality metric, in general. Any method selected for the evaluation of in-vehicle speech intelligibility should also include the associated statistical variability as part of its procedure.

Although no published studies were found to describe the statistical variability of in-vehicle speech intelligibility, the following studies illustrate a variety of examples that discuss statistical variability analysis, including standard deviation and variance as well as other statistical analysis methods applied to the field of automotive acoustics.

Shaver et al (2009) identified a variety of contributing factors related to the vehicle NVH performance variance. They included the dynamic behavior of vehicle rubber components, such as the engine and body mounts, resulting from the variation in their material properties, temperature sensitivity, in-vehicle pre-load of the rubber components and force loading variation from on-road loading conditions. Additionally, Shaver indicated that the variation in rubber properties affects the coupling of the vehicle body structure modes and chassis rigid modes, the overall vehicle dynamic response and consequently, the vehicle NVH variance. Shaver also stated that the manufacturing and assembly process, component stack-up tolerance and assembly plant quality control, particularly for manual operations such as windshield glass installation and body sealing applications, could all be significant contributors to the overall vehicle NVH variability.

At the vehicle component level, Paul (2004) quantified engine NVH variability based the measurements of engine radiated sound and engine mount vibration. Fernholz (2005) used multivariate statistical methods, specifically the Principal Component Analysis (PCA), for a benchmarking study using 99 hydraulic steering pumps and their NVH measurements. Using this method, the entire set of data was analyzed at once and the two pump types with significantly better NVH performance compared to the other pump types were identified.

A statistical analysis of the vehicle acoustical transfer path measurements was performed by Connelly et al (2005). Connelly conducted a standard gage repeatability and reproducibility study of engine noise reduction and tire noise reduction measurements, as well as the variation in noise reduction from vehicle-to-vehicle through acoustical measurements from six compact sedans of the same vehicle line.

Statistical Energy Analysis (SEA) is a common method used in the automotive industry to predict vehicle NVH characteristics. For example, Peng (2011) simulated vehicle wind noise using SEA modeling. Zhang et al (2007) developed an SEA model of a dash mat to optimize mass requirements and acoustical performance in terms of powertrain and road noise attenuation. Wang and Maxon (2011) emphasized the importance of using experimental data for improving the accuracy of the SEA predictions, particularly for complicated SEA models with thousands of subsystems and junctions. However, although SEA models can be used to estimate the vehicle level NVH variability, there is still limited data available to confirm the accuracy of these predictions (Connelly et al, 2005).

In the field of acoustical testing facility validation, Veen et al (2005) demonstrated that the precision expressed in terms of repeatability and reproducibility of random incidence sound absorption measurements obtained in both a small and large size reverberation room were comparable. Based on the measurements acquired from the round robin data from this study, Pan et al (2007) investigated the measurement precision of random incidence sound absorption measurements using automotive seats in small reverberation rooms.

Statistical analysis is popular in other areas of automotive engineering, which are not related to vehicle acoustics. For example, Sun et al (2007) introduced a statistical correlation metric between the numerical solution and test data for automotive crash simulation applications.

2.5.1 Statistical Variability Analysis Using Control Charts

Control chart evaluation is used for statistical process control (SPC) in order to detect any special causes of data variation and reduce the effects of common causes of variation to improve process quality. The control chart calculations are typically based on the ASTM 2587-10 standard.

Samardzic and Pan (2009) used control charts to quantify the statistical variability of sound transmission loss and sound absorption measurements and to set targets for characterizing the acoustical performance of vehicle noise control materials and components. In the same study, the control charts were also used to monitor and improve quality of acoustical material measurements and to select materials for optimal acoustical performance. This work can potentially provide a foundation for control chart application to acoustical measurements related to in-vehicle speech evaluation. As such, the control chart approach can potentially be used to quantify the statistical variability associated with the speech intelligibility evaluation method using an objective evaluation metric as a statistic. The intent would be to provide reference values for the statistical variability for future evaluation of in-vehicle speech intelligibility.

Control chart evaluation consists of a center line, representing the time-averaged value of the statistic, upper control limit (UCL) and lower control limit (LCL), computed from the process statistics and located at three standard errors of the statistic around the center line. The use of three standard errors, also known as "three sigma limits" as defined by the ASTM 2587-10 standard, is based on work by Shewhart (1931). Shewhart originally chose these limits to balance the risk of failing to detect a special cause with the risk of a detecting a special cause when the process is in fact in a state of statistical control, or in other words, a false alarm. Control limits are used to judge whether or not a set of data is in a state of statistical control based on a prescribed degree of risk. Three sigma limits carry a risk of 0.135% of being out of control when the process is actually in control and the statistic has a normal distribution, as explained in ASTM 2587-10. The appropriateness of the three sigma limits to describe the statistical variability of in-vehicle speech intelligibility evaluation has not previously been investigated; for this, a jury test to quantify the statistical variability of the hearing ability of speech in an in-vehicle listening environment is needed.

2.6 In-vehicle Speech Intelligibility for Hearing Impaired Individuals

The interior of an operating vehicle can also be a challenging communication environment, especially for the increasing population of senior drivers many of whom are hearing impaired. Meston et al (2011) found that many individuals have experienced difficulty understanding or following a conversation while driving in a motor vehicle, regardless of age or hearing ability. She also surmised that older adults may have the greatest difficulty in a driving situation due to the high prevalence of hearing loss as well as other age related factors. According to Meston et al (2011), current research suggests that as adults get older they are more affected by distractions in the driving environment and rely on their passenger to aid with certain driving related activities. A study in the field of psychological sciences by Saweikis et al (2004) suggests that while young and old subjects with comparable audiograms tend to have a comparable speech intelligibility performance in quiet listening conditions, the older subjects have more difficulty with speech recognition tasks in degraded listening conditions.

The difference in the response to speech perception in a vehicle interior listening environment specifically, between the normal and the hearing impaired individuals, has not been adequately quantified in the literature. However, Zekveld et al (2010) examined the listening effort during speech perception in difficult listening conditions using pupillometry, and found that subjective listening effort ratings and the pupil response decreased with increasing speech intelligibility. This decrease in the pupil response was relatively small for hearing impaired subjects (Zekveld et al, 2011).

A reduction of hearing threshold associated with typical hearing impairments can significantly reduce the perceived speech intelligibility and the effectiveness of person to person communication inside an operating vehicle. The AI metric, commonly used in the automotive industry to predict speech intelligibility, does not take into account hearing threshold loss. The STI metric is also not a reliable prediction measure of the intelligibility of speech for hearing impaired listeners unless specific corrections are applied (IEC 60268-16:2003). The SII accounts for the effects of elevated hearing threshold levels although its scope of application is limited to ontologically normal listeners. The reason provided in the standard (ANSI S3.5-1997) is that some hearing pathologies may have effects on speech intelligibility above that predicted based on the hearing threshold level alone. These effects are called suprathreshold deficits. They are not well documented and no corrections for the SII procedure are available at this time to account for them. Nevertheless, the current procedure can still potentially provide a fair initial estimate of in-vehicle speech intelligibility for the hearing impaired listeners. In addition, SII is becoming a preferred choice to quantify speech intelligibility within the field of audiology over the currently used audibility index metric (Debonis and Donohue, 2007).

An objective evaluation of in-vehicle speech intelligibility of individuals having common hearing impairments has not been found in literature. This evaluation may account for the effect of elevated threshold levels on in-vehicle speech intelligibility for person to person communication involving drivers with common hearing impairments, for example. This evaluation may also include the effect of hearing threshold levels obtained from audiograms and the impact of vehicle background noise measured for various vehicle operating conditions, road surface types and talker and listener configurations investigated.

The two most common types of sensorineural hearing loss are noise-induced hearing loss and age-related presbycusis. Most often, both types of hearing loss occur symmetrically in both ears. The hearing threshold levels can be obtained from typical audiograms for individuals with noise induced hearing loss and presbycusis, respectively (Debonis and Donohue, 2007) and are shown in Figure 2. The hearing level (HL) represents the pure tone threshold level at a specified frequency minus the reference pure tone threshold that is the minimum sound pressure level of the pure tone capable of evoking an auditory sensation at that same frequency.

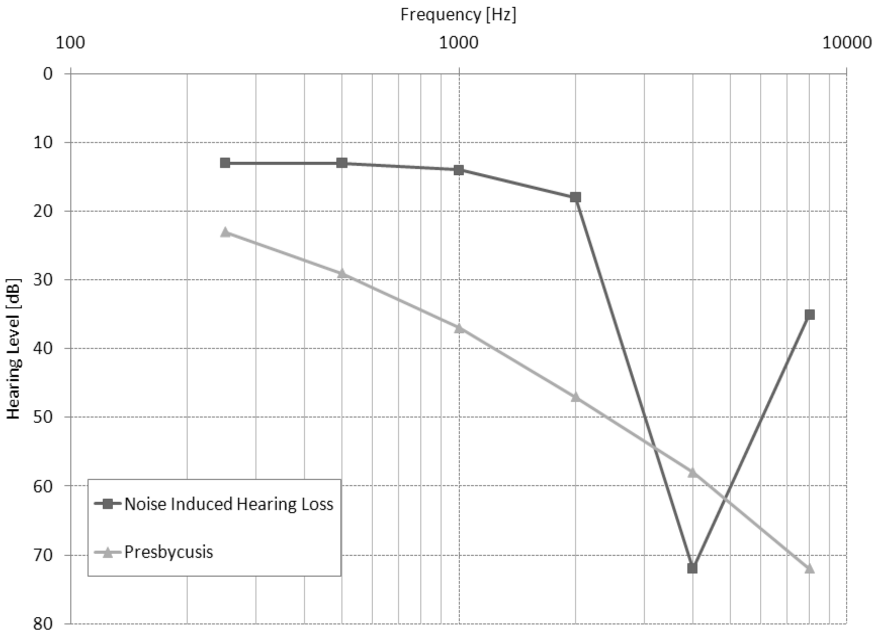


Figure 2: Typical audiogram(s) for individuals with noise induced hearing loss and presbycusis (Debonis and Donohue, 2007).

Therefore, the audiometric zero (0 dB HL) is associated with different sound pressure levels at each frequency. Noise induced hearing loss is progressive, resulting from excessive noise exposure. It is characterized by an audiometric "notch" at 4000 Hz. A potential explanation may be provided by pathologic evidence that demonstrates maximal cochlear hair cell loss in the tonal areas where the 4000 Hz hair cells normally reside in both animals and humans (Rutka, 2003). The amount of hearing loss depends on the sound pressure level and noise spectrum as well as duration of exposure to the noise. The resulting hearing loss will usually differ between individuals resulting in varying amounts of reduction of speech intelligibility.

Presbycusis is a progressive hearing loss due to aging, typically affecting higher frequencies. The majority of changes occur in the basal turn of the cochlea where the high frequency hair cells and their corresponding cochlear nerve neurons are found, however, these changes are non-specific and can also be seen in a vast number of pathologies including the effects of noise upon the inner ear (Rutka, 2003). The progression of hearing loss due to age is more rapid compared to the noise induced hearing loss, especially after age 60.

CHAPTER 3: Speech Intelligibility Metrics

The following chapter provides an overview of the evaluation methods of the three objective speech intelligibility metrics used in this research. AI evaluation is based on the procedure outlined in common automotive Noise, Vibration and Harshness software packages, and it is not standardised. SII evaluation is based on the ANSI S3.5:1997 standard. STI is based on the IEC 60268-16:2003 standard.

3.1 Articulation Index

The AI evaluation method used in the automotive industry consists of determining the difference between the idealized speech spectrum and the background noise and then multiplying this difference by a weighing factor assigned to each one-third octave frequency band between 200 Hz to 6300 Hz. The AI is the sum of contributions from all the one-third octave frequency bands. If the background noise spectrum is higher than the speech spectrum then the contribution is equal to zero. If the speech spectrum is more than 30 dB higher than the background noise spectrum the contribution is equal to 30 dB, as the total dynamic range of speech is assumed to be 30 dB in any frequency band. The AI is computed as:

$$\mathrm{AI} = \sum_{i=1}^{n} \frac{W_i \cdot (L_{s\,i} - L_{p_i})}{30} \qquad (3.1)$$

Here, $L_{s\,i}$ and, L_{p_i} and are the speech and noise spectrum levels and W_i is a frequency weighing factor, as shown in Table 2.

Table 2: Frequency weighing factors for AI calculations.

Third octave frequency band [Hz]	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300
W_i	1	2	3.25	4.25	4.5	5.25	6.5	7.25	8.5	11.5	11	9.5	9	7.75	6.25	2.5

3.2 Speech Intelligibility Index

The SII metric calculation consists of determining the band audibility function and multiplying it by the band importance function at each frequency band under consideration. The SII is then the summation of the results over all the frequency bands. The procedure is available for both the octave and third octave frequencies in the range of 250 Hz to 8000 Hz, and 160 Hz to 8000 Hz, respectively.

The band audibility function is calculated by shifting the signal to noise ratio by 15 dB and dividing the result by the 30 dB range. The signal to noise ratio values range from -15 dB to +15 dB. The resulting band audibility function is then limited to the interval from zero to one. This is quite similar to the final steps in determination of the STI from signal to noise ratio described in the next section.

The band audibility function specifies the effective proportion of the speech dynamic range within the band that contributes to speech intelligibility under conditions which are less than optimal. The band importance function indicates relative significance of a particular frequency band to speech intelligibility. The band importance functions for different speech materials are also available in the ANSI S3.5:1997 standard. Table 3 shows the band importance function for average speech and octave band SII procedure.

Table 3: Band importance function for average speech and octave band SII procedure (ANSI S3.5: 1997).

Octave Band [Hz]	250	500	1000	2000	4000	8000
I_i	0.0617	0.1671	0.2373	0.2648	0.2141	0.0549

The SII is computed as:

$$\text{SII} = \sum_{i=1}^{n} I_i A_i \tag{3.2}$$

Here, I_i is the band importance function and A_i is the band audibility function. The summation is performed over all octave frequency bands. The band audibility function is defined as:

$$A_i = \frac{E_i - D_i + 15}{30} \tag{3.3}$$

Here, E_i is the speech spectrum level, and D_i is the disturbance level, defined as larger of the internal noise spectrum level and the noise spectrum level.

The internal noise spectrum level is the reference internal noise spectrum level increased by the hearing threshold level. The reference internal noise spectrum level is a spectrum level of a fictitious internal noise in the ear of the listener, which, if it were an external masker, would give rise to the reference pure tone threshold; These values is specified in the ANSI S3.5:1997 standard. Hearing threshold level is a pure tone threshold level of a given ear at a specified frequency minus the reference pure tone threshold level, defined as a mean value, at a specific frequency, of the pure tone threshold levels of a large number of ears of ontologically normal subjects within the age limit of 18-30 years inclusive.

3.3 Speech Transmission Index

For STI, an input and an output signal with a sinusoidal intensity modulation $I_i(1+m_i\cos 2\pi Ft)$, and $I_o(1+m_o\cos 2\pi F(t+\tau))$, respectively, are used to obtain the Modulation Transfer Function (MTF), defined as the ratio of the modulation index of the source signal, m_i, and the modulation index of the receiver signal, m_o. The loss of intelligibility is revealed by the reduction in the values of the MTF. The MTF is defined for 14 predetermined modulation frequencies, F, at one third octave intervals and 7 octave band frequencies, k, for the male speech signal and 6 for the female speech signal. The 14 modulation frequencies at one third octave intervals range from 0.63 Hz up to and including 12.5 Hz, and 7 octave bands with centre frequencies ranges from 125 Hz up to and including 8 kHz for male speech and 250 Hz to 6 kHz for female speech. The apparent signal to noise ratio is based on the modulation transfer function, as the reduction of speech intelligibility is related to the decrease of intensity of modulations from the source signal to the receiver signal.

The apparent signal to noise ratio (SNR) is then defined as:

$$SNR_{k,F} = 10\log\left(\frac{m_{k,F}(F)}{1-m_{k,F}(F)}\right) \qquad (3.4)$$

When the SNR is in the range from – 15 dB to 15 dB, its contribution to the STI is linear in the range from 0 to 1. The resulting values are expressed as the transmission index, TI and defined as:

$$TI_{k,F} = \begin{cases} 0 \text{ if } SNR_{k,F} < -15 \\ \dfrac{SNR_{k,F} + 15}{30} \\ 1 \text{ if } SNR_{k,F} > 15 \end{cases} \tag{3.5}$$

The modulation transmission index (MTI) is the average of the $TI_{k,F}$ values of the 14 modulation frequencies for a particular octave band.

$$MTI_k = \frac{1}{14}\sum_{F=1}^{14} TI_{k,F} \tag{3.6}$$

The revised STI (STI_r) is then calculated as the weighted sum of the modulation transfer indices.

$$STI_r = \sum_{n=1}^{7} \alpha_n MTI_n - \sum_{n=1}^{6} \beta_n \sqrt{MTI_n \cdot MTI_{n+1}} \tag{3.7}$$

The weighting factors include octave weighing factors (α) and corrections for the contribution of adjacent frequency bands (β), as shown in Table 4.

Table 4: Weighing factors for male speech (IEC 60268-16:2003).

Octave Band [Hz]	125	250	500	1000	2000	4000	8000
α	0.085	0.127	0.23	0.233	0.309	0.224	0.173
β	0.085	0.078	0.065	0.011	0.047	0.095	-

The MTF can be obtained directly by using a test signal for each of the 98 combinations of modulation frequencies and octave band frequencies associated with the STI calculation, to quantify the reduction in intensity of modulations of the source signal.

CHAPTER 4: Acoustical Measurement and Data Analysis Methods

This chapter will discuss the acoustical measurements and procedures and the subsequent data analysis required for the evaluation of the objective speech intelligibility metrics considered in this work. These include in-vehicle background noise measurements acquired both from a vehicle operated on a dynamometer test cell and on-road. Other signals acquired include speech signal and impulse response measurements. Also described are the necessary HINT speech measurements required for the driving simulator model, the model development itself and the jury testing for the acoustic perception measurements. Lastly, the SII calculations from the jury testing results are described in more detail.

4.1 Acoustical Measurement Methods

In this section, the background noise and speech signal measurements, including the HINT speech material required for the driving simulator model, and impulse response measurements are described. This measured data was subsequently used in the evaluation for the objective speech intelligibility metrics and development of the driving simulator model.

4.1.1 Objective Metrics Calculations

The speech intelligibility metrics were calculated according to the previously described procedures for each ear separately using the background noise measurements and either the measured or the assumed speech measurements, depending on the speech intelligibility metric under consideration. The AI metric was calculated using B&K

LabShop software. The SII metric was calculated using the software available from the website created by the members of the Acoustical Society of America Working Group S3-79, which is in charge of reviewing ANSI S3.5-1997 standard (sii.to). As in previous studies (Farina et al, 2003; Granat, 2008; Viktorovitch, 2005) the STI metric was calculated with weighing factors for male speech and the impulse response method described previously, using Aurora software version 4.3 in accordance to the IEC 60268-16:2003 standard.

4.1.2 Vehicle Dynamometer Measurements of Speech, Impulse Response and Background Noise

In-vehicle background noise, speech and impulse response measurements were conducted in a compact sedan located in a semi-anechoic four wheel chassis dynamometer (Figure 3). The use of the chassis dynamometer allowed for the very controlled speed and load settings to simulate actual vehicle operation for the background noise measurement. The vehicle was placed on rolls with automated wheelbase adjustment and tied down with safety straps during background noise measurements. The speech and the impulse response measurements used for STI calculations were obtained in quiet conditions. The background noise was measured separately from the speech and impulse response measurements.

A B&K Type 4128 HATS was used as the sound source for both the speech and impulse response measurements in quiet conditions. A B&K Type 2716 audio power amplifier powered an artificial mouth with a loudspeaker from which the speech signal was emitted. Pink noise and MLS signals used to study the effect of source signal parameters on the STI calculations, were the source signals for speech measurements.

Figure 3: Vehicle in a semi-anechoic dynamometer for speech, impulse response and background noise measurements with example HATS units' configuration; B&K Type 4100 HATS in the driver location as the receiver, or the listener, and B&K Type 4128 HATS in the passenger front location, as the source, or the talker.

Prior to the in-vehicle measurements, the speech signal was equalized in a fully anechoic room by generating a pink and MLS noise signal and adjusting the spectrum according to the IEC standard specification for male speech (Figure 4).

The loudspeaker gain was set to obtain different sound pressure levels of the equalized signal at a one meter distance from the artificial mouth using both the current (IEC 60268-16:2003) and previous (IEC 60268-16:1998) standard values; 60 dBA and 68 dBA, respectively. The 68 dBA specified in the IEC 60268-16:1998 standard was used in past publications related to automotive STI measurements (Farina et al, 2003; Viktorovitch, 2005; Granat, 2008). In addition, the effect of changing signal sound pressure level on the impulse response measurements was investigated using an equalized 72 dBA MLS signal.

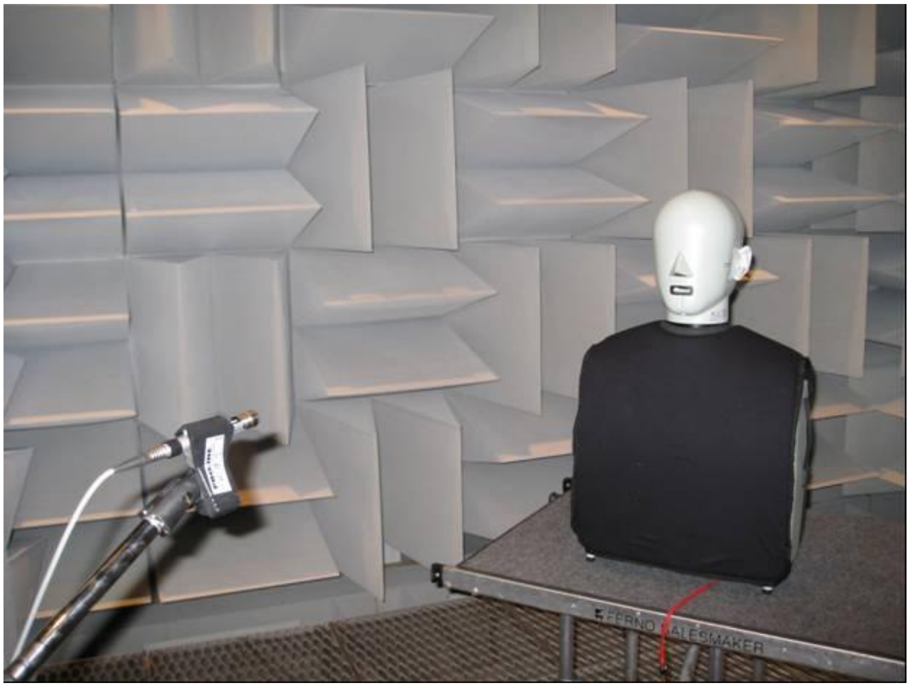


Figure 4: B&K Type 4128 HATS in a fully anechoic room with a microphone at a 1 meter distance from the mouth of the artificial talker for speech signal equalization according to the IEC 60268-16:2003 standard specification for male speech.

The speech signal, impulse response and background noise measurements were obtained for ten talker and listener configurations inside the vehicle, out of twelve possible combinations. The measurements with the talker at the passenger rear left and the listener at the passenger front and the rear right locations were omitted due to time constraints and, to some extent, redundancy. The driver, front passenger and the rear left and right passenger locations were used as the source (talker) as well as the receiver (listener) locations. This was facilitated by placing the two HATS units amongst the different seating positions for the speech, impulse response and background noise measurements. A B&K Type 4100 HATS, was used to measure the sound pressure at the listener locations during the speech, impulse response and background noise measurements. A B&K Type 4128 was also present during the background noise measurements to account for its effect on the sound field inside the vehicle. The HATS units were used to account for the directivity of speech and acoustic properties of the upper body similar to those of a human talker and the listener. The height and position of the HATS units was kept constant for each of the four measurement locations. The tests were conducted with both HATS units facing forward at all times. Each measurement of background noise, speech and impulse response was repeated three times to verify adequate measurement repeatability.

The impulse response was obtained by deconvolving the response to the MLS signals used for the speech measurements with the original signals. The sine sweep technique was also used; a sine sweep signal was generated by the mouth simulator and recorded inside the vehicle. Specifically, 70-second long sine sweep signal ranging from 70 Hz to 12 000 Hz was generated using the B&K Type 4128 and recorded using the B&K Type 4100. The binaural recordings of sine sweep signals were then deconvolved with the inverse of the original sine signal in order to obtain noise-free impulse response (Farina et al, 2003) for each measurement configuration; all the talker and listener configurations considered in the study. The quality of the impulse response measurements obtained from the two methods was compared in terms of the impulse response to noise ratio. The modulation transfer matrices were also obtained using the impulse response method.

The vehicle dynamometer test conditions for the background noise measurements included various constant and linearly increasing speeds on both smooth rollers and textured rollers to simulate different roadway conditions. The rough roll surface was obtained by using bolt-on road shells which are textured coverings installed on rollers to simulate a rough road surface profile. This was done to replicate the actual driving conditions and associated masking noises of a roadway due to different surface profiles.

The steady speed conditions were 50 km/h and 100 km/h and the variable speed condition was an engine run-up having a speed sweep from 1000 rpm to 5000 rpm. Octave band and one third octave sound pressure levels were obtained for the constant vehicle speed conditions and at each 50 rpm increment for the variable engine speed conditions. The speed was adjusted using a computer controlled robot positioner attached to the throttle pedal. The vehicle transmission selector was set to drive during constant speed measurements and second gear for the variable speed measurements. The engine speed, throttle opening and engine oil temperature were monitored during all measurements to ensure that the operating conditions remained consistent to ensure good repeatability of data acquisition. The ambient temperature and pressure were kept constant during the measurements. The background noise data was replayed binaurally prior to post-processing of data to verify the quality of data and to ensure that no unwanted noises such as rattles were present during the measurements.

4.1.3 On-road Background Noise Measurements

The same small sedan model used for the vehicle dynamometer background noise measurements was used for on-road background noise measurements. On-road measurements were obtained to account for the effects of wind noise. The background noise measurements were acquired while operating the vehicle on both a straight section roadway and entrance and exit ramps of an expressway. The measurements were obtained during periods of minimum traffic volumes during the early morning and late night times and under ideal weather conditions. To ensure constant vehicle engine loading, the measurements were made on smooth sections of the road surface, which had no changes in elevation. Once the data was collected, a binaural replay was performed prior to data post-processing to ensure that no unwanted noises such as rattles and vehicle pass-by noise were present during the measurements.

The background noise measurements were obtained using a SoNoScout Binaural Recording and Analysis System Type 3653. The on-road measurements also incorporated global positioning system (GPS) data that were eventually used to extract the vehicle speed corresponding with the sound measurements. This operation is performed using the SoNoScout software. The engine speed was obtained by an engine order extraction method using spectral maps obtained from vehicle interior sound measurements and an ‘Rpm Finder’ feature of the B&K SoNoScout software. The orders are defined as multiples of rotational speed of a vehicle component. For example, engine ordered noise sources are associated with engine speed harmonics.

The measurements were obtained at various vehicle speeds, throttle positions and at various gear settings chosen using the vehicle transmission selector. The interior sound measurements were acquired during the engine speed sweeps at 50 percent and wide open throttle openings and in all four gears. The interior sound measurements were obtained at closed throttle coast downs conditions, at a neutral engine speed sweep condition and at the engine idle speed.

4.1.4 The Hearing in Noise Test (HINT) Measurements for the NVH Driving Simulator Model

The University of Western Ontario’s National Centre for Audiology provided the HINT sentence recordings and associated calibration signal used in WAV file format. The sentences were recorded in the vehicle under quiet conditions having negligible background noise using a B&K HATS Type 4100 located in the driver’s position. The sentences were presented using a B&K HATS Type 4128 located in the passenger front, passenger rear right and passenger rear left locations. The recordings were obtained at levels of 35 dBA to 75 dBA in 2 dB increments. These were adjusted based on the voltage levels required to generate the same signals in an anechoic room at a distance of 1 m from the mouth of the artificial Talker HATS Type 4128. The speech signal was generated and recorded simultaneously using the B&K PULSE LabShop software version 16. A total of 15750 HINT sentence recordings were obtained for various combinations of speech levels and locations of the talker (HATS Type 4128). The listener (HATS Type 4100) remained positioned in the driver's location. The recordings were used as sound objects in development of the driving simulator model.

The sound pressure levels associated with the HINT sentences used in the driving simulator tests matched those recorded inside the vehicle to within 0.2 dB, in the range from approximately 45 dBA to 70 dBA evaluated in 2 dB increments. This test was performed by placing a pair of headphones on a Type 4100 HATS and verifying that the presented levels using the B&K PULSE LabShop software (Figure 5). The HINT calibration signal recorded at these levels and different configurations inside the vehicle was used as the benchmark for any needed adjustments using the NVH Simulator software and the NVH Simulator soundcard mixer.

Figure 5: The sound pressure levels associated with the HINT sentences to be delivered from the NVH Simulator software through the headphones matched those recorded inside the vehicle to within 0.2 dB, in the range from about 45 dBA to 70 dBA, in increments of 2 dB. The headphones were placed on a Type 4100 HATS and the levels were verified using the PULSE LabShop software version 16. The HINT calibration signal recorded at these levels and different configurations inside the vehicle was used as a benchmark for any needed adjustments using the NVH Simulator software and the NVH Simulator soundcard mixer.

4.2 Driving Simulator Model

Once acquired, the measured data was imported into the DTS Data Preparation (NVH Simulator) software and grouped according to the measured operating conditions - vehicle speed, throttle position, gear - in order to generate the sound objects to be imported into the simulator software. The sound objects included the ordered (rpm related) and the masking (background noise) components that were decomposed from the total interior sound associated with each of the measured operating conditions.

A Vold-Kalman filter was used for order extraction involving harmonic sound from the vehicle’s rotating components. For the vehicle level model used in this study, the total vehicle interior sound produced two types of sound objects: ordered and masking. The engine masking component was also extracted using the background noise measurements during the engine speed sweeps while the vehicle gear selector was set to neutral. An additional set of sound objects that were also imported into the simulator software included the speech events; the HINT sentence recordings.

The performance modeling was completed using the DTS Performance Data Preparation software. Lookup tables were used to convert the driver inputs to the various vehicle parameters such as vehicle and engine speed. These lookup tables were created for the vehicle speed and engine speed for each gear as a function of the throttle position. The gearshift table was also populated with parameters specific to the test vehicle engine and used for automatic mode of driving in the simulator. The performance data file was then imported into the NVH Simulator software.

4.3 Driving Simulator Jury Testing

The jury test participants in the first acoustic perception study consisted of 30 participants, 18 males and 12 females between ages of 19 and 30. The average age of the participants was 24 (standard deviation 3.2). All of the participants had normal hearing. The jury test participants in the second acoustic perception study consisted of 10 participants, 9 males and 1 female. In this group, 4 male participants were hearing impaired, their ages ranging from 22 to 67. Their audiograms with hearing threshold information were provided by the participants and used in subsequent SII calculations. The remaining normal hearing participants' average age was 25 (standard deviation 2.8).

For both jury tests, twenty HINT sentences were presented via headphones (corrected for distortion) at intervals of approximately 20 seconds for each of the six measurement configurations considered. Since the recognition of speech material becomes less difficult as it is repeated or reused, each test condition in this study included 20 unique HINT sentences. The duration of the simulated driving test using the HINT and the driving simulator was approximately one hour. The participants were first asked to drive at 50 km/h during which the HINT sentences representing the talker in the passenger front location were played through the headphones (Figure 6). These sentences were played simultaneously with the background noise associated with a particular driving condition (gear, throttle position, engine revolutions per minute). A short break was subsequently provided for the participants before starting a 100 km/h test for the same talker and listener configuration. After a second break, the next set of 50 km/h and 100 km/h tests were conducted with the talker HATS located in the passenger rear right and rear left position. For each test, the levels of the speech signals were adjusted after each sentence according to the response from the participants, as described by the HINT procedure for determining the sentence speech reception threshold (sSRT).

4.4 SII Calculations Using Results from Normal Hearing and Hearing Impaired Driving Simulator Jury Test Participants

The SII calculation based on the ANSI S3.5-1997 standard required the determination of the background noise and speech spectrum levels. The random noise calibration signal created by averaging all of the HINT sentences was delivered using the HATS Type 4128 in the passenger front, passenger rear right and passenger rear left locations while a HATS Type 4100 located in the driver’s seat was used to record the sentences. The SII was calculated from the in-vehicle recordings of HINT calibration signal at the levels associated with the juror’s response to particular HINT sentences during the simulated driving test.

Figure 6: A juror (right) driving the NVH Simulator while the HINT sentence recordings are delivered from the NVH Simulator software (left). The levels of the consecutive HINT sentences are adjusted in 2 dB increments, based on the juror's response.

In total, there were twenty SII calculations associated with each test condition and each of the thirty jury test participants.

Prior to performing any in-vehicle HINT sentence recordings, the calibration signal was played in an anechoic room to determine the necessary voltage levels required to generate the same signal at the overall levels ranging from 35 dBA to 75 dBA, in increments of 2 dB, at a distance of 1 m from the mouth of the HATS Type 4128 artificial talker. Using the reference voltage levels determined in the anechoic room, the HINT calibration signal was then generated inside the vehicle, also from 35 dBA to 75 dBA, in increments of 2 dB.

In one study, the SII was also used to evaluate in-vehicle speech intelligibility using audiograms of common hearing impairments available in literature; however, the predictions were not compared to the actual perception of speech intelligibility using human subjects in a driving environment. In another study, the actual audiograms were used in combination with acoustic perception jury test results of the hearing impaired test participants to calculate the SII at the sSRT, using the novel method for speech intelligibility evaluation presented in the next chapter.

CHAPTER 5: A Novel Method for In-Vehicle Speech Intelligibility Evaluation and Statistical Variability Analysis

The common objective speech intelligibility metrics discussed in Chapter 2 neglect to consider critical parameters that are essential for a complete and accurate in-vehicle speech intelligibility evaluation. As discussed in Chapter 2, these parameters include the directivity of the talker with respect to the listener, the distance between the talker and the listener, binaural listening, hearing profile of the listener, vocal effort, and multisensory hearing. For example, the current objective metrics require that a particular level of vocal effort be specified in their analysis regardless of the evaluation method used. Ultimately, the metrics are evaluated in terms of the scores ranging from zero to one and interpreted based on the subjective descriptions of scores associated with a particular evaluation method or a standard, if such descriptions are available. An alternative, as suggested in this work, to using a particular vocal effort in the evaluation and later interpretation of objective speech intelligibility scores is to consider the sentence speech reception threshold thus eliminating the need for the subjective interpretation of scores by, instead, characterizing the human speech hearing ability in presence of noise, and the associated variability.

This chapter describes a novel method developed for a more complete and accurate assessment of all the parameters affecting speech intelligibility in the context of the in-vehicle listening environment, using a driving simulator. Additionally, the method quantifies the statistical variability associated with human hearing at the speech hearing threshold within an operating vehicle in order to provide targets for future speech intelligibility evaluation.

5.1 Vocal Effort Objective Speech Intelligibility Metrics

The in-vehicle speech intelligibility is typically evaluated objectively using objective speech intelligibility metrics. The metrics' calculations usually require background noise measurements at particular vehicle operating conditions and at a location of the listener inside a vehicle. The speech signal is also required for the calculations. It may be measured or assumed based on the measurement standard recommendations and depending on the evaluation method. It is required that a particular level of vocal effort be specified in the analysis, regardless of the metric used for the evaluation. Lastly, the metrics' results are presented in terms of the scores ranging from zero to one. If the subjective descriptions corresponding to the scores are available for a particular metric, the scores may be interpreted accordingly. For example, the SII values are generally defined as a proportion of the total number of speech cues delivered from the source to the listener, where good communication systems have an SII greater than 0.75, while poor communication systems have an SII below 0.45 (ANSI S3.5-1997). Similarly, the qualification intervals for the STI are rated 'poor' for scores below 0.45 and 'excellent' above 0.75 (IEC 60268-16:2003). There are no publications with similar guidelines related to the subjective interpretation of the AI scores, as used in vehicle applications, where the speech intelligibility as a factor influencing the perception of the overall vehicle sound quality is typically evaluated by customers based on their individual preference (Samardzic and Novak, 2011d). In terms of vocal effort, Samardzic and Novak (2011c) used speech signal levels that comply with the IEC 60268-16:2003 measurement standard for STI. For the 60 dBA signal, the STI values ranged from unintelligible to excellent, depending on the location of the talker and the listener. For higher speech signal levels, such as 68 dBA, the STI value was less sensitive to changes in the vehicle operating conditions. The same study showed that the 60 dBA speech signal, associated with normal vocal effort, according to the SII standard ANSI S3.5-1997, provided at least fair intelligibility at lower speeds, such as city driving at 50 km/h, for all measurement configurations considered. In contrast, an increased vocal effort of at least 68 dBA, considered to be loud, according to the ANSI S3.5-1997 standard, was needed to obtain similar intelligibility scores at higher speeds, such as highway driving, at 100 km/h, due to significantly higher levels of background noise.

The vocal effort required for effective in-vehicle communication is influenced by the level of background noise, the vehicle's interior acoustics, the location of the talker with respect to the listener, as well as the talker's individual speaking style. A suggested alternative to using a particular vocal effort in the evaluation and later interpretation of objective speech intelligibility scores would be to evaluate the in-vehicle sSRT, as suggested by Samardzic et al (2012). Subjective interpretation of scores is no longer necessary as, by definition, the sSRT is a minimally acceptable vocal effort needed for understanding speech. Therefore, the sSRT values in this study, coupled with the corresponding objective speech intelligibility scores, would be used to quantify the hearing ability of normal hearing individuals and the influence of multi-sensory perception on the perception of speech intelligibility in an operating vehicle.

5.2 A Metric Selection for a Statistic in the Control Chart Evaluation

In order to quantify the statistical variability of in-vehicle speech intelligibility, it is first necessary to select the proper variables that would accurately capture all-important influences on the in-vehicle speech intelligibility. Since the in-vehicle speech intelligibility is often evaluated using objective speech intelligibility metrics, an objective speech intelligibility metric would be a reasonable choice for a variable to be used in the statistical analysis. Samardzic and Novak (2011d) investigated the in-vehicle application of common objective speech intelligibility metrics; the AI, the SII and the STI, to identify the most appropriate metric for use in automotive applications. The SII method, utilizing user-defined, measured, speech signal was found to be the most appropriate out of the three metrics for quantifying in-vehicle speech intelligibility. As the effect of reverberation on the loss of in-vehicle speech intelligibility was negligible, this method resulted in a close correlation with the more measurement-intensive STI method and provided an opportunity for a reduction in measurement effort while preserving the accuracy of the results. Therefore, the SII method with measured speech signal is considered in this study, and as a result, the SII is used as a random variable in the statistical analysis.

The objective metrics, including the SII, unfortunately do not include the influence of multi-sensory perception on the assessment of speech intelligibility, which is of particular significance for the in-vehicle listening environment. In order to investigate the effect of multi-sensory perception, Samardzic et al (2012) created a driving simulation and implemented the HINT developed by Nilsson et al (1994), for the evaluation of in-vehicle speech intelligibility. The study revealed that when presented with the same listening task, the jury test participants required on average an approximate 3 dB increase in sound pressure level of the speech material while driving and listening compared to when just listening for an equivalent speech intelligibility performance. Therefore, the statistical variability of multisensory perception and its impact on the assessment of speech intelligibility is considered in this study by using the jury test results obtained by

Samardzic et al (2012) to calculate the SII for different configurations of the talker and vehicle operating conditions

Signal to noise ratio (SNR) results obtained from the in-vehicle sound pressure measurements of speech and background noise are the main contributor to the reduction of in-vehicle speech intelligibility (Samardzic and Novak, 2011b). The SNR ratio is directly related to the SII values per the calculation method described in the ANSI S3.5-1997 standard. The statistical variability associated with in-vehicle sound pressure measurements of speech and background noise used to calculate the SNR is also a potential contributor to statistical variability of in-vehicle speech intelligibility. However, based on the HINT in the driving simulator model by Samardzic et al (2012), the statistical variability of the speech and background noise signal for a particular vocal effort and operating condition, and conversely, a particular SNR, is assumed to be insignificant in this study.

The sound pressure levels associated with the HINT sentences to be delivered from the NVH Simulator software through the headphones matched those recorded inside the vehicle to within 0.2 dB, in the range from about 45 dBA to 70 dBA, in increments of 2 dB. The headphones were placed on a Type 4100 HATS and the levels were verified using the PULSE LabShop software version 16. The HINT calibration signal recorded at these levels and different configurations inside the vehicle was used as a benchmark for any needed adjustments using the NVH Simulator software and the NVH Simulator soundcard mixer. The result of this is that the influence of the speech signal variation on the result associated with any particular vocal effort was minimal.

The influence of the background noise variation on the results during driving was also minimal. The measurements were obtained at the average city and highway speeds of 50 km/h and 100 km/h respectively, and the variation in speed resulted in the average variation of the background noise of less than 1 dB each time a HINT sentence was delivered over the headphones of the driving simulator.

In this study, the statistical variability of in-speech intelligibility was quantified by accounting for the statistical variability in the hearing ability of normal hearing individuals and the influence of multi-sensory perception. The sSRT values from the jury test of thirty participants performed by Samardzic et al (2012) in a simulated driving environment were used to calculate the SII, which is also used as a random variable in the statistical analysis.

In the study by Samardzic et al (2012), the results were presented in terms of the sSRT values associated with different talker and listener configurations and vehicle operating conditions. The SRT values are directly related to the level of the in-vehicle background noise. The main influences on the vehicle interior background noise level are the vehicle design and its operating conditions. Although the sSRT associated with a minimal vocal effort required for understanding speech appears to be a simple and easily understood way of evaluating the in-vehicle speech intelligibility, it is specific to the vehicle design and its operating conditions. In this study, a more generally applicable metric for evaluating in-vehicle speech intelligibility is proposed. The new metric involves SII evaluation at the sSRT. In this context, an accurate evaluation of the sSRT, and subsequently, the in-vehicle speech intelligibility, needs to incorporate the influence of multisensory perception, different talker and listener configurations, including the distance between the talker and the listener, and different vehicle operating conditions. Ultimately, the SII and sSRT values and the associated statistical variability will provide a benchmark for future in-vehicle speech intelligibility evaluation.

The sSRT values obtained from the HINT using the jury consisting of thirty participants and a driving simulation developed by Samardzic et al (2012) were used to conduct the analysis of the statistical variability of in-vehicle speech intelligibility and to establish benchmark values and control limits for the newly proposed speech intelligibility metric for use by the automotive industry. The applicability of the new metric and its control limits, as suggested in this study, was verified by Samardzic and Novak (2012a-submitted) for special cases with variations in hearing threshold levels of the listener, as well as background noise levels associated with different vehicle operating conditions.

5.3 Statistical Variability Analysis Using Control Charts

The SII values were obtained from HINT speech presentation levels and background noise levels at 50 km/h and 100 km/h driving speeds associated with the driving simulation using thirty jury test participants. Three combinations of talker and listener locations were investigated. For all cases the listener was in the driver's location, the talker was located in the passenger front, rear right, and rear left locations. Twenty HINT sentences were played through the headphones of the driving simulator in an adaptive procedure used to calculate the sSRT for a particular vehicle speed and a talker and listener configuration. Each of the thirty jury test participants listened to 120 HINT sentences delivered through the headphones. The control charts were calculated for subgroups of data consisting of multiple numerical measurements for each of the six measurement configurations. A subgroup consisted of SII calculated from the HINT sentence presentation levels and corresponding background noise levels played through the headphones of the driving simulator at a particular vehicle speed and talker/listener configuration. The presentation levels from the last seventeen, out of the total of twenty, HINT sentences played through the headphones for each participant were used in the SII calculations. The same number of sentences was used to calculate the sSRT in the HINT procedure presented by Sudirga et al (2011).

The X-bar and s charts are the two charts used to monitor the level and short-term variability of subgroups of data consisting of multiple numerical measurements. An observation X_{ij} is denoted as j^{th} observation, where $j = 1,...n$, in the i^{th} subgroup, and where $i = 1,...k$. In this study, there are seventeen observations for each of the thirty subgroups or jurors. For each of the k subgroups, the i^{th} subgroup average $\overline{X_i}$, and the i^{th} subgroup standard deviation s_i, are respectively calculated as:

$$\overline{X_i} = \sum_{j=1}^{n} X_{ij} / n \tag{5.1}$$

$$s_i = \sqrt{\frac{\sum_{j=1}^{n} (X_{ij} - \overline{X_i})^2}{n-1}} \tag{5.2}$$

The averages and standard deviations are presented on the X-bar and s charts, respectively. The grand average $\overline{\overline{X}}$, and the average standard deviation $\bar{s}$, over all k subgroups are calculated as:

$$\overline{\overline{X}} = \sum_{j=1}^{n} \overline{X_i} / n \tag{5.3}$$

$$\bar{s} = \sum_{i=1}^{k} s_i / k \tag{5.4}$$

Using the control chart factors, A_3, B_3 and B_4 from Table 1 in ASTM 2587-10, the LCL and UCL for the X -bar chart are calculated as:

$$LCL = \bar{\bar{X}} - A_3 \bar{s} \tag{5.5}$$

$$UCL = \bar{\bar{X}} + A_3 \bar{s} \tag{5.6}$$

The LCL and UCL for the s chart are calculated as:

$$LCL = B_3 \bar{s} \tag{5.7}$$

$$UCL = B_4 \bar{s} \tag{5.8}$$

In addition to SII, the control charts could also be constructed using frequency dependent data, such as the SII band audibility function and signal to noise ratio, also calculated based on the speech and background noise measurements from the HINT in the driving simulator. In contrast to the SII control charts, these charts would not necessarily provide generally applicable speech intelligibility evaluation criteria, because like the SNR, the band audibility function is frequency dependent and the frequency content of background noise and speech response for each vehicle may be different. However, frequency-specific information can potentially be useful for a particular vehicle sound package or component design and acoustical performance benchmarking, as well as for vehicle interior noise issue diagnostics. All of the above mentioned control chart examples are shown in the Section 6.2.2 and 6.2.3.

CHAPTER 6: Results and Discussion

This chapter is organized into two parts. The first part (Section 6.1) summarizes each of the several detailed investigations of automotive applications of the currently available objective speech intelligibility evaluation methods for normal hearing (Sections 6.1.1 through 6.1.3) and hearing impaired individuals (Section 6.1.4). This work lays the ground for developing an alternative method for a more complete and accurate speech intelligibility evaluation. The studies associated with this method are presented in Section 6.2.

6.1 Objective Speech Intelligibility Metrics' Analysis

In this section, the results of four studies related to in-vehicle applications of common objective speech intelligibility metrics are presented. In the first study (Section 6.1.1) a detailed evaluation of in-vehicle speech intelligibility for different driving conditions and talker and listener configurations was conducted using the most comprehensive objective speech intelligibility metric, STI. For this study, several vehicle operating conditions, road surfaces and talker and listener configurations were compared in terms of the STI metric to gain a better understanding of these influences on in-vehicle person to person communication. Individual contributions of background noise and interior vehicle acoustics to the STI were also investigated. In the second study (Section 6.1.2), the source-signal parameters critical for determining the STI are investigated. For this investigation, different signal types and levels for the sound source were used to obtain the in-vehicle speech and impulse response. Background noise included both the constant and variable speed operating conditions for the vehicle under controlled conditions for several talker and listener configurations. In the third study (Section 6.1.3), all of the three most common metrics were investigated and the results compared in the context of in-vehicle speech intelligibility evaluation. The goal was to identify the most appropriate metric, if a single one exists, for use in automotive applications. The objective metrics included the AI, the SII and the STI. In the fourth study (Section 6.1.4), in-vehicle speech intelligibility was evaluated using the SII metric by considering threshold elevation associated with common hearing impairments. In this study, SII was used to predict in-vehicle speech intelligibility. The effect of hearing threshold levels obtained from audiograms (Figure 2) and the impact of vehicle background noise measured for various vehicle operating conditions, road surface types, and talker and listener configurations were investigated. This was done using measured and user-defined speech spectra as described by ANSI S3.5-1997.

6.1.1 In-Vehicle Speech Intelligibility for Different Driving Conditions Using the Speech Transmission Index

The background noise and speech octave band levels and the impulse response were used to calculate the STI for all operating conditions, measurement configurations and road surfaces. For the variable speed condition, the STI was calculated at each 50 rpm increment between 1000 rpm and 5000 rpm. Figure 7 shows an example of the speech and background noise sound pressure levels for one of the ten talker/listener configurations used in the study and at all the octave frequencies required for implementation of the STI calculation procedure. The results for the two constant speed conditions and two road surfaces are illustrated in the same figure.

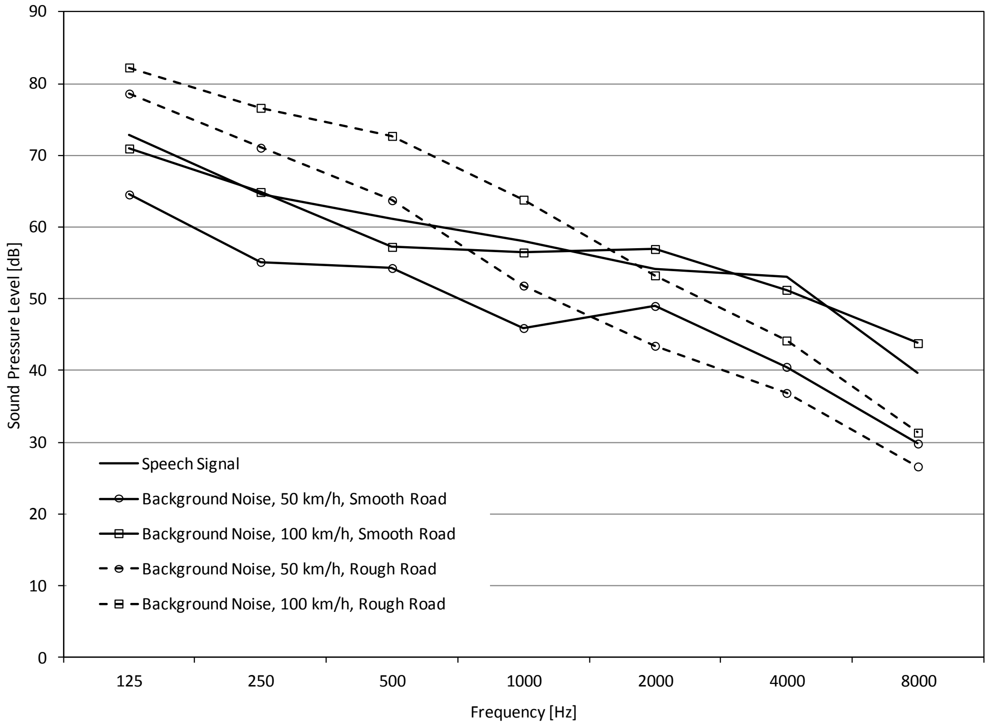


Figure 7: Speech signal and background noise levels over the frequency range used for STI calculations; Example background noise octave spectra was measured at 50 km/h and 100 km/h on smooth and rough roller surfaces, with the receiver, or the listener, in the passenger front location, and the example speech signal octave spectrum measured with the source, or the talker, in the driver location. The higher overall sound pressure levels associated with rough roll operation are not necessarily related to lower STI; In fact, more dominant high frequency content associated with the smooth roll operation is a more significant contributor to the decrease of STI, compared to the rough roll operation, as the weighing factors at higher frequencies used in the STI calculation are higher compared to those at lower frequencies associated with the rough roll operation.

A wide range of (speech) signal to (background) noise ratios in each frequency band is evident, mainly due to various contributions from ordered and masking sources unique to each operating condition. Figure 8 illustrates the impulse response obtained using the same configuration, indicating short reverberation times associated with automotive interiors. The significance of short reverberation times for the STI calculations is revealed in the discussion of the modulation transfer function, later in this section.

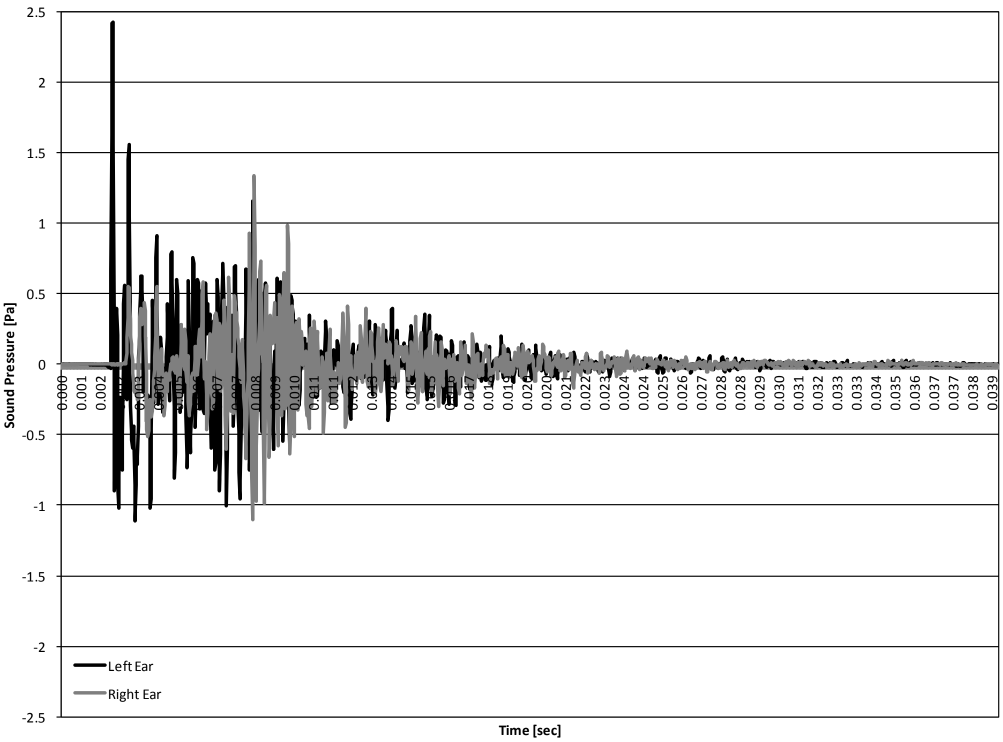


Figure 8: Example binaural impulse response, measured with the receiver, or the listener, in the passenger front location, and the source, or the talker, in the driver location, illustrating short reverberation times typical for automotive interiors.

Table 5 is a summary of the STI results for the constant speed operating conditions. A simple colour scheme is used to indicate the relation between the STI and the subjective descriptions of intelligibility from worst to excellent. From here, the relationship of the results between the various talker to listener positions throughout the vehicle is evident.

At 50 km/h, the speech intelligibility is good at the passenger front position when the talker is in the driver position. It is generally fair when the talker is in the driver or the passenger front position and the listener is at one of the two rear positions. It is worse when the listener is directly behind the talker as the speech signal has a less direct path from the source to the receiver location.

Table 5: STI at the left and the right ears of the listener for various talker and listener configurations, obtained using speech, impulse response and background noise measurements from constant speed operation (50 km/h and 100 km/h) on both, the smooth and the rough rollers.

Driver (Source/Talker)				Passenger Front		Left Ear	Right Ear
				50 km/h	Smooth Road	0.78	0.62
					Rough Road	0.73	0.60
				100 km/h	Smooth Road	0.50	0.35
					Rough Road	0.46	0.33
Passenger Rear Left		Left Ear	Right Ear	Passenger Rear Right		Left Ear	Right Ear
50 km/h	Smooth Road	0.51	0.53	50 km/h	Smooth Road	0.65	0.51
	Rough Road	0.52	0.50		Rough Road	0.56	0.47
100 km/h	Smooth Road	0.23	0.27	100 km/h	Smooth Road	0.37	0.25
	Rough Road	0.22	0.22		Rough Road	0.31	0.22

Driver		Left Ear	Right Ear	Passenger Front (Source/Talker)			
50 km/h	Smooth Road	0.57	0.78				
	Rough Road	0.62	0.79				
100 km/h	Smooth Road	0.34	0.57				
	Rough Road	0.35	0.55				
Passenger Rear Left		Left Ear	Right Ear	Passenger Rear Right		Left Ear	Right Ear
50 km/h	Smooth Road	0.43	0.55	50 km/h	Smooth Road	0.58	0.49
	Rough Road	0.49	0.55		Rough Road	0.50	0.46
100 km/h	Smooth Road	0.17	0.32	100 km/h	Smooth Road	0.30	0.23
	Rough Road	0.20	0.28		Rough Road	0.24	0.18

Driver		Left Ear	Right Ear	Passenger Front		Left Ear	Right Ear
50 km/h	Smooth Road	0.50	0.55	50 km/h	Smooth Road	not measured	
	Rough Road	0.57	0.61		Rough Road		
100 km/h	Smooth Road	0.27	0.33	100 km/h	Smooth Road		
	Rough Road	0.26	0.35		Rough Road		
Passenger Rear Left (Source/Talker)				Passenger Rear Right		Left Ear	Right Ear
				50 km/h	Smooth Road	not measured	
					Rough Road		
				100 km/h	Smooth Road		
					Rough Road		

Driver		Left Ear	Right Ear	Passenger Front		Left Ear	Right Ear
50 km/h	Smooth Road	0.49	0.60	50 km/h	Smooth Road	0.48	0.58
	Rough Road	0.56	0.65		Rough Road	0.55	0.63
100 km/h	Smooth Road	0.27	0.38	100 km/h	Smooth Road	0.26	0.36
	Rough Road	0.27	0.37		Rough Road	0.26	0.36
Passenger Rear Left		Left Ear	Right Ear	Passenger Rear Right (Source/Talker)			
50 km/h	Smooth Road	0.59	0.81				
	Rough Road	0.61	0.78				
100 km/h	Smooth Road	0.31	0.57				
	Rough Road	0.33	0.50				

0-0.3	0.3-0.45	0.45-0.6	0.6-0.75	0.75-1
Unintelligible	Poor	Fair	Good	Excellent

At 100 km/h, the STI values are decreased compared to the 50 km/h STI values by up to about 55%. This is due to the higher background noise at higher speeds, which reduces the apparent signal to noise ratio and consequently adversely affects the speech intelligibility. In addition, at 100 km/h, the speech is unintelligible from the driver or the passenger front positions to the rear passenger positions.

It is better at the ear closer to the source; however, it is still rated poor. In this case, the subjective ratings provided a quick insight about the in-vehicle sound quality in terms of speech intelligibility for configuration and operating conditions.

The intelligibility is worse at the outboard ear compared to the in-board ear of the listener for all the configurations and operating conditions due to the effects of road noise causing a reduction of the apparent signal to noise ratio and consequently, the reduction of speech intelligibility. The difference is most prominent when the talker and the listener are next to each other due to the greater difference in signal to noise ratio between the ears of the listener.

The overall sound pressure levels (dB) associated with the rough roll set-up are higher compared to the same configurations when the vehicle is on the smooth rolls. Although this result is instinctive, the rough roll set-up often provided higher intelligibility results compared to the smooth roll set-up. This is due to the more dominant high frequency content that is associated with the smooth roll operation (see Figure 7), which tends to contribute more significantly to the STI, as the weighing factors at higher frequencies are higher compared to those at lower frequencies usually associated with the rough roll operation (see Table 4). This observation reinforces the significance that the frequency content of the background noise, and not just the overall background noise level, has on STI. One might extend this observation to the importance of the potential negative influence that aerodynamic noise maskers may have on intelligibility compared to roadway noise.

Figures 9 through 12 illustrate the STI results at the four receiver, or the listener, locations inside the vehicle considering different source, or the talker locations, road surfaces and variable engine speed.

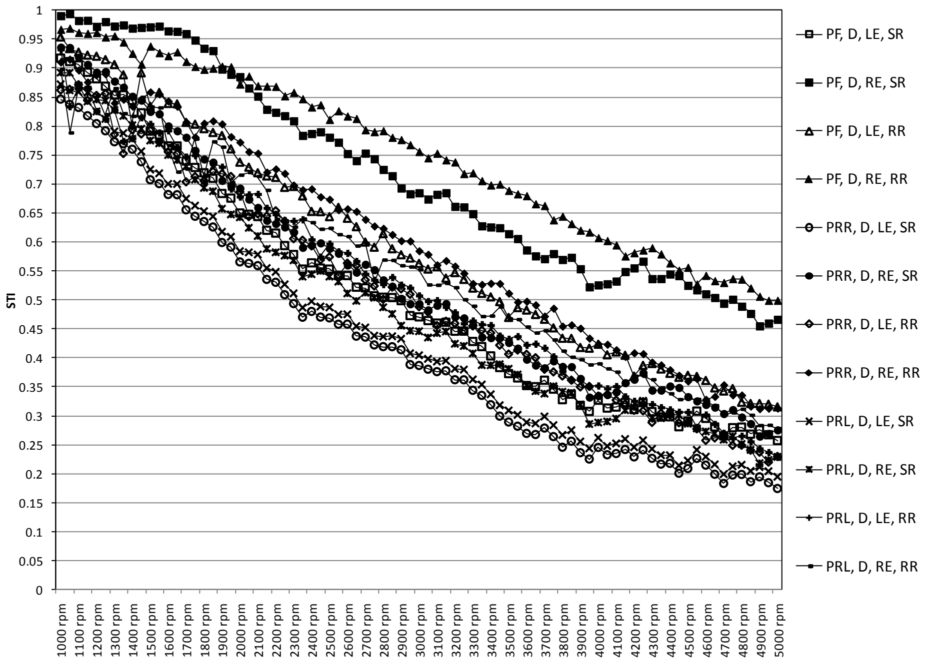


Figure 9: STI at the left ear (LE) and the right ear (RE) of the driver (D) as the listener, and passenger front (PF), passenger rear right (PRR) and the passenger rear left (PRL) as the talker, for variable speed operating condition, obtained using speech, impulse response and background noise measurements on both, the smooth rollers (SR) and the rough rollers (RR).

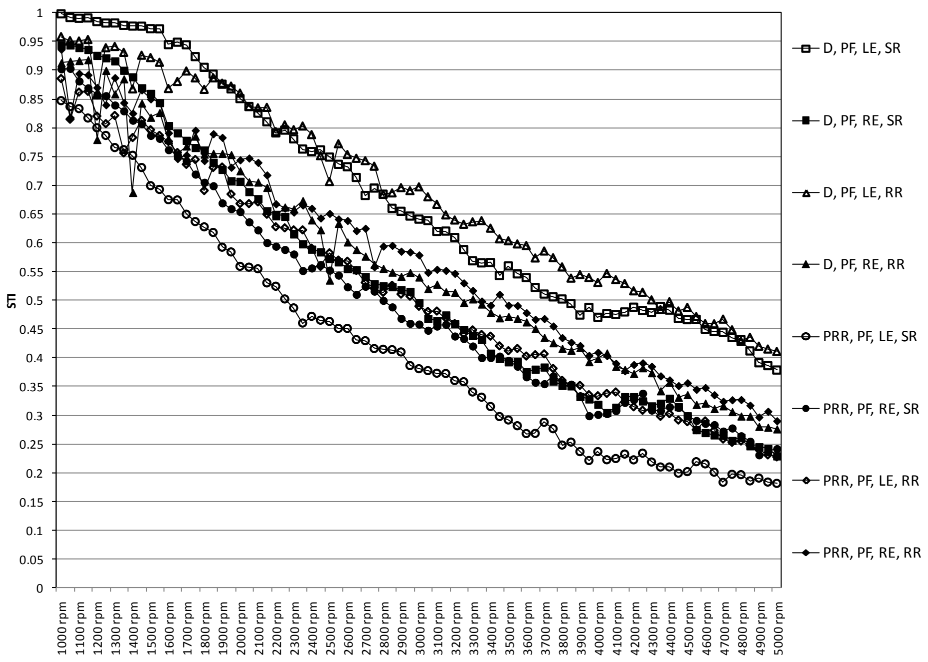


Figure 10: STI at the left ear (LE) and the right ear (RE) of the passenger front (PF) as the listener, and the driver (D) and the passenger rear right (PRR) as the talker, for variable speed operating condition, obtained using speech, impulse response and background noise measurements on both, the smooth rollers (SR) and the rough rollers (RR).

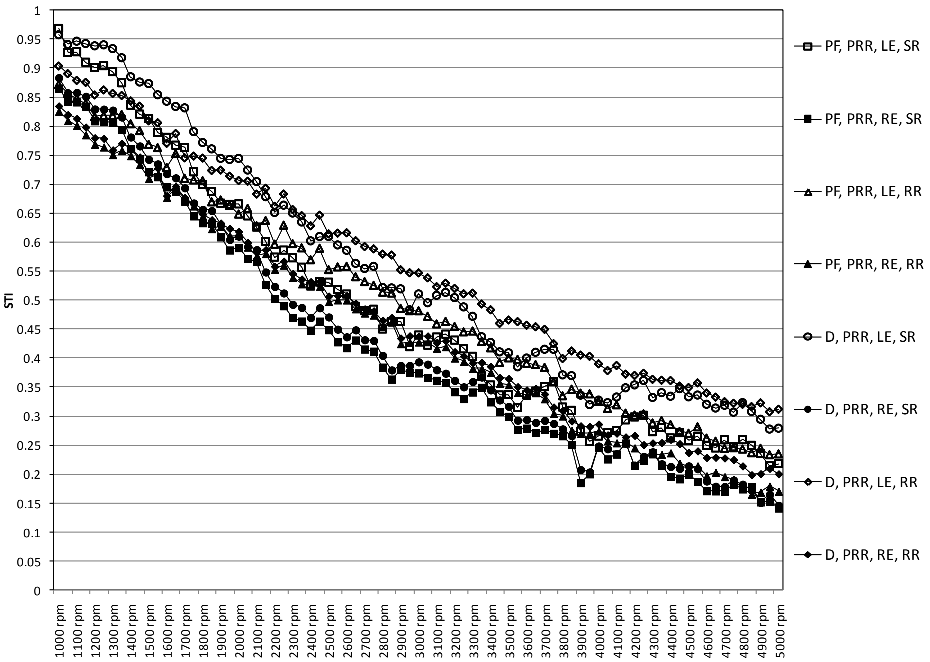


Figure 11: STI at the left ear (LE) and the right ear (RE) of the passenger rear right (PRR) as the listener, and the passenger front (PF) and the driver (PRR) as the talker, for variable speed operating condition, obtained using speech, impulse response and background noise measurements on both, the smooth rollers (SR) and the rough rollers (RR).

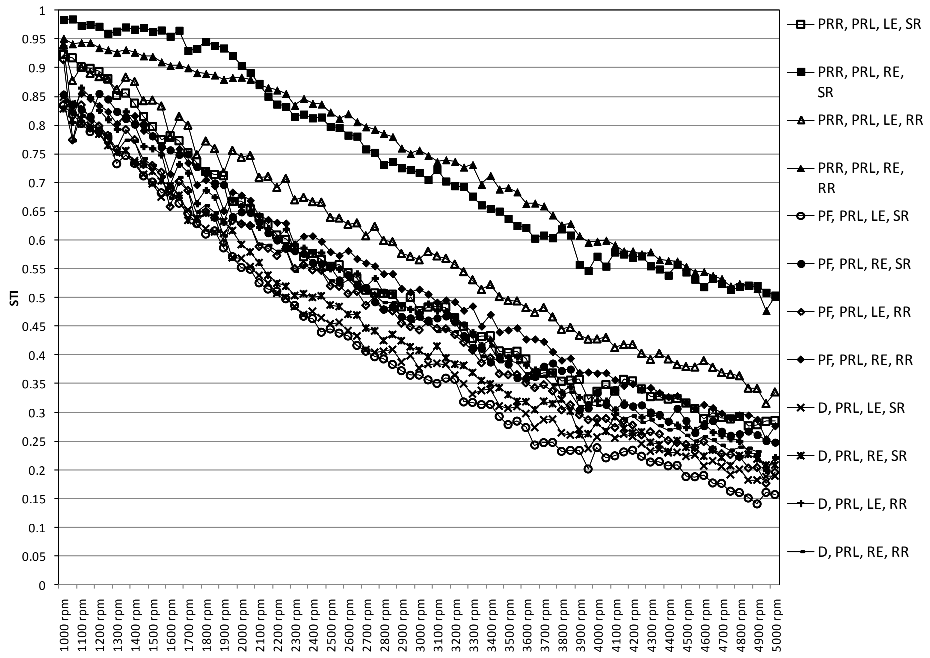


Figure 12: STI at the left ear (LE) and the right ear (RE) of the passenger rear left (PRL) as the listener, and the passenger rear right (PRR), passenger front (PF), and the driver (D) as the talker, for variable speed operating condition, obtained using speech, impulse response and background noise measurements on both, the smooth rollers (SR) and the rough rollers (RR), and calculated after each 50 rpm increment in the range from 1000 rpm to 5000 rpm.

The speech intelligibility is best when the talker and listener are next to each other, much like for the case of the constant speed conditions. The speech intelligibility is decreased when the talker is in the driver or the passenger front position and the listener is at one of the two rear positions. It is worse when the speech signal has a less direct path from the source to the receiver location, i.e., when the listener is directly behind the talker.

During the variable speed operation, the STI decreases with engine speed due to higher levels of background noise and the reduced apparent signal to noise ratio. Generally, the rate of decrease changes at 2000 rpm and 4000 rpm. Between 2000 rpm and 4000 rpm, the rate of decrease is fairly constant. Occasionally sudden decreases in STI are observed for the rough road condition at speeds less than 1500 rpm.

A rate of change of the STI as a function of engine or vehicle speed may influence the actual human perception of speech intelligibility inside a vehicle, depending on the individual driving style and visual cues available to the listener. Similar conclusions may be derived for the variable speed condition in terms of the effect of road conditions on speech intelligibility, although, the trends in terms of overall STI levels occasionally change throughout the range of speeds.

These changes may be significant if a sound quality issue is reported by a customer at a particular operating condition where there also may be a change in perception of speech intelligibility. Ultimately, further subjective testing seems appropriate to investigate the actual human perception of speech intelligibility at these locations and operating conditions.

The binaural STI results indicate that for certain configurations and operating conditions the range of perceived intelligibility, as explained by the subjective description of intelligibility used previously for constant speed condition (see Table 3) is quite different between the two ears. For example, in the passenger rear left location the STI is rated ‘poor’ at the left ear and ‘good’, almost ‘excellent’, at the right ear location, when the source is in the passenger rear right location, at about 3300 rpm on smooth rollers.

A similar result is observed at the driver location when the source is in the passenger front location. Again, subjective testing would help provide feedback on the effects of the differences in STI values between the two ears on human perception of speech intelligibility. Currently, there are no corrections to the STI method that would objectively predict speech intelligibility using binaural measurements of both the speech and the noise signals with varying directivity of the talker, distances between the talker and the listener, and unsteady background noise characterized with ordered and masking sources, all of which are typical conditions in person to person communication in an automobile.

Also, an additional variable affecting the perception of speech intelligibility is the difference in the speech and the background noise signals due to the physical environment itself for different talker and listener configurations, as in communication between the driver or the front passenger and the back row passengers, due to the presence of headrests, for example.

Given in Table 6 are the modulation transfer functions that illustrate the effects of the background noise on the STI using an example configuration with the receiver, or the listener, in the passenger front location, and the source, or the talker, in the driver location.

Table 6: Modulation Transfer Functions with the receiver, or the listener, in the passenger front location, and the source, or the talker, in the driver location, obtained using speech, impulse response and background noise measurements (left), and impulse response only, without signal to noise ratio correction (right). The results indicate that the effects of reverberation on reducing the STI are negligible, and that the background noise is the main contributor to the reduction of the apparent signal to noise ratio and, consequently, the STI.

Modulation Frequency, *F* [Hz]	Octave Band Frequency, *k* [Hz]						
	125	250	500	1000	2000	4000	8000
0.63	0.849	0.868	0.529	0.827	0.5	0.855	0.705
0.8	0.848	0.868	0.529	0.827	0.5	0.855	0.705
1	0.848	0.867	0.529	0.827	0.5	0.855	0.704
1.25	0.848	0.867	0.528	0.827	0.5	0.855	0.704
1.6	0.847	0.866	0.528	0.827	0.5	0.854	0.704
2	0.846	0.864	0.528	0.827	0.499	0.854	0.704
2.5	0.844	0.862	0.527	0.826	0.499	0.854	0.704
3.15	0.841	0.858	0.527	0.826	0.499	0.853	0.703
4	0.837	0.852	0.526	0.825	0.498	0.852	0.702
5	0.831	0.843	0.524	0.823	0.497	0.851	0.701
6.3	0.821	0.829	0.521	0.821	0.495	0.849	0.699
8	0.806	0.808	0.517	0.817	0.491	0.845	0.696
10	0.786	0.781	0.51	0.811	0.487	0.84	0.691
12.5	0.757	0.744	0.501	0.803	0.48	0.832	0.684
MTI	0.73	0.744	0.513	0.722	0.498	0.751	0.623
STI	**0.622**						

Modulation Frequency, *F* [Hz]	Octave Band Frequency, *k* [Hz]						
	125	250	500	1000	2000	4000	8000
0.63	1	0.999	1	1	1	1	0.998
0.8	0.999	0.999	1	1	1	1	0.998
1	0.999	0.999	1	1	1	1	0.998
1.25	0.999	0.998	0.999	1	1	1	0.998
1.6	0.998	0.997	0.999	0.999	0.999	0.999	0.998
2	0.996	0.995	0.998	0.999	0.999	0.999	0.998
2.5	0.994	0.992	0.998	0.999	0.998	0.999	0.997
3.15	0.991	0.988	0.996	0.998	0.997	0.998	0.996
4	0.986	0.98	0.994	0.997	0.996	0.997	0.995
5	0.978	0.97	0.991	0.995	0.993	0.995	0.993
6.3	0.967	0.954	0.985	0.992	0.989	0.993	0.991
8	0.95	0.93	0.977	0.988	0.983	0.988	0.986
10	0.926	0.899	0.965	0.981	0.974	0.982	0.979
12.5	0.892	0.857	0.947	0.97	0.96	0.973	0.969
MTI	0.97	0.956	0.993	1	0.997	1	1
STI (no noise)	**0.995**						

It is apparent that the main contributor to the reduction of the apparent signal to noise ratio is in fact the background noise, as the modulation transfer index and, consequently, the STI, at all the octave bands, is virtually 1, without considering the effects of background noise, i.e. signal to noise ratio. In addition, according to the IEC 60268-16:2003 standard, large reductions in values in each octave band column indicate that reverberation is the main factor in reducing intelligibility. Constant or slightly reducing values as in Table 6 indicate the presence of noise. Therefore, the effects of reverberation on the STI are negligible. This is due to the highly absorptive nature of the small volume automotive interior and its short reverberation times as indicated earlier in Figure 8. The measurement and the data processing effort can therefore possibly be minimized by not having to obtain the impulse response and considering the speech and background measurements only for the STI calculations.

6.1.1.1 Summary of the Results

The overall sound pressure level of background noise is often used to benchmark vehicles in terms of NVH performance. Reducing sound pressure level in the vehicle interior (dB) is a common goal in designing automotive sound packages. The results of this study indicate that higher sound pressure levels, depending on the frequency makeup, are not necessarily associated with lower speech intelligibility. The STI method and the measurement protocol presented in this study may be used in benchmarking vehicles in terms of interior sound quality as it relates to speech intelligibility. It can also be used to diagnose vehicle interior noise issues and modify parts of vehicle sound packages to provide potential improvements to speech intelligibility at different operating conditions and locations inside the vehicle. However, without further subjective testing, it is unclear whether certain trends observed in the STI results presented over a wide range of common vehicle operating conditions are significant in perception of in-vehicle speech intelligibility. These trends include significant differences in STI values (based on the subjective descriptions of intelligibility provided in the IEC EN 60268-16:2003) between the ears of the listener, the differences in the rate of change of STI in unsteady background noise at any given speed and the differences in STI for different configurations of the talker with respect to the listener particularly from the back to front locations.

It was found that the effects of in-vehicle reverberation on reducing speech intelligibility were negligible; the measurement effort for future in-vehicle STI studies could then be reduced by considering the speech and background noise measurements only, due to their predominant contribution to the apparent signal to noise ratio, and not measuring the impulse response.

The work presented in Section 6.2 incorporates an NVH driving simulator in order to model the perception of speech intelligibility using human subjects in a lab environment. An actual driving experience is simulated to offer a practical perspective and potentially interpreting the objective speech intelligibility scores, such as the STI.

6.1.2 Source Signal Parameters in Vehicles for Determining the Speech Transmission Index

Table 7 shows a comparison between the STI values for 60 dBA and 68 dBA speech signals for constant speed operating conditions and for different locations of the talker and the listener inside the vehicle. As indicated previously, a simple colour scheme is used to indicate the relation between the STI and the subjective perception of speech intelligibility. It is seen that increasing the speech signal sound pressure level from 60 dBA to 68 dBA increases the STI values by up to 30%. The subjective perception is subsequently improved significantly in some cases (for example, from ‘unintelligible’ to ‘fair’, ‘poor’ to ‘good’, etc.) based on the ranges of STI values and the corresponding subjective descriptions of the perceived speech intelligibility described in Table 7. For the case where the vehicle speed was increased from 50 km/h to 100 km/h, the speech intelligibility was found to decrease by as much as 25%. There was also a larger drop in intelligibility at the inboard ear at 100 km/h when the talker and the listener were located next to each other for the 60 dBA speech signal case compared to the 68 dBA speech signal.

Table 7: STI, Constant Vehicle Speed.

Driver (Source/Talker)

Passenger Front		Left Ear	Right Ear
50 km/h	60 dBA	0.78	0.62
	68 dBA	0.99	0.93
100 km/h	60 dBA	0.50	0.35
	68 dBA	0.85	0.70

Passenger Rear Left		Left Ear	Right Ear
50 km/h	60 dBA	0.51	0.53
	68 dBA	0.78	0.80
100 km/h	60 dBA	0.23	0.27
	68 dBA	0.51	0.56

Passenger Rear Right		Left Ear	Right Ear
50 km/h	60 dBA	0.65	0.51
	68 dBA	0.90	0.79
100 km/h	60 dBA	0.37	0.25
	68 dBA	0.65	0.53

Passenger Front (Source/Talker)

Driver		Left Ear	Right Ear
50 km/h	60 dBA	0.57	0.78
	68 dBA	0.83	0.98
100 km/h	60 dBA	0.34	0.57
	68 dBA	0.62	0.86

Passenger Rear Left		Left Ear	Right Ear
50 km/h	60 dBA	0.43	0.55
	68 dBA	0.72	0.83
100 km/h	60 dBA	0.17	0.32
	68 dBA	0.47	0.61

Passenger Rear Right		Left Ear	Right Ear
50 km/h	60 dBA	0.58	0.49
	68 dBA	0.84	0.76
100 km/h	60 dBA	0.30	0.23
	68 dBA	0.57	0.50

Passenger Rear Left (Source/Talker)

Driver		Left Ear	Right Ear
50 km/h	60 dBA	0.50	0.55
	68 dBA	0.78	0.82
100 km/h	60 dBA	0.27	0.33
	68 dBA	0.55	0.62

Passenger Front		Left Ear	Right Ear
50 km/h	60 dBA	not measured	
	68 dBA		
100 km/h	60 dBA		
	68 dBA		

Passenger Rear Right		Left Ear	Right Ear
50 km/h	60 dBA	not measured	
	68 dBA		
100 km/h	60 dBA		
	68 dBA		

Passenger Rear Right (Source/Talker)

Driver		Left Ear	Right Ear
50 km/h	60 dBA	0.49	0.60
	68 dBA	0.76	0.87
100 km/h	60 dBA	0.27	0.38
	68 dBA	0.53	0.67

Passenger Front		Left Ear	Right Ear
50 km/h	60 dBA	0.64	0.60
	68 dBA	0.90	0.89
100 km/h	60 dBA	0.34	0.32
	68 dBA	0.63	0.62

Passenger Rear Left		Left Ear	Right Ear
50 km/h	60 dBA	0.59	0.81
	68 dBA	0.85	0.99
100 km/h	60 dBA	0.31	0.57
	68 dBA	0.59	0.85

0-0.3	0.3-0.45	0.45-0.6	0.6-0.75	0.75-1
Unintelligible	Poor	Fair	Good	Excellent

In general, the speech sound directivity effects are also apparent as STI scores are higher for configurations for which the speech signal has a more direct path from the talker to the listener; for example, from the driver or the front passenger to the rear passenger locations, as opposed to from the rear passenger locations to the driver or the front passenger.

The intelligibility is worst when the talker is directly in front of the listener for all vehicle operating conditions. The STI scores are lower for the outboard ear compared to the in-board ear due to the effects of road noise. This was observed for all operating conditions and configurations, with most significant difference for configurations when the talker and the listener are next to each other.

Figures 13 to 16 illustrate changes in STI with engine speed for the 60 dBA and 68 dBA speech signal.

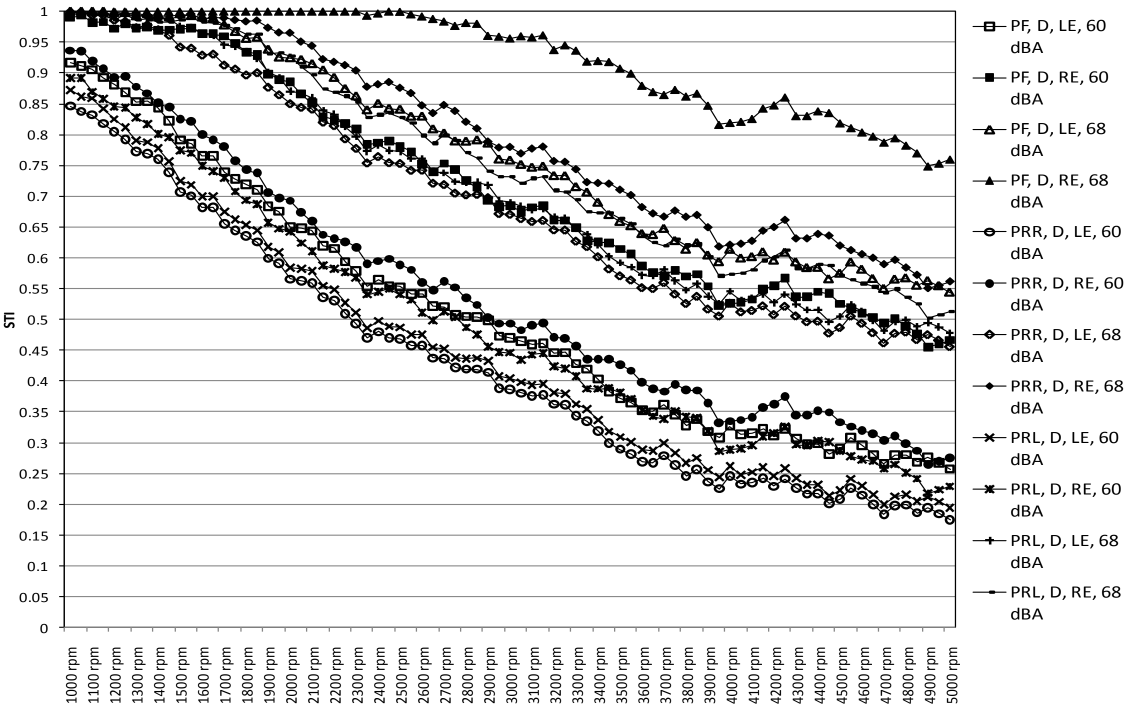


Figure 13: STI, Driver, Variable Engine Speed.

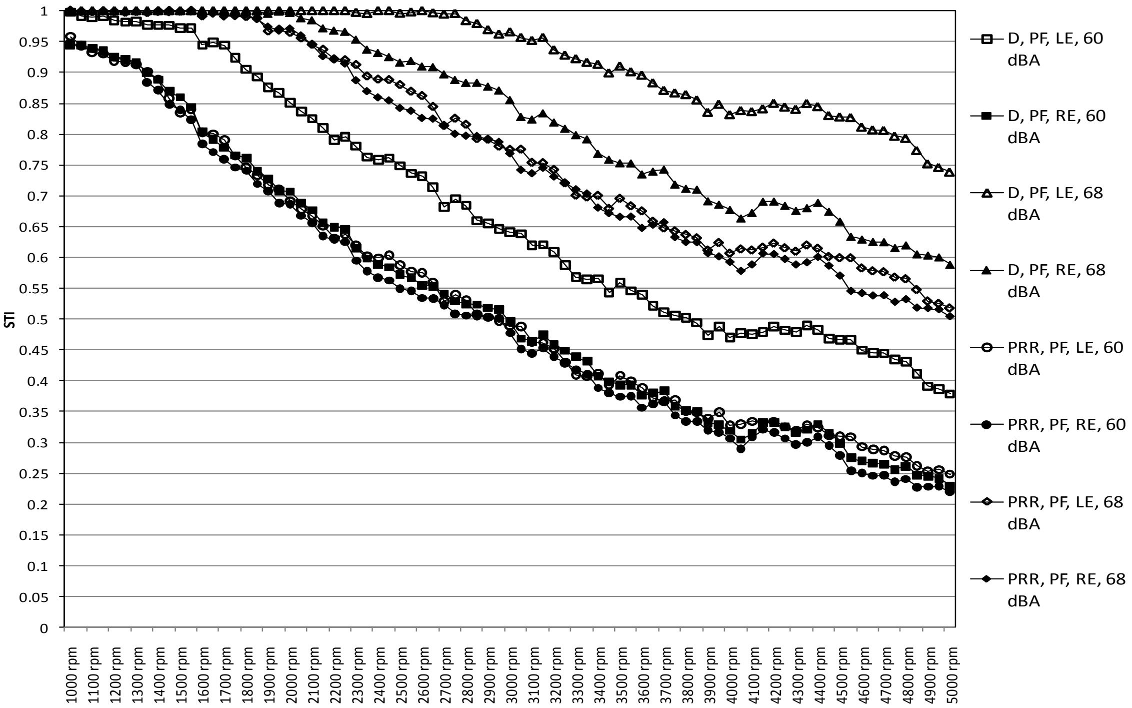


Figure 14: STI, Passenger Front, Variable Engine Speed.

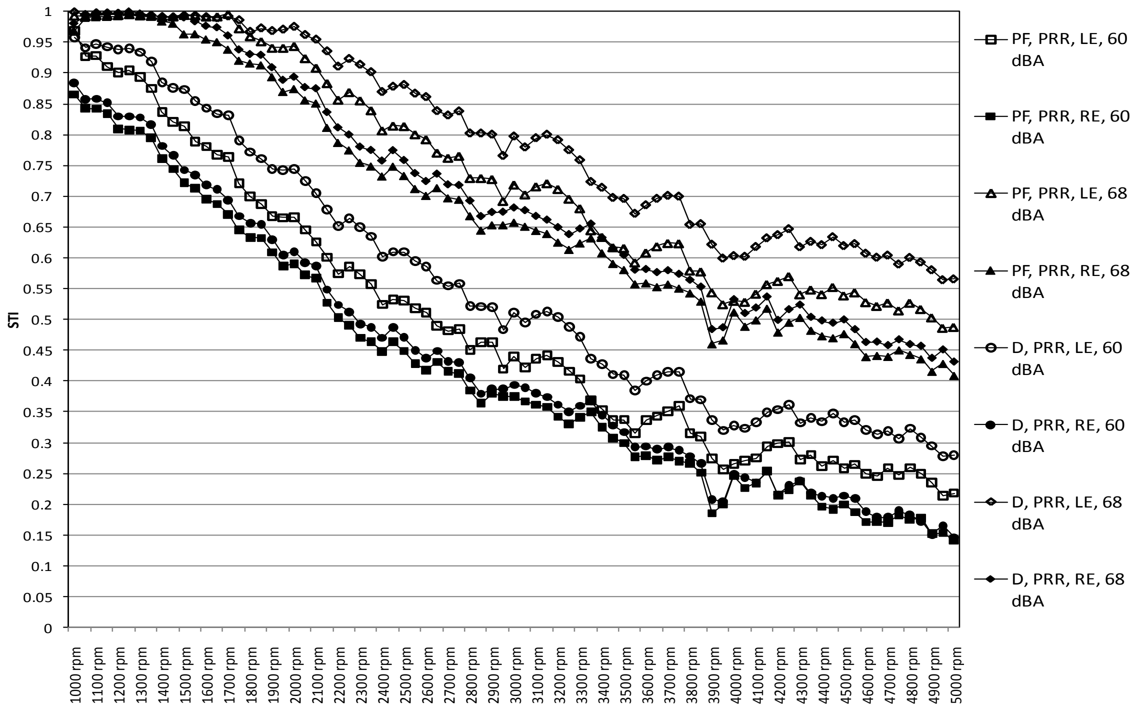


Figure 15: STI, Passenger Rear Right, Variable Engine Speed.

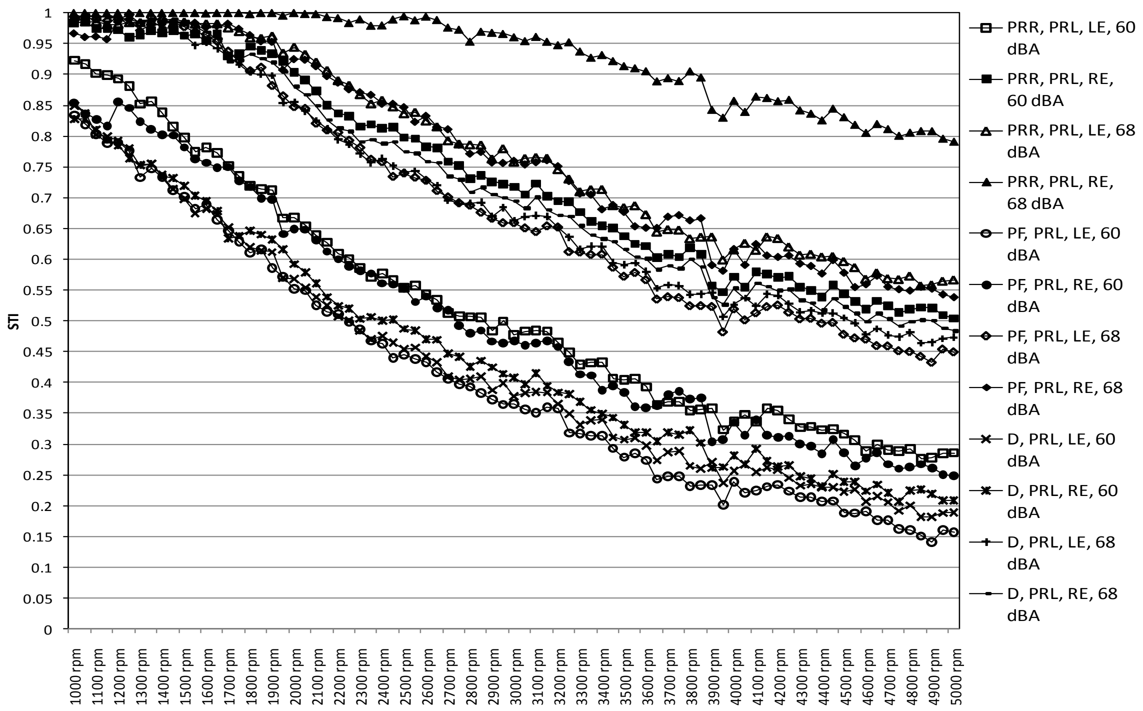


Figure 16: STI, Passenger Rear Left, Variable Engine Speed.

A similar trend in terms of overall STI values associated with the different talker and listener locations can be observed for the speech levels considered at any given engine speed. Significant improvements in speech intelligibility are also realized, particularly at higher speeds, when the difference between the STI values associated with the speech levels is greater. In general, the range of STI values at a given operating condition and location inside the vehicle is smaller at the 68 dBA speech level compared to 60 dBA speech level. At low speeds, there is less fluctuation of the STI values, in addition to a more constant rate of change with respect to the vehicle speed.

According to the definition of STI, the range of values where the apparent signal to noise ratio is linearly related to STI is from -15 dB to 15 dB. Above and below this range the STI is assigned values of 0 and 1, respectively. When the 68 dBA speech signal is generated at low vehicle speeds, and when the talker and the listener are next to each other, the STI frequently equals 1 because the signal level is greater than the background noise level by more than 15 dB. For all other configurations at low speeds within the range of 1000 rpm to 1500 rpm, and occasionally up to 2000 rpm, the STI is fairly constant or it has a low rate of decrease with speed. At these conditions, the STI is greater than 0.9 and the speech intelligibility is rated excellent. At approximately 2000 rpm the STI starts to decrease rapidly. In comparison, for the 60 dBA speech level the rate of decrease of STI is more rapid at low vehicle speeds below 2000 rpm.

Figure 17 shows the original and the equalized MLS and pink noise signals generated by the loudspeaker mounted in the Type 4128 HATS and measured in the anechoic room, including the required gain settings from the audio power amplifier. As both signals were equalized in terms of spectrum according to the IEC standard for male speech

(+/- 1 dB), the STI results obtained by using both types of signals were identical, assuming the same background noise and impulse response measurements. The STI data presented in this paper were obtained using the equalized pink noise signal. The equalized pink noise signal required a higher amplifier gain compared to the equalized MLS signal. At 60 dBA, the difference between the two values was 10 dB. Similarly, for 68 dBA, the difference was 7 dB. A gain value was also set for the equalized MLS signal at 72 dBA. Attempting to set a gain value to provide 72 dBA with the equalized pink noise signal resulted in clipping, and as such, the loudspeaker was unable to generate the required sound pressure level. An equalized pink noise signal then ultimately put more strain on the loudspeaker compared to an equalized MLS signal for any given sound pressure level.

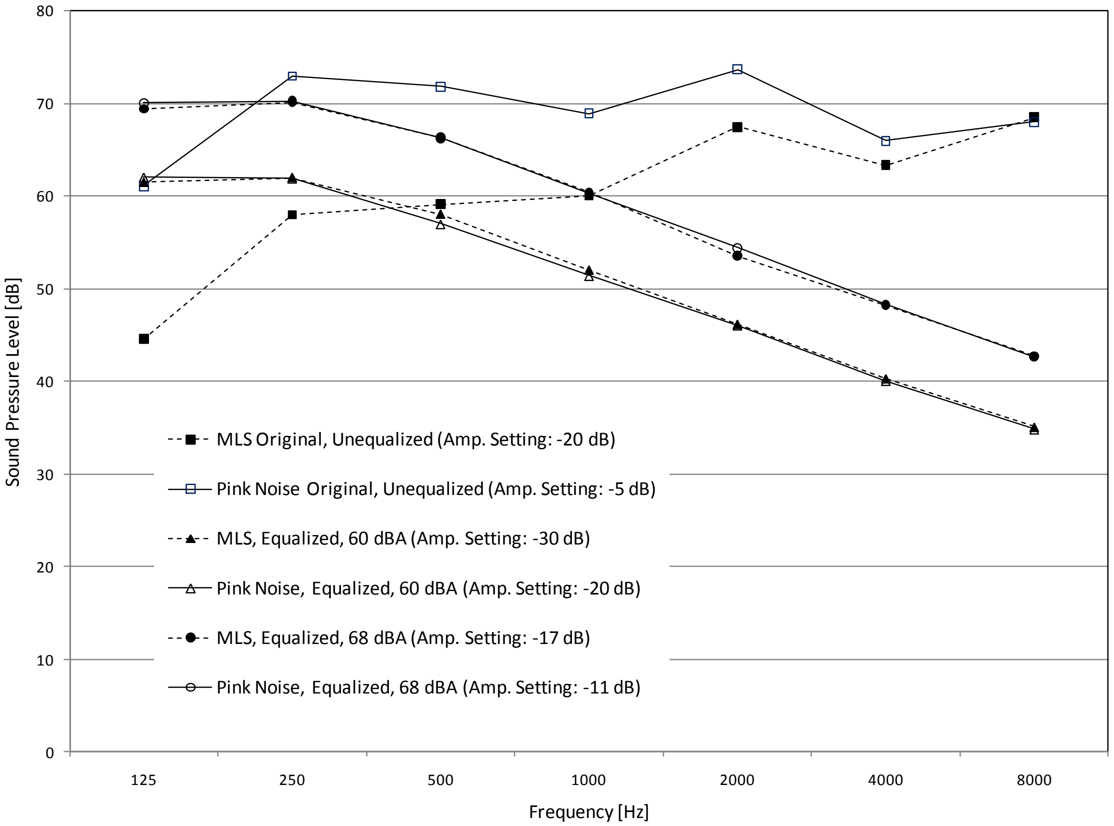


Figure 17: Speech Signal Equalization, MLS and Pink Noise Signals with Amplifier Gain Settings.

The Peak to Noise Ratio (PNR) is used as an impulse response measurement quality parameter. It is a logarithmic ratio of the maximum impulse response level and the noise level. Its value must be at least 35 dB for a quality measurement (ISO 3382-2:2008). Table 8 shows changes in PNR using the MLS technique with different signal levels as well as the sine sweep technique to obtain the impulse response for an example talker/listener configuration. Similar results were observed for the remaining eight configurations. When the signal is set to 60 dBA, the PNR is above 35 dB at all of the octave frequencies of interest. As the signal level increases, the PNR decreases. When the 68 dBA and 72 dBA equalized MLS signals are used for impulse response calculations, the 35 dB criteria for signal quality is not satisfied. The sine sweep technique provides the best PNR, however it requires that additional measurements be made, thus lengthening the acquisition procedure. The results indicate that the speech signal equalized and set to 60 dBA may also be used to obtain the impulse response without additional measurements. This speech and impulse response data in combination with the background noise data is used to calculate the STI.

Table 8: Example Peak to Noise Ratios [dB] using Different Equalized MLS Signal Levels and Sine Sweep to Obtain Impulse Response (Talker Location: Driver, Listener Location: Passenger Rear Right).

	Frequency [Hz]						
	125	250	500	1000	2000	4000	8000
60 dBA	52	44	38	48	48	57	54
68 dBA	49	37	33	42	40	43	42
72 dBA	46	34	29	38	36	39	39
Sine Sweep	62	72	62	91	98	106	96

6.1.2.1 Summary of the Results

This study presented results on the effects of different types and levels of sound source signals on STI calculations using various vehicle operating conditions as well as talker and listener measurement configurations inside a vehicle. For a 60 dBA speech signal (current IEC standard) and constant speed operation, the STI values range from ‘unintelligible’ to ‘excellent’, depending on the location of the talker and the listener. For a 68 dBA speech signal (previous IEC standard), the STI is at least ‘fair’ and its value was found to be less sensitive to changes in the vehicle operating conditions. The speech signal level from the current standard provides satisfactory PNR for any method for obtaining IR. A more detailed investigation is needed to determine whether or not the value (60 dBA) is realistic using a wide range of vehicle operating conditions, vehicle types and actual human listeners. This is a motivation for further investigation using acoustic perception jury testing within a driving simulator, as presented in Section 6.2. The 60 dBA signal, associated with “normal” vocal effort (ANSI S3.5-1997), provided adequate (at least “fair”) intelligibility at lower speeds, such as city driving (50 km/h), for all measurement configurations. An increased vocal effort of at least 68 dBA, considered to be “loud” (ANSI S3.5-1997), was necessary to obtain similar intelligibility scores at higher speeds, such as highway driving (100 km/h), due to significantly higher levels of background noise. Again, a subjective study using human subjects in a simulated vehicle environment would be conducted to investigate the speech sound pressure level under which speech communication is expected to be intelligible.

6.1.3 In-vehicle Application of Common Speech Intelligibility Metrics

The speech intelligibility metrics for constant speed operation on both the smooth and the rough roll surfaces are summarized in Tables 9 through 12, for various talker and listener locations. A simple colour scheme is used to categorize results for all the metrics, according to the ranges of subjective descriptions of speech intelligibility, as specified in the STI standard. The categories seem appropriate for the SII values, generally defined as a proportion of the total number of speech cues delivered from the source to the listener, where good communication systems have an SII greater than 0.75, while poor communication systems have an SII below 0.45 (ANSI S3.5-1997). Similarly, the qualification intervals for STI are rated ‘poor’ for scores below 0.45 and ‘excellent’ above 0.75 (IEC 60268-16:2003). There are no publications with similar guidelines related to the subjective interpretation of articulation index scores, as used in vehicle applications, where the speech intelligibility as a factor influencing the perception of the overall vehicle sound quality is typically evaluated by customers based on their individual preference. In order to remain consistent, the AI values are categorized in the same groups with subjective descriptions of speech intelligibility as SII and STI. It should be noted that the SII(nve) calculation is based on a fixed speech spectrum associated with normal vocal effort, per ANSI S3.5-1997 standard (Figure 18). The SII(m) calculation is based on the same 60 dBA measured speech spectrum used for STI calculations in the previous studies (Sections 6.1.1 and 6.1.2).

Table 9: Speech Intelligibility Metrics, 50 km/h, Smooth Road.

Driver (Source/Talker)	Passenger Front (Receiver)		Passenger Rear Left (Receiver)		Passenger Rear Right (Receiver)	
	Left Ear	Right Ear	Left Ear	Right Ear	Left Ear	Right Ear
AI	0.80	0.80	0.80	0.90	0.90	0.80
SII(nve)	0.74	0.69	0.63	0.68	0.62	0.58
SII(m)	0.85	0.70	0.54	0.55	0.62	0.49
STI	0.80	0.63	0.50	0.51	0.66	0.51

Passenger Front (Source/Talker)	Driver (Receiver)		Passenger Rear Left (Receiver)		Passenger Rear Right (Receiver)	
	Left Ear	Right Ear	Left Ear	Right Ear	Left Ear	Right Ear
AI	0.70	0.80	0.80	0.90	0.90	0.80
SII(nve)	0.59	0.67	0.55	0.61	0.69	0.64
SII(m)	0.56	0.78	0.51	0.61	0.55	0.48
STI	0.57	0.79	0.47	0.57	0.58	0.49

Passenger Rear Left (Source/Talker)	Driver (Receiver)		Passenger Front (Receiver)		Passenger Rear Right (Receiver)	
	Left Ear	Right Ear	Left Ear	Right Ear	Left Ear	Right Ear
AI	0.70	0.80	not measured		not measured	
SII(nve)	0.50	0.58				
SII(m)	0.49	0.56				
STI	0.51	0.55				

Passenger Rear Right (Source/Talker)	Driver (Receiver)		Passenger Front (Receiver)		Passenger Rear Left (Receiver)	
	Left Ear	Right Ear	Left Ear	Right Ear	Left Ear	Right Ear
AI	0.70	0.80	0.80	0.80	0.80	0.90
SII(nve)	0.44	0.52	0.65	0.60	0.71	0.78
SII(m)	0.47	0.57	0.64	0.60	0.61	0.85
STI	0.49	0.60	0.64	0.61	0.60	0.82

0-0.3	0.3-0.45	0.45-0.6	0.6-0.75	0.75-1
Unintelligible	Poor	Fair	Good	Excellent

Table 10: Speech Intelligibility Metrics, 50 km/h, Rough Road.

Driver (Source/Talker)	Passenger Front (Receiver)		Passenger Rear Left (Receiver)		Passenger Rear Right (Receiver)	
	Left Ear	Right Ear	Left Ear	Right Ear	Left Ear	Right Ear
AI	0.80	0.80	0.90	0.90	0.90	0.80
SII(nve)	0.68	0.67	0.62	0.64	0.55	0.54
SII(m)	0.78	0.68	0.53	0.51	0.55	0.44
STI	0.74	0.61	0.53	0.50	0.57	0.47

Passenger Front (Source/Talker)	Driver (Receiver)		Passenger Rear Left (Receiver)		Passenger Rear Right (Receiver)	
	Left Ear	Right Ear	Left Ear	Right Ear	Left Ear	Right Ear
AI	0.80	0.80	0.90	0.90	0.90	0.80
SII(nve)	0.64	0.69	0.56	0.58	0.61	0.60
SII(m)	0.61	0.79	0.51	0.57	0.48	0.43
STI	0.64	0.80	0.49	0.55	0.50	0.46

Passenger Rear Left (Source/Talker)	Driver (Receiver)		Passenger Front (Receiver)		Passenger Rear Right (Receiver)	
	Left Ear	Right Ear	Left Ear	Right Ear	Left Ear	Right Ear
AI	0.80	0.90	not measured		not measured	
SII(nve)	0.57	0.63				
SII(m)	0.55	0.61				
STI	0.58	0.62				

Passenger Rear Right (Source/Talker)	Driver (Receiver)		Passenger Front (Receiver)		Passenger Rear Left (Receiver)	
	Left Ear	Right Ear	Left Ear	Right Ear	Left Ear	Right Ear
AI	0.80	0.90	0.80	0.80	0.90	0.90
SII(nve)	0.51	0.57	0.59	0.59	0.72	0.74
SII(m)	0.53	0.61	0.58	0.57	0.62	0.80
STI	0.56	0.66	0.59	0.59	0.62	0.79

0-0.3	0.3-0.45	0.45-0.6	0.6-0.75	0.75-1
Unintelligible	Poor	Fair	Good	Excellent

Table 11: Speech Intelligibility Metrics, 100 km/h, Smooth Road.

Driver (Source/Talker)			Passenger Front (Receiver)			Driver (Receiver)			Passenger Front (Source/Talker)		
				Left Ear	Right Ear		Left Ear	Right Ear			
			AI	0.60	0.60	AI	0.50	0.60			
			SII(nve)	0.44	0.42	SII(nve)	0.35	0.45			
			SII(m)	0.56	0.43	SII(m)	0.32	0.56			
			STI	0.50	0.35	STI	0.32	0.56			
Passenger Rear Left (Receiver)			Passenger Rear Right (Receiver)			Passenger Rear Left (Receiver)			Passenger Rear Right (Receiver)		
	Left Ear	Right Ear		Left Ear	Right Ear		Left Ear	Right Ear		Left Ear	Right Ear
AI	0.60	0.60	AI	0.60	0.60	AI	0.50	0.60	AI	0.60	0.60
SII(nve)	0.34	0.42	SII(nve)	0.35	0.30	SII(nve)	0.24	0.35	SII(nve)	0.41	0.36
SII(m)	0.25	0.30	SII(m)	0.35	0.22	SII(m)	0.20	0.35	SII(m)	0.28	0.21
STI	0.22	0.26	STI	0.37	0.25	STI	0.18	0.32	STI	0.30	0.23

Driver (Receiver)			Passenger Front (Receiver)			Driver (Receiver)			Passenger Front (Receiver)		
	Left Ear	Right Ear		Left Ear	Right Ear		Left Ear	Right Ear		Left Ear	Right Ear
AI	0.50	0.60	AI	not measured		AI	0.50	0.60	AI	0.60	0.60
SII(nve)	0.27	0.36	SII(nve)			SII(nve)	0.21	0.30	SII(nve)	0.36	0.33
SII(m)	0.26	0.34	SII(m)			SII(m)	0.24	0.35	SII(m)	0.35	0.32
STI	0.27	0.34	STI			STI	0.27	0.39	STI	0.34	0.33
Passenger Rear Left (Source/Talker)			Passenger Rear Right (Receiver)			Passenger Rear Left (Receiver)			Passenger Rear Right (Source/Talker)		
				Left Ear	Right Ear		Left Ear	Right Ear			
			AI	not measured		AI	0.60	0.60			
			SII(nve)			SII(nve)	0.43	0.52			
			SII(m)			SII(m)	0.33	0.60			
			STI			STI	0.32	0.57			

0-0.3	0.3-0.45	0.45-0.6	0.6-0.75	0.75-1
Unintelligible	Poor	Fair	Good	Excellent

Table 12: Speech Intelligibility Metrics, 100 km/h, Rough Road.

Driver (Source)			Passenger Front (Receiver)			Driver (Receiver)			Passenger Front (Source)		
				Left Ear	Right Ear		Left Ear	Right Ear			
			AI	0.50	0.50	AI	0.50	0.60			
			SII(nve)	0.38	0.37	SII(nve)	0.32	0.41			
			SII(m)	0.50	0.37	SII(m)	0.28	0.52			
			STI	0.46	0.33	STI	0.34	0.55			
Passenger Rear Left (Receiver)			Passenger Rear Right (Receiver)			Passenger Rear Left (Receiver)			Passenger Rear Right (Receiver)		
	Left Ear	Right Ear		Left Ear	Right Ear		Left Ear	Right Ear		Left Ear	Right Ear
AI	0.60	0.60	AI	0.60	0.50	AI	0.60	0.60	AI	0.60	0.50
SII(nve)	0.31	0.34	SII(nve)	0.26	0.24	SII(nve)	0.26	0.29	SII(nve)	0.32	0.29
SII(m)	0.21	0.21	SII(m)	0.24	0.13	SII(m)	0.19	0.27	SII(m)	0.17	0.12
STI	0.22	0.22	STI	0.32	0.23	STI	0.20	0.28	STI	0.24	0.18

Driver (Receiver)			Passenger Front (Receiver)			Driver (Receiver)			Passenger Front (Receiver)		
	Left Ear	Right Ear		Left Ear	Right Ear		Left Ear	Right Ear		Left Ear	Right Ear
AI	0.50	0.60	AI	not measured		AI	0.50	0.60	AI	0.50	0.50
SII(nve)	0.25	0.34	SII(nve)			SII(nve)	0.20	0.27	SII(nve)	0.30	0.29
SII(m)	0.22	0.31	SII(m)			SII(m)	0.20	0.30	SII(m)	0.28	0.26
STI	0.26	0.35	STI			STI	0.27	0.37	STI	0.34	0.30
Passenger Rear Left (Source)			Passenger Rear Right (Receiver)			Passenger Rear Left (Receiver)			Passenger Rear Right (Source)		
				Left Ear	Right Ear		Left Ear	Right Ear			
			AI	not measured		AI	0.60	0.60			
			SII(nve)			SII(nve)	0.41	0.44			
			SII(m)			SII(m)	0.30	0.52			
			STI			STI	0.33	0.50			

0-0.3	0.3-0.45	0.45-0.6	0.6-0.75	0.75-1
Unintelligible	Poor	Fair	Good	Excellent

In general, the nature of correlation between the different scores and subjective intelligibility tests is unknown, or whether or not the same score obtained using different metrics is associated with the same subjective response in terms of speech intelligibility; No direct comparison between various methods is available using, for example, the same speech material.

For automotive sound package development, it is known that a difference in articulation index of only about 0.06 (6%) is considered to be significant (Ebbitt, 2001). From Tables 7 to 10 the difference in scores using different methods can be as high as 10%, which is potentially significant.

The more dominant high frequency content associated with the smooth roll operation compared to the rough roll operation was found to contribute more significantly to the reduction of speech intelligibility for all three metrics. The weighing factors associated with the AI, SII and STI calculations are higher at higher frequencies compared to those at lower frequencies usually associated with the rough roll operation. The result is that the intelligibility scores are actually higher for the rough road operation compared to the smooth roll operation. This is despite the higher overall sound pressure levels associated with the rough roll operation compared to the same set-up when the vehicle is on the smooth rolls. A similar finding was obtained in a previous study also conducted in a semi-anechoic vehicle dynamometer (Section 6.1.1).

Additionally, the presence of wind noise, which is not accounted for in a semi-anechoic vehicle dynamometer test cell, would likely provide additional masking at higher frequencies and reduce any differences between the rough and smooth road surface sound pressure levels at those frequencies.

In general, the articulation index scores are significantly higher compared to the other three methods mainly due to the 82 dBA overall level of its assumed speech spectrum (Figure 18).

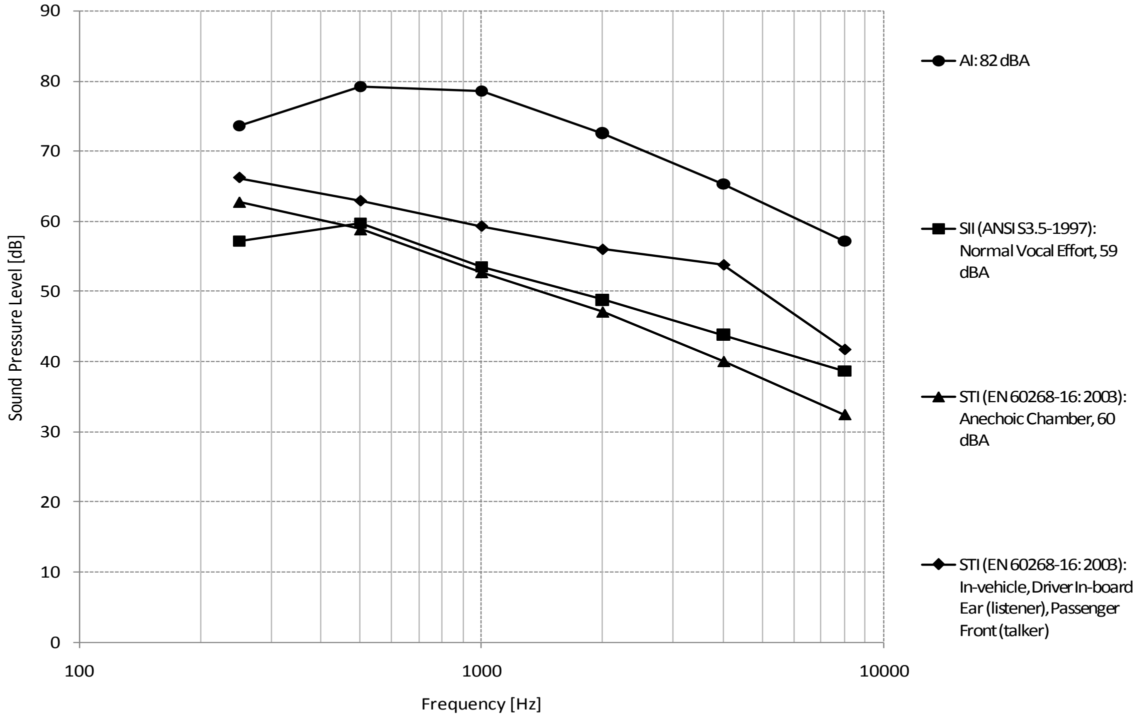


Figure 18: Speech Spectra Specifying Standards (if applicable) Associated with the Metrics Under Investigation - AI, SII and STI.

Coincidentally, this particular value is associated with ‘shouting’ vocal effort according to the ANSI S3.5-1997 standard, and it is significantly higher compared to the 60 dBA level used by the other methods considered in this study. Based on the AI values, the speech intelligibility is fairly constant at different listener locations in the vehicle. The AI values are mainly influenced by the background noise that does not change significantly at different listener locations inside the vehicle. The effects of the directivity of the talker and different distances between the talker and the listener are not taken into account, despite their contribution to variation in actual speech intelligibility for different combinations of the talker and the listener; the same assumed speech spectrum is used for all measurement configurations and operating conditions under consideration and both ears of the listener.

The assumed reference spectrum for calculating SII(nve) is associated with ‘normal’ vocal effort measured in free field at a one meter distance from the talker’s mouth. The effect of the distance between the talker and the listener is also taken into account in the calculations, as described in ANSI S3.5-1997 standard. Due to the effects of the directivity associated with in-vehicle communication between passengers, the reference measurement setup is not reproduced exactly inside the vehicle. However, it is still important to apply the correction for the distance as it results in a more realistic prediction for speech intelligibility.

The SII(m) and the STI methods use the same measured speech spectrum, and naturally account for the directivity and the distance between the talker and the listener, as opposed to the AI and SII(nve) methods discussed previously. This is evident by the difference in the results between the methods using the assumed versus the measured speech spectra in the calculations. Figure 3 illustrated that the measured speech spectrum after the equalization in the anechoic room at one meter distance from the artificial talker, according to the IEC standard. An example of an in-vehicle measurement of the same speech signal is provided in the same figure for the listener’s inboard ear for one of the measurement configurations. The difference between the two spectra is due to the effects of the directivity and the distance between the talker and the listener.

The SII(m) and STI scores were closely correlated. This supports findings from the previous study showing that the effects of reverberation for vehicle applications are negligible, since SII method does not account for these effects, as opposed to the STI method. Thus, the loss of speech intelligibility is mainly due to background noise at various vehicle operating conditions.

Any difference between SII(m) and STI values may be due to differences in the frequency weighing factors and calculation methods associated with each metric. The speech intelligibility metrics were also calculated for variable speed conditions, for each of the ten configurations from Tables 7 through 10, between 1000 rpm and 5000 rpm, in increments of 50 rpm, for both types of road surface profiles and both ears of the listener. The results illustrated in Figures 19 through 26 are for the in-board ear of the listener in various listening locations and road surface profiles.

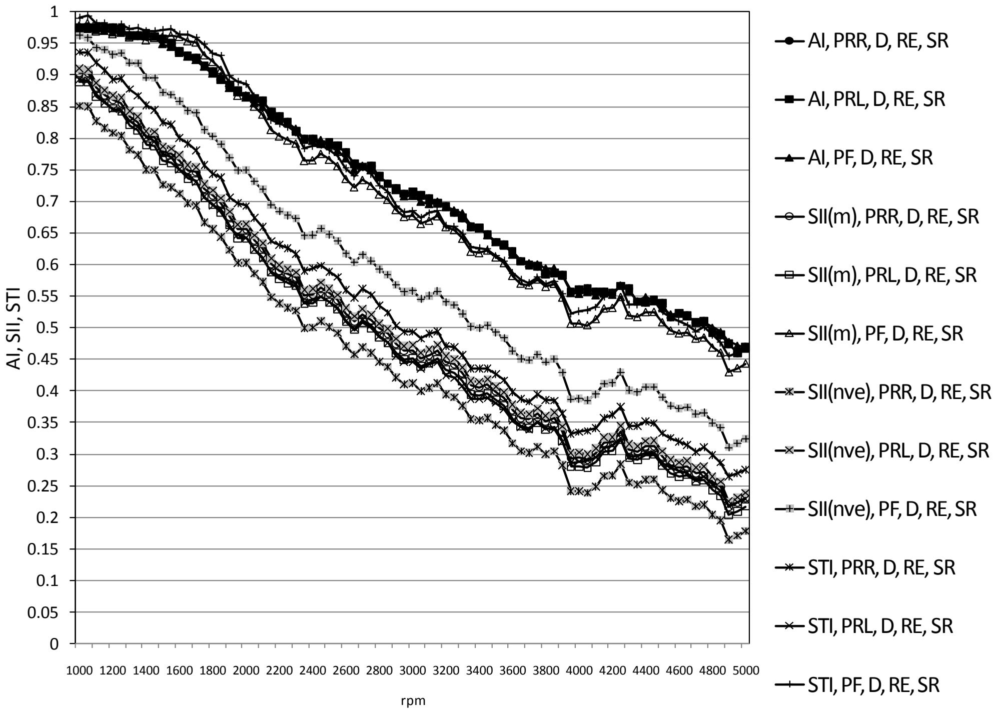


Figure 19: Speech Intelligibility Metrics when the Listener is in the Driver Position, Inboard Ear, Smooth Road.

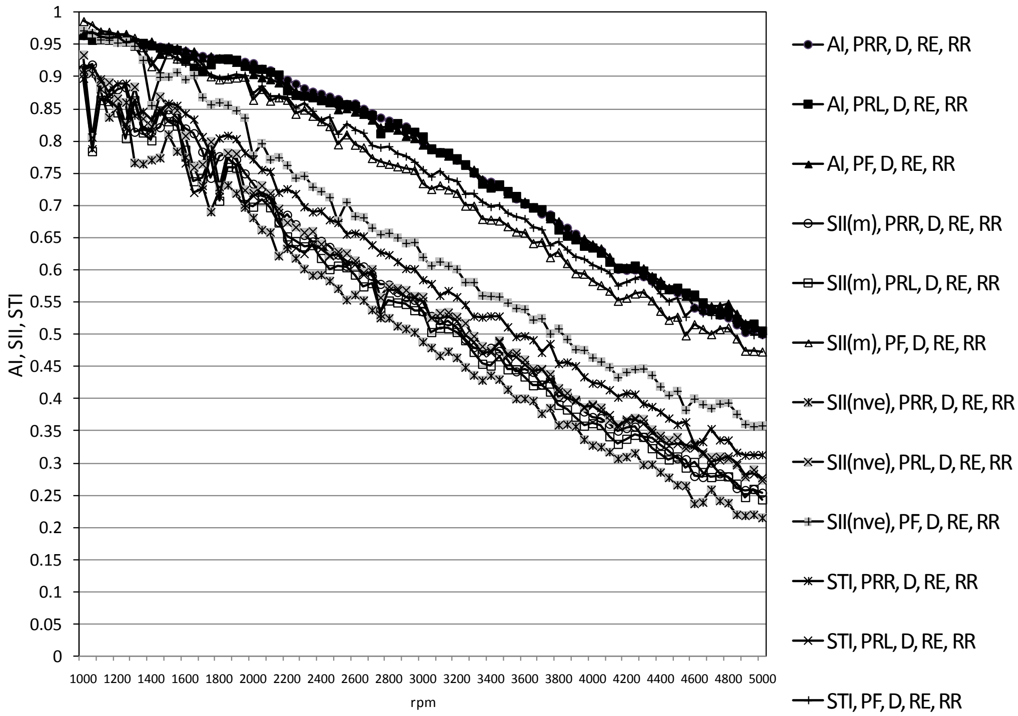


Figure 20: Speech Intelligibility Metrics when the Listener is in the Driver Position, Inboard Ear, Rough Road.

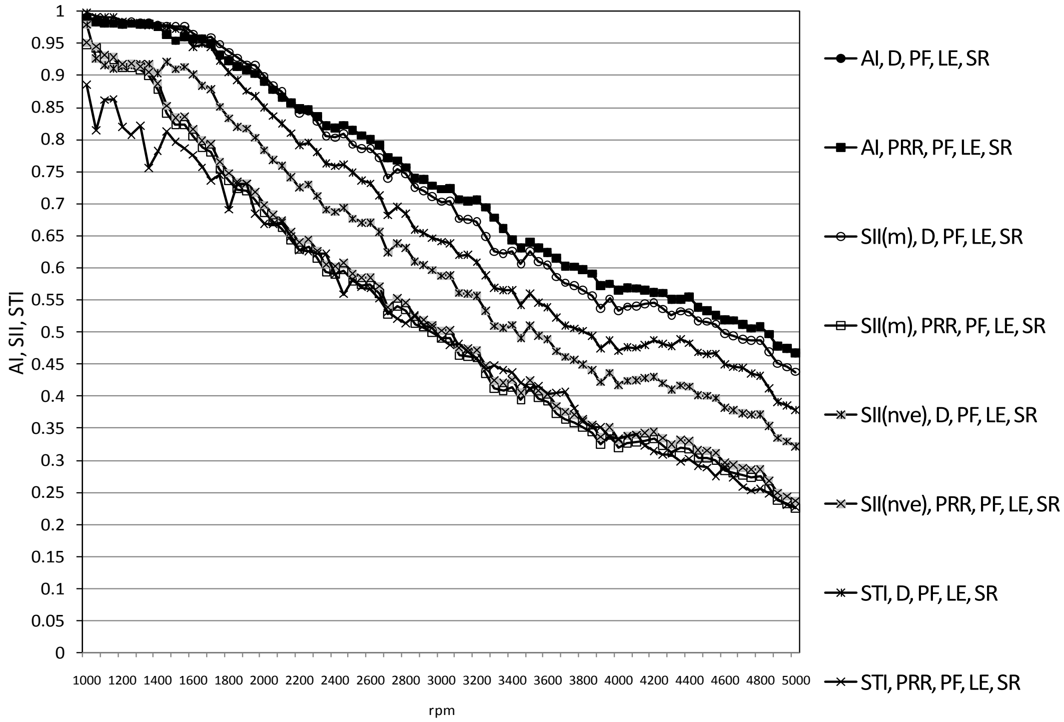


Figure 21: Speech Intelligibility Metrics when the Listener is in the Passenger Front Position, Inboard Ear, Smooth Road.

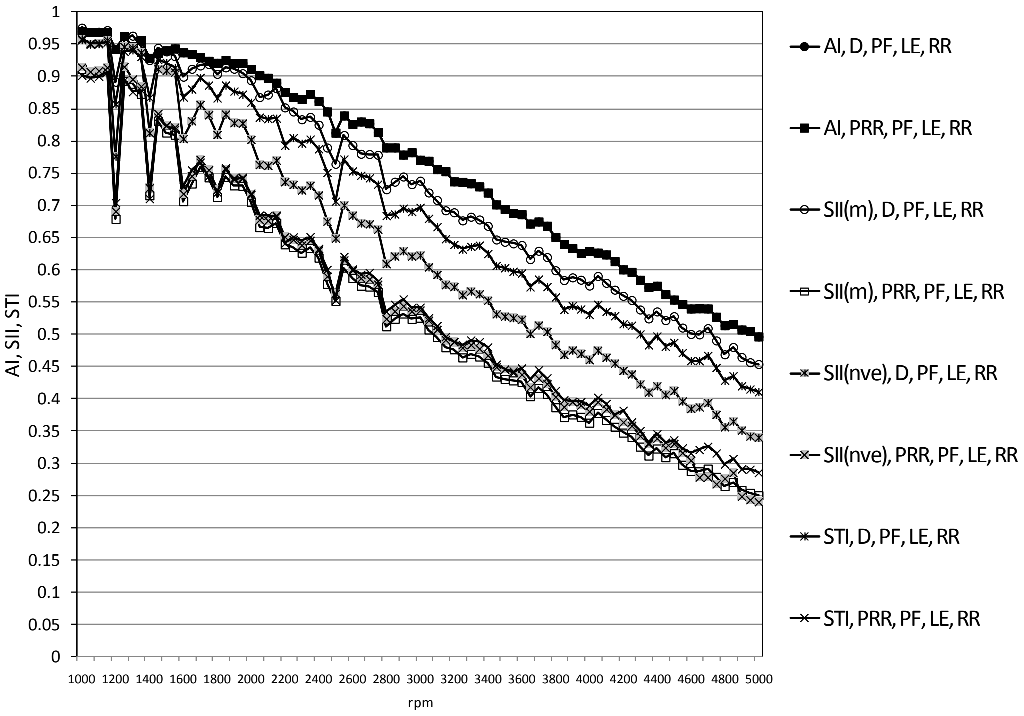


Figure 22: Speech Intelligibility Metrics when the Listener is in the Passenger Front Position, Inboard Ear, Rough Road.

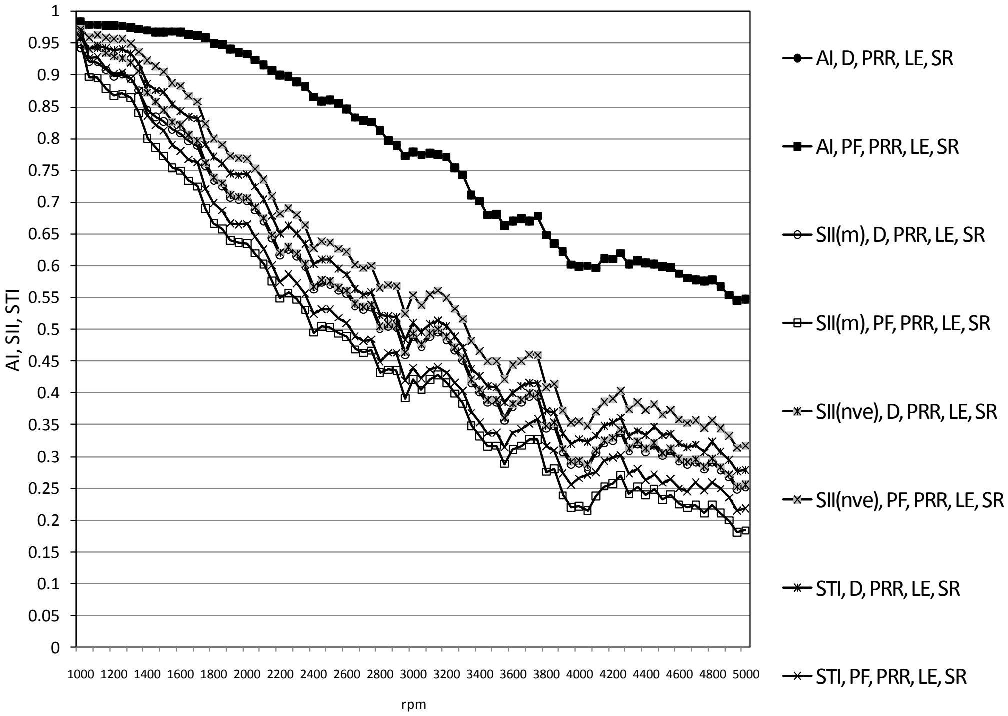


Figure 23: Speech Intelligibility Metrics when the Listener is in the Passenger Rear Right Position, Inboard Ear, Smooth Road.

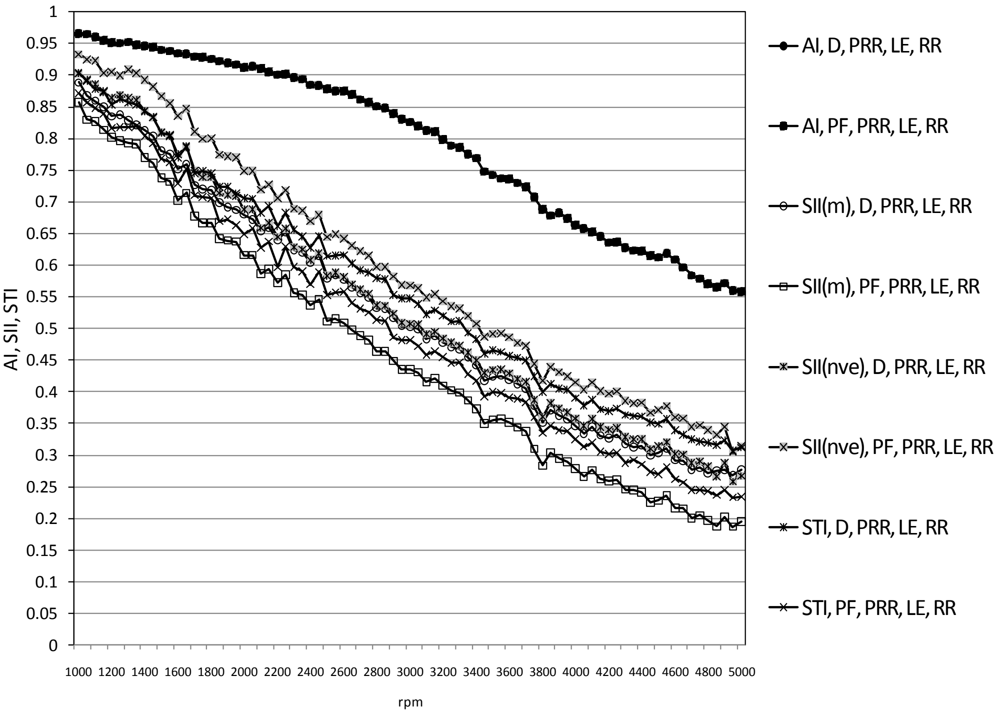


Figure 24: Speech Intelligibility Metrics when the Listener is in the Passenger Rear Right Position, Inboard Ear, Rough Road.

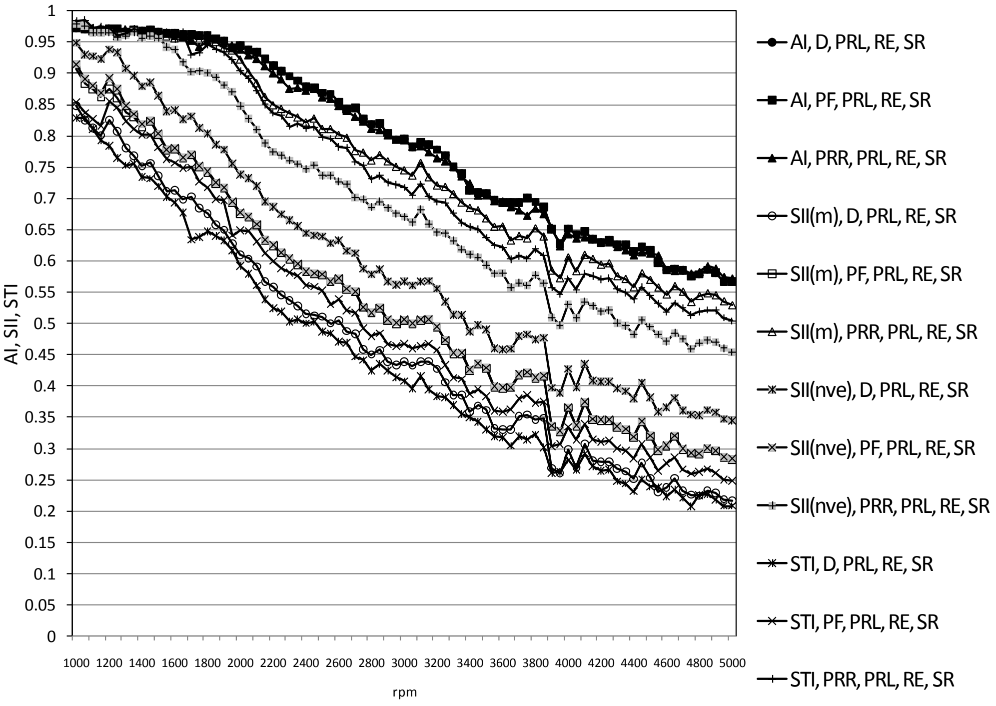


Figure 25: Speech Intelligibility Metrics when the Listener is in the Passenger Rear Left Position, Inboard Ear, Smooth Road.

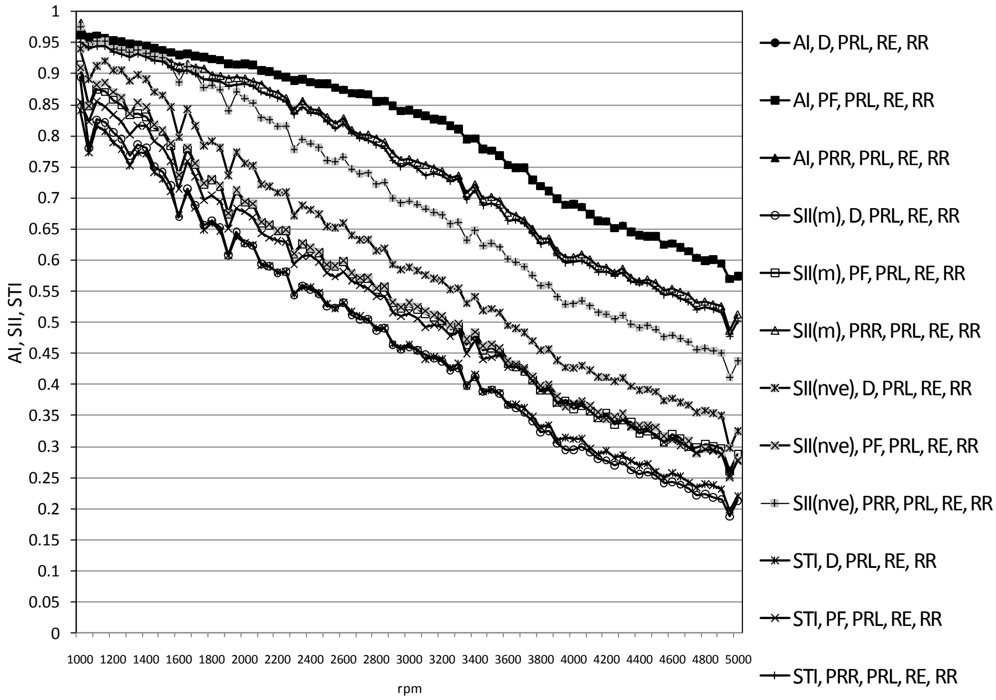


Figure 26: Speech Intelligibility Metrics when the Listener is in the Passenger Rear Left Position, Inboard Ear, Rough Road.

The trends at different speeds are similar to the corresponding configurations and road surface at constant speeds (Tables 9 through 12) in terms of the overall amplitudes. Wide ranges of scores associated with almost any particular operating condition, configuration and road surface are apparent, indicating the influence of a variety of factors such as binaural listening, directivity and locations of the talker and the listener, in quantifying the in-vehicle speech intelligibility. Also, differences between scores associated with different metrics can be significant (often greater than 10%). In addition, the magnitude of the differences often changes with operating conditions, i.e. increasing speed. The rate of change of speech intelligibility is also different for different metrics at any given speed. As observed in the previous studies, the rough road condition provides a more linear decrease with speed compared to the smooth road condition. In addition, there is more fluctuation for the rough road condition at low speeds, compared to the smooth road condition where the majority of the fluctuations occur at higher speeds. Again, a subjective evaluation is suggested and should incorporate the effects of multi-sensory perception in order to evaluate speech intelligibility in the context of the vehicle interior listening environment.

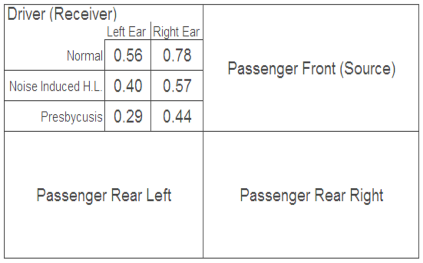
6.1.3.1 Summary of the Results

A complete objective assessment of speech intelligibility between passengers in a vehicle should include measurements of both the speech and the background noise signals to account for the effects of the directivity, binaural listening and the distance between a talker and a listener on speech intelligibility. The AI, currently the most frequently used metric in the automotive industry, does not account for these effects. Measurements of simulated background noise and speech similar to those found in real communication between passengers in a vehicle are needed to obtain this assessment. In this study, the SII(m) and STI methods provided this complete assessment. The SII(m) method resulted in a close correlation with the more measurement-intensive STI method. Since the SII(m) method does not require impulse response measurements, it can reduce the measurement effort while preserving the results' accuracy. Subjective testing is needed for further in-vehicle speech intelligibility investigation, as the common metrics provide a wide range of scores for a given measurement configuration and operating condition. This is the subject of work dealing with acoustic perception jury testing within a simulated driving environment, as described in Section 6.2.

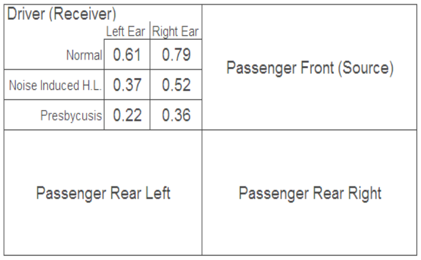
6.1.4 In-vehicle Speech Intelligibility for the Hearing Impaired Using Speech Intelligibility Index

Tables 13 through 18 illustrate the results for the constant speed operation for the different talker and listener configurations and road surfaces. For a communication system to be considered good, it is expected to have an SII in excess of 0.75. Poor communication systems will have an SII below 0.45 (ANSI S3.5-1997).

Table 13: SII, Talker is in Passenger Front Location, 50 km/h, Smooth Road (left), Rough Road (right).

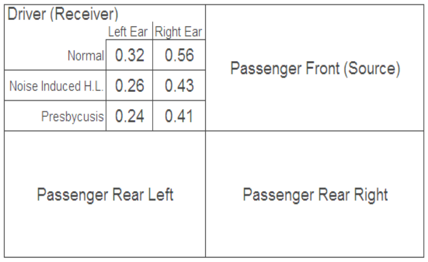


Driver (Receiver)	Left Ear	Right Ear	
Normal	0.56	0.78	Passenger Front (Source)
Noise Induced H.L.	0.40	0.57	
Presbycusis	0.29	0.44	
Passenger Rear Left			Passenger Rear Right

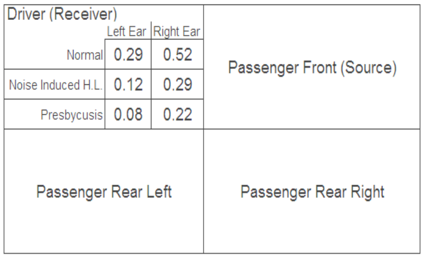


Driver (Receiver)	Left Ear	Right Ear	
Normal	0.61	0.79	Passenger Front (Source)
Noise Induced H.L.	0.37	0.52	
Presbycusis	0.22	0.36	
Passenger Rear Left			Passenger Rear Right

Table 14: SII, Talker is in Passenger Front Location, 100 km/h, Smooth Road (left), Rough Road (right).

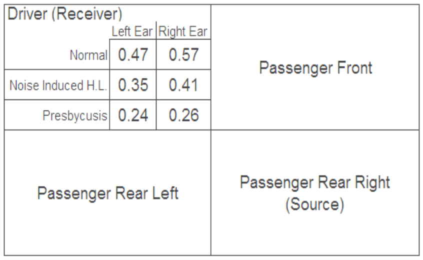


Driver (Receiver)	Left Ear	Right Ear	
Normal	0.32	0.56	Passenger Front (Source)
Noise Induced H.L.	0.26	0.43	
Presbycusis	0.24	0.41	
Passenger Rear Left			Passenger Rear Right

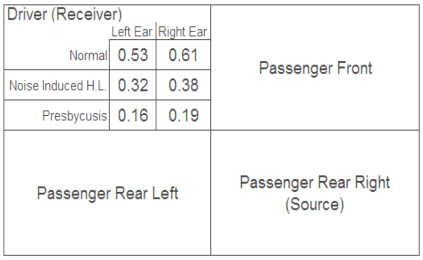


Driver (Receiver)	Left Ear	Right Ear	
Normal	0.29	0.52	Passenger Front (Source)
Noise Induced H.L.	0.12	0.29	
Presbycusis	0.08	0.22	
Passenger Rear Left			Passenger Rear Right

Table 15: SII, Talker is in Passenger Rear Right Location, 50 km/h, Smooth Road (left), Rough Road (right).



Driver (Receiver)	Left Ear	Right Ear	
Normal	0.47	0.57	Passenger Front
Noise Induced H.L.	0.35	0.41	
Presbycusis	0.24	0.26	
Passenger Rear Left			Passenger Rear Right (Source)



Driver (Receiver)	Left Ear	Right Ear	
Normal	0.53	0.61	Passenger Front
Noise Induced H.L.	0.32	0.38	
Presbycusis	0.16	0.19	
Passenger Rear Left			Passenger Rear Right (Source)

Table 16: SII, Talker is in Passenger Rear Right Location, 100 km/h, Smooth Road (left), Rough Road (right).

Driver (Receiver)	Left Ear	Right Ear	
Normal	0.24	0.35	Passenger Front
Noise Induced H.L.	0.20	0.27	
Presbycusis	0.19	0.23	
Passenger Rear Left			Passenger Rear Right (Source)

Driver (Receiver)	Left Ear	Right Ear	
Normal	0.23	0.32	Passenger Front
Noise Induced H.L.	0.09	0.14	
Presbycusis	0.04	0.06	
Passenger Rear Left			Passenger Rear Right (Source)

Table 17: SII, Talker is in Passenger Rear Left Location, 50 km/h, Smooth Road (left), Rough Road (right).

Driver (Receiver)	Left Ear	Right Ear	
Normal	0.49	0.56	Passenger Front
Noise Induced H.L.	0.37	0.42	
Presbycusis	0.26	0.27	
Passenger Rear Left (Source)			Passenger Rear Right

Driver (Receiver)	Left Ear	Right Ear	
Normal	0.55	0.61	Passenger Front
Noise Induced H.L.	0.33	0.38	
Presbycusis	0.18	0.20	
Passenger Rear Left (Source)			Passenger Rear Right

Table 18: SII, Talker is in Passenger Rear Left Location, 100 km/h, Smooth Road (left), Rough Road (right).

Driver (Receiver)	Left Ear	Right Ear	
Normal	0.26	0.34	Passenger Front
Noise Induced H.L.	0.22	0.28	
Presbycusis	0.21	0.24	
Passenger Rear Left (Source)			Passenger Rear Right

Driver (Receiver)	Left Ear	Right Ear	
Normal	0.22	0.32	Passenger Front
Noise Induced H.L.	0.08	0.16	
Presbycusis	0.03	0.08	
Passenger Rear Left (Source)			Passenger Rear Right

The measurements were conducted in a semi-anechoic vehicle dynamometer test cell, so the results do not account for the effects of wind noise, which would potentially provide masking at higher frequencies and reduce differences between the rough and smooth road surface sound pressure levels at those frequencies. The difference between SII scores associated with the rough and smooth road operation would also potentially be reduced.

The SII is significantly lower at the outboard ear when the talker is located in the passenger front position. This is because the talker and the listener are closer to each other compared to other configurations. It is also due to directivity effects as the speech signal has a more direct path to the driver/listener inboard ear. The results are similar for both cases when the talker is located in the rear passenger positions.

The rate of decrease of SII between the cases of 50 km/h to 100 km/h is less rapid for the hearing impaired individuals compared to the normal hearing. The SII for the case of presbycusis is least sensitive to changes in speed compared to the other two cases. The SII scores are also significantly lower for the case of presbycusis compared to the other two cases. They are consistently below the criterion for good communication system, even for the most conservative cases at low vehicle speeds and smooth surface types.

For the case of normal hearing, the rough roll operation resulted in higher speech intelligibility index compared to the smooth roll operation for all the speeds and measurement configurations considered. This is despite the fact that the overall sound pressure levels during rough roll operation were higher compared to the same configurations when the vehicle was operated on the smooth rolls. The reason for this is a high frequency component in the vehicle noise associated with the smooth roll operation that significantly contributes to the reduction of SII. This is because the weighing factors at the higher frequencies are greater than those at the lower frequencies which are more associated with the rough roll operation (Samardzic and Novak, 2011b). The threshold loss at higher frequencies tends to reduce this effect so the difference between SII scores for the smooth and the rough roll operation is less for the case of noise-induced hearing loss and presbycusis. As explained previously, although counter intuitive, the scores are actually higher for the smooth rolls operation. Illustrated in Figures 27 through 29 are results from the variable speed operation of the vehicle for different road surfaces, talker and listener configurations, and ears of the listener.

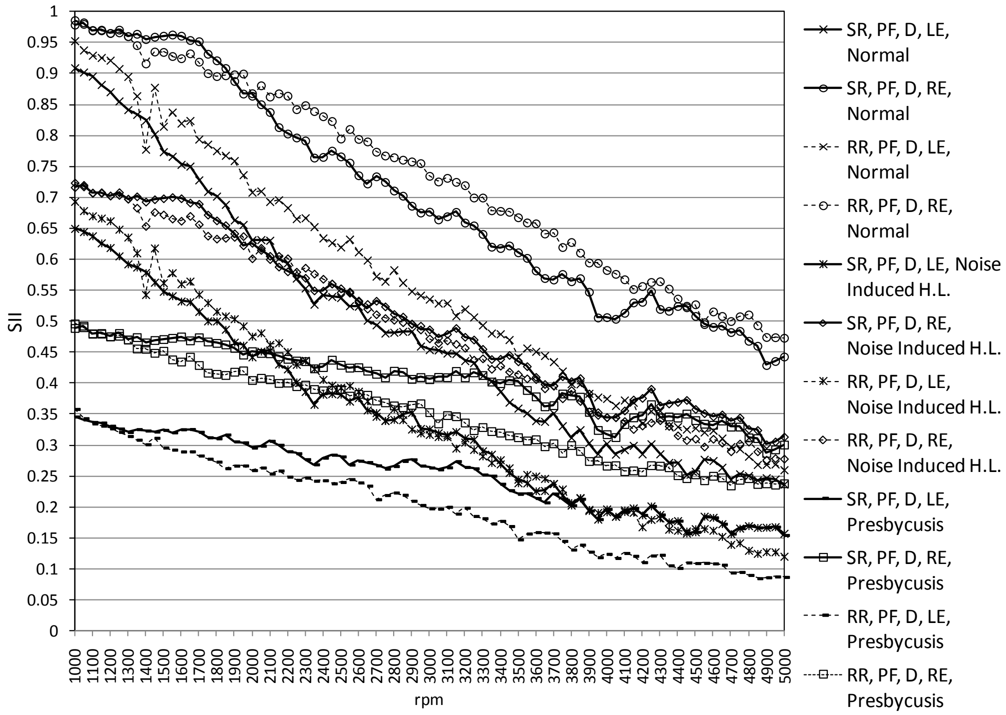


Figure 27: SII vs. Engine Speed, Talker is in Passenger Front Location.

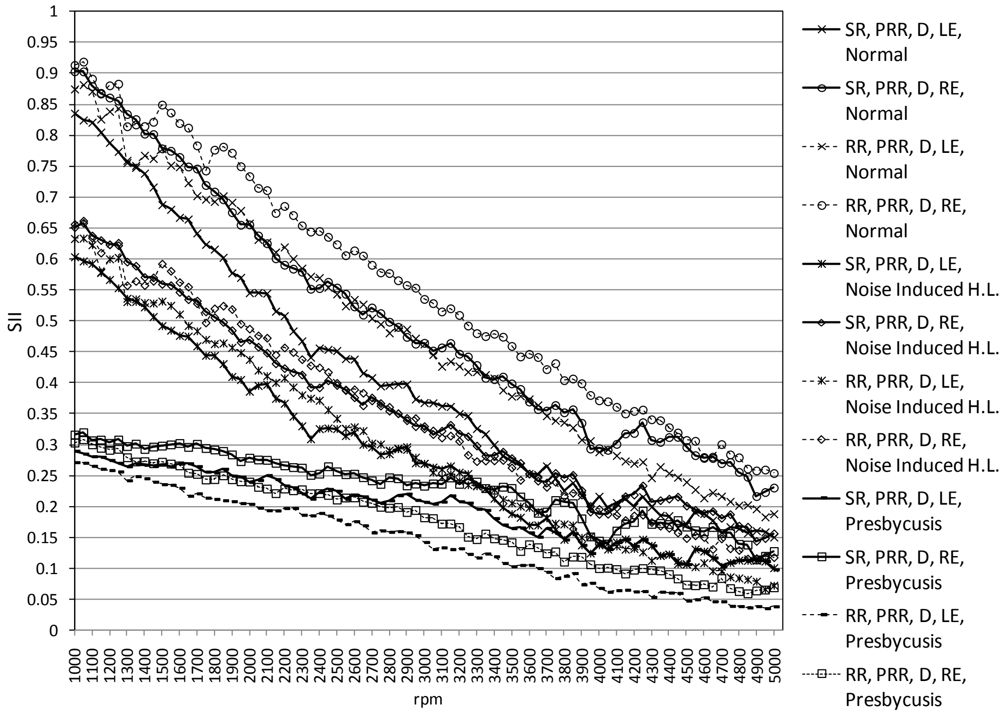


Figure 28: SII vs. Engine Speed, Talker is in Passenger Rear Right Location.

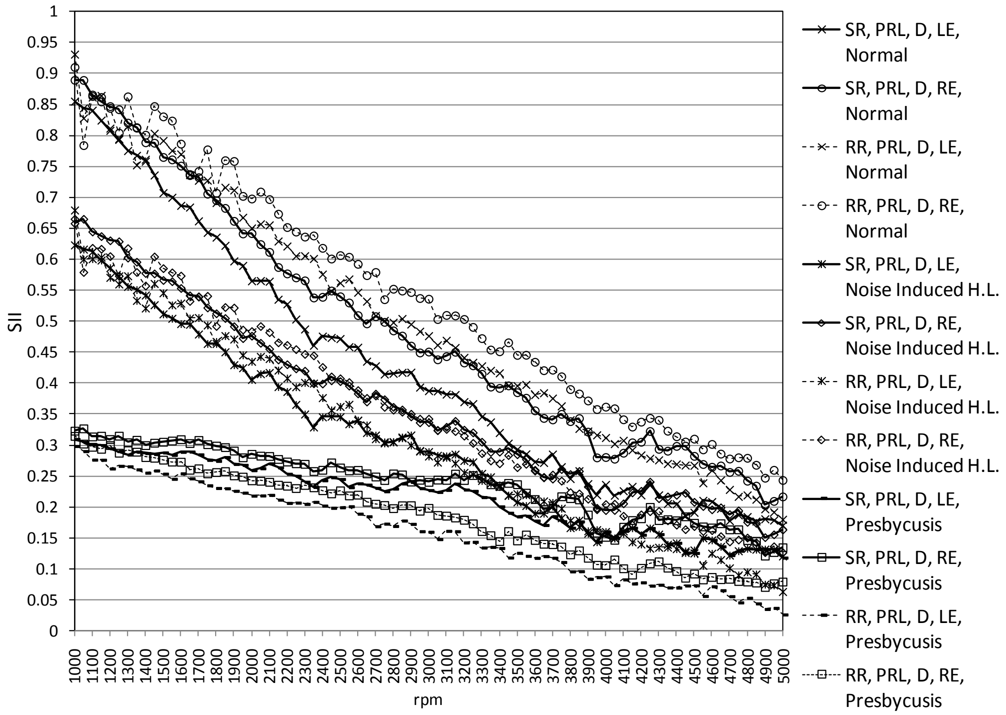


Figure 29: SII vs. Engine Speed, Talker is in Passenger Rear Left Location.

The SII was computed at 50 rpm increments over the entire range of speeds. The trends are similar to those discussed previously for the constant speed operation. In addition, the results for the rough road condition show more fluctuation of the SII at low speeds. The scores associated with the case of presbycusis are generally low and less sensitive to changes in speed compared to the other two cases.

According to the definition of SII, speech intelligibility may potentially be improved by increasing the level of the speech signal and/or reducing the level of background noise, i.e. increasing the signal to noise ratio. The vocal effort associated with the speech signal in this study is assumed to be fixed and independent of the level of background noise. The recommended minimum performance rating for speech intelligibility and vocal effort varies for different applications (ISO 9921:2003). For critical situations where short messages are exchanged, a fair intelligibility at least is recommended at an increased vocal effort (loud) corresponding to 72 dBA at one meter distance in front of the mouth. For a relaxed type of person to person communication over a longer time, more typical of in-vehicle applications, a good level of intelligibility is recommended allowing for a normal vocal effort corresponding to 60 dBA at one meter distance in front of the mouth. Previous studies related to in-vehicle speech intelligibility used a 68 dBA speech signal equalized at a one meter distance in free field (Viktorovitch, 2005; Granat, 2008; Farina et al, 2003).

It was found in a recent study that decreasing this value to a more reasonable value of approximately 60 dBA (also specified in recent versions of the two most common speech intelligibility standards; IEC 60268-16:2003, ANSI S3.5-1997) reduces the speech intelligibility scores by about 30% (Samardzic and Novak, 2011c). However, from an automotive customer's point of view, reduced background noise in the vehicle interior would be a preferred alternative to increasing vocal effort for more effective communication. This requires the optimization of the sound package design to target background noise reduction in frequencies critical to speech.

6.1.4.1 Summary of the Results

In-vehicle speech intelligibility was quantified at various operating conditions and talker and listener configurations using the SII by considering the threshold loss associated with noise-induced hearing loss and presbycusis. The results reveal poor speech intelligibility for most situations considered and provide evidence for the need for improving interior sound quality in terms of speech intelligibility for hearing impaired drivers such as senior aged drivers. Further, this works provides the motivation for including the hearing impaired individuals in acoustic perception jury testing within a driving simulator, as presented in Section 6.2.3.

6.2 A Novel Method for Improved In-Vehicle Speech Intelligibility Evaluation

The shortcomings of the common objective speech intelligibility metrics, as discussed in Section 6.1, were addressed by developing an alternative method for in-vehicle speech intelligibility evaluation. In this section, the implementation of the HINT was carried out within a driving simulator in order to evaluate the speech intelligibility in a vehicle between driver and passenger for a variety of driving speeds and the configurations of the talker and of the listener. The sentence sSRT was determined for each of the various communication situations using an acoustic perception jury testing with thirty normal-hearing participants (Section 6.2.1). Next, the results from the novel method for speech intelligibility evaluation described in Chapter 5 are discussed are presented in Section 6.2.2. The statistical variability was quantified by evaluating the SII at the sSRT obtained from the previous study. For both studies, the background noise utilized in the driving simulator model was based on the vehicle dynamometer acoustical measurements. In another study (Section 6.2.3), both normal hearing and hearing impaired individuals participated in the acoustic perception jury testing. Additionally, in this study, the contributions to the loss of speech intelligibility from the ordered and masking noise sources including wind were quantified. The background noise utilized in the simulator model was based on on-road measurements. Lastly, in Section 6.2.4 the impact of the band importance function for the HINT used in the evaluation of the SII at the sSRT, as used in studies described in Sections 6.2.2 and 6.2.3 was quantified.

6.2.1 The Evaluation of Speech Intelligibility in a Simulated Driving Environment Using the Hearing in Noise Test (HINT)

The effects of the multisensory nature of driving on the perception of speech intelligibility would be evident by comparing the results of the HINT from the driving simulator jury test and the vehicle dynamometer jury test conducted by researchers from the University of Western Ontario, National Centre for Audiology (Sudirga et al, 2011). In this study, the HINT was mainly a listening task without the effects of the visual stimuli or the expectation of controlling the vehicle in terms of steering or the gas or the brake pedal as found in a real driving situation. The driving simulator jury test consisted of the HINT listening task mixed with the vehicle background noise measured in the vehicle dynamometer. The sound perceived by the participants over the headphones was associated with various vehicle operating conditions, dictated by the input from the driver of the simulator. These inputs included the gas and brake pedal position that control the speed of the vehicle and the visual presentation of the surroundings, all of which contributed to simulating a realistic driving scenario. Table 19 shows an average difference of about 3 dB between the two conditions; therefore, when presented with the same listening task the participants required a 3 dB higher sound pressure level of the HINT speech material while driving and listening compared to when just listening, for an equivalent speech intelligibility performance. The values in brackets represent standard deviation (dB), calculated for each talker and listener combination and vehicle operating condition.

Table 19: HINT sentence Speech Reception Threshold, sSRT, as measured in free field at 1 m distance from the mouth of the artificial talker HATS Type 4128, (dBA). The values in brackets represent standard deviation (dB).

		Hearing in Noise Test, Sentence Speech Reception Threshold, sSRT, dBA		
		NVH Simulator Jury Test, 30 Participants	Vehicle Dynamometer Jury Test, ** 9 Participants	Δ
Talker Location	Vehicle Speed			
Passenger Front	50 kph	48.74 (1.68)	45.43 (1.55)	3.31 (0.13)
	100 kph	51.94 (1.48)	49.56 (1.24)	2.38 (0.24)
Passenger Rear Left	50 kph	52.92 (2.08)	49.08 (1.3)	3.84 (0.78)
	100 kph	56.45 (1.78)	52.53 (1.19)	3.92 (0.59)
Passenger Rear Right	50 kph	52.73 (1.96)	49.52 (1.64)	3.21 (0.32)
	100 kph	56.17 (2.12)	53.51 (1.37)	2.66 (0.75)
			**Sudirga *et al*, 2011	3.22 (0.47) (Avg.)

The standard deviation of the NVH simulator jury test results was slightly higher when compared with the vehicle dynamometer jury test results. In all instances the difference was less than 1 dB. Figure 30 shows a HINT response of a single participant ('11') of the NVH Simulator jury test, with all of the talker locations and road and vehicle operating conditions. Figures 31 through 36 illustrate HINT results from the 30 participants of the NVH Simulator jury test, at all the driving conditions and locations of the talker.

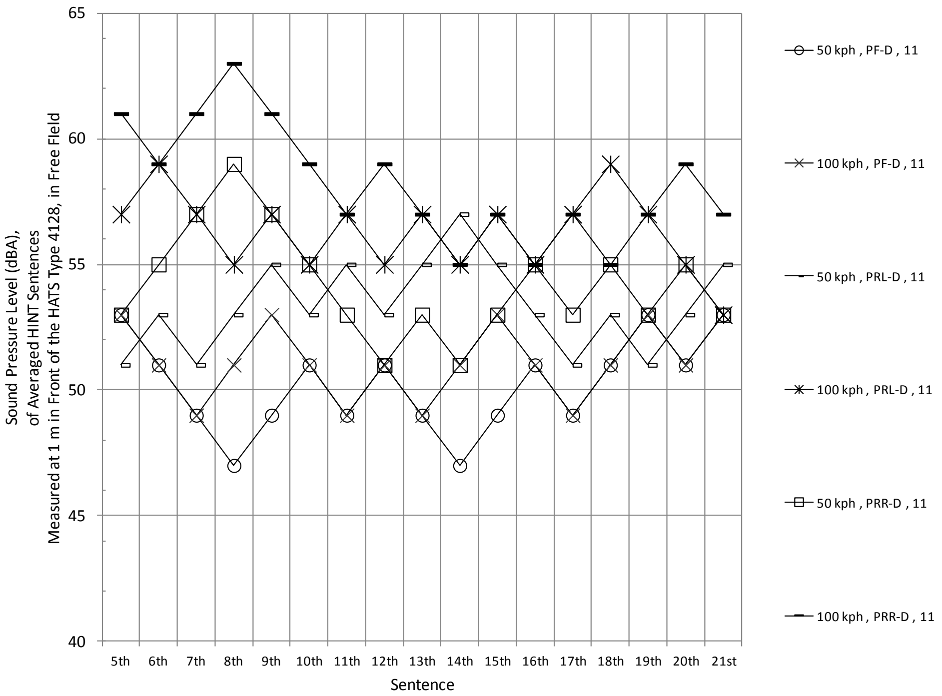


Figure 30: Hearing in Noise Test (HINT) response of a single participant ('11') of the NVH Simulator jury test, with all of the talker locations and road and vehicle operating conditions.

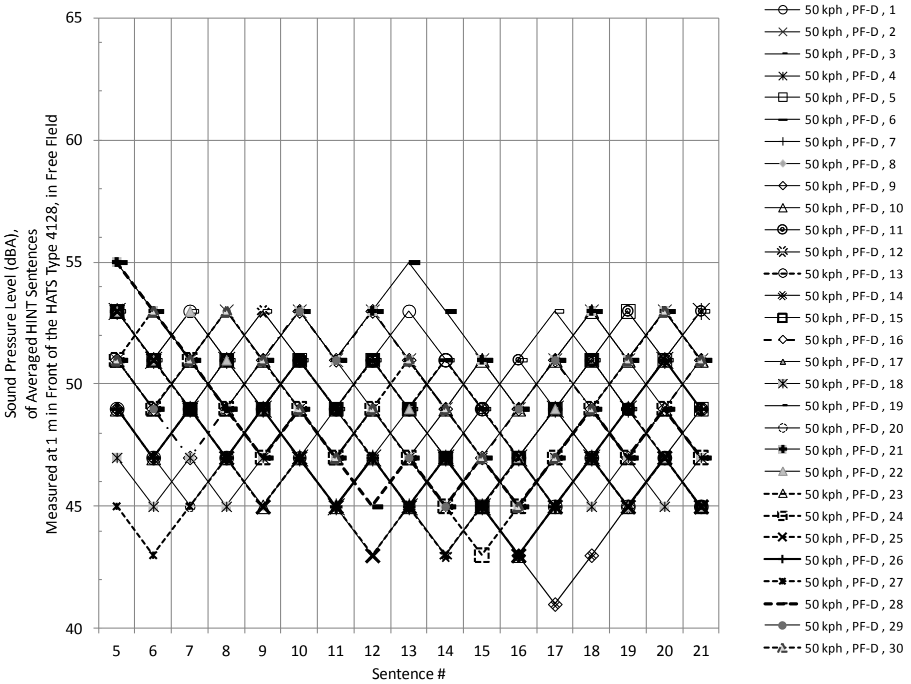


Figure 31: Hearing in Noise Test (HINT) Results from the 30 participants of the NVH Simulator jury test, driving at 50 km/h on a country road with curves, with the talker in the passenger front (PF) location. Maximum range of response for a sentence was 12 dB.

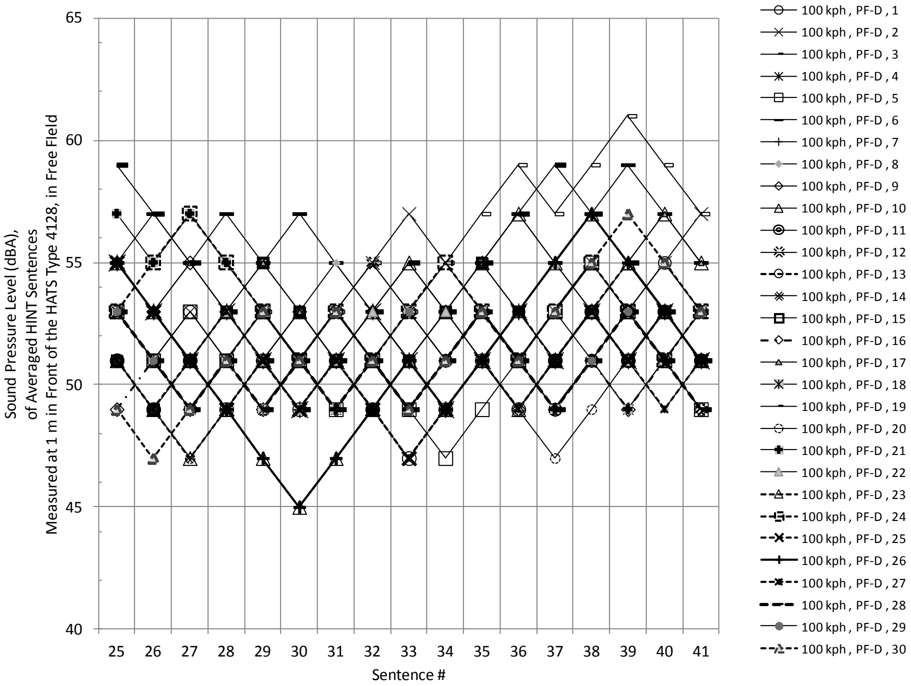


Figure 32: Hearing in Noise Test (HINT) Results from the 30 participants of the NVH Simulator jury test, driving at 100 km/h on a straight country road, with the talker in the passenger front (PF) location. Maximum range of response for a sentence was 12 dB.

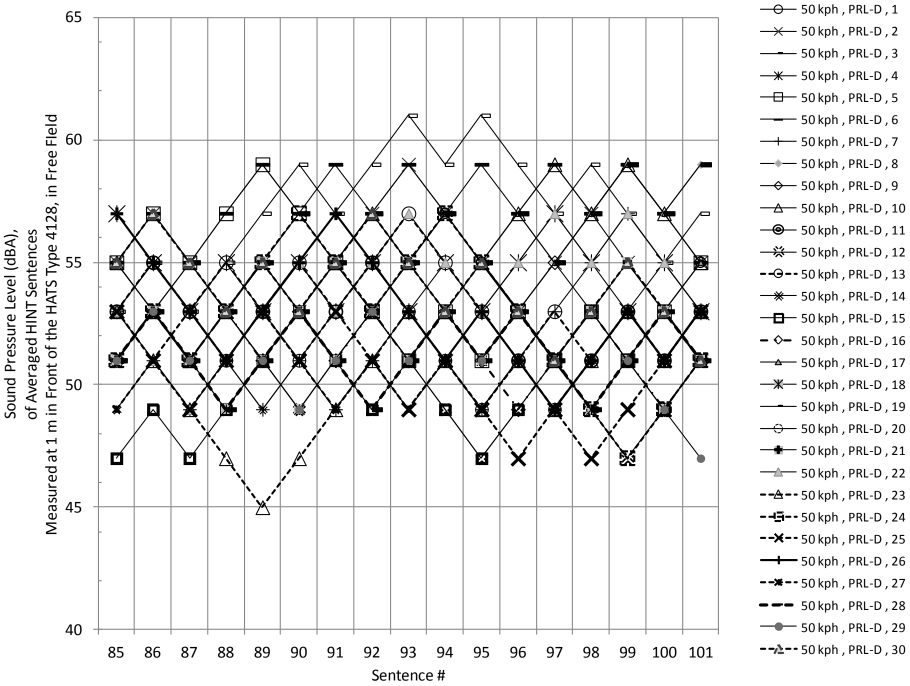


Figure 33: Hearing in Noise Test (HINT) results from the 30 participants of the NVH Simulator jury test, driving at 50 km/h on a country road with curves, with the talker in the passenger rear left (PRL) location. Maximum range of response for a sentence was 14 dB.

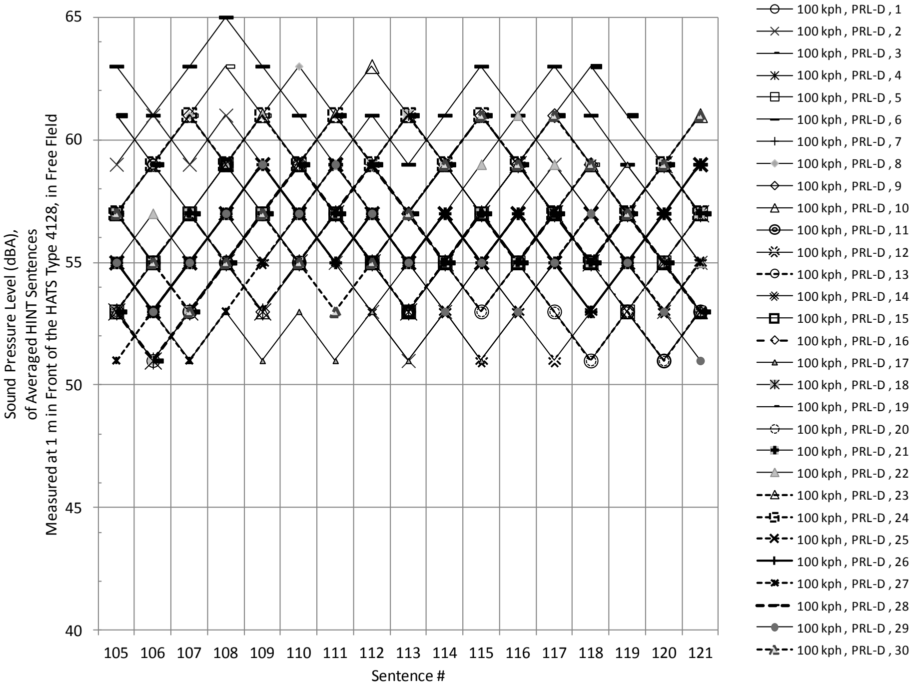


Figure 34: Hearing in Noise Test (HINT) response from the 30 participants of the NVH Simulator jury test, driving at 100 km/h on a straight country road, with the talker in the passenger rear left (PRL) location. Maximum range of response for a sentence was 12 dB.

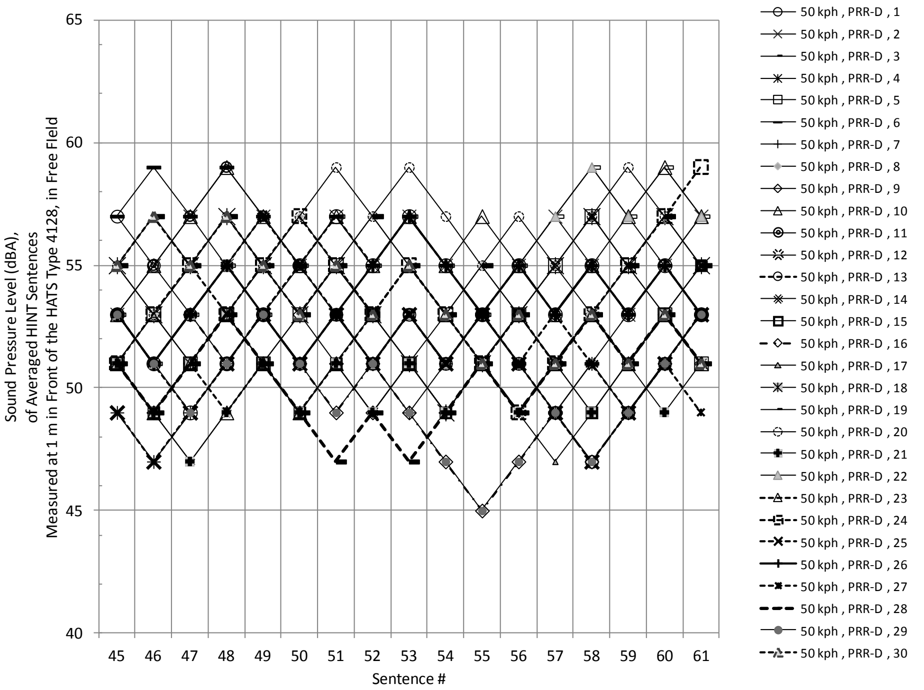


Figure 35: Hearing in Noise Test (HINT) response from the 30 participants of the NVH Simulator jury test, driving at 50 km/h on a country road with curves, with the talker in the passenger rear right (PRR) location. Maximum range of response for a sentence was 12 dB.

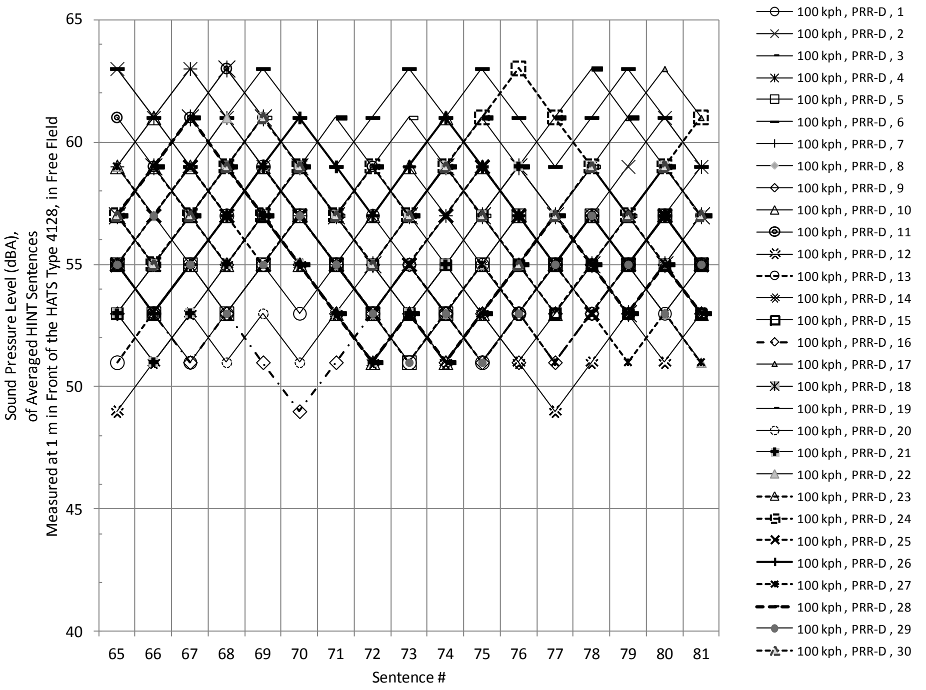


Figure 36: Hearing in Noise Test (HINT) response from the 30 participants of the NVH Simulator jury test, driving at 100 km/h on a straight country road, with the talker in the passenger rear right (PRR) location. Maximum range of response for a sentence was 14 dB.

The maximum range of response for a sentence was between 12 dB and 14 dB. The talker locations and vehicle speeds with instances of the highest maximum ranges of response for a sentence (about 14 dB) were also associated with highest standard deviations (Table 19).

There were no significant differences in hearing threshold levels between the two rear passenger locations; with less than 0.3 dB difference between the passenger rear left and passenger rear right locations, for both vehicle speeds considered. There was an approximate 4 dB difference in hearing threshold levels between the front and the rear talker locations. In addition, the average signal to noise ratio difference as well as the difference in vocal effort between 50 km/h and 100 km/h was equivalent for all of the talker and listener configurations considered, given the same speech intelligibility performance.

Table 20 shows the binaural sound pressure levels of the HINT calibration signal corresponding to the measured sSRT for each vehicle speed and talker location, and background noise at each vehicle speed. The passenger front talker location resulted in the highest binaural sound pressure level difference in the driver's location compared to the other two talker locations; the passenger rear left and right locations. For this particular configuration, the ear closer to the talker location showed an equivalent (less than 1 dB difference) average speech sound pressure level compared to the one produced from the remaining two talker locations, for an equivalent speech intelligibility performance. Therefore, the signal to noise ratio of the ear closer to the talker appeared to be the main influence in determining the in-vehicle speech intelligibility performance when the binaural difference in the speech sound pressure level is significant.

Table 20: Binaural sound pressure level (dBA) of the HINT calibration signal (averaged HINT sentences) measured in vehicle at levels associated with the measured sentence Speech Reception Thresholds (sSRT's), and binaural sound pressure level of vehicle interior background noise (dBA).

		Sound Pressure Level (dBA) of Averaged HINT Sentences Measured in-Vehicle, Associated with sSRT Levels		Sound Pressure Level (dBA) of Background Noise Measured in-Vehicle	
Talker Location	Vehicle Speed	Left Ear	Right Ear	Left Ear	Right Ear
Passenger Front	50 kph	52.84	56.25	60.70	59.00
	100 kph	56.51	59.96	71.30	68.80
Passenger Rear Left	50 kph	57.00	56.48	60.70	59.00
	100 kph	60.30	59.50	71.30	68.80
Passenger Rear Right	50 kph	56.79	55.59	60.70	59.00
	100 kph	59.85	58.69	71.30	68.80

Despite the advantages of the HINT compared to the other available subjective speech intelligibility tests, as outlined by Nilsson et al (1994), the results of the HINT, have previously never been compared to any of the other objective speech intelligibility metrics mentioned above. In addition, they have not been mentioned in the standards associated with these metrics, mainly the IEC 60268-16:2003 and ANSI S3.5-1997, for the STI and the SII metric, respectively. For example, the IEC 60268-16:2003 provides relations between the intelligibility scores from several subjective intelligibility measures including the phonetically balanced (PB) words test, Consonant Vowel Consonant (CVC) words test, and sentence intelligibility based on the Speech Reception Threshold (SRT) test. The reference for the SRT test, however, is not provided in the standard. For that reason, it cannot be associated with the HINT method, which also involves determining the SRT. The ANSI S3.5-1997 standard provides band importance functions for various nonsense syllable tests, PB words tests, Diagnostic Rhyme Test, short passages of easy reading material and SPIN monosyllables.

The common objective speech intelligibility metrics are calculated using the background noise measurements, either fixed or measured speech signal measurements and, for the case of the STI metric, the impulse response measurements. Ultimately, all of the metrics provide a measure of the intelligibility of speech using values from 0 for completely unintelligible to 1 for perfect intelligibility. In addition to the differences between scores associated with the different metrics given the same operating conditions and talker and listener configurations (Samardzic and Novak, 2001d), the objective metrics also do not include the influences of the multi-sensory perception, specific to the in-vehicle listening environment which, as shown earlier, proved to be significant. Acoustic in-vehicle measurements commonly obtained in the automotive industry are used for the various objective metrics calculations and benchmarking. A consequence of the above observation is the suggestion these tests be used to create a driving simulation for jury testing as described in this study, for a future standard method to provide a complete and a more accurate evaluation of in-vehicle speech intelligibility.

According to Moore (2003), the details of how the complex acoustical patterns of speech are interpreted by the brain are still not fully understood. Moore also states that the high redundancy of speech makes it an efficient method of communication where speech intelligibility is relatively unaffected even by difficult conditions such as severe distortion interruption or background noise. Therefore, using natural speech material in the form of a sentence-type test such as the HINT instead of the word tests mentioned earlier provides a more realistic scenario for evaluating the understanding of everyday speech, in an attempt to include the mentioned complexities.

The effective range of objective speech intelligibility scores for word tests is wider, compared to sentence-type tests (Table F.1 of ISO 9921:2003(E));the ranges of scores are assigned various subjective intelligibility ratings such as ‘excellent’, ‘good’, ‘fair’, ‘poor’ or ‘bad’. However, the ratings and scores provide little practical insight into characterizing the speech intelligibility in a communication environment such as a vehicle interior, in addition to the fact that there is no standardized method currently in place; objective or subjective alike, in the automotive industry that would address the interpretation of the meaning of such a characterization. Due to the redundancy of words in a sentence and speech in general, the sentence-type tests show saturation at certain values of objective test scores. It would then be reasonable to assume that if the HINT test result comparisons to the same scores were available, they would show a similar saturation limit. In other words, for sentence-type tests, there is a point (a sound pressure level) after which the speech is understood in its entirety. Below that point, it is not understood. This speech intelligibility evaluation method is easily understood, simple and universally applicable. Therefore, the sSRT as described in the HINT procedure and implemented in the driving simulator in this study appears to be a viable alternative metric for evaluation of in-vehicle speech intelligibility.

The majority of the NVH simulator jury test participants commented that a greater effort was required for listening and understanding sentences delivered from the rear passenger locations. This is despite the same HINT evaluation criteria (adaptive procedure to obtain 50% correct of all the sentences presented), and consequently, the same intelligibility performance for all the listener location configurations. The listening difficulty was not rated as it was not a part of the formal HINT procedure; however, future studies should extend the HINT method presented here to determine a vocal effort that would create the same listening effort from various locations of the talker, to complement the current HINT results from the procedure proposed in this study.

6.2.1.1 Summary of the Results

The goal of this study was to present a new method for evaluating the in-vehicle speech intelligibility by using a simulated driving environment and the HINT. The current standardized testing protocols used by the automotive industry do not include the evaluation of in-vehicle speech intelligibility. For example, AI, which is the most commonly used objective speech intelligibility metric in the automotive industry, does not incorporate some of the significant factors that can have an influence on the assessment of in-vehicle speech intelligibility in its calculation method. Examples include the distance between the talker and the listener and directivity. In addition, all of the current objective speech intelligibility metrics, including the AI, provide a wide range of scores given the same operating conditions and talker and listener configurations inside a vehicle. Further, these metrics do not include the influences that multi-sensory perception has on the assessment of speech intelligibility, which is particularly significant inside an operating vehicle. However, these influences are all incorporated into the HINT implemented in the simulated driving environment as shown in this study.

The results indicate that, when presented with the same listening task, the participants required on average an approximate 3 dB increase in sound pressure level of the HINT speech material while driving and listening compared to when just listening, for an equivalent speech intelligibility performance. When the talker was in the front passenger location, next to the listener who was driving the binaural difference in the speech sound pressure level was significant. In this case, the signal to noise ratio of the ear closer to the talker was the main influence on the in-vehicle speech intelligibility performance.

A future standard method for a more accurate evaluation of in-vehicle speech intelligibility is proposed by implementing the HINT using a driving simulator and further quantifying speech intelligibility as described in Section 6.2.2. It is suggested that the acoustic in-vehicle measurements commonly obtained in the automotive industry for the various acoustic metrics calculations and benchmarking also be used for creating a driving simulation for jury testing as described in this study. Future studies should also include an evaluation of the listening effort and determining the vocal effort required to obtain the same listening effort from the listener from any location of the talker.

6.2.2 A Novel Method for In-Vehicle Speech Intelligibility Evaluation and Statistical Variability Analysis

The SII evaluated at the sSRT and the associated statistical variability presented in this study provide reference values for future evaluation of in-vehicle speech intelligibility using the described novel method.

The following examples illustrate control charts using SII, SII band audibility function and SNR as random variables. The centerline has been omitted from the charts for clarity of presentation. Figure 37 illustrates an example SII and standard deviation control chart X -bar and s charts) calculated for the right ear of the listener at sSRT using the HINT in a driving simulator at 100 km/h. Listener was in the driver location while the talker was in the rear right location.

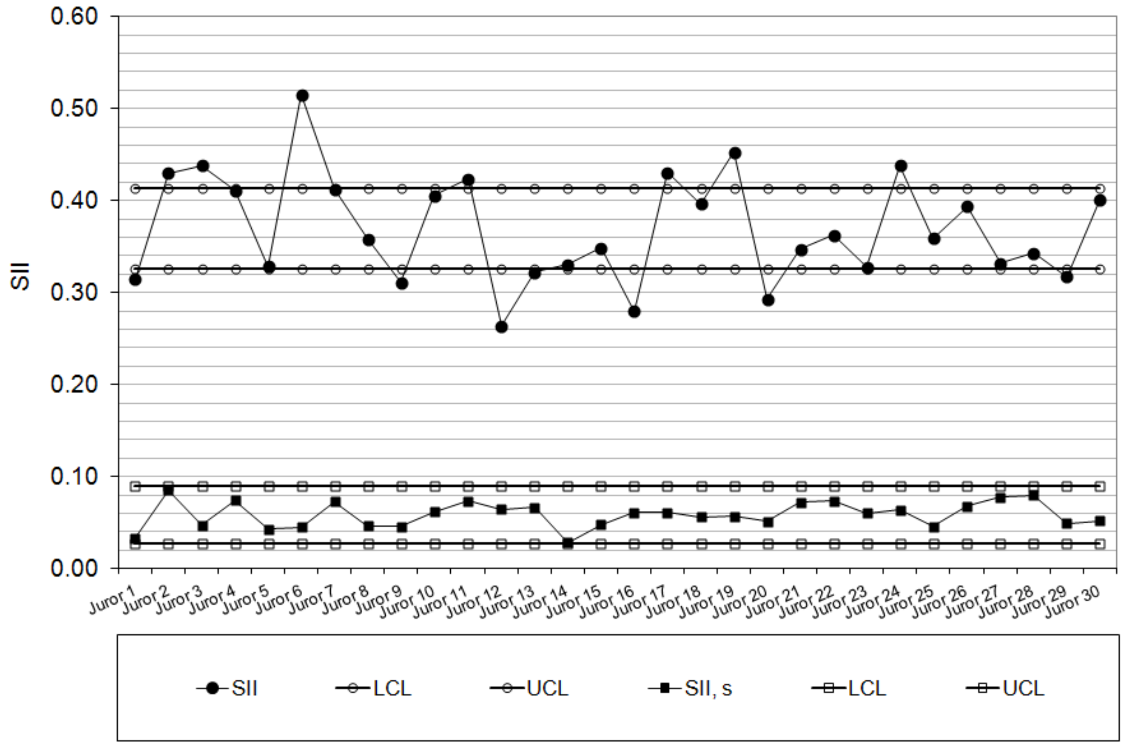
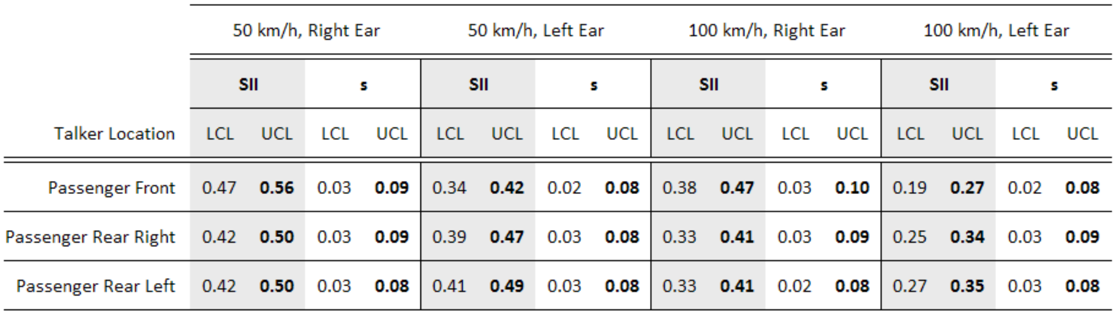


Figure 37: Example SII (top) and standard deviation (bottom) control chart (X -bar and s charts), calculated for the right ear of the listener at sSRT using the HINT in a driving simulator at 100 km/h. Listener was in the driver location, talker was in the rear right location. The three sigma control limits calculated are based on the ASTM 2587-10 standard formulations. It appears that the SII data points are contained within six, as opposed to three, standard deviations away from the mean. The six sigma limits may be a good recommendation for the selection of the specification limits in this case. The standard deviation values are contained within the three sigma limits.

For other speeds and configurations of the talker and the listener the corresponding control limits and standard deviation are summarized in Table 21. The values presented in Table 21 serve as a reference for future evaluation of in-vehicle speech intelligibility based on the SII at sSRT.

Table 21: SII and standard deviation control limits, calculated at sSRT using the HINT in a driving simulator for all operating conditions and configurations of the talker and with the listener in the driver location. The values presented provide a benchmark for future evaluation of in-vehicle speech intelligibility. The three sigma control limits calculated are based on the ASTM 2587-10 standard formulations.



	50 km/h, Right Ear				50 km/h, Left Ear				100 km/h, Right Ear				100 km/h, Left Ear			
	SII		s		SII		s		SII		s		SII		s	
Talker Location	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
Passenger Front	0.47	**0.56**	0.03	**0.09**	0.34	**0.42**	0.02	**0.08**	0.38	**0.47**	0.03	**0.10**	0.19	**0.27**	0.02	**0.08**
Passenger Rear Right	0.42	**0.50**	0.03	**0.09**	0.39	**0.47**	0.03	**0.08**	0.33	**0.41**	0.03	**0.09**	0.25	**0.34**	0.03	**0.09**
Passenger Rear Left	0.42	**0.50**	0.03	**0.08**	0.41	**0.49**	0.03	**0.08**	0.33	**0.41**	0.02	**0.08**	0.27	**0.35**	0.03	**0.08**

Examining Figure 37, the majority of SII data is dispersed between the process mean and the three sigma control limits, however, about a third of the data points are outside the limits. It appears that all of the data points would be contained within six, as opposed to three, standard deviations away from the mean. Therefore, the six sigma limits may be a good recommendation for the selection of the specification limits; potentially a design judgement by a vehicle interior acoustics engineer. The exception to this is the data associated with Juror 6, which may be found outside even the six sigma limits. Juror 6 had the highest sSRT and, therefore, the highest SII at sSRT, particularly at high speeds, as seen from the results for the particular talker and listener configuration shown in Figure 37. It was noted that Juror 6 commented to be less comfortable while driving and focusing on listening at high speed that, in general, required a higher level of concentration. The data reveals a likely scenario for some individuals in an actual high speed driving situation, although perhaps not for the majority. In any case, knowing the control limits, the specified level of confidence and the associated variability, as summarized in Table 21, the desired specification limits and the importance of the changes to the SII based on the variability may be selected.

The fact that the SII values on the control chart exceed the three sigma limits set by Shewhart (1931) and implemented in the ASTM 2587-10 standard, does not necessarily indicate a special cause of variation, but rather an inherent variability in this type of data. The special cause of variation is often characterized with outliers in the data. For instance, in the study by Samardzic and Pan (2009), a few data points on the control chart associated with sound absorption measurements obtained at the conditions of high humidity were found outside the three sigma limits, thus indicating a special cause of variation in the data. In contrast, the SII obtained in this study from thirty jury test participants is randomly dispersed about the centerline without outliers, with the exception of the aforementioned data from Juror 6. Jurors associated with SII data from about a third of the data points found outside the control limits had not exhibited any unusual responses in their driving or hearing experience during the test. They had no hearing issues or apparent similarities in driving behavior, or any apparent general differences related to the simultaneous driving and listening compared to the rest of the jurors, all of which would be potential indicators for a special cause of variation in the data.

The standard deviation values shown in Table 21 are contained within the three sigma control limits, as shown by the example Figure 37. The same trend is present in charts from other configurations summarized in Table 19. In general, the maximum standard deviation value of approximately 0.1 (10 percent) is a minimum significant change in terms of the SII evaluated at sSRT for the evaluation of in-vehicle speech intelligibility for all configurations and speeds. The specification limits and the variability may be used to assess the significance of the potential vehicle interior acoustic design changes or noise issues in terms of their effect on speech intelligibility. The application may also be extended to the design of the various communication devices and hearing aids algorithms for in-vehicle application.

Samardzic et al (2012) found that when the talker was in the front passenger location next to the listener in the driver location, the binaural difference in the speech sound pressure level was significant and the signal to noise ratio of the ear closer to the talker was the main influence on the in-vehicle speech intelligibility performance.

From the perspective of the statistical analysis in this study, Table 21, in a similar manner, indicates that the difference in terms of SII for this configuration is significant; 14 percent at 50 kph and 20 percent at 100 kph, when comparing the upper control limits. Subsequently, the SII of the ear closer to the talker may be used to evaluate the in-vehicle speech intelligibility performance. This assumption for SII evaluation would be valid for individuals with normal hearing or individuals with bilateral, symmetrical hearing loss.

It should also be noted that the majority of the NVH simulator jury test participants commented that a greater effort was required for listening and understanding sentences delivered at 100 km/h, compared to 50 km/h. This is despite the same HINT evaluation criteria (adaptive procedure to obtain 50% correct of all the sentences presented), and consequently, the same intelligibility performance for all the listener location configurations. The difference in SII scores by about 0.1 between the two speeds may be related to this observation. The listening difficulty was not formally rated during the HINT procedure; however, future studies should extend the HINT method presented here to determine a vocal effort that would create the same listening effort from various locations of the talker, to complement the current SII results in this study.

Figures 38 and 39 indicate example control charts and standard deviation based on the band audibility function used to calculate the SII. Figures 40 and 41 illustrate example frequency-specific SNR values with control limits that were also used in SII calculations. The figures contain data from the control chart as a function of frequency, providing a different perspective on the same set of data. The control limits based on three standard deviations again seem inadequate for this type of data and, as argued previously for the case of the SII, the specification limit may be set to model a six sigma process.

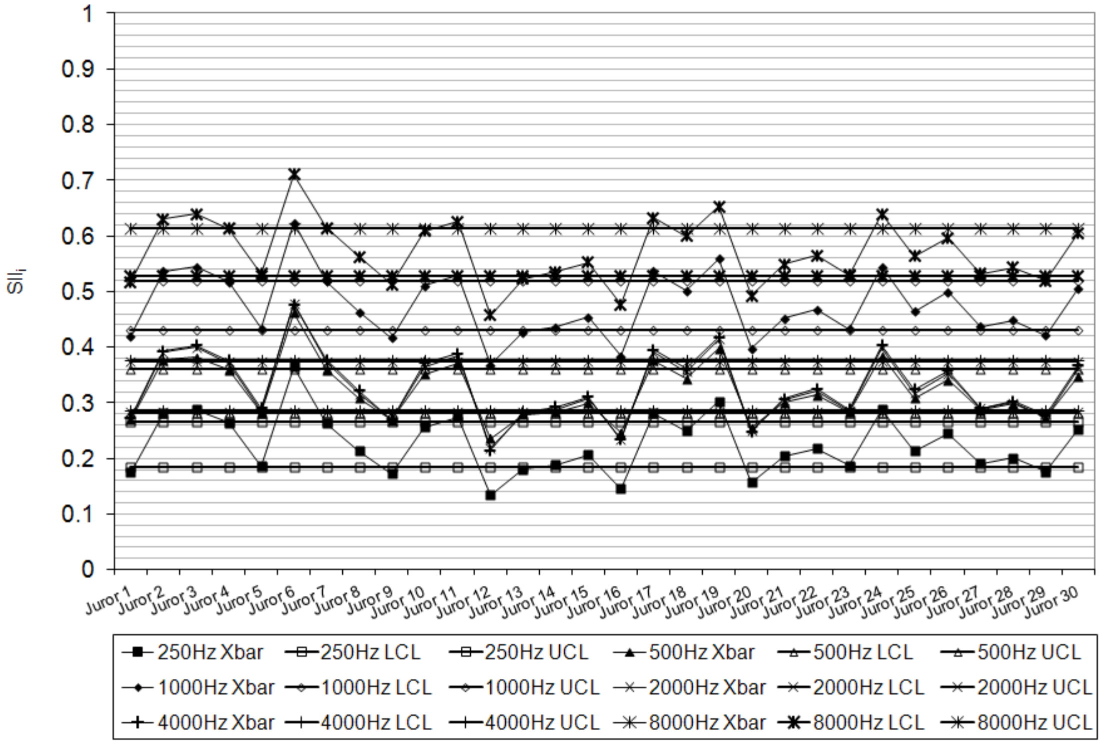


Figure 38: Example SII Band Audibility Function X -bar chart calculated for the right ear of the listener at sSRT using the HINT in a driving simulator at 100 km/h. The listener was in the driver location, and the talker is in the rear right location. The control limits based on three standard deviations do not incorporate all of the data points and, as argued previously for the case of the SII, the specification limit may be set to model a six sigma process. The frequency specific information from the SII Band Audibility Function may be potentially useful in determining the effect that modifications the background noise at particular frequencies have on in-vehicle speech intelligibility. This is one of the most common projects in vehicle interior acoustic engineering.

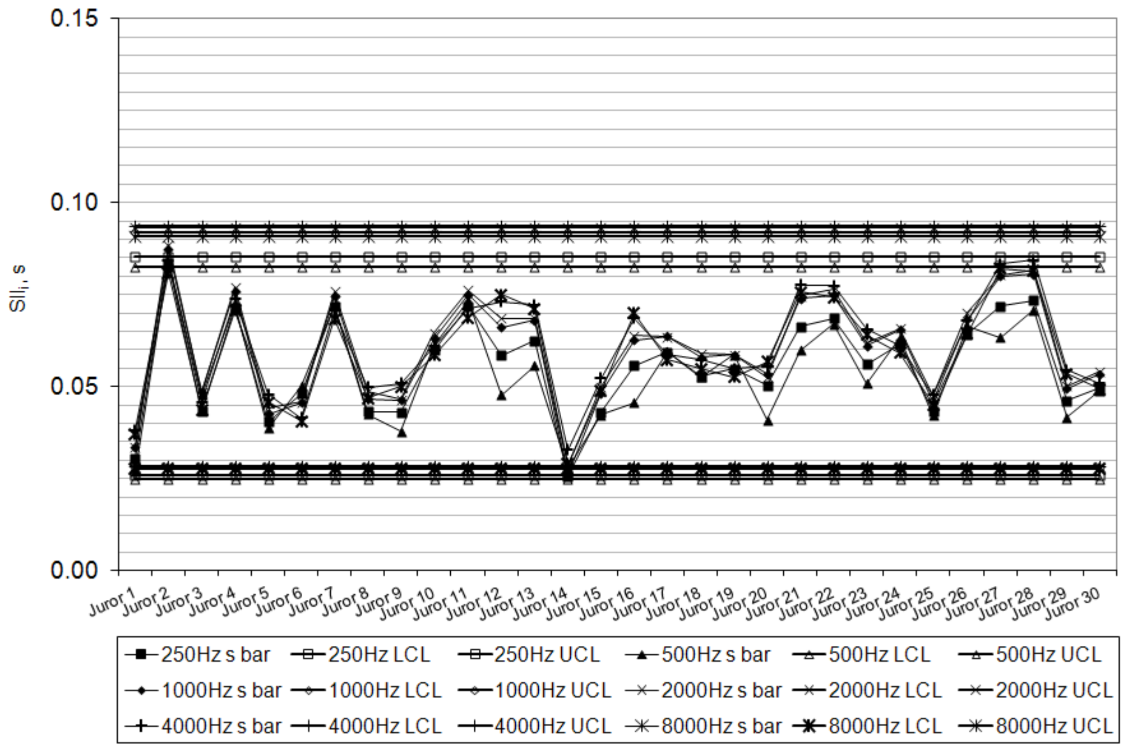


Figure 39: Example SII Band Audibility Function *s* chart, calculated for the right ear of the listener at sSRT using the HINT in a driving simulator at 100 km/h. The listener was in the driver location while the talker is in the rear right location. The SII standard deviation values are contained within the three sigma limits.

The standard deviation values are contained within the three sigma limits, as shown in the previous examples using the SII (Figure 37). The frequency specific information from the above examples may potentially be useful for determining the effect that modifications to the background noise at particular frequencies have on in-vehicle speech intelligibility. This is a common project for vehicle interior acoustic engineering. For this, information presented in Table 21 and Figures 38 through 41 can be utilized.

For example, assuming that a re-designed inner dash silencer provides an in-vehicle background noise reduction within a specific frequency band, one can calculate the associated band audibility function and/or signal to noise ratio and compare the values to the target frequency band six-sigma control limits (see Figures 38 and 40).

A design improvement would be validated if the band audibility function and/or signal-to-noise ratio exceeds the benchmark, six sigma, upper control limit at that frequency, and while the associated measurement variability does not exceed the upper control limits (Figure 39 and 41).

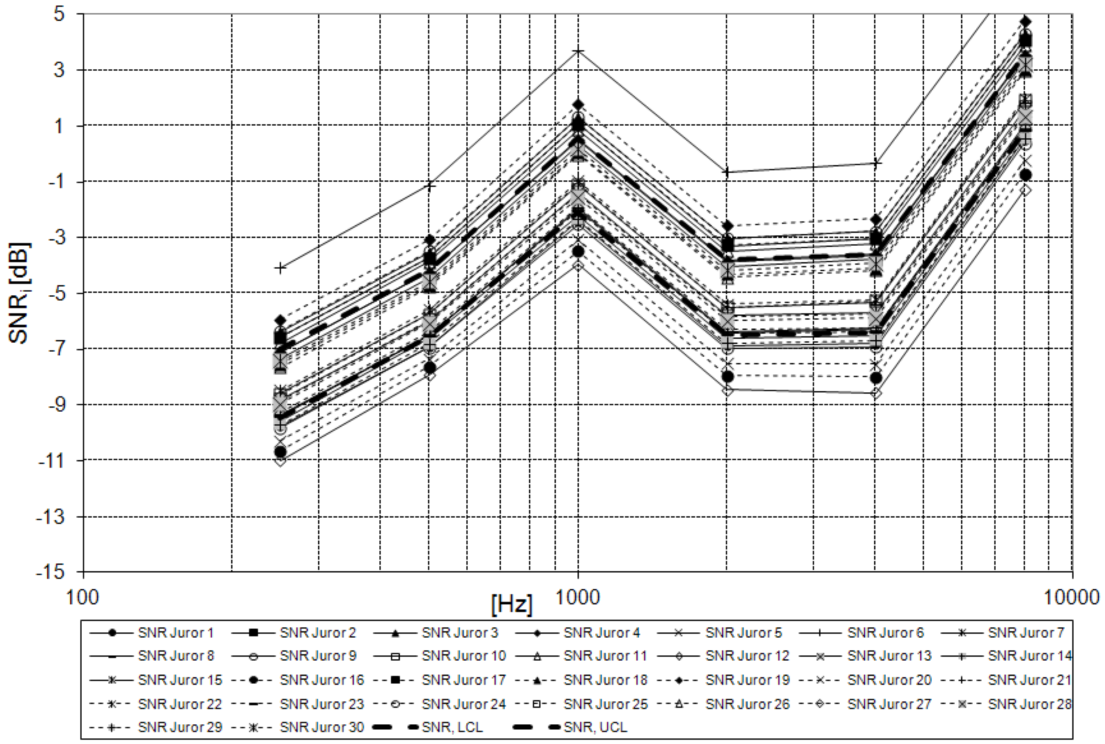


Figure 40: Example SNR with control limits from X -bar chart calculated for the right ear of the listener at sSRT using the HINT in a driving simulator at 100 km/h. The listener was in the driver location, while the talker is in the rear right location. The figure contains data from the corresponding control chart as a function of frequency, providing a different perspective of the same set of data. The control limits based on three standard deviations do not incorporate all of the data points and, as argued previously for the case of the SII, the specification limit may be set to model a six sigma process.

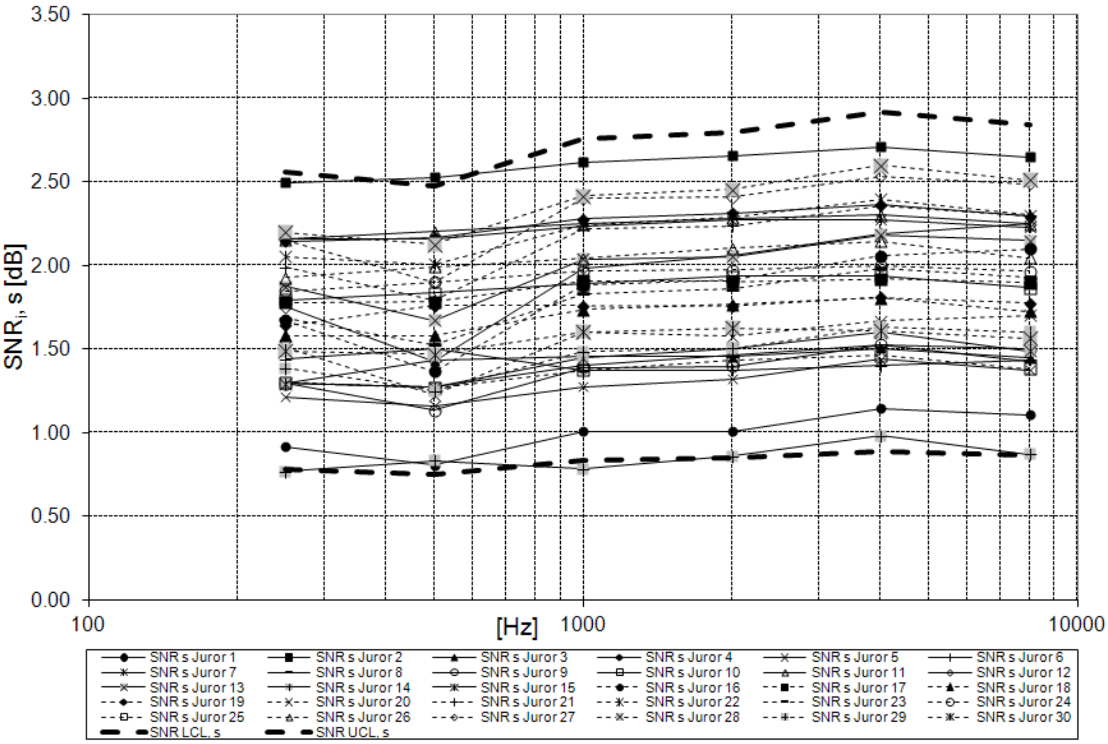


Figure 41: Example SNR standard deviation with control limits from s chart, calculated for the right ear of the listener at sSRT using the HINT in a driving simulator at 100 km/h. The listener was in the driver location and the talker is in the rear right location. The figure contains data from the control chart as a function of frequency, providing a different perspective of the same set of data. The SNR standard deviation values are contained within the three sigma limits.

6.2.2.1 Summary of the Results

A novel method for evaluating in-vehicle speech intelligibility is proposed. The sSRT coupled with the corresponding objective speech intelligibility scores are used to quantify the hearing ability of normal hearing individuals and the influence of multi-sensory perception on the perception of speech intelligibility in an operating vehicle. The SII based on measured speech signal is evaluated at the sSRT using the HINT results from jury testing in a simulated driving environment (Section 6.2.1). The statistical variability analysis was performed using control charts. The SII values evaluated at the sSRT and the associated statistical variability, in terms of standard deviation, presented in this study are references for future evaluation of in-vehicle speech intelligibility. Recommendations for future work include the quantification of the variability of vocal effort and vehicle interior background noise for incorporation into the speech intelligibility evaluation.

6.2.3 The Analysis of the Reduction in Vehicle Speech Intelligibility for Normal Hearing and Hearing Impaired Individuals in a Simulated Driving Environment with Contributions from the Ordered and Masking Noise Sources

The six sigma control limits from a previous jury test (Section 6.2.2) are shown as a reference in the first line of Tables 22 through 24. Subsequent values are associated with the SII calculations at the sSRT for the normal hearing (NH) and hearing impaired (HI) jury test participants. The normal hearing data shown is the average SII at sSRT from the six jury test participants.

Table 22: SII evaluated at the sSRT, and the associated variability, s, for talker in the passenger front location. The upper and lower control limits (UCL* and LCL*) are shown as references, and refer to the six sigma control limits based on the study by Samardzic et al (2012).

	50 km/h, Right Ear		50 km/h, Left Ear		100 km/h, Right Ear		100 km/h, Left Ear	
	SII	s	SII	s	SII	s	SII	s
Talker Location	LCL* UCL*	LCL* UCL*	LCL* UCL*	LCL* UCL*	LCL* UCL*	LCL* UCL*	LCL* UCL*	LCL* UCL*
Passenger Front	0.47 **0.56**	0.03 **0.09**	0.34 **0.42**	0.02 **0.08**	0.38 **0.47**	0.03 **0.10**	0.19 **0.27**	0.02 **0.08**
NH (Avg.)	0.33	0.06	0.20	0.05	0.31	0.06	0.12	0.03
HI1	0.27	0.04	0.31	0.07	0.23	0.03	0.33	0.07
HI2	0.46	0.08	0.17	0.05	0.39	0.04	0.08	0.04
HI3	0.32	0.06	0.19	0.04	0.32	0.05	0.18	0.03
HI4	0.52	0.05	0.00	0.00	0.47	0.07	0.00	0.00

Table 23: SII evaluated at the sSRT, and the associated variability, s, for talker in the passenger rear right location. The upper and lower control limits (UCL* and LCL*) are shown as references, and refer to the six sigma control limits based on the study by Samardzic et al (2012).

	50 km/h, Right Ear				50 km/h, Left Ear				100 km/h, Right Ear				100 km/h, Left Ear			
	SII		**s**		**SII**		**s**		**SII**		**s**		**SII**		**s**	
Talker Location	LCL*	UCL*	LCL*	UCL*	LCL*	UCL*	LCL*	UCL*	LCL*	UCL*	LCL*	UCL*	LCL*	UCL*	LCL*	UCL*
Passenger Rear Right	0.42	**0.50**	0.03	**0.09**	0.39	**0.47**	0.03	**0.08**	0.33	**0.41**	0.03	**0.09**	0.25	**0.34**	0.03	**0.09**
NH (Avg.)	0.29		0.05		0.25		0.05		0.19		0.05		0.13		0.04	
HI1	0.25		0.02		0.43		0.04		0.19		0.03		0.40		0.07	
HI2	0.34		0.03		0.19		0.02		0.28		0.07		0.12		0.06	
HI3	0.29		0.05		0.27		0.05		0.19		0.08		0.22		0.05	
HI4	0.49		0.06		0.00		0.00		0.49		0.13		0.00		0.00	

Table 24: SII evaluated at the sSRT, and the associated variability, s, for talker in the passenger rear left location. The upper and lower control limits (UCL* and LCL*) are shown as references, and refer to the six sigma control limits based on the study by Samardzic et al (2012).

	50 km/h, Right Ear				50 km/h, Left Ear				100 km/h, Right Ear				100 km/h, Left Ear			
	SII		**s**		**SII**		**s**		**SII**		**s**		**SII**		**s**	
Talker Location	LCL*	UCL*	LCL*	UCL*	LCL*	UCL*	LCL*	UCL*	LCL*	UCL*	LCL*	UCL*	LCL*	UCL*	LCL*	UCL*
Passenger Rear Left	0.42	**0.50**	0.03	**0.08**	0.41	**0.49**	0.03	**0.08**	0.33	**0.41**	0.02	**0.08**	0.27	**0.35**	0.03	**0.08**
NH (Avg.)	0.28		0.05		0.27		0.05		0.18		0.05		0.14		0.04	
HI1	0.30		0.03		0.48		0.05		0.18		0.03		0.36		0.05	
HI2	0.36		0.03		0.21		0.02		0.26		0.06		0.11		0.05	
HI3	0.25		0.07		0.24		0.07		0.24		0.04		0.24		0.06	
HI4	0.48		0.06		0.00		0.00		0.41		0.12		0.00		0.00	

Compared to the results from the previous study, the SII scores were on average 10% lower than the lower control limits (LCL) for all conditions, although the standard deviation was contained within the reference control limits. The UCL values were not exceeded and could be used as benchmarks in future studies as they represent the minimum proportion of audible speech that needs to be available to the listener at the speech reception threshold.

As in the previous study (Section 6.2.2) involving normal hearing participants in a driving simulation and the HINT, all the test participants, both normal hearing and the hearing impaired, indicated that a greater listening effort was required when the talker was located in the rear passenger locations as compared to the front passenger location. For each configuration of the talker and the listener, the same HINT procedure was used and the speech intelligibility was quantified by the sSRT; the presentation level required a listener to recognize the speech materials correctly 50% of the time. In each test scenario, the speech at sSRT levels was just barely perceptible by the participants. Interestingly, the results indicate that person to person communication at sSRT levels was not necessarily associated with the same listening effort; the conditions of minimal intelligibility required for understanding speech was dependent upon a combination of influences, including the directivity and the distance of the talker with respect to the listener, vocal effort, and the signal to noise ratio. The relationship between these influences is not necessarily captured by the SII. As stated previously, the UCL for the SII values at sSRT for a particular driving situation may still be used as benchmarks. However, for the lower control limit, it was found that the increase in the listening effort was reflected by a decrease in SII scores. This implies that for more challenging listening situations, the sSRT is associated with a lower SNR and lower SII score. Therefore, an SII at sSRT is sensitive to the changes in SNR.

The above arguments pertaining to the SII sensitivity to the SNR are further reinforced by the simulator jury test results using the model from on-road background noise measurements. The signal to noise ratio at the sentence speech reception threshold levels in different listening environments varied; on average, the SNR was -8 dB for the semi-anechoic dynamometer test cell background noise measurements and -14 for the on-road background noise measurements. In general, as the hearing conditions got more challenging for lower SNR, the auditory speech perception adapted such that lower SII scores characterize the sSRT at lower SNR, all using same speech material. The band importance functions remain constant for each driving condition as the same speech material is used. Further detailed studies are recommended to investigate the interaction between multisensory hearing and SNR at the SII at sSRT within a driving environment. Another potential influence may be the shape of the background noise spectrum and its similarity to the speech spectrum; According to Rhebergen et al (2005), in the presence of one or more interfering talkers, the more similar the target and masker are, the more the listener is confused or distracted. This in turn results in poorer speech intelligibility performance. In this case, the difference in SII scores may be due to any differences between the background noise measured in vehicle dynamometer compared to the on-road measurements and the speech spectrum. Figure 42 illustrates an example where the shape of both the vehicle dynamometer and on-road background noise spectra are quite different from the shape of the speech signal as well as from each other. In addition, the vehicle dynamometer background noise has sharper transitions in spectra - an increase between 1000 Hz and 4000 Hz then a decrease from 4000 Hz to 8000 Hz, while the on-road background noise spectra are steadily decreasing within the entire range of frequencies. Based on the SII results, this ‘smooth’ shape of the background noise spectrum of the on-road measurements may have resulted in a more favorable listening environment for speech intelligibility in noisy conditions such as a vehicle interior.

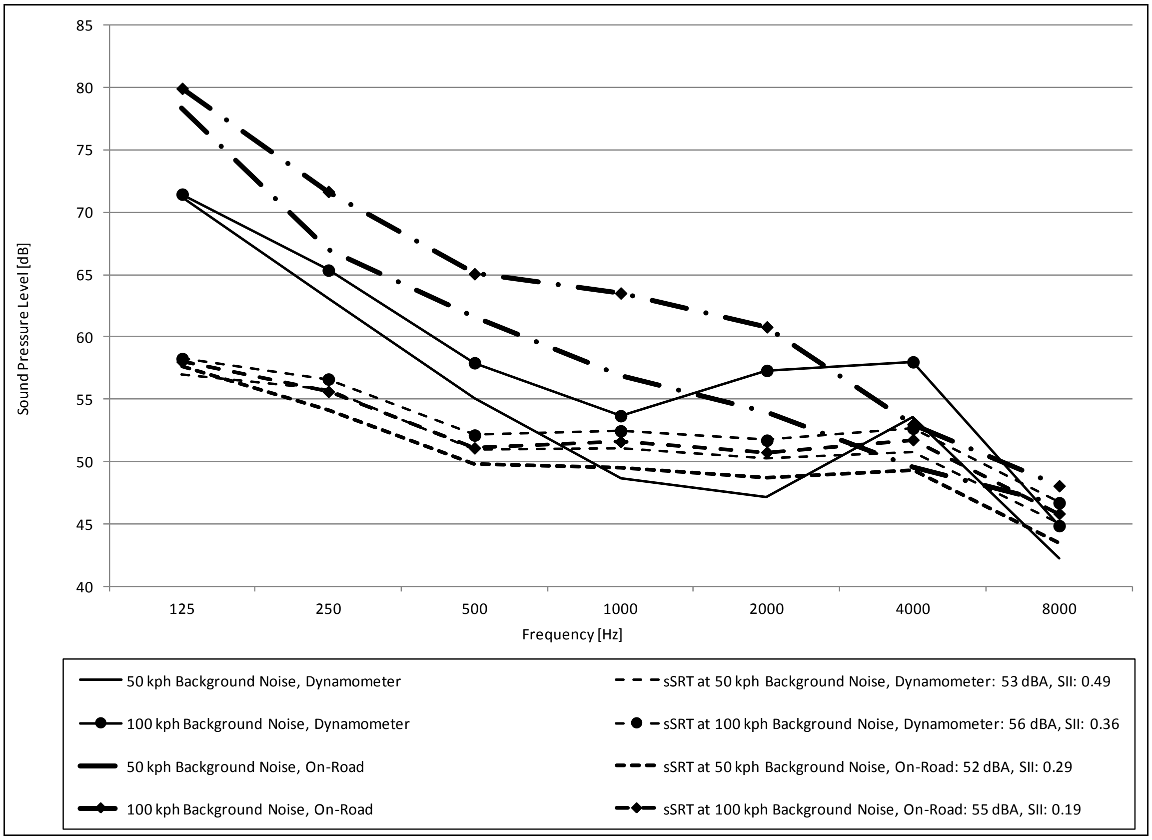


Figure 42: The HINT speech signal spectra at the indicated sSRT and the corresponding background noise spectra at 50 kph and 100 kph, for an example configuration - talker in the driver's location and listener in the passenger rear right location. The SII scores are also provided.

In conclusion, unexpectedly, it was found that the SII at the sSRT is sensitive to the changes in the SNR; the SII at sSRT was different for different background noise spectra resulting from vehicle dynamometer and on-road measurements. Therefore, it is not plausible to use a standard or a benchmark set of control limits associated with the SII values evaluated at the SRT for a particular set of vehicle operating conditions and talker and listener configurations. Instead, currently, without such benchmarks it is important to evaluate speech intelligibility in the context of the listening environment, such as a driving environment. The evaluation should be conducted for each vehicle and listening situation and evaluated according to the test procedure described in this study.

The results from previous SII at SRT studies were obtained in conditions free from the complexities associated with the in-vehicle listening environment, such as binaural, multidirectional and multisensory listening, as shown in this study. The SNR and SII values at SRT were to some extent comparable to the ones found in this study and warrant further research on the subject, particularly as it relates to the field of audiology. For example, Rhebergen and Versfeld (2005) fixed the masking noise at 60 dBA and found that the SII value of 0.35 representing the information required to reach the speech reception threshold occurred at the SNR of -4.5 dB for stationary masking noise and -12 dB for fluctuating masking noise. Rhebergen and Versfeld (2005) used a method similar to the SRT method for sentences in the present study. In contrast to the present study, the sentences in the study by Rhebergen and Versfeld (2005) have been presented monaurally and using speech-shaped masking noise. Similarly, in the study by Rhebergen et al (2006), all noise conditions had a long-term average spectrum equal to the long-term average spectrum of the target female speech material while the subjects received the signals monaurally at their best ear at a fixed noise level of 65 dBA. In another study by Rhebergen et al (2009), the monaural SRT at the better ear was also measured.

Figure 43 illustrates an example of the SII evaluation at the SRT using background noise components decomposed from the measurements of the total on-road background noise.

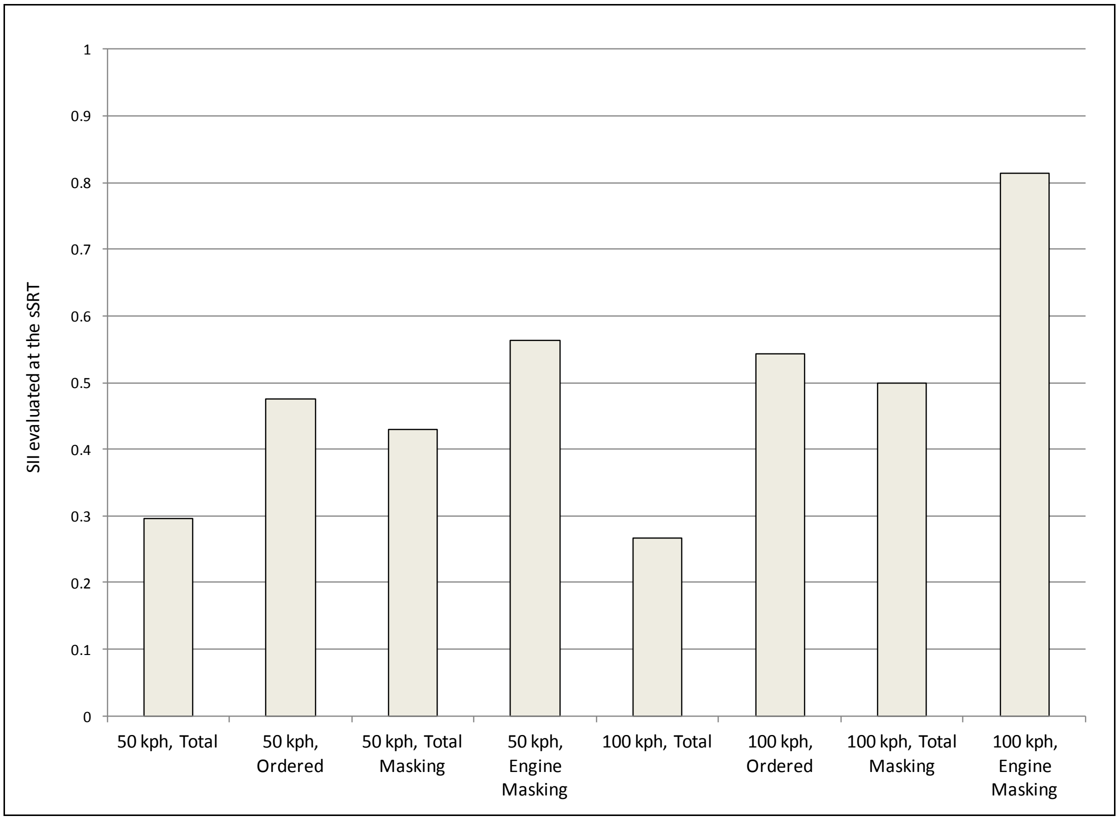


Figure 43: Example SII evaluation at the SRT using the HINT sentence responses of a single normal-hearing participant (NH4) during a driving simulation, at 50 kph and 100 kph, when the talker is in the passenger front (PF) location. In this example, the octave data used in the SII calculations was based on the background noise and speech measurements obtained at the right ear of the driver/listener. The SII was calculated for the contributions of the ordered, total masking, and engine masking components of the total background noise, to investigate the effect of these components on the loss of speech intelligibility.

The contribution to the reduction of speech intelligibility may be studied for the various operating conditions, talker and listener configurations and ears of the listener. For the example shown in Figure 43, the total masking noise sources are the most significant contributors to the reduction of speech intelligibility at both speeds. Compared to the ordered noise sources, the SII scores using this noise component resulted in the lowest SII values. The contribution of the ordered sources of noise is insignificant at 100 kph compared to 50 kph, as the SII score is close 80 percent.

6.2.3.1 Case Studies of the Hearing Impaired Jury Test Participants

The hearing threshold levels used in the SII calculations in this study were obtained from each of the participants' audiograms (Figure 44), based on the hearing tests administered by certified audiologists.

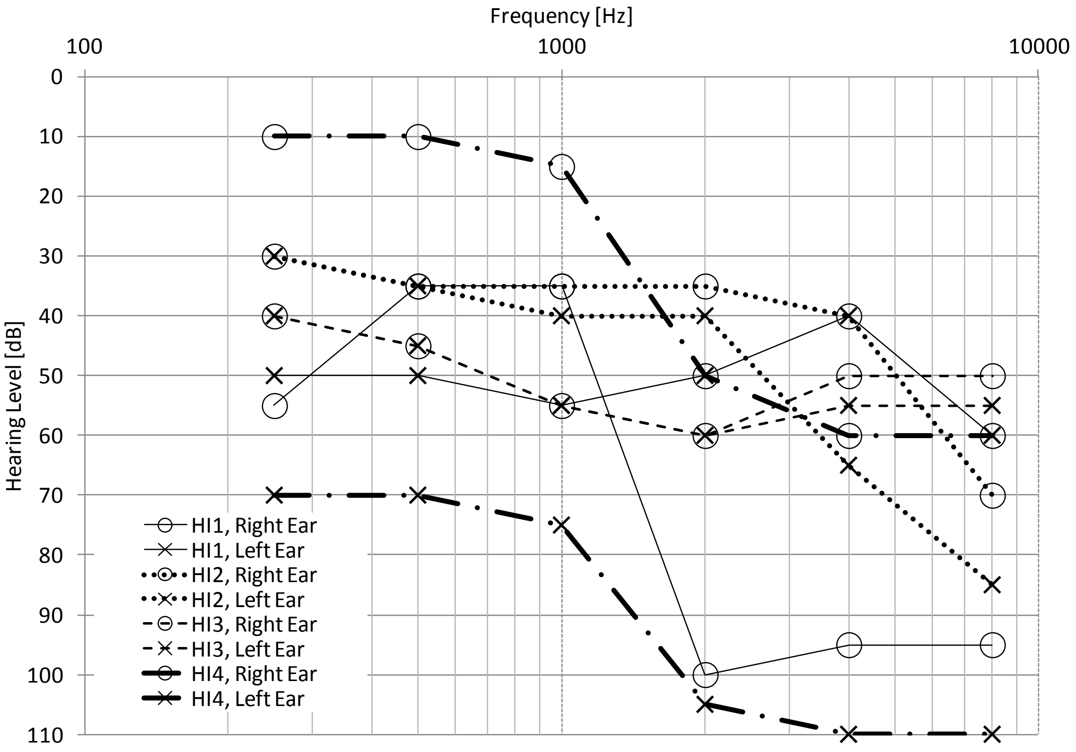


Figure 44: Hearing threshold levels obtained from the audiograms of the four hearing impaired (HI) driving simulation jury test participants.

Three out of the four participants were wearers of hearing aids. They reported to occasionally wearing their assistive devices while driving their vehicles due to the fact that, from their experience, it was difficult to get the signal amplification benefit from their hearing aids in noisy environments such as a vehicle interior. In this study, the HINT in the driving simulator was performed without hearing aids so that the hearing threshold information from audiograms was directly used in SII calculations without any modifications to address frequency filtering associated with the use of the hearing aids.

The hearing level (HL) represents the pure tone threshold level at a specified frequency minus the reference pure tone threshold, which is the minimum sound pressure level of the pure tone capable of evoking an auditory sensation at that same frequency (Debonis and Donohue, 2007). According to Clark (1980), normal hearing range is between -10 and 15 dB HL. The ‘slight’ and ‘mild’ hearing loss is defined from 16 to 25 dB HL, and 26 to 40 dB HL, respectively. The ‘moderate’ and ‘moderately severe’ hearing loss is defined from 41 to 55 dB HL, and 56 to 70 dB HL, respectively. Lastly, the ‘severe’ and ‘profound’ hearing loss range is from 71 to 90 dB HL and greater than 91 dB HL, respectively.

The relationship between the SII value and the sSRT for hearing-impaired listeners is less clear compared to the normal hearing listeners (Rhebergen et al, 2010), however, according to Rhebergen et al (2006), hearing-impaired subjects often require SII values that exceed 0.33, which indicates that correction only for audibility in the ANSI S3.5-1997 SII standard is not sufficient. The exception is for cases of mild hearing loss. An elevated SII associated with an observed SRT is often associated with a supra-threshold deficit in such listeners (Rhebergen et al, 2010).

Additional variability in the results exists because an audiogram is generally measured at octave frequencies with an accuracy of about +/- 5 dB. Rhebergen et al (2010) found that a 5 dB error per octave frequency may lead to approximately a 16.7% audibility difference compared to an ideal prediction. According to Rhebergen et al (2010), the reliability of the absolute-threshold estimate is a major factor in the variance of SII predictions in quiet conditions. However, it may also be an issue in noisy conditions, as is the case in this study, when considering the elevated hearing threshold levels associated with the hearing impaired jury test participants in the simulated driving test. In general, Rhebergen et al (2010) recommends using absolute thresholds recorded at 1/3-octave frequencies for more reliable results rather than using just the octave frequencies for which the audiogram is routinely measured.

6.2.3.1.1 Case Study 1 – HI1

The participant reported a history of otosclerosis treated with stapendectomy for the right ear resulting in a high frequency sensorineural hearing loss. Pure tone air and bone conduction testing revealed an essentially moderate mixed hearing loss for the left ear and a mild to profound hearing loss for the right ear. The participant also reported using binaural hearing aids for about 15 years.

Samardzic and Novak (2011) found that the signal to noise ratio of the ear closer to the talker was the main influence on the in-vehicle speech intelligibility performance when the binaural difference in the speech sound pressure level was significant. That is, when the talker was in the front passenger location next to the listener who was driving. The same is for the participant where the ear associated with less hearing loss (better ear) was the main influence on the in-vehicle speech intelligibility performance. In case study 1, unfortunately, the participant’s better ear was farther away from the talker, especially when the talker is in the front driver location.

For the left, or ‘better’, ear mainly influencing the speech intelligibility perception, the SII results indicated a higher than average variability in terms of the standard deviation as well as the SII score, and therefore, the corresponding SNR, or vocal effort, associated with the speech reception threshold condition.

6.2.3.1.2 Case Study 2 – HI2

The (HI2) participant's hearing loss can be described as mild sloping to severe in the right ear, and mild sloping to profound in the left ear. The participant also reported symptoms of tinnitus usually in the form of a constant high-pitched sound, which occasionally changes in severity. In addition, the participant reported the occasional masking of speech, especially when the frequency content of the speech signal is within a higher frequency range, as the case for a female voice. The HINT implemented in the driving simulator is based on a male voice (Nillson et al, 1994) so this condition may or may not have an effect on the results of the participant HI2 in this study. The right ear associated with less severe hearing loss is closer to the talker in the passenger front and passenger rear right location and may be a favourable circumstance in this case as the listener is positioned in the driver location in this study. The SII in this case was a valid predictor of speech intelligibility by taking into account the hearing threshold elevation, as the SII scores from this participant were comparable to those of the normal hearing listeners. This is despite the fact that the hearing loss of participant HI2 ranged from mild to profound. It would be interesting to note that an alternative situation may also be plausible for individuals diagnosed with tinnitus; Schaette and McAlpine (2011) found that many tinnitus patients present with a normal audiogram. It was suggested that this was possibly a result of a homeostatic response of neurons in the central auditory system to reduced auditory nerve input in the absence of elevated hearing thresholds. Traditional theories assume that tinnitus is triggered by cochlear damage, which would be manifested by elevated hearing thresholds in the audiogram.

6.2.3.1.3 Case Study 3 – HI3

The participant (HI3) has a moderate to moderately severe, bilateral symmetrical, flat hearing loss, characterized with approximately equal hearing threshold levels over the entire range of frequencies in both ears. The participant is a wearer of hearing aids and reported that the condition was present since childhood as well as during the initial acquisition of language. In this case, the SII was a valid predictor of speech intelligibility by taking into account the hearing threshold elevation, as the SII scores from this participant were comparable to those of the normal hearing listeners.

6.2.3.1.4 Case Study 4 – HI4

The participant (HI4) has a profound hearing loss in the left ear. The SII score of zero was calculated as a consequence for this ear at all operating conditions and talker and listener configurations. The right ear has some hearing potential and, as the ear is located closer to the talker in the passenger front and passenger rear right location, potentially provides a favourable condition for the perception of speech intelligibility from the driver's location. According to the participant's audiogram, the hearing test was conducted only between 500 Hz and 4000 Hz. As such, for this study the missing 250 Hz and 8000 Hz HL data required for the SII calculations were assumed to be the same as HL measured at 500 Hz and 4000 Hz, respectively.

Although the ear closer to the talker is the main influence on the in-vehicle speech intelligibility performance when the binaural difference in the speech sound pressure level is significant (Samardzic et al, 2012), it appears in this case that the lack of any hearing ability in one (worse) ear may have an effect on the participant's overall hearing ability. The SII scores associated with the 'better' ear were approximately 20% higher compared to the average, as the participant HI4 needed higher than average SNR, or vocal effort at the speech reception threshold.

6.2.3.2 Summary of the Results

The SII was evaluated at the sSRT for various vehicle operating conditions and talker and listener configurations based on on-road interior sound measurements that include the effects of vehicle wind noise. The jury test participants had various hearing profiles; both normal hearing and hearing impaired. It was found that the SII at sSRT is sensitive to the changes in SNR; the SII scores were lower for the on-road background noise measurements, compared to the dynamometer background noise measurements, implying the SRT occurred at lower or less favourable SNR. The SII was a fair predictor for the hearing impaired individuals, depending on the severity and the ear location associated with the more severe hearing loss, however, due to the highly heterogeneous nature of hearing loss in general, it needs to be evaluated on the case by case basis. It is also recommended to evaluate the hearing thresholds in one third octave frequency bands for improved accuracy of the results.

The SII at sSRT was also calculated individually for the ordered and masking contributors of vehicle interior background noise as an example of the analysis of relative significance of the vehicle background noise sources to in-vehicle speech intelligibility. The total masking noise sources are the most significant contributors to the decrease of speech intelligibility at both speeds. Compared to the ordered noise sources, the SII scores using this noise component resulted in the lowest SII values. The contribution of the ordered sources of noise is insignificant at 100 kph compared to 50 kph, as the SII score is close 80 percent. The method presented can be used to design vehicle sound package components as well as vehicle operating conditions and associated background noise in order to achieve the desired in-vehicle speech intelligibility, particularly the speech reception threshold.

Future work may incorporate a more detailed, component-level driving simulator model where the identification of random sound sources may be performed after the order extraction from the measured vehicle noise. For example, Crew et al (2003) proposed that for random sound analysis in the driving simulator, including road and tire noise, coherence-based methods such as multiple coherent output power, or principle component analysis, are applied to separate the various sources. Wind noise is produced by subtracting the harmonic and random components already decomposed from the overall sound considering that once the harmonic and random components are removed from the overall sound, the only sound remaining is the wind noise.

6.2.4 The Impact of the Band Importance Function in the Evaluation of the Speech Intelligibility Index at the Speech Reception Threshold within a Simulated Driving Environment

A novel method for evaluating in-vehicle speech intelligibility using the SII is based on a measured speech signal, per ANSI S3.5-1997 standard, and it is evaluated at the sentence sSRT in a simulated driving environment. In this context, the impact of different band importance functions in the evaluation of the SII using the HINT in a driving simulator is investigated. The motivation for this study is the fact that the band importance function for the HINT speech material used in this research is currently not developed for the ANSI S3.5-1997 standard also used in this research as a basis for SII calculations.

The speech signal used in the calculations was based on in-vehicle recordings of random noise calibration signal created by averaging all of the HINT sentences. The SII was calculated from the in-vehicle recordings of HINT calibration signal at the levels associated with the average jurors' response to particular HINT sentences during the simulated driving test.

The impact of different band importance functions (BIF's) in the evaluation of the SII using the HINT in a driving simulator is investigated by using the BIF's from a variety of speech material available in the ANSI S3.5-1997 standard: Nonsense syllable tests, PB-words, NU6 monosyllables, Diagnostic Rhyme Test, Short passages and SPIN monosyllables (Table 25).

Table 25: Octave Band Importance Functions for Various Speech Tests (ANSI S3.5-1997).

Frequency Band [Hz]	Average Speech	Nonsense Syllable tests	PB-words	NU6 Monosyllables	Diagnostic Rhyme Test	Short Passages	SPIN Monosyllables
250	0.0617	0.0437	0.1549	0.0853	0.096	0.1004	0.0871
500	0.1671	0.1294	0.1562	0.1912	0.2043	0.2551	0.1493
1000	0.2373	0.2025	0.2165	0.211	0.2343	0.196	0.2206
2000	0.2648	0.3117	0.2768	0.309	0.2643	0.2322	0.3022
4000	0.2142	0.2576	0.1488	0.1682	0.1501	0.1744	0.2102
8000	0.0549	0.0551	0.0468	0.0353	0.051	0.0419	0.0306

Figures 45 through 47 illustrate the results of the SII calculations at sSRT. The sSRT for each vehicle operating condition and talker and listener configuration was an average of the sSRT's of the five participants obtained from jury testing using the driving simulator. The BIF's from Table 25 were applied in the calculations for each combination of speech and background noise levels, and for each ear of the listener. The deviation in SII between the average speech BIF and the various other BIF's did not exceed 4 percent (Figures 45 through 47). In addition, according to Samardzic and Novak (Section 6.2.3), the three sigma limits for standard deviation in SII at sSRT evaluated at test conditions similar to those in this study are between 2 and 9 percent.

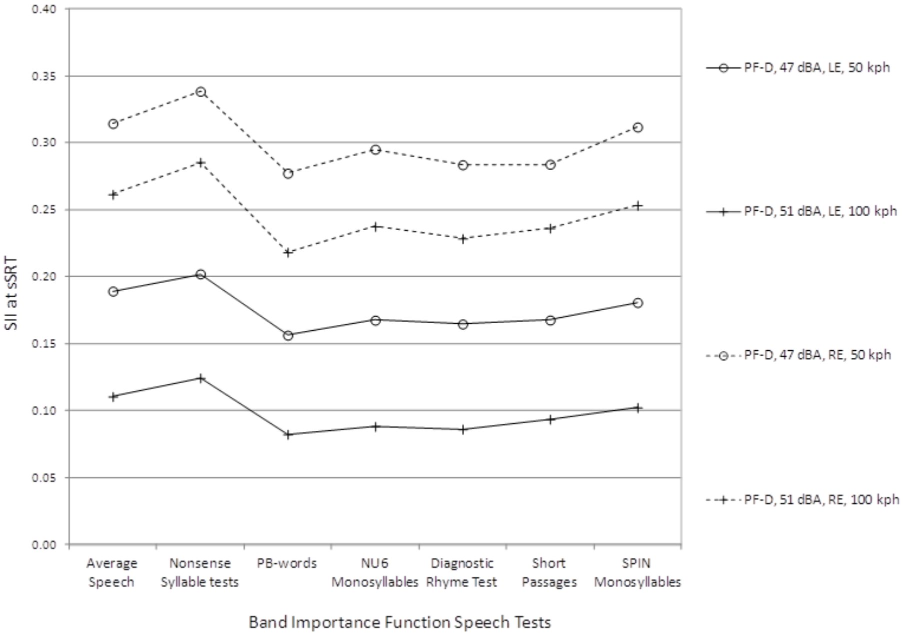


Figure 45: The speech intelligibility index evaluated at 50 kph and 100 kph at the average sentence Speech Reception Threshold (dBA), using band importance functions from various speech tests, per ANSI S3.5-1997 standard. Passenger front (PF) is talker location, driver (D) is listener, while LE and RE represent the left and the right ears of the listener, respectively.

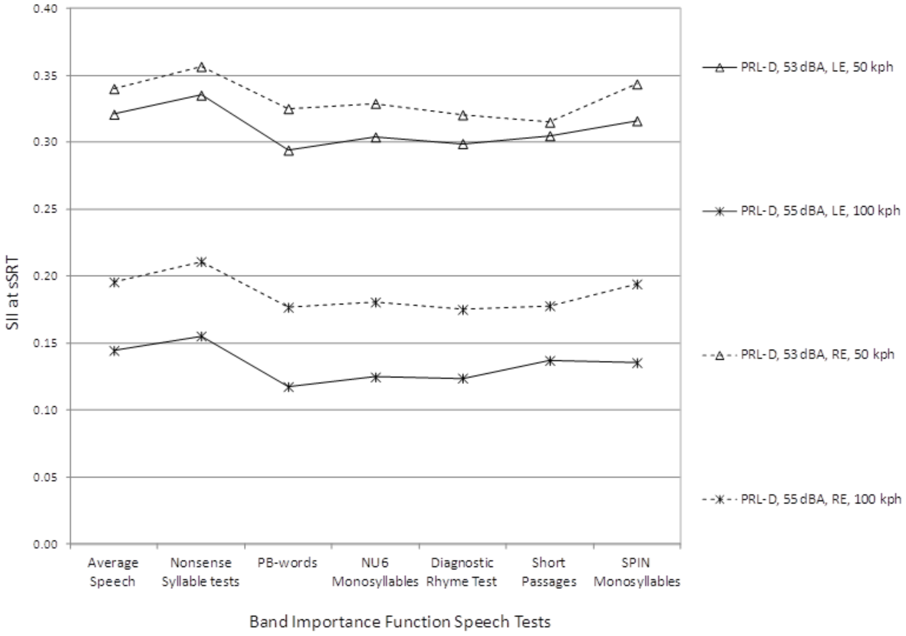


Figure 46: The speech intelligibility index evaluated at 50 kph and 100 kph at the average sentence Speech Reception Threshold (dBA), using band importance functions from various speech tests, per ANSI S3.5-1997 standard. Passenger rear left (PRL) is talker location, driver (D) is listener, while LE and RE represent the left and the right ears of the listener, respectively.

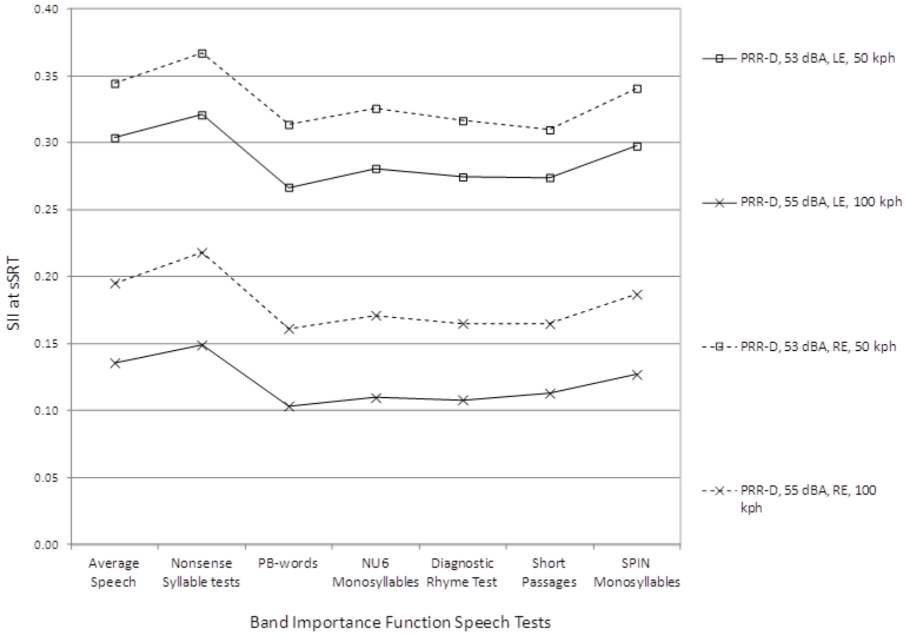


Figure 47: The speech intelligibility index evaluated at 50 kph and 100 kph at the average sentence Speech Reception Threshold (dBA), using band importance functions from various speech tests, per ANSI S3.5-1997 standard. Passenger rear right (PRR) is talker location, driver (D) is listener, while LE and RE represent the left and the right ears of the listener, respectively.

Therefore, at constant background noise conditions, such as driving at 50 kph and 100 kph as considered in this study, the SII appears to be relatively insensitive to the changes in the band importance function. In this research, the band importance function for average speech was used. According to the ANSI S3.5-1997 standard, the band importance function for average speech provides accurate predictions across different communication situations and for communications situations where contextual, linguistic, semantic and syntactic constraints vary within a situation.

CHAPTER 7: Conclusions and Recommendations

In this chapter, the conclusions and recommendation are listed to summarize the main results of this research and to provide suggestions for further investigation of in-vehicle speech intelligibility, respectively.

7.1 Conclusions

The following conclusions were reached after thorough analysis of the results of this research:

- In quantifying in-vehicle speech intelligibility using the most comprehensive objective speech intelligibility metric - the STI, it was found that higher sound pressure levels, depending on the frequency makeup, are not necessarily associated with lower speech intelligibility. In addition, without acoustic perception jury testing it is unclear whether certain trends observed in the STI results presented over a wide range of common vehicle operating conditions are significant in perception of in-vehicle speech intelligibility. These trends include significant differences in STI values, based on the subjective descriptions of intelligibility scores provided in the IEC EN 60268-16:2003 standard, between the ears of the listener, the differences in the rate of change of STI in unsteady background noise at any given speed and the differences in STI for different configurations of the talker with respect to the listener particularly from the back to front locations. It was found that the effects of in-vehicle reverberation on reducing speech intelligibility were negligible; the measurement effort for future in-vehicle STI studies could then be reduced by considering the speech and background noise measurements only, due to their predominant contribution to the apparent signal to noise ratio, and not measuring the impulse response.

- The results on the effects of different types and levels of sound source signals on STI calculations using various vehicle operating conditions as well as talker and listener measurement configurations inside a vehicle were investigated. For a 60 dBA speech signal (current IEC standard, EN 60268-16:2003) and constant speed operation, the STI values range from ‘unintelligible’ to ‘excellent’, depending on the location of the talker and the listener. For a 68 dBA speech signal (previous IEC standard, EN 60268-16:1998), the STI is at least ‘fair’, based on the subjective descriptions of intelligibility scores, and its value was found to be less sensitive to changes in the vehicle operating conditions. The speech signal level from the current standard provides satisfactory Peak to Noise Ratio for any method for obtaining impulse response. An acoustic perception jury testing is needed to determine a realistic vocal effort required for adequate in-vehicle speech intelligibility. The 60 dBA signal, associated with “normal” vocal effort (ANSI S3.5-1997), provided adequate (at least “fair”) intelligibility at lower speeds, such as city driving (50 km/h), for all measurement configurations. An increased vocal effort of at least 68 dBA, considered to be “loud” (ANSI S3.5-1997), was necessary to obtain similar intelligibility scores at higher speeds, such as highway driving (100 km/h), due to significantly higher levels of background noise. An acoustic perception jury testing in a simulated vehicle environment would be conducted to investigate the speech sound pressure level under which speech communication is expected to be intelligible.

- In evaluating in-vehicle speech intelligibility using the best known objective speech intelligibility metrics - the Articulation Index, the Speech Intelligibility Index (SII) and the Speech Transmission Index (STI) - it was found that the SII method, utilizing user-defined, measured, speech signal was the best out of the three metrics for quantifying in-vehicle speech intelligibility. Since the effect of reverberation on the loss of speech intelligibility was negligible, this method resulted in a close correlation with the more measurement-intensive STI method, thus potentially providing a reduction in measurement effort while preserving the accuracy of the results, since the SII method does not require impulse response measurements. Common metrics provide a wide range of scores for a given measurement configuration and operating condition. The scores could also be interpreted differently for each metric. These shortcomings lay the ground for developing acoustic perception jury testing and a novel method for in-vehicle speech intelligibility evaluation.
- The Speech Intelligibility Index (SII) was evaluation at various vehicle operating conditions and talker and listener configurations by considering the threshold loss associated with common hearing impairments - noise-induced hearing loss and presbycusis. The results reveal poor speech intelligibility for most listening situations considered and provide evidence for the need for improving interior sound quality in terms of speech intelligibility for hearing impaired drivers such as senior aged drivers. Further, this work provided additional motivation for including the hearing impaired individuals in acoustic perception jury testing within a driving simulator.

- In an acoustic perception jury testing utilizing the HINT within a driving simulator it was found that when presented with the same listening task, the participants required on average an approximate 3 dB increase in sound pressure level of the HINT speech material while driving and listening compared to when just listening, for an equivalent speech intelligibility performance. When the talker was in the front passenger location, next to the listener who was driving the binaural difference in the speech sound pressure level was significant. In this case, the signal to noise ratio of the ear closer to the talker was the main influence on the in-vehicle speech intelligibility performance.
- A proposed novel method for evaluating in-vehicle speech intelligibility involves evaluating SII at the sSRT using acoustic perception jury test results obtained within a simulated driving environment. The background noise measurements used in creating the simulator model were obtained using a vehicle dynamometer. The statistical variability analysis was performed using control charts. Using this method the hearing ability of normal hearing individuals and the associated statistical variability was quantified thus providing a benchmark for future evaluation of in-vehicle speech intelligibility.
- Another driving simulator model incorporated jury test participants with various hearing profiles and on-road interior sound measurements used to include the effects of vehicle wind noise. It was found that the SII at sSRT is sensitive to the changes in SNR; the SII scores were lower for the on-road background noise measurements, compared to the dynamometer background noise measurements, implying the SRT occurred at lower or less favourable SNR. The SII was a fair

predictor for the hearing impaired individuals, depending on the severity and the ear location associated with the more severe hearing loss, however, due to the highly heterogeneous nature of hearing loss in general, it needs to be evaluated on the case by case basis.

- In the same study, the SII at sSRT was also calculated individually for the ordered and masking contributors of vehicle interior background noise as an example of the analysis of relative significance of the vehicle background noise sources to in-vehicle speech intelligibility. This information can be used to design vehicle sound package components as well as vehicle operating conditions and associated background noise in order to achieve the desired in-vehicle speech intelligibility, particularly at the speech reception threshold.

7.1.1 Significant Contributions to Research

The following contributions associated with this research have been made to the state of the art:

- A detailed investigation of all common objective speech intelligibility metrics for in-vehicle applications and laying groundwork for an improved evaluation method to include directivity and the distance of the talker with respect to the listener, binaural listening, hearing profile of the listener, vocal effort, and multisensory hearing, all particular to an in-vehicle listening environment. In general, the research suggests that a higher practical value of common speech audiometric test results may be achieved by facilitating the speech testing within an applicable listening environment; for the case of this research, simulated driving environment.

- Development of an innovative method for the evaluating of in-vehicle speech intelligibility by implementation of HINT, a common audiometric speech test, within a simulated driving environment, and subsequent quantification of speech intelligibility using the SII, the most practical objective speech intelligibility metric for in-vehicle applications, by evaluation at the sentence speech reception threshold.
- Quantifying statistical variability of speech hearing ability of normal hearing and hearing impaired individuals using a simulated driving environment under a variety of vehicle operating conditions and listening situations, all using control charts.
- Quantifying the effect of the individual sources of sound to the vehicle interior sound, specifically their effect on speech intelligibility, in the context of the above speech intelligibility evaluation method. This evaluation provides the potential for modifying the vehicle components or operating conditions that contribute to the reduction of in-vehicle speech intelligibility.

7.2 Recommendations

- Incorporate a variety of vehicle types as well as hearing profiles and further, to investigate parameters related in-vehicle speech intelligibility evaluation.
- Quantify the statistical variability of vocal effort and vehicle interior background noise in the evaluation of in-vehicle speech intelligibility.

- Perform an acoustic perception jury testing to evaluate the relationship between the listening effort and the vocal effort for a variety of vehicle operating conditions and listening situations.
- Develop a more detailed, component-level driving simulator model where the identification of random sound sources may be performed after the order extraction from the measured vehicle noise. The noise sources may include wind, tire, engine, transmission, intake, exhaust systems. The contribution of each of the noise sources to the loss of speech intelligibility may be quantified, as presented in this research.
- Evaluate the hearing thresholds at one-third octave frequency bands, instead of one-octave frequency bands presented in conventional audiograms, for improved accuracy of the objective speech intelligibility metric results calculations.

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APPENDICES

Appendix A: Equipment Specifications

A1: Bruel and Kjaer Type 4100 Head and Torso Simulator

MICROPHONES AND PREAMPLIFIERS
Two Type 4190–L–002 microphone/preamplifier assemblies with built-in TEDS, each comprising a ½″ Falcon Range Microphone Type 4190 placed in the bottom of the concha, and Falcon series Preamplifier Type 2669 L with charge injection calibration (CIC) facility and LEMO connector
Microphone Sensitivity: 50mV/Pa. Individually calibrated
Upper Limit of Dynamic Range: 148 dB SPL at 3% distortion
Max. Sound Pressure Level:
159 dB peak with Preamplifier Type 2669 and mains driven power supplies
138 dB peak with Preamplifier Type 2669 and battery power supplies
Preamp. Lower Limiting Frequency: <2Hz (–3dB)

PINNA SIMULATOR
Dimensions similar to those specified in ITU–T Rec. P.58, IEC 959 and ANSI S3, 36–1985, except for the ear canal extensions

HEAD AND TORSO SHAPES
The main dimensions comply with the dimensional requirements of ITU–T Rec. P.58 and the reports from IEC 959 and ANSI S3 36–1985

SHOULDER DAMPING FABRIC
The shoulders, chest and back are covered with a damping fabric to adjust diffraction. The fabric has a minimum of 10% absorption in the range of 100Hz to 20 kHz.

LEFT/RIGHT EAR TRACKING
±1 dB up to 5 kHz
±3 dB up to 8 kHz

CALIBRATION
Sensitivity calibration can be made using a calibrator or pistonphone with Calibration Adaptor DP 0887

DIMENSIONS AND WEIGHT
Head Height: 700mm (27.6″)
Torso: 480 × 440 × 210 mm (18.9 × 17.3 × 8.3″)
Weight: 7.9 kg (17.4 lb.)

A2: Bruel and Kjaer Type 4128 Head and Torso Simulator

LISTENER FREQUENCY RESPONSE
Conforms to ITU-T Rec. P.58 for measurements on telecommunications devices and to IEC60318–7 and ANSI S3.36–1985 for measurements on air conducting hearing aids.

EAR SIMULATOR
IEC 60318–4/ITU-T Rec. P.57 Type 3.3-based calibrated ear simulator complying with ITU-T Rec. P.57, IEC 60318–4 and ANSI S3.25 standards. Output from the ear simulator is via a 7-core 3 m cable (2.3 m from the bottom of the torso) terminated with a Lemo (1B) plug. For connection to a preamplifier input socket of Brüel & Kjær Power Supplies, Analyzers, etc., a Lemo-to-Brüel & Kjær adaptor is supplied
Typical Sensitivity: 11.6 mV/Pa = –38.7 dB (±1.5 dB) re 1 V/Pa @ 250 Hz
3% Distortion Level: 162 dB re 20 µPa at eardrum position

LEFT EAR TO RIGHT EAR TRACKING
±1 dB up to 5 kHz, ±3 dB up to 8 kHz (measured using the same ear simulator)

PINNA SIMULATORS
Dimensions similar to those specified in ITU-T Rec. P.58, IEC 60318–7 and ANSI S3.36. Minor adjustments in the dimensional details have been made which enable Type 4128-C to conform with the acoustic specifications of these documents in the frequency range 100 Hz to 8 kHz. Types 4158-C and 4159-C are supplied with calibrated pinna simulators. An additional pair of uncalibrated hard pinna simulators are available as accessories.

MOUTH SIMULATOR
Input to mouth simulator via 0.75 m cables (0.2 m from the bottom of the torso) terminated with banana-sockets
Sound Pressure Distribution: conforms to ITU-T Rec. P.58
Mouth Opening: W × H: 30 × 11 mm (1.18 × 0.43″)
Equivalent Lip Plane Position, CL: 6 mm in front of the sound radiation opening
Mouth Reference Point, MRP: 25 mm in front of mouth CL
Continuous Output Level at MRP:
Min. 110 dB SPL, 200 Hz to 2 kHz
Min. 100 dB SPL, 100 Hz to 8 kHz
Typical Sensitivity at 1 kHz: 80 dB SPL 2 V/500 mm
Distortion (Harmonic Components up to 8 kHz) at 94 dB SPL:
<2%, 200 Hz to 250 Hz; <1% >250 Hz

DIMENSIONS AND WEIGHT
The main dimensions comply with the dimensional requirements of ITU-T Rec. P.58 and the reports from IEC 60318–7 and ANSI S3.36-1985
Total Height, Head and Torso: 695 mm (27.4″)
Torso: Height: 460 mm (18″), Width: 410 mm (16″), Depth: 183 mm (7.2″)
External Neck Diameter: 112 mm (4.4″)
Head Angles: Vertical or tilted 17° forwards
Weight: 9 kg (19.8 lb.)

A3: Bruel and Kjaer Type 2716 Audio Power Amplifier

FREQUENCY RESPONSE (8Ω, 1W)
20 Hz . 20 kHz: +0, .1 dB

INPUTS AND OUTPUTS
Gain: 30 dB ± 1 dB
Input Attenuator: 0 . 30 dB in 6 dB ± 0.3 dB steps
Impedance: 20 kΩ
Common Mode Rejection: 50 dB@1 kHz
Slew Rate: 25 V/µs
Output Impedance: 0.03Ω
Hum and Noise: More than 105 dB below max. power
Channel Separation: 70dB@10kHz

FRONT PANEL
Gain Controls: 2 . channels, A and B
Clip Indicator: 2 red LEDs, fast peak and slow release or shorted output
Protection Indicator: 2 yellow LEDs, 80°C at heat sink or 12 kHz at full power
Present Indicator: 2 green LEDs, . 25 dB at Input
On Indicator: 2 green LEDs, DC rail voltage for channel A and B

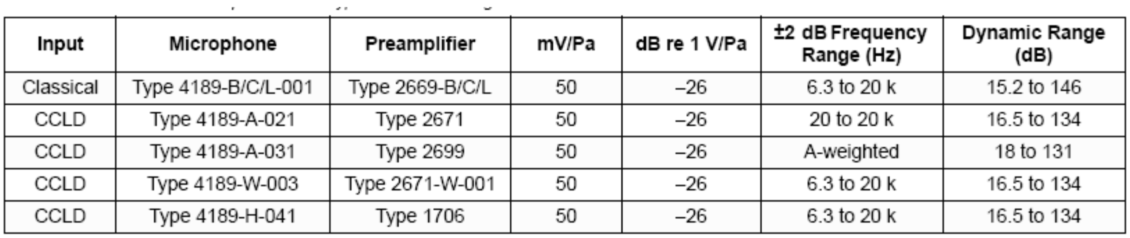
REAR PANEL
Input Connectors: Two XLR-type, 3-pin female (pin 2+) and 1/4″ jack
Output Connectors: Two Neutrik®, 4-pin, Speakon® sockets
Link: Stereo . Link/Bridge A + B
Clip Limiter: On/Off

POWER REQUIREMENTS
Voltage Selector: 230V/115V

DIMENSIONS
W × H × D: 48.3 × 4.4 × 28.0 cm
(19 × 1.7 × 11 inches)

WEIGHT
7.5 kg (16.5 lb.)

A4: Bruel and Kjaer Free Field TEDS (Transducer Electronic Data Sheet) Microphones



Input	Microphone	Preamplifier	mV/Pa	dB re 1 V/Pa	±2 dB Frequency Range (Hz)	Dynamic Range (dB)
Classical	Type 4189-B/C/L-001	Type 2669-B/C/L	50	–26	6.3 to 20 k	15.2 to 146
CCLD	Type 4189-A-021	Type 2671	50	–26	20 to 20 k	16.5 to 134
CCLD	Type 4189-A-031	Type 2699	50	–26	A-weighted	18 to 131
CCLD	Type 4189-W-003	Type 2671-W-001	50	–26	6.3 to 20 k	16.5 to 134
CCLD	Type 4189-H-041	Type 1706	50	–26	6.3 to 20 k	16.5 to 134

Temperature Range

The read/write temperature range of the TEDS chip is guaranteed by the chip manufacturer up to 85ºC (185ºF) only, but the TEDS chip will survive the full specified temperature range of the TEDS microphone/ preamplifier without any damage.

Standard preamplifiers (Types 2669, 2670, 2671, 2699) go to 80°C (176°F). High-temperature preamplifier Type 1706 goes to 125°C (257°C). Remember also to use cables with the correct temperature range.

Cable Length

TEDS will normally work with cables up to 100 m (328 ft).

A5: Bruel and Kjaer Type 4231 Sound Calibrator

STANDARDS SATISFIED
EN/IEC 60942 (2003), Class LS and Class 1, Sound Calibrators
ANSI S1.40 – 1984, Specification for Acoustic Calibrators

SOUND PRESSURE LEVELS
94.0 dB ±0.2 dB (Principal SPL) or
114.0 dB ±0.2 dB re 20 μPa at reference conditions

FREQUENCY
1kHz ±0.1%

SPECIFIED MICROPHONE
Size according to IEC 61094-4:
– 1″ without adaptor
– 1/2″ with adaptor UC-0210 (supplied)
– 1/4″ with adaptor DP-0775 (optional)
– 1/8″ with adaptor DP-0774 (optional)

EQUIVALENT FREE-FIELD LEVEL
(0° incidence, re Nominal Sound Pressure Level)
– 0.15 dB for 1/2″ Brüel & Kjær Microphones. See Type 4231 User Manual for other microphones

EQUIVALENT RANDOM INCIDENCE LEVEL
(re Nominal Sound Pressure Level)
+0.0 dB for 1″, 1/2″, 1/4″ and 1/8″ Brüel& Kjær Microphones

NOMINAL EFFECTIVE COUPLER VOLUME
>200cm3 at reference conditions

DISTORTION
<1%

LEVEL STABILITY
Short-term: Better than 0.02 dB (as specified in IEC 60942)
One Year: Better than 0.05 dB (σ = 96%)
Stabilization Time: <5 s

REFERENCE CONDITIONS
Temperature: 23°C ±3°C (73° ±5°F)
Pressure: 101 ±4 kPa
Humidity: 50%, –10% +15% RH
Effective Load Volume: 0.25cm^3

ENVIRONMENTAL CONDITIONS
Pressure: 65 to 108 kPa
Humidity: 10 to 90% RH (non-condensing)
Effective Load Volume: 0 to 1.5 cm^3

INFLUENCE OF ENVIRONMENTAL CONDITIONS (Typical)
Temperature Coefficient: ±0.0015 dB/°C
Pressure Coefficient: +8 × 10–4 dB/kPa
Humidity Coefficient: 0.001 dB/%RH

POWER SUPPLY

Batteries: 2 × 1.5 V IEC Type LR6 (“AA” size)

Lifetime: Typically 200 hours continuous operation with alkaline batteries at 23°C (73°F)

Battery Check: When Type 4231 stops working continuously, and only operates when the On/Off button is held in, the batteries should be replaced.

DIMENSIONS AND WEIGHT

(Without case)

Height: 40 mm (1.5″)

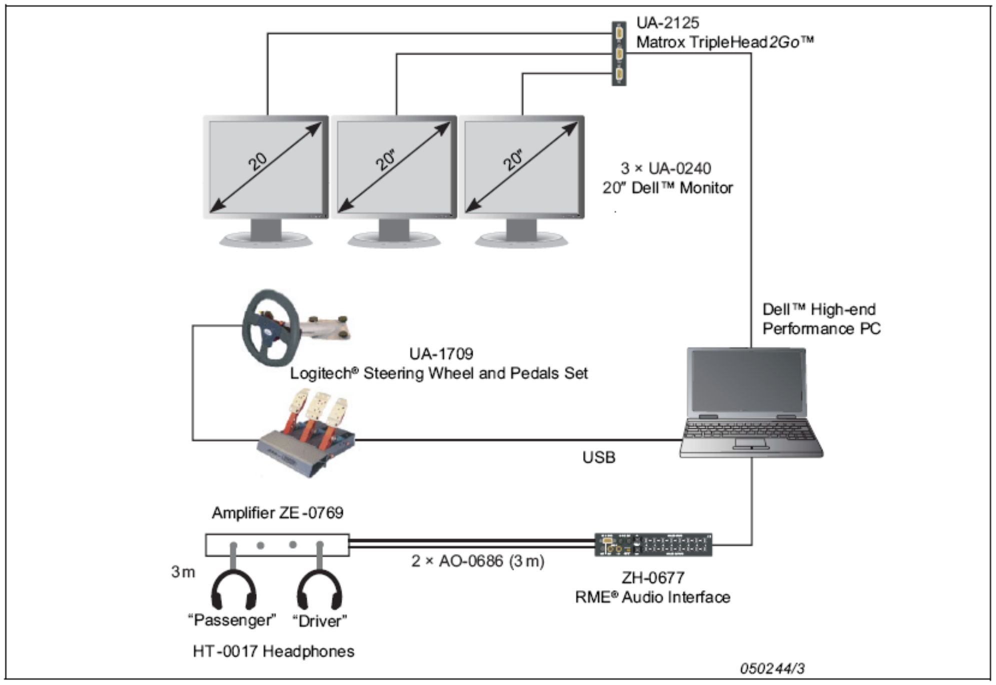
Width: 72 mm (2.8″)

Depth: 72 mm (2.8″)

Weight: 150 g (0.33 lb.), including batteries

Note: All values are typical at 25°C (77°F), unless measurement uncertainty or tolerance field is specified. All uncertainty values are specified at 2 σ (i.e., expanded uncertainty using a coverage factor of 2).

A6: Bruel and Kjaer Desktop Simulator Hardware Overview and Specifications



DTS CORE AND VISUALS TYPE 8601-A-N

Core software: all other modules plug into this. Includes data management, virtual prototype assembler, test manager, and runtime manager.
Enables user to configure data into vehicle models, build a virtual vehicle for assessment, choose which vehicles to compare in a test, and drive the vehicles interactively with virtual instrumentation for feedback of vehicle rpm, gear and speed.
Data types which can be evaluated interactively using DTS Core include:

- spectra
- time histories
- order profiles

Adds a choice of visual scenarios to the simulation, allowing the user to drive as though in a real car. Includes traffic and the ability to define a sequence of road surfaces to allow the user to experience the NVH when driving from one surface to another.

DTS ENGINEERING TYPE 8601-B-N

Engineering style interface to NVH data, giving a button for each sound configured in a virtual vehicle. Mixer-style interface, where user can play any combination of sounds, and hierarchical interface, where intelligence helps decide which sounds make correct combinations for the vehicle.
Allows components (for example, engine mount contributions or intake orifice contribution for example) to be switched on/off, substituted for new versions, and modifications to the sound of individual components to be made (using filtering tools).
User can apply filter sets to sound objects in the simulation. Filtering can be applied at any level/component included in the simulation.
Allows user to set targets very quickly by interactively applying filters while driving the vehicle to check that the outcome is optimal for all driving conditions. Includes a set of pre-defined filters representing engineering rules of thumb, for example addition of secondary firewall, balancer shaft for 4-cylinder engine, double glazing, triple sealing, etc..

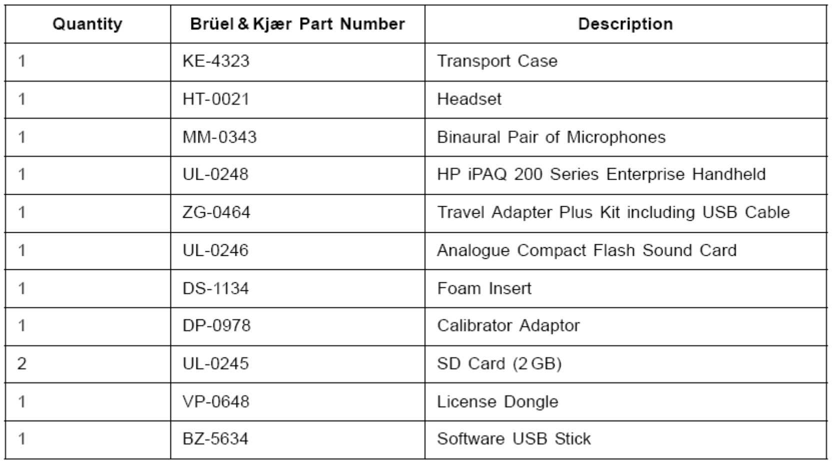
DTS PERFORMANCE DATA PREPARATION TYPE 8601-C-N

Module to configure a free-driving performance model from vehicle speed/time and rpm/time curves.
Permits editing of an existing model to meet new design criteria.

DTS VEHICLE LEVEL DATA PREPARATION TYPE 8601-K-N

This module prepares NVH data to allow the user to perform free driving in an NVH Simulator.
This can be done by decomposing the noise of the vehicle into engine related noise and the residual noise (for example, wind, road, tyre noise).

A7: SonoScout Binaural Recording and Analysis System Parts List and Specifications



Quantity	Brüel & Kjær Part Number	Description
1	KE-4323	Transport Case
1	HT-0021	Headset
1	MM-0343	Binaural Pair of Microphones
1	UL-0248	HP iPAQ 200 Series Enterprise Handheld
1	ZG-0464	Travel Adapter Plus Kit including USB Cable
1	UL-0246	Analogue Compact Flash Sound Card
1	DS-1134	Foam Insert
1	DP-0978	Calibrator Adaptor
2	UL-0245	SD Card (2 GB)
1	VP-0648	License Dongle
1	BZ-5634	Software USB Stick

Microphones

Cartridge Type: Prepolarized, gold-plated condenser element with vertical diaphragm
Microphone Size: 12.7mm (0.5 in.) length, 5.4 mm (0.21 in.) capsule diameter
Frequency Range: 20 Hz . 8 kHz, ± 2 dB re 1 kHz, 3 dB soft boost at 8 - 20 kHz when measured in free field for individual microphones at 0° incidence
Sensitivity: Nominally 20 mV/Pa ±3 dB at 1 kHz
Equivalent Noise Level, A-weighted: Typically 23 dB(A) re 20 μPa
Maximum Sound Pressure Level: 134 dB SPL before damage
Total Harmonic Distortion: <3% at 114 dB SPL (sine)
Preamplifier Output Impedance: 30 . 40Ω

Cable Drive Capability: Up to 3m (10 ft.)
Cable Length: 1.40 m (4.6 ft.) from capsule to connector
Weight: <10 g (down to cable clip)

SoNoScout Case (with system components stored inside)
Dimensions: 164 × 322 × 450 mm (6.5 × 12.7 × 17.7 in.)
Weight: 3.6 kg (7.9 lb.)

A8: LAN-XI Data Acquisition Hardware for Bruel and Kjaer PULSE Software

LAN-XI Data Acquisition Hardware Type 3660 covers a range of input/output modules that can be used stand-alone, in a distributed network or in frames holding up to 11-modules. Fully compatible with PULSE IDAe hardware, LAN-XI hardware is extremely flexible and can be easily reconfigured as requirements demand into systems from 2 channels to more than 1000.

Power over Ethernet

PoE is implemented according to IEEE 802.3af. PoE is wired Ethernet LAN technology that, with a suitable PoE LAN switch, allows the power needed for each module to be carried by screened shielded twisted pair (S/STP or S/FTP) CAT6 LAN cables rather than by separate power cables. This minimises the number of cables required and results in lower cost, less downtime, easier maintenance and greater installation flexibility. PoE switches, such as the Linksys® SRW2008MP, 8-port Gigabit Switch, and PoE Injectors, such as ZyXEL PoE-12 Power over Ethernet (a single-port PoE injector), can be used.

Silent operation

Operation is silent as the modules have no cooling fan – the ribbed design provides enough cooling when used stand-alone.

Phase matching over LAN - PTP

For most sound and vibration applications, sample-synchronous and phase-matched measurements are a must. If no synchronisation method is used, two or more sampling systems will drift apart over time. Even the best clock systems available will, in less than 10 seconds, drift so far apart that the sample correlation will drop to an unacceptable level for high-quality sound and vibration measurements. Traditional measurement systems have a common sample clock ensuring synchronisation between measurement channels located in the same front-end frame. Newer systems have offered various cable-based synchronisation techniques between different front-ends – all with the significant disadvantage of requiring extra cabling.

With LAN-XI, Brüel & Kjær introduces a new technique to ensure sample-synchronous measurements over the same LAN connection used for transferring the measurement data. This simplifies the measurement system's cabling and makes it possible to perform sample-synchronous measurements over long distances, eliminating the effect of delays over the cable and interconnected switches.
PTP synchronisation provides a whole new set of possibilities for combining measurement systems located different places: closer to the actual measurement point, in different rooms/test cells, long distances between equipment. The only thing that is required is a LAN connection.

The IEEE 1588 Precision Time Protocol

PTP synchronisation measures the delays between individual PTP components using a special algorithm (see the IEEE 1588 standard*). By doing this, all delays can be accurately measured, and the individual clocks can be set to exactly the same time. On top of this, the phase drift of the "slave" clocks is continuously measured and counter-adjusted by a control loop, which adjusts the slave clocks' speed. All Brüel & Kjær Sound & Vibration applications will work with either a high-performance 1 gigabit switch or a dedicated PTP switch.

Interchangeable front panels

The modules allow front panels to be interchanged freely, with a variety of connectors for different transducers and applications. See Input Channel section for list of supported transducers.

This results in fewer patch panels, less cable "spaghetti", fewer cable adaptors and faster system setup.

Most connector panels can be used on any module. If an illegal combination is used, such as connecting a front panel that has LEMO (multipurpose) connectors to a module that only supports DeltaTron™ and voltage (B-versions), the module will stop during power-up and display an error message.

Input channels

Frequency Range 51.2 / 102.4 kHz
100% independent channels

The input channels on a module can be set up independently. You can set up the high-pass filters and input gain separately and attach different types of transducers to different channels. The microphone polarization voltage can be switched on or off for each module.

Overload and cable break detection

Input modules use two methods to detect transducer cable breaks or whether the wrong conditioning has been chosen. For microphones, their supply current is monitored. For DeltaTron™ accelerometers (or microphones using DeltaTron™ preamplifiers), the supply voltage is monitored. If a conditioning error, such as a broken cable, is detected, an error is indicated as an overload on the specific channel.

IEEE 1451.4 transducers

Input modules support TEDS transducers allowing automatic front-end and analyzer setup based on information stored in the transducer. TEDS information includes, for example, sensitivity, serial number, manufacturer and calibration date.
The individual frequency response of a transducer can be corrected for using Transducer Response Equalisation (REq-X) to achieve higher accuracy over extended frequency ranges.

Ground-loop noise suppression

The modules' floating/grounded, differential input design and the fact that all external connections (LAN, power supply) are galvanically isolated in the module provide optimal ground-loop noise suppression.

Protection

If the signal input level to a module significantly exceeds the measuring range, the input will go into protection mode for at least 0.5 s until the signal falls again. While protected, the input is partly switched off and the input impedance is greatly increased (The measured value will be strongly attenuated but still detectable).

160 dB in one measuring range - DYN-X technology

Dyn-X is an innovative range of state-of- the-art input modules with a single input range from 0 to 10Vp and a useful analysis range exceeding 160 dB. To date, high-quality transducers and preamplifiers have outperformed measuring equipment with regard to linearity and dynamic performance, being able to deliver a noise- and distortion-free signal over a dynamic signal range of 120 to 130 dB broadband and 160 dB narrow-band.

With Dyn-X technology the entire measurement and analysis chain matches or outperforms the transducer used for measurement. This eliminates the need for an input attenuator for ranging the analysis-system input to the transducer output. All you need to do to get excellent results is choose the right transducer.

Output channels

The two output channels on Type 3160 can be used as high-quality signal generators with a frequency range from 0 to 51.2 kHz and can supply the signals necessary for performing system analysis.

Type 3160 is designed around a powerful digital signal processor and a low-noise, 24-bit, D/A converter. Type 3160 has exceptional flexibility, stability and accuracy. Output levels are adjustable in hardware (two ranges) with maximum outputs of 316mVpeak and 10Vpeak. High-quality levels from 1 μV to 316mV or 10 V are obtained. The output signal is provided by a BNC connector and can be referred to ground or floating. It is possible to add a DC offset, but any unwanted DC offset is automatically removed. When Type 3160 is powered by PoE, only the generator channels and two input channels can be used. If DC or mains power is available, the generator channels and all four input channels can be used.

Linearity

Frequency linearity is better than ±0.1 dB over the entire frequency range, and amplitude linearity is better than 0.1 dB over at least 100 dB amplitude range referred to full scale.

Overload

Output voltages above 11Vpeak or output currents above 40mApeak are indicated as overloads by the circular LEDs on the output channels.

Appendix B: A Complete List of HINT Sentences Used for Jury Testing

PF-D	50 kph	1. (A/the) boy fell from (a/the) window.
		2. (A/the) wife helped her husband.
		3. Big dogs can be dangerous.
		4. Her shoes were very dirty.
		5. (A/the) player lost (a/the) shoe.
		6. Somebody stole the money.
		7. (A/the) fire was very hot.
		8. She's drinking from her own cup.
		9. (A/the) picture came from (a/the) book.
		10. (A/the) car (is/was) going too fast.
		1. (A/the) boy ran down (a/the) path.
		2. Flowers grow in (a/the) garden.
		3. Strawberry jam (is/was) sweet.
		4. (A/the) shop closes for lunch.
		5. The police helped (a/the) driver.
		6. She looked in her mirror.
		7. (A/the) match fell on (a/the) floor.
		8. (A/the) fruit came in (a/the) box.
		9. He really scared his sister.
		10. (A/the) tub faucet (is/was) leaking.

B1: Passenger front (PF) as talker, Driver (D) as listener, at 50 kph.

PF-D	100 kph	1. They heard (a/the) funny noise.
		2. He found his brother hiding.
		3. (A/the) dog played with (a/the) stick.
		4. (A/the) book tells (a/the) story.
		5. The matches (are/were) on (a/the) shelf.
		6. The milk (is/was) by (a/the) front door.
		7. (A/the) broom (is/was) in (a/the) corner.
		8. (A/the) new road (is/was) on (a/the) map.
		9. She lost her credit card.
		10. (A/the) team (is/was) playing well.
		1. (A/the) little boy left home.
		2. They’re going out tonight.
		3. (A/the) cat jumped over (a/the) fence.
		4. He wore his yellow shirt.
		5. (A/the) lady sits in the chair.
		6. He needs his vacation.
		7. She’s washing her new silk dress.
		8. (A/the) cat drank from (a/the) saucer.
		9. Mother opened (a/the) drawer.
		10. (A/the) lady packed her bag.

B2: Passenger front (PF) as talker, Driver (D) as listener, at 100 kph.

PRR-D	50 kph	1. (A/the) boy did (a/the) handstand.
		2. They took some food outside.
		3. The young people (are/were) dancing.
		4. They waited for an hour.
		5. The shirts (are/were) in (a/the) closet.
		6. They watched (a/the) scary movie.
		7. The milk (is/was) in (a/the) pitcher.
		8. (A/the) truck drove up (a/the) road.
		9. (A/the) tall man tied his shoes.
		10. (A/the) letter fell on (a/the) floor.
		1. (A/the) silly boy (is/was) hiding.
		2. (A/the) dog growled at the neighbours.
		3. (A/the) tree fell on (a/the) house.
		4. Her husband brought some flowers.
		5. The children washed the plates.
		6. They went on vacation.
		7. Mother tied (a/the) string too tight.
		8. (A/the) mailman shut (a/the) gate.
		9. (A/the) grocer sells butter.
		10. (A/the) baby broke his cup.

B3: Passenger rear right (PRR) as talker, Driver (D) as listener, at 50 kph.

PRR-D	100 kph	1. The cows (are/were) in (a/the) pasture.
		2. (A/the) dishcloth (is/was) soaking wet.
		3. They (have/had) some chocolate pudding.
		4. She spoke to her eldest son.
		5. (An/the) oven door (is/was) open.
		6. She's paying for her bread.
		7. My mother stirred her tea.
		8. He broke his leg again.
		9. (A/the) lady wore (a/the) coat.
		10. The cups (are/were) on (a/the) table.
		1. (A/the) ball bounced very high.
		2. Mother cut (a/the) birthday cake.
		3. (A/the) football game (is/was) over.
		4. She stood near (a/the) window.
		5. (A/the) kitchen clock (is/was) wrong.
		6. The children helped their teacher.
		7. They carried some shopping bags.
		8. Someone (is/was) crossing (a/the) road.
		9. She uses her spoon to eat.
		10. (A/the) cat lay on (a/the) bed.

B4: Passenger rear right (PRR) as talker, Driver (D) as listener, at 100 kph.

PRL-D	50 kph	1. School got out early today.
		2. (A/the) football hit (a/the) goalpost.
		3. (A/the) boy ran away from school.
		4. Sugar (is/was) very sweet.
		5. The two children (are/were) laughing.
		6. (A/the) fire truck (is/was) coming.
		7. Mother got (a/the) sauce pan.
		8. (A/the) baby wants his bottle.
		9. (A/the) ball broke (a/the) window.
		10. There (is/was) a bad train wreck.
		1. (A/the) boy broke (a/the) wooden fence.
		2. (An/the) angry man shouted.
		3. Yesterday he lost his hat.
		4. (A/the) nervous driver got lost.
		5. (A/the) cook (is/was) baking (a/the) cake.
		6. (A/the) chicken laid some eggs.
		7. (A/the) fish swam in (a/the) pond.
		8. They met some friends at dinner.
		9. (A/the) man called the police.
		10. (A/the) truck made it up (a/the) hill.

B5: Passenger rear left (PRL) as talker, Driver (D) as listener, at 50 kph.

PRL-D	100 kph	1. (A/the) neighbor’s boy (has/had) black hair.
		2. The rain came pouring down.
		3. (An/the) orange (is/was) very sweet.
		4. He took the dogs for a walk.
		5. Children like strawberries.
		6. Her sister stayed for lunch.
		7. (A/the) train (is/was) moving fast.
		8. Mother shut (a/the) window.
		9. (A/the) bakery (is/was) open.
		10. Snow falls in the winter.
		1. (A/the) boy went to bed early.
		2. (A/the) women cleaned her house.
		3. (A/the) sharp knife is dangerous.
		4. (A/the) child ripped open (a/the) bag.
		5. They had some cold cuts for lunch.
		6. She’s helping her friend move.
		7. They ate (a/the) lemon pie.
		8. They (are/were) crossing (a/the) street.
		9. The sun melted the snow.
		10. (A/the) little girl (is/was) happy.

B6: Passenger rear left (PRL) as talker, Driver (D) as listener, at 100 kph.

Appendix C: Letter of Information and Consent to Participate in Research

LETTER OF INFORMATION AND CONSENT TO PARTICIPATE IN RESEARCH

TITLE OF STUDY

Investigation of In-Vehicle Speech Intelligibility for Normal Hearing and Hearing Impaired Listeners Using a Desktop Driving Simulator

PRINCIPAL INVESTIGATOR

Nikolina Samardzic, University of Windsor
kojovic@uwindsor.ca

INVITATION TO PARTICIPATE

You are being invited to participate in a research study that measures the effectiveness of speech communication in vehicles. This letter is intended to provide you with the information you require to make an informed decision on participating in this research. Please take the time to read this information and feel free to ask questions if there is anything unclear to you. You will be given a copy of this letter for your records.
The research is being conducted for Nikolina Samardzic's Doctoral Dissertation under the supervision of Dr. Colin Novak. The research is being funded by the Ontario Research Fund.

PURPOSE OF THE STUDY

The purpose of this investigation is to quantify in-vehicle speech intelligibility between a driver and a passenger using the Hearing in Noise Test (HINT) and a desktop driving simulator. The loss of speech intelligibility under a variety of vehicle operating conditions and driver and passenger configurations is investigated. The results of this study will help in gaining a more detailed understanding of in-vehicle communication and future research of developing new in-vehicle hearing technologies. This would include the development of new cabin designs to facilitate better communication in vehicles as well as the development of better in-vehicle communication systems.

PROCEDURES

If you volunteer to participate in this study you will be asked to drive a desktop driving simulator at either 50 km/h or 100 km/h. As you are driving, speech will be played to you through the headphones and you will be asked to repeat back what you have heard. While you are listening, the sound level of the speech might be increased or decreased, which may make listening slightly easier or more difficult. The test is expected to last up to one hour.

POTENTIAL RISKS AND DISCOMFORTS

Overall risks involved in this research are minimal. The sound level of the noise stimuli played over the headphones of the desktop simulator will always be within the range encountered in a vehicle moving between 50 km/h and 100 km/h. The sound level of speech played simultaneously through the headphones will be close to your threshold of hearing. The study will be terminated if you report any signs of physical or emotional discomfort while driving the desktop simulator or at any point during the study.

POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

You may not benefit directly from participating in this study, but your participation will help in understanding the nature of in-vehicle communication and speech intelligibility. The results of this study can potentially be used in assisting with the development of new vehicle designs as well as the development of in-vehicle communication systems for improved speech intelligibility.

COMPENSATION FOR PARTICIPATION

Participation in this research is voluntary and you will not be paid to participate in this research.

CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission.

PARTICIPATION AND WITHDRAWAL

Participation in this study is voluntary. You may refuse to participate, refuse to answer any questions, or withdraw from the study at any time with no consequences.
If you decide to withdraw or if you are withdrawn before the study is completed, we will ask for your permission to retain and use your data collected up to that point. If you decline permission, your data and contact information will be destroyed. However, it will only be possible to do so if they have not been included in any publication.

FEEDBACK OF THE RESULTS OF THIS STUDY TO THE SUBJECTS

The research findings will be available once published. If interested, a hard copy or an electronic copy of the publication would be provided to you.

SUBSEQUENT USE OF DATA

The study data may be used in subsequent studies.

RIGHTS OF RESEARCH SUBJECTS

If you have questions regarding your rights as a research subject, contact: Research Ethics Coordinator, University of Windsor, Windsor, Ontario, N9B 3P4; Telephone: 519-253-3000, ext. 3948; e-mail: ethics@uwindsor.ca

SIGNATURE OF RESEARCH SUBJECT/LEGAL REPRESENTATIVE

I understand the information provided for the study "Investigation of In-Vehicle Speech Intelligibility Using a Desktop Driving Simulator "as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____

Name of Subject

____ ____________________

Signature of Subject Date

SIGNATURE OF INVESTIGATOR

These are the terms under which I will conduct research.

_______________________________________ _____________________

Signature of Investigator Date

VITA AUCTORIS

Nikolina Samardzic was born in 1980 in Sarajevo, Bosnia and Herzegovina. She graduated from Interlochen Arts Academy, Interlochen, Michigan in 1998. She attended the University of Windsor, Windsor, Ontario where she received the Bachelor of Applied Science degree in Mechanical Engineering with Automotive Option in 2002, graduating with Distinction. She obtained her Master of Applied Science degree in Mechanical Engineering from the University of Windsor in 2005. From 2002 until 2008 her employment experience included conducting numerous noise and vibration measurement and simulation projects in the automotive industry; first, at the Ford Motor Company Powertrain Engineering Research and Development Centre, and then at Rieter Automotive North America. Nikolina is currently a candidate for the degree of Doctor of Philosophy in Mechanical Engineering at the University of Windsor.